Maintenance and Repair

A Maintenance and Repair Management Performance Model for Tugs

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by

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Abstract

Maritime transport covers about 90% of world trade and is seen as one of the most cost-effective way of transporting goods. In order to safely accommodate vessels calling into ports, tugs are operated to assist various sized vessels with navigating, manoeuvring and berthing. Competition within the ship handling market has always been fierce. Boskalis Towage, through a network of joint ventures, offers harbour- and terminal towage services around the world, comprised of about 450 vessels. With operating a large fleet comes large Operating Expenses (OPEX). In order to deliver a more cost effective service Boskalis turns to business intelligence (BI) to help with the decision-making process. Maintenance is crucial for the operation of the vessels, but also a large part of the expenses. Large deviations in maintenance costs and operational performance exist between the joint ventures. However, the reasons behind these deviations are yet unclear due to the absence of continuous monitoring capabilities. The objective is therefore to increase the management capabilities of detailed performance monitoring of M&R expenses and performance of tugs, through which possible improvements can be determined.

The M&R of tugs is influenced by various factor, such as utilisation, operational location and installed equipment. This research has evaluated the current Enterprise Performance Management (EPM) of Boskalis Towage and used literature on Maintenance Performance Management (MPM) in order to erect a *multi-criteria hierarchical function specific framework* which is a framework for maintenance performance monitoring. The presented framework covers aspects of alignment with business objectives and plan, strategy and implementation. Moreover, the framework presents the maintenance function and its areas of performance measuring of *equipment-*, *cost-* and *process performance* across the organisational hierarchy.

By performing a regression analysis of the maintenance data, this has also resulted in an increased understanding of the relationship between maintenance costs, operational data and vessel characteristics. As a result, an equation with acceptable statistical accuracy for running repairs has been found. The implementing of the MPM framework on the maintenance of tugs has resulted in the MPM model. This model focusses on the running repairs and dry docking direct costs and activities, incorporating basic maintenance types, i.e. Preventive Maintenance (PM) and Corrective Maintenance (CM). Running repairs have been evaluated in the time domain while the evaluation of dry docking have been evaluated as events due to their relationship with regulatory surveys. The model incorporates operational-, maintenance- and financial data, tug specifications and operational conditions in order to evaluate maintenance performance. Maintenance Performance Indicators (MPIs) have been established to determine deviations and deficiencies among the different aspects of M&R. Challenges were faced on the aspects of data quality and data management, especially in the areas of maintenance process. The model has been validated through detailed evaluation of five selected tugs. The underlying reasons for the underperformance of these tugs have been found and verified with knowledgable bodies and thus validating the model and its ability to determine underperformance and deviations.

An alternative performance analysis method, Data Envelopment Analysis (DEA), has been researched and shows promise. The Slack-Based Measure (SBM) DEA model is a non-parametric frontier approach, based on Linear Programming (LP), to evaluate performance based on slacks ()room for improvement) of Decision Making Units (DMUs). The method is capable of determining similarities in inefficiency in maintenance performance, comparing it to results from the MPM model. It therefore proves the method is capable of quick evaluation of maintenance performance and of determining new maintenance targets. However, the model is simplistic, and requires further detailing and is unable to determining underlying reasons for underperformance.

The regression equation and DEA have been used to formulate a so-called performance region which describe the lower- and upper bounds of the running repair costs for individual tugs. Unfortunately, data quality doesn't allow for the determining of these bounds for all vessels nor for dry docking. New key benchmarking targets have been established through quartile values for respective Maintenance Performance Indicators (MPIs). With this newly obtained knowledge, future maintenance performance evaluation of tugs can now be performed with a higher detail through analysis conducted with the developed MPM model.

Preface

I started this journey that lead to this thesis into the possibilities of managing maintenance investments performed on harbour towage vessels. Harbour towage is a vital part of our global transport network, which ensures that vessels are capable of safely entering and exiting harbours under difficult conditions. I have come to consider the towage industry as a symbiosis where one can't function without the other. Maintaining these towage vessels for operation is not only crucial for the functioning of the vessels itself but also for the symbiosis and the safeguarding of the vessels they assist. This research is a step towards an improved capability of maintenance performance monitoring of tugs. I hope that the methodology and structuring of this research has illustrated the possibilities of maintenance performance monitoring from the perspective of Boskalis and has supplied extended knowledge and capabilities through the division of Boskalis Towage.

During this research, Boskalis decided to sell its shares in two of the major towage joint ventures. Even though this was the case, this research is still considered to be relevant and applicable to the other respective joint ventures. It also shows possibilities for maintenance performance monitoring in other business areas.

First of all, many thanks my supervisor at Boskalis, Laurens Both, for introducing me to the world of towage and allowing me to conduct my research. His knowledge and expertise concerning operational improvements have lead me to new ideas and insights for my research. In return, I hope to have shown you that there are interesting methods which are yet unknown to standard operational excellence practices and that it may be worth to discover new areas.
Within JV, I would like to thank Charlie Donker and Georgios Lazaris for their technical insights when it came to tug specifics and detailed information concerning the towage market. Without their inside knowledge and supply of critical data, this research would have seen far more challenges.

Furthermore, I would like to thank my supervisors at the University. My sessions with Koos Frouws and Edwin van Hassel allowed me to see the forest for the trees. Their insight, consideration and recommendations pulled me through rough patches.

Throughout my research I have had the pleasure of meeting many new people at Boskalis, including the graduates, which have provided support and allowed to be express my thoughts, concerns, enthusiasm and pride to have been a part of the organisation of Boskalis. I am thankful for their time, effort, and interest they took into my research. I hope that our paths may cross again somewhere in the near future. A special thanks to Coen de Korte for all the coffee breaks.

On a personal note, I would like to express my gratitude towards my parents and brother who stood by me during every step of my career as a student and provided personal reflection through every step of the way. And lastly, I would like to personally thank my lovely girlfriend for encouraging me to bring out the best in myself throughout my studies, thesis research and personal life.

Kevin Drenthe
Delft, August 19, 2019

List of Terms, Acronyms and Symbols

Glossary

bollard pull

is the static force exterted by a vessel on a fixed tow line at zero speed. This is the typical measure of tugboat performance

girting

may also be refereed to as girthing, tripping or girding. A towing line under tension will exert a heeling moment on the tug if the line is secured around amidships and is leading off towards the beam. As with any vessel which heels over due to an external force, a righting lever is formed as the centre of buoyancy moves towards the centre of the tug's underwater volume, countering the heeling moment and pushing the tug back upright. However, if the force in the towline is sufficiently powerful, it may overcome the tug's righting lever and cause it to capsize or "girth" [West of England].

indenture level

level of subdivision of an item from the point of view of a maintenance action [International Electrotechnical Commission (IEC), 2004]. Examples of indenture levels could be a subsystem, a circuit board, a component. The indenture level depends on the complexity of the item's construction, the accessibility to subitems, skill level of maintenance personnel, test equipment facilities, safety considerations, etc.

skeg

is an aftward extension of the keel inteded to keep the boat moving straight and to protect the propeller and rudder from underwater obstructions [The Editors of Encyclopaedia Britannica, 2018].

Acronyms

ARV	Asset Replacement Value
ASD	Azimuth Stern Drive
ATD	Azimuth Tractor Tug
BI	Business Intelligence
BSC	Balanced ScoreCard
CAPEX	Capital Expenditures
CBM	Condition-Based Maintenance
CM	Corrective Maintenance
CPP	Controllable Pitch Propeller
CRS	Constant Returns To Scale
CSF	Critical Success Factor
DEA	Data Envelopment Analysis
DMU	Decision Making Unit
DNV	Det Norske Veritas
DOM	Design-Out of Maintenance
DRS	Diminishing Returns To Scale
DWT	Dead Weight Tonnage

EPM	Enterprise Performance Management
FBM	Failure-Based Maintenance
FLNG	Floating Liquefied Natural Gas
FMECA	Failure Mode, Effect, and Criticality Analysis
FPP	Fixed Pitch Propeller
FPSO	Floating Production, Storage and Offloading
FSO	Floating Production and Offloading
HSSE	Health, Safety, Security and Environment
IAEA	International Atomic Energy Agency
IMO	International Maritime Organisation
IRS	Increasing Returns To Scale
ISM	International Safety Management
KPI	Key Performance Indicator
KRA	Key Result Area
LOA	Length Over All
LP	Linear Programming
M&R	Maintenance and Repair
MAE	Mean Absolute Error
MARPOL	International Convention for the Prevention of Pollution from Ships
MPI	Maintenance Performance Indicator
MPM	Maintenance Performance Management
MTBF	Mean-Time-Between-Failures
MTTD	Mean-Time-To-Diagnose
MTTF	Mean-Time-To-Failure
MTTR	Mean-Time-To-Repair
OBM	Opportunity-Based Maintenance
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OPEX	Operating Expenses
OVMSA	Offshore Vessel Management and Safety Assessment
PdM	Predictive Maintenace
PDSA	Plan/Do/Study/Act
PI	Performance Indicator
PM	Preventive Maintenance
RCM	Reliability-Centered Maintenance
RMSE	Root Mean Squared Error
ROI	Return on Investment
RT	Rotor Tug
RTS	Returns To Scale
SBM	Slack-Based Measure
SOLAS	Safety of Life at Sea
TBM	Time-Based Maintenance
TMSA	Tanker Management and Safety Assessment
TPM	Total Productive Maintenance
UBM	Use-Based Maintenance
VLCC	Very Large Crude Carrier
VRS	Variable Returns To Scale
VSP	Voith-Schneider Propeller

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Introduction

1
Research Introduction

1.1. Background

Maritime transport is crucial to the world's economy. More than 90% of all trade is transported by ship and is seen as one of the most cost-efficient way of transporting large amount of goods across the world [Organization, 2018]. In the first semester of 2018 the port of Rotterdam achieved a throughput of 232.8 million tonnes [Port of Rotterdam, 2018]. All these vessels berthing at port are handled by tugs. The same applies to vessels that berth at onshore and offshore terminals. Competition in the ship handling market has always been extremely fierce. Towage operators have to compete with respect to price, availability and safety [Maritime Journal, 2013]. Competition is particularly fierce in Europe where numerous service providers operate per port [GmbH and Co., 2016, Port Of Antwerp, 2018].

Through a worldwide network of joint ventures the towage division of Royal Boskalis Westminster, formerly known as Smit, offers harbour- and terminal towage services. Boskalis provides harbour towage operations through multiple joint ventures in the Far East and South Asia (Keppel Smit Towage), America[1] (Saam Smit Towage), Europe (Kotug Smit Towage) and is active in approximately 90 ports across 36 countries. The towage services for both onshore- and offshore terminals are carried out through Smit Lamnalco.

The operations associated with harbour- and terminal towage include port and coastal towage, offshore support, escort services, ship-to-ship operations, firefighting, anti-pollution, all of which are performed by a variety of vessel-types which operate under different long and short term contracts. Comprised of about 450 vessels and around 4,700 crew members, the different joint ventures provide service to thousands of vessels around the world each year.

Operating a large fleet of vessels results in large Operating Expenses (OPEX) during the operational lifetime of the vessel, which are both time and voyage dependent. As the competition is fierce in most of the towage sub-markets, the margins within these markets are considered small. To increase profit margins and increase its position in the market, Boskalis wants to tackle the expenditures. To do so, Boskalis turns to Business Intelligence (BI) to help with the decision-making process.

The future goal of Boskalis is to effectively use both financial and operational data acquired from the individual joint ventures to analyse costs and operational performance (of individual assets) across the different joint ventures. Through analysis deviations in costs and operational performance can be pinpointed. From there the root cause of these operational and cost differences can be recognised. This way operational information helps explain deviations in financial performances. With this knowledge Boskalis wants to find opportunities to reduce costs or improve operational performance throughout all their partnerships. Besides improving performance and reducing costs, this information is expected to assist in financial and performance forecasting as well as result in more accurate budgeting.

In recent years Boskalis has made great efforts to reduce costs in various areas, such as fuel, crew, fleet and procurement. However, reducing the Maintenance and Repair (M&R) costs are still to be addressed within

[1] North and South America.

most of the joint ventures. Maintenance is crucial for the operation of the vessels, but also a large part of the expenses.

At first glance Boskalis has concluded that there are large differences in costs and operational performance between the joint ventures. However, the reason for these deviations is yet unclear. This makes M&R an area where a lot of knowledge can be gained from a management perspective, which may lead to improvements at operational level.

The goal is therefore to increase knowledge of M&R through the design and construction of a M&R management decision model, in which the performance and costs of M&R can be compared across the joint ventures and their assets.

1.2. Problem Statement

The towage market has one of the smallest margins due to competition. To cut OPEX and/or to improve performance, Boskalis wants to enhance its capability of detailed operational evaluation of the different joint ventures by establishing a way to analyse costs and performance of M&R. However, the absence of a digital solution as well as consolidation of data has resulted in a limited possibility of in-depth evaluation. Therefore, the following problem statement can be constructed.

> *Currently, Boskalis is not able to effectively use the knowledge of the different joint ventures to identify potential maintenance and repair improvements due to a lack of performance monitoring with sufficient level of detail. This is due to consolidated data and a non-standardised way of performing maintenance.*

1.3. Objective

The background and problem statement show the need to establish a M&R management model to analyse costs and performance and to identify potential improvements. This leads to the following objective:

> *The main goal of this thesis is to increase the possibility to perform detailed monitoring of maintenance and repair expenses and performance of tugs, through which possible improvements can be determined.*

Performance within the objective statement refers to the maintenance effectiveness on tugs. As maintenance impacts the availability and operational performance of a tug, the maintenance effectiveness is therefore assumed to be linked to the operational performance of the tug.

1.4. Main Research Question

The objective stated above can be distilled to form of a main research question. Answering this main question will lead to the result of this research.

> *Can a maintenance and repair management model on costs and performance be constructed to monitor maintenance investments and identify potential areas of improvement across the joint ventures of Boskalis Towage and how will this be shaped, given the current performance management system and business structure?*

Within the main question *Costs and Performance* are defined as asset performance indicators, which need to be determined. *Areas of improvements* are defined as changes which will increase overall profit or reduce costs. *Current business structure* implies that no structural changes are made with respect to Boskalis and its business arrangements with the joint ventures. Further elaboration will commence in the scope, section 1.5.

1.5. Scope

The main question leaves room for interpretation. This paragraph will discuss the scope of this research.

As formulated in the previous section, the objective is to improve investment and performance monitoring of M&R and identify areas for improvements by constructing a M&R management model. As this model will be used by Boskalis Towage, the model is primarily intended for use at a management level, where the information of the joint ventures is assessed. The level of detail or drill down capabilities will be based on research. The amount of detailing will not be on individual items of sub-systems (e.g. individual cylinders of an engine). Determining the drill down level will result from literature regarding maintenance management and performance management.

As stated in the main research question, the possibilities of future incorporating the M&R management model in the current Enterprise Performance Management (EPM) is taken into account. Technopedia [2019] defines EPM as; “a type of business planning that relates to business intelligence (BI), which involves evaluating and managing performance of an enterprise to reach performance goals, enhance efficiency or maximize business processes.” The EPM system reflects the company’s goal settings, helps monitor progress, identifies and draws attention to financial implications, helps with decision-making, etc. [Leahy, 2003a]. To ensure that the model is suitable to operate within the current EPM, it is evaluated. Information from Boskalis Towage and literature will be used to map the EPM. Mapping the EPM will also assist in determining the drill down level.

Furthermore, it is decided to not address the current business structure between Boskalis and the joint ventures. Boskalis does not have the desire to change current business structures or affect the operational part of each individual joint venture. This may be a goal for the future, however the aim and focus at this moment is on gaining insight in cost and performance differences in maintenance.

Defining M&R and its sub-parts is important to be able to compare between the different joint ventures and decide which areas to take into consideration. Additionally, literature with respect to M&R management is required. Obtaining knowledge regarding M&R management systems will contribute to both the structuring of data and information required as well as the construction of the M&R model. By determining the importance and the link between maintenance performance and profit, cost-effective improvements can be associated with increasing maintenance performance. Literature regarding maintenance management will also help decide which level of operational and technical detail is desired and required to construct the M&R model.

To be able to apply literature regarding maintenance management on the evaluation of ship maintenance performed, it is evident to review the different aspects which come to play in ship maintenance. This will help understand the fundamentals that make up the maintenance costs and what drives these costs.

Information and evaluation with respect to the spare part suppliers will not be taken into account as the goal is to gain insight in M&R and identify potential areas of improvement. The products or work performed by the suppliers are seen as an input into the model. It is acknowledged that addressing and streamlining the process of procurement has an impact on M&R, however the focus of this research is on comparing costs and performances of tug maintenance.

As stated in the background, the joint ventures operate about 450 towage vessels worldwide across multiple joint ventures. In order to make this research more approachable and reduce the amount of expected data, the choice is made to focus on one joint venture, JV respectively. The reasons for this choice is twofold. JV’s headquarter is located in Rotterdam, which make it easier for face-to-face meetings in order to discuss data, results and conclusions. Secondly, JV operates multiple ports in Europe. Using this meso-level to formulate the M&R model will make the research and data volume more approachable but it is also believed that it is translatable to macro-level. Data concerning fleet composition of JV will include vessel main characteristics. These data are used to determine how the vessels might be evaluated and compared in the M&R management model. Whether this might be based on installed equipment, contract, bollard pull, etc. is to be determined.

Additionally, it is considered vital to understand which systems are most important and/or critical for the operational functioning of the tugs. This will help establish a cost categorisation scheme fit for the M&R model and elaborated on the areas/equipment which require a higher level of detail.

The effectiveness of the M&R management model will be determined through discussions with and reviewed by the controllers of Boskalis Towage. Furthermore, the model will be validated through a case study performed on the fleet of JV. The results will be validated through the technical bodies of knowledge within JV.

Conclusions following these results will include potential areas of improvement within the fleet or specific tugs will be based on possible cost reductions or performance increase as a result of differences in maintenance. The aim is to be able to make these conclusions through utilisation of the M&R management model and the information acquired from the joint ventures as input.

1.6. Activities

The activities to be performed are crucial in achieving the goals of this research as well as limiting the overall time spent on this research. After completing all activities this research should give improved insight in costs and performance of M&R. To be able to achieve this goal the following steps are to be taken:

- Performance Management Analysis
- Fleet & Joint Venture Evaluation
- Construction of Maintenance and Repair Management Model
- Fleet Maintenance and Repair Analysis

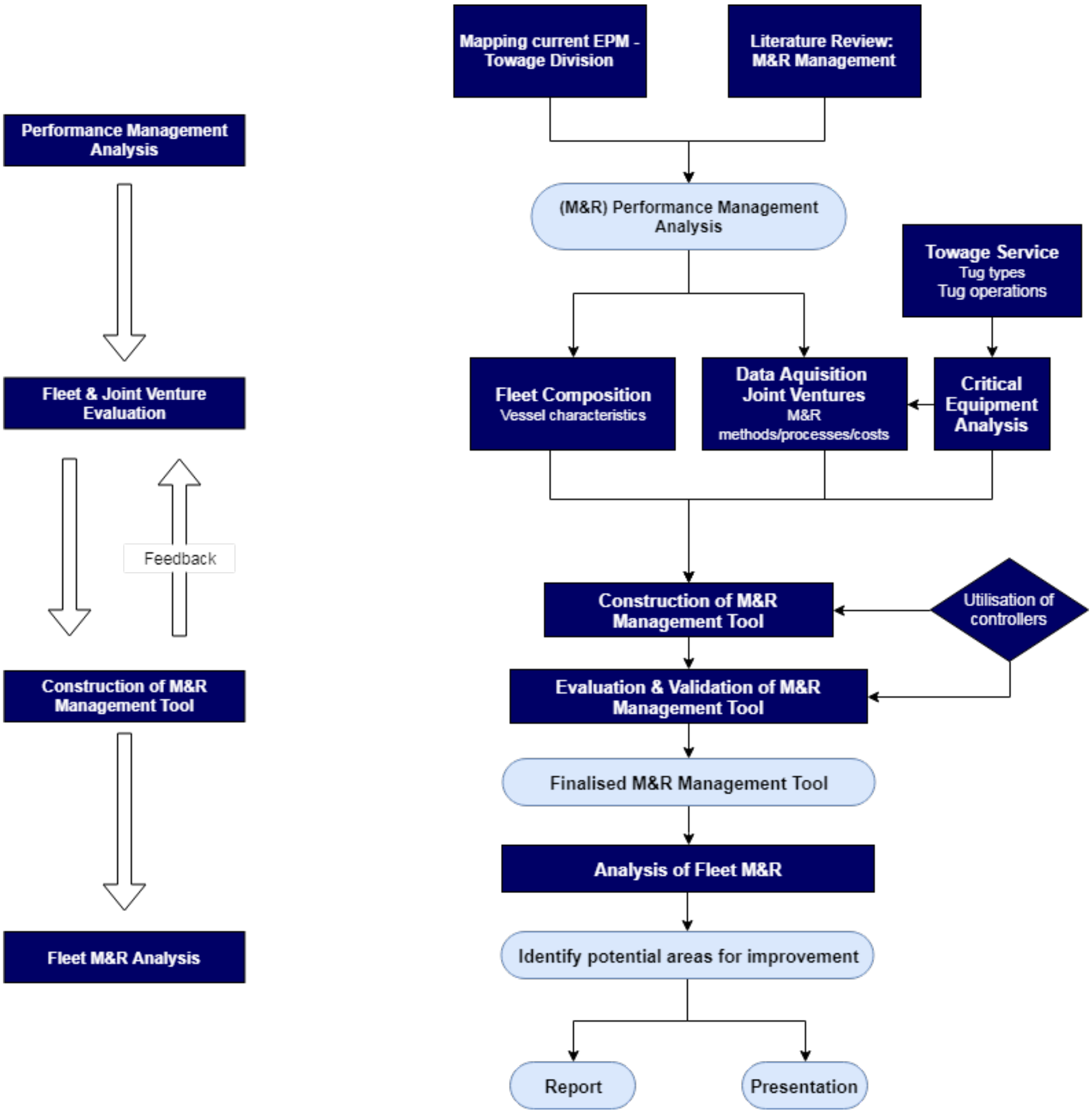


Figure 1.1: Schematic overview of activities [Own source].

1.6.1. Evaluation of Management

First and foremost, it is important to understand the current EPM of the Boskalis Towage Division. This will include a stakeholder and information flow analysis. Understanding the requirements for the M&R management model and how it should complement the EPM currently in place, is important for the future implementation of the M&R management model.

Secondly, this part elaborates on the towage service. This includes defining and elaborating on the different generic tug operations and the different tug types as well as the equipment installed. This information is of interest as it helps identify and structure the different variables within the model.

Another aspect of this part is the equipment criticality analysis. As the model is intended to monitor maintenance from a strategic and tactical level, a critical equipment analysis will determine which specific equipment requires a higher level of detail in the model. The criticality analysis also helps determine what equipment has a lesser priority over others.

For the construction of the M&R model in a later stage of the research, information from JV is required to create the initial data pool. The required data from the joint ventures is distilled alongside literature research regarding M&R and the mapping of the current EPM of the Boskalis Towage. The third section of this part will reflect the fleet composition, supplying information about vessel characteristics. This information is quantified based on different characteristics.

With the results from the acquired data the maintenance model can be constructed.

1.6.2. Performance Management

This second part elaborates on a literature review regarding maintenance performance management. The reviewing of literature is split in two. The first part discusses literature concerning maintenance management. Besides establishing definitions and characterisations of maintenance management, the first part also discusses subjects needed to establish a maintenance management system. These subjects include establishing objectives and strategy, implementation, reviewing maintenance types, policies and drill down level.

By performing a literature review regarding M&R management, the first step towards data acquisition and the construction of the management model is made. At the end, this part will contain generic information regarding maintenance management, an indication of the drill down level of the model and information regarding possible maintenance performance management practises and indicators.

1.6.3. Ship Maintenance

Foremost, this section will consist of literature review regarding ship maintenance and what it consists of and what are the main influencers and drivers of maintenance performed. Furthermore, it elaborates on the different cost aspects that make up ship maintenance costs. Secondly, this section focusses on the performance management of maintenance and how this is currently applied in the maritime industry. Main points of interest are to establish a generic view of maintenance performance management and to gain insight in maritime maintenance performance management cases which may are already applied.

1.6.4. Construction of M&R Management model

This part will consist of the steps performed and the decisions made that will lead to the finalised M&R management model. The model itself and all its sub-party are elaborated to full extent. This part will also discuss how the model is linked within the current EPM structure. Discussing the M&R management model is important for future improvement and development of the model and deciding whether the model complies with the initial expectation as well as function/objective set by the Boskalis Towage-Division.

An important aspect during the construction phase of the model is ensuring the possibility of future implementation of the model. It needs to be kept in mind throughout the construction. Continuous reflection and discussion with the controllers will help to insure this.

This part will also discuss the validity of the M&R management model. The model will be tested by introducing specific case scenarios where the results/conclusions are known. This will also help review and fine-tune the model.

The result of this section is a M&R management model which can be used to evaluate and compare M&R costs and performance across different joint ventures, and can be integrated within in the current EPM structure.

1.6.5. Fleet Maintenance and Repair Analysis

Up unto this point the M&R management model has not been used to analyse the acquired data in order to pinpoint possible improvements with respect to M&R.

The model will be validated through a case study performed on the fleet of JV. A number of tugs will be selected based on the results and conclusions found through the model. These results are then discussed with different business levels within JV in order to validate the results and conclusions and thus the model.

Furthermore, specific areas of improvement are elaborates as a result of analysing the fleet. Pinpointing these areas of improvement should be a result obtained through the use of the model itself as it is the goal of this research to construct a M&R management model to also identify potential areas of improvement.

1.7. Reading Guide

This report consist of five parts which make up the core. Part I includes the Research Introduction, which has been presented in this chapter. It holds all supporting information to this report, including but not limited to problem statement, objective and scope.

The second Part, Reading Guide, introduces the readers to the current business enterprise of Boskalis and its joint ventures in chapter 2. This is followed by chapter 3, which contains all relevant information concerning the towage services. It contains relevant information on general towage operations, vessel types and equipment. These specifics are used to structure the required data and model framework in part IV. Knowledgable readers may resort themselves to the intermediate conclusions of both chapter 2 and chapter 3.

Part III contains all relevant literature which has been researched in order to proceed with part IV. Within this literature part, the focus has been on three aspects. The first being Maintenance and Repair Management (chapter 4), which discusses how maintenance management may be structures and what crucial aspects to take into account. Chapter 5, Maintenance Performance Management, elaborates on how the performance of maintenance can be measured, monitored and analysed. As part of performance analysis, an additional chapter (6) has been dedicated to a performance analysis method called Data Envelopment Analysis (DEA). The final aspect is that of Ship Maintenance. This chapter (7) contains important information about ship maintenance and concludes which aspects will be taken into consideration in the next part.

The next part (IV) contains the proposed maintenance and repair performance management framework in chapter 8. All information obtained in prior parts contribute to the proposed framework in this chapter. The proposed framework is presented, including the selected software and performance analysis. Chapter 5 elaborates on the constructed maintenance and repair performance management model within the respective software program.

The subject of Maintenance Performance Analysis (chapter 10) is part of part V. This chapter presents all performance analysis work which is performed on the maintenance data in order to benchmark performance across vessels. In this chapter the model is also validated and the results and capabilities of the performance analysis method of DEA discussed. After this analysis chapter, the result is the reader has gained an understanding of the practices of maintenance and repair performance management and is able to confirm whether the goal of this research has been met. Conclusions regarding this research are subject of chapter 11. Followed by Recommendations for Future Research in chapter 12.

All supporting content can be found in the appendices in Part VI.

II

Towage Service and Business Structure

2

Enterprise Performance Management - Boskalis Towage

This chapter elaborates on the current Enterprise Performance Management (EPM) structure of Boskalis Towage and its joint ventures. This chapter is intended to understand the current EPM by mapping it, including its information flows, and illustrate deficiencies and possible opportunities.

Firstly, the corporate business structure which make up the joint ventures will be elaborated on in section 2.1. In section 2.2 the major shareholders are presented as well as important stakeholders. The next section elaborates on the current information flows and is split into four major areas of EPM; Strategy and Performance Measurement; Planning, Budgeting and Forecasting; Financial Consolidation and Reporting and Cost and Profitability Analysis. Section 2.4, Intermediate Conclusions Chapter 2, concludes this chapter en elaborates on what is learnt from evaluation of the current EPM. Moreover, this section discusses possible opportunities as a result of these deficiencies.

2.1. Corporate Structure

As earlier indicated in chapter 1, Boskalis is in a mutual partnership with the other party and thus both equal shareholder. As a result of this partnership, both parties jointly need to agree on how the joint venture is managed and by whom. This means that for the erection of the board, both partner supply managers which represent them in the board. Figure 2.1 shows a concise version of the structure of the joint ventures.

2.2. Shareholders, Stakeholders and Actors

This section elaborates on the different shareholders of the above mentioned joint ventures and the most important stakeholders which are dependent on the performance for reasons other than stock or financial performance.

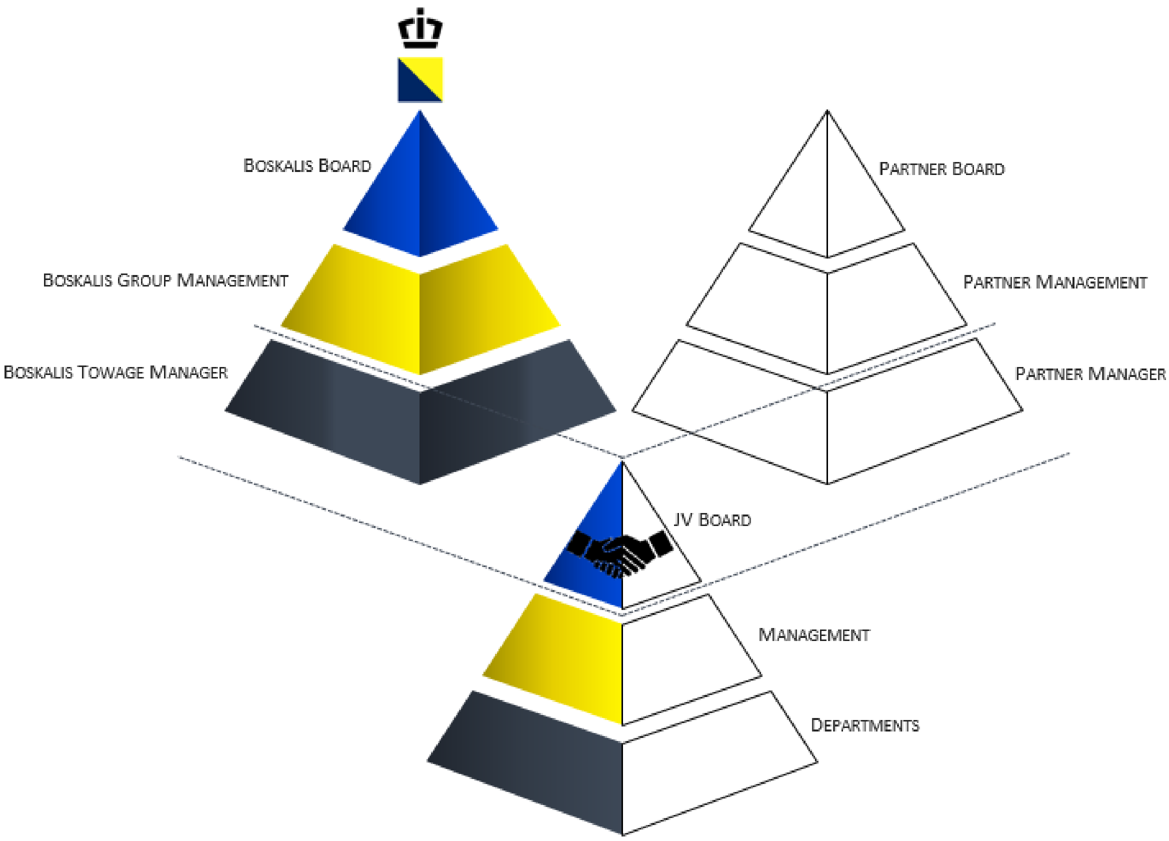


Figure 2.1: Joint venture corporate structure

Shareholders

KOTUG

KOTUG is a towage service provider operating across the globe [International, 2019]. Areas of expertise include terminal and harbour towage, offshore operations and salvage operations. Besides the joint venture KOTUG has with Boskalis its subsidiary, they provide terminal, offshore and salvage services under their own brand. In the Bahamas terminal towage activities are lead by KOTUG Seabulk Maritime LL. Recently, KOTUG and Petroconsult have joined forces to establish KOTUG PETRO Maritime (KPM) operating out of Egypt in which they own 90% of the shares [International, 2019].

SAAM

SAAM is a multinational company operating out of Chile is a subsidiary of Sociedad Martiz SAAM S.A., an open stock corporation. SAAM proves trade services by means of port terminals, towage and logistics in 13 countries throughout North, Central and South America [SAAM, 2019]. It is associated with SSA Marine, which is the largest terminal operators in the United States and supplies towage services in cooperation with SMIT. SAAM operates its own towage services in Costa Rica and collaborates with others companies in Ecuador, Guatemala and Uruguay.

Keppel Shipyard Investments

Keppel Shipyard Investments is part of Keppel Offshore & Marine, operating under the Keppel Corporation [Marine, 2019]. The conglomerate, with its headquarters in Singapore, consists of multiple businesses that specialises in offshore & marine, property, infrastructure and asset management. The joint venture of Keppel Smit Towage is its only towage service in the Asia Pacific region since merging operationally with Maju Maritime in early 2000 [Marine, 2019]. The towage vessels built for the joint venture between Smit and Keppel are frequently built by Keppel themselves at one of their yards, making them a stakeholder which respect to newbuild vessels besides just a shareholder [Marine, 2019].

Rezayat

The Rezayat Group's operations extend across different industries, focussing on trading, construction, support services, manufacturing, financial services and investment [Group, 2019]. Smit Lamnalco is the only marine service that Rezayat Group offers. This includes management and operation of ports and oil and gas terminals, fleet charters, diving services, pilotage, ship agency, marine and offshore supply base operations, and supply of marine and safety products [Group, 2019]. The Rezayat Group also operates in shipbroking and executes marine works, seaport works, operation and management of vessels, tugs and marine equipment, weather forecasting and marine transportation [Group, 2019].

It can be concluded that the above mentioned shareholders, except for KOTUG, all have additional interests in other industries. However, the similarity is that they have interest in either harbour operations or terminal operations. This coincides with the fact that Boskalis has established international joint ventures with these parties for their local presence as well as connection and link with either harbour or terminal operations. In that respect, KOTUG is more of a direct competitor in areas in which it is not in collaboration with Boskalis its subsidiary, SMIT.

Stakeholders & Actors

Stakeholders and actors are different compared to shareholders as they also rely on performance for reasons other than stock or financial performance. Based on information obtained the following table could be established with each stakeholders interests and impact it might have on maintenance operations.

Table 2.1: List of stakeholders and their impact on maintenance operations.[Own Source]

Stakeholder	Interests	Impact on Maintenance
Shareholders	Revenue Company sustainability	-
Clients	Quality towage assist at a reasonable price Safe and on-time towage operations	Availability requirement in contract has impact on maintenance window.
Employees	Salary/wage Job satisfaction Job security	Manage and perform maintenance operations.

Table 2.1 and table 2.2 elaborate on the possible impact that different shareholders and actors might have on maintenance. Boskalis falls within the shareholder definition of stakeholder. They are involved in the strategical decision-making process and assist in additional areas for improvement. Second stakeholder are considered to be the clients, as they require a certain availability or up-time of the vessels, as according to their contracts. Another important stakeholder are the of the employees of the different joint ventures, as they performer the required maintenance thus having direct impact on the quality of performed maintenance as well as the monitoring of vessel and equipment condition.

In that respect, suppliers can be seen as important actors as they can have both direct and indirect impact on maintenance. They perform maintenance on specialised equipment, but also supply equipment in which the quality of the equipment is important in determining the amount of maintenance and maintenance costs over time. The quality of equipment as it effects maintenance over time is also applicable for shipbuilders. A ship repair yard can be seen equal to the direct maintenance impact of employees, as they are the ones performing the maintenance tasks.

There are two actors, the Port Authorities and Classification Society, which have direct impact maintenance activity as they might retain a vessel or withhold important certificates if a vessel is not compliant to regulations. Classification Societies further dictates maintenance procedures and regulations which also directly impact maintenance operations. These will be elaborated further in 7.

It can be concluded that there are many factors that may impact maintenance operations. The resulting three mayor areas which are aimed to be taken into account for the construction of the maintenance performance management model are; Regulatory bodies; Suppliers of asset, equipment and labour; and Clients.

Table 2.2: List of actors and their impact on maintenance operations. [Own Source]

Actors	Interests	Impact on Maintenance
Port Authorities	Capture and retaining port activity and ensure safe execution of port activity.	Can force owner to make repairs if unsafe scenarios are found.
Classification Society	Ensuring that vessel is compliant with regulations	Can withhold classification certificates, which are required to register the ship and obtain marine insurance, if vessel is not compliant with classification rules.
Suppliers	Selling and supplying goods/equipment required for towage operations and maintaining of the vessel.	Supplying equipment, fuel, expertise, etc. required to maintain the vessel in operational state.
Ship Repair Yards	Performing maintenance repair work on vessels.	Performs maintenance work with a certain quality.
Shipbuilders	Selling and producing new vessels.	Vessel and equipment quality affects the amount of maintenance it might require during its lifetime.

2.3. Information Flow

In this section, the flow of information between the joint ventures and the shareholding companies are elaborated upon. This is done to evaluate current status quo and to determine shortcomings in the current information supplied. The following areas will be discussed; strategy and performance measures; planning budgeting and forecasting; financial consolidation and reporting; cost and profitability analysis.

2.3.1. Strategy and Performance Measurement

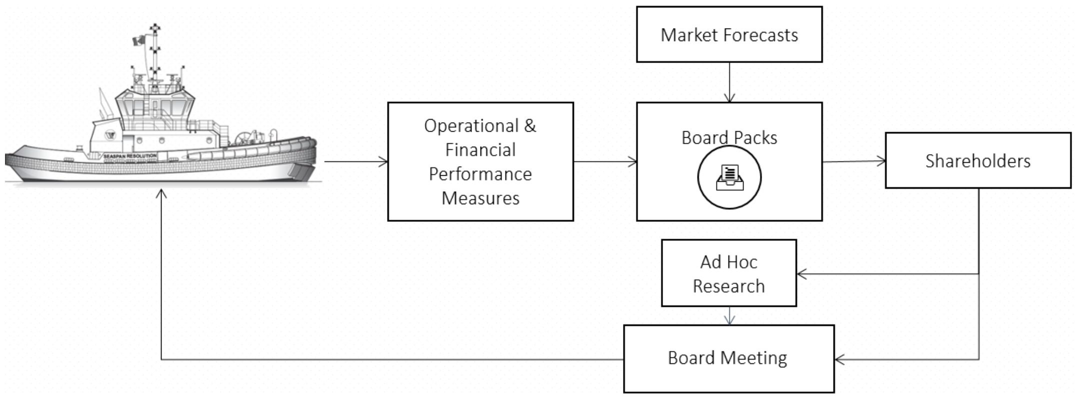


Figure 2.2: Strategy and performance information flow

Every quarter the joint ventures present management information through board meetings and are elaborated in so called 'board packs'. The board packs consist of 6 parts;

1. SHE-Q: Incidents & Accidents
2. Ports & Terminal of Operations: Locations & Fleet
3. Highlights of the month
4. Operational & Fleet
5. Market Information
6. Financials

The majority of the board packs discuss market and financial development. Only financial performance measures are elaborated upon in these documents. Occasionally, an overview of maintenance expenses are shown and briefly explained. However, this often limited to one PowerPoint slide. Whenever deficiencies or abnormalities are established, ad hoc research is then performed to understand the reason behind these deficiencies. Introducing operational performance indicators such as for maintenance and repair would shift the board pack towards a more operational informative report rather than financial and market dominant. As a result, the aim is that the board packs will include the results from the model. An overview of the information flow is shown in fig. 2.2.

2.3.2. Planning, Budgeting and Forecasting

Every fourth quarter a budgeting and forecasting report are made for the next year. Each quarter of the operational year actuals are presented and a new forecast is made. At the end of the year the actual results are presented. Based on the actuals and the differences they show compared to the forecast, further research is performed to determine the reasons for these differences. Again, this illustrates the shortcomings of traditional accounting based performance measuring, discussed in section 5.1, resulting in reactive actions.

2.3.3. Financial Consolidation and Reporting

For the consolidation and reporting, Boskalis uses BPM which is a Business Process Management Software. Joint ventures have the ability to submit their financials into the program. Boskalis can then use Excel to produce reports based on the inputted information. Information is generally reported per vessel for each entity in a profit and loss structure. The financial controller at Boskalis noted that explanations for financial deviations are minimal to none and often given upon request. This suggests that there is a need for more information that elaborates on these deviations.

2.3.4. Cost and Profitability Analysis

Cost and profitability analysis is generally performed at the management level of the joint ventures. At this level the information for each tug is known and used to produce the information supplied in the different board packs and meetings. This suggests consolidation of information used in analysis which evidently results in a less complete picture of the current situation. The two main financial analyses are an evaluation of the balance sheet and how it compares to the budget and quarterly forecasts. Furthermore, a set of financial Key Performance Indicators (KPIs) are calculated:

Profit and Loss
EBITDA / Turnover
Overhead / Turnover
Return Ratios
ROCE = EBIT / Capital Employed
ROE = Net Result / Equity
Financial Covenants
BNDES Covenants = Liabilities / Total Assets

The above KPIs reflect the use of mainly financial performance indicators. However, the underlying operations that make up the results used in these KPI calculations aren't elaborated in their own set of KPIs. It is believed that this may be one of the reasons why ad hoc research is performed as a result of primarily financial results and indicators. By incorporating additional operational KPIs one may gain insight in all aspects, for example maintenance and repair. Knowing more about how operational factors affect financial results will help to establish more accurate budgeting and forecasting and tailored to different geographical locations or equipment.

2.4. Intermediate Conclusions Chapter 2

The analysis of the current status quo between the joint ventures and Boskalis result in a couple of interesting conclusions regarding nature of collaboration, the function of Boskalis and the information which is relayed back to the partnering companies.

First off, the relationship between Boskalis and the joint ventures is considered to be open, transparent and at a mutual level. This is attributed to the mutual understanding and the establishment of a partnership through a joint venture rather than a structure where a company is majority shareholder. It is believed that this contributes to the overall close collaboration between the two.

Secondly, the function of Boskalis is concluded to be primarily governing of nature. This is understandably as the joint ventures are self operating entities with accountability and reporting obligations towards the partnering companies. The strategy behind the joint ventures is to benefit of access to global market intelligence and international best practices through their partnering companies, while sill maintaining independent, regional operations and using local knowledge to operate effectively. This is the main vision when the joint ventures were established.

The third conclusion that can be drawn is that the reporting through board packs are largely financial and market dominated, leading to believe that the current EPM can be categorised as traditional financial. It is noted that the interest in introducing more operational information is present. However, the gathering and analysis of detailed operational data is often project based, rather than periodically performed. Possible improvements in understanding financial data could be obtained by periodically gathering and understanding operational data. Literature will be discussed regarding this subject in part III.

Discussing these findings within Boskalis have lead to the following evaluation and learning steps in which the maintenance and repair model will eventually contribute, from a holding perspective. The first is that the model should, to some extent, be able to evaluate the budgeted maintenance and repair costs with the actuals.

This first step is determining if there are differences and the amount of difference between actual and budgeted spendings on maintenance and repair.

The second steps of interest is if can be determined what the reasons are for these deviations through detailed reporting. This includes both financial information and operational information. To what extent detailing is interested and available will be based on research in chapter 3. However, it is acknowledged that it is of interest to incorporate an equipment level of detail, as this addresses one of the three areas of interest discussed in section 2.2, concerning the suppliers of asset and equipment. Gaining knowledge and being able to make conclusions regarding equipment maintenance performance will help with manufacturer and equipment selection for new vessels, but also help understand where the main costs are spent.

This knowledge can then be used to distinguish the key parameters from less important parameters, which help determine a way to benchmark maintenance and repair. Which, as a result, can possible be used for tug or fleet specific forecasting.

3

Towage Services

This chapter focusses on the world of tugs. It is of importance to understand that tugs with different operational purposes have different design features and therefore have different handling characteristics. This is due to, but not limited to, hull design, engine type, propulsion configuration and towing winch power, design and allocation.

Throughout the years a lot of development has been realised on the hull design of tugs as well as propulsion systems to every increase operational performance, including bollard pull. To compare the different tugs with respects to M&R across the different joint ventures, the functional properties of the different types of tugs are discussed and tabulated.

Typically, tugs are categorised according to their type of work, discussed in 3.1 and then categorised through the location of their type of propulsion system. It is therefore natural to firstly elaborate on the different Towage Operations and then the tug categories, their characteristics and different types. Following, a list of the different technical systems is presented and elaborated in section 3.3.

3.1. Tug Operations

Tugs are generally designed to perform one or more specific functions. This is based on specific tasks, their area of operations, what type of ship they handle, navigational obstacles and maritime laws [Radišić, 2003]. The following areas of operations can be identified in different types of tugs operations;

- Harbour operations
- Terminal operations
- Escort operations
- Salvage/Rescue operations
- Offshore operations

3.1.1. Harbour Operations

Harbour operations/towage can be seen as the "classic" form of tug operations. Tugs assist large vessels, such as Very Large Crude Carrier (VLCCs) or container vessel, onto or of a berth by pushing and pulling as required. In this situation tugs are required for most large ships which do not have rudder control when operating at very low speeds, 6 knots or below [Allan, 2006], at thus very susceptible for wind and current forces.

Harbour tugs typically range from 20 to 30 meters in length and have a installed engine power between 2 and 5 MW, however there are exceptions as they depend on the size of the port and the types of ships handled.

3.1.2. Terminal Operations

Terminal operations is referred to as operations which concern on- or off-shore oil & gas terminals. The tugs provide towage assistance at port facilities as well as floating facilities such as FSO, FPSO, FLNG, etc. Besides the services of escorting and berthing the tugs also supply safety cover, including fire-fighting capabilities and oil pollution control.

Onshore terminals experience less severe environmental conditions in comparison with offshore terminals. Therefore, the operational capabilities of the tugs are scaled up due to the larger forces as a result of the sea-state, wind and proximity of the assisted vessel. Additionally, due to waves the rated push or pull performance is difficult to sustain. The magnitude of the line forces can be amplified up to 10 time bollard pull and therefore have a higher chance of towline failure [Allan, 2006]. Deck fittings and winches experience larger stresses compared to onshore terminal operations varying up to five times bollard pull. This all can lead to structural damages.

3.1.3. Escort Operations

As technological improvements have given large vessel more manoeuvrability [Msc, 2002], bringing to life the escort tugs. These type of tugs are designed to rapidly and safely provide emergency steering and braking control over a ship which has lost propulsion and/or steering control in a confined waterway and critical coastal areas [Allan, 2006]. Escort towing is labelled as a distinguished operation due to the fact that it takes place at high speeds exceeding 6 knots.

Escorting tugs obtain their required braking forces and ship control steering through the so called indirect towing mode where the tug uses both hydrodynamic forces and its propulsion.

3.1.4. Salvage/Rescue Operations

Salvage/rescue tugs are generally larger vessel in comparison with the previous operations. These tugs are stationed in notorious shipping lanes in order to assist vessels in distress. The vessels are equipped with specialized winches and pumps, etc. which are used to prevent vessels from sinking or re-float them when beached. These operations mostly occur in bad weather conditions and not in the security of the harbour. The vessel is therefore designed for fast response speed, long-distance towing capabilities and large sea keeping possibilities [Allan, 2006].

3.1.5. Offshore Operations

Offshore operating tugs provide specialised towage services related to offshore, wind farms, dredging oil and gas industry (moving rigs, construction, decommissioning) [KOTUG, 2019]. Smaller tugs, up to 80 ton bollard pull, are tasked with coastal water towage activity while deep see towage project are generally done by larger tugs or in some cases Anchor Handling Tugs. Offshore operations related to wind farms or gas industry require additional firefighting capabilities.

Each specific type of operation has a different operational profile, leading to believe that different operations could be performed more effectively by a tug type which matches these operations to a better extent. As a result, it is concluded that the type of operation, besides having an impact on tug specifications and installed equipment, also defines how a tug is operated. An escort operation may require less frequent high thrust output or strain equipment more frequently in comparison with harbour towage, offshore or other operations. This relationship between operation specific and its impact on tug specifications and equipment utilisation won't be researched in full extent in this research but will be taken into account when evaluating for possible causes for deviations in maintenance performance.

3.2. Main Tug Types

The next section will discuss the tug categorisations based on their thrust configuration. As the different joint ventures only operate harbour, terminal and escort vessels the following sections regarding tug types will be focussed on the type of tugs that perform these specific tug operations. There are four basic categories of tugs based on their thruster configuration; Conventional, Stern Drive, Tractor and Rotor (RT). These configurations are elaborated including their characteristics [Shipownersclub][Port].

The choice was made for these categorisations because they are different in the location of their non-retractable propulsors. A conventional tug has a propeller fixed to a horizontal shaft. A Stern Drive is a non-conventional propulsor which is located in the aft part of the tug. The Tractor tug has its propulsors located at the forward part of the vessel. A Rotor tug has propulsors in both forward and aft part of the tug. This makes it possible to group the different tugs in one of these categorisations.

3.2.1. Conventional Tug

The oldest types of tugs and the largest number of tugs belong to this type. These tugs are used worldwide and their characteristics vary. The towing point is located approx. at 45% of LOA from aft [Shipownersclub][Port].

These tugs can be equipped with Fixed Pitch Propeller (FPP), single or twin propeller and single rudders with fixed nozzles. The new built conventional tugs generally have steering nozzles, Controllable Pitch Propeller (CPP) including nose rudders. Twin-screw conventional tugs have an increased manoeuvrability in comparison with a singe propeller tugs, as the two propellers can be operated independently and in opposite directions. An example is shown in figure 3.1.

To improve manoeuvrability the conventional screw can be fitted with a steerable nozzle, a bow thruster or a retractable azimuth bow thruster. Tugs fitted with azimuth bow thrusters are referred to as "Combi-Tugs".

Characteristics

- Manoeuvrable and effective for most work, however less manoeuvrable than the ASD or tractor tugs.
- Good steering ability, especially as a forward pulling tug.
- Good sea-keeping ability.
- Good bollard pull to power output.
- Towing point is usually situated just aft of amidships.
- Astern bollard pull reduced by up to 50% of forward bollard pull.
- Increased risk of girting when towing.

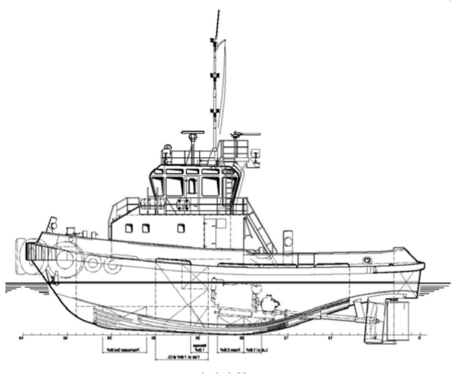


Figure 3.1: Conventional type tug. [LTD]

The location of the pivot point when no tow-line is fastened is similar to that of a conventional ship, about 1/4 from the bow of the tug. Once the tow-line is connected the pivot point moves astern to the towing point, usually the towing hook. When the tug is dragged astern, there is an increased risk of girting [Shipownersclub][Port].

3.2.2. Stern Drive

The Stern Drive category is a tug where the normal propellers and shafts are replaced by an alternative propulsion units. This tug category is generally fitted with two azimuth thrusters in nozzles at the stern or a Voith-Schneider Propeller (VSP) [Shipownersclub][Port].

The towing point of the Stern Drive tug is situated on the foredeck. However, some ASD tugs can have additional towing points situated on the aft deck.

The Stern Drive tug is sometimes referred to as "reverse-tractor tugs" This definition is mainly applied to tugs with stern-mounted azimuthing propellers but with limited or no towing location on the aft deck. Figure 3.2 shown an exemplary design of an ASD tug.

Characteristics

- Low relative draught.
- Good steering characteristics, except when going astern at higher speeds.
- Towing points is just forward or just aft of midship.
- Underwater hull form improves the dynamic stability of the tug.
- Bollard pull going astern is reduced only by approx. 10%.
- Manoeuvrable and able to pull effectively over the stern or bow. Towing winches often fitted both fore and aft.
- Risk of girting when towing over the stern.
- Enhanced training of tug masters required when operating the forward winch.

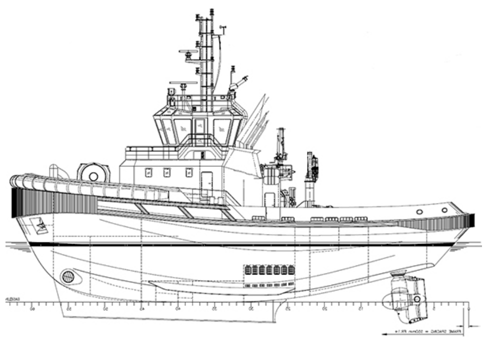


Figure 3.2: Example of a ASD tug. [LTD]

3.2.3. Tractor Tug

The tractor tug design is unlike the conventional tug design. There propulsion units are located at the forward end of the tug. This is generally at $0.3x$LOA from the bow.

The towing point is located at the opposite end of the tug, close to the stern thereby producing a large turning momentum. This potentially gives a poor steering performance, which is overcome by fitting a large centreline skeg [Shipownersclub][Port].

The propulsors can be comprised of azimuth thrusters or VSP. The VSP were introduced mainly for their exceptional manoeuvrability and safety in operation, which is inherent in the tractor principle. An exemplary design of a VSP tractor tug is shown in figure 3.3.

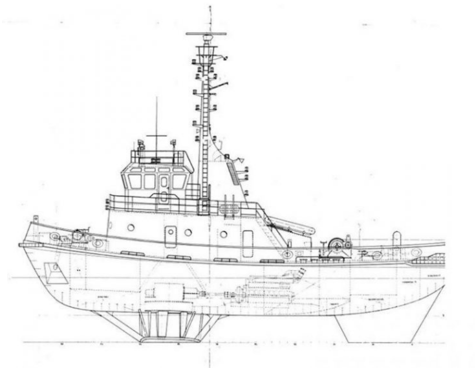


Figure 3.3: Example of a VSP Tractor tug. [LTD]

Characteristics

- Very manoeuvrable, especially in tight areas.
- Reduced risk of girting.
- Reduced manoeuvrability if towing from forward at higher speeds.
- Reduced directional stability, particularly in open waters.
- Reduced bollard pull per kilowatt output.
- Relatively deeper in draught therefore increased risk of bottom damage from grounding.
- Increased training required for tug masters.

3.2.4. Rotor Tug (RT)

The rotor tug is a patented design and is different to the other designed based on the locations of its propulsors. The propulsion configuration consists of three azimuthing thrusters placed in a triangular configuration. Two azimuth thrusters are placed at the forward end of the tugs and one astern on the centreline of the tug. Many ports are acquiring this type of tug for ship assistance. An example of the rotor tug is shown in figure 3.4 [Shipownersclub][Port].

For this research the description of a rotor tug will be identified as a tug with both a propulsor at the forward and aft part of the tug.

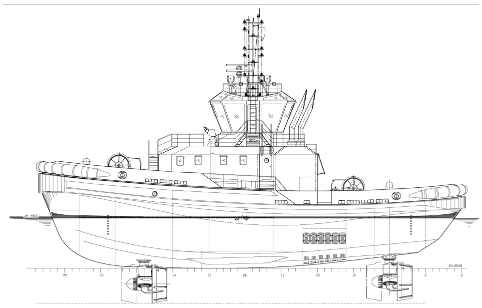


Figure 3.4: Typical Rotor Tug configuration. [Brokers, 2018]

Characteristics

- Highly manoeuvrable, useful in confined spaces.
- Similar towing ability from forward and aft towing winches.
- Good towing performance over the stern and bow; 100% BP ahead and astern; 65% of BP athwartships.
- Good residual redundancy in case of engine failure.
- Additional tug master training required.

The different type of tugs can be categorised within one of these four tug categories. In the table below the known tug types are all categorised.

Table 3.1: Tug categorisation.[Shipownersclub] [Port]

Categorisation	Tug Type	Acrostic
Conventional Tug	Conventional Screw Tug	
	Combi-Tug	
Stern Drive Tug	ASD	Azimuth Stern Drive
	RSD	Reverse Stern Drive
	Z-Tech	
	VSP	Voith-Schneider Propeller
Tractor Tug	VST	Voith-Schneider Tractor
	ATD	Azimuth Tractor Drive
Rotor Tug	RT	Rotor Tug
	ART	Advanced Rotor Tug
	SDM	Ship Docking Module
	CRT	Carrousel RAVE Tug
	EDDY	Efficient Double-ended DYnamic
	Giano	

3.3. Technical Systems and Criticality

As part of this research it was proposed to perform a criticality analysis in order to determine operations critical equipment from less critical equipment. After consultation with JV they provided their finding on an internal research on equipment criticality. The choice has been made to adopt these findings for this research and therefore not performing a separate research.

Table 3.2: List of main- and sub-systems used in criticality analysis. [Courtesy of JV]

Main System	Sub System	Main System	Sub System
Air System	Starting Air	Winches	Winch Hydraulic System
	Control Air		Winch Electronic System
	Air Compressors		Winch Drums
	Air Piping	Electronic Safety Devices	Fire Detection System
Fuel System	Fuel Filters		Alarm System
	Fuel Oil Purification	Bilge/Fire Pump With Piping Systems	Bilge Pump
	Fuel Oil Piping		Fire Pump
	Fuel Oil Transfer		Bilge System Piping
Main Propulsion	Main Engines		Fire System Piping
	Thrusters	Nautical	Pilot Communication Devices
	Steering and Engine Control Systems		GMDSS Equipment
	Clutches		Radar Systems
	Engine Control and Shutdown Systems		Navigation Equipment
	Cooling Systems	Environment	Fuel/Lube Oil Bunker Manifold Safe -All Overflow Tank
Ship Services	Electrical Power System		Waste Oil/Waste Water Manifold
	Auxiliary Engines		Sewage Treatment
	Emergency Electric Power Systems		Oily Water Separator or OW Storage
			Waste Disposal
			Oil spill Response Kit Available

The criticality list of technical systems is a result of the research conducted by JV , focussed on their habour- and offshore towage. The reasons that kicked off this internal research was the ISM Code par. 10, which will be discussed in section 5.2, and the revision of their Quality, Health, Safety and Environmental procedures within JV. This criticality research was used to establish the reporting criticality of a failure and the availability requirements of spare parts. The list of selected 'Main Systems' and corresponding 'Sub-Systems' is shown in table 3.2 [Groeneweg].

The list was used to calculate the operational reliability of each sub-system. This was done through the following calculation:

$$\text{Average Consequence} = \frac{\text{Consequence in Port Operations} + \text{Consequence in Offshore Operations}}{2} \quad (3.1a)$$

$$\text{Risk} = \text{Likelihood} * \text{Average Consequence} \quad (3.1b)$$

$$\text{Operational Reliability} = \text{Risk} * \text{Service Reliability} \quad (3.1c)$$

It can be questioned whether the calculation of average consequence is limited in its consideration of the difference in consequences of port operations and offshore operations, however, as the amount of port operations is significantly higher than that of offshore operations one might say that this balances the weighted differences between the two. It is therefore noted that this is an assumption made by experts in the towage sector and therefore reliable enough to adopt in this research.

The *likelihood* of failure occurring is scored 1 through 4 based on frequency of occurrence, redundancy, environmental impact and time factor. The *consequence* of a failure is rated 1 through 3 based on the low, minor or severe rated consequence for operation, ship crew and communication. The *Service Reliability* takes into the account whether the knowledge of repairing the failure is possessed by crew, the technical department or service specialist. This is rated 0.25 through 1.

The resulting *Operational Reliability* is used to determine how maintenance will be performed. Low resulting sub-systems is assigned to regular shipboard maintenance with additional record keeping. Mid-level sub-system are assigned to regular shipboard maintenance and additional record keeping in the maintenance system. Defect that occur must be reported. Maintenance of high scoring sub-systems entails shipboard maintenance and record keeping in the maintenance system with additional spare parts or replacements available within a day. The selection of service provider should be selected based on availability after office hours and within reasonable time. Scoring and extreme score will label the sub-systems and high priority where shipboard maintenance is a priority point, defects must be reported, spares and/or replacements should be on board or directly available by the technical department. Service providers should be selected to be available after office hours and available within reasonable time.

For the interest of this research, the sub-systems which have been classified high or mid-level are listed below. The internal criticality research did not identify a category 1 sub-system. This begs to differ if the criticality research conducted was constructed accordingly as the assigned ranges of values may have resulted in the eventual result. Nonetheless, this information is valuable as it does show the criticality of the sub-systems in relation to each other and identifies which sub-system is 'more' critical than another, taken into account the subjectiveness of the research.

Mid-Level Priority	**High Priority**
Air Piping	Steering and Engine Control Systems
Main Engines	Clutches
Thrusters	
Engine Control and Shutdown Systems	
Electrical Power System	
Emergency Electric Power system	
Fire Detection System	
Alarm System	
Radar Systems	
Navigation Equipment	

3.4. SFI Group System

Some time after this criticality research, JV established an SFI Coding and Classification System. However, this was not related to equipment criticality, but focussed on structuring equipment based cost coding. The SFI Group System is a widely used classification system for maritime and offshore industry worldwide [Xantic, 2001]. It provides a functional subdivision of technical and financial ship or rig information. It was first released in 1972 and used to control operations by tying together different operations like: purchasing, accounting, maintenance, technical records, etc. As a result, JV erected a maintenance and repair oriented SFI

Group System for a tug shown in table 3.3.

The SFI Group System makes for an interesting solution for the Maintenance and Repair Performance Management model as it could be used as a way of indexing cost and comparing these over time. Secondly, the main and sub-groups addressed in the SFI Goup System, table 3.3, contain similarities with the (sub-)systems in the criticality research. A side note is that the desired indenture level, or level of detail, of the model, is still to be determined. In consultation with the controllers within the towage group, the SFI Group System as presented in table 3.3 is deemed detailed enough for possible implementation in the maintenance model.

Table 3.3: SFI Group System for a tug [Courtesy of JV]

SFI Code	**SFI Description**
4131	SHIP MAINTENANCE
4131.1	SHIP GENERAL
4131.10	Engineering & Drawings
4131.108	Charts / Publications
4131.11	Insurance, Classification
4131.112	Classification, Regulating Bodies & Certificates
4131.14	Docking
4131.144	Docking Costs
4131.2	HULL
4131.23	Tanks & Voids
4131.26	Hull Outfitting
4131.264	Hull & Fendering
4131.27	Material Protection, External
4131.275	Superstructure
4131.28	Material Protection, Internal
4131.281	Accommodation
4131.3	EQUIPMENT FOR CARGO
4131.33	Special Cargo Handling Equipment
4131.330	Equipment for Cargo
4131.4	SHIP EQUIPMENT
4131.41	Navigation Equipment
4131.42	Communication Equipment
4131.43	Anchoring Mooring and Towing Equipment
4131.437	Towing Material
4131.438	Towing Winches
4131.44	Miscellaneous System
4131.440	Miscellaneous System
4131.5	EQUIPMENT FOR CREW AND PASSENGERS
4131.50	Lifesaving Protection and Medical Equipment
4131.503	Lifesaving, Safety and Emergency Equipment
4131.57	HVAC
4131.58	Sanitary Systems
4131.581	Sanitary System
4131.584	Portable Water System
4131.6	MACHINERY MAIN COMPONENTS
4131.60	Diesel Engine for Propulsion
4131.601	Main Engines
4131.62	Other Types of Propulsion Machinery
4131.625	Hybrid System
4131.63	Propellers, Transmission, Foils
4131.637	Couplings
4131.65	Motor Aggregates for Electric Power Productions
4131.651	Auxiliary Engines
4131.7	SYSTEMS FOR MACHINERY MAIN COMPONENTS

4131.70	Fuel Oil Systems
4131.701	Fuel System
4131.71	Lube Oil System
4131.711	Lube Oil System
4131.72	Cooling System
4131.722	Cooling Water System
4131.73	Compressed Air Systems
4131.79	Automation System
4131.8	SHIP COMMON SYSTEMS
4131.80	Ballast/Bilge Systems
4131.801	Ballast System
4131.803	Bilge System
4131.81	Fire & Lifeboat Alarm, Fire Fighting & Wash Down System
4131.814	External Fire Fighting
4131.85	Electric System
4131.86	Electrical Power Supply
4131.868	Shore Power
4131.9	SUBSTANCES
4131.91	Chemicals
4131.92	Dirty Oil & Waste
4131.93	Fresh Water
4191.94	Lubricants & Grease
4191.95	Paint

3.5. Intermediate Conclusions chapter 3

Based on this chapter a couple of conclusions can be made regarding tug operations, type and equipment that will impact the maintenance performance model.

First of all, the location in which the tug operates will indirect and directly impact maintenance in two ways. The indirect impact is the selection of a fit for purpose tug, meaning a tug which can perform the required operations. This dictates the vessel specifications and equipment installed, resulting in an impact on maintenance. The direct impact is that of the operations itself. The tug will perform certain operations that have impact on the tug itself and its equipment. Although these dependencies are not part of this research, it is of interest to take into account when looking for possible improvement or changes to make when maintenance performance issues are pinpointed. For instance, maintenance on a certain towage vessel might seem high in comparison with other towage vessels. The explanation for this higher amount of maintenance could be related to the towage operations it is performing or operational location.

The second point of interest is the type of tug and its link between type of operations, as discussed prior, and with operating in different location. Tug types and their design meet operational requirements, but are at the same time affected by their operating environment. This is also an important factor to take into account when allocating a tug at a certain port. A tug specific design might be made for high manoeuvrability, but require more fuel in transit, making it ideal for short towage assists and less favourable for large escort operations. This will inherently impact the amount maintenance required as the vessel is less favourable for certain operations at certain locations. The combination of tug type, including its characteristics, while operating in a given location is of interest and therefore taken into account in this research.

The third conclusion is the influence that equipment has on both operations effectiveness and maintenance. As addressed above, selecting the right equipment to do the assigned operation is important for an effective operation. The selection of this same equipment inherently dictates that maintenance is to be performed in order to keep it operational. Some equipment is more critical than others or might be used more thus requiring more maintenance. Through an internal research [Groeneweg], a list of mid- and high level critical equipment was adopted, see section 3.3. This list will be used in the maintenance evaluation process. The SFI Group Coding System that followed it, shown in section 3.4, has been deemed comprehensive enough in which it comprises all essential system groups within a tug. It will therefore be incorporated into the maintenance performance model as a way to categorise system specifics.

III

Literature Review

4

Maintenance and Repair Management

Chapter 4 elaborates on management of maintenance and repair. Before a maintenance management model can be constructed, it is necessary to define and understand what maintenance management entails. Therefore, literature is used to supply a definition of maintenance management and its characterisation in section 4.1. This is de bases to further discuss the objectives, strategy, responsibility and implementation of maintenance. Section 4.2 discusses these topics.

After understanding the fundamentals of maintenance management, section 4.3 elaborates on the different maintenance types according to literature. Furthermore, this section discusses maintenance policies, activities and indenture level as these are all important aspects of maintenance which make up a company's maintenance plan.

Based on the information of prior sections, the intermediate conclusions are drawn in section 4.4.

4.1. Maintenance Management Definition and Characterisation

4.1.1. A Definition of Maintenance Management

According to Webster's Dictionary [Dictionaries, 2019], *management* characterises the process of leading and directing all or parts of an organisation, often a business, through the development and manipulation of resources (e.g. human, financial, material, intellectual or intangible). One can also see management as an action of performing measurements on a regular basis to reach certain goals by adjusting a plan and performing the required actions.

Maintenance management therefore characterises the process of leading and directing maintenance organisation. Before elaborating on maintenance management, it is imperative to understand the process of maintenance organisation, with the resources belonging to it.

In accordance with the European Committee for Standardisation, *maintenance* is defined as the combination of all technical, administrative and managerial actions during the life cycle of an item, component or equipment intended to retain it in, or restore it to, a state in which it can perform the required function(s) for an item which are considered necessary to provide a given service [CEN, 2010]. This definition of maintenance clarifies the objective of maintenance and elaborates on the underlying function of maintenance management, which is defined as follows [CEN, 2010]:

> *"All the activities of the management that determine the maintenance objectives or priorities (defined as targets assigned and accepted by the management and maintenance department), strategies (defined as a management method in order to achieve maintenance objectives), and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving methods including economical aspects in the organization."*

This definition of maintenance management is closely aligned with other found literature regarding maintenance [Campbell et al., 2011, Pintelon and Parodi-Herz, 2008, Shenoy and Bhadury, 1998]. Wireman [2005] considers maintenance management as managing all assets owned by a company, with the goal of maximizing the return on investment on the specific asset. Or how a maintenance system can be portrayed as a simple input-output system [Duffuaa and Raouf, 2015]. The input into the system are manpower, management, tools, equipment, etc., and the output of the system is an equipment which is working reliably to reach the planned operation.

For this research the definition of maintenance management established by the European Committee [CEN, 2010] for Standardisation is assumed guiding.

The following step is to review the main aspects of the above-mentioned definition of maintenance management, i.e.:

- Maintenance objectives or priorities;
- Maintenance strategies (and responsibilities);
- Maintenance implementation by mean such as planning, maintenance control and supervision, and;
- Improving methods including economical aspects in the organisation.

The four points mentioned above can be summarised into two aspects which will help understand managing maintenance effectively and efficiently;

- The maintenance management process. Elaboration on the course of action and the series of stages/steps required and;
- The maintenance management framework, discussing the supporting framework and the basic system, needed to manage maintenance.

4.1.2. Effectiveness and Efficiency of Maintenance Management

The process of maintenance management can be divided into two parts: the *definition of the strategy*, and the *strategy implementation*.

Strategy definition

The first part, the definition of the strategy, results from the maintenance objectives, which is derived directly from a business its business plan. This part of the process of maintenance management is key for the success of maintenance within the organisation. This also determines the effectiveness of the implementation of the maintenance plans, schedules, improvements and controls. Dealing with these problems to reach an effective maintenance strategy, reflects the ability to foresee the correct maintenance requirements. Implementing an effective maintenance strategy will lead to minimising the maintenance indirect costs, associated with production/service losses, and ultimately, customer dissatisfaction [Pintelon and Parodi-Herz, 2008].

Effectiveness indicates how well a department or function meets its goals or needs, and often described in terms of quality of the service provided, from a customer's perspective. With regard to maintenance, effectiveness can represent overall company satisfaction with the capacity and condition of an asset [Wireman, 2005]. In this case, effectiveness describes the correctness of the process and its sub-processes which produce the required result.

Strategy Implementation

The second part, strategy implementation, has a different level of significance. The ability to tackle the maintenance management implementation problem will allow for the minimisation of direct maintenance costs, such as labour and other resources. In this part the process deals with the efficiency of management. Efficiency indicates the acting or production with minimum waste, expenses, or unnecessary effort. It compares the quantity of service provided to the used resources. Efficiency measures how well a certain task is performed, not whether the task itself is correct. Therefore, efficiency can be understood as providing the same or superior maintenance at the same cost [Wireman, 2005].

4.2. Maintenance Objectives, Strategy, Responsibility and Implementation

This section discusses what maintenance objectives and strategies are and how they are established, followed by the distribution of responsibility and implementation of maintenance strategy.

4.2.1. Maintenance Objectives

Business objectives are established through the needs of the customers, shareholders, and other stakeholders [Campbell and Reyes-Picknell, 2006]. These business objectives can be grouped into four main objective perspectives: profitability, risk, growth and operating conditions [Anderson et al., 2004, Bacidore et al., 1997]. It looks into both tangible (financial) and intangible aspects of the business process. Below, the different aspects and how they are related to maintenance are discussed.

Profitability refers to the ability of an enterprise to make profits. It is often a priority for businesses. It is a necessary condition to allow a business to reach the other objectives. Therefore, maintenance should contribute to the profitability and the competitiveness of the business, or the effectiveness of the administration and public services.

Asset-, environment- and people safety is another objective in current businesses. Although laws and regulations establish a framework for safety, increased risk can result as a subsequence of installing new equipment, interdependence of new and existing equipment, etc.

Growth refers to the growth rate of an enterprise and their potential and can be important in different moments of the product life cycle.

Operating conditions is about the internal processes and operations in a business. Indicators of assets use and costs are often used to monitor operational performance. This ensures the continues improvement and development of the business.

To achieve these above-mentioned business objectives a business strategy is required. These can be translated into maintenance objectives. Typical goals for maintenance management in organisations can be classified into three groups [Wireman, 2005]:

1. Technical Objectives
   These objectives discuss the operational imperatives of the business sector. These are linked to a satisfactory level of equipment availability and people safety.

2. Legal Objectives
   Legal objectives refer to mandatory and manufacturer regulations. It is a maintenance objective to fulfil existing regulations and legislations for electrical devices, pressure equipment, vehicles, protection equipment, etc.

3. Financial Objectives
   These objectives satisfy the technical objective at a minimum cost. For a long term perspective, life cycle cost should be a suitable measure for this.

These maintenance objectives are assigned targets which have been established and accepted by the management and maintenance department. Assigning targets is critical, typically recursive, and often time-consuming.

4.2.2. Maintenance Strategy

The maintenance strategy process closely follows that of a standard organisational process, according to Crespo Marquez [2007] and Tsang [1998], respectively shown in fig. 4.1. Derived from the corporate vision, goals and objectives the objective for maintenance can be established. These objectives may include equipment availability, reliability, risk, safety, budget, etc. Besides the objectives, additional areas concerning maintenance policy, organisation, resources and capabilities can be elaborated on [Parida and Kumar, 2006]. It is of importance that the maintenance objectives reflect that of the vision, goals and objectives of the organisation.

However, according to Parida and Kumar [2006] there is a mismatch in real life between what is expected from external and internal stakeholders and the capability, between the goals of the organisation and the objectives of maintenance planning, and between the execution of maintenance and the reported data and analysis. Therefore, there is a need to map the maintenance process and identify the gap between the expected maintenance performance and execution.

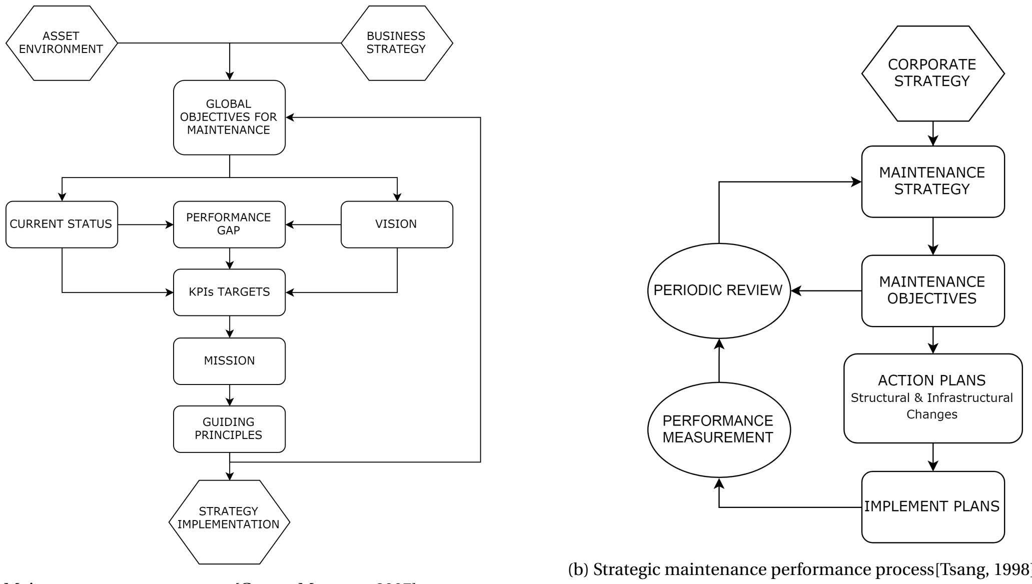
Determining performance measures through the use of KPIs assist in pinpointing possible improvements. They are applied to evaluate effectiveness and find ways to reduce downtime, costs and waste, operate more efficiently, etc. [Parida and Kumar, 2006] KPIs with respect to maintenance will further be elaborates in section 5.1.

The establishment of maintenance principles is important to guide strategy implementation by means of planning, execution, analysis, assessment and improvement of maintenance.

4.2.3. Maintenance Responsibilities

The maintenance strategy adopted leads to the determination of different responsibilities across different activity levels. These responsibilities are distributed across different participants, such as equipment manufacturer, vendor, purchaser and third/external parties providing a type of maintenance service.

Possible scenarios, functions and responsibilities should be identified, assigned and communicated to equipment user, parts of the organisation and external parties.



(a) Maintenance strategy process[Crespo Marquez, 2007]

(b) Strategic maintenance performance process[Tsang, 1998]

Figure 4.1: Maintenance strategy processes

A business structure where a holding company holds shares of the actual corporation, the holding company is part of the establishment of the corporate strategy through an elected board of directors which protects the interest of the holding company [Kennon, 2018]. The board of directors hires the CEO, in turn, hires his direct subordinates. In the case of maintenance, the board of directors, CEO and its direct subordinates are part of the decision-making which establishes strategy, objectives and future planning. Through the board of directs and election of the CEO, the holding company has an influence on the heading of the company and the above mentioned decision-making.

4.2.4. Strategy Implementation

Maintenance management actions are generally in accordance with the three levels of business activities; strategic, tactical, and operational [Parida and Chattopadhyay, 2007, Pintelon and Parodi-Herz, 2008], shown in fig. 4.2. However, depending on the organisational structure, the hierarchical levels could be more than three [Parida and Chattopadhyay, 2007].

Strategic Level

At strategic level the business priorities are translated into maintenance priorities. To meet these priorities, this process crafts mid-to-long term strategies to address current or potential gaps in the performance of equipment maintenance. Resulting from this process is a generic maintenance plan [Crespo Marquez, 2007, Marquez and Gupta, 2006].

Maintenance priorities at strategic level are established through determining critical targets in business operations. Through, for example a criticality analysis, performance measures can be established. Strategic actions are then developed to address specific issues for critical items. Other actions can consist of acquisition of required skills and technologies for the micro-level improvement of maintenance effectiveness and efficiency at business level. A holding company may play an important role in this as it may have more experience or possess the knowledge to make establish these priorities. This depends on the strategy of the holding company and to what extent it wants to control business operations.

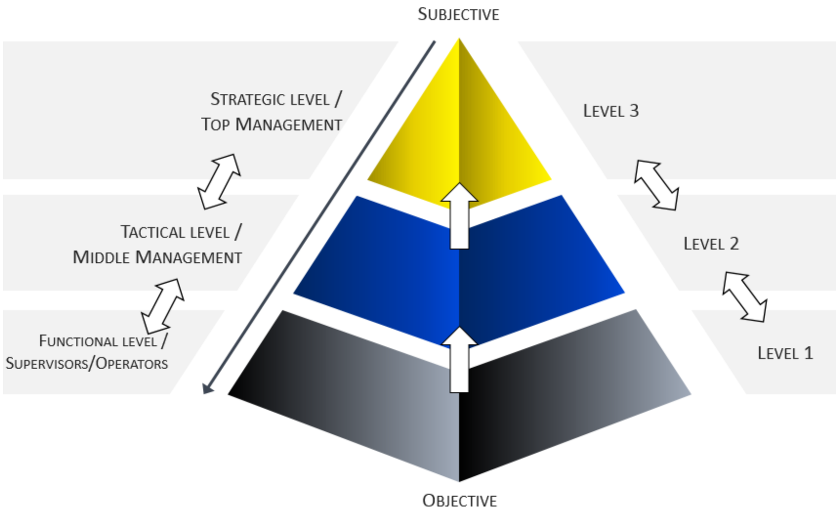


Figure 4.2: Three levels of activity [Parida and Chattopadhyay, 2007]

Tactical Level
On tactical level, to fulfil the maintenance plan, the correct assignment of maintenance resources (skills, materials, test equipment, etc.) is addressed. A detailed program consisting of all tasks specified and the resources assigned. At this level of activity the competence is required to discriminate among a variety of resources that may be assigned in order to execute a certain maintenance task at a certain asset, location and time. Such action would spell out the tactical maintenance policies.

Operational Level
Actions at operational level ensure that maintenance tasks are carried out by accomplished technician, on time, following the correct procedures, and using the appropriate tools. Procedures at this level are needed for preventive works, troubleshooting, and equipment repairs. Diagnosis of equipment failures has become a critical function at this level. The process of troubleshooting therefore relies heavily on the maintenance information system.

Capturing collective management experience at all three levels, and adapting these to the best practice, will result in a maintenance system that can continuously improve, and adapt automatically to new and changing organisational targets [Crespo Marquez, 2007, Pintelon and Parodi-Herz, 2008].

4.3. Maintenance Types, Policies, Activities and Indenture Level

Having discussed the fundamentals that form the basis of maintenance management, the next section will discuss the different types, policies, activities and indenture level of maintenance.

4.3.1. Maintenance Types

In section 4.1 the definition of maintenance, according to the European Committee for Standardisation (CEN) [CEN, 2010], combines both actions intended to retain an item in, or restore it to, a state in which it can perform a task or function required to provide a given service. This leads to the first classification of two maintenance types; retaining and restoring. These two types are more commonly known as "preventive" and "corrective" [CEN, 2010]. The European Committee for Standardisation presents the following types of maintenance, shown in fig. 4.3.

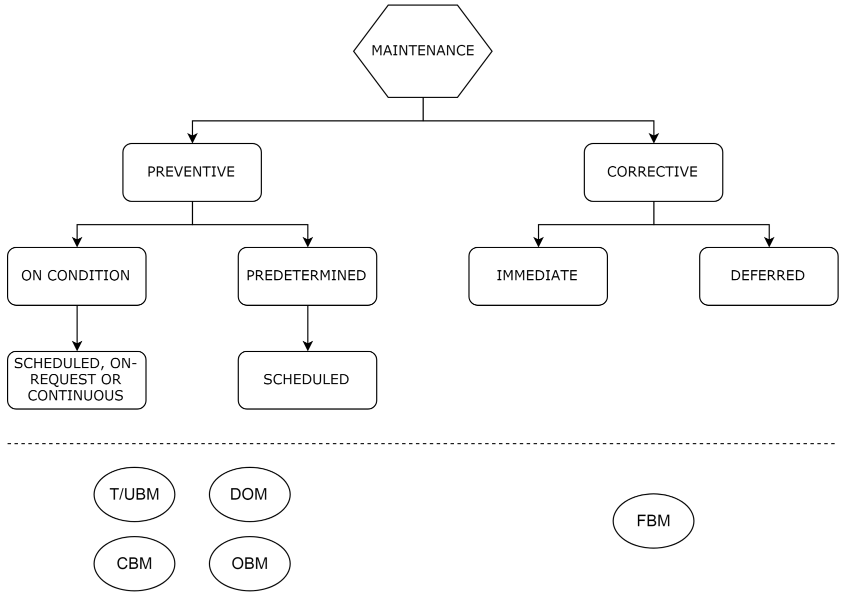


Figure 4.3: Maintenance types and policies [CEN, 2010, Pintelon and Parodi-Herz, 2008]

Preventive Maintenance
Preventive Maintenance (PM) is defined as maintenance that is carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the function of an item. PM can be either predetermined or condition based, according to the European Committee for Standardisation [CEN, 2010]:

> Predetermined maintenance
> *Predetermined maintenance* which is carried out in accordance with established intervals of time or number of units of use (i.e. *scheduled maintenance*), without item condition investigation [CEN, 2010].
>
> Condition based maintenance
> PM based on performance and/or parameter monitoring and its subsequent actions. The monitoring of performance and parameters may be *schedule, on-request or continuous*. Included in Condition-Based Maintenance (CBM) is *Predictive Maintenace (PdM)*, which is defined as a CBM carried out in accordance with a forecast derived from analysis and evaluation of parameters which reflect the degradation of the equipment [CEN, 2010].

Corrective Maintenance
Corrective Maintenance (CM) is maintenance which is carried out after the fault recognition and is intended to put an item into a state in which it can perform a required function. According to CEN [2010], CM can be split into immediate or deferred:

> Immediate maintenance
> *Immediate maintenance* is a CM that is carried out without any form of delay after registering the fault to avoid unwanted consequences [CEN, 2010].
>
> Deferred maintenance
> CM which is not carried out immediately after a fault is detected but delayed in accordance with given rules or guidelines [CEN, 2010].

It can be stated that the replacement of a component before it fails may, under certain circumstances, be economically more viable than replacing a component when it fails. It is important to determine whether preventive replacement is appropriate and identify the best time to replace the component [ReliaSoft, 2019].

4.3.2. Maintenance Policies

According to Pintelon and Parodi-Herz [2008], the five following general types of maintenance policies can be considered as a result of the defined maintenance types; Failure-Based Maintenance (FBM), Time-Based Maintenance (TBM)/Use-Based Maintenance (UBM), Condition-Based Maintenance (CBM), Opportunity-Based Maintenance (OBM) and Design-Out of Maintenance (DOM). A short description of each policy is shown in table 4.1. These policies have been incorporated in fig. 4.3.

Table 4.1: Maintenance policies [Pintelon and Parodi-Herz, 2008]

Policy	Description
FBM	CM actions are carried out after a breakdown of asset or equipment.
TBM / UBM	PM actions are carried out after a specific elapsed time. CM is applied when necessary. UBM assumes that the behaviour of the failure can be described and is assumed to have an increasing failure rate over time.
CBM	PM actions are carried out every time a system parameter exceeds a predetermined value.
OBM	For some equipment maintenance is performed until the "opportunity" arises due to the repair of another more critical component. Whether to perform OBM depends on the expectation of its residual value, which in turn depends on the utilisation.
DOM	The aim of DOM is to redesign parts of equipment which require a high level of maintenance effort or spare part costs or have an unacceptable high failure rate. This might be effective in the case of high maintenance costs or downtime costs.

Failure-Based Maintenance (FBM)

FBM is still applied in current day providing that the cost of PM is equal to or higher than the costs of CM. Additionally, FBM is considered useful in case of random failure behaviour, with a constant failure rate. In this case TBM and UBM are not able to reduce the failure probability. FBM policy is also applied for installations or equipment where PM is expensive and impracticable.

Time-Based Maintenance (TBM) / Use-Based Maintenance (UBM)

The policies of TBM and UBM are applied if the CM costs are higher than that of the PM costs, or if necessary due to the criticality of the equipment as a result of, for example, safety hazard issues. These policies are also introduced in case of increased failure behaviour.

Condition-Based Maintenance (CBM)

CBM was generally applied where the investment in condition monitoring of equipment was justified because of high risks, like in aviation. In the last half-century, it has become a more accepted maintenance policy in the process industry. However, technical feasibility is still a hurdle as it is often a challenge to assign an unambiguous indicator that will reflect the state of the equipment and thus indicate failure [Wiseman, 2006]. CBM is also particularly interesting as it can reduce costs in spare parts replacements as a result of accurate and timely forecasts of failures. Pintelon and Parodi-Herz [2008] state that CBM is based on asset criticality (safety, environment and operational impact) and costs (failure rates). Applying CBM requires the use of analytical tools, such as Failure Mode, Effect, and Criticality Analysis (FMECA) and RCM to determine the likelihood of failure and how it would occur. FMECA is a systematic process to identify all possible ways in which failure can occur.

Opportunity-Based Maintenance (OBM)

A passive maintenance policy is that of OBM. It is generally applied for non-critical equipments with a relative long operational lifetime. No separate maintenance programs are scheduled for these components. Maintenance is performed if the opportunity arises to perform maintenance as a result of another component is being maintained.

Design-Out of Maintenance (DOM)
A more proactive policy is that of DOM. The policy implies that maintenance is pro-actively tackled in the early stages of the product life cycle. This way maintenance related problems can potentially be solved. DOM policies are intended to avoid maintenance all together, through, this is not realistic. This results in the consideration of a different set of requirements in the early stages of design. Modifications in these early design stages are either to increase reliability by increasing the Mean-Time-Between-Failures (MTBF) or increasing maintainability by reducing the Mean-Time-To-Repair (MTTR), see fig. 4.4. Some equipment modifications only require ergonomic considerations to reduce MTTR, while others might needs a totally new design. DOM initiatives are often combined with efforts to increase occupational safety or increase production capacity [Pintelon and Parodi-Herz, 2008].

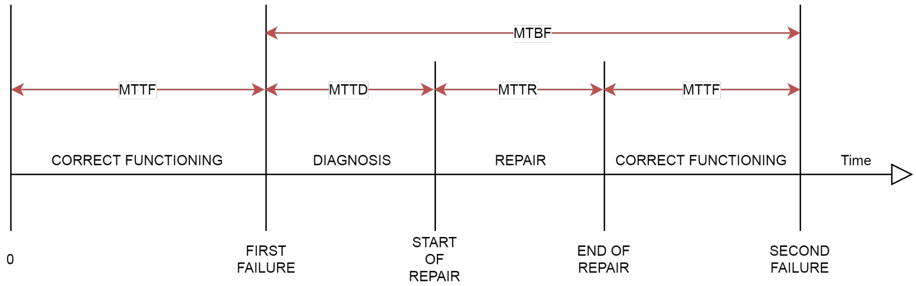


Figure 4.4: Failure timeline[1] [Wikiwand]

4.3.3. Maintenance Activities

The different types of maintenance mentioned above are important adjective of so called maintenance actions, however they are not the definitions of maintenance actions. Maintenance types consist of a set of maintenance activities or actions in a given sequence.

CM actions are repairs or restoring actions which are performed following a breakdown or loss of function. These actions are considered reactive. Corrective actions are difficult to predict as the failure of equipment is stochastic and breakdowns unforeseen.

Precautionary actions is a grouping of "predictive, preventive, proactive and passive" actions. The fundamental aim is to reduce the probability of failure of the asset or equipment and/or to anticipate and/or avoid the consequences of failures [Pintelon and Parodi-Herz, 2008]. *Preventive Maintenance (PM) actions* were adopted as the link was made between the number of cycles a mechanical component was in use and specific failures of the component. The philosophy behind PM is that the equipment makes it from one planned service to the following planned service without failure as a result of fatigue, neglect or wear. *Predictive Maintenance (PdM)* techniques are designed to determine the condition of the equipment in-service and from there predict when maintenance should be performed.This way of maintenance promises cost savings over routine or time-based PM as tasks are only performed when required. *Proactive maintenance* is an action which is performed to prevent failure of equipment, a machine or a material in the future. Examples are activities such as inspections, tests and procedures[Corrosionpedia, 2018]. It focusses on root causes, and dealing with those issues before failure occurs. *Passive maintenance* actions can be described as actions which are scheduled as other maintenance actions are being performed. Passive actions are low priority and do not result in a functional failure or reduced safety.

A list of most common maintenance activities are listed below [CEN, 2010]:

Inspection
Checking for inconsistencies by measuring, observing, testing or gauging relevant characteristics of an item. Inspection is often carried out before, during or after maintenance activity.

Monitoring
Activity performed manually or automatically to observe the actual state of the equipment. It distinguishes itself from inspections as it evaluates any changes in the parameters over time, or given a num-

[1] Mean-Time-To-Diagnose (MTTD) and Mean-Time-To-Failure (MTTF)

ber of operations. Monitoring is often carried out in the operating state.

Routine maintenance
Regular or repeated elementary maintenance activity which does not require special qualification, authorisation or tools. For example, cleaning, tightening of connections, checking liquid levels, etc.

Overhaul
A comprehensive set of actions and examinations which are performed to maintain required level of availability and safety of the equipment. Usually performed at prescribed intervals of time or number of operations and generally refers to a partial or complete dismantling of the item or equipment.

Rebuilding
Action following the partial or complete dismantling of an item or equipment and the repair/replacement of components which have reached the end or their lifetime. It differs from overhaul in that actions may include improvements and/or modifications.

Repair
An action focussed on restoring the required function of faulty equipment. Included in repair are often the following actions: fault diagnosis, fault correction, and function check-out.

4.3.4. Maintenance Indenture Level

There is a relationship between maintenance actions and equipment complexity [Crespo Marquez, 2007]. The more complex an item, the more need for technical subdivision of an item. The maintenance of complex items require the item to be subdivided into so-called indenture level.

Many modern system are comprised of many interconnected elements. Establishing a cause and effect relationship between these elements is difficult because of their extent, time delay, or because their rare impact in systems behaviour. Carrying out maintenance of complex systems requires knowledge and understanding of causes of equipment functional failure. Maintenance tries to eliminate these causes of functional failure which are located at different levels of the equipment structure. There are different factors that influence the definitions of the equipment indenture level [Crespo Marquez, 2007]:

- Complexity of equipment construction;
- Accessibility to the different subsystems;
- The mandatory skill level for the maintenance personnel;
- The need for precise safety considerations;
- etc.

4.4. Intermediate Conclusions Chapter 4

Maintenance management has developed itself into an all important action to add value to business operations. As stated by the CEN [2010], maintenance is a combination of all technical, administrative and managerial actions during the life cycle of an item, component or equipment intended to retain it in, or restore it to, a state in which it can perform the required function(s) for an item which are considered necessary to provide a given service.

A well-established maintenance management plan, should reflect the business its objectives and business plan [Pintelon and Parodi-Herz, 2008]. The maintenance plan determines the effectiveness of the implementation of maintenance plans, schedules, improvements and controls. These problems need to be dealt with to reach an effective maintenance strategy which meets the requirements of stakeholders. The aim is that the maintenance process should be performed with minimal waste, e.q. high efficiency. As this research focusses on evaluating, e.q. benchmarking, maintenance it is concluded that the aim of the maintenance performance management framework and the model leading from it are aimed at measuring efficiency.

The maintenance plan of any business starts with well-defined maintenance objectives. These are based on general business objectives, such as profitability, risk, growth and operating conditions [Anderson et al., 2004, Bacidore et al., 1997]. Maintenance management objectives are split in terms of technical-, legal-, and financial objectives. In order to establish a model which can monitor maintenance, it is assumed the objectives of the model itself should consist of the same maintenance management objective categorisation previously mentioned. Legal objectives are left out of incorporation within the tool as the aim of this research is to benchmark cost and performance of maintenance and repair. Additionally, it is assumed that these joint ventures are generally compliant with these regulations, as it would impact the operations severely.

Following the defining of the maintenance objectives is the maintenance strategy which elaborates on additional areas such as policies, organisation, resources, responsibilities and capabilities. Based on the objectives and strategy, action plans are established and implemented. This implementation is performed in different levels of a business. This is generally split into three business activity levels; strategic, tactical and operational [Parida and Chattopadhyay, 2007].

Every joint venture may apply a different maintenance strategy and following action plans and implementation. Therefore, it is necessary to elaborate on the key specifics that make up the maintenance strategy. The structure of implementation in different organisational levels, i.e. strategic, tactical and operation, illustrate the importance of linking business objectives with eventual action at these different hierarchical levels. It is therefore decided to apply this structure, in hierarchical sense, when erecting the maintenance objectives of the model itself.

Within each joint venture, different maintenance types, policies, activities and indenture levels make up the maintenance strategy. In order to monitor and evaluate the maintenance strategy applied, a choice needs to be made what to take into account from a holding perspective that is Boskalis Towage. It is decided to monitor the two main maintenance types; *preventive* and *corrective* [CEN, 2010]. The reason for focussing on the two main maintenance types is mainly due to expected lack of detailed information concerning the policies applied and how these are applied. Secondly, increasing the detailed evaluation of maintenance policies will increase the complexity of the framework and thus the model. It is therefore decided to stick to two main maintenance types as a way of evaluation.

As discussed in this chapter, equipment selection affects maintenance performed. It is concluded that equipment complexity also adds to how maintenance is performed on the equipment itself. In order to gain insight in the relationship between different equipment and their contribution to maintenance, the indenture level will be focussed on, but not limited to, the critical equipment within a tug. This primarily due to the impact of critical equipment on vessel operational status as well as reducing the complexity of the model. The list of critical equipment is provided in section 3.3. In addition to the list of critical equipment, section 3.4 introduces the SFI Group System which is adopted as indenture level regarding equipment level of detail. This system has shown to be a widely adopted in the maritime industry [Xantic, 2001]. Secondly, the level of detail of the grouping system is such that it incorporates the majority of the critical equipment previously discussed.

Now that the main aspects of the maintenance and repair tool regarding maintenance management are defined and the importance of it being linked with the corporate objectives and strategy explained, the next chapter (5) will elaborate on how performance of maintenance is managed. The conclusions in this chapter and chapter 5 will both contribute to the erection of the maintenance performance framework and tool, elaborated in chapter 8.

5

Maintenance Performance Management

Chapter 5 of part III discusses the subject of maintenance performance management. In order to evaluate the process of maintenance, it is important to understand the fundamentals of performance management and in particular that of maintenance. Explaining the need and the added value of maintenance performance measuring and illustrating how it complements maintenance strategy development is essential as a justification of this research.

Furthermore, the knowledge obtained concerning maintenance performance management will give shape to the maintenance management model in part IV.

Section 5.1 starts with an explanation and justification of maintenance performance management. This includes definitions of performance measures and why these measures are used, followed by definitions of different types of performance indicators. In this section, the categorisation of these performance indicators are reviewed based on literature. Additionally, the hierarchical structure of performance indicators is discussed as well as maintenance performance management implementation issues and challenges. section 5.2 elaborates on the maintenance performance management applied in different industries. This also includes a review of maintenance performance management already being implemented in the maritime industry. Next, methods concerning performance analysis are discussed in section 5.3. This information is required to be able to analyse the performance of maintenance. The intermediate conclusions as a result of this chapter are drawn in section 5.4.

5.1. Maintenance Performance Management (MPM)

Organisations are operating under a dynamic business environment and continuous pressure to enhance their capabilities to create value for their customers and improve the cost-effectiveness of their operations. Besides formulating maintenance policies and strategies, it is important to evaluate the efficiency and effectiveness. To sustain and survive under such challenging circumstances, implementing an appropriate performance measurement system can ensure that actions are aligned to the strategies and objectives [Parida et al., 2015, Tsang, 2002].

Maintenance Performance Management (MPM) can be defined as the multidisciplinary process of measuring and justifying the value created by maintenance investments, and meeting the organisational stakeholders requirements viewed strategically from the overall business perspective [Parida and Chattopadhyay, 2007]. MPM allows for understanding the value created by maintenance, re-evaluate and revise maintenance policies and techniques, justify investments in new trends and techniques, revise resource allocations, and understand effects of maintenance on other functions and on stakeholders, as well as on health and safety, etc. [Parida and Kumar, 2006, Wireman, 2005].

5.1.1. Performance Measurement

Measurement is the act of assigning values to properties or characteristics. The objective of it is to quantify a situation or to understand the effect of observed items [Kumar et al., 2013]. Measuring performance is essential to ensure continuous improvement within a business [Wireman, 2005]. According to literature [Amaratunga and Baldry, 2002], the act of *performance management* can be defined as; "the use of performance measurement information to effect positive change in organisational culture, systems and processes, by helping to set agreed-upon performance goals, allocating and prioritising resources, informing managers to either confirm or change current policy or programme directions to meet those goals, and sharing results of performance in pursuing those goals". Arts et al. [1998] see performance measurements as a means to control maintenance in the goal to reduce costs, increase productivity, ensure process safety and meet environmental standards. A performance measurement system can be described as the set of metrics used to quantify both the efficiency and effectiveness of actions [Neely et al., 1995]. The importance and the link between efficiency and effectiveness of maintenance within the maintenance strategy definition and implementation has already been touched upon in section 4.1.2.

In Kumar et al. [2013], a *performance measure* is described as a number and a unit of measure. This is a combination of a number, expressing the magnitude, and a unit, giving a meaning to the number. Utilising multiple measures expressed in ratios between two or more fundamental units, resulting in a new unit. Therefore, an *indicator*, is a combination of a set of performance measurements. In general business practices these are known as Performance Indicators (PIs) and KPIs. Kumar et al. [2013], Parida and Chattopadhyay [2007], Tsang [2002] all refer to maintenance indicators as *Maintenance Performance Indicator (MPI)*. These MPIs are an important aspect of MPM as they link the maintenance strategies with the overall organisational strategy [Tsang, 2002]. According to Arts et al. [1998], a major issue in the measuring of maintenance performance is the formulation and selection of MPIs that reflect the organisational strategy and supply the maintenance management with quantitative information on the performance of the maintenance strategy. Examples of quantitative measures are quality, downtime, output, number of stops short or long, etc. Examples of qualitative measures include employees' satisfaction, environmental aspects, etc. [Parida and Chattopadhyay, 2007]. The principles shared by most of the writers are:

- Measures are organisational specific and should be linked to the organisation's strategy.
- Multiple measures, internal and external, financial and non financial measures, performance drivers and outcome measures, should be used to create balance in perspective, and to communicate causal relationships to strive for success.
- Measures should be user-friendly, simple, easy to use and easily accessed.
- Measures should be performed at different levels of the hierarchy, and they should be aligned and integrated across an organisation's functions.
- Employees should be involved in formulating strategies and identifying the related performance measures.
- The organisation's structure should encourage behaviour and support operations of the management system.
- Effectiveness of the system should be periodically reviewed to see if it still contributes to the overall organisational performance or that it should be adapted or improved.

Literature shows that there are numerous performance measurement frameworks developed over the years [Parida et al., 2015]. These frameworks all have their specific areas of measure, indicators and criteria. A compilation of numerous developed performance measurement frameworks is given in Table table A.1 in Appendix A. According to Parida et al. [2015], the different performance measures can be categorised under five types of performance measurement frameworks, as shown in fig. 5.1.

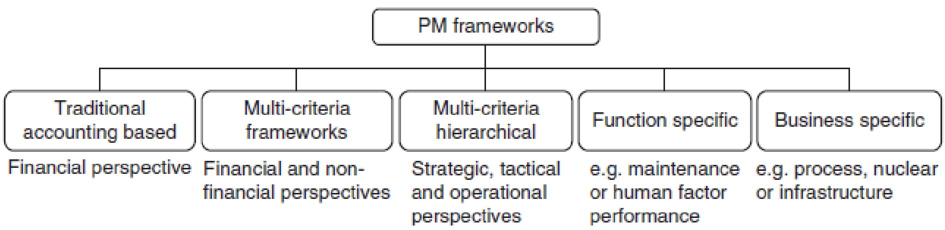


Figure 5.1: Performance measurement frameworks categorisation. [Parida et al., 2015]

There are similarities and differences in measures and indicators between the different frameworks. However, authors acknowledge that these indicators can be assigned to certain general types of indicators, in accordance with the definition of Weber and Thomas [2005]. These types will be discussed in section 5.1.2.

5.1.2. Types of Performance Indicators

In this section the different performance indicators types are discusses as they are described by literature. As stated in the previous section, it is acknowledged that a well-established performance system requires variety of different type of measures. The following are discussed: *leading, lagging, hard, soft, performance killers, performance drivers* and *cost killers.*

Leading vs lagging

PIs are broadly classified as leading or lagging indicators. *Leading indicators* are indicators which warn the user about not achieving the objectives before there is a problem [Encyclopedia Britannica, 2018]. These indicators fairly reliably turn up or down before the general economics status improves or deteriorates. Leading indicators work as *performance drivers* and alerts the organisation to ascertain the present status in comparison to the reference one. Soft or perceptual measures like stakeholder and employee satisfaction are often leading indicators as they are highly predictive of financial performance. Tracking these measures lead to less worry about tomorrow's budgets [Kumar et al., 2013].

Lagging indicators generally change direction after the economic status does. These indicators are useless for prediction as they are outdated and indicate the condition after the performance has taken place. Examples of lagging indicators are maintenance cost per unit and the Return on Investment (ROI).

The link between leading and lagging indicators makes it possible to control the process and monitor a process. These indicators should be chosen in accordance with the maintenance strategy [Kumar and Ellingen, 2000, Kumar et al., 2013].

Hard vs soft

In many instances, processes can be measured directly. Time and costs are quantities and relatively easy to measure. However, measures such as size and type of maintenance teams are particular sensitive and more complicate and can only be measured with more subjective methods [Kumar et al., 2013]. This suggests that indicators fall into two broad groups, "hard" and "soft" indicators. *Hard indicators* include indicators which are measurable through extraction and extrapolation of data from a database, like a computer maintenance management system (CMMS) and enterprise resource planning databases. Examples of hard indicators are absenteeism, purchase orders, energy consumption, etc.

As *soft indicators* are seen as interesting indicators, they can be rendered problematic by the absence of sources and their lack of hard objectivity or reliability, according to Kumar et al. [2013]. The group of soft indicators include all the measures relating to human components, such as impact on training activity on the quality of repairs, or time required for diagnosis and improvement. These measures are generally difficult to quantify in records.

So, the choice of measures and the indicators derived from the measures are conditioned by their accessibility and reliability, especially in the case of soft indicators, as they are affected by human factors. The human element is indispensable in the measurement of maintenance as they have direct influence on the repairs [Kumar et al., 2013]. However, to assess the status of a maintenance system and to correct critical points, the use of objective tools are becoming more important. Mathematical models and some indicators can be used to assess the probability that a team is performing inspection, maintenance or repair successfully, and determine the average time between failures. In other words, two actors are involved in MPM; *people* and *mathematical models.* People provide information on their operational position in the company, while models provide information on effectiveness and efficiency related to cost or time. Combining these, results in the objectives of excellence noted by Katsllometes [2004]; *efficiency, effectiveness* and *staff involvement.*

Performance drivers, performance killers and cost drivers

Besides leading, lagging, hard and soft indicators, literature further discusses the classification of indicators which are performance drivers, performance killers and cost drivers. Numerous European Union research projects consider these aspects of MPIs to reduce the maintenance time or delays and optimise productivity, besides resource and capacity utilisation [Automain, 2012].

Performance drivers are viewed as inputs within a process which drives the performance to deliver the objectives. Kaplan and Norton [1996; 2010] use the term performance driver in their Balanced ScoreCard (BSC) framework. Within this framework, non-financial indicators complement financial measures of past performance which can act as the drive of future performance. Tsang [1998; 2002] and Parida and Kumar [2009] describe performance drivers as equivalent to lead indicators, which have the ability to predict future outcome. Several authors also mentioned that a lead indicator can be a performance driver which acts like an early warning system [Parida and Chattopadhyay, 2007, Parida and Kumar, 2006, Patra et al., 2009].

Inputs in a process, which perform negatively, are defined as *performance killers* by Parida and Kumar [2009], Tsang [1998; 2002]. Markeset and Kumar [2005] dictates performance killers as factors/issues that reduce performance without being strong enough to stop a process. Examples given by Markeset and Kumar [2005] are; equipment with critical uptime, health, safety and environment; bottlenecks in capacity, administration and inventory; incompetence; lack of proper tools and facilities; faulty procedures and checklists; and inadequate information, communication flow and systems, etc. According to CEN [2010], the excessive or non-optimised corrective maintenance tasks are considered to be performance killers. Preventive or corrective maintenance tasks are considered to be either performance drivers or cost drivers as per their application and achieved results.

According to Porter [1985], *cost drivers* are "the structural determinants of cost of an activity, reflecting any linkages or interrelationships that effect it". It can be assumed that cost drivers determine the cost behaviour within the activities. These reflect the link between these activities and other activities and relationships that affect it.

5.1.3. Categorisation of Maintenance Performance Indicators

Literature identifies different categories with respect to MPIs. This section will discuss MPIs categorisation of a couple of well-known maintenance methodologies/concepts.

An early categorisation of MPIs was performed by Nakajima [1988]. Nakajima provides the Total Productive Maintenance (TPM) concept and additionally provides a quantitative MPI called Overall Equipment Effectiveness (OEE) to measure the productivity of manufacturing equipment. OEE identifies and measures losses in availability, performance/speed and quality. According to Nakajima [1988], OEE supports the improvement of equipment effectiveness and productivity. The concept of OEE has become popular and is widely used as a quantitative tool to measure production performance of industries [Huang et al., 2003, Muchiri and Pintelon, 2008].

Coetzee [1997] defines four MPI categories; maintenance results (availability, Mean-Time-To-Failure (MTTF), Mean-Time-To-Repair (MTTR) and production rate); maintenance productivity (manpower utilisation, efficiency and maintenance cost component over total production cost); and maintenance operational purposefulness (scheduling intensity, breakdown intensity, breakdown severity, work order turnover, schedule compliance and task backlog) and maintenance cost justification (maintenance cost per unit production, stock turnover and maintenance cost over replacement value).

Campbell and Jardine [2001] have assigned these MPIs into six categorisations; maintenance productivity, maintenance organisation, maintenance costs, maintenance efficiency, maintenance quality and overall maintenance results.

In 2006, Campbell and Reyes-Picknell classifies MPIs into three categories; equipment performance (e.g. reliability, availability, etc.), cost performance (e.g. maintenance, labour and material cost) and process performance (e.g. ratio of planned and unplanned work, schedule compliance, etc.)

Parida and Chattopadhyay [2007] proposed their multi-criteria hierarchical framework as a solution for MPM (fig. 5.2). The framework consists of multi-criteria indicators for each level of management level, i.e. the strategic, tactical and operational level. The multi-criteria indicators are categorised as equipment-/process-related (e.g. OEE, availability, quality), maintenance task related (e.g. quality of maintenance task, preventive maintenance, corrective maintenance), cost-related (e.g. maintenance cost per unit, production cost per unit), impact on customer satisfaction (number of quality complaints, customer satisfaction), learning and growth (e.g. number of new ideas, skills development), Health, Safety, Security and Environment (HSSE) (e.g. number of accidents, number of legal cases), employee satisfaction (e.g. employee absentees, employee complaints).

The CEN (European Committee for Standardisation) [2007] presented the maintenance measures' classification, through their framework EN 15341, in terms of economic, technical and organisational. Cabral [2009] classified the economical and technical measures into four individual groups: time-related factors, human effort-related factors, number of events and cost-related factors.

According to Muchiri et al. [2010] the indicators can be split into two major and six minor categorisations. The two major categorisations, maintenance process indicators and maintenance results indicators, are based on the principle of leading and lagging indicators which is established by Weber and Thomas [2005]. In the case of the major categorisation of maintenance process indicators, the minor categorisations are: work identification, work planning and scheduling, and work execution indicators. For the major categori-

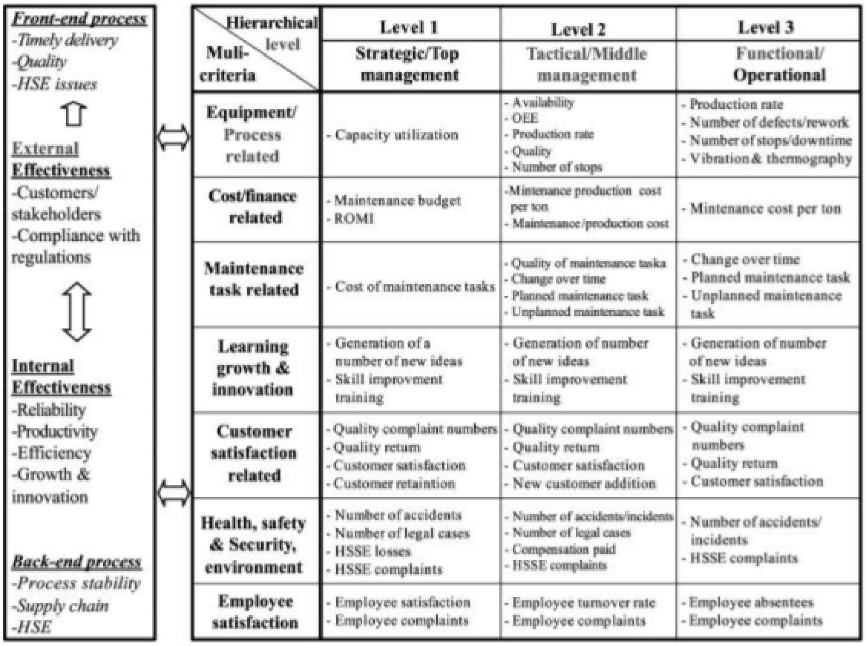


Figure 5.2: An exemplary multi-criteria hierarchical maintenance performance measurement (MPM) framework supplied by Parida and Chattopadhyay [2007]

sation of maintenance results, there are three minor categories: equipment performance, maintenance costs and safety and environment indicators.

Besides the literature discusses above, a couple of other have been reviewed. What can be seen between all proposed categorisations is that they portray three main aspects; technical aspects or indicators concerning themselves with asset performance, financial performance or ratios of costs, and the aspect of work or processes which are focussed on time or frequencies. Some authors show more elaborate categorisation or more focus on one aspect or another. All reviewed literature has been summaries in table 5.1.

Table 5.1: Summary of maintenance performance measurement categories.

Nakajima [1988]	**Coetzee [1997]**	**Arts et al. [1998]**	**Dwight [1995; 1999]**	**Campbell and Jardine [2001]**
OEE	Maintenance results Maintenance productivity Maintenance operational purposefulness Maintenance cost justification	Strategic level Tactical level Operational level	Overt (visible) bottom-line impact measurement Profit-loss and visible cost impact measurement Instantaneous effective measures System audits Time related performance measures	Maintenance productivity Maintenance organisation Maintenance costs Maintenance efficiency Maintenance quality Overall maintenance results

Campbell and Reyes-Picknell [2006]	**Parida and Chattopadhyay [2007]**	**CEN [2007]**	**Muchiri et al. [2010]**	**Duffuaa and Raouf [2015]**
Equipment performance Cost performance Process performance	Equipment-/process related Maintenance task related Cost-related Impact on customer satisfaction Learning and growth HSSE Employee satisfaction	Economic Technical Organisational	Work identification Work planning and scheduling Work execution Equipment performance Maintenance costs Safety and environment	Economic Technical

5.1.4. Hierarchy of Performance Indicators

Indicators are commonly formulated at different corporate levels. Each level serves a certain purpose for a specific user. Generally, the highest level of management refers to aspects that affect firm performance. At the functional level the management traditionally deals with the physical condition of assets. The use of measures at the level of systems and subsystems helps to solve problems. In measures at corporate level indicate a problem, then the lower level of indicators should define and clarify the cause of the weakness that

has caused this problem [Galar et al., 2011, Wireman, 2005]. Mitchell et al. [2002] states that a hierarchy of different parameters which are linked to the business goals, are vital for success of a programme for managing corporate physical assets. Many authors agree that multifaceted maintenance requires metrics that serve specific levels of the organisation's hierarchies [Grenčík and Legát, 2007, TRADEPBMSIGO, 1995].
According to Kahn and Gulati [2006], KPIs should be used to set up a hierarchical methodology to quantify project improvements in the maintenance function. By visualizing the expected benefits, the process variations and trends, they can be monitored. The KPIs should be controlled for continuous improvements. For Kahn and Gulati [2006], a KPIs is a traceable process metric which allows for decision-making aimed at established objectives. Maintenance KPIs should include indicators on corporate level (e.g. OEE), financial level (e.g. overall maintenance budget compared to the replacement cost, etc.) Like TRADEPBMSIGO [1995], Kahn and Gulati [2006] proposed five levels of KPIs, each with its own requirements and users: maintenance costs, availability of equipment, OEE, production costs and performance.

Wireman [2005] defines different indicators into the following hierarchical levels; the first layer could be at the corporate strategic level; second, the supporting level could be the financial PIs; the third level could be the efficiency and effectiveness indicators; and the fourth and fifth levels could be the tactical and functional PIs(see fig. 5.3). They should properly be connected to the levels of the corporate vision and the company mission.

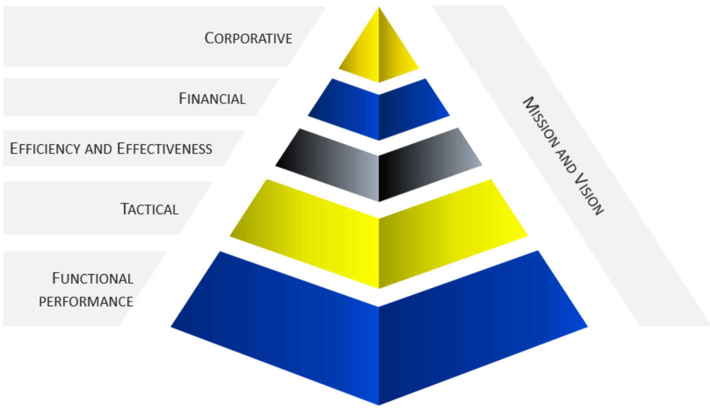


Figure 5.3: Hierarchy of indicators in maintenance according to Wireman [2005]

According to Kumar et al. [2013], these concepts suffer from a hierarchical structure which condemns the low levels to work with operational and functional indicators, while assigning economic indicators to the top management, thus dividing the analysis and creating indicators of first and second categories.

As earlier discussed, Parida and Chattopadhyay [2007] have established a multi-criteria hierarchical framework comprised of three levels; corporate/strategic level, tactical/managerial level and functional/operational level. However, more hierarchical levels could be formed based on the organisational structure. Parida and Chattopadhyay [2007] notes that indicators are determined from the top down, as it is important to satisfy the needs of the stakeholders/shareholders.

5.1.5. MPM Implementation Issues and Challenges

Performance measurement systems have shown to impact and increase performance and competitiveness of organisations through the use of more balanced metrics. However, there are some issues according to Kaplan and Norton [1996] and Bourne et al. [2003]. Kaplan and Norton [1996] identified four barriers. These are:

1. Vision and strategy not actionable
   This occurs when the senior management fail to achieve a consensus as to how the vision should be achieved. This results in groups perusing different goals and agendas. Effort is neither coherent nor linked to the established strategy.

2. Strategy is not linked to department, team and individual goals
   As a result, individuals continue to follow the old traditional performance criteria and discard the introduction of the new strategy. This can be worsened by an unaligned incentive system.

3. Strategy is not linked to resource allocation
   Strategy is not linked to resource allocation when long term strategic planning process and annual budgeting process are separated and result in funding capital allocations becomes unrelated to strategic priorities.

4. Feedback is tactical and not strategical
   This occurs when feedback concentrates on short-term results and little time is spent for the review of indicators of strategy implementation and success.

Bourne et al. [2003] performed a literature review on the implementation of performance measurement initiatives and notes a couple of issues. Time and expenses are required to implement a MPM system. Secondly, if there is a lack of leadership or resistance to change, implementation won't occur at all or at a slower rate. Thirdly, the vision and mission may not be actionable if there are difficulties in the determining the relative importance of activities and identifying the true drivers. Additionally, the establishing of goals may be negotiated rather than based on stakeholders requirements. To facilitate the needs of the stakeholders, the goals are to be dictated by these requirements. Fifthly, striving for perfection can undermine success. Moreover, strategies not linked to the department, team and individual goals can result in following old traditions, like Kaplan and Norton [2010] states. Seventhly, if too many indicators are selected for monitoring they may dilute the overall impact of the MPM system. Additionally, if indicators are poorly defined they won't produce the expected results. Ninthly, if a highly developed information system is required but data is hard to come by, the MPM system won't be implemented. Finally, quantifying results in areas that are more qualitative in nature may be a challenge to implement in the system.

Leadership support may be the most important aspect in the success of a MPM [Bourne et al., 2003]. From a leadership position it is essential to able to justify the advantages of a MPM system. Parida and Kumar [2006] identifies several key factors for justifying the implementation of a MPM system. The first is that measuring the value created by maintenance helps to show what the added value is in the entire process. Secondly, a MPM system can help justify investment in new equipment or personnel. Furthermore, a MPM system can help justify the revision and possible relocation of resources. HSE issues can also be highlighted and pinpointed through the use of a MPM system. Fifthly, through the implementation, more knowledge is obtained of the overall process leading to a knowledge focussed management. Furthermore, a MPM system can help adapt to new trends in operation and decide on new maintenance strategies or even organisational structural changes.

Åhrén [2008], Stenstrom et al. [2013] both recognise the difficulties regarding poorly defined and large number of indicators and databases in the planning and performance measuring of railway infrastructures. Concerning these large number of measures, companies generally report large numbers of measures to their senior management [Parida et al., 2015], thereby confusing detail with accuracy. The number of indicators at strategic level depend on the number of senior managers, but aggregation is needed since there are several hundreds of indicators at operational level. Aggregation of data is a weakness of traditional performance measurement systems since it might make the indicator abstract as underlying factors may not be known [Parida et al., 2015]. The *link and effect* model tries to resolve this by complementing indicators with the underlying factors responsible for the performance, see fig. 5.4. The link and effect model is elaborated in appendix B.

As often addressed by literature in prior sections, it is important to align the corporate mission, vision, objectives and hierarchical levels with that of the MPM. Some authors [Kumar et al., 2013, Parida and Chattopadhyay, 2007] suggest adopting the BSC approach developed by Kaplan and Norton and later adapted by Tsang [1998] for measuring maintenance performance. The method measures maintenance performance using the following four perspectives; financial perspective, customers' perspective, internal processes perspective, and perspective of learning growth. Alsyouf [2006] criticises the BSC approach suggested by Tsang et al. [1999]. Arguing that the four non-hierarchic perspectives are top-down performance measures and do not take into account the extended value chain; i.e. the technique ignores suppliers, employees and stakeholders. Besides the new BSC technique, Tsang et al. [1999] also presents a Data Envelopment Analysis (DEA) technique, which is a non-parametric quantitative approach to analyse performance. The concepts of performance analysis is further discussed in section 5.3.

Furthermore, due to the fast development of new technologies in performance measurement a performance measurement system should be proactive and dynamic [Parida et al., 2015]. Changes in the enterprise resource planning system or computer maintenance management system may alter the performance

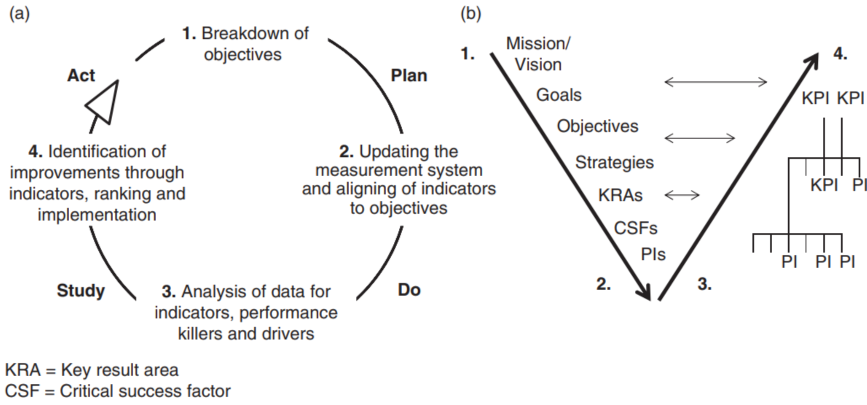


Figure 5.4: The link and effect model based on (a) a four-step continuous improvement process and (b) a top-down and bottom-up process. The numbers in (b) represents the steps in (a) [Stenstrom et al., 2013].

measurement practices and monitoring of historical asset condition data.

5.2. Maintenance Performance Management in Different Industries

According to Parida and Kumar [2009], the greatest challenge for measuring performance of maintenance is the implementation of the MPM system under a real and industrial set up. Different industries use different MPM frameworks to control, monitor and evaluate their maintenance performance. Organisations like the International Atomic Energy Agency (IAEA) had developed safety indicators for nuclear power plants in 2000. The Society for Maintenance and Reliability Professionals (SMRP) and the European Federation of National Maintenance Societies (EFNMS) organise work groups and workshops to identify and select MPIs for different industries. Other examples of industries which have tried implementing MPM frameworks are the nuclear industry, oil and gas, railway, process industry and energy sectors [Parida and Kumar, 2009]. Different approaches are taken for the establishment of the MPM frameworks, as per the stakeholders' requirements.

The implementation of MPM frameworks and MPIs in the oil and gas industry were used extensively due to the growing and competitive nature of business. Therefore, the focus within these frameworks are on productivity, safety and environmental issues. An integrative approach was introduced, incorporating safety attributes for the operation of the oil and gas production unit. Indicators were established for each individual unit suited to their individual needs, depending on the designed performance and cost and benefit of operation/maintenance [Kumar and Ellingen, 2000, Parida and Kumar, 2009]. See appendix C table C.1.

The railway operation and maintenance is there to provide a service to a user/customer, while meeting required regulations. Present, requirements are to perform cost effective maintenance while operating a punctual and cost-effective rail road transport system. Resulting from a research project performed by Åhrén [2008] for the Swedish rail roach transport system, numerous maintenance performance indicators were identified. These are shown in appendix C table C.2.

In the last decade, measuring performance maintenance has increase in the utility, manufacturing and process industry. Organisations are interested to know the return on investment made in maintenance spending, while meeting stakeholders requirements, business objectives and strategy [Parida and Kumar, 2009]. Balanced, holistic and integrated multi-criteria hierarchical MPM models were developed to measure performance in a wood palletisation plant and an energy producing service industry of Sweden [Parida et al., 2005]. The MPIs for the process and utility industry, according to Parida et al. [2005], can be found in appendix C appendix C.3.

The maritime industry has performed little work on MPM frameworks. The maritime industry concentrates on assessment and measures on ship safety and pollution prevention. An example is the Tanker Management and Safety Assessment (TMSA) and Offshore Vessel Management and Safety Assessment (OVMSA) by the Oil Companies International Marine Forum (OCIMF), the Sustainable Development Strategy by Fisheries and Oceans Canada, and the Marine Safety Performance Plan of the United States Coast Guard. As the titles of the different projects indicate, there is an increased focus on the safety and pollution of ships.

The TMSA and the OVMSA are two set of guidelines to measure and asses the operations' management systems of respectively tankers and offshore vessels, developed by the OCIMF. Both guidelines consist of 12 different elements of management practices. They provide an approach for safety and environmental excellence for ship operators. Element four in the TMSA and OVMSA discusses reliability and maintenance standards, and the main objectives of this part is to establish maintenance standards so all tankers and offshore vessels in a fleet are able to operate safely with minimal risk of an incident occurring [Turker and Er, 2008].

Besides the earlier discussed safety guidelines for offshore vessels and tankers, the International Maritime Organisation (IMO) provides the International Safety Management (ISM) Code. This Code provides an international standard for the safe management and operation of ships at sea. The ISM Code establishes safety-management objectives and requires a safety-management system to be established by ship owners, organisation or person responsible for operating the ship and has agreed to take over all duties and responsibilities imposed by the Code [International Maritime Organisation (IMO), 2018]. Section 10 within the ISM Code addresses 'Maintenance of the Ship and Equipment'. It states that procedures should be established to ensure that the ship is maintained in conformity with the provisions of the relevant rules and regulations and any additional requirements which may be established by the Company, e.g. so called person or company responsible. To do so the Company should ensure that inspections are held at appropriate intervals; non-conformity is reported; appropriate corrective actions are taken; and records of these activities are maintained. Furthermore, it addresses the need to identify critical equipment and technical systems which may result in hazardous situations and the aim to promote reliability measures of such equipment systems through regular testing. These measures should be integrated in the ship's operational maintenance routine.

5.3. Performance Analysis

Establishing a MPM system and maintaining it is one thing, but understanding the fundamentals that need to be changed in order to achieve maintenance objectives requires analysis is a different challenge. Performance analysis is the measure and comparison of levels of achievement of specific objectives [Tsang et al., 1999]. To measure operational performance in single-input, -output cases, defining productivity as the ratio of output to input is seen as an adequate measure. The analysis becomes more difficult and complex when multiple inputs and multiple outputs are involved. The inputs and outputs can all have different units of measure. In the case of comparing maintenance performance of a railway system, the inputs can include available kilometres, passenger trips per day, rolling stock and station facilities, etc. The operating and management costs per car operating kilometre, and car operating kilometre per total staff plus contract hours are examples of outputs [Tsang et al., 1999].

Data Envelopment Analysis (DEA) in a non-parametric approach developed by Charnes et al. [1978], which can be used to compute multiple-input, multiple-output productivities. It does not require preassigned weighting of inputs and outputs. DEA uses Linear Programming (LP) modelling of Decision Making Units (DMUs) in the peer group. DEA is often used together with multiple regression analysis to identify the significant factors contributing to superior performance of the DMUs. This procedure has been used to compare the operational performance amongst airlines [Schefczyk, 1993], hospitals [Ozcan and McCue, 1996], schools [Thanassoulis, 1996] and special economic zones in China [Zhu, 1996]. This methodology of comparing input and output whilst not fully including a maintenance function shows promise. As discussed in part II, maintenance is a function of many aspects. DEA may be a solution for peer evaluation between the different tugs. The additional possibility of multi-regression analysis makes the methodology even more interesting. Therefore, the specifics of DEA are discussed in chapter 6.

5.4. Intermediate Conclusions Chapter 5

Performing maintenance operations under a dynamic business environment and in a cost-effect manner is a challenge. A Maintenance Performance Management (MPM) system can add value through a multidisciplinary process of measuring and justifying the value created by maintenance investments. MPM allows to understand the value created by maintenance, re-evaluate and revise maintenance policies and techniques, justify investments in new trends and techniques, etc. [Parida and Kumar, 2006, Wireman, 2005]. MPM systems are comprised of performance measures and indicators. These measures and indicators, in this case Maintenance Performance Indicator (MPI), are an important aspect of MPM as they link the maintenance strategies with the overall organisational strategy Tsang [2002]. Arts et al. [1998] acknowledges that the formulation and selections of the correct MPIs that reflect the organisational strategy and supply quantitative information on performance of the maintenance strategy is a challenge. Examples of quantitative measures are quality, downtime, output number of stops, etc.

Based on literature Parida et al. [2005] has categorises five different performance measure frameworks. These are *traditional accounting based, multi-criterial framework, multi-criteria hierarchical, function specific* and *business specific*. Based on the definitions presented by Parida et al. [2005], it has decided to erect a *Multi-criteria Hierarchical Function specific framework*. The reason for combining multiple definitions in order to establish this specific maintenance framework is threefold. The first being that the goal of this research is to increase detailed monitoring of maintenance expenses and performance, meaning that in additional to accounting based monitoring the desire is to incorporate and link operational perspectives. This leads to the first part within the framework definition, which is *Multi-criteria*.

Secondly, the framework definition is specified as *Hierarchical*. This incorporated due to the conclusions made in chapter 4 where the importance of maintenance management and how it transcribes within the different business levels. This structures the framework and corresponding model in accordance with the different business level and additionally allows for possible link and effect capabilities, which may allow for complementing indicators with underlying factors [Parida et al., 2015].

Thirdly is the part of *function specific*. This part specifically defines the framework to be formulated for a specific function, e.g. maintenance performance. It is evident that if the aim of this research is to structure a model which allows for maintenance monitoring, the framework should likewise focus on this function.
The next step is to elaborate different types of performance indicators. The different types are described as; *leading* vs *lagging*, *hard* vs *soft* and *performance killers, drivers* and *cost drivers*. Literature agrees that incorporation of different performance indicators leads to a balanced performance evaluation in maintenance management [Automain, 2012, Kaplan and Norton, 2010, Kumar and Ellingen, 2000, Kumar et al., 2013, Porter, 1985]. It is therefore aimed to provide a diverse set of performance indicators which fall within one of above mentioned type of performance indicators.

For the structuring of the different indicators, one of the parts of the defined framework can be used; *Multi-criteria*. Parida and Chattopadhyay [2007] introduces the multi-criteria hierarchical framework, shown in fig. 5.2. It is adopted for this research as it combines two import aspects. Firstly, it takes into account the aspects of both financial and non-financial perspectives. Secondly, it reflects the business levels, for which the importance has been elaborated in chapter 4 and chapter 5. Seeing as organisation are typically structured hierarchically, literature agrees with establishment of different maintenance requirements at different operational levels [Galar et al., 2011, Grenčík and Legát, 2007, TRADEPBMSIGO, 1995, Wireman, 2005]. Additionally, KPIs should be used to set up a hierarchical methodology to quantify project improvements in the maintenance function [Kahn and Gulati, 2006]. The downfall of hierarchical structures is that it condemns the lower levels to work in operational and functional indicators, while assigning economic indicators to top-level or management level.

The last item to address is the adoption of the categorisation of the maintenance performance indicators, as discussed in section 5.1.3. It has been shown that various authors categories MPIs differently, as summarised in table 5.1. Based on literature it is decided to adopt the categorisation of Campbell and Reyes-Picknell [2006], *Equipment-*, *Cost-* and *Process performance* respectively. The reason behind this choice is twofold. It is believed that the definition into the three respective categories are both simplistic and holistic. Simplistic as it can be easily communicated and understood by the different business levels which is imperative for a successful adoption. Secondly, the maintenance function, within the entire framework, is assumed to be a function of these three aspects.

Resulting from this decision, a framework illustrating the maintenance function was found in Muchiri et al. [2011], which is a prime illustrative example of the three categorisation discussed above and presented by Campbell and Reyes-Picknell [2006]. Muchiri et al. [2011] has developed a conceptual performance measurement framework for the maintenance function shown in fig. 5.5, which shows how the maintenance and corporate objectives align with maintenance effort/process. Resulting from this maintenance process are maintenance results, which are defined as equipment performance and maintenance costs. Performance analysis can be performed on these results. An additional added value of this maintenance function framework is that is distinguishes leading- and lagging indicator allocation within the maintenance framework. The maintenance strategy formulation part is left out of the maintenance performance model as the aim of this research evaluate maintenance cost and performance, i.e. efficiency. Evaluation of the maintenance strategy would fall within the effectiveness of maintenance which may be up for evaluation as a result of this research.
Summarising the above conclusions, the following three key choices can be noted, regarding the definition of

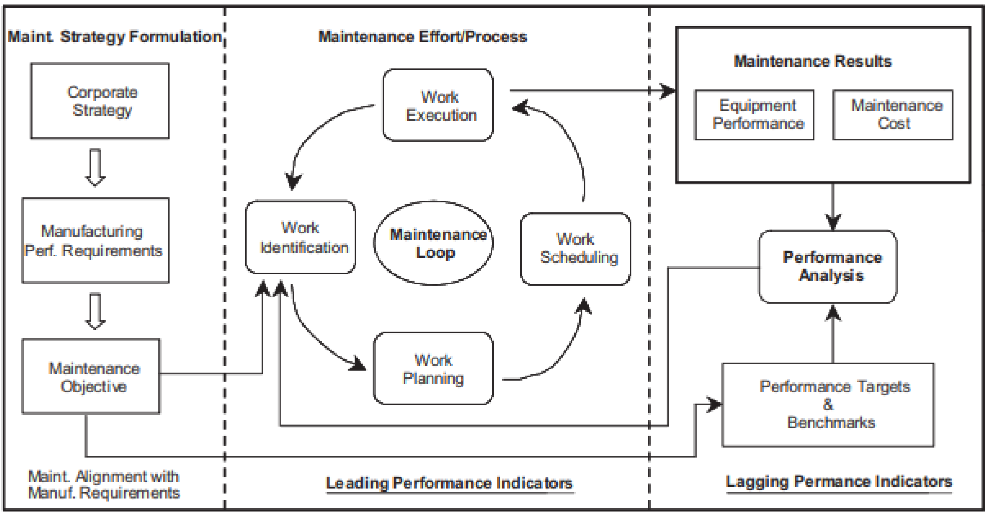


Figure 5.5: The performance measurement framework for the maintenance function [Muchiri et al., 2011]

the framework:

1. A multi-criteria hierarchical framework is chosen for the defining and categorisation of the different Maintenance Performance Indicator (MPI) with the aim of incorporating financial- and non-financial perspectives, and including reflecting the hierarchical business structure within the framework and model.

2. In contrary to the multi-criteria presented by Parida and Chattopadhyay [2007], shown in fig. 5.2, the categorisation of Campbell and Reyes-Picknell [2006] is adopted due to its simplistic and holistic categorisation of the maintenance function, comprised of equipment-, cost- and process related indicators.

3. The framework of Muchiri et al. [2011] is used as example for the construction of the maintenance function framework, due to the observation that the three categorisation, adopted through Campbell and Reyes-Picknell [2006], are represented within the maintenance function framework.

There are numerous hurdles when implementing a MPM system [Bourne et al., 2003]. A couple of important aspects are that; the vision and strategy should be actionable and achievable; the strategy should be linked to departments, teams and individual goals; the strategy should be linked to resource allocation; and feedback does not loop back to strategic level. An important weakness of traditional performance measurement system is aggregation of data. The *link and effect* model tries to resolve this by complementing indicators with the underlying factors responsible for the performance, see fig. 5.4.

Analysing the acquired performance measures and indicators is equally important as the establishment of the MPM framework and system [Tsang et al., 1999]. The analysis of MPM performance indicators is dependent on the input data, output data as well as the MPM structure and its objective. It is acknowledged that to be able to performance an adequate analysis is imperative to understand changes required in maintenance to increase performance. In that respect, a promising method, DEA, is discussed and elaborated upon in chapter 6.

In this chapter, the concept of MPM has been discussed and has given useful insights in the establishment of a MPM system, its characteristics and challenges. Based on discussed literature, a choice has been made to propose a *multi-criteria function specific hierarchical* framework. Having made this decision, chapter 8 will elaborate on the framework and the maintenance performance model which is based on this framework. However, before this chapter the performance analysis methodology of DEA will be discussed in chapter 6. After that, part IV will, in depth, discuss the choices made for the construction of the MPM model.

6

Data Envelopment Analysis (DEA)

Tsang et al. [1999] literature regarding Maintenance Performance Management in chapter 5 lead to the introduction of Data Envelopment Analysis (DEA), which is a non-parametric approach used to compute multiple-input, multiple-output productivities. This methodology is believed to be of value to this research as it presents an additional method of analysing peer performance, i.e. benchmarking. This chapter will elaborate on the basic principles of DEA. Based on literature the reason behind the selection of this methodology will be elaborated and a model type is chosen and a way of incorporating it in the model. It is aimed to add this model to the maintenance performance model in part IV.

This chapter will start off which a short background of this methodology and how it has developed over the years. Section 6.2 elaborates on the basic principles of DEA and the underlying mathematics. Section 6.3 discusses the different DEA model types and what distinguishes them from each other. Section 6.5 addresses the possible input, output and data issues that may occur when implementing DEA. The last section consists of the model selection and how it may be implemented in the maintenance and repair performance monitoring model in part IV.

6.1. Background

DEA has seen great variance of applications throughout the years [Cooper et al., 2007]. It has opened up possibilities to research cases which have been to complex for other approaches due to the relationships between multiple inputs and multiple outputs involved. Examples are the evaluation of maintenance activities of U.S. Air Force bases, police forces in England and Wales as well as performance of branch banks in Cyprus and Canada [Cooper et al., 2007] and the efficiency of universities in educational performance and research functions in the U.S, England and France.

The name DEA was first introduced in 1978 by Charnes et al., built on a concept of Farrel in 1957. The practical development of the concept was not feasible as computing equipment was not present. As technology developed, the methodology was applied to complex problems consisting of multiple inputs and outputs. The introduction of linear programming allowed the method to be used in varied scenarios. Nowadays, linear programming and technological development have lead to the capability of running numerous iterations required for DEA on an average computer with use of simple DEA-coding programs or even Microsoft Excel [Paradi et al., 2018]. Paradi et al. acknowledge the capabilities of DEA, however only a small portion of published work deals with DEA in a real-life applied problem and even fewer publish results using DEA in production systems [Paradi et al., 2018]. DEA currently continues to heavily focus on understanding and improving performance of defined DMUs, but have also recently recognised DEA its ability to identify relationships in complex operating data [Sherman and Zhu, 2013].

6.2. Basic Principles

As states in prior section, DEA is driven by underlying linear programming mathematics. The principle of linear programming will not be topic of discussion in this research. A general understanding of the mathematics is helpful for understanding literature, however it is not mandatory to understand the benefits and ways to implement DEA, as suggested by Paradi et al. [2018]. To understand the principles of linear programming and its applications, it is advised to consult Jansen and Bard [2003] or other literature regarding linear programming.

The DEA method is a so called frontier approach. Paradi et al. [2018] states, “Frontier approaches identify and asses the areas or examples of best performance or best practice within the sample, i.e. those located on the ’frontier’”. An illustrative example of the frontier approach is shown in fig. 6.1. This shows the efficient frontier and best performing DMU B on that frontier. The name Data Envelopment Analysis comes from this property because in mathematical parlance, such a frontier is said to "envelop" these points [Cooper et al., 2007]. All other DMUs are inefficient with respects to DMU B. The approach, as suggested by Paradi et al. [2018], suggests the best performance within the group of operating units being evaluated and does not promise or even suggest that these represent the theoretically best performance. There are two types of frontier approaches: *parametric* and *non-parametric*. Parametric specifies a frontier function to be fitted to the data, with or without accounting for noise in the dataset. DEA is a non-parametric approach, which means that no prior functional form is assumed for the frontier. This non-parametric approach includes the simple assumption of piecewise linear connections of units on the frontier [Paradi et al., 2018]. Paradi et al. state that the ability of DEA to be used without functional form is a very powerful characteristic as it can be used and analysed without knowing the production function, which links inputs to outputs. This is highly interesting for benchmarking maintenance as it is dependent of many variables and impacted by many factors.

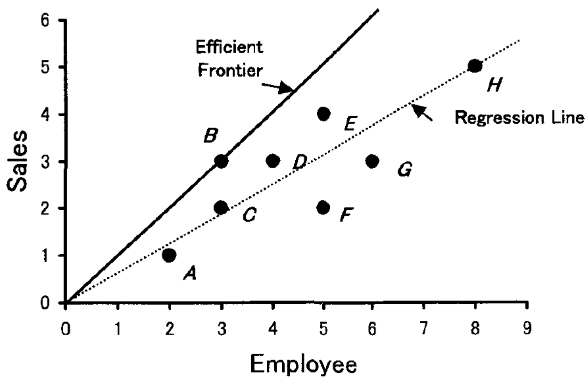


Figure 6.1: Regression Line vs. Frontier Line [Cooper et al., 2007]

Given fig. 6.1, one might attempt to use a statistical approach and fit a regression line to the data, showing in fig. 6.1. As normally determined in statistics, this line passes through the "middle" of these data points. The data points above this regression line could be seen as excelling at their tasks while the others are seen as inferior. Through the magnitude of the deviation from this fitted line, one can measure the degree of excellence of inferiority [Cooper et al., 2007]. The frontier line designates the best performance, in this case store B, and measures the efficiency of other units with respect to the frontier. So, there is a fundamental difference between statistical approaches via regression analysis and DEA. The statistical approach reflects "average" or "central tendency" behaviour of the data, while DEA deals with best performance and evaluates the performance based on the deviations from the frontier line [Cooper et al., 2007]. The efficiency of others relative to the best performance store (B) can be measured by:

$$0 \leq \frac{\text{Sales per employee of others}}{\text{Sales per employee of B}} \leq 1 \tag{6.1}$$

It is not reasonable to assume that this efficient frontier line stretches to infinity with the same slope. This characteristic can be defined through the definition of *Returns To Scale (RTS)*. This characteristic is model dependent and will be elaborated upon in section 6.3. The principles of RTS are elaborated in section 6.2.1. Another key characteristic of DEA is its orientation, meaning the focus of improvement, which is either focussed on input reduction, output increase or both. This will further be explained in section 6.2.2 and elaborated in section 6.3.

6.2.1. Return-to-Scale (RTS)

In accordance with OECD [2001], RTS refers to " the rate by which output changes if all inputs are changed by the same factor. Constant returns to scale: a k-fold change in all inputs leads to a k-fold change in output. Under increasing returns to scale, the change in output is more than k-fold, under decreasing returns to scale; it is less than k-fold." The three laws of RTS are explained using fig. 6.2.

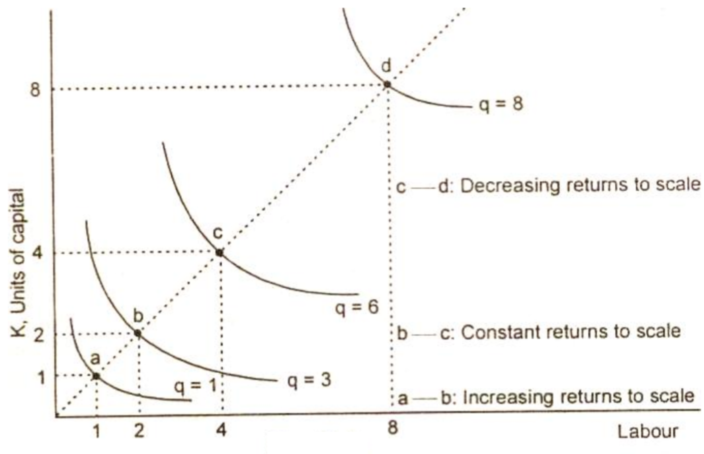


Figure 6.2: Returns to Scale [Economicsconsepts, 2019]

Increasing Returns to Scale

A production is said to exhibit Increasing Returns To Scale (IRS) in cases where the output increases more than in proportion to an equal percentage increase of all inputs [Economicsconsepts, 2019]. In fig. 6.2, when production is increased from point a to point b, the inputs of labour and units of capital increase by a factor of 2. The production amount increased from 1 to 3, shown by the $q = 1$ and $q = 3$ isoquant, which is higher than a factor of 2. The production function has an IRS in this range. When there is an increase in scale of production, it leads to lower average costs per unit produced due to the economies of scale [Economicsconsepts, 2019].

Constant Returns to Scale

In that respect, the production function from point b to point c has a Constant Returns To Scale (CRS). The increase of input has a proportional increase of output, $q = 6$ [Economicsconsepts, 2019]. The production function is said to exhibit CRS. In this instance, the constant scale of production has no effect on average cost per unit produced.

Diminishing Returns to Scale

The last law is that of Diminishing Returns To Scale (DRS). This implies that the increase of outputs is proportionally smaller than the increase in all outputs. Figure 6.2 shows an increase in output from point c to point d is smaller than 2, while the increase of inputs are a factor of 2 [Economicsconsepts, 2019]. The scale of production leads to higher average cost per unit produced.

Variable Returns to Scale

Besides these three laws or RTS, DEA also acknowledges a Variable Returns To Scale (VRS) principle. It is a principle which allows for existence of VRS, i.e. IRS, CRS or DRS [Paradi et al., 2018]. A VRS model is often applied in DEA to gain additional insight to efficiencies obtained in CRS models. The ratio between CRS/VRS gives a measure of the DMUs scale efficiency, meaning the effect on its productivity from potentially not operating at the optimal scale [Paradi et al., 2018]. This relationship between CRS and VRS holds for all DEA models.

There are more so called *technology assumptions* which are used in various DEA models and software. The above mentioned RTS cases are most commonly used as they are basic and more easily to understand. For this research, it is aimed to incorporate one of the above mentions RTS characteristics, however, if software allows for more in-depth evaluation through use of other technology assumptions they will be researched for their significance in helping to better understand the efficiency measures that come with DEA.

6.2.2. Orientation

As priorly mentioned, the orientation of a DEA model refers to the focus of improvement. Within DEA, the definition of orientation will result in an efficiency measure regarding the direction the viewpoint taken in improving the inefficient units. The efficiency results will be expressed in goals to reduce excess inputs consumed or expand shortfalls in outputs produced, respectively, to move the inefficient unit to the frontier [Paradi et al., 2018]. DEA also has the possibility of allowing so called non-orientation, which implies the pursuit of both input reduction and output expansion.

6.2.3. Other Key Characteristics

DEA is seen as particularly useful as an efficiency measure and evaluation methodology in cases where sample units, termed Decision Making Unit (DMU), with multiple inputs and outputs operate under comparable conditions [Paradi et al., 2018]. It primarily is used to measure technical efficiency, i.e. focuses on levels of inputs vs outputs. Another key characteristic of DEA is that it can incorporate inputs and outputs in their natural unit of measure and don't require conversion to the same units.

Another advantage of DEA stated by Paradi et al. [2018] is "that it suggests explicit improvement targets for inefficient DMUs, namely the benchmark or point on the frontier to which it is being compared in order to measure its efficiency." The point on the frontier is a linear combination of one or more actual DMUs which are efficient. Inefficient DMUs are presented with a relevant set of efficient DMUs, its so called *reference set*. Identifying the amount of excess resources used or potential increases of outputs for inefficient units in comparison with efficient units may well be the most powerful characteristic of DEA [Paradi et al., 2018].

Now that the basic principle of DEA has been discussed as well as its significance as an analytic and management model, the next section will discuss three basic types of DEA models and possible extensions.

6.3. DEA Model Types

According to Paradi et al. [2018], there are three types of basic DEA models: *radial*, *additive* and *slack-based measure* models. A short description of each model is supplied below, including their properties. For elaboration of the equations that make up the models, it is referred to Cooper et al. [2007].

Radial Model

There are two basic radial models. The original DEA model proposed by Charnes et al. [1978], termed the CCR model, and the BCC model, named after Banker et al. [1984]. The term "radial" refers to the model examining input possibilities on a line extending radially from the point of origin, as shown in fig. 6.3a.

In a CCR radial model, the DMUs efficiency score is measures through the contraction of its inputs and/or its outputs expanded. The contraction or expansion occurs proportionately, exhibiting CRS. The orientation of the model can be input- and output-oriented. For a model with m input variables,s output variables, and m DMUs, the form of the input-oriented model given by Cooper et al. [2007] can be expressed as:

$$\begin{aligned} & \min_{\theta,\lambda} \theta \\ \text{subject to} \quad & \theta x_o - \mathbf{X}\lambda \geq 0 \\ & \mathbf{Y}\lambda \geq y_o \\ & \lambda \geq 0, \end{aligned} \tag{6.2}$$

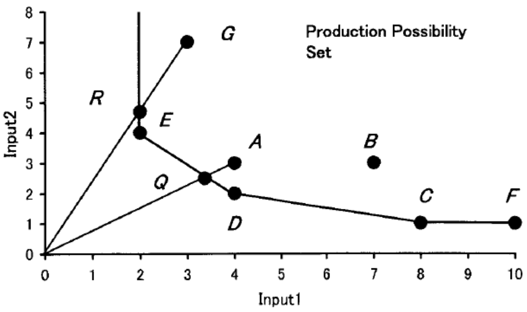
where x_o and y_o are column vectors of inputs and outputs respectively for DMU_o, which is the DMU being evaluated. **X** and **Y** represent the matrices of inputs and output vectors for all DMUs. λ is the column vector of intensity variables denoting linear combinations of DMUs. θ in this equation is the objective function, which is a radial contraction factor which can be applied to the inputs of DMU_o.

It is possible to further improve the DMUs production performance after radial optimization [Paradi et al., 2018] through second stage optimization. As in linear programming, a second stage of DEA can be run to research additional input reductions and output expansions which are termed *slacks*. For a detailed explanation of slack and the DEA equations, it is referred to Jansen and Bard [2003] and Paradi et al. [2018] respectively.

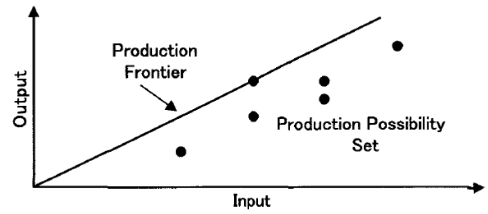
The BCC radial model by Banker et al. [1984], is a model where the technology assumption exhibits VRS. The envelopment from of the input-oriented model is given by Cooper et al. [2007]:

$$\begin{aligned} & \min_{\theta_B,\lambda} \theta_B \\ \text{subject to} \quad & \theta_B x_o - \mathbf{X}\lambda \geq 0 \\ & \mathbf{Y}\lambda \geq y_o \\ & e_n\lambda = 1 \\ & \lambda \geq 0. \end{aligned} \tag{6.3}$$

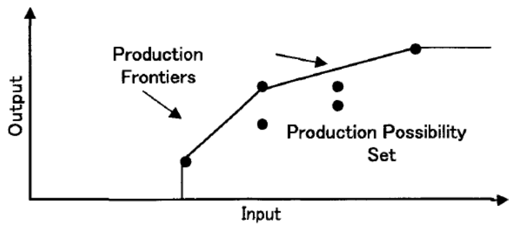
The principle difference between eq. (6.2) and eq. (6.3) is the addition of a constraint which sums of the intensity variables, $\lambda's$, to be equal to one in case of VRS. This limits a DMU to being compared to other DMUs that are roughly the same operational scale. This allows for the existence of VRS. The impact of this constraint on the frontier is shown in fig. 6.3c.



(a) Radial Model [Cooper et al., 2007]



(b) Production Frontiers of CCR [Cooper et al., 2007]



(c) Production Frontiers of BCC [Cooper et al., 2007]

Figure 6.3: CCR production frontier compared to BCC

Additive Model

Paradi et al. [2018] notes that the most powerful use of DEA is the modelling of situations involving multiple inputs and multiple outputs. During improvement evaluations a trade-off can be made between one input and another. It is referred to as a mix or allocative efficiency of the DMUs. Radial DEA models generally avoid mix issues as they look at proportional changes to input and outputs in the first stage.

The additive model addresses the input and output mixes of DMUs. The model aims to determine the maximum extent to which slacks can be taken out of the evaluated DMU. Additive models are generally used as non-oriented models. The VRS envelopment form, by Cooper et al. [2007], is given in eq. (6.4). Results of an additive model are not easily expressed in efficiency scores. The optimal objective function value of eq. (6.4) is zero, meaning that the unit will have no slack. The data in the additive model can hold values, and is *translation invariant*, which means that a constant can be added or subtracted across all values of a particular variable in all DMUs without affecting the results. However, this makes the model not unit invariant. Measuring a variable in miles as opposed to kilometres could affect the analysis results [Paradi et al., 2018].

$$\begin{aligned} & \max_{\lambda,s^-,s^+} z = e_m s^- + e_s s^+ \\ \text{subject to} \quad & \mathbf{X}\lambda + s^- = x_0 \\ & \mathbf{Y}\lambda - s^+ = y_o \\ & \lambda \geq 0, s^- \geq 0, s^+ \geq 0. \end{aligned} \tag{6.4}$$

fig. 6.4 illustrates the additive model and how it considers input excess and output shortfall simultaneously to determine a point on the efficiency frontier which is most distance from point D.

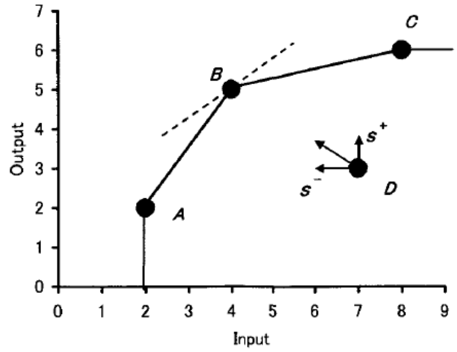


Figure 6.4: Additive model [Cooper et al., 2007]

Slack-Based Measure Model

The Slack-Based Measure (SBM), by Tone [2001], was formulated as an improvement on the additive model as it would be able to supply a standard efficiency score and be unit invariant, and also allow for input and/or output mix considerations. An example of a model is the input-oriented CRS SBM:

$$\begin{aligned} & \min_{\lambda, s^-, s^+} \rho = 1 - \frac{1}{m} \sum_{i=1}^{m} \frac{s_i^-}{x_{io}} \\ \text{subject to} \quad & \mathbf{X}\lambda + s^- = x_0 \\ & \mathbf{Y}\lambda - s^+ = y_o \\ & e_n\lambda = 1 \\ & \lambda \geq 0, s^- \geq 0, s^+ \geq 0. \end{aligned} \tag{6.5}$$

The SBM model, like the additive model, maximizes the total input slacks but are considered proportion of the initial input value and not considered absolute terms [Paradi et al., 2018]. An input- and output-oriented SBM model could also undergo a second stage slack optimization in the output and input respectively.

Comparing eq. (6.5) and 6.2 it can be seen that the SBM, in opposed to the CCR, maximizes the average proportional input contraction across all the inputs.

Summary of Basic Models

A summary of the basic DEA models is given by Cooper et al. [2007], shown in fig. 6.5. Cooper et al. [2007] includes five considerations which need be taken into account when selection of a model.

Model		CCR-I	CCR-O	BCC-I	BCC-O	ADD	SBM(Hybrid)
Data	X	Semi-p	Semi-p	Semi-p	Free	Free	Semi-p
	Y	Free	Free	Free	Semi-p	Free	Free
Trans.	X	No	No	No	Yes	Yes[a]	No
Invariance	Y	No	No	Yes	No	Yes[a]	No
Units invariance		Yes	Yes	Yes	Yes	No	Yes
θ^*		[0, 1]	[0, 1]	(0, 1]	(0, 1]	No	[0, 1]
Tech. or Mix		Tech.	Tech.	Tech.	Tech.	Mix	Mix
Returns to Scale		CRS	CRS	VRS	VRS	C(V)RS[b]	C(V)RS

[a]: The Additive model is translation invariant only when the convexity constraint is added.
[b]: C(V)RS means Constant or Variable returns to scale according to whether or not the convexity constraint is included.

Figure 6.5: Summary of model characteristics [Cooper et al., 2007]

1. **Shape of the Production Possibility Set**
   Preliminary surveys on the production function may identify a preferable choice of model through use of, for example, linear regression analysis, or expert opinions. The preferable DEA model can then be chosen to fit the situation. It should be noted that traditional regression-based analysis deal with single output and multiple input cases [Cooper et al., 2007].
2. **Input or Output Oriented**
   As addressed in section 6.2.2, there are three choices of orientation aimed to project the inefficient DMUs on the efficient frontier: *input-oriented*, aimed to reduce input amounts while at least holding present output levels; *output-oriented*, aimed to maximize output levels under at most the present input consumption; *non-oriented*, which tackle both input and output challenges. If efficiency is the only topic of interest, then all the orientation will all yield the same results. However, the additive and BCC model might give other estimations of inefficiency due to their calculations [Cooper et al., 2007].
3. **Translation Invariance**
   In fig. 6.5 it can be seen whether a model has an efficiency measure θ^*. θ^* is a dependent on the coordinate system of the data set. The additive model, which is θ^*-free, are coordinate-free and translation invariant. The SBM model has been developed to overcome the deficiency of not having a one-dimensional efficiency measure like θ^*.
4. **Number of Inputs and Output Items**
   One of the issues that may arise when implementing DEA is the lack of DMUs. DEA measures efficiency *empirically* relative to the sample of data supplied. Having too few DMUs will result in a large portion of the DMUs being efficient. Therefore, a general rule of thumb is given by Banker et al. [1989] as a minimum number of DMUs in relation to the number of variables:

   $$n \geq \max\{m * s, 3(m+s)\} \tag{6.6}$$

   In eq. (6.6), m, s and n are the number of inputs, outputs and DMUs respectively. This formula is seen as a rule of thumb rather than an actual rule. It is advised by Cooper et al. [2007] to start with a small set of input and output items and gradually increase the amount to observe the effects of the added items. Additional extensions may lead to a sharper discrimination among DMUs [Cooper et al., 2007]..
5. **Try Different Models**
   If the characteristics of the production frontier can not be identified through preliminary survey, Cooper et al. [2007] says "it may be risky to just rely on one particular model." It is therefore wise to try multiple models and compare results and relay these to expert knowledge. Cooper et al. [2007] elaborates on a methodology through use of statistical regression and DEA to cross-check each other.

6.4. DEA Extensions

There are a few practical extensions to DEA which may help with discrimination among the different DMUs. A number of practical extensions, according to Paradi et al. [2018], are shortly addressed below. For full explanation of the extensions, it is recommended to read the literature referred to with each extension.

1. **Limits or Restrictions**
   In some cases DEA may chose optimal weight which result in a zero input or output. To tackle this limits or restriction can be assigned [Paradi et al., 2018]. This can be based on expert opinions or derivations from average price levels. There are two common used methods: *assurance region* and *cone-ratio*. The assurance region restrict ratios of specific pairs of input and/or output weight to fall within defined ranges [Thompson et al., 1986]. The cone-ratio restrict input and/or output weight into a multidimensional cone defined by a set op non-negative direction vectors [Charnes et al., 1989].
2. **Non-controllable Variables**
   DMUs may in some cases not have full control over the choices regarding levels of mixes of inputs and outputs. This may not be case by decisions of higher lever management or environmental factors, such as population or income levels of their locations. These variable are deemed *non-controllable variables*. It can be incorporated in the efficiency analysis [Banker and Morey, 1986a].
3. **Categorical Variables**

DEA models assume that all data is continuous, numerical quantities. However, an extension can be added which can also incorporate data that are limited to certain discrete values, or that are qualitative in nature, with use of *categorical variables* [Banker and Morey, 1986b]. This requires the categorical variable to be inherent, logical rank ordering. To avoid unfair comparisons, a DMU will only be compared to other DMUs which have the same or worse categorical variable values.

4. **Super-Efficiency**
   In the case that a DEA finds a large portion of DMUs to be efficient, DEA does not discriminate between the efficient units. *Super-efficiency* extensions of DEA models have been developed to address this issue [Andersen and Petersen, 1993]. It removes the to be evaluated DMU so that the upper limit of one of the obtained efficiency scores is removed. This results in a score which can be greater than one, which can be used to rank efficient units.
5. **Window Analysis**
   DEA can also be used on time series data on the same DMUs. This is called *window analysis*, i.e. subdividing the entire time series span of data into so called smaller windows. This can be used to evaluate the efficiency trend over time. The windows are generally rolling and constant of size. This method can also be used to increase the effective number of DMUs being evaluated and therefore increasing the discriminatory power of DEA in limited-sized samples.
6. **Malmquist Index**
   A second technique to examine efficiency trends, is the *Malmquist index* [Fare and Grosskopf, 1992]. It measures the *total factor productivity change* experienced by a DMU between two periods. This change can be decomposed between an efficiency change of the DMU and a technological change in the location of the efficient frontier [Färe et al., 1994]. Malmquist indices can be calculated through the use of either CRS or VRS efficiency scores.

Understanding these different additions will help to determine improve the model as a whole. Adding constraint through limitations or defining con-controllable variable will result in a better reflection of the real-life situation. Regarding the implementation of the additives, it is aimed in this research to establish a base model application of DEA and implement some above mentioned additives, based on available data and results of the base model.

Before an adequate base model is chosen with or without additives, the possible issues of DEA are discussed in section 6.5.

6.5. Input, Output, and Data Issues

Besides the selection of the most appropriate model, an issue faced when establishing a DEA model is how to formulate the model so it reflects the process of the DMUs in a real-life situation. The results from DEA, implying directions on how to improve operations, will be the prime deliverable handed towards managers. The challenge here is to translate the results into actions and as a result to enhance performance. Structuring a model which reflects the actual process and uses variables which reflect the environment managers deal with on a day-to-day basis is imperative in making the results meaningful and actionable. The requirements of the model may cause disagreement with academic approaches where pure theory often governs rather than practical reality [Paradi et al., 2018].

The inputs of DEA may easily use variable selected in the business intelligent part of the model. Variables which have been selected and seen as a practical measure for performance monitoring may well be suited for application in DEA. This is taken in mind when structuring data and variables in the model.

6.6. Model Selection and Implementation

Based on the information supplied in prior sections, a choice has been made on which model to add to the maintenance and repair performance management model. The idea behind the addition of this method of benchmarking is to introduce an alternative approach which is more academic in nature and can be compared to traditional business intelligence approaches and use of KPIs. The challenge is to link this academic approach to a practical use, as discussed by Paradi et al. [2018].

Based on the characteristics of the different basic models, shown in fig. 6.5, the Slack-Based Measure (SBM) is selected as an addition to the maintenance model. This choice has been made based on four main items. First being that the SBM model allows for the calculation of an efficiency score, in comparison to an additive model. Secondly, a SBM model is unit invariant, making the changing variable units not affect the measurement results. Thirdly, the model allows for mix consideration of input and/or output, also known as allocative efficiency of DMUs. Within the maintenance model this may, for example, allow for financial allocation between maintenance running costs and dry docking docks. Additional weight factors can be applied to the allocation as to hold a more representative split of expenses between running costs versus dry docking costs. Whether to implement additional weight factors will be discussed with experts as it may gravely impact the efficiency scoring results. The last reason for selecting SBM is the capability of running more variations of technical assumptions, i.e. RTS. This allows for flexibility in the definition of the production function as a result of preliminary reviewing through regression analysis.

Based on the above mentioned statements, SBM model is seen as the DEA model which may fit the bill based on its characteristics. Nevertheless, advise of Cooper et al. [2007] will be taken into account as to try different models and see how it reacts to different model characteristics. This won't be done with all DEA model as this will increase computation time and DEA model evaluation. This aim of this part of the research is to introduce and evaluate the possibility of introducing a more academic approach to benchmarking maintenance and repair.

There are numerous ways to implement DEA using existing software packages. Different extensions for Microsoft Excel have been made to use DEA in analyse performance between DMUs. However, the choice has been made to use an open-source programming language named "R" [R Project, 2019]. CRAN [2019] introduces the programming language R as a "language and environment for statistical computing and graphics. It is a GNU project which is similar to the S language and environment which was developed at Bell Laboratories (formerly AT&T, now Lucent Technologies) by John Chambers and colleagues." The programming language provides a variety of statistical and graphical techniques, and is highly extensible. Firstly, this programming language is open-source and thus free to download and use making it independent of any licence agreements which may apply when using software packages. Secondly, the possibilities of being incorporated into more and more business software makes it, as described by CRAN [2019], extensible to additional software. For these reasons the programming language of R is selected as programming language. The program can be downloaded through the website: `https://cran.r-project.org`.

6.6.1. DEA Packages in R

There are numerous DEA packages for R which may be suitable for use in the maintenance performance management model. The packages are constructed by different authors and are open for use [CRAN, 2019]. These packages are tested regularly on machines running different operating systems to ensure that they work accordingly. These packages can easily be installed in R and their manuals including explanations can also be found on `https://cran.r-project.org`.

Table 6.2 shows the different DEA packages which have been found and their year of publication, technology assumptions and pros and cons. Based on table 6.2, the package *FEAR* is deemed inadequate due to main reason of it not being in the CRAN [2019] repository and thus not frequently checked for its functionality. Secondly, the publication date and manual suggest not a lot of updates have been supplied throughout the year, making it less suitable for use. The *rDEA* package is deemed better than the *deaR* package, however, due to the manual lacking explanation and the fewer functionalities in comparison with other package, the *rDEA* package is seen as unsuitable. This results in the choice between the packages *Benchmarking* and *deaR*. Both packages are deemed suitable for use in this research, however, the package *deaR* is deemed most suited due to its additional ability of handling fuzzy data. The manuals of the *deaR* package can be found at Coll-Serrano et al. [2018] respectively.

6.7. Intermediate Conclusions chapter 6

DEA has shown its applicability in a wide range of different entities that include not only businesses but also government and non-profit agencies [Cooper et al., 2007]. The non-parametric frontier approach that is DEA allows for the evaluation, i.e. benchmarking, of different DMUs through the use and assumption of linear programming and piecewise linear function of the frontier. The approach has shown to add value in addition to regression analysis as it allows for peer evaluation and target definition.

Table 6.2: Evaluation table of different DEA packages in R [Own Source]

DEA Package	Year of Publication	Technology Assumptions	Pros	Cons
FEAR	2008	-	Simplistic R script concerning DEA	Not in the CRAN repository and thus not frequently checked for functionality Unable to specify technology assumptions
rDEA	2016	VRS CRS NIRS[a]		Explanation of functionalities in the manual are not elaborate Fewer functionalities
Benchmarking	2018	VRS DRS CRS IRS ADD[d], FRH[e] FDH(+)[f]	The script is checked using literature examples. Notes as programming being an improvement on FEAR [Bogetoft and Otto, 2018] Includes Stochastic Frontier Function (SFA)	
deaR	2018	CRS VRS NIRS NDRS[b] GRS[c]	The script is checked using literature examples. Specific SBM efficiency function Fuzzy data handling capabilities	

[a] NIRS: Non-increasing returns to scale [b] NDRS: Non-decreasing returns to scale [c] GRS: General returns to scale
[d] ADD: Additive [e] FRH: Free Replicability Hull [f] FDH: Free Disposability Hull

Based on the characteristics of three basic DEA models, discussed in section 6.3, a choice has been made on which DEA model is most applicable in the sense of maintenance and repair. The choice of a SBM model was made due to its ability of calculating an efficiency score θ^* in contrast to an additive model. Secondly and thirdly, a SBM model is unit invariant and allows for mix considerations of input and/or output, known as allocation efficiency. The additional possibility of assigning weight factors amongst input and/or output is an added value to the SBM model. The last reason is the ability of applying different technical assumptions. This will help in tuning the model in which the efficiency frontier will best fit the data and represent the real-life effects between inputs and outputs.

For the erection of the SBM it is of importance to define its characteristics, including *technology assumption*, which may be derived from regression analysis, as suggested Cooper et al. [2007]. Besides the selection of technology assumption, it is of importance to also select orientation of the model. For the time being both input- and output-orientations are assumed as it is of interest to see what results are formulated with respect to excess inputs consumed or expand shortfalls in outputs produced.

A decision with respect to DEA extensions will be done in part IV. This is mainly due to the link between data input and the extensions themselves. From Cooper et al. [2007], Paradi et al. [2018] it is concluded that the addition of extensions are there to further supply boundaries and/or constraints to the model which help to further define the model. The selection of inputs and outputs will also be addressed in part IV and will result from chapter 9.

Besides the selection of the appropriate model, careful consideration is needed to select the different evaluation configurations. Based on conclusions made in chapter 3 regarding the importance of the type of operations, operational location, type of tug and equipment installed the following evaluation configurations are selected for DEA;

- Fleet
- Port
- Tug Type
- Sister vessels

It is expected that comparing all vessels within each joint venture may result in a distorted view as may variable dependencies play an important roll in affecting these results. Therefore, it is interesting to decompose the fleet in different element and evaluating these. Splitting the fleet into the evaluation configurations of port, tug type and sister vessels may give valuable insight behind the efficiency performance differences between the tugs. Furthermore, type of operation is left out of consideration in this research due the fact that the towage operations performed researched are predominately harbour towage operations. Nonetheless, differences with respect to harbour operations are taken into considerations due to port characteristics and specifications. It is believed that these gravely influence operations and the intensity of harbour towage. In the next chapter an in-depth evaluation of the aspects of ship maintenance is performed from which additional evaluation configurations may be selected based.

Besides the selection of a SBM model, the choice has also been made to implement this DEA model through use of an open-source programming language called; *R*, which is a language used for statical computing and graphics. This program is selected due to it being open-source and highly extensible to other software. Additionally, multiple DEA packages have shown to be available in *R* which allow for easy evaluation of the added value of DEA as a way of benchmarking maintenance and repair. Resulting from an evaluation made in section 6.6.1, the package of *deaR* has been chosen as it a registered package in CRAN [2019], contains a specific SBM model function capability and has possibility of handling fuzzy data. Nevertheless, the recommendation of Cooper et al. [2007] will be taken into consideration, as to try different models. Besides the SBM model functionality, *deaR* shows capability of applying different model types.

The next part will elaborate on the maintenance and repair performance management model. This will start of with the model definition in chapter 8 followed by the elaboration of the actual model in chapter 9. This chapter will also include the implementation of the DEA model alongside the business intelligence model.

7

Ship Maintenance

Before elaborating on the principles of maintenance performance measuring, the topic of ship maintenance is addressed. First off, the general aspects of ship maintenance and repair are elaborated in section 7.1, followed by maintenance regulations in section 7.2. Next, section 7.3 discusses the ship maintenance costs. Finally, the ship maintenance models are discussed in section 7.4, followed by the intermediate conclusions in section 7.5..

7.1. Ship Maintenance and Repair

The maintenance of ship is taken into consideration in the early stages of ship design [Hengst, 1999, Shields et al., 1975]. Through close collaboration between the designers, owners and classification societies, plans for preventive maintenance are reviewed to confirm that these plans are acceptable in accordance with the classification society's requirements after construction [Ingram, 2001].

The maintenance of individual ship components are scheduled within the maintenance scheduling plan to minimise downtime and thus maximise the ship's availability. Availability of the ship is only possible if the components/systems are operational and comply with regulations. If these components are not operational, the ship is classes as unavailable, and maintenance will be required [Deris et al., 1999].

In the marine industry, ship maintenance can be carried out in two different conditions as shown in fig. 7.1. The split between the two conditions, shown in fig. 7.1, is dependent on the maintenance procedure required. This is dependent on whether the vessel requires underwater maintenance, a major overhaul or just minor maintenance, but also dependent on the type and size of the ship. Some vessels, due to their seize or hull form, require specialised dry docks or can't dock all together [Deris et al., 1999]. Besides the maintenance procedure required for each equipment, ship maintenance is also dependent on the location of the equipment inside the ship.

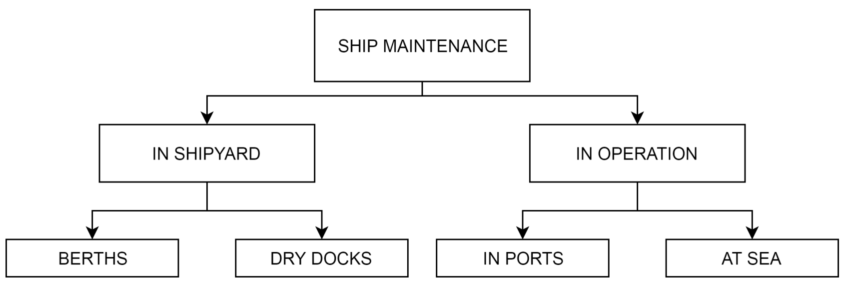


Figure 7.1: Types of ship maintenance [Alhouli et al., 2009]

These variables all affect the overall maintenance scheduling. Furthermore, knowledge of the condition of equipment and whether maintenance on the equipment can be performed at sea, in port, at a berth or in a dry-dock is important to forecast future maintenance expenses.

Ship maintenance, like other industry areas, typically employ two maintenance types; breakdown maintenance (corrective) and preventive maintenance [Shields et al., 1975]. Breakdown maintenance policies are usually conducted without any preventive maintenance, except for the essential lubrication and minor adjustments, so called running maintenance. Preventive maintenance aims to reduce the number of breakdowns, and can either be predetermined, i.g. scheduled, or condition based.

Determining when maintenance should be conducted was based on operating experience and manufacturer recommendations. In the last 30 to 40 years, more is based on condition monitoring of equipment to extent operational lifetime of equipment [Ingram, 2001]. Maintenance work conducted on ships generally fall into one of the following four actions; *Inspection*, an examination of equipment to identify its state; *Survey*, performed by a Classification Society, a survey is carried out to verify that the ship remains in complains with regulations. This is generally done simultaneously with a major overhaul [International Association of Classification Societies, 2011]; *Minor overhaul*, involves partially stripping down equipment, i.g. selected (sub-)components of equipment; *Major overhaul*, Fully strip down of equipment and machinery items.

Work performed at a shipyard generally consists 75% of routine ship maintenance, while the remaining 25% consists of damage repair and ship conversions [Mackenzie, 2004].

7.2. Maintenance Regulations

7.2.1. Periodical Class Surveys

As priorly discussed, maintenance of ships can be carried out either in operation or at a shipyard, which requires a dock to maintain the underwater hull of the ship. The docking of vessels is costly and is generally planned conjunction with class surveys. Each classed vessel is subject to a specific programme of periodic surveys after delivery [International Association of Classification Societies, 2011]. To maintain their class, ships are subject to survey. The surveys are carried out in accordance with relevant requirements in order to confirm that the hull, machinery, equipment and appliances all comply with the applicable Rules. In this subsection, the different types of surveys will be discussed, according to Det Norske Veritas (DNV) rules for classification of ships Pt. 7 of Ch. 1 Sec. 1 and optional 'TUG' class notation requirements Pt. 7 of Ch. 1 Sec. 6 Det Norske Veritas AS [2015]. The following definition of survey scheduling is taken from DNV Rules and shown in fig. 7.2.

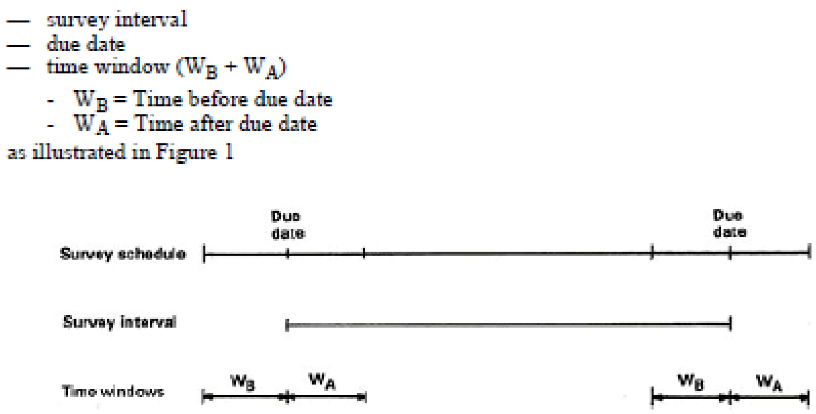


Figure 7.2: Survey schedule [Det Norske Veritas AS, 2015]

All ships are subject to periodical survey in accordance with requirements in order to confirm that hull, machinery, equipment and systems remain in satisfactory condition and in compliance with approval or accepted standards. Periodical surveys are categorised according to one of the following levels of survey requirements; *annual survey, intermediate survey* and *complete survey*. The survey required in conjunction with issuance of new class certificate is called; *renewal survey*. The following specific surveys may be scheduled according to one or more of the categories named above:

- bottom survey
- propeller shaft survey
- propeller connection survey
- propulsion thruster survey

- boiler survey (including steam generator survey)
- thermal oil heater survey
- survey of optional class notation (voluntary class notation)

Regulations typically require a hull and machinery annual survey and a hull and machinery complete (special) survey every 5 years, in accordance with International Association of Classification Societies [2011]. The periodic survey are to be carried out at prescribed intervals and within applicable time windows. They may be split in different parts and progress within the time window. All requirements of the survey should be completed by the end of the time windows, see fig. 7.2. Both the *boiler survey* and *bottom survey* do not require survey windows.

For certain ships, the survey intervals may be reduced, e.g. for ships with new or novel design, systems or items exposed to abnormal rate of wear or failure. The scope of the survey may be extended when compliance with the rules are not satisfactorily, or when the surveyor suspects the ship is not maintained in accordance with basis of retention of class.

Ships built for a special service, and therefore in requirement of specialised equipment related to an optional class notation, may be subject to additional survey requirements. The additional survey requirements in case of tugs are addressed in the next paragraph.

Optional class notation 'TUG'

The optional class notation 'TUG' adds additional remarks concerning the *annual survey* and the *renewal survey*.

During the annual survey, winch and other equipment related to towing and anchor handling shall be surveyed and function tested to the extent deemed necessary by the Surveyor, taking into account manufacturers recommendation. The survey includes function testing of emergency release systems. This statement in the rules of DNV illustrate that Surveyors base their surveying on manufacturers' recommendations on maintainability of equipment. In the field this is named to be according to Original Equipment Manufacturer (OEM). This suggests that the maintenance policy suggested is mainly Time-Based Maintenance (TBM) or Use-Based Maintenance (UBM) [Det Norske Veritas AS, 2015].

During the renewal survey, as a minimum, the equipment is to be tested and surveyed according to the following rules. All equipment for towing and anchor handling including towing hooks, winches, towing guide pins, etc. are to be thoroughly inspected. This includes inspection of foundations. Non destructive examination may be required by the Surveyor. All safety functions including emergency load released are to be tested, as is functioning of equipment intended to be used without power supply. Load test of equipment, including emergency release under load shall be done taking into account manufacturers recommendations with respect to test load [Det Norske Veritas AS, 2015].

Postponement of periodical surveys

Except for the annual and intermediate surveys for main class, the Class Society accept a request to postpone periodical surveys upon special consideration. Postponement of main class renewal survey, boiler survey and bottom survey may be considered only in exceptional circumstances. The postponement of these surveys shall not exceed 3 months. The postponement of periodical surveys will not affect the surveys next due date.

Postpone of the renewal survey may be granted only upon the owner's written request and is needs to be received well in advance of the expiry date of the classification certificate. The postponement shall be based on satisfactory result from a sighting survey.

Survey schedules

The scheduling of the different surveys for tugs, according to the Rules, can be summarised in a table as shown in table 7.2. This table shows the survey scheduling for Tug 30, which is classed through Lloyds Register. The scheduling of the different survey will be addressed with use of shown schedule.

Table 7.1: Survey Planner for Tug 30 [Lloyd's Register, 2019]

Survey	Due Date	Assigned Date	Range Date
Hull			
SS - Special	17 Sep 2019	18 Sep 2014	18 Jun 2019 - 17 Sep 2019
AS - Annual	17 Sep 2019	20 Aug 2018	18 Jun 2019 - 17 Sep 2019
BTMS - Bottom Survey	17 Sep 2019	24 Nov 2017	17 Sep 2019 - 17 Sep 2019
Machinery			
ES - Engine Special	30 Sep 2019	30 Sep 2014	30 Jun 2019 - 30 Sep 2019
DIRP1 - Directional Propeller	30 Nov 2022	30 Nov 2017	30 Nov 2022 - 30 Nov 2022
DIRP2 - Directional Propeller	30 Nov 2022	30 Nov 2017	30 Nov 2022 - 30 Nov 2022
Statutory			
SER - Safety Equipment Renewal	17 Sep 2019	18 Sep 2014	18 Jun 2019 - 17 Sep 2019
RTR - Radiotel. Renewal	17 Sep 2019	18 Sep 2014	18 Jun 2019 - 17 Sep 2019
PLR - Loan line Renewal	17 Sep 2019	18 Sep 2014	18 Jun 2019 - 17 Sep 2019
MOR - MARPOL I (Oil) Renewal	17 Sep 2019	18 Sep 2014	18 Jun 2019 - 17 Sep 2019
MAR - MARPOL VI (Air) Renewal	17 Sep 2019	18 Sep 2014	18 Jun 2019 - 17 Sep 2019
MSR - MARPOL IV (Sewage) Renewal	17 Sep 2019	18 Sep 2014	18 Jun 2019 - 17 Sep 2019

Hull SS - Special Survey
The hull special survey is a complete survey. Complete surveys are denoted as (2.5 years), (5 years) or (15 years). In this case, the interval of the hull special survey is every 5 years. Surveys required to be concurrent with the renewal survey are to be completed no later than at the completion of the renewal survey.

Hull AS - Annual Survey
The hull AS is an annual survey which occurs yearly.The due date corresponds to the anniversary date of the class assignment or the expiry of the previous classification certificate, if different.

Hull BTMS - Bottom Survey
The bottom survey is planned every $2\frac{1}{2}$ years, or twice every 5 years, making it an intermediate survey. Between the successive bottom surveys, the interval is not to exceed 36 months. The survey is to be carried out on or before the due date, no time window. One bottom survey is to be carried out in conjunction with the renewal survey, i.e. not more than 15 months prior to classification certificate expiry date. Also, one bottom survey is to be carried out in conjunction with main class intermediate survey. The last requirement is not applicable for 'TUG' class notations [Det Norske Veritas AS, 2015].

Machinery - Engine Special
Engine specials are complete surveys which are carried out every 5 years, same as the hull special survey. Survey required to be concurrent with the renewal survey are to be completed no later than at the completion of the renewal survey [Det Norske Veritas AS, 2015].

Machinery - Directional Propeller
The DIRP1 and DIRP2 are complete surveys of the thrusters and thus carried out every 5 years. The Tug 30 has two thruster, thus two certificates. It is recommended to carry out the survey in conjunction with bottom survey. When the survey requires the ship to be out of the water, the survey is to be carried out in conjunction with bottom survey in dry dock.

Statutory
All statutory surveys; SER, RTR, PLR, MOR, MAR, MSR are all renewal surveys, which means surveys intervals are set at 5 years, corresponding to the classification certificate expiry date. The survey is to be completed within a time window of 3 months before the due date. Surveys and thickness measurements of tanks or spaces can not be credited towards both intermediate and renewal surveys [Det Norske Veritas AS, 2015].

Table 7.2: Recap of survey schedules in accordance with DNV rules

Survey	Survey interval
Hull SS	Complete survey (5 years)
Hull AS	Annual survey
Hull BTMS	Intermediate survey (2 1/2 years)
Machinery ES	Complete survey (5 years)
Machinery DIRP	Complete survey (5 years)
Statutory	Renewal survey (5 years)

7.2.2. Port state control inspections

Starting in 1995, the IMO adopted a resolution which provides guidance on port state control inspections. These inspections are there to identify ship deficiencies and its equipment or crew. The procedures are not mandatory, but many countries have adopted them [Kidman, 2003]. Ships with serious shortcoming are detained or even banned. Names of the vessel are published on a website to publicly notify the shortcomings [Stopford, 2009].

According to the IMO, ships are to be selected from lists of vessels arriving in port, often using statistical techniques to identify higher-risk vessels. Examples of factors taken into account are; flag, age and ship type. The inspection consists of three parts: a general external inspection of the ship on boarding; a check of certificates; and a more thorough 'walk around'. The walk around includes checking the condition of exposed decks, cargo-handling gear, navigation and radio equipment, life-saving appliances, fire-fighting arrangements, machinery spaces, pollution prevention equipment, and living and working conditions [Stopford, 2009]. During the inspection the inspector works through a detailed check-list and notes any deficiencies. 'Deficiencies' are noted when some aspects of the ship does not comply with the requirements of a convention. If significant deficiencies are found, a more detailed inspection may be required, and if the ship is considered to be unsafe to be allowed to proceed to sea, a detention order will be made. A detention can be made based on the Load Lines Convention if there are any structural shortcomings; or under MARPOL if pollution prevention methods are not met; or under SOLAS if the crew operates under unsafe conditions.

7.3. Ship Costs

Starting with the basics, the cost of operating a ship depends on a combination of three factors, according to Stopford [2009]. Firstly is the ship, or asset, which sets the broad framework of costs through fuel consumption, number of crew, and its physical condition, which dictates the requirement for repairs and maintenance. Secondly are the costs of bought-in items; bunkers, consumables, crew wages, ship repair cost and interest rates, which are subject to economic influences. Thirdly, costs affected by the efficiency of owners of the assets, including administrative overheads and operational efficiency. Stopford [2009] classifies five standard cost classification:

1. Operating costs
   Expenses involved in the day-to-day running of the ship. Costs of crew, stores and maintenance.

2. Periodic maintenance costs
   Expenditures when the ship is dry-docked for major repairs, usually at the time of its special survey. Under international accounting standards the total periodic cost over the maintenance cycle is capitalised and amortised. These costs are treated as cash item when incurred and therefore seen separately from operating costs.

3. Voyage costs
   Variable costs associated with voyages. These include items as fuel, port charges and canal dues.

4. Capital costs
   Costs concerning the financing of the ship. These costs take the form of dividends to equity, which are discretionary, or interest and capital payments on debt financing, which are not.

5. Cargo-handling costs
   Costs representing the expenses of loading, stowing and discharging cargo. They are particular important in the liner trades.

Since the standard cost classification of 'cargo-handling costs' is not relevant in the operations of tugs, this cost classification is disregarded. Looking in depth into the structuring of the above mentioned cost classifications, fig. 7.3 shows key points which are considered within each of the cost classifications according to Stopford [2009]. Although the percentile values are illustrated for bulk carrier, the general classification as well as key points are deemed similar.

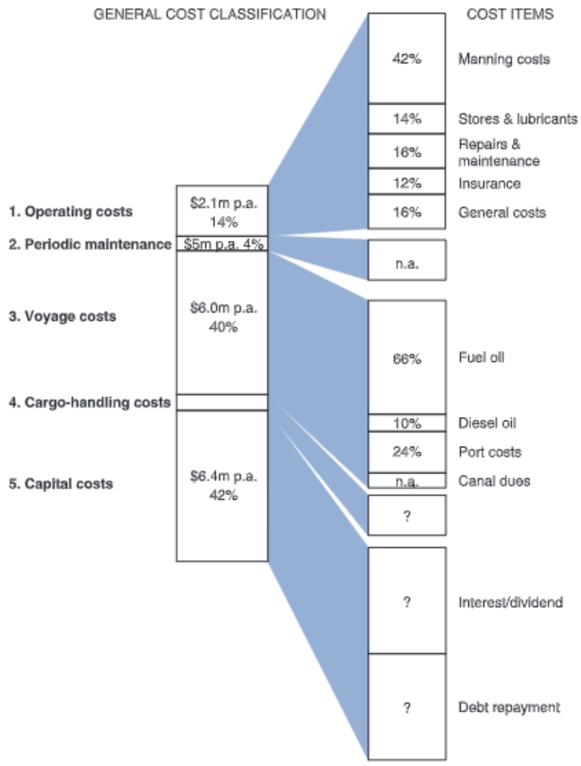


Figure 7.3: Analysis of the major costs of running a bulk carrier[1] [Stopford, 2009].

7.3.1. Operating Maintenance and Repair Costs

The expenses associated with operating costs are connected with the day-to-day running of the vessel and day-to-day repair and maintenance. This is excluding fuel, which is included in the voyage expenses. The dry-docking costs are addresses separately [Stopford, 2009].

Routine maintenance accounts for roughly 16% of the operational costs, which covers routine repairs needed to maintain vessel standards dictated by the company, classification society and charterers of the vessel. This is about 2% of the entire cost of a Capesize bulk carrier. According to Stopford [2009], broadly speaking, routine maintenance covers the following three aspects:

1. Routine maintenance
   Maintaining main engine and auxiliary equipment, painting non-wetted surface and steel renewal in areas which can safely be accesses while ship is in operation. As with any equipment, maintenance costs tend to increase with age.

2. Breakdowns
   Mechanical failures resulting in additional costs outside the covered routine maintenance. Work is often conducted at a ship repair yard on 'open order' and therefore likely to be expensive. Additional costs are made due to loss of operational time.

3. Spares
   Replacement parts for equipment.

[1] Analysis for a 10-year-old Capesize bulk carrier under the Liberian flag at 2005 prices. Relative costs depend on many factors that change over time, so this is just a rough guide.

As can be expected, maintenance costs increase substantially with age, a 20-year-old vessel might cost twice as much compared to a more modern vessel. Expenditure on spare parts and equipment replacement is likely to increase with age [Stopford, 2009].

7.3.2. Periodic Maintenance Costs

The second general cost classification, as illustrated in fig. 7.3, involves expenditure for the costs of interim dry-docking and special surveys. According to Stopford [2009], it accounts for about 4% of the costs, through this depends on both age and condition of the vessel. As earlier explained in section 7.2.1, to maintain a ship in class for insurance purposes, it requires regular surveys with a dry-docking to determine its seaworthiness. These surveys become more extensive with age and all defects must be remedied before a certificate is issued. At older ship age, the surveys result in considerable expenses. Additional, when dry-docking the underwater hull of the vessel can be relieved of its marine growth, which reduces the operational efficiency of the hull.

Table D.1 in appendix D shows an overview of 18 individual periodic maintenance items and costs for a standard Capesize and how it evolves over time. The main aspects to note is that some items stay rather constant over time, such as the cost of dry dock use, whilst others, such as steel replacement and work, increase drastically with age. It is noteworthy that all these costs depend on ship specifics. According to Stopford [2009], owners who operate PM policies may incur lower costs, while vessel in bad condition may experience much higher costs. It is expected that the distribution of maintenance costs across the different areas, shown in appendix D, to be different as the hull of a tug is respectively smaller in comparison to the Capesize tanker. It is interesting to evaluate this distribution in comparison with findings in Stopford [2009]. Another interesting observation which can be made from this data, is that the average annual cost and daily cost, for periodic maintenance, increases about 2.2 times between the age of 0 – 5 and 16 – 20. Whether this holds for tugs will be analysed in chapter 10.

7.3.3. Direct and Indirect Measurable Maintenance Costs

The above mentioned cost items for the operating costs' categorisation, two different types of measures costs are defined by Shields et al. [1975]. These are direct and indirect measurable costs. Looking specifically at direct maintenance costs, it describes all costs which are directly linked towards maintenance, which include dry-docking repair, voyage maintenance repair, irrecoverable damages, and spare parts [Shields et al., 1975].

The second is that of indirect maintenance costs, which include the costs of some other operations. The crew performs maintenance when the vessel is in operation. This indicates that part of the crew's time is used for maintenance. Since the crew on board the vessel is part of the maintenance function, it needs to be considered part of the maintenance cost. This results in the conclusions that part of the provision costs (store) must also be appointed to maintenance. Indirect losses due to equipment failure may also be deemed an indirect maintenance costs. However, as it is a result of negligence with respect to maintenance, it is assumed as a resulting loss of profit. For further reference this is defined as *loss of opportunity*.

Shields et al. [1975] used above mentioned cost types and the following five major cost classifications to address operating costs of a six-year old 75,000-ton bulk carrier; personnel, storing, maintenance, insurance and general. The percentiles of each cost classification and type with respect to operating costs are shown in table 7.3. Shields et al. [1975] their research shows that when looking at indirect related costs, part of the direct costs of personnel and storage are indirectly related to maintenance. When assuming an indirect cost relation, the maintenance costs makes up for 42% of the total operational costs, comprised of 28% direct maintenance costs, 12% indirect personnel costs and 2% indirect storage costs. Concluding that the maintenance costs, assuming an indirect cost relation, is seen as the highest costs among all operating costs. Shields et al. [1975] assigns a higher percentage of operating costs towards maintenance in compared to Stopford [2009]. The conclusion to be made from Shields et al. [1975] is that there are indirect costs related to maintenance which can not directly be measured. Measuring these indirect costs is deemed challenging as it required close registration of work performed and the costs related to it.

Table 7.3: Direct and indirect operating costs of a 75,000-ton bulk carrier [Shields et al., 1975]

Cost Type	Personnel	Storage	Maintenance	Insurance	General
Directly Measurable Costs	36%	10%	28%	23%	3%
Indirectly Measurable Costs	24%	8%	42%	23%	3%

7.4. Ship Maintenance Models

In recent years, numerous researched have developed maintenance models addressing ship maintenance. Reviewing a couple of these researched may help with the establishment on an effective maintenance performance model.

A number of researches, including Inozu and Karabakala [1994], Jambulingam and Jardine [1986], Perakis and Inozu [1991], research the selection of specific maintenance types and policies, elaborated upon in chapter 4. The aim of the research was to determine whether the chiller unit required a PM inspection or adjustment, and find an optimal PM interval between major overhauls to minimise manpower costs.

Inozu and Karabakala [1994] evaluated replacement models, applicable in the marine industry, to determine the optimum maintenance strategy. Then, they presented a new deterministic model approach to group replacement under budget constraints. The objective of the model was to minimise total discounted cost of replacements and major maintenance actions, taken into account component age, time of installation and based on a fixed budget.

The focus of the researches performed by Inozu and Karabakala [1994], Jambulingam and Jardine [1986], Perakis and Inozu [1991] concerned maintenance strategy and policy selection. This is seen as part of selecting the most effective maintenance policies and not aimed and measuring efficiency.

Besides the prior mentioned researches, other research such as De Boer et al. [1997] and Pillay et al. [2001] address the efficiency measuring side of maintenance, specifically focussed on the maintenance process. De Boer et al. [1997] established a basic framework and algorithm of a decision support system aiming to enhance the process and capacity planning at a large repair shop. This research concentrates on planning and execution of maintenance projects and established framework characteristics of a standard database to support process planning.
Pillay et al. [2001] studied the maintenance of equipment of fishing vessels using delay-time analysis. Through their study, a model is proposed to optimise inspection period of equipment on fishing vessels. Operating and failure data was gathered and used to demonstrate the delay-time concept in the study. The time to failure of equipment is a function of its maintenance concept, according to Pillay et al. [2001]. The time period between the first sign of abnormalities and eventual failure is called the delay time. Probability failure functions and rates are central in the delay-time model to reduce downtime of fishing vessels.

Kavussanos et al. [2004] introduces an econometric model to explain the determinants of expenditure in ship maintenance and repair. Using data acquired from Greek ship owners and management companies, 112 vessels of different types were collected. It is shown in their study that maintenance expenditure is positively related to utilisation, age and size. The effect of age is found to be stronger on vessels younger than 20 years, due to the fact that vessels less than 20 years old can be sold more easily on the second-hand market. Order vessels are more constrained by safety regulations. Ship owners are less reluctant to spend more once the vessel passes it's 4^{th} and especially its 5^{th} special survey. Another conclusion made is this research is that the maintenance expenses with respect to utilisation, age and size, in 1999, show existence of significant economies of scale. Finally, the type of ship, flag, classification and maintenance yard were determined to be significant determinants of the total cost of maintenance.

Reviewing above mentioned researches regarding maintenance models it is concluded that little research addresses the principle of benchmarking maintenance through of cost and performance, especially from a holding perspective. Nonetheless, a number of interesting conclusions can be made which assist in the erection of the model. De Boer et al. [1997] has shown the importance of a framework on which to model the eventual model as it forms the foundation. Secondly, the importance of the reviewing maintenance process and its performance is seconded by Pillay et al. [2001], which is part of the framework adopted and shown in fig. 5.5. Furthermore, research by Kavussanos et al. [2004] has confirmed the impact of numerous determinants of maintenance expenditures, namely utilisation, age, size as well as vessel type, flag, classification and maintenance yard. These areas have also come to light in previous chapters.

7.5. Intermediate Conclusions Chapter 7

This chapter has discussed several interesting aspects which are adopted for the construction of the model. Additionally, several conclusions have been made as a result of literature in this chapter. This section will discuss these conclusions and adopted aspects for the model.

It can be concluded that the maintenance of ships and their equipment are directly linked with the availability of the vessel to operate [Deris et al., 1999]. The maintenance operations and planning are first of all the dependent on the equipment condition itself, its location in the vessel and the location of the ship. These dictates whether maintenance is or can be performed during operation or at a shipyard. Ship maintenance is thus split between two conditions, based on the maintenance process required. For the model this split between maintenance 'in operation' or 'in shipyard' is adopted and from now on be stated as *running repairs* and *dry-docking repairs*. These two definitions for the labelling of maintenance costs and activity is known within the departments of Boskalis Towage. It is therefore self-evidently to assume the same definitions. As a result, ship maintenance costs can thus be split into two areas; *running repair costs*, e.q. operating maintenance costs, and *dry-docking costs*, e.q. periodic maintenance costs [Stopford, 2009]. The maintenance operating costs are described by costs associated with routine maintenance, breakdowns and spare parts. These operating costs are directly linked with the age of the vessel [Stopford, 2009]. Periodic maintenance cost, the second general cost classification, involves expenditure of costs of interim dry-docking and special surveys. These costs, like the maintenance operating costs, are ship dependent. So vessel characteristics are to be taken into account when evaluating maintenance cost and operational performance differences.

Moreover, Stopford [2009] presents an estimation for the operating- and periodic maintenance costs within the overall costs of a bulk carrier in fig. 7.3, which are found to be 2% and 4% respectively. It is expected that the percentages of these costs in relation to the overall costs to be different, however, it is interesting to evaluate whether the ratio of $\frac{1}{2}$ between operating- and periodic maintenance costs are similar for that of a tug. Additionally, appendix D, illustrating the lifetime maintenance costs of a standard Capesize bulk carrier, shows an increase of average annual costs and daily costs of about 2.2 between Capesize vessels aged 0 – 5 and 16 – 20. Whether this holds for tugs is to be evaluated using the model [Stopford, 2009].

Besides the two prior noted general cost classification, two other types of costs are defined by Shields et al. [1975]; *direct-* and *indirect measurable maintenance costs*. The first are costs directly linked which maintenance, while indirect concern costs not directly linked, such as crew on board performing continued maintenance during operations, and stores. Even though the existence of indirect costs are acknowledged, determining the exact costs associated will be a challenge. Presumed is that the costs associated with maintenance performed by personnel of the technical department as well as labour costs as a result of dry-docking are expenses which are part of direct maintenance costs. Maintenance performed by crew are deemed indirect as these costs fall under general crewing costs. It is decided that these costs won't be taken into account as a rough estimation could influence the results. Secondly, it is suggested to take this into consideration when evaluating crew performance and expenses in a separate research.

As one may expect, regulations dictate specific programmes of periodic surveys for all vessels to able to stay in class [International Association of Classification Societies, 2011]. The three main time-based surveys have been defined as *annual survey, intermediate survey* and *special survey*. The different specific surveys, such as bottom survey, boiler survey and optional class notation, are all to be performed during one of the three named time-based surveys. Therefore, these three basic surveys will be used in evaluating the dry-docking as it is assumed, in consultation with technical specialists from joint ventures, that acquiring historical data regarding specific performed survey, such as bottom and boiler surveys, is hard to come by. Furthermore, knowledgable bodies within JV have indicated that annual surveys conducted on their vessels are mostly performed within a few hours and hardly affect operations. Data concerning annual surveys, duration in particular, is therefore difficult to acquire.

Focussing on the additional 'TUG' class notation, it is acknowledged that additional surveying of towing and anchor handling dedicated equipment is required during the annual survey and special survey. As manufacturers' recommendations are taken into account by Surveyors [Det Norske Veritas AS, 2015], it indicates that this is an important factor which dictates maintenance actions, scheduling and costs. As a result, it is important to take into account equipment which is crucial to perform towage assists and is therefore critical. Assigning criticality to systems has already been discussed in chapter 3.

In most cases, dry-docking activity is performed in combination with surveys [Det Norske Veritas AS, 2015]. Based on this conclusion, the evaluation of the dry-docking activity will be event-based. Meaning, that the aim is to compare dry-docking activity and costs of each dry-docking with other dry-dockings. As dry-docking costs are seen as CAPEX, they are capitalised and amortised for each dry-docking and expensed systematically over an estimated period until the next dry-docking activity. The actual costs associated with the dry-docking are maybe before and after the dry-docking but are still assigned directly to that specific dry-docking. For this research it is of interest to know the costs directly related to the equipment.

In contrary to the selection of event-based evaluation of the dry-docking activity and costs, it has been decided to evaluate the running repair activity and costs in a time-based way. As running repairs occur during the operational year of a tug, it is believed to be of interest to see how costs are distributed over the year. This would allow for quick pinpointing of larger than expected expenses instead of having the costs consolidated in a year, which may obscure large expenses in a given maintenance activity. Furthermore, as vessel tend to switch between ports from year to year or even multiple times within a year, it is imperative to take into account these changes in operational location of the tug but also in maintenance cost allocation across the different ports or entities.

The evaluation of different ship maintenance models has shown different approaches which are taken into consideration for the construction of the MPM tool. It is observed that a lot of equipment and vessel specific maintenance models are established, based on RCM. These models are generally established and applied to a specific system or equipment and go in depth on the failure modes and effects of equipment and its components. Moreover, a lot of models discuss the scheduling of maintenance. As time is an important factor in costs, reducing the maintenance time is directly liked to the total maintenance cost of a ship. Cost functions based on PM variables has been a study to more precisely measure the total PM scheduling costs [Oke and Charles-Owaba, 2006]. This shows that the forecasting of costs is a challenge, which is acknowledged within the Boskalis Towage division. However, not a lot has been researched regarding the monitoring and comparing/benchmarking of maintenance practices across multiple vessels. It is believed that this is mainly due to the numerous variables that influence maintenance operations as well as its costs. Besides the state and age of equipment and ships, the type of ship, classification, flag, location of maintenance, spare parts supplier, equipment manufacturer, as well as vessel utilisation and how the vessel is operated, all determine the amount of maintenance a vessel requires and as a result the cost of maintenance. Additionally, benchmarking within a company, or internally, may require a lot of reference data which might not be available. Comparing with the competition is even more challenging due to lack of information on the competitor.

Now that insight has been gained on the aspects of ship maintenance operations, regulations, costs and prior work performed, conclusions and decisions have been made which are used for the erection of the maintenance model. Armed with the knowledge obtained from literature in prior chapters, part IV will elaborate on the constructed maintenance and repair performance management model. Chapter 8 discusses the framework on which the model is built. Chapter 9 will present the scope of data used in the model and elaborate on the model itself in detail.

IV

Maintenance and Repair Performance Management Model

8

Defining The Maintenance and Repair Performance Management Framework

Now that the information required to construct the maintenance performance management framework has been discussed in prior chapters, including but not limited to; the current state of performance management within Boskalis Towage, ship maintenance and maintenance performance management. Prior to the elaboration of constructed maintenance model, the proposed framework on which the model is based is discussed in this chapter.

This chapter will first of all present the maintenance performance framework which has been selected using literature in prior chapters. Section 8.2, section 8.3 elaborates on the specifics of the model following the steps discussed in section 4.1, Maintenance Management Definition and Characterisation, which are; *Model Objective* and *Model Strategy*. Section 8.4 will provide and elaborate on the selected maintenance performance indicators within this model. This section is followed by the software selection in which the model is constructed and the reason behind the selection of this particular software. This part coincides with the *Model Implementation* step. The final section, section 8.6 summarizes the different performance analysis methods which the model uses to evaluate, i.e. benchmark, the maintenance performance. Following this chapter, chapter 9 presents the established maintenance performance model in its entirety.

8.1. Maintenance Performance Framework

Based on literature a number of choices were made in chapter 4 and chapter 5 regarding the establishing of the maintenance performance framework, which will form the basis for the maintenance model.

Four decisions have been made regarding the aspects of maintenance management. Firstly, the choice has been made to focus on efficiency measuring of maintenance and not on the effectiveness of the process of maintenance. It is believed that results from measuring efficiency can help determine possible inefficiencies regarding the effectiveness of maintenance, which can then, as a result, be evaluated outside this maintenance model. Secondly, it has been chosen to formulate the model through the three steps presented by CEN [2010]; *Model Objectives*, *Model Strategy* and *Model Implementation*. The model formulation can be found on the right side of the proposed model. Thirdly, the choice was made to incorporate the business levels presented by Parida and Chattopadhyay [2007]. Finally, an indenture level is selected, which is based on the SFI Group coding presented in section 3.4, while also taking in mind the criticality analysis and the resulting critical equipment in section 3.3.

Decisions made regarding the aspects of maintenance performance management are threefold. The first decision is the choice for the construction of a *Multi-criteria hierarchical function specific framework*. This to both comply with the choice of erecting a framework which reflects the selected business levels and focusses on financial and non-financial perspective of the maintenance function. For this, the 'performance measurement framework describing the maintenance function' proposed by Muchiri et al. [2011] is adopted. Thirdly, the framework of Parida et al. [2015] is used to incorporate the maintenance performance measurement categorisation according to Campbell and Reyes-Picknell [2006].

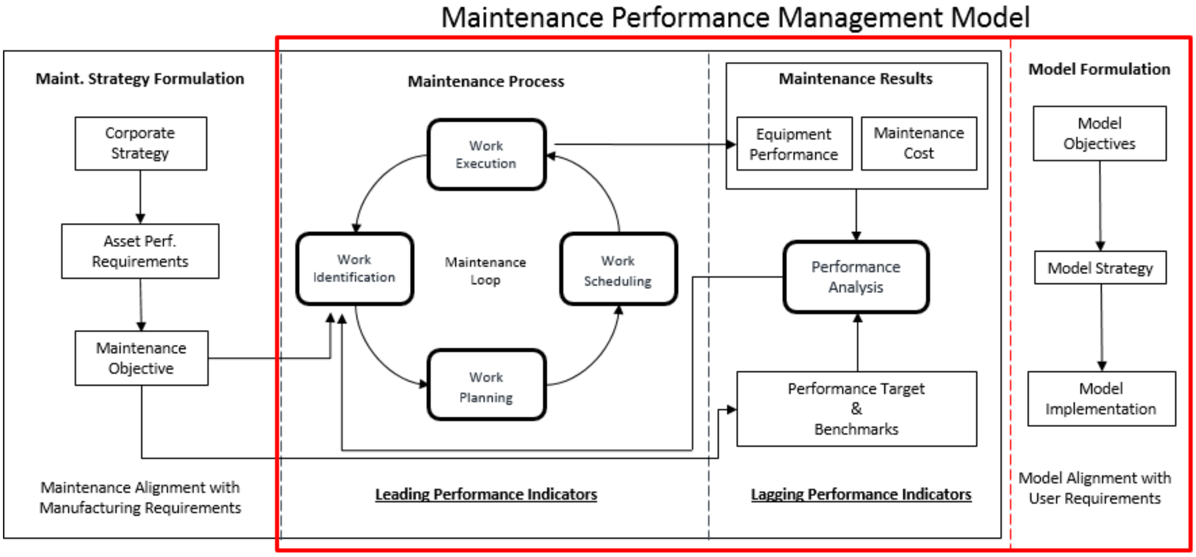


Figure 8.1: Proposed Maintenance Performance Management Model [based on Muchiri et al. [2011]]

The proposed maintenance model will be elaborated based on its three parts. The first being the *model formulation*, which is shown on the right side of the model, followed by the *maintenance process*, on the right side, and finally by the *maintenance results* and *performance analysis*, which includes targets and benchmarking.

Starting off with the maintenance function framework proposed by Muchiri et al. [2011], which is the basis of the proposed maintenance performance management model. Figure 8.1 shows the performance measurement framework for the maintenance function, including the added *model formulation* on the right side of the model, which are the three steps of maintenance management supplied by CEN [2010].

The first part of the proposed section of the framework aims to alight corporate strategy with the asset performance requirements, in this case the tug operating requirements. Based on these requirements the objectives regarding maintenance are made, e.g. policy, budget etc.

The next part of the framework is the maintenance process, on the left side of the model in fig. 8.1. This starts off with the work identification as a result of the maintenance objectives, followed by the work planning, scheduling and execution. *Work identification* tackles with the identification of the right work to be performed at the right time, controlling failure modes affecting equipment ability to perform intended functions or services. *Work planning* part develops procedures and work orders for the maintenance activities identified and required resources. *Work scheduling* includes the evaluation of all resource and time required for the execution. This also takes into account the impact of maintenance work on the availability of the equipment. *Work execution* ensures the scheduled work is carried out within the assigned time frame and resources. This part of the framework coincides with the process part of the multi-criteria hierarchical framework shown in fig. 8.2. Muchiri et al. [2011] emphasis that maintenance indicators should be defined for each step in order to continuously monitor the process. And as the process is the determinant of the maintenance results, the indicators related with the process are referred to as *leading indicators*.

Once the maintenance is performed, the *maintenance results* are then distilled from the maintenance process itself in order to be evaluated and analysed. Muchiri et al. [2011] explains the two maintenance results in terms of equipments' performance and condition, as well as maintenance costs and use of resources. These two aspects of the framework proposed by Muchiri et al. [2011] are also reflected in fig. 8.2. Following these results, careful analysis of the maintenance results is performed as to identify performance gaps and hence support continuous improvements. This includes comparison of the achieved results with targets, historical data and trend analysis Muchiri et al. [2011]. Since results are known after a given period or event, the maintenance indicators which are situated in this part of the framework are referred to as *lagging indicators* Muchiri et al. [2011].

Translating the function specific framework of Muchiri et al. [2011] towards the multi-criteria hierarchical

		Hierarchical Levels		
		Strategic	Tactical	Operational
Multi-Criteria	Equipment Performance			
	Cost Performance			
	Process Performance			

Figure 8.2: Proposed multi-criteria hierarchical framework

part of the framework have lead to the proposal of the second stage of the framework, as shown in fig. 8.2. This part of the framework is used to establish the maintenance performance indicators so that they align with the three categorisations, equipment-, cost- and process performance respectively, defined by Campbell and Reyes-Picknell [2006].

As earlier indicated, one of the aims is to align the categorised indicators with the business levels, which were adopted from CEN [2010]. These are shown in the headers of fig. 8.2.

The following sections will discuss the main objectives of the maintenance model categorised in *Technical-*, *Legal-* and *Financial-objectives*, in accordance with Wireman [2005]. Furthermore, the strategic set-up of the model is discussed and how it should incorporate the different aspects which directly or indirectly impact maintenance strategy and activity.

8.2. Model Objectives

The model objectives stated below are derived from business requirements established from the needs of the eventual end-user of the model, which is the Boskalis Towage Division. Close consideration has lead to the establishment of four main technical objectives, three financial objectives and one legal objective. The different objectives are discussed including their aim to service specific business levels.

Technical

- T1 Monitor operational performance of entities/ports at a management level.
- T2 Evaluate different entities/ports and tugs with respects to operational performance and maintenance activity, servicing the operational level.
- T3 Evaluate maintenance performed and thus the maintenance strategy, servicing the operational management at tactical level.
- T4 Help understand where maintenance activity in concentrated at equipment level for technical management at operational level.

At management level or strategic level, the aim is to allow for evaluation of the combination of utilisation of tugs and maintenance expenses. Showing year-on-year changes can shown the manager how entities have performed in comparison with last year and compare them with each other.

At tactical level, the objective of the model is to be able to evaluate the different entities/ports and tugs operating these ports. Looking into the operational performance and maintenance activity at a more detailed level can give more insight in the relations between utilisation, maintenance activity and the location in which the tug is operating. This may help with possible asset allocation in the sense that tugs may operate more efficiently at a different location. Efficiency here refers to the use of capital for maintenance activity and the utilisation of the tug. A vessel with notorious higher maintenance costs due to higher running hours may benefit from operating a port were running hours are lower per operation or running hour, leading to lower maintenance costs. However, this should not be the only aspect to take into account when looking at re-allocating a vessel. Specific port and regulatory requirements as well as market and operational requirement heavily influence the choice of re-allocation. It is believed that maintenance, as a result of operations, should also be taken into account.

Additionally, at tactical level it is of interest to evaluate the maintenance types between the different entities/port locations. As discussed in section 4.3, Maintenance Types, Policies, Activities and Indenture Level, the European Committee for Standardisation (CEN)[CEN, 2010] defines two commonly known maintenance types; *preventive* and *corrective*. It is considered to be of interest to see the amount of preventive and corrective maintenance at entity/port level and tug level as to see if the applied maintenance types are actually performed in accordance with maintenance strategy. Secondly, it is of interest to see the ratio between operating- and periodic maintenance, as concluded from Stopford [2009].

Furthermore, it is of interest to locate concentrations of maintenance, specifically at tactical and operational level. i.e. the allocation of maintenance time and costs at equipment level. This may help to get an understanding the maintenance requirements between different tugs and specific equipment, contributing to possible benchmarking between manufacturers with respects to the equipment they provide. The concentration of maintenance activity may also be a factor of operational conditions, thus taking into account location of operation is imperative in the evaluation.

One may argue that the proposed objectives are not elaborate enough and may not take into account all detailed aspects of maintenance. As this proposed framework is to be used by the Boskalis Towage department, the aim, as indicated in the goal of this research, is to come up with an adequate indenture level from which the division is able to perform detailed maintenance analysis, without increasing complexity to a large extent. Increasing detail will result in undermining the goal of investment monitoring from an abstract level as a partner of a joint venture.

Financial

- F1 Monitoring of maintenance and repair costs of tugs at a strategic level.
- F2 Monitor maintenance costs at detailed equipment level, servicing operational management level and technical management.
- F3 Increase capabilities of tugs specific forecasting, servicing operational and tactical level.

At strategic level (management level) it is aimed to evaluate the maintenance and repair costs and process of the different entities. Seeing if an entity has remained within its budget and how it has performed compared to other entities and changes over the years are the first indicators that unexpected deviations have occurred regarding maintenance expenses.

Having these costs at detailed equipment level helps determine the cost concentration of maintenance costs within specific tugs. This is imperative in order to understand the maintenance and what the main drivers are.

Finally, the information obtained to facilitate the above mentioned objective are aimed to aid in the forecasting capabilities of maintenance and repair costs. Having obtained data to facilitate the different levels of management, this can also be used to help with more accurate budgeting of maintenance costs as more detailed data is available. The aim here is to be able to check future forecasts which are supplied by the relevant joint venture, in this case JV.

Legal

- L1 Comply with regulatory bodies, such as Class Society and Flag State regulations.

Regarding legal objectives, the aim is not to monitor compliance of regulatory bodies through use of the MPM-model as the maintenance strategy of the said joint venture itself is to comply with regulatory bodies. In many occasions and as described in chapter 4, the amount of maintenance generally surpasses regulatory requirements. However, it may be of interest to take into account, for example, the number of reported issues as a result of regulatory inspections. As they have a direct impact on the operational state of the vessel, it might be an added value to see how many times or total operational time is lost due to regulatory inspections as a result of required maintenance.

The above mentioned levels are in accordance with fig. 4.2, concerning the three levels of activity, as described by Parida and Chattopadhyay [2007]. This figure can be used to create the below shown in table 8.1.

Table 8.1: Financial and technical objectives belonging to the different activity levels, in accordance to Parida and Chattopadhyay [2007] [Own Source]

Strategic Level	1. Monitor operational utilisation 2. Monitor M&R costs
Tactical Level	1. Evaluate M&R activity and operational performance of entities/ports and tugs 2. Evaluate applied maintenance types 3. Increase capability of tug specific M&R forecasting
Functional Level	1. Monitor maintenance costs at equipment level 2. Help understand where maintenance activity and costs are concentrated at equipment level

Even though forecasting is not part of this research, it is believed that with the supplied information a more detailed prediction and budget can be made. Therefore, the additional objective of increasing forecasting capabilities is a result of the presented data and conclusions.

8.3. Model Strategy

The strategy of the Maintenance Performance Management (MPM)-model is to allow for extensive evaluation of tugs through operational and financial performance of maintenance and repair. To be able to facilitate this across the different business levels discussed in previous section, it has been decided to focus on five sets of so-called *dimensions* within the MPM-model. These five have been deemed necessary for good evaluation of maintenance due to their direct or indirect impact on maintenance activity and costs. These five dimensions are shown in fig. 8.3.

Figure 8.3: Maintenance performance management model dimensions within the model strategy [Own Source]

Operational data refers to the output of towage assists performed by the assets, in this case the tugs. This can be seen as the 'utilisation' of the assets. As maintenance expenditure has been concluded to be positively related to utilisation, according to Kavussanos et al. [2004], it is important to include this.

Maintenance data refers to the maintenance activity which is performed on the vessels. Due to the link between maintenance activity, downtime and thus availability to operate, it is important to include maintenance time in order to evaluate the maintenance process [Weber and Thomas, 2005].

Tug specifications concerns the different technical specifications of the tugs within the fleet. As Stopford [2009] suggests, age and condition are major factors in maintenance cost factors as well as what equipment is installed. With key technical specification of each tug, analysis can be performed on the maintenance expenses, taking in mind the different installed equipment within each tug. This may be key in determining deviations in maintenance costs between different tugs or similar tugs operating different ports.

Financial data concern the maintenance and repair costs for performed maintenance on the tugs. These include running maintenance, dry docking expenses, book value and other financial related data. The financials are seen as a result of the performed maintenance, which in its turn is a result of the utilisation of the asset.

The dimension of *operational conditions* is of interest here due to the interest within the division to see whether conclusions can be made on asset allocation, looking at maintenance as a result of operating at a given port. Environmental conditions at certain port as well as port dimensions, etc. is believed to impact the operational results of the tugs. As previous discussed in the dimensions of tug specifications, the impact of operating a tug at a different location may result in more effective utilisation of that asset leading to lower maintenance costs and thus an improved maintenance performance.

With the above mentioned information, the following key focus areas are selected for investigation; *Fleet-*, *Port-/Entity-*, *Tug Type-*, *Sister Vessel-*, *Equipment-* Performance. The aim to be able to review individual vessels within the entire fleet, its operating port, its tug type, sister vessel and other installed equipment. It is believed that purely reviewing the vessels within a fleet does not take into account the effect of operating a different location, having a different design and installed equipment. Therefore, it is important to include these different areas of evaluation in the model.

The following step is to define the different maintenance performance indicators, bearing in mind the adopted business levels in the multi-criteria hierarchical framework in fig. 8.2 and the proposed maintenance performance model in fig. 8.1.

8.4. Maintenance Performance Indicators

Following the proposed maintenance performance framework for the model, the challenge arises to identify the performance indicators that will tell whether the maintenance performed is performed well. Using the proposed multi-criteria hierarchical framework shown in fig. 8.2 numerous indicators can be assigned. As literature suggests, it is of importance to incorporate both maintenance process (leading) indicators and maintenance results (lagging) indicators. These should support monitoring and control of performance, as well as identify performance gaps, support learning and improvements, focus on actions which aim to reach the maintenance objectives and focus on resource allocation that impact operational performance.

Close discussions with the members within the Boskalis Towage Division have lead to the following list of maintenance performance indicators. These indicators are split between maintenance process indicators, equipment performance and cost performance in accordance with the model in fig. 8.1.

8.4.1. Maintenance Process Indicators

The indicators located within the maintenance process monitor and evaluate the maintenance tasks performed so that the objective of the asset can be performed, in this allowing the tug to perform tugmoves. The maintenance process is defined through: work identification, work planning, work scheduling, and work execution. For each of the mentioned processes key performance indicators are shown in table 8.2, including what hierarchical level they service.

For work identification, maintenance should identify potential failures and attend to these in order to prevent total shutdown. Preventive maintenance work is known to mitigate failure consequences, such as increased downtime, maintenance cost, safety and environmental hazards. The key performance indicators for work identification are the percentage of preventive maintenance work over a specific period. Recommended target for this indicator is 75-80% [Mackenzie, 2004, Weber and Thomas, 2005], which leaves for 25-20% or corrective work. This can also be specified by the maintenance objectives specified. The amount of corrective work may give an indication of the breakdown intensity and responsiveness of unplanned work.

The following processes are that of maintenance planning and scheduling. A high percentage of planning is crucial to maximise maintenance efficiency and ensuring the availability of necessary resources. The indicator showing the efficiency of planning is that of planning intensity and quality of planning, which is the percentage of planned work and percentage of work requiring rework due to planning. Suggested targets by Weber and Thomas [2005] are 95% of all work orders and below 3% respectively. The category of work scheduling holds the indicator illustrating the schedule realisation rate, which means the percentage of scheduled man-hours to the total man-hours. The suggested target is above 95% of all work.

The work execution performance indicators help monitor the maintenance job carried out. Among the selected indicators are total downtime, mean-time-to-repair, schedule compliance (percentage of orders complete in scheduled period) and quality of execution (percentage of maintenance work requiring rework). Suggested targets for schedule compliance is above 90% and quality of execution below 3%, respectively [Weber and Thomas, 2005].

Although Weber and Thomas [2005] suggest different targets for above mentioned indicators, it should be noted that these targets may be different for different organisations and different areas. Therefore, these targets are presumed a rough indicator instead of a hard target.

8.4.2. Equipment Performance Indicators

The indicators making op the equipment performance part of the maintenance model can be explained through part of the Overall Equipment Effectiveness (OEE) [Nakajima, 1988], which is a metric supporting

Table 8.2: Summary of leading maintenance performance indicators.

Hierarchy Level	Category	Measure / Indicators	Units	Description
Tactical + Operational	Work Identification	Percentage of preventive work	%	No. of preventive maintenance hours / Total amount of maintenance hours
Tactical + Operational		Percentage of corrective work	%	No. of corrective maintenance hours / Total amount of maintenance hours
Operational	Work Planning	Planning intensity	%	Planned work / Total work done
Operational		Quality of Planning	%	Percentage of work orders needing rework due to planning / All work orders
Tactical + Operational	Work Scheduling	Schedule realisation rate	%	Work orders with scheduled date earlier or equal to late finish date / All work orders
Tactical + Operational	Work Execution	Downtime	Hours	Total Downtime
Tactical + Operational		Mean Time to Repair (MTTR)	Hours	Total Downtime / No. of failures that impact operations
Operational		Schedule Compliance	%	Percentage of work orders completed in scheduled period before late finish date
Tactical + Operational		Quality of Execution (Rework)	%	Percentage of maintenance work requiring rework

management with information concerning asset availability and planning rate, performance rate and quality rate. The performance rate and the quality rate are part of the operational performance and deemed outside the scope of this research, as this research focusses on maintenance performance. Therefore, the performance- and quality rate, as suggested within the OEE metric, shown in fig. 8.4, are disregarded within the equipment performance indicators. However, it is of interest to know the current state of the equipment. Therefore, it is suggested to introduce an alternative quality rate which reflects the state of the equipment. This introduces a qualitative metric which is established through a knowledgable bodies, ranging between 0-100%. The remaining part of OEE, availability, is of interest within the scope of this research. The availability is a function of the planned and unplanned downtime respectively.

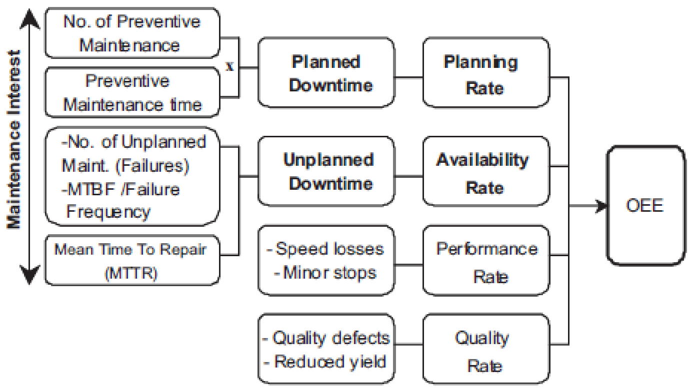


Figure 8.4: Maintenance indicators making up the OEE metric [Muchiri et al., 2011]

Among other key indicators, shown in table 8.3, are the equipment failure frequency, measured by MTBF and the number of unplanned maintenance interventions as it is the primary function of maintenance to reduce or eliminate failures and their consequences.

8.4.3. Cost Performance Indicators

The resulting maintenance costs, shown in fig. 8.1, is directly influenced by the efficiency of maintenance performed. Maintenance cost and other related cost indicators are thus important measures of maintenance performance. Efficiently planning and utilisation of resources can potentially minimise maintenance cost.

Table 8.3: Lagging maintenance performance indicators.

Hierarchy Level	Category	Measure / Indicators	Units	Description
Operational	Equipment Performance	No. of failures	No.	No. of Failures
Tactical + Operational		Failure / Breakdown Frequency	No. / Unit Time	No. of failures per unit time (Measure for Reliability)
All		Availability	%	Uptime/(Uptime + Downtime)
All		Quality Rate	%	Quality Rate based on the condition of the asset
All	Cost Performance	Direct Maintenance Cost	€	Total Corrective and Preventive Maintenance Costs
All		Maintenance TM Intensity	€ / Tugmove	Maintenance cost per tugmove performed in a period
All		Maintenance RHr Intensity	€ / RHr	Maintenance cost per unit of time
Strategical + Tactical		Maintenance Cost as % ARV	%	Maintenance Cost / Asset Replacement Value (ARV)

The therefore selected cost performance indicators are summarised in table 8.3. The first indicators is the total maintenance cost, which can be split is costs made for preventive and corrective work. Secondly is the maintenance intensity, which is the cost per unit produced. In this research it can be translated as the cost of maintenance per unit of service in a period, e.g. tugmoves.

Another important indicator is the maintenance cost per operating hour, i.e running hour. As it is concluded in chapter 7 that the maintenance cost in directly linked to the utilisation of the vessel [Kavussanos et al., 2004], the choice has been made to include this metric alongside the maintenance cost per tugmove as this metric does not take into account the geographical characteristics of the port. Tugs operating a port with lower running hours per tugmove may show increase performance in maintenance cost per tugmove due to the larger amount of tugmoves, but shown higher maintenance costs per running hour. In order to take this effect into account, the metric of maintenance cost per running hour is introduced into the cost performance.

The last metric is the percentage of maintenance cost to the Asset Replacement Value (ARV), also referred to as Estimated Replacement Value(ERV) [CEN (European Committee for Standardisation), 2007, Gulati, 2013, Weber and Thomas, 2005]. This metric compares the expenditure of maintenance with other equipment of varying size and value. The ARV as denominator normalises the measurement give that different equipment vary in size and value. Gulati [2013] suggests annual measuring of this metric. For this research, a value of €[redacted] for the ARV is assumed, which is based on the most research purchase of an undisclosed tug.

8.4.4. Link and Effect

Numerous authors of literature discussed in chapter 5 discuss the added value of the *link and effect* capabilities [Bourne et al., 2003, Parida et al., 2015, Stenstrom et al., 2013]. The fundamental behind the link and effect model has been elaborated upon in chapter 5 and additional information supplied in appendix B. Seen as the added value of this method has been expressed, it has been applied on the prior mentioned maintenance performance indicators. The resulting link and effect diagrams, comprised of numerous performance indicators are shown in fig. 8.5 and fig. 8.6.

The first link and effect diagram, fig. 8.5, shows the link between costs made in both areas of running repairs and dry docking, and operational results. The left side shown the linkage of preventive- and corrective running repair costs, i.e. direct running repair maintenance cost. These combined result in the running repair costs. On the other side, the choice has been made to split the dry docking costs into intermediate survey (IS) and special survey (SS) and Emergency Docking (ED) costs respectively. Detailed information detailed equipment cost and whether these were preventive or corrective of nature is unfortunately not available. Therefore,

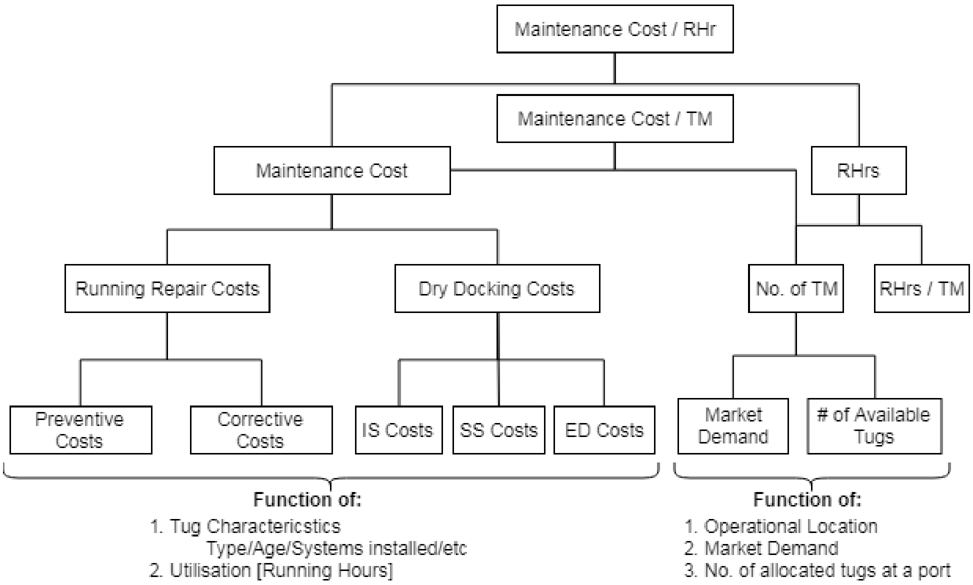


Figure 8.5: Link and effect diagram of variables and performance indicators

it is presumed that IS and SS are planned and therefore preventive. Unplanned dry docking activities which are not related to IS or SS are labelled EDs as they are not linked to survey events performed by Classification Societies. Activity which are not related to maintenance, such as collisions, are not taken into account as they are not a consequence of the maintenance function. The summation of both running repair costs and dry docking costs result in the total maintenance costs. It is concluded that these costs are a function of vessel specifics, such as design, age and installed equipment as well as the utilisation [Kavussanos et al., 2004], i.e. running hours.

The right side of the diagram illustrates the operational side of towage operations, which are a function of supply and demand mechanism, which is dependent on the port and the number and type of incoming and outgoing vessels requiring towage assistance. The influence of port characteristics and the market is not part of this research, however it is kept in mind when benchmarking towage vessels through the combination of maintenance costs and operational performance, i.e. maintenance intensity and maintenance per operating hour. Resulting from the market demand and the no. of available tugs for operation, are a number of service units, i.e. tugmoves. Combining the maintenance costs and the number of performed tugmoves leads to the maintenance intensity.

Knowing the amount of tugmoves is not equivalent to knowing the amount of operating time a tugs has performed. As earlier noted, the geographical location dictates the running hours in respect to the amount of tugmoves performed. It is assumed that this is a function of the type of towage operations executed at a port and the layout of the port itself. As this research focusses solely on harbour towage services, it is assumed that all towage activity are identical across the different ports. This leaves the impact of the port layout on the running hours per tugmove, or operational hours per unit of service. Combining this with the amount of tugmoves performed, results in the running hours the tug has performed. Finally, the metric of maintenance running hour intensity can be formed as a function of the total maintenance cost and the running hours.
The second link and effect diagram which can be established reflects the maintenance process, and in particular time, through a couple of leading maintenance performance indicators, leading up to the availability of the equipment. This link and effect diagram is a modified OEE, as illustrated in fig. 8.4. The choice has been made to differentiate between time spent for running repairs and dry docking, similar to previous diagram. The resulting downtime, as a function of time spent for running repairs and dry docking, results in the availability percentage of the tug. fig. 8.4 shows that the maintenance activity is a function of the number of unplanned maintenance, the number of planned maintenance and time required to repair the failure [Muchiri et al., 2011].

The two diagrams, fig. 8.6 and fig. 8.5 help understand the underlying principles of the different maintenance performance indicators and how they contribute to the key maintenance performance indicators [Daven-

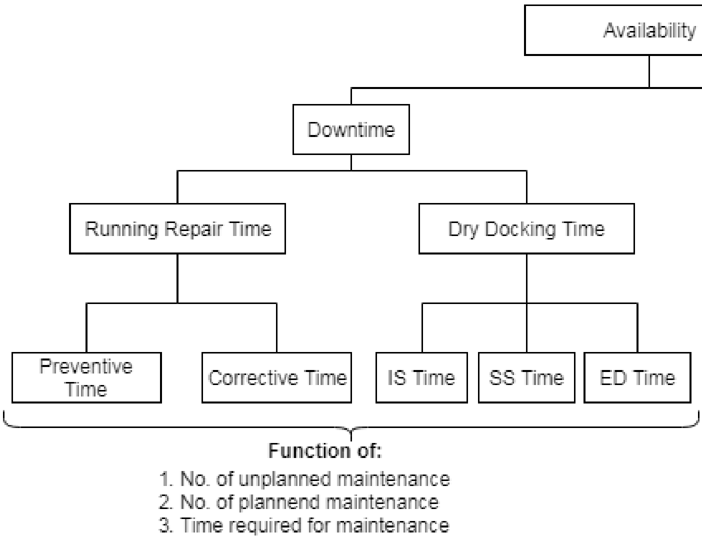


Figure 8.6: Link and effect diagram of variables making up the maintenance performance indicators

port et al., 2001, Karim et al., 2009]. This allows for continuous monitoring through underlying factors, as illustrated in fig. B.3.

8.4.5. Maintenance - Best Practice Key Benchmarks

As stated by Kaydos [1991], a good performance measurement system does not necessarily require an extreme high level of precision. The main importance is to understand and monitor trend of a movement in an indicators and how it compares with historical values. Since literature research regarding the benchmarking of ship maintenance has not resulted in benchmarking targets, the choice has been made to adopt maintenance benchmarking target from the production industry. It should be noted that these benchmarking targets are industry dependent, as stated by numerous authors [Campbell et al., 2011, Kahn and Gulati, 2006, Kaydos, 1991, Muchiri et al., 2011]. An extensive list is presented by Gulati [2013] which show various performance indicators divided into quartiles. The list with quartile values is shown in the fig. 8.7.

8.5. Software - Power BI

Now that the framework is defined, the dimensions of interest and the MPIs selected, the preliminary model can be constructed. But before this can commence, the software package needs to be selected in which to build the model. For this research and the implementation of the model, the choice has been made for Power BI. Microsoft Power Bi can be described as " a cloud based data analysis, which can be used for reporting and data analysis from wide range of data source. Power BI is simple and user-friendly enough that business analysts and power users can work with it and get benefits of it. On the other hand Power BI is powerful and mature enough that can be used in enterprise systems by BI developers for complex data mash-up and modelling scenarios." [Rad, 2015] The program is free to download and allows for basic Business Intelligence analysis to be performed. Secondly, the Boskalis Towage Division and other departments within the Boskalis company are starting to get familiar with the Microsoft Power BI programme, making it an already known programme within the company. Boskalis also hold a licence for the commercial version of the Microsoft Power BI service which includes numerous extensions and capabilities compared to the free version. The program can be download from `https://powerbi.microsoft.com`.

Microsoft states that the use cases for Power BI are general used to [Miscrosoft, 2019];

- Connect multiple streams of data
- Transform and clean data in order to create data models
- Create interactive table visualisations which represent the data
- Create interactive reports

The software programme also allows for live connection to different servers or data pools in order to collect,

	Quartile I	II	III	IV
Plant /Organization/ Process				
Maintenance Costs as % RAV	< 2.5	2.5% -3.0%	3.0% -5.0%	>5.0%
Maintenance Costs per Unit Output		*Varies by Production Unit (5 – 15 %)*		
Return on Net Assets (RONA)		*Varies by Organization*		
Percentage Overtime	< 5 %	5 – 10 %	10 – 20 %	> 20 %
Training Hours /Person	> 80	48 - 80	20 – 48	< 20
Safety Performance – OSHA Injuries/200K Hours	< 0.5	0.5 – 1	1-3	> 3
Overall Asset / System / Process				
Availability	> 97%	95%-97%	95%-80%	< 80%
Downtime as % of Total Scheduled (Operating) Hours		< 1 %	1 – 3 %	3 – 5%> 5 %
Overall Equipment Effectiveness (OEE)	> 80 %	70 - 80 %	40– 60 %	< 40 %
Planning & Scheduling and MRO Store				
Reported Hours in CMMS as % of Total Paid Hours	> 99%	95%-99%	80%-95%	< 80%
Work Hours Expended on Blanket Work Orders as % of Total	> 30%	< 10%	10%-20%	20%-30%
Planned Work as % of Total Work	> 85%	75%-85%	65%-75%	< 65%
Planning Accuracy (Estimated Hours to Actual Hours)	Estimate ± 20%	Estimate ± 10%	Estimate ± 25%	Estimate ± 15%
Schedule Compliance in %	> 90%	75%-90%	60%-75%	< 60%
Reactive Work (Emergency, Break-in Work) as % of Total	> 30%	< 10%	10%-20%	20%-30%
Labor Effectiveness (Wrench Time) in %	> 60%	50%-60%	30%-50%	< 30%
Rework (Poor Quality) Hours in % of Total Work Hours	> 10%	< 2%	2%-5%	5%-10%
Work Orders Closed with Comments – Data Quality	< 60%	> 95%	80%-95%	60%-80%
Inventory Turns (MRO store)	> 2	1.5 – 2	1 – 1.5	< 1
Inventory Accuracy - %	> 98 %	95 – 98 %	90 – 95 %	< 90 %
Maintenance, Preventive & CBM/PdM				
Preventive and CBM/PdM Hours as % of Total Hours	< 20%	60%	40–60%	20–40%
Preventive and CBM/PdM Schedule Compliance	> 95%	90%–95%	75%–90%	< 75%
Work Created by PM & CBM/PdM as % of Total Hours	< 10 %	> 25 %	20 – 25 %	10 – 20 %
Root Cause Failure Analysis (RCFA) Performed for Failures	< 60%	> 95%	80%–95%	60%–80%
Reliability Program				
Mean Time between Failure / Repair –MTBF/MTTR tracked		*Varies by organization and types of assets*		
Faults detected prior to failure	>95%	80% – 95%	50% – 80%	< 50%
Failures due to lubrication % of total	0%	< 5%	5% – 20%	20%

Figure 8.7: List of key maintenance and reliability best practices benchmarks [Gulati, 2013]

evaluate and monitor data. For this research, such a connection is not researched or implemented in this model as it is addresses other topics and problems than focussed on in this research. The data structured for the model is therefore static. Nonetheless, it may be an added value to incorporate this in the future in order to allow for continuous monitoring and evaluating maintenance. In order to incorporate this for of data flow, more research on the possibilities is required. For this research, static data, which is not linked to an external database, is used to construct the model in the Power BI model elaborated in chapter 9.

8.6. Maintenance Performance Analysis

The maintenance performance analysis of the towage fleet of JV will be performed in two steps. The first phase will use the Microsoft Power BI software, in which the model is built, to discriminate between the different tugs. It has been decided to select five tugs for evaluation and validation of the model. The selection of these five tugs will be based on one of the key maintenance performance indicators. In order to select the indicator, a simple regression analysis performed between the different metrics within the maintenance function. This will help identify which of the prior mentioned indicators are leading in the comparison between the maintenance performance of tugs. The regression analysis is presented in section 10.1.

After the selection of five underperforming tugs, based on the selected maintenance performance indicators, the model will be used to evaluate each individual vessel with use of the different metrics and indicators in order to make definitive conclusions regarding the maintenance performance of the tugs. These conclusions are then presented to the technical bodies within JV and cross-checked in order to validate the model. Discussions that follow will be included in the performance analysis of the individual tugs.

Secondly, the fleet will be evaluated through a basic DEA model suggested in chapter 6. As decided in this chapter, the use of the open source program R and available packages are used to establish a Slack-Based Measure (SBM) model. The technology assumption required for this evaluation will result from the simple regression analysis presented in the next chapter. The evaluation configurations of fleet, port, tug type and sister vessels are central within DEA. Results and conclusions of the SBM DEA are presented in chapter 10.

8.7. Intermediate Conclusions Chapter 8

Within this chapter the maintenance performance framework was presented and elaborated upon. This all was done prior to the erection of the maintenance performance model. The following key choices were made with respect to the model framework on which the model is built.

Firstly, based on literature the proposed maintenance performance model was presented in fig. 8.1. This function specific framework is based on Muchiri et al. [2011]. The model is divided into maintenance process and maintenance results, which include equipment performance and maintenance performance. Based on these results, performance analysis is performed through comparison to performance targets and benchmarks. The three areas of equipment performance, cost performance and process performance can be translated into a multi-criteria hierarchical framework, based on Campbell and Reyes-Picknell [2006], presented in fig. 8.2.

Alongside the proposed model, the model objectives have been formulated. These have been split into three categories; technical, financial and legal. The technical objectives focus on the monitoring and evaluation of operational and process performance of entities and ports, evaluation of maintenance performed and obtaining knowledge about concentration of maintenance activity at different business levels. Financial objectives include the monitoring of maintenance investments from entity, port and equipment level and increase the capabilities of tug detailed forecasting of maintenance. The only legal focus is that all tugs should be compliant with regulations of Class, Flag State, etc.

The strategy of the model is to incorporate operational-, maintenance-, financial data, tug specifications, and operational conditions within one model in order to evaluate maintenance performance across entities, ports and fleet. Resulting from these areas, five different scopes were selected to perform evaluation. These are fleet-, port-/entity, tug type-, sister vessel- and equipment performance.

Following the defined performance scopes different performance indicators were presented for process-, equipment- and cost performance, where process performance indicators are labelled as leading indicators and equipment- and cost- performance indicators are lagging. These are presented in table 8.2 and table 8.3, respectively. Numerous authors discuss the issue of performance indicators lacking explanation of the fundamentals of indicators [Bourne et al., 2003, Parida et al., 2015, Stenstrom et al., 2013]. Therefore, the link and effect method was introduced to elaborate on key performance indicators. These have been presented in fig. 8.5 and fig. 8.6 linking costs for both running repair and dry docking towards maintenance costs RHr intensity and maintenance coost TM intensity. Moreover, maintenance time is related to downtime and availability.

Due to the fact that no benchmarking targets could be found with respect to ship maintenance performance monitoring, the decisions was made to adopt benchmarking targets from the production industry as a preliminary measure for benchmarking. These were presented in fig. 8.7.

Following the definition of the model framework, an adequate software program was selected. Microsoft Power BI was selected as software program as it is known within the organisation of Boskalis and Boskalis Towage. Secondly, the program is promoted as a data analysis program which can be used for reporting and data analysis. For these two reasons, the Power BI software program was selected.

The last part concerned itself with the selection of a performance analysis method. Aside from the selected performance indicators within the framework, literature has presented an alternative method of performance analysis. DEA has presented itself as an effective way of evaluation processes with multiple inputs and outputs. It was decided to construct this in the open source program R as it allows from quick implementation of DEA packages.

9 Maintenance Performance Model

Following the model definition in previous chapter, this chapter will present the constructed Maintenance Performance Model. Firstly, the scope in which the MPM-model will function is presented in section 9.1. This includes operational specifics of the different ports operated by JV, its fleet and key information concerning the asset maintenance plan. The first two supply the important information required for the model. The asset maintenance plan reflects the maintenance strategy of JV. In the second part of this chapter, the Maintenance Performance Management Model built, using the Microsoft Power BI software, is presented in section 9.2. This section elaborates on the data that in the model, the data flow of the model and the user interface of the dashboard. The results following from the model are presented and discussed in the next chapter, chapter 10.

9.1. Model Scope

For the scope of this research and the erection of the MPM-model, the choice has been made to evaluate the tug fleet of JV and use this as a case study. The reason for this choice is twofold. The first being that there has always been close communication between Royal Boskalis and JV due to the fact that the joint venture operates out of Port A, making it easier to obtain data, expertise needed and the possibility of face-to-face meetings. This will help with understanding the data supplied and the discussion of the results/conclusions. Secondly, due to the fact that JV operates in numerous ports around Europe, it is assumed that it represents a simplistic version of an evaluation across all joint ventures, worldwide. This drastically reduces the complexity of maintenance benchmarking.

JV facilitates towages operation round-the-clock in 12 European Ports. With their fleet of about 70 tugs, they operate major ports around Europe. Local teams supply services across the different ports and are supported by a dedicated central coordinating team in the Port A head office, in the Netherlands [Smit, 2019]. The corporate infographic in fig. 9.1 shows an illustrates the operating area of JV across Europe.

For this research, the port of Port J has been left out of the evaluation as the data did not show any operational activity in this port. That operations at Port J are outsourced to another party. A short description of the operating ports and their characteristics are discussed in section 9.1.1. The different tugs within the fleet of JV are presented in section 9.1.2.

Table 9.1: Throughput by commodity in million tonnes in 2017 [Department of Transport, 2018a;b, Port of London Authority, 2018, ?].

Port	Port A	Port B	Port C	Port D	Port E	Port F	Port G	Port H	Port I
Iron ore and scrap	31.2	0.6	2.1	1.2	2.6	0.0	7.7	11.8	4.3
Coal	25.8	0.0	0.0	0.0	0.5	0.0	6.6	7.8	1.1
Agribulk	11.1	0.3	1.7	1.4	1.0	0.2	5.1	7.5	0.5
Other dry Bulk	12.1	1.2	3.4	13.1	8.1	1.1	12.1	4.0	2.0
Subtotal dry bulk	**80.2**	**2.1**	**7.2**	**15.7**	**12.2**	**1.3**	**31.5**	**31.1**	**7.9**
Crude oil	104.2	12.2	7.8	0.0	6.0	0.0	0.0	0.8	0.0
Mineral oil products	79.2	8.4	2.3	13.5	52.9	2.8	13.8	10.7	1.6
LNG	2.0	0.0	0.0	0.2	0.0	1.0	0.0	0.0	0.0
Other liquid bulk	28.9	0.4	0.6	1.0	14.2	0.3	5.5	2.2	0.0
Subtotal liquid bulk	**214.3**	**21.0**	**10.7**	**14.7**	**73.1**	**4.1**	**19.3**	**13.7**	**1.6**
Total bulk goods	**294.5**	**23.1**	**17.9**	**30.4**	**85.3**	**5.4**	**50.8**	**44.8**	**9.5**
Containers	**142.6**	**9.6**	**5.4**	**10.5**	**123.0**	**15.4**	**1.0**	**90.3**	**54.2**
Roll-on/Roll-off	23.8	1.3	7.7	7.8	5.1	15.0	3.7	54.2	0.0
Other general cargo	6.5	0.1	1.1	1.3	10.3	1.3	11.2	9.3	9.3
Total breakbulk	**30.3**	**1.4**	**8.8**	**9.1**	**15.4**	**16.3**	**14.9**	**63.5**	**9.3**
Total throughput	**467.4**	**34.1**	**32.1**	**50.0**	**223.7**	**37.1**	**66.7**	**198.6**	**73.0**
Total Market Share	**39.5%**	**2.9%**	**2.7**	**4.2%**	**18.9%**	**3.1%**	**5.6%**	**16.8%**	**6.2%**

Unit: Gross weight x 1 million metric tons

[redacted]

Figure 9.1: Corporate Infographic of JV.

9.1.1. Ports of Operation

As concluded in chapter 7, the operational location impact the utilisation of equipment and thus maintenance required. For this reason, important characteristics of each operating port which may influence towage operations is presented. First of all, to get an understanding of scale of the number of vessels entering the ports, an overview of the amount of trade is presented. Furthermore, geographical aspects of the different ports is summarised, including important hydrographic characteristics, weather and tidal impact and towage regulations.

In order to get an understanding of the type and amount of vessels arriving at each port, tables table 9.1, fig. 9.2 and table 9.2 have been established. Looking at table 9.1, it can be stated that there are three ports which dominate the market in terms of market share. Port A leads with a throughput of 467.4 million metric tons and a market share of 39.5%. Followed by Port E and Port H. Figure 9.2 shows the division of commodities across the different ports.

Table 9.2: Number of vessels in ports by type in 2017 [European Statistics, 2019].

Port	Port A	Port B	Port C	Port D	Port E	Port F	Port G[a]	Port H	Port I
Liquid bulk tanker	6,564	1,380	1,207	1,137	5,103	724	635	256	625
Dry bulk carrier	926	12	259	303	7	-	549	20	573
Container ship	6,094	1,123	779	1,787	4,293	298	1	4,933	3,558
Specialised carrier	182	814	35	98	1,261	5,040	-	15	-
General cargo, non-specialised	5,949	6,688	4,254	3,955	3,395	305	1,850	841	694
Total number of vessels[b]	**19,746**	**10,213**	**6,557**	**7,302**	**14,223**	**7,725**	**3,038**	**6,579**	**5,839**

[a] Number of vessels only known for Ghent. [b] Total number of vessels includes additional vessels types.

Table 9.3: Number of vessels in ports by gross tonnage in 2017 European Statistics [2019].

Entity Code	H020	H048	H050	H058	H060	H061	H062	H084	H085
Port	Port A	Port B	Port C	Port D	Port E	Port F	Port G[a]	Port H	Port I
From 100 to 499 GT	1	5	5	99	25	172	8	15	3
From 500 to,999 GT	30	2	35	2	48	41	12	251	6
From 1,000 to 1,999 GT	713	205	331	390	704	269	253	330	103
From 2,000 to 2,999 GT	1519	674	937	698	1362	596	932	296	125
From 3,000 to 3,999 GT	1175	296	434	246	1051	270	347	173	248
From 4,000 to 4,999 GT	775	6270	166	261	769	101	215	35	2
From 5,000 to 5,999 GT	459	91	390	106	558	162	115	126	60
From 6,000 to 6,999 GT	492	33	29	15	158	19	63	177	158
From 7,000 to 7,999 GT	1437	236	362	522	486	245	27	285	160
From 8,000 to 8,999 GT	707	74	155	69	511	56	34	64	69
From,9,000 to,9,999 GT	553	84	67	194	381	121	31	307	353
From 10,000 to 19,999 GT	3382	212	2026	850	1802	719	197	1166	1467
From 20,000 to 29,999 GT	2330	224	1187	2504	2063	3023	207	538	569
From 30,000 to 39,999 GT	1105	92	180	192	803	489	462	211	298
From 40,000 to 49,999 GT	501	210	52	123	738	507	134	225	532
From 50,000 to 79,999 GT	2521	878	130	320	1580	742	1	535	1331
From 80,000 to,99,999 GT	937	175	11	278	516	31	0	327	472
From 100,000 to 149,999 GT	456	168	60	130	401	116	0	428	126
From 150,000 to 199,999 GT	636	267	0	9	259	45	0	343	485
From 200,000 to 249,999 GT	17	17	0	0	4	1	0	7	12
From 250,000 to 299,999 GT	0	0	0	0	0	0	0	0	0
300,000 GT or over	0	0	0	0	0	0	0	0	0
Total number of vessels[b]	**19,746**	**10,213**	**6,557**	**7,008**	**14,223**	**7,725**	**3,038**	**5,839**	**6,579**

[a] Number of vessels only known for Ghent. [b] Total number of vessels includes additional vessels types.

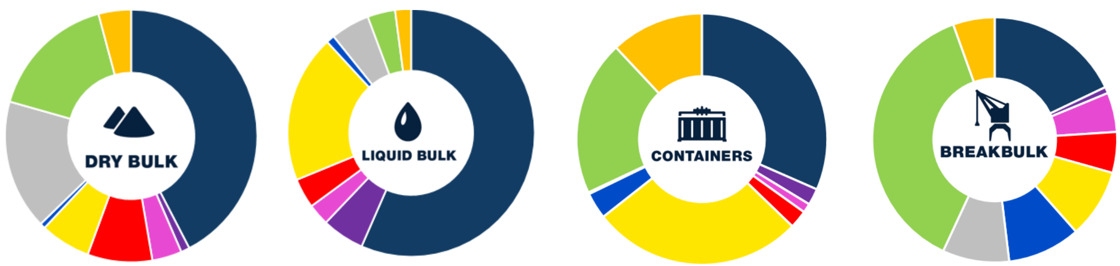


Figure 9.2: Graphical representation of throughput by commodity in 2017

It is interesting to note the differences is tonnage between the different ports. Where Port A dominates the dry bulk and liquid bulk, it competes with Port E in the container market. Together with the table 9.2 and table 9.3, a good understanding can be made on the amount, type and size of vessels which operate each port. The reason why this may be of interest is due to the conclusions that port regulations have been found to dictate towage requirements based on five main criteria; visibility, wind area, vessel type, Dead Weight Tonnage (DWT) and vessel dimensions [Peel Ports, 2019, Port Of Antwerp, 2018, **?**]. How these five criteria dictate port specific towage regulations is presented for each specific port.

A couple of interesting conclusions which can be made as a result of the above shown tables. The first being one regarding the container throughput at Port H. Table 9.1 shows a lower throughput in comparison with Port E. However, the number of container vessels which have entered Port H is larger than that of Port E. The conclusions can be made that the size of the container vessels which operate Port H are smaller of size in comparison with those operating Port E. Therefore, the required number of tugs needed to escort, tow, berth or unberth the vessel may differ.

An additional interesting conclusion, is the throughput of Roll-on/Roll-off vessel which operate Port H. Ro-Ro vessels generally have a large wind surface area which makes them susceptible to high wind speeds. The same principle holds for container vessels. Dry- or liquid bulk carriers generally have a lower freeboard and are thus less prone to wind increases, but are more susceptible to tidal changes and speeds.

For each of the operating ports, information regarding port layout and towage regulations has been collected and elaborated in appendix I. A summary of how this impacts the towage operating is presented below, focussed on three aspects; impact on towage duration, impact due to locks and meteorological impact.

Table 9.4: Summary of the impact of port characteristics on towage operations.

	Towage Time	Locks	Meteorological
Port A	+	−	~
Port B	~	−	+
Port C	+	+	+
Port D	+	+	+
Port E	+	+	~
Port F	~	+	+
Port G	+	+	~
Port H	+	−	~
Port I	+	+	~

9.1.2. JV Towage Fleet

For the case study of JV, the following fleet of tugs is relevant, table 9.5. table 9.5 shows a summarised version of the extensive fleet list in appendix E. The list shown below includes the vessels MMSI, which is used as an ID across the entire model, and other vessel characteristics. The list in appendix E includes extensive information such as; gross tonnage, fire fighting capacity, dimension, design, engine-, auxiliary-, thruster- and winch data. Along with table 9.5, table 9.6 is presented. This table shown the different sister vessels within the fleet. The sister vessel code has been established in order to structure the different sister vessel grouping and take into account possible expansion of the fleet of JV and possible introduction of other joint ventures. The coding is noted as SIS_*"JVs abbreviation"*_*"Group number"*. This has been done in order to create a unique ID which can be used within the Microsoft Power BI model.

Table 9.5: Summary of JV tugs.

MMSI	Name	Tug Type	Bollard Pull	Year Built	Current Operational Location
[redacted]	Tug 1	ATD	72	2018	Port A
[redacted]	Tug 2	Conv	40	1991	Port G
[redacted]	Tug 3	ASD	45	1988	Port G
[redacted]	Tug 4	ATD	72	2018	Port B
[redacted]	Tug 5	ASD Hybrid	60	2015	Port G
[redacted]	Tug 6	ASD	55	1997	Port A
[redacted]	Tug 7	ASD	55	1998	Port A
[redacted]	Tug 8	Conv	40	1985	Port G
[redacted]	Tug 9	ASD Hybrid	60	2018	Port A
[redacted]	Tug 10	RSD	75	2018	Port I
[redacted]	Tug 11	VSP	43	1995	Port E
[redacted]	Tug 12	ASD	84	2017	Port A
[redacted]	Tug 13	RT Hybrid	84	2010	Port A
[redacted]	Tug 14	RT	84	2012	Port B
[redacted]	Tug 15	RT Hybrid	80	2014	Port I
[redacted]	Tug 16	RT Hybrid	80	2014	Port D

[redacted]	Tug 17	RT	78	1999	Port I
[redacted]	Tug 18	RT	84	2009	Port I
[redacted]	Tug 19	RT	78	1999	Port I
[redacted]	Tug 20	RT	84	2009	Port I
[redacted]	Tug 21	ASD	80	2013	Port H
[redacted]	Tug 22	ASD	52	1998	Port A
[redacted]	Tug 23	ASD	60	2012	Port A
[redacted]	Tug 24	ASD	60	2012	Port H
[redacted]	Tug 25	ASD	65	2008	Port A
[redacted]	Tug 26	ASD	65	2008	Port B
[redacted]	Tug 27	ASD	65	2008	Port A
[redacted]	Tug 28	ASD	58	2007	Port C
[redacted]	Tug 29	ASD	52	1999	Port C
[redacted]	Tug 30	ASD	95	2009	Port A
[redacted]	Tug 31	ASD	58	2007	Port C
[redacted]	Tug 32	ASD	60	2009	Port A
[redacted]	Tug 33	ASD	60	2007	Port B
[redacted]	Tug 34	RT	80	2011	Port F
[redacted]	Tug 35	ASD	60	2008	Port A
[redacted]	Tug 36	RT	80	2011	Port F
[redacted]	Tug 37	ASD	95	2009	Port A
[redacted]	Tug 38	VSP	43	1996	Port C
[redacted]	Tug 39	ASD	60	2008	Port A
[redacted]	Tug 40	ASD	60	2009	Port A
[redacted]	Tug 41	ASD	96	2009	Port B
[redacted]	Tug 42	VSP	36	1987	Port C
[redacted]	Tug 43	ASD	84	2017	Port F
[redacted]	Tug 45	ASD	39	1991	Port G
[redacted]	Tug 45	Conv	39	1991	Port G
[redacted]	Tug 46	ATD	45	1992	Port A
[redacted]	Tug 47	ATD	45	1992	Port A
[redacted]	Tug 48	VSP	43	1997	Port A
[redacted]	Tug 49	ASD	45	1992	Port G
[redacted]	Tug 50	ASD	45	1993	Port G
[redacted]	Tug 51	VSP	43	1996	Port A
[redacted]	Tug 52	VSP	43	1997	Port G
[redacted]	Tug 53	ASD	65	2007	Port E
[redacted]	Tug 54	ASD	65	2004	Port F
[redacted]	Tug 55	ASD	80	2010	Port E
[redacted]	Tug 56	ASD	66	2005	Port G
[redacted]	Tug 57	ASD	65	2007	Port E
[redacted]	Tug 58	ASD	80	2010	Port E
[redacted]	Tug 59	ASD	65	2007	Port E
[redacted]	Tug 60	ASD	64	2009	Port E
[redacted]	Tug 61	ASD	65	2007	Port E
[redacted]	Tug 62	ASD	64	2009	Port E
[redacted]	Tug 63	ASD	65	2005	Port F
[redacted]	Tug 64	ASD	65	2005	Port G
[redacted]	Tug 65	ASD	39	1992	Port C
[redacted]	Tug 66	ATD	70	2014	Port D
[redacted]	Tug 67	ATD	70	2014	Port I
[redacted]	Tug 68	ATD	70	2012	Port H
[redacted]	Tug 69	ATD	70	2012	Port H
[redacted]	Tug 70	ATD	45	1982	Sold
[redacted]	Tug 71	ATD	45	1981	Sold

Table 9.6: The grouping of Sister vessels.

Sister Vessel Code	Name
SIS_JV_001	Tug 13 Tug 14 Tug 18 Tug 20
SIS_JV_002	Tug 15 Tug 16
SIS_JV_003	Tug 34 Tug 36
SIS_JV_004	Tug 17 Tug 19
SIS_JV_005	Tug 21
SIS_JV_006	Tug 30 Tug 37 Tug 41
SIS_JV_007	Tug 54 Tug 56 Tug 63 Tug 64
SIS_JV_008	Tug 25 Tug 26 Tug 27 Tug 57 Tug 60 Tug 61 Tug 62
SIS_JV_009	Tug 6 Tug 7
SIS_JV_010	Tug 45 Tug 49 Tug 50 Tug 65
SIS_JV_011	Tug 58 Tug 55
SIS_JV_012	Tug 23 Tug 24 Tug 28 Tug 31 Tug 32 Tug 33 Tug 35 Tug 39 Tug 40
SIS_JV_013	Tug 5 Tug 9
SIS_JV_014	Tug 29
SIS_JV_015	Tug 1 Tug 4 Tug 66 Tug 67 Tug 68 Tug 69
SIS_JV_016	Tug 53 Tug 59
SIS_JV_017	Tug 11 Tug 38 Tug 48 Tug 51 Tug 52
SIS_JV_018	Tug 22
SIS_JV_019	Tug 42
SIS_JV_020	Tug 46 Tug 47
SIS_JV_021	Tug 2 Tug 45 Tug 12
SIS_JV_022	Tug 12 Tug 43

9.1.3. JV - Asset Maintenance Plan

During this research, JV proposed a new asset management for the tugs of JV. This asset management plan and philosophy is elaborated on using the diagram shown in fig. 9.3. The focus will be on the part concerning criticality and strategy as the others fall outside this research.

The first item to understand is the maintenance philosophy. This philosophy is a result of internal discussions about the maintenance framework and maintenance objective the company aspires to achieve. This philosophy is formulated into five key objectives;

1. Maintain licence to operate
2. Vessel uptime of 350 days per year
3. Vessel maintenance aligned with operating and criticality strategy
4. Vessel budgets managed
5. Goods and services delivered in-time

Objective one is a straight forward one, as it dictates that the vessels should have all required certificates required to operate. This includes all required documentations and licences to operate in the first place. This

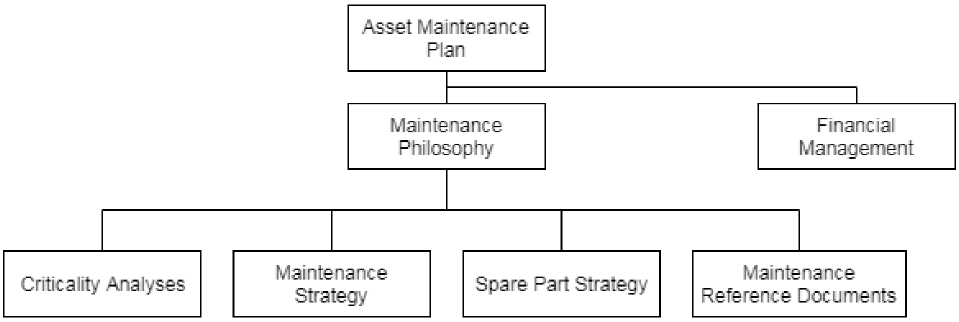


Figure 9.3: Maintenance Plan of JV [Courtesy of JV]

coincides with the conclusions in previous chapter that regulatory bodies are key actors in the operational status of the towage vessels.

The second objective is the goal of achieving a minimum uptime of 350 days per year. This requirement results from internal evaluation of average downtimes and thus uptime of vessels over the years. This objective is adopted as a requirement when evaluating vessel availability throughout its operating year.

Thirdly, is aligning maintenance with operating and criticality strategy. The operating strategy is nothing more than having the right amount of tugs operational at any given time as required by market. The maintenance planning should take into account this demand. The part of the maintenance strategy is based on system criticality. This will be elaborated shortly.

Objective four is managing the budgeting of maintenance costs as good as possible. Currently, the rule of thumb regarding budgeting maintenance costs is, as discussed in chapter 2, Enterprise Performance Management - Boskalis Towage, based on averages per year per asset. Running repair costs are estimated to be around €80K per year and dry docking costing around €200K per dry docking.

The final objective is regarding the delivery of spare parts and services provided in order to repair the tug. The MTTR dictates the total downtime and thus uptime of the vessel. Since achieving the goal of an uptime of 350 days a year is also an objective, this goal directly impact the second objective.

Alongside the maintenance philosophy and objectives that come with it, is financial management. This part concerns itself the budgeting, reporting and other financial aspects to assist the maintenance philosophy and activities that fall within the asset maintenance plan.

Criticality Analyses
The maintenance strategy is based on the criticality of the equipment. Within each tug the different system, equipments and parts are defined. The criticality of each of the different systems, equipment and parts is then defined. It can be assumed that the selection of critical equipment is equal to the adopted system criticality in chapter 3. The four different criticality labels are; ISM critical, Safety critical, Operational critical and Non-critical. ISM critical systems are systems labelled by the ISM code [International Maritime Organisation (IMO), 2018].

Maintenance Strategy
Based on these four areas, the following two maintenance strategies are applied. In the case of an ISM or Safety critical system, the maintenance strategy as suggested by Original Equipment Manufacturer (OEM) is applied. In the case of a non-critical system, the strategy of OEM is applied including additional specific strategies, adopted by JV throughout the years. The type of maintenance policies applied, as addressed in section 4.3.2, are based on vessel age. JV has adopted a policy more focussed on preventive maintenance during the first 5 years of the vessel. Between the ages of 5 and 22.5 years the maintenance policy is more condition based. From the age off 22.5 until 25, the maintenance policy of breakdown maintenance is adopted.

It should be noted that the above stated asset maintenance plan is a recently adopted plan and not yet fully implemented across the company. This is a result of the desire to manage maintenance more effectively and increasing knowledge through acquiring of more data. This implies that current data is lacking in some areas and will be discussed in the next section where a summary of the data is presented which was available and used within the model.

9.2. Maintenance Performance Management Model - Power BI

In order to fully explain the maintenance performance model as is, first the data flow in its entirety is shown in fig. 9.4. The top flow shown the currently built data flow where a static Excel data base has been created. This data is connected within the Microsoft Power BI application and visualised through different Power BI dashboards. Based on these dashboards a report can be formulated related to maintenance for specific tugs, parts of the fleet in certain ports or specific tug types.

It is believed that this data model could be expanded and automated in the future. Resulting from analysis within the dashboard and the following reports, operational adjustments regarding maintenance intervals, allocation of tugs or other decisions can be adjusted using custom program, for example Power Apps. This could then activate or alter specific workflows or workflow activities. These Apps could be structured within Microsoft Flow, for example. This directly adds or changes certain maintenance actions or vessel operations. Results of these changes are then fed back into the dynamic data base and again used for performance evaluation within the Power BI application and dashboards.

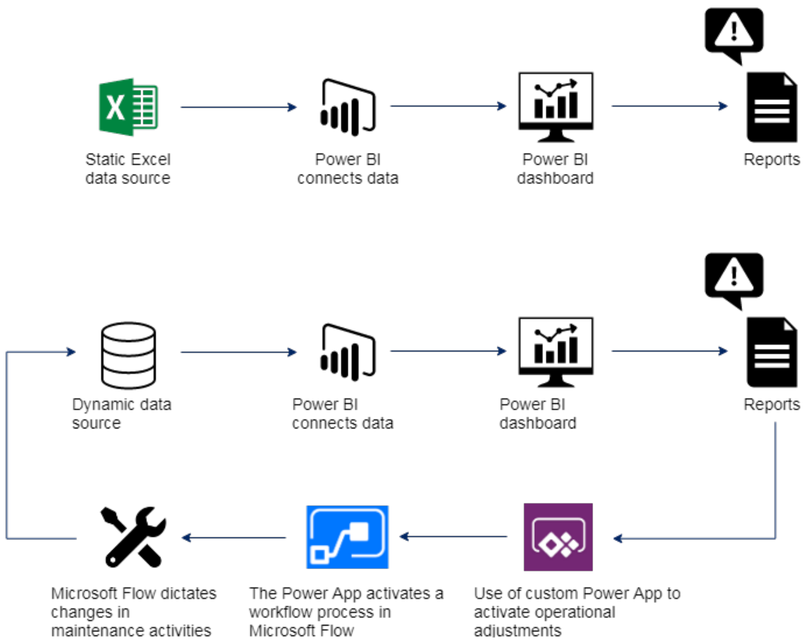


Figure 9.4: Current and Possible future data flows

9.2.1. Data

Now that the general data flow scheme has been presented in fig. 9.4, the next step is to elaborate on the respective data which has been used within the model. The available data, which is used in this research, spans back a maximum of 3 years. This is due to two reasons. The first being that the establishment of the JV joint venture was finalised in the beginning of 2016, resulting in smaller than desired historical database. It would be more favourable to at least cover a full maintenance cycle which is from renewal survey to renewal survey and thus spanning at least 5 years. Unfortunately, this is not the case.

The data within the model has been structured in accordance with the choice of combining operational data, maintenance costs and maintenance activity in the form of time spent on maintenance. Aside from these three areas, the addition of various lookup tables has been introduced which act as unique ID's or are used to transform data. All tables are elaborated below.

Lookup Tables

The first set of data tables are the lookup tables. As earlier stated, these tables include unique ID's and data which are used to filter the operational-, cost- and maintenance activity data respectively. The first table, *'10100 Exchange Rate'*, allows for the transformation of costs to a selected currency. For this model this has been fixed to Euro. However, it is possible to change currencies. The second data table contains data concerning tug specifics, *'10200 MMSI'*. The data included in this table has been shown in appendix E. Thirdly is

Table 9.7: Table data list of Power BI Model

(a) Data list of lookup tables

Table Code	Table Name
10100	Exchange Rate
10200	MMSI
10300	PL Locations
10400	SFI Coding
10500	JV SisterList

(b) Data list of operational tables

Table Code	Table Name
110	Tugmoves
120	Fuel Oil
130	Running Hours

(c) Data list of cost tables

Table Code	Table Name
200	PL Running JV
200	PL DryDocking JV
200	Book Value

(d) Data list of maintenance process tables

Table Code	Table Name
300	RR Time JV
400	DryDocking JV

the table which covers all the operating ports, *'10300 PL Locations'*. The relevant ports have been presented in section 9.1.1. *'10400 SFI Coding'* contains the specific of the adopted SFI System Grouping which has been presented in table 3.3. The final table is a list of Sister Grouping within the fleet, *'JV SisterList'* This table is the equivalent of the table shown in table 9.6.

Concerning the establishing of the lookup tables, a couple of observations and conclusions were made. The *'1200 MMSI'* table was constructed with use of a list with impartial fleet data and no full data list was available. The final list was constructed using external data from online sources. This is a prime example of the current level of data management and warehousing. This statement regarding the current level of data management are shown across multiple data tables.

Operational Tables

The first operational data table, *'110 Tugmove [TM]'*, includes the all maintenance activity of the tugs. For the tugmoves, i.e. assists performed, data is available regarding the date performed, time performed, amount of assists, location, name of the vessels assisted, type of vessel assisted and the customer. Although the data concerning customer data is not used in this research, it has been included to allow for possible customer research. An example is shown in appendix F.

The *'120 Fuel Oil'* table consist of total fuel oil consumed. The reasons for this is due to the inconsistency in data registration. Fuel oil consumption were, for some vessels, directly related to specific equipment, e.q. main engine or auxiliary. However, other consumption registrations only reflected the total refuelled fuel oil. For this reason, it is assumed that registered fuel oil consumption reflects the total amount of consumed fuel oil. A second challenge was that fuel oil consumption was registered in different time frames, ranging from daily, monthly quarterly and yearly. In order to achieve consistency in data across the fleet, data was transformed into portraying monthly consumption of fuel oil.

The same challenges regarding fuel oil were tackled within the running hour data. The same transformation of data was applied in order to portray monthly running hour data across the fleet and therefore stay consistent. This is captured in *'130 Running Hours'*. For hybrid vessels the RHrs of the hybrid system has been taken into account.

Cost Tables

The data tables associating with the costs within the model are divided between costs made for running repairs, *'PL Running JV'*, and dry docking, *'PL DryDocking JV'*. After discussions with the financial controllers within the towage divisions, the yearly book value of the tug was added. This was of interest to the financial controllers as it portrays the vessel depreciation over time. And in contrary to the performance indicator representing maintenance cost versus the Asset Replacement Value (ARV), this includes depreciation of value due to increasing age. Literature does not acknowledge this as a sound way of asset cost evaluation with respect its value. It has therefore been added but is not leading and can be used at the controller's discretion.

There were two major challenges which arose during the gathering and structuring of cost data. The first being that the Boskalis Towage Division did not have access to all maintenance cost data at individual tug level, let alone per equipment or SFI Group Coding. Furthermore, table 9.8 and table 9.9 show the profit and loss statements of the ports of Port E and Port I respectively. It can be seen that large amount of costs are not assigned to specific assets. And in the case of Port I, nothing is labelled to a specific vessel. The reason for the lacking of detailed data is a result of financial consolidation of data where the goal is to end up with a correct profit and loss statement which is to be presented to the shareholders. It is observed that maintenance costs of specific tugs are relocated to a different booking account, i.e. 'other' or 'no asset', leading up to the annual report. This issue should be addressed in the future in order to allow for continuous and accurate monitoring of maintenance costs.

In order to fill in these gaps, specific data was requested from JV directly regarding both running repair costs and dry docking costs. This data was combined in order to complete the cost data base. In hind sight, it would have been better to request the data entirely from the JV database for consistency reasons.

Table 9.8: Running repair costs of Port E split across the individual tugs

	Year				
Tug	2015	2016	2017	2018	**Grand Total**
Tug 11		€ 138,581	€ 62,265		**€ 200,847**
Newbuild No 661		€ 107,514	€ 68,440		**€ 175,955**
Newbuild No 662		€ 112,286	€ 84,292		**€ 196,578**
No asset	€ 836,660				**€ 836,660**
Others		€ 20,352	€ 57,709	€ 684,581	**€ 762,643**
Tug 52		€ 431	€ 3,544		**€ 3,975**
Tug 53		€ 82,426	€ 74,942		**€ 157,368**
Tug 56		€ 5,000			**€ 5,000**
Tug 57		€ 73,925	€ 66,939		**€ 140,865**
Tug 59		€ 123,416	€ 87,517		**€ 210,933**
Tug 60		€ 121,359	€ 82,143		**€ 203,503**
Tug 61		€ 83,820	€ 65,084		**€ 148,905**
Tug 62		€ 85,847	€ 72,933		**€ 158,781**
Tug 64		€ 5,058	€ 3,455		**€ 8,513**
Grand Total	**€ 836,660**	**€ 960,020**	**€ 729,269**	**€ 684,581**	**€ 3,210,532**

Table 9.9: Running repair costs of Port I split across the individual tugs

	Year			
Tug	2016	2017	2018	**Grand Total**
No asset	€ 858,320			**€ 858,320**
Others		€ 561,547	€ 625,429	**€ 1,186,976**
Grand Total	**€ 858,320**	**€ 561,547**	**€ 625,429**	**€ 2,045,297**

The second challenge was the absence of detailed allocation of costs to specific systems. This was available for a number of vessel and not always covering all years. This may be a result of switching between different financial consolidation software. As a result, not all data could be transferred into the new programs.

It is believed that the quality of the data can be increased through the introduction of automated registration systems. Financial IT solutions has developed rapidly over the years and is believed to be a solution in this case. JV is, at the time of this research, improving in this area through increased automation.

Maintenance Time Tables

The maintenance time tables have been split between running repairs and dry docking activity, as shown in fig. 8.6. The static database was built using data sheets of individual tugs where the maintenance time was split into berthing days, dry docking days, running repair hours (no effect on operations) and running repair hours (operational stop). The maintenance times for berthing and dry-docking were joined together to be labelled dry docking. It is assumed that in water maintenance activity performed at a repair yard is equal to a dry docking activity.

Running maintenance activity which resulted in operational stops are easily linked to time spent on corrective maintenance. However, assigning the running repair maintenance time, not effecting operations, to either corrective or preventive was more complicated. Corrective actions may have been take after the observing a failure during a rest period or crew change, or when the vessel wasn't operating. Based on the added notes, assumptions were made on whether the activity performed was either preventive or corrective.

The table of *'400_DryDocking_JV'*, shown in fig. 9.6, concerns itself with the specific dry docking information. As it was decided to handle dry docking activity as an event based action, due to it being closely linked to regulatory activities of Class Societies, the table contains all relevant data, including a unique ID for all dry docking events. This unique ID is a combination of the name of the tug, the year of dry docking and the dry dock number that year. For example, in the case of an emergency dry docking by Tug 14, which is the second in 2017, the unique dry docking ID is: *DD_RAm_1702*. The table further contains data such as start- and end-date, type of dry docking, labelled as 'Intermediate-Survey' (IS), 'In-Water-Survey' (IWS), 'Special-Survey' (SS) and 'Emergency Drydocking' (ED). In the case of damages, e.q. non maintenance and repair related, the dry docking is labelled as 'Damage'. Furthermore, the table contains two SFI Coding columns to portray the major reasons for the dry docking.

From the above discussed data tables, one clear trend can be seen across the board. The data quality is somewhat lacking and needs to be improved in order to perform maintenance analysis with a higher certainty. As earlier suggested, automating the registration of actions may increase data quality on the one had, but still may requires human intervention in order to check the data or elaborate on details. The proposed structure within this research is a preliminary way of structuring both data and dashboards. More professional and dedicated IT companies and solutions could perform these tasks more effectively. The proposed structure can be used as a foundation for the further development.

Furthermore, in order to be able to monitor maintenance from the Boskalis Towage Division, more data should be made available between JV and Boskalis Towage Division which is automatically made available. Currently, data is obtained through individual enquiries which takes time and burdens personnel with additional administrative tasks.

9.2.2. Data Flow Charts

Now that the data tables have been elaborated on, including the information that they contain. The next step is to elaborate on how these data tables are related to each other within the Power BI data model. This will be done by focussing on the two main maintenance activities, running repairs and dry docking. Using the Power BI software, data flow diagrams can be shown to illustrate the different relations between the data tables.

Running Repair Data Flow

The first data flow diagram is shown in fig. 9.5, which shows the running repair dependencies between the different data tables. The main table, situated on the left, contains all tug related data, *'10200_MMSI'*. The *MMSI* of the vessels acts as a unique ID which is used across the other tables. Through the *MMSI* ID this table is linked to all other tables.

The second column of data tables are the so called lookup tables. Aside from a data list containing al date information, this column also includes *'10100_ExchangeRate'*, *'10300_PL_Locations'*, *'10400_SFI_Coding'* and *'10500_JV_SisterList'*. The choice has been made to structure the minimal time domain in months as daily information is considered too detailed. The date table is connected to all relevant data tables as shown in fig. 9.5. As the tugs tend to be re-allocated to different ports during their operational lifetime, it is important to take this into account. The relocation of tugs is covered through the introduction of *'10300_PL_Locations'*. A challenge arose between the operational location of the tugs and the documented running hours. The running hours were largely monthly documented and it so happens that a tug would operate multiple ports within that given month. This made it impossible to determine the amount of running hours the tugs had made within each port. In order to compensate for this the ratio between tugmoves was used to split the running hours between the respective operating ports. It is acknowledged that this is a fix and has an impact on the quality of the results. Nonetheless, it was concluded that assigning the running hours to both operating ports or dividing it equally across both ports weren't viable solutions to tackle this challenge. Therefore,

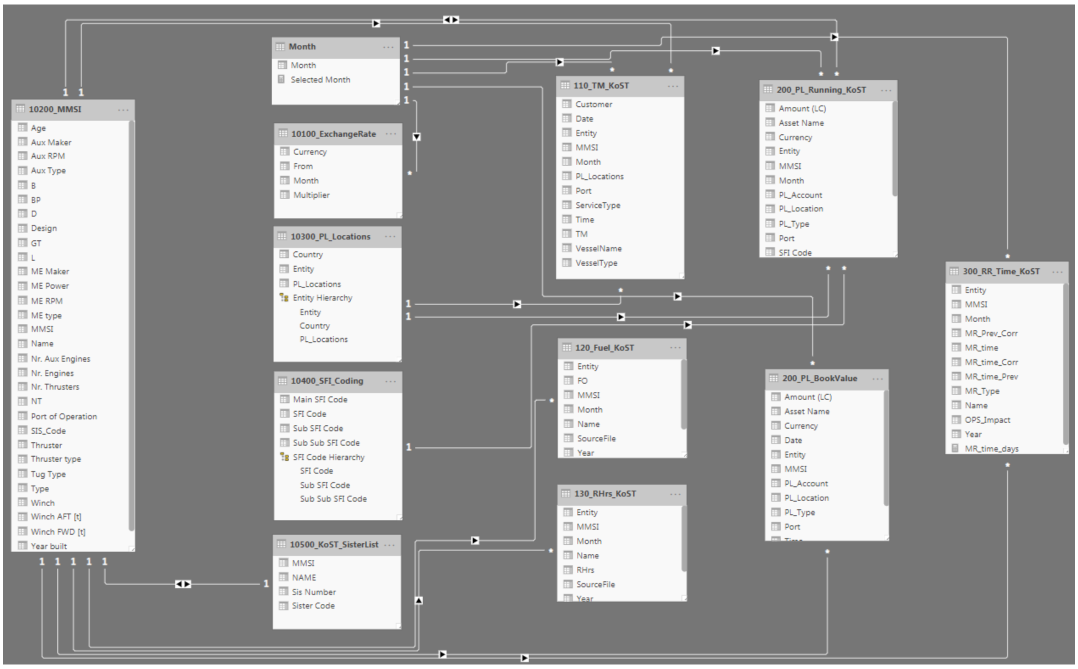


Figure 9.5: Running repair data flow diagram from the Power BI Model.

the choice was made to divide the running hours in accordance with the tugmoves made. The tables of *'10400_SFI_Coding'* and *'10500_JV_SisterList'* are used to be able to evaluate the different equipment costs with each other and compare between different sister vessels.

The middle column of table are all tables concerning the operational data of the tug, including the number of tugmoves, fuel oil consumption and running hours.

The fourth column contains all financial data tables related to the running repair costs of the tugs and the book value of the tug. The Asset Replacement Value (ARV) of the tug is not visualised in this data flow diagram as it is a parameter and a single value used for measurement calculations and not part of the data flow model.

The last table and column is that of the maintenance time spent on running repairs for each tug.

Dry Docking Data Flow

As a result of modelling the dry docking activity as an event, the respective data flow diagram is less elaborate in comparison with the running repair diagram.

On the left-hand side the MMSI table can be seen, which is the same as the table for the running repair diagram. The second column show the relevant tables of dates, PL location, SFI System Coding and the Sister Vessel List.

The operational data, i.e. tugmoves, running hours and fuel oil consumption, are left out of this diagram as they are directly calculated and shown in the *400_DryDocking_JV* table.

The financial tables relevant for this diagram is that of the costs associated with the specific dry docking and the book value. Unfortunately, no data was available on the exact cost allocation to specific equipment. This data was available in individual invoices, however, it was decided not to include all these detailed information as it would have taken considerable amount of time to from this database. It is acknowledged that this does not allow for detailed evaluation of the allocation of costs within dry docking activity. However, the total cost of the dry docking activity in combination with the information in the *400_DryDocking_JV* table, concerning the main reasons for the dry docking, conclusions can be made on what the main cost driver may have been within that specific dry docking. In order to allow for more detailed analyses of cost allocation, it is imperative to collect and store detailed data on these cost allocations.

The last data table on the right, *400_DryDocking_JV*, contains all the data relevant to the dry docking.

9.2.3. User Interface

The following section will present the different user interfaces which have ben constructed within the maintenance performance management model within Microsoft Power BI. Along with figures showing the user

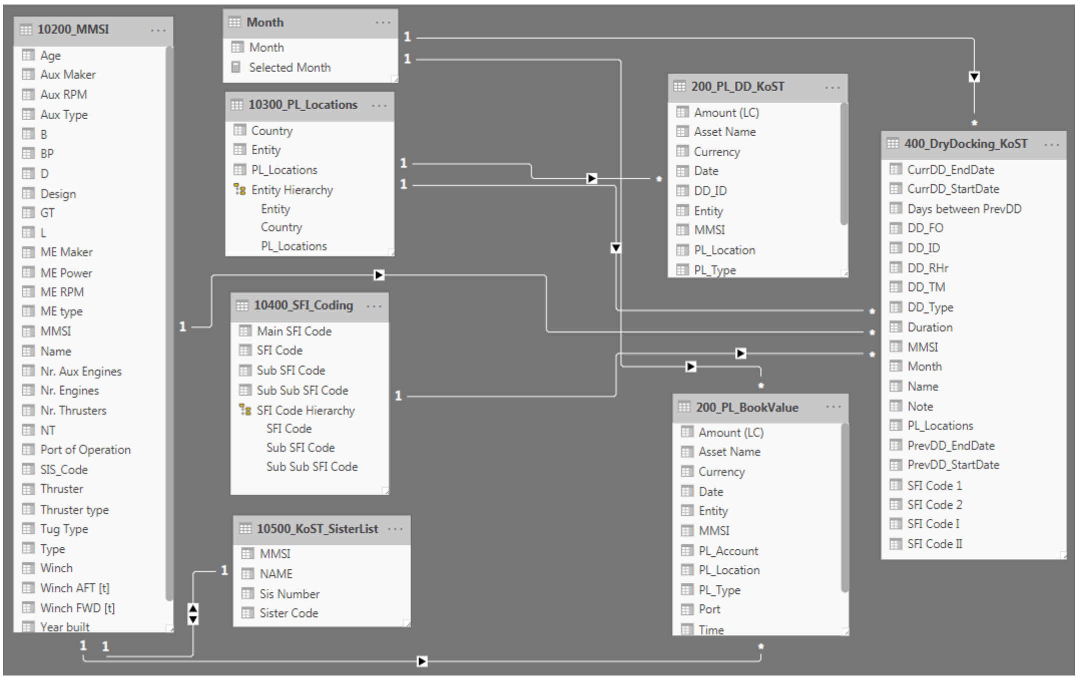


Figure 9.6: Dry Docking data flow diagram from the Power BI Model.

interface, the different visualisation are explained. As aimed in the construction of the model, different interfaces have been made for different levels of the organisation. They will be explained starting from management to operational.

Actual vs Budget

Figure 9.7 shows the initial page within the model. This page shows the budget and actuals of the different repair costs.

On the left top the different accounts can be selected in order to look at specific repair costs. The top graph visually shows the difference between the actual and the budgeted repair costs. Below the graph tables show in detail the different budgeted and actual costs split across the different accounts, countries, ports and tugs. The right table shows the percentile difference between the budgeted and actual amounts.

Management Summary

The second page is the page which is functional for the higher management within the Boskalis Towage Division. This page is designed to give an overview of the total maintenance costs and different maintenance performance indicators and metrics.

The left top hand of the page presents the general overview of the number of vessels, the availability % by month, maintenance costs and the average maintenance costs per year. Below that the average maintenance costs are presented along with the *maintenance RHrs intensity* and *maintenance TM intensity*. In the middle, the year-over-year percentile changes of maintenance costs are presented. These are split between running repairs and dry docking as well as split across the respective countries. The tables on the right side presents the detailed amounts of maintenance costs across the different countries and ports. Additionally, these table show the number of tugs operating in that country and port, and the average maintenance costs. The bottom tables, starting from the left, show the top 10 tugs with the highest average maintenance RHrs intensity indicator, running repair costs and dry docking costs. Additionally, the bottom 10 tugs with the lowest availability percentile are shown. This allows the manager to quickly see underperforming tugs based on these MPIs. The right bottom clustered bar charts shown the top 5 systems which are the cost drivers for running repair and dry docking.

The aim for this interface is for the higher management to be able to view how the different entities are performing, identify yearly changes in maintenance costs, which systems are the cost drivers within mainte-

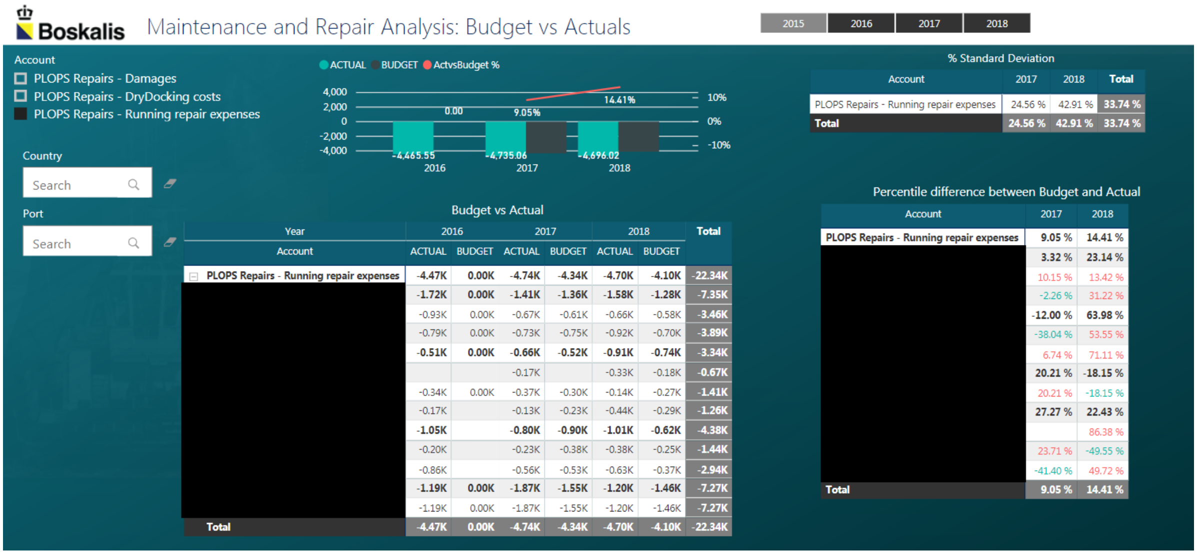


Figure 9.7: Actual vs Budget page in the Power BI performance model

nance and which tugs are performing the worst looking at maintenance cost per running hour, maintenance cost per tugmove, average dry docking cost per year and lowest average availability.

Figure 9.8: Management summary page within the Power BI management model

Fleet

Figure 9.9 shows the third page within the Power BI model is that showing the entire fleet. This page consists of filters allowing for selection of a specific port and tug type. A large table shows all critical information which is needed to be able to evaluate the tugs from an abstract level. Included is critical information such as the average and ratios of running repair- and dry docking costs, total maintenance cost per running hour, maintenance cost as percentile of the Asset Replacement Value (ARV) and availability percentage. Coloured data-bars and colour gradients are used to highlight differences among the tugs.

Besides the table and filters, this page also shows a graph with the average running repair costs and dry docking costs by age. This is presented in order to show how and if running repair costs are noticeably higher with increasing age and dry docking to be larger around important ages where specific surveys occur.

In addition, three graphs have been added which use the 'Tukey's method' to identify outliers within the dataset. Tukey's method for finding outliers is based on the quartiles of the data. The interquartile range (IQR) is the range between quartile 1 (Q1) and quartile 3 (Q3). Assuming a IQR of 1.5 means that the values are identified as outliers if they are more than 1.5 times the interquartile range from the quartiles [Statistics & Data Science, Carnegie Mellon Unviversity, 2013]. A commonly used value for IQR is 1.5 which as also been used within these graphs. The three graphs represent the total maintenance cost, running repair costs and dry docking costs vs independent variables; running hours, age and bollard pull.

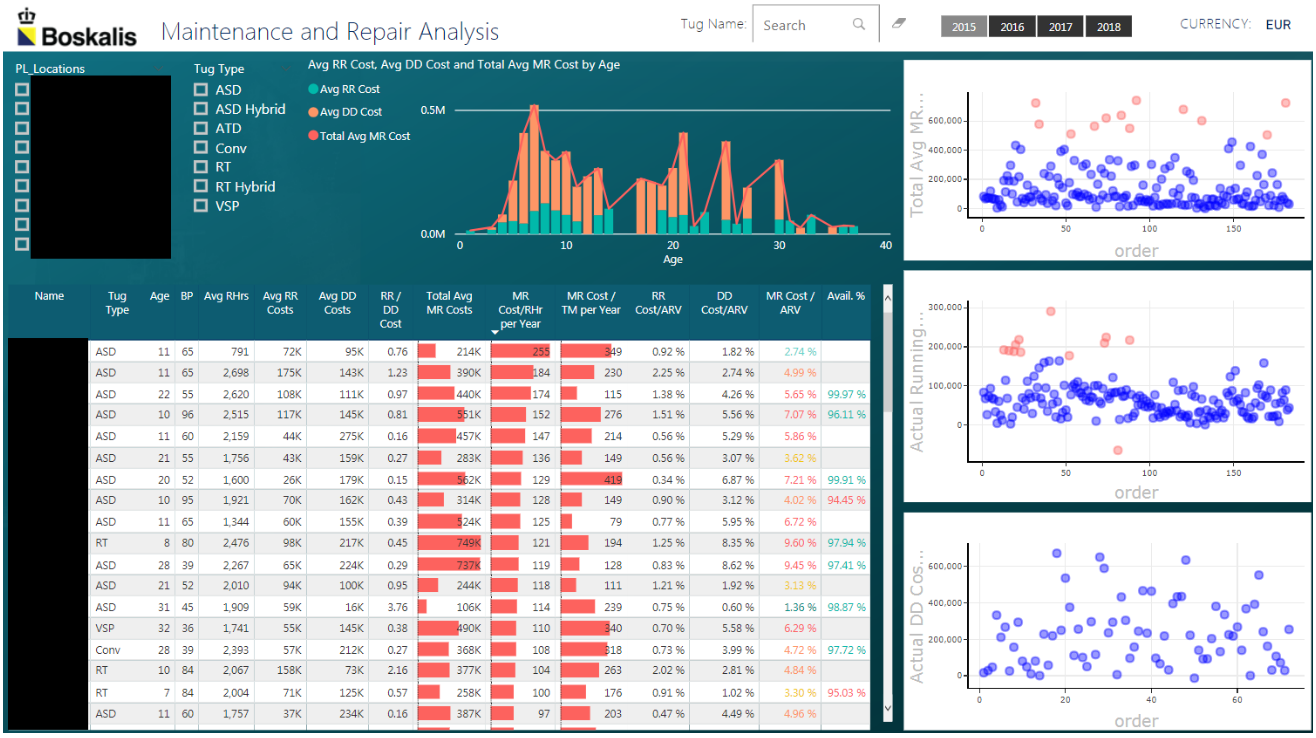


Figure 9.9: Fleet summary page within the Power BI management model

Running Repair

The following part, concerning itself with in-depth detailing of running repair data, consisting of two pages. The first being a page which focusses on the running repair costs across the different operating ports. The second focusses on the running repair costs across the different tug types. These respective pages are shown in fig. 9.10 and fig. 9.11. These two pages are constructed for the tactical and operational level.

Figure 9.10 shows the running repair costs across the different operating ports, i.e. PL Location. In the top left the total running repair costs are shown including the average running repair cost per tug per year and how these costs are slip across the different ports. An additional graph shows the top 10 tugs with the highest average running repair cost.

A timeline of the running repair costs, including the maintenance performance indicators; cost per running hour and tugmoves are shown. In order to illustrate the ratio between running repair cost and the total maintenance cost, the costs for dry docking have been added in this visualisation.

The lower left of the page show the most important details for each port, including the total amount of running hours and tugmoves performed in that location. The table also shows the percentile of preventive maintenance time is performed within the port. The data concerning maintenance times is minimal and deemed not complete enough for effective evaluation. It is however included here to illustrate the use and added value.

Furthermore, a table presenting the running hours per tugmove and fuel oil consumption per tugmove hour have been added. It is decided that these are of interest as these indicators reflect operational conditions within each location. Ports with larger water area and thus having longer towage assists generally have a higher running per tugmove. The indicator showing the fuel oil per tugmove is an additional indicator of interest as it is related to the operational load. It is acknowledged that specific fuel consumption of tugs also impact the fuel per running hour and thus these values are not solely dictated by type of towage operation, e.q. berthing or escorting.

The right side of the page shows a table showing the different tugs, grouped by sister code. The tows the performance indicators for each individual tug. This setup allows for filtering of both port location and of sister vessels. The top right shows the Tukey's graph which can be used to quickly identifying running repair cost outliers.

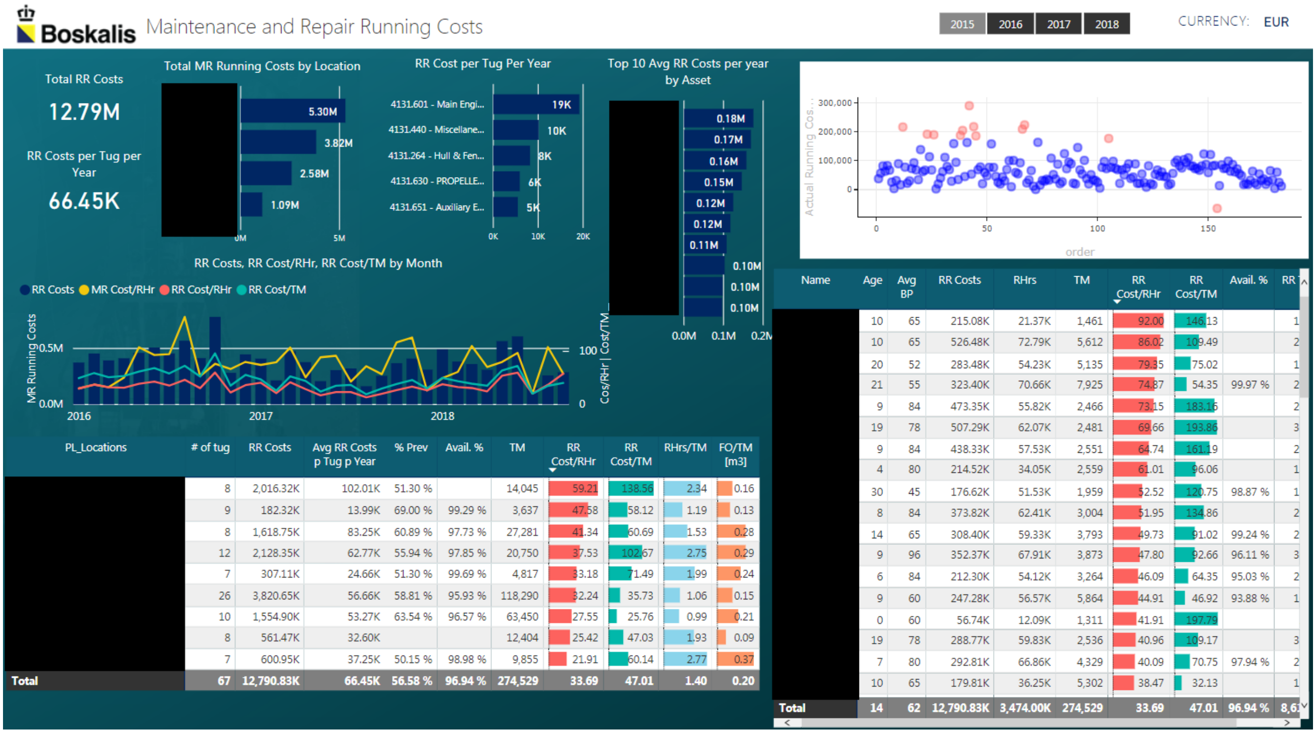


Figure 9.10: Running repairs across ports (Power BI management model)

The second page concerning running repair, is that which relates the running repair costs and process with the different tug types. The goal of this page is to gain knowledge on differences and variations between the different tug types.

The page starts of with a table with a summary of the different tug types, the number of tugs, maintenance process metrics and other performance indicators. On the left side of the page the different tugs can be filtered to the users liking. The right side of the page shows the fleet with their respective performance indicators, but this time they are grouped by tug type and can be expanded accordingly.

The middle of the page show the different indicators in a decreasing bar chart style to show the drivers among the different tug types. The middle graph is a more informative one as it compares the average running repair cost for each individual tug with the average of their respective sister group and their tug type group. This shows whether individual tugs deviate from the averages of the sister group of tug type. Additionally, a table is supplied to show the trend and variation in running repair cost per running hour for each tug type.

The right bottom shows two bar chart graphs which present the top five average running repair costs per tug per year for different systems as well as maintenance time split in preventive and corrective.

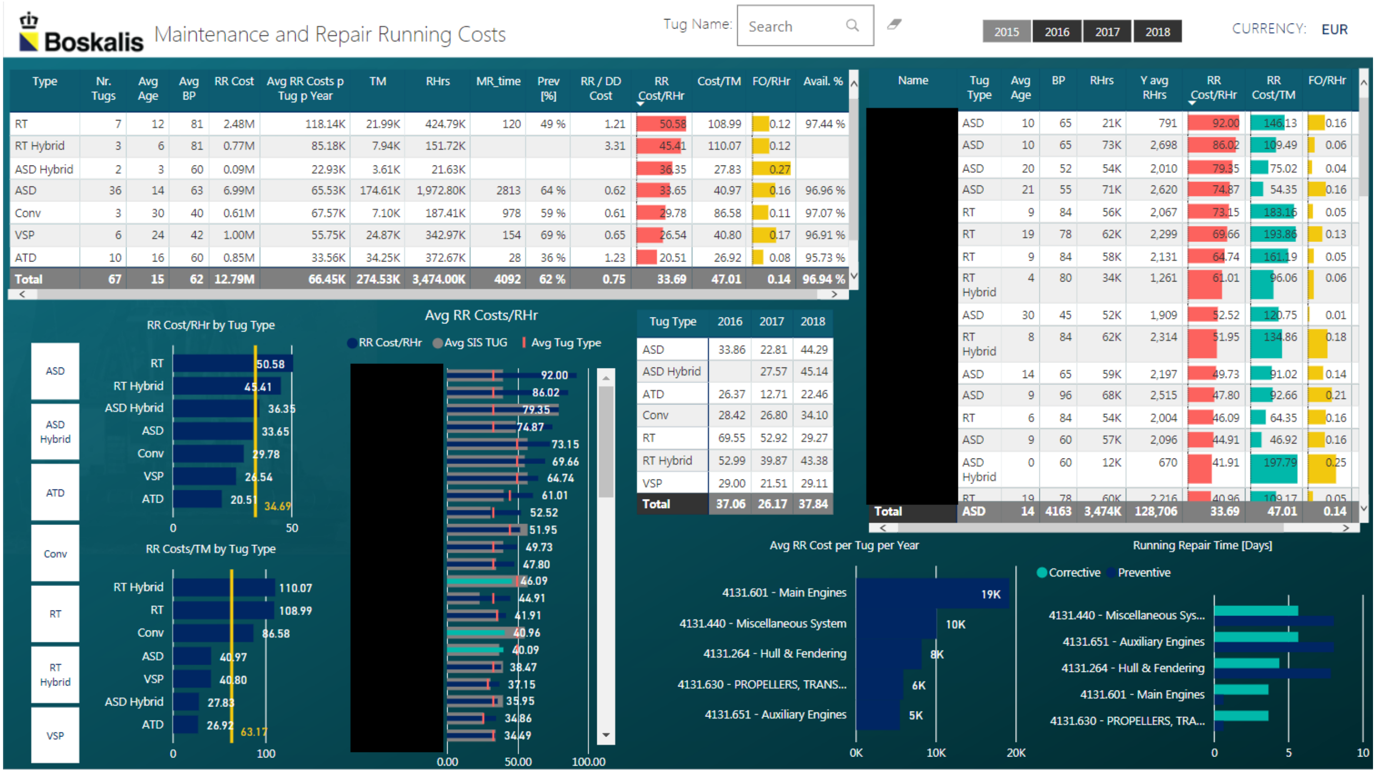


Figure 9.11: Running repairs across tug types (Power BI management model)

Ship Detail

The following tab allows for ship specific evaluation. This tab is designed for the tactical and operational level. It has been constructed so that detailed evaluation of maintenance cost and process.

On the left hand side all important characteristics of the vessel are presented, including an illustrative image which is a general image based on the vessels type. In the top middle, a timeline is shown with the running repair costs and dry docking costs. Below the graph, a table is situated showing the detailed information concerning operational data of the tug and the performance indicators. This can be expanded to show all relevant data split out over operated ports.

One level lower, the process related indicators are shown, if known. This table shows the number of preventive and corrective actions, percentile of preventive work, total downtime and availability percentage. Next to this table the top 5 SFI Grouping System are shown based on running repair costs. If detailed data concerning the cost distribution over the different system was available a same table could be made for each tug specific dry docking action. Instead, the bottom table shows an overview of all dry dockings the tug has had, including; dry docking type, costs, location, start date, duration and the main reason for the performed dry docking portrayed by the SFI Codes. Notes obtained showing extended information concerning each dry docking is shown in the last column.

On the right side, two performance indicators for the selected tug are compared with the average of the same tug type and sister vessels. The variation in percentage is presented, including two graphs illustrating the trend over the time period. Below the trend line, two visualisation are shown which present the selected tug and its sister vessels. Included is also a line showing the tug type average.

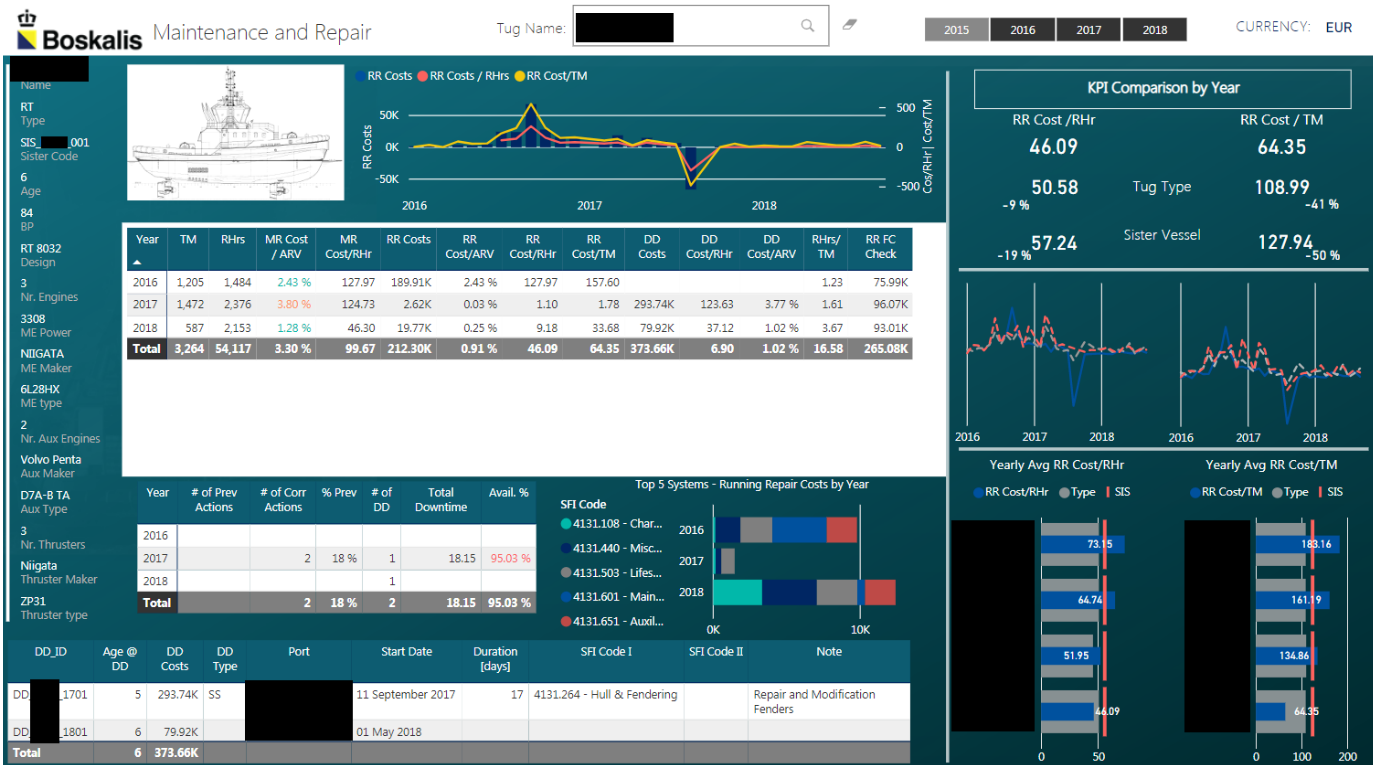


Figure 9.12: Detailed ship tab within the Power BI management model

Dry Docking

Figure 9.13 shows the first of two tabs which presents the data concerning dry docking data across the different ports. This tab shows average dry docking costs per dry docking and per tug per year across the different ports. The total yearly costs are shown in the table in the right top of the tab. The middle row of the tab illustrate the timeline of dry docking activity and total cost, which helps to visualise whether the costs in certain periods increased compared to the costs made. The middle visualisation shown the number of dry dockings for each type by port. Furthermore, it also shows the average yearly cost per tug and dry docking across the different tug types, including the average duration of the dry docking. The bottom shows all detailed information concerning the individual dry dockings which make up the visualisations at the top part of the tab.

The second page on dry docking, concerns itself with the different types of dry dockings and their duration, as defined in chapter 8. The left side shows the average costs between the different dry docking types and their average yearly cost per tug. This data is also split across the different tug types in the visualisation next to it. The right side displays a table with relevant information. The second row focusses itself on the duration of dry dockings, which are split across different dry docking types and tug types. A violin chart shows the distribution of the dry docking data and includes various information concerning the data; including mean and standard deviation. The large right table on the right shows all individual dry docking data. A graph at the bottom illustrates the average dry docking cost and duration by vessel age.

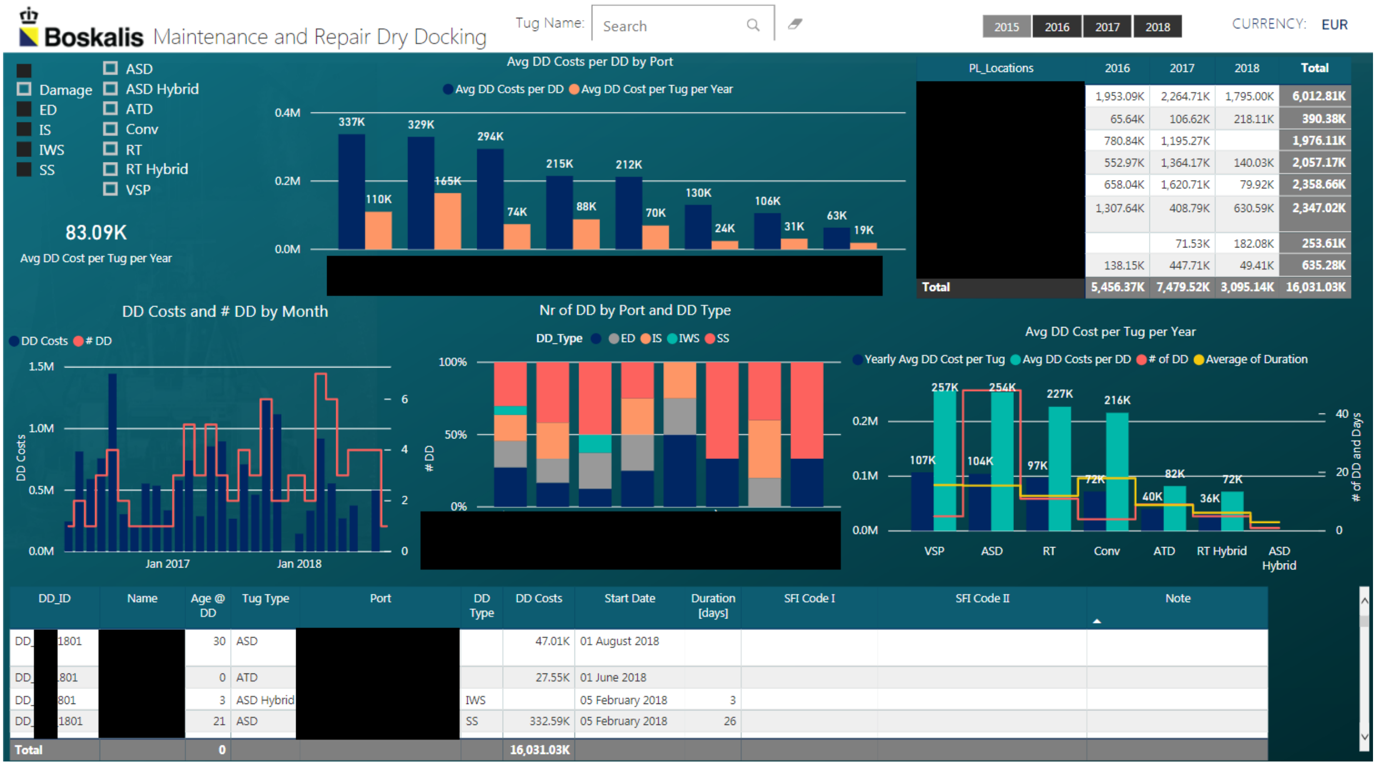


Figure 9.13: Dry Docking tab 1 (Power BI management model)

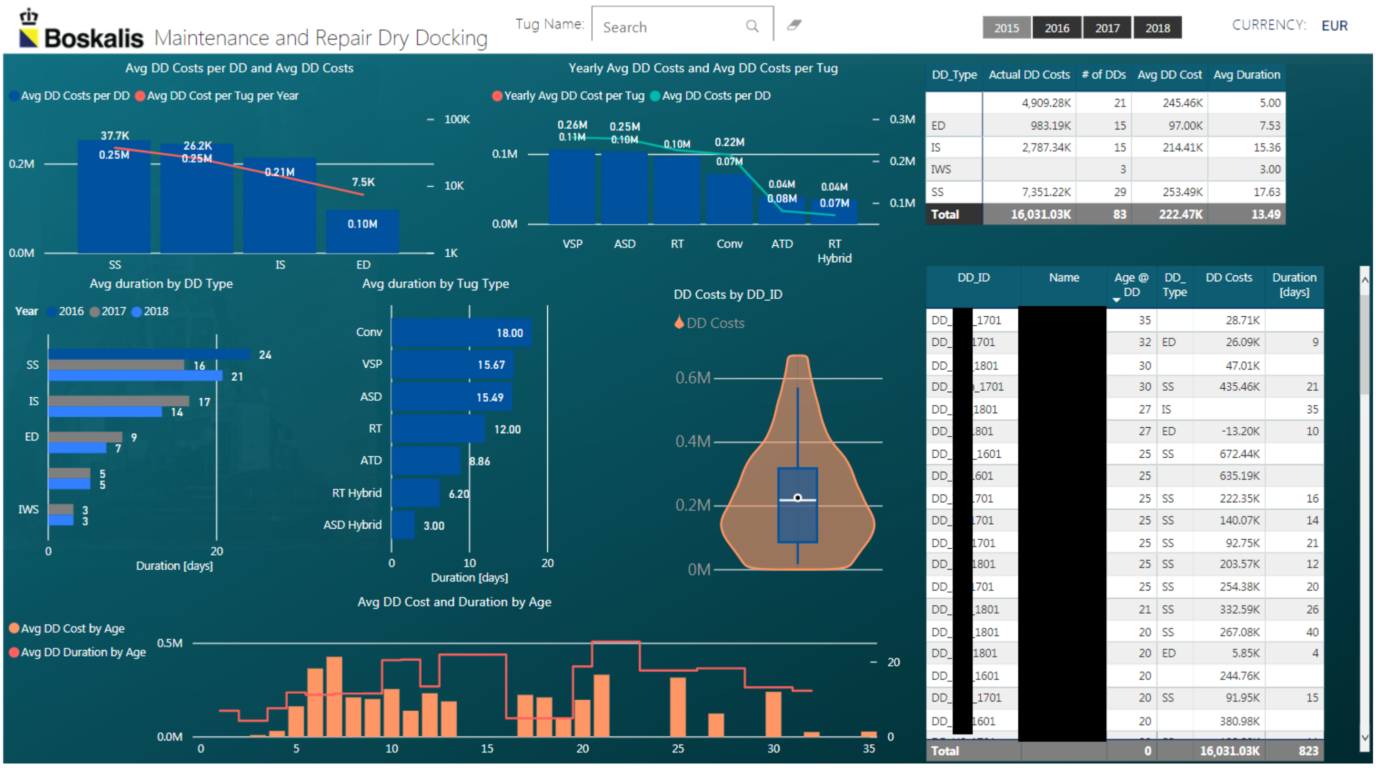


Figure 9.14: Dry Docking tab 2 (Power BI management model).

Equipment
The last two tabs present data at equipment level. This information has been split between running repair and dry docking.

The first tab (fig. 9.15) shows crucial information for the different system components, based on the SFI Group Coding structure. On the left-hand side it shows the average running repair costs per tug per year for each system. The middle two bar charts visualise the highest average cost across different system types and makers. This can be altered to the users liking to reflect main engines, auxiliary engines, thrusters, etc. This tab further shows the top five systems based on percentage of grand total cost and the top five systems based on percentage of grand total running maintenance time. The table below shows all relevant data concerning the installed equipment within individual tugs.

The second tab (fig. 9.16) shows the same information as for running repair, but shows this for the dry docking data. The layout is identical.

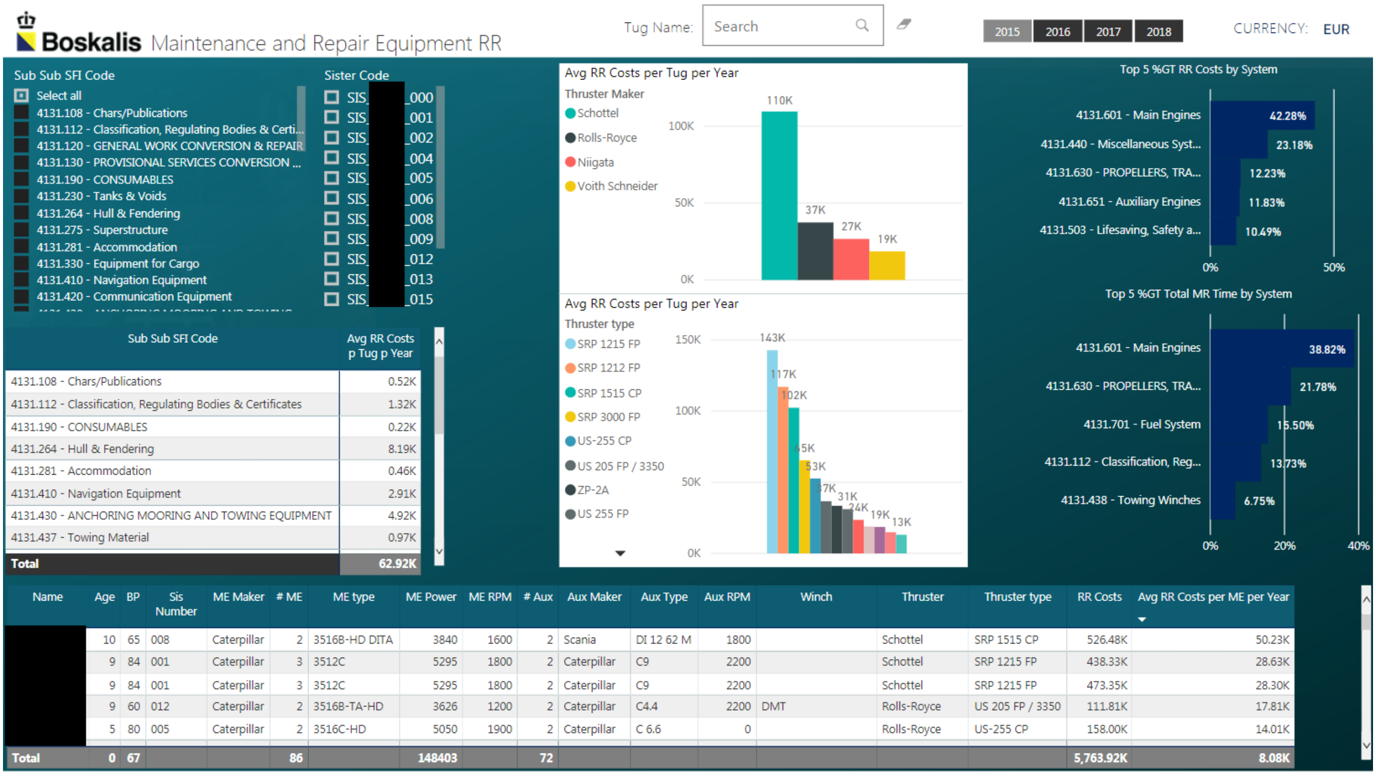


Figure 9.15: Detailed equipment evaluation of running repairs (Power BI management model)

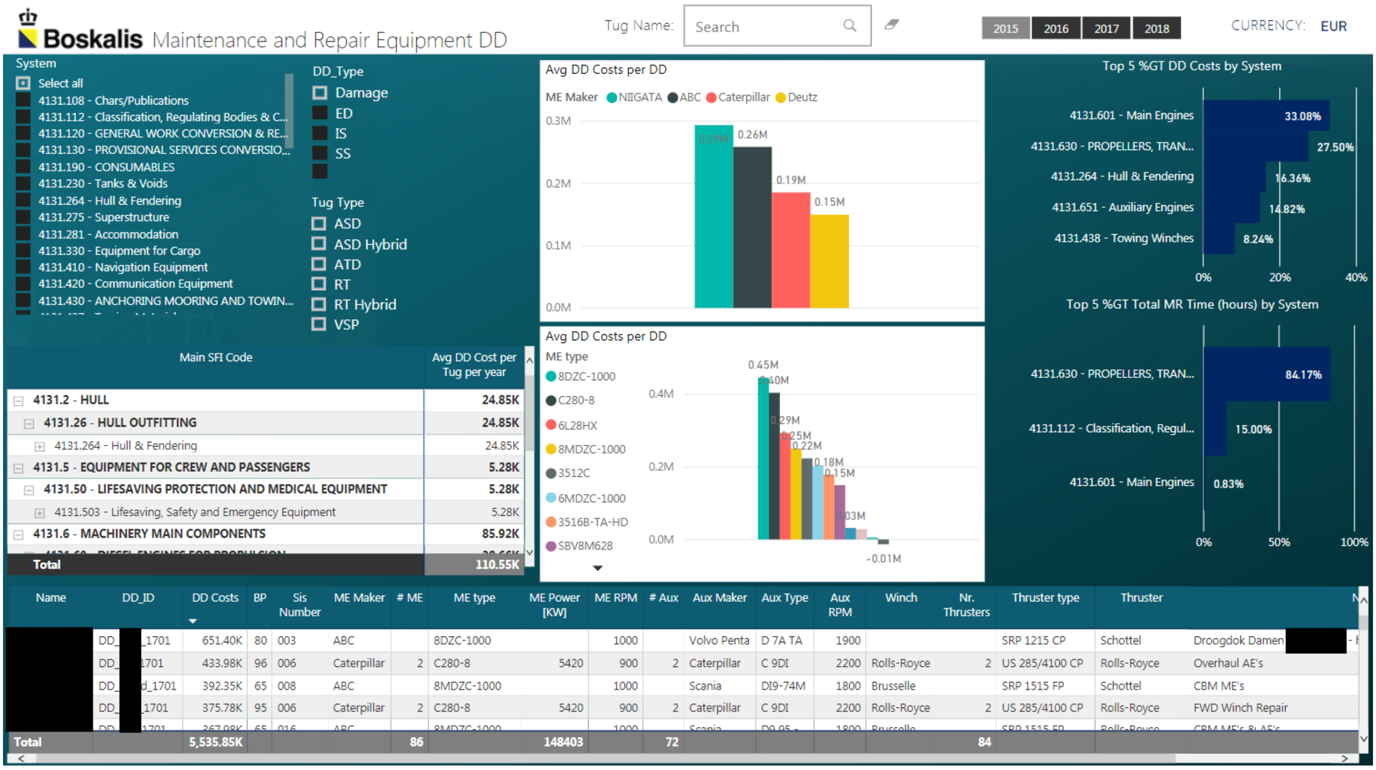


Figure 9.16: Detailed equipment evaluation of dry docking (Power BI management model)

9.3. Intermediate Conclusions Chapter 9

Based on the model framework, this chapter has presented the constructed maintenance performance model in Power BI, including; scope, data flow and data structuring, and the different user interfaces. The scope of the construction of the model was done using data of the fleet of JV because relation and communication between Boskalis Towage and JV is considered outstanding. This allows for easy obtaining of data and expertise.

From the acquired maintenance data of JV, a data and data list was established of all relevant information. The list of data tables was presented in table 9.7. The tables have been grouping into four main groups; *lookup tables*, *operational tables*, *cost tables* and *maintenance process tables*.

Issues regarding data quality have been discussed in the areas of fleet data. Moreover, financial consolidation of data within Boskalis Towage have lead to the merger to two data sets, one from Boskalis Towage and one from JV. In hindsight, it would have been better to acquire the entire dataset from JV as the one of Boskalis Towage showed consolidation and no maintenance costs allocated to specific tugs, as shown in table 9.8.

Additional challenges throughout the construction of the model was determining the fuel oil consumed and running hours operated of a specific tug within a specific port. These data variables have been registered monthly for each vessel. Vessels operating multiple ports didn't allow for correct allocation of running hours and fuel oil consumption within respective ports. In order to overcome this a correction was applied based on the about of tugmoves performed within that port. This is a temporary solution and it is therefore advised to start labelling running hours and fuel oil consumption within a respective ports.

Moreover, through the construction of the model it has been found that the quality of data concerning maintenance process; failure frequency, maintenance time, whether corrective or preventive, is low. In order to be able make conclusions with a higher certainty, it is advised implement a method for the registration of such data. Ideally, this should be automated to some extent.

Construction of a simple and user-friendly user interface in which critical and relative information can be found for respective users was found to be a challenge. It is believed that a professional organisation or individual with experience in the construction of user-friendly reporting tools may present a different setup of the maintenance performance model. However, the presented user interfaces holds all important data and is therefore found to be usable as a preliminary version of the maintenance performance model.

V
Maintenance and Repair Performance Management Analysis

10

Maintenance Performance Analysis

In this chapter, the results are presented of the benchmarking of maintenance using the maintenance performance management tool, as presented in previous chapter. With use of the model, a number of topics are addressed and presented. First off, using the model capabilities, a regression analysis is performed on the different variables. The primary reason for this is to get a better understanding of the relation between the different variables. Secondly, it is of interest to see if there are any correlations between tugs specifications and the resulting maintenance cost. Thirdly, the correlation plots can be used to identify the technology assumption used in the DEA analysis. In addition, a stepwise regression is performed to see whether an equation can be formulated to describe the maintenance costs. Finally, the analysis will determine which performance indicator should be assumed leading in order to discriminate between the different tugs and select five vessels for validation.

Following the regression analysis, section 10.2 presents the results and general conclusions which are distilled from the data using the maintenance performance management model. These conclusions made are related to maintenance performed across the fleet in general, port specific, tug type specific, ship specific and equipment related. As a result, five vessels are selected for validation. The individual conclusions of the five selected vessels and whether the conclusions align with knowledgable bodies within JV, are presented in section 10.3.

Section 10.4 elaborates on the results of the DEA analysis. The result are presented including a discussion on how they relate to the results found in the model. Like in section 10.2 and decided in chapter 6, the focus of the DEA configurations will be on fleet, port, tug type and sister vessels.

10.1. Linear Regression Analysis

10.1.1. Simple Linear Regression of maintenance costs and operational variables

The first step in regression analyses is to plot the variables in order to see whether there are directly visible correlations between the data variables. Figure 10.1 shows the relationship between the different operational variables, i.e. tugmoves, running hours and fuel oil, and the maintenances cost for both running repairs and dry docking. Data concerning maintenance process/time was not included due to the low data quality. Figure 10.1 shows some correlations between the different variables. The coefficient of correlation 'R' is presented in the graphs showing the data points. The coefficient of correlation is the degree of relationship between the two variables. The 'R^2', also known as the coefficient of determination, is shown on the left-hand side of the matrix. This shows the percentage variation in y which is explained by the x variable.

First off, there is a positive correlation between the fuel oil consumed and running hours. This is obvious as being able to operate the vessel requires the consumption of fuel oil. The relation between these two are not entirely linear as the amount of fuel consumed is dependent on the installed equipment and also a function the operational load [Woud and Stapersma, 2002].

A more important conclusion which can be made using fig. 10.1 is that there is no strong linear correlation between the different operational variables and the maintenance costs. It is interesting to see that the highest correlation coefficient and coefficient of determination are found between the fuel oil consumption and the maintenance cost. The reason behind this may be due to that the fuel oil consumption is a function of both the hours spent operating and the operational load during operations. As higher operational loads may result in larger amounts of maintenance costs, the fuel oil consumption may portray a better relation with the maintenance cost. However, the coefficients are not conclusive enough to determine the main drivers of maintenance costs.

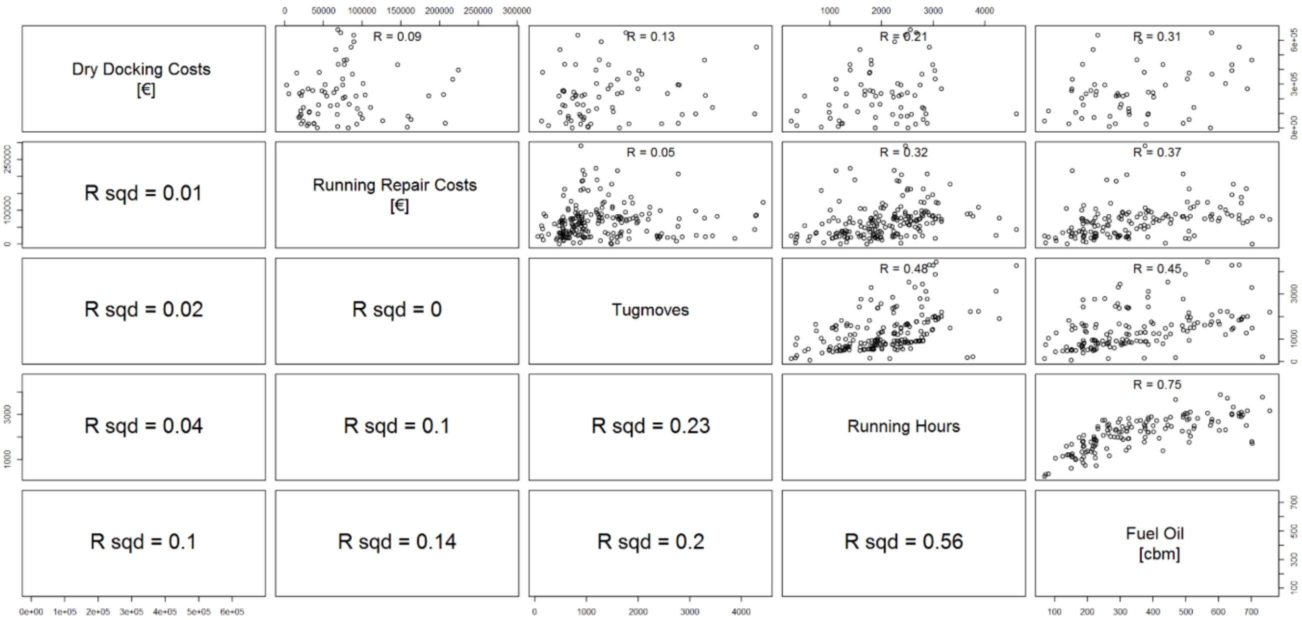


Figure 10.1: Correlation plots between maintenance cost and operational data.

10.1.2. Stepwise Regression in R of maintenance cost and operational variables

In order to get a better understanding of the relation between the different variables and see whether combining these variables will increase the performance modelling of the maintenance costs, two stepwise linear regression analyses are performed; one for the running costs and one for the dry docking costs. Stepwise linear regression is a method of regressing multiple variables while simultaneously removing variables which aren't important [Kassambara, 2019, University of Leeds, 2019]. This method help with the selection of variables in the data set which results in model with the lowest prediction error. In this application the aim is to use stepwise linear regression to identify which variables correlate with the maintenance costs. For this regression analysis, the open source program R is used as it is allows for quick regression analysis through use of available packages.

The code which has been used to produce the stepwise regression results presented below, can be found in appendix G. The results from the stepwise regression in R have been divided into a model which describes the running repair- and the dry docking costs.

Running Repair

The first output table from the R script is shown in fig. 10.2a. This table shows the metrics and their standard deviation for the comparison between the different model configurations. *nvmax* refers to the number of variables in the model. nvmax = 2 specify the best 2-variable model. The *Root Mean Squared Error (RMSE)* and *Mean Absolute Error (MAE)* are two metrics which measure the predicted error of each model. The lower the RMSE and MAE, the better the model. The *Rsquared* indicates the correlation between the observed values and the values predicted by the model. The larger the value of Rsquared, the better the model.

In this case, it can be seen that the RMSE and MAE are both lower for the model with three variables. Additionally, the Rsquared is also higher, 0.25. Meaning that the model with three variables performs better. Figure 10.2b shows which variables are best performing in the model. Since there are a maxima of three variables, tugmoves, running hours and fuel oil are all within the best model. An asterisk specifies that a given variable is included in the corresponding model.

Figure 10.2: Output summary of stepwise regression analysis on running repairs .

```
# Model Accuracy
step.model$results
```

```
##   nvmax     RMSE  Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1     1 44594.89 0.1785642 32803.07 17208.78  0.1722874 9257.896
## 2     2 44087.96 0.2209847 32865.37 17326.96  0.1538266 9031.086
## 3     3 43599.91 0.2453890 32245.20 17619.68  0.1938052 9356.414
```

(a) Output summary of best performing models with different number of variables.

```
# Summary of the model
summary(step.model$finalModel)
```

```
## Subset selection object
## 3 Variables  (and intercept)
##      Forced in Forced out
## TM       FALSE      FALSE
## RHrs     FALSE      FALSE
## FO       FALSE      FALSE
## 1 subsets of each size up to 3
## Selection Algorithm: 'sequential replacement'
##          TM  RHrs FO
## 1  ( 1 ) " " "*"  " "
## 2  ( 1 ) "*" "*"  " "
## 3  ( 1 ) "*" "*"  "*"
```

(b) Output summary of selected variables for each best performing model.

Resulting from the results presented above, we can evaluate the different regression coefficients for the respective variables. These are presented in fig. 10.3a. It is surprising to see that the number of tugmoves are negatively correlated with the running repair costs. This can be attributed to large running repair activities which take much time and result in large costs, resulting in a decreased number of tugmoves.

Figure 10.3b shows the different coefficients and how they relate to each other within the model. The signif. codes elaborate on the significant p-value. The p-value relates to the probability of observing any value equal or larger than t. A small p-value means that it is unlikely that the relationship between the predictor and response value is due to chance. A typical cut-off point for p-value is 5% [Rego, 2019]. The p-value of RHrs, 0.0216, indicates that we can conclude that there is a stronger relationship between running hours and running maintenance in comparison with the other variables.

It is interesting to note the negative coefficient related to tugmoves. This may be due to the relationship between running hours, tugmoves and maintenance performed. Due to a large amount of maintenance hours and work, maintenance cost is increased and also the available hours reduced which may reduce number of tugmoves. However, this also is the case with running hours. The effect these have on each other could have reflected in the data and result in a relative small negative coefficient.

With this knowledge, it can be concluded that the indicator maintenance RHr intensity is a more favourable indicator to use than maintenance TM intensity.

```
# Compute model
lm(RR~ TM + RHrs + FO, data = RR)
```

```
##
## Call:
## lm(formula = RR ~ TM + RHrs + FO, data = RR)
##
## Coefficients:
## (Intercept)           TM          RHrs            FO
##    20903.47        -8.73         18.60         53.00
```

(a) Regression coefficients of the best performing model describing the running repair costs.

```
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 20903.470  12210.567   1.712   0.0892 .
## TM             -8.730      4.927  -1.772   0.0786 .
## RHrs           18.600      8.001   2.325   0.0216 *
## FO             53.002     35.421   1.496   0.1368
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

(b) Summary of coefficients of the best performing model describing running repair costs.

Figure 10.3: Output regression coefficients for running repairs.

Dry Docking

Figure 10.4 shows the output summary of the models with different numbers of variables.The RMSE and MAE show that the model containing three variables is the most favourable in accurately calculating dry docking costs, which are tugmoves, running hours and fuel oil.

```
# Model Accuracy
DD.model$results

##   nvmax     RMSE  Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1     1 175406.0 0.2960345 142127.3 62766.24  0.3679292 49097.38
## 2     2 181496.6 0.1363544 149078.0 59639.66  0.1630828 44344.11
## 3     3 174970.0 0.3158136 141251.7 67309.52  0.3430221 45426.04
# Summary of the model
summary(DD.model$finalModel)

## Subset selection object
## 3 Variables  (and intercept)
##      Forced in Forced out
## TM       FALSE      FALSE
## RHrs     FALSE      FALSE
## FO       FALSE      FALSE
## 1 subsets of each size up to 3
## Selection Algorithm: 'sequential replacement'
##          TM  RHrs FO
## 1  ( 1 ) " " " "  "*"
## 2  ( 1 ) "*" "*"  " "
## 3  ( 1 ) "*" "*"  "*"
```

Figure 10.4: Output summary of best dry docking models with different number of variables.

Figure 10.5 shows the resulting coefficients for the model describing the dry docking costs. The coefficient for running hours is found to be negative. This, like the tugmoves in the running repair analysis, could be due to the reason that large dry docking operations with large costs will result in a smaller possible amount of running hours. The standard deviation of the running hours is of such magnitude that the coefficient could be also positive. The resulting p-values don't give further confidence in the model as all values are larger than 5%, suggesting that there is no real statistical significant relationship between the different variables and the dry docking costs.

These conclusions question whether these resulting models are reliable enough to hold in predicting the maintenance costs for both running repairs and dry docking costs. It has therefore been concluded that the resulting models don't portray the required confidence levels to be deemed usable. However, the outputs of the running repair analysis do show that the relationship between running hours and running repairs are larger than the other variables. Therefore, it can be concluded that the indicators concerning itself with the maintenance costs holds for running repair costs, but not so much for the dry docking costs. The next step is to evaluate whether introducing vessel characteristics may improve the model.

```
# Coeff of best model
coef(DD.model$finalModel,3)

##  (Intercept)           TM         RHrs           FO
## 168497.68947     16.90876     -4.96442     69.18017
```

(a) Regression coefficients of the best performing model describing the dry docking costs.

```
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept) 168497.689  85533.115   1.970   0.0539 .
## TM              16.909     16.264   1.040   0.3031
## RHrs            -4.964     12.635  -0.393   0.6959
## FO              69.180     47.385   1.460   0.1500
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

(b) Summary of coefficients of the best performing model describing dry docking costs.

Figure 10.5: Output regression coefficients.

10.1.3. Stepwise Regression in R between maintenance costs, operating variables and vessel characteristics

For the second step of stepwise regression, the following vessel characteristics have been introduced into the stepwise regression code in R; age, bollard pull, installed power, main engine rpm. The choice for these are based on the findings of Kavussanos et al. [2004], which concluded that age and installed equipment are related to maintenance cost. Correlation plots between the maintenance costs and the vessel specifics are shown in fig. 10.6. The full R code can be found in appendix H.

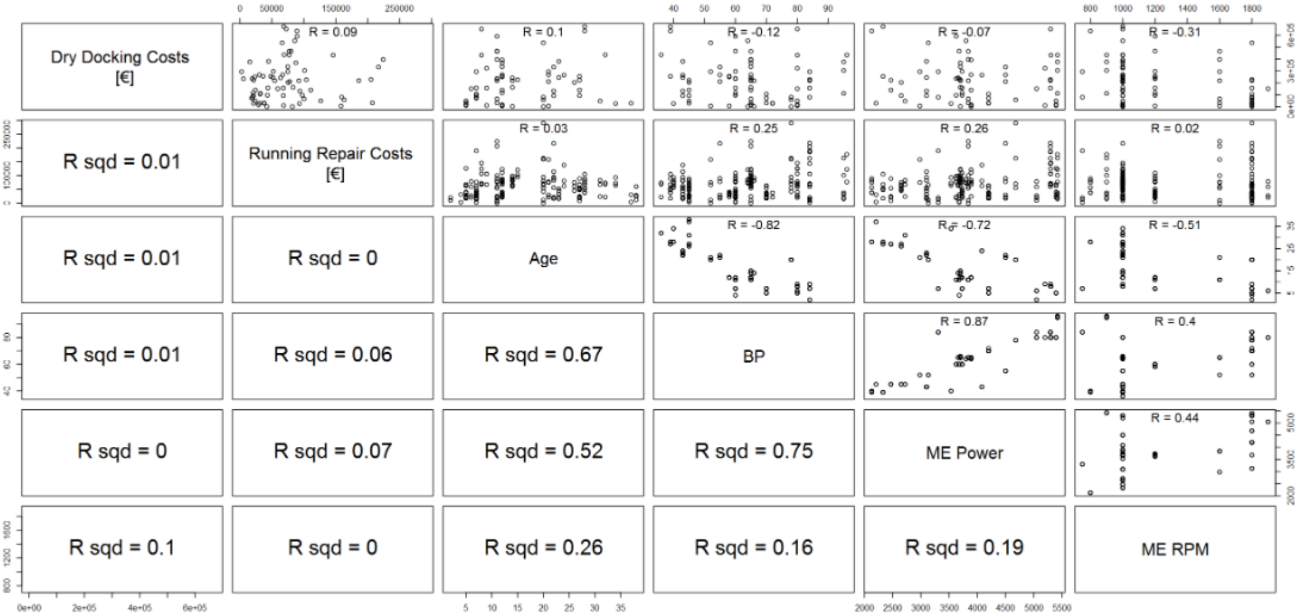


Figure 10.6: Correlation plot showing the most significant correlations between maintenance cost and vessel characteristics.

Running Repair

Figure 10.7a shows the output of the stepwise regression analysis using the variables of running maintenance cost, running hours, age, bollard pull, main engine power, main engine rpm. It can be found in fig. 10.7a and fig. 10.7b that the RMSE and MAE are smallest when all variables are included in the model. The multiple R squared and the adjusted R squared of the model are 0.24 and 0.21, respectively.

Figure 10.7: Summary of stepwise regression analysis on running repairs costs and operational variables and vessel characteristics.

```
# Model Accuracy
step.model$results

##   nvmax     RMSE   Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1     1 51345.24 0.02097146 38984.89 7644.838 0.01387145 4397.449
## 2     2 49103.53 0.09701698 35208.34 7432.340 0.07361030 4024.514
## 3     3 47507.34 0.16352173 33559.38 7788.930 0.10612718 4176.339
## 4     4 47161.64 0.17459541 33946.21 9495.601 0.12865413 5438.285
## 5     5 46150.06 0.19996485 33412.22 8878.083 0.13819625 5019.924
# Summary of the model
summary(step.model$finalModel)

## Subset selection object
## 5 Variables  (and intercept)
##          Forced in Forced out
## RHrs         FALSE      FALSE
## Age          FALSE      FALSE
## BP           FALSE      FALSE
## ME.Power     FALSE      FALSE
## ME.RPM       FALSE      FALSE
## 1 subsets of each size up to 5
## Selection Algorithm: backward
##          RHrs Age BP  ME.Power ME.RPM
## 1  ( 1 ) "*"  " " " " " "      " "
## 2  ( 1 ) "*"  " " "*" " "      " "
## 3  ( 1 ) "*"  "*" "*" " "      " "
## 4  ( 1 ) "*"  "*" "*" " "      "*"
## 5  ( 1 ) "*"  "*" "*" "*"      "*"
```

(a) Summary of models with different operating variables and vessel characteristics.

```
summary(RR.model)

##
## Call:
## lm(formula = RR ~ RHrs + Age + BP + ME.Power + ME.RPM, data = RR)
##
## Residuals:
##    Min     1Q Median     3Q    Max
## -84581 -27100  -4283  18395 167217
##
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept) -1.578e+05  3.822e+04  -4.127 5.88e-05 ***
## RHrs         2.210e+01  4.870e+00   4.539 1.10e-05 ***
## Age          2.708e+03  7.254e+02   3.733 0.000262 ***
## BP           1.403e+03  5.526e+02   2.539 0.012073 *
## ME.Power     8.307e+00  8.002e+00   1.038 0.300759
## ME.RPM       2.106e+01  1.231e+01   1.710 0.089172 .
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 45250 on 161 degrees of freedom
##   (34 observations deleted due to missingness)
## Multiple R-squared:  0.2338, Adjusted R-squared:   0.21
## F-statistic: 9.827 on 5 and 161 DF,  p-value: 3.255e-08
durbinWatsonTest(RR.model)

##  lag Autocorrelation D-W Statistic p-value
##    1       0.1327759      1.732183   0.044
##  Alternative hypothesis: rho != 0
```

(b) Summary of best performing model with different operating variables and vessel characteristics.

When looking closer at the p-values shown in fig. 10.7b, it can be found that the significance of the variables of running hours and age are more significant, followed by bollard pull. The main engine RPM are more significant in this model than the main engine power. In order to increase the significance and reduce the p-value of the individual variables the choice has been made to reduce the possible number of variables which make up the model. Reducing the allowable number of variables to describe the running repair costs, increased the p-values of the variables. Reducing the nvmax, number of max variables to either 4 or 3, results in the most promising results, shown in fig. 10.8b. However, the resulting multiple R-sqaured and adjusted R-squared are reduced by 8.5% and are 0.22 and 0.21, respectively. The p-values have improved well below the suggested 5%.

Figure 10.8: Output Summary of stepwise regression analysis on best performing model with a maximum of 3 variables.

```
# Model Accuracy
step.model$results

##   nvmax     RMSE  Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1     1 49417.38 0.1148337 36231.57 10990.39  0.1371700 6014.877
## 2     2 46322.77 0.2411391 33322.73 11992.85  0.2218319 7345.011
## 3     3 45655.38 0.2583696 33059.22 10769.69  0.2381900 7026.278
# Summary of the model
summary(step.model$finalModel)

## Subset selection object
## 5 Variables  (and intercept)
##          Forced in Forced out
## RHrs         FALSE      FALSE
## Age          FALSE      FALSE
## BP           FALSE      FALSE
## ME.Power     FALSE      FALSE
## ME.RPM       FALSE      FALSE
## 1 subsets of each size up to 3
## Selection Algorithm: backward
##          RHrs Age BP  ME.Power ME.RPM
## 1  ( 1 ) "*"  " " " " " "      " "
## 2  ( 1 ) "*"  " " "*" " "      " "
## 3  ( 1 ) "*"  "*" "*" " "      " "
```

(a) Output summary 1 of the best performing model with a maximum of 3 variables.

```
summary(RR.model)

##
## Call:
## lm(formula = RR ~ RHrs + Age + BP, data = RR)
##
## Residuals:
##    Min     1Q Median     3Q    Max
## -93454 -26064  -4762  17254 181974
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) -97203.077  28047.055  -3.466  0.00066 ***
## RHrs            20.760      4.227   4.911 2.02e-06 ***
## Age           1569.609    555.937   2.823  0.00528 **
## BP            1620.280    319.393   5.073 9.65e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 44670 on 181 degrees of freedom
##   (16 observations deleted due to missingness)
## Multiple R-squared:  0.2184, Adjusted R-squared:  0.2055
## F-statistic: 16.86 on 3 and 181 DF,  p-value: 1.058e-09
durbinWatsonTest(RR.model)

##  lag Autocorrelation D-W Statistic p-value
##    1       0.1844602      1.628778   0.016
##  Alternative hypothesis: rho != 0
```

(b) Output summary 2 of the best performing model with a maximum of 3 variables.

In order to check that there are no autocorrelation effects between the residuals of the variables found in fig. 10.8b, the Durbin-Watson (D-W) autocorrelation test is performed. This to ensure that there is no autocorrelation in the residuals [Kenton, 2019]. The statistic D-W value will have a value between 0 and 4, where 2.0 means there is not autocorrelation. Values between 0 and 2 indicate a positive autocorrelation and a value between 2 and 4 indicate a negative autocorrelation. The D-W Statistic value in fig. 10.8b shows a value of 1.63. A rule of thumb is that the values for the D-W statistic test normally falls within the range of 1.5 and 2.5 [Kenton, 2019]. The calculated D-W statistic value is therefore found within respective range and therefore no concerning autocorrelation is found between the residuals.

The equation holding the variables of running hours, age and bollard pull describes the maintenance cost function for running repairs in a good way and can be used to estimate and predict running repair costs across the entire fleet as well as a way of comparing yearly resulting running repair costs per tug. Therefore, the model using three variables is used in the Power BI model and on the 5 selected tugs for validation of the entire model. This is done in section 10.3.

Dry Docking

The introduction of the vessel characteristics to the stepwise regression analysis of the variables and the dry docking costs do not improve the modelling capabilities. The output shows that the dry docking costs are best modelled using only the main engine RPM. Proposed model shown less favourable capabilities of modelling the dry docking costs. The p-value of the main engine RPM is just below 5%, suggesting a relationship. However, the multiple R-squared and adjusted R-squared are 0.07 and 0.05, which is considered to low to be able to represent the data with high certainty.

```r
# Model Accuracy
DD.model$results
```

```
##   nvmax     RMSE  Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1     1 189092.5 0.2556968 152725.9 42417.06  0.2815555 30816.64
## 2     2 200522.6 0.2237371 161243.2 47349.98  0.2744202 37957.36
## 3     3 204253.5 0.2305340 164257.7 48391.81  0.3302318 39163.31
## 4     4 208326.9 0.1500154 167012.9 49575.98  0.2787673 41691.66
## 5     5 211009.8 0.1711494 169289.2 47592.53  0.2804870 41039.37
```

```r
summary(lm(DD~ ME.RPM , data = DD))
```

```
##
## Call:
## lm(formula = DD ~ ME.RPM, data = DD)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -398996 -143389  -31733   95444  555252
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) 427710.2    82168.2   5.205 2.57e-06 ***
## ME.RPM        -130.8       64.0  -2.044   0.0454 *
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 191600 on 59 degrees of freedom
##   (8 observations deleted due to missingness)
## Multiple R-squared:  0.06613,    Adjusted R-squared:  0.0503
## F-statistic: 4.178 on 1 and 59 DF,  p-value: 0.04543
```

Figure 10.9: Output summary of best performing model with operational variables and vessel characteristics

It is therefore concluded that the equations for the modelling of the dry docking costs are not suitable for the prediction of dry docking costs. The formula presented for three variables holds potential for adoption as a way of predicting running repair costs. The equation is;

$$\text{Running Repair Costs} = 20.760 * \text{RHrs} + 1569.609 * \text{Age} + 1620.280 * \text{BP} - 97203.077 \tag{10.1}$$

Due to the fact that a sound equation describing the dry docking costs can not be established using the current data, the statement that the average annual maintenance cost increases about 2.2 times between the age of 0-5 and 16-20, as suggested in section 7.5, can not be verified. However, the equation describing the running repair costs can give an indication. Figure 10.10 shows the percentile increase in running repair costs between a 5 and 20 year old tug with varying running hours and bollard pull. It is found that the percentile increase of running repair costs ranges between 2.9 and 1.2 for low bollard pull and low running hours, and high bollard pull and high running hours, respectively. The decreasing difference for higher bollard pull and running hours are a result of the increased significance of the coefficients for bollard pull and RHrs.

		BP												
		35	40	45	50	55	60	65	70	75	80	85	90	95
RHrs	1200				2.42	1.95	1.72	1.58	1.48	1.41	1.36	1.32	1.29	1.26
	1400			2.87	2.14	1.82	1.64	1.52	1.44	1.38	1.34	1.30	1.28	1.25
	1600			2.40	1.95	1.71	1.57	1.48	1.41	1.36	1.32	1.29	1.26	1.24
	1800		2.84	2.13	1.81	1.63	1.52	1.44	1.38	1.34	1.30	1.27	1.25	1.23
	2000		2.39	1.94	1.71	1.57	1.48	1.41	1.36	1.32	1.29	1.26	1.24	1.22
	2200	2.81	2.11	1.81	1.63	1.52	1.44	1.38	1.34	1.30	1.27	1.25	1.23	1.21
	2400	2.37	1.93	1.71	1.57	1.47	1.41	1.36	1.32	1.29	1.26	1.24	1.22	1.21
	2600	2.10	1.80	1.63	1.52	1.44	1.38	1.34	1.30	1.27	1.25	1.23	1.21	1.20
	2800	1.92	1.70	1.56	1.47	1.41	1.36	1.32	1.29	1.26	1.24	1.22	1.21	1.19
	3000	1.79	1.62	1.51	1.44	1.38	1.34	1.30	1.27	1.25	1.23	1.21	1.20	1.19
	3200	1.70	1.56	1.47	1.41	1.36	1.32	1.29	1.26	1.24	1.22	1.21	1.19	1.18
	3400	1.62	1.51	1.43	1.38	1.33	1.30	1.27	1.25	1.23	1.21	1.20	1.19	1.17
	3600	1.56	1.47	1.40	1.35	1.32	1.29	1.26	1.24	1.22	1.20	1.19	1.18	1.17
	3800	1.51	1.43	1.38	1.33	1.30	1.27	1.25	1.23	1.21	1.20	1.19	1.17	1.16
	4000	1.47	1.40	1.35	1.32	1.28	1.26	1.24	1.22	1.20	1.19	1.18	1.17	1.16

Figure 10.10: Difference in running repair cost between a 5 and 20 year old tug for different BP and running hours per year.

It is concluded that the observation in section 7.5 concerning the increase of maintenance costs in one which is a factor of multiple variables, as researched in this chapter. It can therefore be stated that the assumption, by Stopford [2009], of a maintenance cost increase of 2.2 as a result of increasing age is an acceptable estimation. The assumption is within the calculated range of 1.2 - 2.9. However, it may vary dependent on utilisation (RHrs) and installed power (bollard pull). The second observation, concerning the ratio of 1/2 between annual running repair costs and annual dry docking costs, is to be evaluated in section 10.2.

Now that proposed equations for running repair costs have been established, the next step in this analysis is to present general conclusions regarding the maintenance performance of the fleet, ports, tug types and sister vessels, using the constructed maintenance performance management model constructed in Microsoft Power BI.

10.2. Model Results

To illustrate the use of the model, results found and conclusions made are presented below. These conclusions will be focussed on results which help the management of Boskalis Towage to judge the current maintenance performance and help with future decisions regarding maintenance. Decisions regarding the maintenance process will not be so profound as the others as the data quality limits the quality of general conclusions.

With use of the model the following general finding have been made regarding maintenance costs and the maintenance cost/RHr and cost/TM values which can be used to evaluate the fleet in the future. Table 10.1 shows that, for the entire fleet, the average costs of running repair costs is about €66K per tug per year and €83K per tug per year for dry docking. The ratio between running repair and dry docking is found to be 0.75 within this dataset. This is different than the suggested 1/2 by Stopford [2009]. This may be a result of the fact that tugs operate at a given port and thus operate from a home base. As tugs tend to be waiting for mobilisation, it gives more opportunity for maintenance and repair actions to be performed during operational hours. The Capesize vessels researched by Stopford is constantly in transit and does not have the luxury of operating from a home base where equipment manufacturers and mechanics can easily be called upon and fix issues. However, seen as the dataset could be improved this ratio may change as the data is more complete. With this knowledge the management of Boskalis Towage can question future maintenance costs and performance with these values.

Table 10.1: Summary of fleet performance for the year 2016-2018.

Year	Avg RR Cost	Avg DD Cost	MR Cost/RHr	MR Cost/TM
2016	€ 89K	€ 88K	€ 73	€ 119
2017	€ 59K	€ 115K	€ 77	€ 107
2018	€ 50K	€ 46K	€ 72	€ 86
Average	**€ 66K**	**€ 83K**	**€ 74**	**€ 104**

A further benefit of the model is that is allows for link-and-effect capabilities from entity level towards tug and system level. Figure 10.12 and fig. 10.13 show for each country and each individual port the total maintenance costs and the average costs based on the number of vessels operating that port. With this table Boskalis Towage is able to determine changes is costs across the different countries and ports. From this point an even more detailed evaluation can be made of each port. These tables also show how the maintenance costs relate to previous years and if major changes have been made regarding the number of vessels operating each port. Based on this information an even more detailed evaluation of the respective port can be made and evaluated which tugs have contributed to the increase of certain costs or have resulted in the underperforming of tugs with respect to certain indicators, such as; RR cost/RHr, RR cost/TM, RHrs/TM, FO/TM, availability percentage, etc. As an example, the table concerning itself with the performance of running repair costs for ports is presented in fig. 10.11.

PL_Locations	# of tug	RR Costs	Avg RR Costs p Tug p Year	% Prev	Avail. %	TM	RR Cost/RHr	RR Cost/TM	RHrs/TM	FO/TM [m3]
[redacted]	8	2,016.32K	102.01K	51.30 %		14,045	59.21	138.56	2.34	0.16
	9	182.32K	13.99K	69.00 %	99.29 %	3,637	47.58	58.12	1.19	0.13
	8	1,618.75K	83.25K	60.89 %	97.73 %	27,281	41.34	60.69	1.53	0.28
	12	2,128.35K	62.77K	55.94 %	97.85 %	20,750	37.53	102.67	2.75	0.29
	7	307.11K	24.66K	51.30 %	99.69 %	4,817	33.18	71.49	1.99	0.24
	26	3,820.65K	56.66K	58.81 %	95.93 %	118,290	32.24	35.73	1.06	0.15
	10	1,554.90K	53.27K	63.54 %	96.57 %	63,450	27.55	25.76	0.99	0.21
	8	561.47K	32.60K			12,404	25.42	47.03	1.93	0.09
	7	600.95K	37.25K	50.15 %	98.98 %	9,855	21.91	60.14	2.77	0.37
Total	**67**	**12,790.83K**	**66.45K**	**56.58 %**	**96.94 %**	**274,529**	**33.69**	**47.01**	**1.40**	**0.20**

Figure 10.11: Port performance on running repair costs for 2016-2018.

Figure 10.12 shows consecutive increases of average RR cost per tug for 2016 and 2017 in Port I. After close in-

Year	2016			2017			2018		
Country	MR RR	#	AvgMR-RR	MR RR	#	AvgMR-RR	MR RR	#	AvgMR-RR
[redacted]	**2,306K**	**24**	**96K**	**1,439K**	**24**	**63K**	**1,557K**	**24**	**65K**
	720K	10	72K	389K	9	43K	446K	10	45K
	824K	8	103K	367K	7	61K	428K	5	86K
	763K	11	69K	684K	11	62K	682K	12	57K
	1,099K	**12**	**92K**	**991K**	**11**	**90K**	**488K**	**12**	**41K**
	250K	6	50K	138K	6	23K	173K	7	25K
	849K	7	121K	852K	7	122K	315K	5	63K
	1,772K	**21**	**84K**	**1,048K**	**23**	**46K**	**1,001K**	**25**	**40K**
	1,772K	21	84K	1,048K	23	46K	1,001K	25	40K
	375K	**9**	**42K**	**344K**	**14**	**26K**	**371K**	**19**	**21K**
				69K	5	14K	113K	8	14K
	254K	6	42K	210K	6	42K	137K	6	27K
	122K	3	41K	65K	4	16K	121K	7	17K
Total	**5,553K**	**62**	**90K**	**3,822K**	**65**	**59K**	**3,417K**	**67**	**51K**

Figure 10.12: Summary of average running repair costs per tug by country and port.

Year	2016			2017			2018		
Country	MR DD	#	AvgMR-DD	MR DD	#	AvgMR-DD	MR DD	#	AvgMR-DD
[redacted]	**2,519K**	**24**	**105K**	**3,394K**	**24**	**141K**	**851K**	**24**	**35K**
	553K	10	55K	1,364K	9	152K	140K	10	14K
	658K	8	82K	1,621K	7	232K	80K	5	16K
	1,308K	11	119K	409K	11	37K	631K	12	53K
	138K	**12**	**12K**	**519K**	**11**	**47K**	**231K**	**12**	**19K**
		6		72K	6	12K	182K	7	26K
	138K	7	20K	448K	7	64K	49K	5	10K
	1,953K	**21**	**93K**	**2,265K**	**23**	**98K**	**1,811K**	**25**	**72K**
	1,953K	21	93K	2,265K	23	98K	1,811K	25	72K
	846K	**9**	**94K**	**1,302K**	**14**	**93K**	**218K**	**19**	**11K**
	66K			107K	5	21K	218K	8	27K
	781K	6	130K	1,195K	6	199K		6	
		3			4			7	
Total	**5,456K**	**62**	**88K**	**7,480K**	**65**	**115K**	**3,111K**	**67**	**46K**

Figure 10.13: Summary of average dry docking costs per tug by country and port.

spection of the tugs operating in Port I it was found that in both 2016 and 2017 numerous tugs where showing increased costs (fig. 10.14). For 2016 it was found that Tug 20 and Tug 18 where the main cost drivers. Their RR cost/RHr were between €80 and €100 per RHr which is larger the types average of €50 (fig. 10.16). Tug 20 shows large costs for the specific system of main engines (€100K) and anchor mooring and towing equipment (€55K). Tug 18 shows identical large costs for mainly the main engines (€110K). These costs for these two RTs have resulted in the increase costs for Port I in 2016. The amount of RHrs and TM for each tug does not shown significant decreases in operational respect and thus are purely as a result of increased costs. Comparing the actual RR costs with the RR targets from eq. (10.1) it is found that these vessels indeed have higher running repair costs than expected.

Detailed inspection of Port I tugs in 2017 have lead to identifying Tug 19, Tug 18 and Tug 20 as underperforming. Tug 19 shows high costs in the periods of March and October of 2017. The costs were related to 'Miscellaneous System' (€226K). Unfortunately, this does not help to elaborate on the underlying reason. Tug 18 shows increased running repair costs for 'Main Engines' (€143K) made in March 2017. This is interesting as the Tug 18 has shown large repair costs for main engines in the prior year. Tug 20 shows similar costs for main engine repair (€144K) in April 2017. The above mentioned underperforming tugs is seconded when evaluating the RTs across all years. Figure 10.15 shows all RTs and RT Hybrids in relation to the tug type average and sister group average.

With this information the Boskalis Towage can identified tugs and the underlying systems resulting in increased costs within Port I for 2016 and 2017. With this knowledge the department can flag the according vessels and keep an eye on them in the future. If increased costs related to main engines continue to portray these vessels, this may be a cause of concern and further detailed research may be assigned to the main engines.

PL_Locations	# of tug	RR Costs	Avg RR Costs p Tug p Year	% Prev	Avail. %	TM	RR Cost/RHr	RR Cost/TM	RHrs/TM	FO/TM [m3]
[redacted]	7	849.35K	121.34K	51.30 %		5,991	61.84	141.77	2.29	0.10
	3	121.53K	40.51K			1,041	60.98	116.74	1.91	0.15
	8	823.82K	102.98K	63.34 %	98.90 %	8,951	51.55	92.04	1.79	0.31
	11	762.50K	69.32K	62.08 %	98.44 %	6,998	35.58	108.96	3.08	0.30
	21	1,771.91K	84.38K	68.31 %		30,286	33.99	58.51	1.72	0.28
	10	719.87K	71.99K	70.06 %	99.41 %	30,952	28.14	23.26	0.83	0.16
	6	253.55K	42.26K	45.87 %	97.36 %	3,868	27.52	65.55	3.02	0.39
	6	249.98K	50.00K			4,787	26.44	52.22	1.97	
						2				
Total	62	5,552.50K	89.56K	62.39 %	98.92 %	92,876	37.06	59.78	1.64	0.22

(a) Summary of port performance for 2016.

Name	Age	Avg BP	RR Costs	RHrs	TM	RR Cost/RHr	RR Cost/TM	Avail. %	RR Target
RT Pioneer	18	78	290.58K	2K	893	117.88	325.40		108.61K
RT Peter	8	84	205.08K	2K	965	85.95	212.52		100.99K
RT Rob	8	84	186.05K	2K	912	79.54	204.01		100.01K
ZP Bison	3	70	13.40K	0K	145	44.76	92.44		27.14K
RT Emotion	3	80	62.53K	1K	951	43.04	65.75		67.29K
RT Innovation	18	78	94.56K	2K	978	38.82	96.69		107.99K
ZP Bulldog	5	70	0.05K	0K	13	1.77	3.50		24.60K
Total	9	78	852.25K	11K	4,857	74.73	175.47		280.35K

(b) Tug performance of Port I in 2017.

Figure 10.14: Tug performance of Port I in 2016 and 2017.

As it has been found in literature and through the stepwise linear regression in section 10.1 that maintenance costs are impacted by utilisation and vessel characteristics. In that respect, the results presented in table 10.1 can be considered a bit simplistic especially when taking into account the many differences between the tugs. Even so, the model supplies the possibility of tug type evaluation and the individual vessels within each type. An exemplary table of the model is shown in fig. 10.16.

With this table it can be seen that RTs are the main cost drivers. This as a result of increased number of installed components, such as engines and propulsion, and larger bollard pull. Comparing the hybrid version of the RT with the normal version, it can be found within the dataset the hybrid RTs are about €5 cheaper per RHr when it comes to RR costs. Knowledgable bodies within JV acknowledge that in their experience, the hybrid RTs operate at lower maintenance costs in comparison with their counterparts.

The results concerning the ASD hybrid and ASD are inclusive as the data quality of the ASD hybrids is low, especially the noted RHrs.

A question formulated by JV was whether the ASD where outperforming the VSP. Looking at fig. 10.16 it can be concluded that the average performance of ASDs is lower than that of the VSP. However, this may be related due to the fact

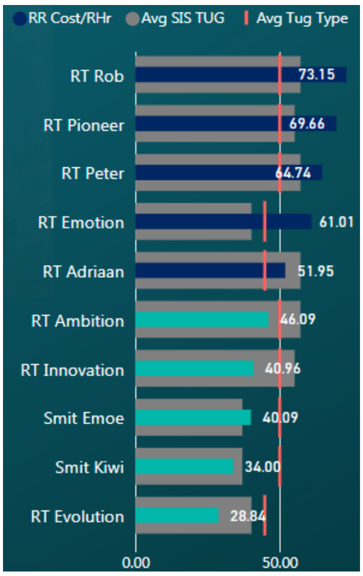


Figure 10.15: Evaluation of RT and RT Hybrid on RR cost/RHr versus tug type average and sister group average.

Type	Nr. Tugs	Avg Age	Avg BP	RR Cost	Avg RR Costs p Tug p Year	TM	RHrs	MR_time	Prev [%]	RR / DD Cost	RR Cost/RHr	FO/RHr	Avail. %
RT	7	12	81	2.48M	118.14K	21.99K	424.79K	120	49 %	1.21	50.58	0.12	97.44 %
RT Hybrid	3	6	81	0.77M	85.18K	7.94K	151.72K			3.31	45.41	0.12	
ASD Hybrid	2	3	60	0.09M	22.93K	3.61K	21.63K				36.35	0.27	
ASD	36	14	63	6.99M	65.53K	174.61K	1,972.80K	2813	64 %	0.62	33.65	0.16	96.96 %
Conv	3	30	40	0.61M	67.57K	7.10K	187.41K	978	59 %	0.61	29.78	0.11	97.07 %
VSP	6	24	42	1.00M	55.75K	24.87K	342.97K	154	69 %	0.65	26.54	0.17	96.91 %
ATD	10	16	60	0.85M	33.56K	34.25K	372.67K	28	36 %	1.23	20.51	0.08	95.73 %
RSD						0.17K							
Total	**67**	**15**	**62**	**12.79M**	**66.45K**	**274.53K**	**3,474.00K**	**4092**	**62 %**	**0.75**	**33.69**	**0.14**	**96.94 %**

Figure 10.16: Tug type evaluation table.

Name	Tug Type	Avg Age	RHrs	RR Cost/RHr	RR Cost/TM	FO/RHr	Avail. %
[redacted]	ATD	0	11K	30.94	22.74	0.12	
	ATD	6	26K	30.28	51.82	0.06	
	ATD	37	33K	28.61	56.70	0.05	
	ATD	4	33K	19.94	43.32	0.06	
	ATD	4	46K	19.26	42.28	0.04	
	ATD	6	45K	18.07	34.51	0.04	
	ATD	36	48K	16.71	24.51	0.12	
	ATD	26	70K	15.52	17.77	0.12	95.50 %
	ATD	26	60K	12.91	16.40	0.11	95.96 %
	ATD	0			20.79		
Total	**ATD**	**15**	**373K**	**20.51**	**26.92**	**0.08**	**95.73 %**

Figure 10.17: Overview of ATD performance for 2016-2018.

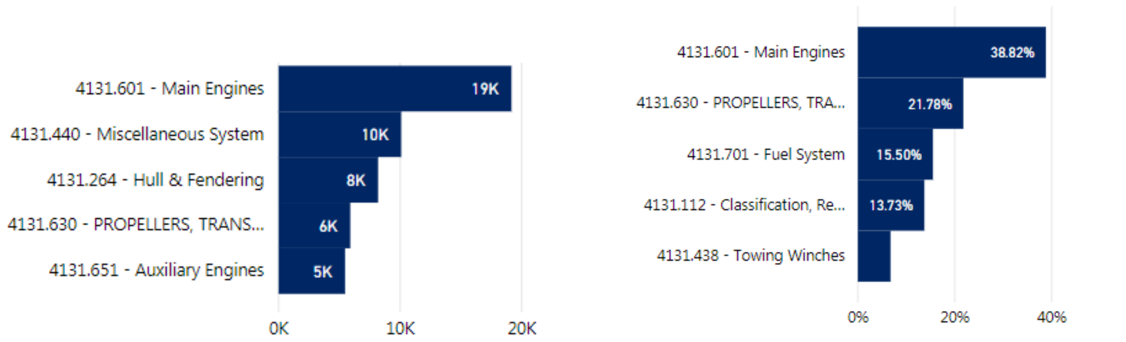
Table 10.2: Summary of ATD RR cost/RHr performance for the year 2016-2018.

	2016	2017	2017
ATD	26.37	12.71	22.46

that the average bollard pull of the ASDs is higher, even though the average age is lower.
Another interesting observation to be made is that the ATDs are portraying low RR cost/RHr. The individual tugs shown in fig. 10.17, don't give conclusive reasons for the lower RR cost/RHr. However, when looking at how it portrays across the years, shown in table 10.2 it is found that in 2017 the average RR cost/RHr for ATDs was very low, €12.71. The reason for this may be due to reason that five out of eight vessels had a special survey dry docking in 2017. Nevertheless, it seems that the ATD is in general a tug with low running repair costs. After relaying this with JV, they suggested that this may be due to the fact that ATDs, even though having an escort notation, are generally not assigned to escort jobs. Due to their hull design and thruster placement, JV has learned from experience that these vessels are less capable of performing indirect towage manoeuvres needed for escort operation. The tugs are therefore primarily assigned to berthing and unberthing operations, which requires fewer high load power demands. The tugs are thus being utilised differently compared to the majority of other tugs. This may lead to fewer breakdowns and may be a reason for the lower running repair costs.

A level more detailed, the model shows what the main cost and process driver are for running repairs, shown in fig. 10.18. It should be noted that the data quality for maintenance time is considered low. It is interesting to see that the critical systems, shown in table 3.2, recur in the lists showing the cost and process drivers.

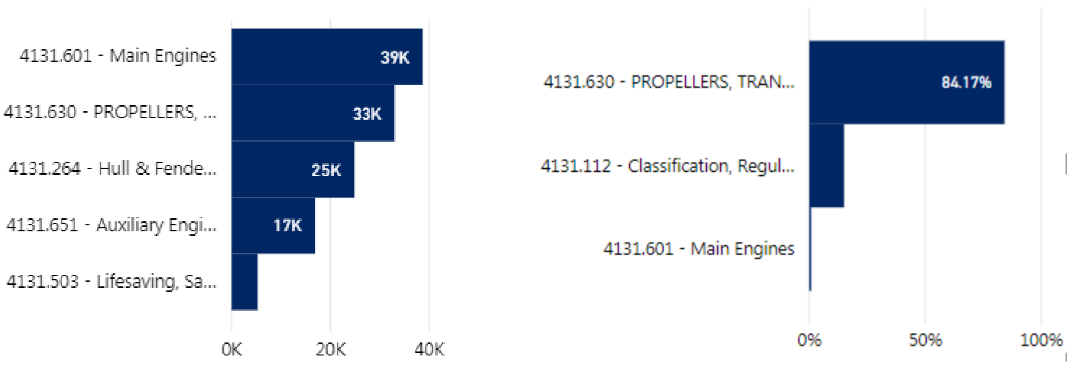
The same can be done with respect to systems cost allocation for dry docking. However, the dry docking costs and maintenance time not being allocated to a specific system makes the results found for dry docking non-definitive. Nonetheless, the results are presented in fig. 10.19. When relaying the results to the technical department of JV they confirmed the observation that the impact of the propeller, transmissions and foils on the total cost and maintenance time is more significant compared to running repairs. It is understandably as the majority of work done on propellers, transmission and foils commence when the tugs are in the dry



(a) Top 5 system for average running repair cost per tug per year. (b) Top 5 systems for percentage of total running repair maintenance time.

Figure 10.18: Maintenance cost and process drivers for running repairs.

dock and not while in the water. It is recommended to complete the dataset and see whether the results holds.



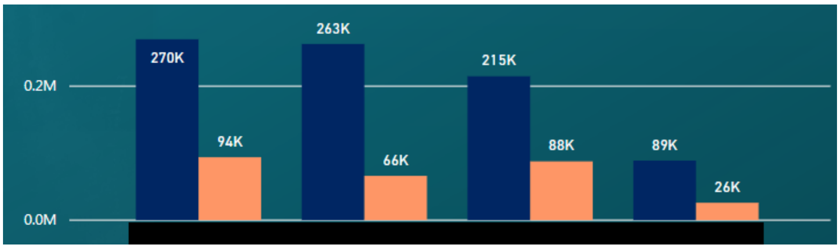
(a) Top 5 system for average dry docking cost per tug per year. (b) Top systems for percentage of total running repair maintenance time.

Figure 10.19: Maintenance cost and process drivers for dry docking.

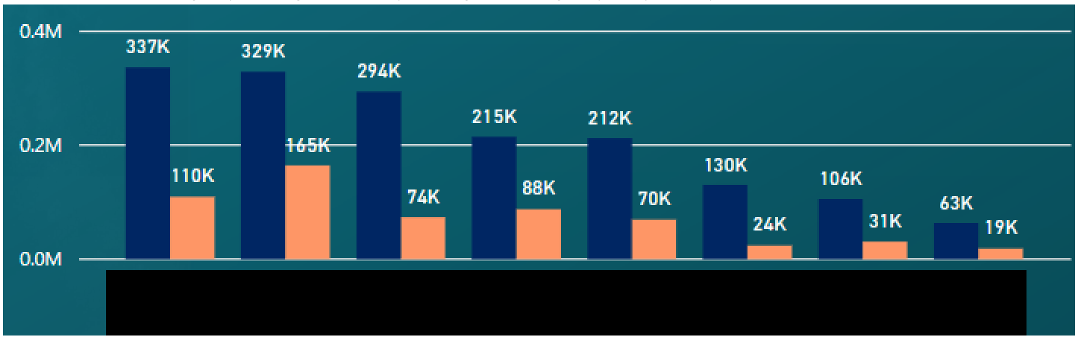
Like with running repair, the model also supplies management with conclusions regarding the dry docking at different port locations and across different tug types. Figure 10.20 shows this detailed information for different countries and port locations. It is noticeable that even though Port A shows the largest number of dry docking occurrences, the average cost per dry docking and cost per tug is lower than that of Port F, Port C and Port E.

Table 10.3: Number of dry dockings per port and dry docking type.

Ports		**ED**	**IS**	**IWS**	**SS**
Port A	9	6	6	2	10
Port G	2	2	3		5
Port E	1	2		1	4
Port F	2	2	2		2
Port I	4	2	2		
Port C	2				4
Port H		1	2		2
Port B	1				2



(a) Average dry docking costs per dry docking and per tug per year by country.



(b) Average dry docking costs per dry docking and per tug per year by port.

Figure 10.20: Average dry docking costs per dry docking costs per tug by country and port.

Table 10.4: Summary of dry docking data for different tug types.

Tug type	**Nr. of dry dockings**	**Avg cost per tug per year** [x €1,000]	**Avg cost per dry docking** [x €1,000]	**Average Duration** [Days]
VSP	5	107	257	16
ASD	48	104	254	15
RT	11	97	227	12
Conventional	4	72	216	18
ATD	9	40	82	9
RT Hybrid	5	36	72	6
ASD Hybrid	1	-	-	3

With the use of the model, it can be found that the higher average costs for Port E are a result of a total of four special survey, making up 50% of all dry docking activity. These four surveys included overhauls of main engines for Tug 57, Tug 61, Tug 59 and Tug 53. Three of the four dry dockings costs between €300K and €400K, which is substantially compared to the fleet average of €253K, shown in table 10.5. Unfortunately, cost allocation per system is not available within the model and so no conclusions can be found on the major cost driver within each of above mentioned special surveys. If these costs would be allocated to specific systems, the model would be able to compare the dry docking costs of different manufacturers and system types in order to determine increased costs - or maintenance process trends.

In addition, the Power BI model presents info concerning average dry docking costs for different tug types (table 10.4). From this table the conclusions can be made that VSPs are considered most costly within the fleet, within the current data set. The technical department of JV seconds this conclusion as the complexity of the VSP and technical expertise required to maintain the thruster configuration results in higher costs.

Furthermore, it can be seen that the average costs for ATDs and RTs hybrids are low, mainly due to ATD special surveys which where below €200k. Moreover, the majority of dry dockings were intermediate surveys and occasional emergency dry dockings with low costs. The low average dry docking costs for RTs was also due the occurrences of mainly intermediate surveys. Many RTs where scheduled for a special survey at the end of 2018 and beginning of 2019. It is expected that these averages will increase with more special dry docking data.

Table 10.5: Summary of dry docking data for different dry docking types.

Dry docking type	**Nr. of dry dockings**	**Avg cost per dry docking** [x €1,000]	**Average Duration** [Days]
-	21	245	5
Emergency dry docking	15	97	8
Intermediate survey	15	214	15
In water survey	3	-	3
Special survey	29	253	18

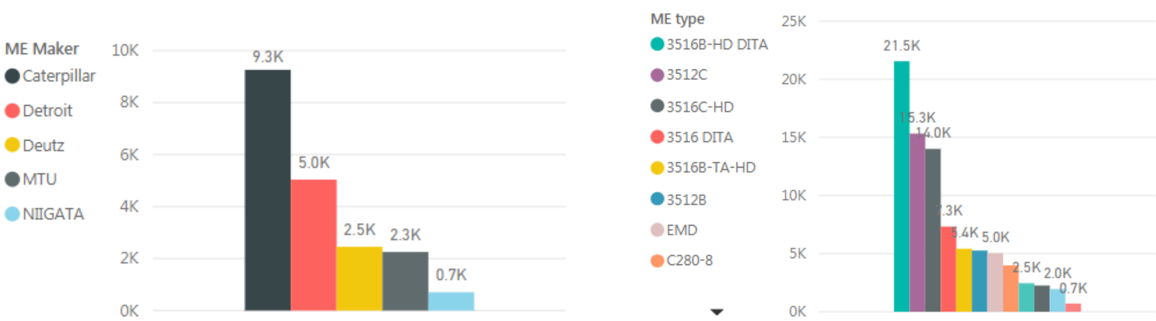
Unlike the dry docking costs, detailed evaluation of manufacturers and system types is possible for running repairs as a result of cost allocation. The following three critical systems and cost drivers are elaborated below; main engines, auxiliary engines and thrusters.

When looking into the yearly average engine costs per engine for different engine manufacturers and engine types, it is found that main engines produced by Caterpillar have a higher yearly average costs (fig. 10.21). With the model it is found that the following main engine types show yearly average running repair costs per main engine of above €8K, which is the fleets average; 3516B-HD DITA, 3512C, and 3516-HD. It is interesting to see these three engines are installed within the majority of RTs and some ASDs (table 10.6).

Table 10.6: Tugs with Caterpillar 3516B-HD DITA, 3512C and 3516-HD main engines installed.

Tug Name	**Engine type**	**Yearly avg RR Cost**
Tug 27	3516B-HD DITA	€ 50K
Tug 18	3512C	€ 29K
Tug 20	3512C	€ 28K
Tug 21	3516B-HD DITA	€ 14K
Tug 13	3512C	€ 13K
Tug 25	3516B-HD DITA	€ 8K
Tug 26	3516B-HD DITA	€ 6K
Tug 16	3512C	€ 5K
Tug 15	3512C	€ 2K

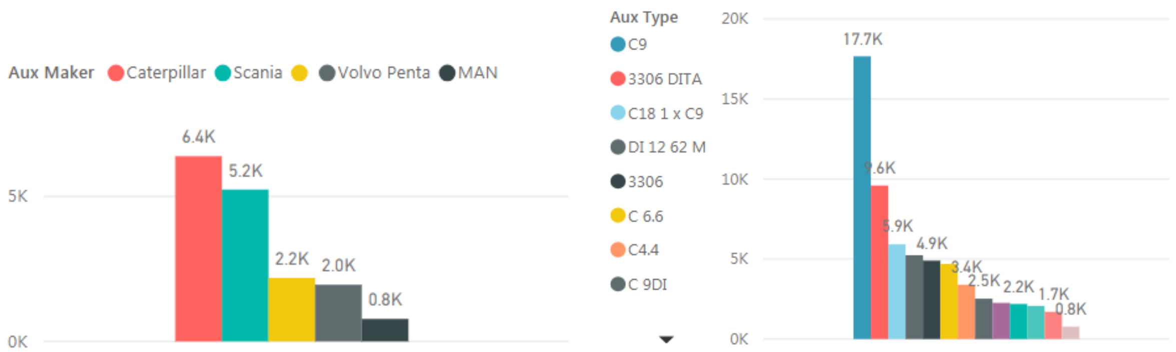
The main perpetrators for the high average cost per main engine is due to Tug 27, Tug 18, Tug 20, Tug 21 and Tug 13. In fig. 10.14b it was presented that Tug 20 and Tug 18 were underperforming tugs in 2016 and 2017 as a result of increased main engines costs. It is found here that the average running repair costs per main engine is higher in comparison with other engines. Tug 27 has also been found one of the top 10 underperforming tugs with respect tot total maintenance cost per running hour. This tug is set to be evaluated in more detail in section 10.3.



(a) Yearly average running repair costs per engine by engine manufacturer. (b) Yearly average running repair costs per engine by engine type.

Figure 10.21: Yearly average main engine running repair costs per main engine.

The same can be done for auxiliary engines, as shown in fig. 10.22a. The auxiliary engines of Caterpillar and Scania show a higher average running repair costs per tug per year. Due to the fact Caterpillars are more frequently used within the fleet, it is possible to evaluate the different installed auxiliaries. Comparing the fleets average of € 5.5K per tug per year, only the Caterpillars stand out within the manufacturers. Therefore, the focus will be on the Caterpillar engines. Figure 10.22b shows that the C9 and the 3306 DITA are significantly higher than the average running repair costs per tug per year. Relaying this back to the technical department confirms that the C9 has shown increased maintenance requirements and costs. This information can be used to evaluate the installed equipment in newbuild tugs. As a result of increased running repair costs for specific auxiliary engines, the choice can be made to switch to a different auxiliary engine. Based on the data presented below it is ill-advised to install Caterpillar C9 auxiliary engines in future tugs.



(a) Yearly average auxiliary engine running repair costs by manufacturer.

(b) Yearly average auxiliary engine running repair costs by Caterpillar auxiliary engine type.

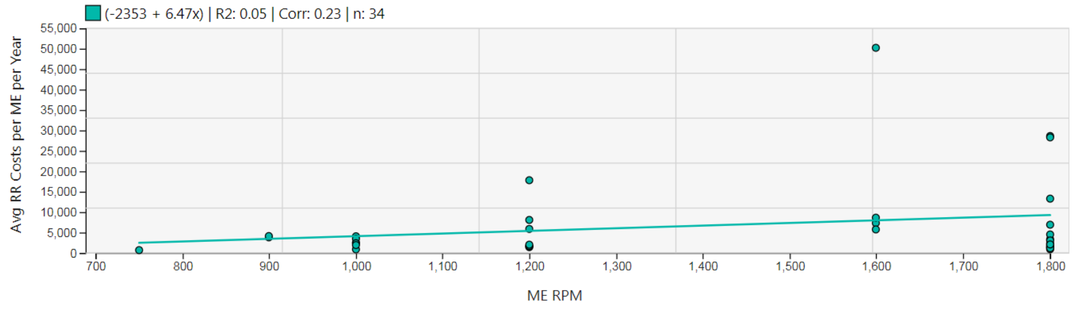
Figure 10.22: Yearly average running repair costs of auxiliary engines by manufacturer and type.

Another interesting evaluation can be made on the main engines and auxiliary engines with use of the Power BI model. Having incorporated detailed vessel data concerning number of installed engines and RPM of the engines, allows for the evaluation of cost increase as a result of higher RPM engines. Molland [2008] elaborated on the increased maintenance costs for high RPM engines in respect to low RPM engines. Therefore, it may be of interest to know what the increase of engine RPM will have on yearly average maintenance costs for both main- and auxiliary engines. This can be used to help make decisions on engine selection in newbuilds. The results are shown in fig. 10.23 which shows the yearly average running repair costs for main engines (ME) and auxiliary engines (Aux) at increasing RPM. As all engines in the dataset are above 1,000 RPM, they are considered high speed engines.

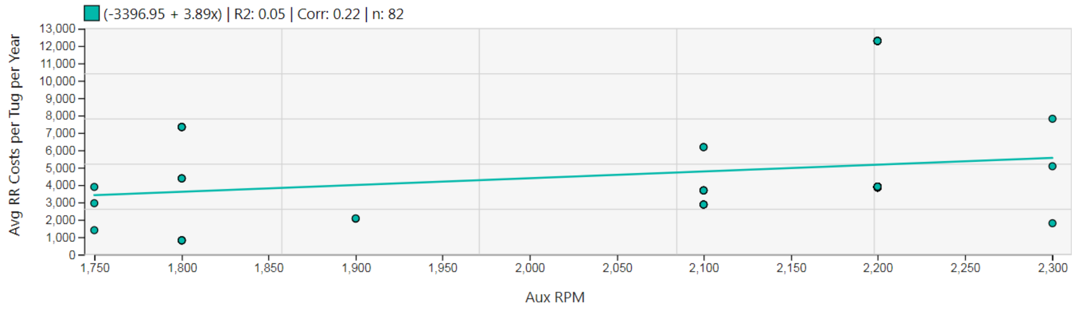
It is found that increased RPM does increase the yearly average running repair costs for both main engine and auxiliaries. The correlation information is found above the respective plots. It is found that for every RPM increase the yearly average running repair costs for main engine repairs is increased by €6.47. For the auxiliary engines this is €3.89. This can be taken into account when evaluating installation of different engine types with different RPM.

Looking into the last critical equipment, the thrusters, the following conclusions have been made as a result of fig. 10.24. It shows that the Schottels are showing larger yearly average running repair costs. The observation that VSP are less costly than CPP and FPP does not hold as the number of known costs associated with VSP is singular. Making this observation inconclusive. More data is required on specifics costs for VSPs.

Looking in detail into the different thruster types it can be seen that one thruster types stands out, which is the Schottel SRP 1515 CP. This CPP shows a yearly average running repair cost of €11.4K which is significantly larger than the other thrusters. The technical department of JV could confirm that they experience increased issues with the Schottel SRP 1515 CP. It seems that CPP are prone to debris and sediment which comes into the seals. This leads to leakages of the seals and requires the seals to be replaced. This apparently happens especially in ports with large tidal differences, due to higher water velocities which pick up sediment more easily, and where a lot of fishing activity takes place. The technical department specify the English ports as ports with more frequent thruster issues as a result of the larger impact of tidal and the port of Port A as a port with large amount of fishing activity and debris. Due to time constraint this could not be verified through the Power BI model. However, it is believed that a visualisation can be constructed in order to validate this. As a result, it may be calculated what the increased costs are a result of the increased failure frequency of thruster



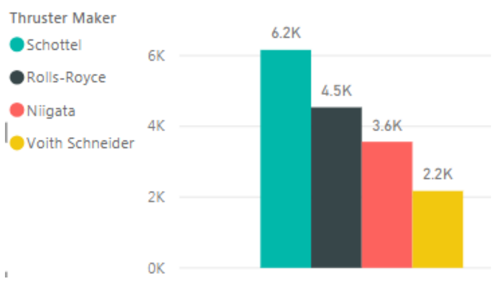
(a) Main engine running repair costs vs RPM.



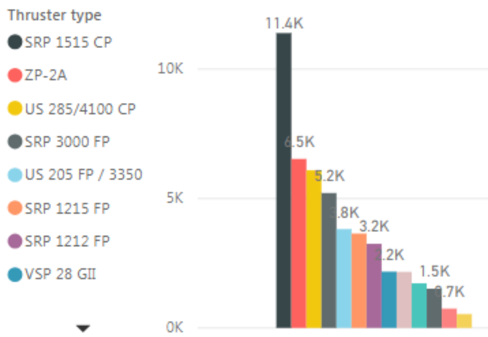
(b) Auxiliary engine running repair costs vs RPM.

Figure 10.23: Impact of increasing RPM on the running repair costs of main- and auxiliary engines.

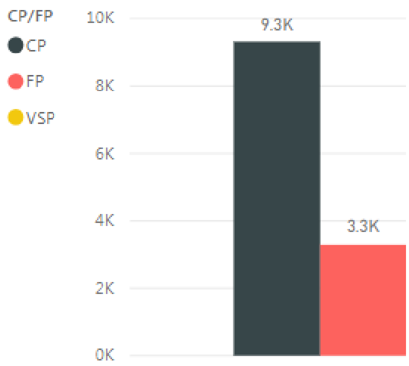
in these ports. It may then be advised to switch to FPP in these areas in order to reduce the failure frequency of thruster seals.



(a) Yearly average thruster running repair costs by manufacturer.



(b) Yearly average thruster running repair costs by type.



(c) Yearly average running repair costs of CPP vs FPP.

Figure 10.24: Summary of yearly average running repair costs.

10.2.1. Tug Selection

In order to validate the model and ensure that the conclusions made in section 10.2 are deemed valid and correct, it is proposed to select five vessels for evaluation and validation of the model. The selection of these five vessels is done based on the 'maintenance RHr intensity' presented in table 8.3. The choice for the use of this maintenance performance indicator as a means of vessel selection is based on the regression analysis performed in section 10.1.2.

As stated, the selection of the five 'validation tugs' is based on the 'maintenance RHr intensity' [€/RHr]. As a result, the following five tugs are selected;

Table 10.7: Five selected tugs for validation and their maintenance RHr intensity.

Name	Type	Age	BP	€/RHr
Tug 26	ASD	10	65t	255
Tug 27	ASD	8	65t	184
Tug 6	ASD	9	55t	174
Tug 41	ASD	9	96t	152
Tug 35	ASD	10	60t	147

It is noticeable that these underperforming vessels are around 10 years old and all ASDs. The reason for them all being ASDs may be a result of the higher amount of ASDs within the fleet. The ages being about 10 years may be a result of increased costs as a result of special surveys or large intermediates performed at the age of 7.5.

10.3. Model Validation

This next section will elaborate on each of the above mentioned tugs with use of the model and elaborate on the underlying reason for the tug's underperformance. The aim is to be able to identify when and what the underlying reason is and to see whether the occurrence is a one case scenario and whether a possible solution can be formulated based on knowledge known from other tugs and the different ports. The results presented below have been discussed with the technical bodies of JV and their comments and additional information incorporated.

10.3.1. Tug 26

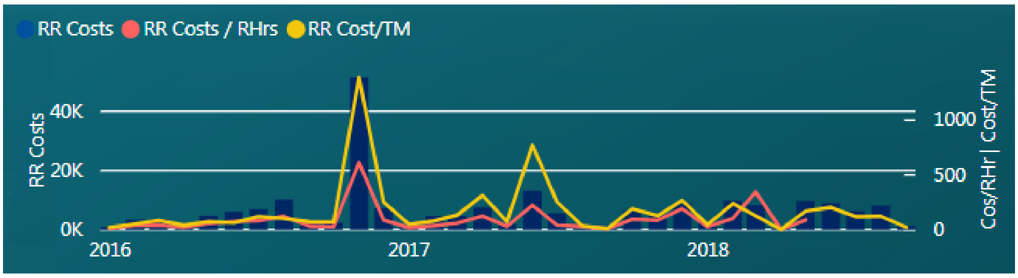
Tug 26 is a 10 year old ASD tug which has been operating around different locations during the course of three years. Within the dataset the tug was operated in Tug 12 and Port D in 2016, and Port B and Port D in 2017 and 2018.

Name	Tug 26
Tug Type	ASD
Sister code	008
Age	10
BP	65t
Design	ASD RAmpart 3200
Nr of ME	2
ME Power	3840 kW
ME Maker	Caterpillar
ME Type	3516B-HD DITA
Nr of Aux	2
Aux Maker	Scania
Aux Type	DI 12 62 M
Nr of Thrusters	2
Thruster Maker	Schottel
Thruster Type	SRP 1515 CP

Figure 10.25a and fig. 10.25b show the main table and the running repair cost per running hour (RR €/RHr) and tugmove (RR €/TM), including the total running repair (RR) costs. Using this table and figure it can be found that the large RR costs can be found in the month of November 2016 and a smaller cost in June 2017, which resulted in increased RR €/RHr and TM. This is confirmed in fig. 10.25a where the MR Cost/ARV is somewhat higher in comparison with 2017. Looking at the RR Cost/ARV it can be concluded that the main reason for increased maintenance in 2016 is due to running repair costs. Gulati [2013] suggests a total maintenance cost per ARV below 2.5% to be within the first quartile. Assuming a ratio of 1/2 between RR and DD cost, would put the value of 1.25% within the third quartile, using fig. 8.7.
Looking closer at the RR cost and how they compare to eq. (10.1), shown in the last column of fig. 10.25a, it is found that the RR cost for this tug is higher across all years than expected. This is seconded by comparing the RR cost/RHr with that of the same tug type and sister vessels, which are 92.00, 34.11 and 39.78, respectively. Before compared the tug with its sister vessels and their operational location, a detailed look into the equipment shows an interesting reason for the increased RR cost.

Year	TM	RHrs	MR Cost / ARV	MR Cost/RHr	RR Costs	RR Cost/ARV	RR Cost/RHr	RR Cost/TM	DD Costs	DD Cost/RHr	DD Cost/ARV	RHrs/ TM	RR FC Check
2016	649	1,008	2.14 %	165.27	100.95K	1.29 %	100.15	155.55	65.64K	65.12	0.84 %	1.55	41.60K
2017	382	851	0.76 %	70.11	59.66K	0.76 %	70.11	156.18				2.23	39.91K
2018	430	515	3.49 %	529.27	54.46K	0.70 %	105.75	126.65	218.11K	423.52	2.80 %	1.20	34.50K
Total	**1,461**	**2,374**	**2.74 %**	**254.88**	**215.08K**	**0.92 %**	**92.00**	**146.13**	**283.76K**	**119.53**	**1.82 %**	**1.62**	**116.01K**

(a) Summary of maintenance performance indicators for Tug 26.



(b) Monthly running repair costs, running repair cost per RHr and TM for Tug 26.

Figure 10.25: Maintenance performance indicators and timeline of Tug 26.

Table 10.8: Top 5 systems by running repair cost and percentage by year.

Year	2016		2017		2018		Yearly Average	
Equipment	Amount [€]	%	Amount [€]	%	Amount [€]	%	Amount [€]	%
4131.430 - Anchor Mooring and Towing Equipment	2.40K	2%	2.24K	4%	3.90K	7%	2.85K	4%
4131.440 - Miscellaneous Systems	7.22K	7%	15.38K	26%	11.62K	21%	11.41K	18%
4131.503 - Lifesaving, Safety and Emergency Equipment	4.96K	5%	9.30K	16%	8.52K	16%	7.59K	12%
4131.601 - Main Engines	9.76K	10%	14.89K	25%	9.96K	18%	11.54K	18%
4131.630 - Propeller, Transmissions, Foils	60.41K	60%	1.25K	2%	10.43K	19%	24.03K	27%

Table 10.8 shows the top 5 systems with the highest RR costs for Tug 26. It is noticeable that '4131.630 - Propeller, Transmission, Foils' are larger in both 2016 and 2018 compared to the fleets yearly average of €5.9K. Another interesting note is the large cost appointed to Miscellaneous Systems. This may be a result of not knowing the correct account to assign the respective costs to, or the specific system is not accounted for within the SFI Grouping System. Relaying this to the technical department of JV did not result in finding the reasons for these increased costs.

Detailed research in the different thruster types, it was found in fig. 10.24 that the thrusters by Schottel are more expensive, especially the 'SRP 1515 CP'. It has been found that the increased running repair costs of the Schottel SRP 1515 CP have contributed in overall increased running repair costs of Tug 26.
Figure 10.25b further shows an increased MR Cost/ARV and MR Cost/RHrs for 2018. Looking at the difference between running repair and dry docking, it is found that dry docking costs in March 2018 is the main driver of the increased maintenance cost. Comparing the dry docking costs for the special survey (SS) of March 2018, €218.11K, with the fleet's average for all dry docking types and the average for SS, €222.17K and €253.49K respectively, it can be concluded that the costs for this dry docking does not seem out of the ordinary. The duration of 19 days is acceptable around the average of 21 days for a SS.

DD_ID	Age @ DD	DD Costs	DD Type	Port	Start Date	Duration [days]	SFI Code I	SFI Code II	Note
DD_[redacted]1601	8	65.64K		[redacted]	01 July 2016				
DD_[redacted]1801	10	218.11K	SS	[redacted]	05 March 2018	19			10 year
Total	**10**	**283.76K**							

Figure 10.26: Dry docking information of Tug 26

With the above presented information, it is found that the Tug 26 is underperforming due to the increased costs associated with propeller, transmission and foils. The underlying reason has been found to be the Schottel SRP 1515 CP with notoriously higher costs which can be assigned to its thruster type but also to the fact that it is a CPP which are known for increased maintenance activity and cost due to the effect of debris and sediment on the seals and mechanism.

Looking for a possible solution through the comparison between the other sister vessels, it can be stated fig. 10.27 shows and increase in RR cost/RHr for the areas of Port D and Port B. The large RR cost/RHr is purely due to one tug, Tug 27, which has operated in Port A. As Tug 27 is one of the tugs selected for validation, this will be addressed in section 10.3.3. Based on this information, it could be suggested to operate Tug 26 in Port E, where the RR cost/RHr and RR cost/TM are less. The suggested re-allocation of Tug 26 should not only be based on the findings presented above but also based on the market and port requirements.

Name	2016	2017	2018	Total
[redacted]	**40.60**	**55.98**	**18.84**	**38.47**
	0.34		21.35	**10.85**
			74.24	**74.24**
	43.72	55.99		**49.85**
	100.15	**70.11**	**105.75**	**92.00**
	172.41	102.63	55.71	**110.25**
		54.48	294.79	**174.63**
	1.26			**1.26**
	24.24	**73.00**	**160.83**	**86.02**
			25.92	**25.92**
	24.24	73.00	297.42	**131.55**
	24.24	**21.19**	**34.55**	**26.66**
	24.28	21.19	34.55	**26.67**
	39.21	**32.69**		**35.95**
	39.25	32.69		**35.97**
	27.95	**-21.47**	**5.55**	**4.01**
	27.95	-21.47	5.55	**4.01**
	29.34	**23.07**	**32.44**	**28.28**
	29.34	23.07	32.47	**28.29**
Total	**33.74**	**30.31**	**55.28**	**39.78**

[redacted]

Figure 10.27: Yearly running repair costs per running hour for sister group 008 by location.

10.3.2. Tug 27

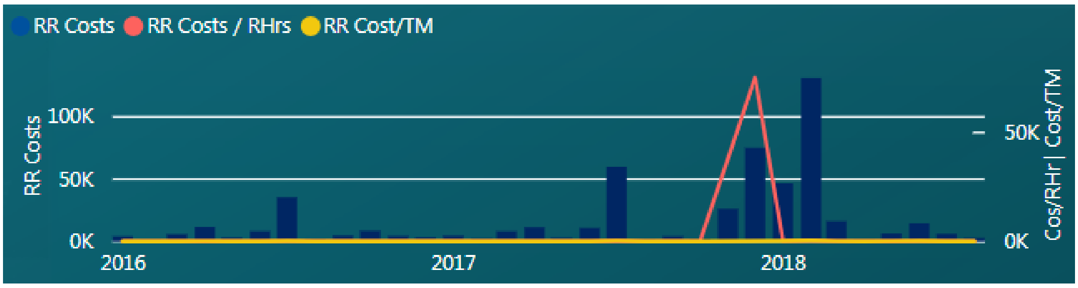
Tug 27 is a 10 year old ASD tug with an ASD RAmpart 3200 design, similar to the Tug 26. The vessel has been operating in Port A in 2016 and 2017. In the year 2018 it has transferred to Port B, where it has operated the rest of the year.

From the fig. 10.28a and fig. 10.28b the following conclusions are made. Tug 27 shows increased RR costs in both 2017 and 2018, which are found to be associated with increased costs for '4131.601 - Main Engines' in especially December of 2017 and February 2018, €54K and €130K respectively. This leads to an overall increase in RR cost/RHr and RR cost/ARV for the respective years. The comparison with eq. (10.1) also shows that for the years 2017 and 2018, the respective maintenance costs should be substantially smaller for the amount of running hours. The spike in RR cost/RHrs indicates that the Tug 27 has almost no running hours in this month and thus experiencing a large downtime. Unfortunately, detailed maintenance time is unknown for the Tug 27 and thus the downtime and availability percentage within that year can not be calculated.

Name	Tug 27
Tug Type	ASD
Sister code	008
Age	10
BP	65t
Design	ASD RAmpart 3200
Nr of ME	2
ME Power	3840 kW
ME Maker	Caterpillar
ME Type	3516B-HD DITA
Nr of Aux	2
Aux Maker	Scania
Aux Type	DI 12 62 M
Nr of Thrusters	2
Thruster Maker	Schottel
Thruster Type	SRP 1515 CP

Year	TM	RHrs	MR Cost / ARV	MR Cost/RHr	RR Costs	RR Cost/ARV	RR Cost/RHr	RR Cost/TM	DD Costs	DD Cost/RHr	DD Cost/ARV	RHrs/TM	RR FC Check
2016	1,695	3,830	1.19 %	24.24	92.86K	1.19 %	24.24	54.78				2.26	100.18K
2017	2,788	2,870	3.09 %	84.11	209.47K	2.69 %	73.00	75.13	31.89K	11.11	0.41 %	1.03	81.81K
2018	1,129	1,394	7.95 %	445.13	224.16K	2.87 %	160.83	198.54	396.26K	284.31	5.08 %	1.23	52.75K
Total	**5,612**	**8,093**	**4.99 %**	**184.50**	**526.48K**	**2.25 %**	**86.02**	**109.49**	**428.14K**	**52.90**	**2.74 %**	**1.44**	**235.07K**

(a) Summary of maintenance performance indicators for Tug 27.

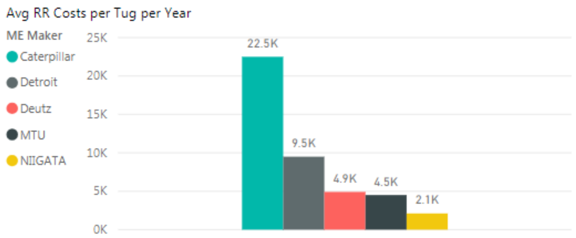


(b) Monthly running repair costs, running repair cost per RHr and TM for Tug 27.

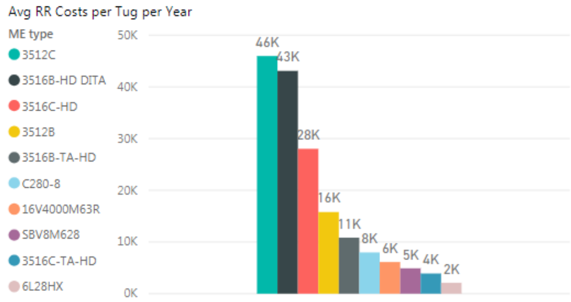
Figure 10.28: Maintenance performance indicators and timeline of Tug 27.

Looking into the respective systems to see what drives the running repair costs of the Tug 27, table 10.9 shows increased costs for '4131.430 - Anchor Mooring and Towing Equipment' and '4131.601 - Main Engines'. The main engines yearly average cost are larger than the fleet's average cost of €19K per year and sister group 008 of €43K.

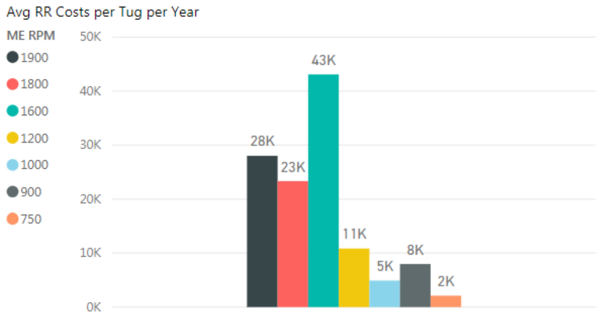
Looking into detail at the different main engine manufacturers, main engine types and engine RPM, shown in fig. 10.29. Figure 10.29a shows larger costs for main engines of Caterpillar. Similar to the Tug 26 and the evaluation of thruster types, Caterpillar engines are most used within the fleet. Figure 10.29b shows significant higher costs for Caterpillar engines 3512C and 3518B-HD DITA. These two engines have an RPM of 1800 and 1600 respectively. The Caterpillar 3516C-HD has an RPM of 1900, which shows that all the higher range RPM engines are notoriously higher in running repair costs. Higher RPM engines are known for increased manufacturing and maintenance costs due to their increased complexity as shown in fig. 10.23 [Molland, 2008].



(a) Yearly average running repair costs for different main engine manufacturers.



(b) Yearly average running repair costs for different main engine types.



(c) Yearly average running repair costs for different main engine RPM.

Figure 10.29: Detailed evaluation of main engine manufacturers, main engine types and RPM.

Table 10.9: Top 5 systems by running repair cost and percentage by year for Tug 27

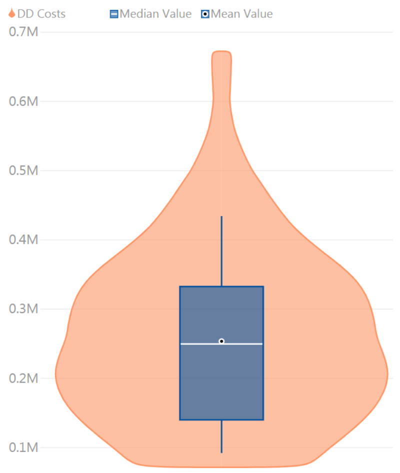
Year	2016		2017		2018		Yearly Average	
Equipment	Amount [€]	%	Amount [€]	%	Amount [€]	%	Amount [€]	%
4131.264 - Hull & Fendering	201	0%	18.18K	9%	0	0%	6.13K	3%
4131.430 - Anchor Mooring and Towing Equipment	38.82K	42%	23.27K	11%	3.26K	1%	21.78K	18%
4131.440 - Miscellaneous Systems	3.90K	4%	29.27K	14%	13.84K	6%	15.67K	8%
4131.503 - Lifesaving, Safety and Emergency Equipment	10.26K	11%	14.31K	7%	7.44K	3%	10.67K	7%
4131.601 - Main Engines	17.74K	19%	101.28K	48%	182.35K	81%	100.46K	50%

In addition to the increased running repair costs found in the end of 2017 and beginning of 2018, DD Cost/ARV indicate a small repair in April 2017 and a larger one in March 2018. According to the knowledgable bodies of JV, the small repair was due to a yearly alignment check of the propulsion line. Based on these findings the turbos were also replaced, resulting in higher costs.

The next year, Tug 27 had its 10 year special at a cost of €396.26K. This is near the upper side of the standard deviation of all dry dockings and above that of all special surveys, shown in fig. 10.31. The main cost drivers for this docking where found to be propulsion and main engine related which have both been found to be main cost- and process drivers, as shown in fig. 10.19.

DD_ID	Age @ DD	DD Costs	DD Type	Port	Start Date	Duration [days]	SFI Code I	SFI Code II	Note
DD[redacted]_1701	9	31.89K	ED	[redacted]	17 April 2017	5	4131.601 - Main Engines	4131.410 - Navigation Equipment	GPS Turbo's
DD[redacted]_1801	10	396.26K	SS		01 March 2018				
Total	**10**	**428.14K**							

Figure 10.30: Dry docking information of Tug 27.



Number of special surveys	29
Maximum	672.44K
Minimum	71.53K
Median	249.65K
Mean	253.49K
Standard Deviation	134.56K

Figure 10.31: Violin plot of special surveys including data details.

Based on the conclusions found, it would be advised to continue to closely monitor the maintenance costs and actions performed for the Tug 27. Similar to the Tug 26, it would be advised to operate it at the port of Port E for a period. If indicators don't improve it would be advised to see if the vessels is fit to keep operating within the fleet or possible replacement of the main engine with an engine with known lower maintenance costs. Another suggestion is to not install Caterpillar 3516B-HD DITA engines in future tugs, based on their increased costs.

10.3.3. Tug 6

Tug 6 is a 55t BP ASD tug operating the port of Tug 12. Its 21 years of age makes it older than the prior discussed tugs. It operates as a 24/7 tug, meaning it operates around the clock.

Name	Tug 6
Tug Type	ASD
Sister code	009
Age	21
BP	55t
Design	Aarts Marine BV
Nr of ME	2
ME Power	4500 kW
ME Maker	Deutz
ME Type	SBV8M628
Nr of Aux	2
Aux Maker	MAN
Aux Type	D2866 E
Nr of Thrusters	2
Thruster Maker	Schottel
Thruster Type	SRP 1212 FP

During the operational years of 2016 and 2017 Tug 6 has been operating very well. It's number of tugmoves and running hours are high due to it operating 24/7. As a result the indicators of maintenance and repair cost/RHr is significantly lower for these two years. The total maintenance cost/ARV also show this as they are well below the first quartile of 2.5% as suggested in fig. 8.7 by Gulati [2013].

What does stand out is its performance in the year of 2018. It can be noticed that the amount of running hours and tugmoves have decreased and the cost of running repairs in combination with a dry docking action, has resulted in an increase of both cost as a percentage of the ARV, RHrs and TM. The increase in costs which resulted in this increase can be found in May 2018. Detailed info in running repairs show that large costs were made for '4131.264 - Hull & Fendering'. The significant reduction in running hours and tugmoves suggest that the Tug 6 has been operating fewer hours due to hull repairs. This can also clearly be seen in table 10.10, which shows the top 5 cost drivers for Tug 6. The rest of the running repair costs are within reason of fleet and tug type averages.

Year	TM	RHrs	MR Cost / ARV	MR Cost / RHr	RR Costs	RR Cost/ARV	RR Costs / RHrs	RR Cost/TM	DD Costs	DD Cost/RHr	DD Cost/ARV	RHrs/ TM	RR FC Check
2016	2,218	3,718	1.15 %	24	89.70K	1.15 %	24.12	40.44				1.68	98.93K
2017	3,873	3,028	0.22 %	6	16.80K	0.22 %	5.55	4.34				0.78	86.16K
2018	1,834	1,113	7.04 %	494	216.89K	2.78 %	194.92	118.26	332.59K	298.90	4.26 %	0.61	47.97K
Total	**7,925**	**7,859**	**5.65 %**	**83**	**323.40K**	**1.38 %**	**41.15**	**54.35**	**332.59K**	**42.32**	**4.26 %**	**0.99**	**233.52K**

Figure 10.32: [Summary of maintenance performance indicators for Tug 6.

Table 10.10: Top 5 systems by running repair cost and percentage by year for Tug 6.

Year	2017		2018		Yearly Average	
Equipment	Amount [€]	%	Amount [€]	%	Amount [€]	%
4131.264 - Hull & Fendering	0	0%	185.49K	86%	92.75K	43%
4131.503 - Lifesaving, Safety and Emergency Equipment	4.54K	27%	1.16K	1%	2.85K	14%
4131.601 - Main Engines	1.49K	9%	14.86K	7%	8.18K	8%
4131.630 - Propellers, Transmission, Foils	0K	0%	4.39K	2%	2.20K	1%
4131.850 - Electric Systems	1.74K	10%	6.79K	3%	4.27K	7%

Looking at the only sister vessel, Tug 7, the difference between these two regarding running repair costs is small. There is an insignificant difference in RR cost/RHr and TM which is found between the two vessels. The main difference is due to the increase running repair costs associated with hull & fendering repairs. Leading to the conclusions that the running repair costs/RHr and TM are found to about the same between 24/7 tugs and tugs operating in blocked schedules.

The dry docking occurrence in February 2018 have contributed to the increased total maintenance cost/ARV. The total amount of dry docking costs, €332.59K, is just within the upper limit of €388.05K for a special survey dry docking. The duration of this dry docking is also higher than generally for a special survey. Feedback from the technical department of JV have confirmed that this specific dry docking was abnormal due to a number of reasons. The first being that unexpected tasks lead to increase duration of the dry docking. Secondly, that the work required consisting of an overhaul of the main engines, auxiliaries and propulsion, which are all considered to be main cost drivers (fig. 10.19). This resulted in this specific dry docking to be both high is cost and duration.

DD_ID	Age @ DD	DD Costs	DD Type	Port	Start Date	Duration [days]	SFI Code I	SFI Code II	Note
DD_[redacted]_1801	21	332.59K	SS	[redacted]	05 February 2018	26			
Total	**21**	**332.59K**							

Figure 10.33: Dry docking information of Tug 6.

10.3.4. Tug 41

The Tug 41 is one of the high BP tugs within the fleet of JV. With its 96t BP and its two main engines with 5420kW each, its considered an excessive amount of BP for the towage operations and requirements by various ports by staff within JV. During the years of 2016 through 2018, it has operated multiple ports including; Port F and Port G in 2016; Port B, Port F and Port G in 2017; and Port F and Port G in 2018. It is found that the vessel often switches between Port F and Port G within a year as they are rather close to each other.

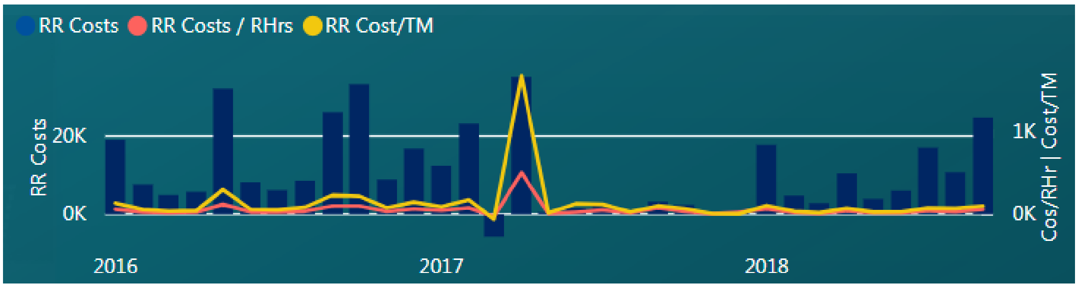
Figure 10.34b shows that during 2016 and in the beginning of 2017, Tug 41 has experienced occasional increased running repair cost, however the running repair cost/RHr and TM stay relatively constant aside from one instance in April 2017. This is due to the shift of the tug towards a different location. Halfway through March the tug was relocated towards Port B and started operating there halfway through April. This resulted in the increase of RR cost/TM but a less significant increase in the RR cost/RHr due to the fact that RHrs were made for re-allocation but no TM were made. Interesting to see is that the costs reduce drastically as the vessel operates in Port B and are increased as it operates in Port F again. This is due to reason that the Tug 41 was sent to Port B to cover the dry docking of another vessel, which transferred to Port F. They prepare the vessel for the crossing to Port B and for its operation there which also results in an increase in costs just prior to the re-allocation. Non-priority repairs are then addressed when returning to Port F, as can

Name	Tug 41
Tug Type	ASD
Sister code	006
Age	9
BP	96t
Design	3213 Big Cat
Nr of ME	2
ME Power	5420 kW
ME Maker	Caterpillar
ME Type	C280-8
Nr of Aux	2
Aux Maker	Caterpillar
Aux Type	C9 DI
Nr of Thrusters	2
Thruster Maker	Rolls-Royce
Thruster Type	US 285/4100 CP

be seen in fig. 10.34b. Unfortunately, no detailed information was obtained about the allocation of cost to specific system components in the year of 2016. Therefore, no definitive conclusion can be formed concerning the underlying reasons for the increase of costs in various months, as can be seen in fig. 10.34b.

Year	TM	RHrs	MR Cost / ARV	MR Cost / RHr	RR Costs	RR Cost/ARV	RR Costs / RHrs	RR Cost/TM	DD Costs	DD Cost/RHr	DD Cost/ARV	RHrs/ TM	RR FC Check
2016	1,490	3,328	2.27 %	53	177.20K	2.27 %	53.25	118.93				2.23	138.42K
2017	791	1,390	6.55 %	368	77.09K	0.99 %	55.46	97.46	433.98K	312.21	5.56 %	1.76	99.76K
2018	1,592	2,827	1.26 %	35	98.07K	1.26 %	34.69	61.60				1.78	131.16K
Total	**3,873**	**7,545**	**7.07 %**	**104**	**352.37K**	**1.51 %**	**46.70**	**92.66**	**433.98K**	**57.52**	**5.56 %**	**1.95**	**369.34K**

(a) Summary of maintenance performance indicators for Tug 41.



(b) Monthly running repair costs, running repair cost per RHr and TM for Tug 41.

Figure 10.34: Maintenance performance indicators and timeline of Tug 41.

Figure 10.34a shows the similar increase of both RR cost/RHr and TM in 2016 and 2017. The cost/RHr and TM reduce when the vessel operated one location and doesn't lose non-effective operating hours. Comparing this with its sister vessels, Tug 30 and Tug 37, the Tug 41 is operating above 32.28 and 37.63 RR cost/RHr for respective tug type average and sister vessel average. The difference between sister vessels is again explained by Tug 41 shifting operating location while Tug 30 and Tug 37 both operate in the Port of Tug 12 during the year 2016, 2017 and 2018. The reduction in tugmoves as a result of re-allocation can also be seen between Tug 41, average of tug type and average of sister vessel, which are 92.66, 45.00 and 57.54 respectively for RR €/TM.

Data obtained from Tug 41 does include maintenance time information for years 2016 and 2017. This shows that during 2016 the tug has been operating within the target of operating 350 days per year. However, 2017 the tugs has experiencing longer downtime as a result of a dry docking in October 2017. This dry docking activity can also be found in fig. 10.34a.

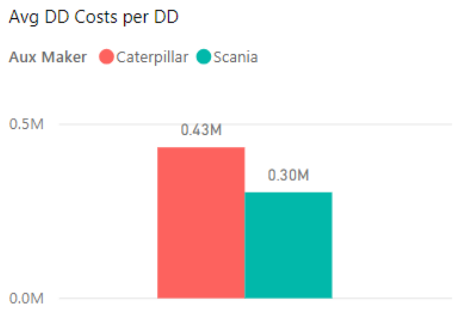
Year	# of Prev Actions	# of Corr Actions	% Prev	# of DD	Total Downtime	Avail. %
2016	10	8	70 %		4.50	98.77 %
2017	4	4	86 %	1	23.92	93.45 %
2018						
Total	**14**	**12**	**79 %**	**1**	**28.42**	**96.11 %**

Figure 10.35: Availability of Tug 41.

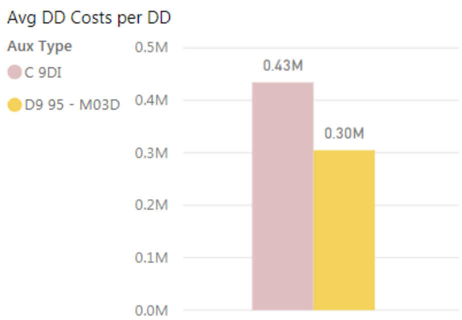
The dry docking in October of 2017 cost €433.98K for an intermediate survey which was driven by an auxiliary engine overhaul. Within the dataset, the Tug 63 and Tug 59 also experienced auxiliary engine overhauls. It can be found through fig. 10.37 that auxiliary costs are known to be cost drivers for dry docking, within the known dataset. It can be seen that the C9 auxiliary of Caterpillar shows increased yearly average costs compared to the Scania D9 95. A more detailed split of the different costs allocated to a system can give more conclusive evidence of underperforming auxiliary engines. Nonetheless, the technical department could verify that the Caterpillar C9 auxiliary engines are notorious for their larger costs are more frequent failure. The decreased performance of the C9 has also been discussed and shown in fig. 10.22.

DD_ID	Age @ DD	DD Costs	DD Type	Port	Start Date	Duration [days]	SFI Code I	SFI Code II	Note
DD_[redacted]1701	8	433.98K	IS	[redacted]	23 October 2017	19	4131.651 - Auxiliary Engines		Overhaul AE's
Total	**8**	**433.98K**							

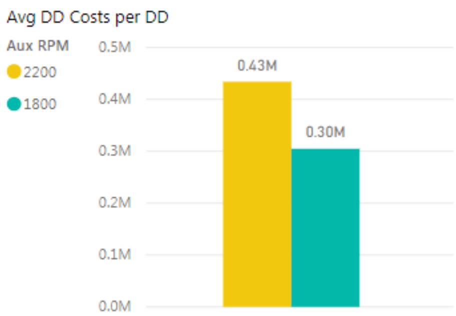
Figure 10.36: Dry docking information of Tug 41



(a) Yearly average dry docking costs for different auxiliary manufacturers for tugs with known auxiliary overhauls



(b) Yearly average dry docking costs for different auxiliary types for tugs with known auxiliary overhauls



(c) Yearly average dry docking costs for different auxiliary RPM for tugs with known auxiliary overhauls

Figure 10.37: Detailed evaluation of auxiliary engine manufacturers, auxiliary engine types and RPM

Using the information presented above the following conclusions have been made. Tug 41 has been operating averagely with respect to running repairs. 2016 has shown higher costs which shows in both RR cost/ARV, RHr and TM, and compared to eq. (10.1). Operating the vessels at a single location and minimising re-allocation of the tug may result in the vessel operating closer to its sister vessels, in terms of RR cost/RHr.

The excessive total maintenance cost/ARV has been found to be a result of higher dry docking costs associated with an intermediate survey in which the auxiliary engines have been overhauled. Assuming that these costs are mostly driven by costs associated with the overhaul performed, it was found that the Caterpillar C9 auxiliary engine shows higher yearly average costs. General conclusions regarding this auxiliary engine similarly shows increase running repair costs for this engine. This conclusion is seconded by the technical department of JV. Further detailing of information regarding cost allocation of individual dry docks could help strengthen this conclusion.

From the management perspective of Boskalis Towage, this information can be used in the consideration of new build projects and can help with the decision-making of installing auxiliary engines types and the selection of certain manufacturers. It would be ill-advised to install Caterpillar C9 auxiliary engines in future tugs, based on the known data.

10.3.5. Tug 35

The Tug 35 in a 10 year old ASD 2810 tug which operates as a 24/7 tug in the Port of Tug 12. The tug has not had any re-allocation within the dataset. From the management tab in the Power BI model, it can be seen that the Tug 35 has the highest yearly average dry docking cost. Together with this knowledge and fig. 10.38, it is found that the vessel has had two dry dockings within the dataset.

Name	Tug 35
Tug Type	ASD
Sister code	012
Age	10
BP	60t
Design	ASD 2810
Nr of ME	2
ME Power	3626 kW
ME Maker	Caterpillar
ME Type	3516B-TA-HD
Nr of Aux	2
Aux Maker	Caterpillar
Aux Type	C4.4
Nr of Thrusters	2
Thruster Maker	Rolls-Royce
Thruster Type	US 285/3350 FP

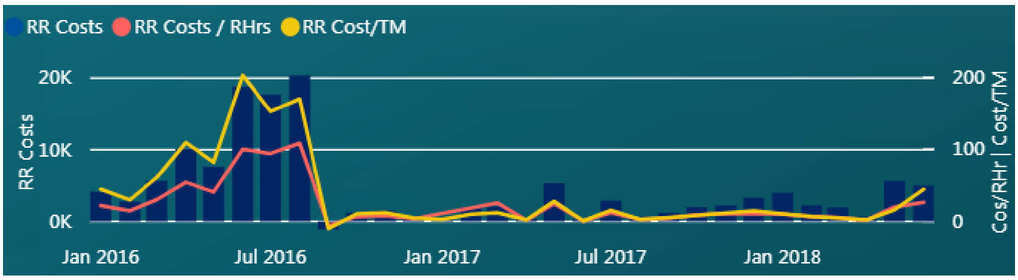
Firstly, looking at the running repair data, it is found that the running repair costs have generally been higher in 2016, ranging between €10K and €20K per month. Unfortunately, no detailed allocation of costs are known and therefore, no knowledge is obtained about the reason for the increase. The last column in fig. 10.38a, showing the calculation using the stepwise regression analysis, shows a minor difference between it and the actual running repair costs. This is however relatively small in comparison with prior found differences as a result of increased running repair costs, such as Tug 6 in fig. 10.32. The RR cost/RHr and TM are also around the average of both tug type and sister vessels, which are 20.27, 32.28, and 24.45 respectively for RR cost/RHr and 28.93, 45.00, 31.90 respectively for RR cost/TM.

Detailed running repair costs are inconclusive about the reason for the increased cost/RHr during a large period of 2016. However, upon further discussion with the JV, it was found that the Tug 35 has shifted towards a 24/7 operating tug within Port A about 1.5 years ago. This drastically increases the running hours of the tug vs the costs it makes. As a result, the RR cost/RHr decreases drastically.

An interesting notice is the change in RHrs/TM from the year 2016 compared to 2017 and 2018. The increase in the amount of RHrs for the 2016 may be due to the issues which shows increased costs in 2016, but also due to the dry docking which took place in 2016. The third possibility could be that the Tug 35 was assigned as an 24 hour vessel from 2017 and as a result has had a decrease RHr/TM.

Year	TM	RHrs	MR Cost / ARV	MR Cost / RHr	RR Costs	RR Cost/ARV	RR Costs / RHrs	RR Cost/TM	DD Costs	DD Cost/RHr	DD Cost/ARV	RHrs/ TM	RR FC Check
2016	1,287	2,256	8.71 %	301	89.42K	1.15 %	39.64	69.48	590.19K	261.61	7.57 %	1.75	59.41K
2017	2,413	2,240	0.29 %	10	22.41K	0.29 %	10.01	9.29				0.93	60.64K
2018	2,408	1,979	3.27 %	129	19.34K	0.25 %	9.77	8.03	235.80K	119.12	3.02 %	0.82	56.80K
Total	**6,108**	**6,471**	**5.86 %**	**148**	**131.17K**	**0.56 %**	**20.27**	**28.93**	**825.99K**	**127.65**	**5.29 %**	**1.06**	**177.38K**

(a) Summary of maintenance performance indicators for Tug 35.



(b) Monthly running repair costs, running repair cost per RHr and TM for Tug 35.

Figure 10.38: Maintenance performance indicators and timeline of Tug 35.

From fig. 10.38a it can be concluded that the main contributors to the decreased performance rating of the Tug 35, based on total maintenance cost/RHr, are the two dry dockings in 2016 and 2018. The second dry docking, occurring in June of 2018, is the second special survey (10 years). The cost and duration of this dry docking is within reason of the fleets average and that of the special surveys. Unfortunately, for this and the dry docking occurring in June 2016, no detailed information was obtained for the dry docking. The dry docking of 2016 shows significantly higher cost, €590.19K. Assuming the age of 8 in 2016, this would mean that the vessel could have undergone an intermediate survey where an overhaul was performed. A follow-up with the technical department has confirmed the assumption of an intermediate survey in 2016. The main items on the request for approval for expenditure where; top end overhaul of main and auxiliaries (including turbo chargers, coolers and starting devices), maintenance of both thrusters and fore winch, replacement of clutch couplings, modification of boxcoolers and cleaning of all tanks. The budget request was submitted for €387K, however resulted in a substantially larger total of €590,19K. The inclusions of many cost drivers in the intermediate survey have resulted in excess in costs for this particular dry docking. It would be advised to better consider what work to perform within a specific dry docking. Including to many activities will evidently result in going over budget.

DD_ID	Age @ DD	DD Costs	DD Type	Port	Start Date	Duration [days]	SFI Code I	SFI Code II	Note
DD_[redacted]_1601	8	590.19K		[redacted]	01 June 2016				
DD_[redacted]_1801	10	235.80K	SS	[redacted]	11 June 2018	19			10 year
Total	**10**	**825.99K**							

Figure 10.39: Summary of dry docking information of the Tug 35

10.4. DEA

As discussed in section 8.6, aside from the use of the Microsoft Power BI model, this research has looked into an alternative way of performance analysis on the maintenance data. Data Envelopment Analysis (DEA) presented itself in literature as a way of measuring performance based on multiple input and output. The functionality of DEA is tested through its implementation and through discussion of the results. Even though the aim in this research is to introduce a basic describing performance analysis method, it will give a first insight in the opportunities of implementation and discusses possible improvement for future development. The code which has been used to run the DEA analysis is shown in appendix J.

Based on the available data, the following variables have been selected for the DEA performance analysis; running repair costs, dry docking costs, running hours and tugmoves. The fuel oil consumption and maintenance process data have been left out of consideration due to the low data quality. The DEA method aims to reduce the input, and increase the output. Therefore, the variables concerning costs are labelled input variables while the operational variables are the output.

Based on the results found in section 10.1, regarding the regression between the different variables, it has been decided to implement a non-increasing return-to-scale. The slopes of the regression equation, when comparing the operational variables vs cost variables, are positive. However, as the input and output orientation is different due to the DEA method aiming to reduce input, i.e. cost, and increase output, i.e. operational hours, the return-to-scale has been chosen to be non-increasing. This means that it can have either a decreasing- or constant return-to-scale. The constant return to scale has been included as it allows for a more variable model.

Furthermore, the choice has been made to apply a 'non-oriented' orientation which results in a model which searches for the most favourable targets based on both input and output orientation. This allows for selection of both increased operational output or decreased maintenance cost by the DEA method and select target based on the lowest slack towards the efficiency frontier.

The last choice made is defining of the tugmove variable as a 'non-controllable' variable. As it has been concluded that the number of tugmoves is mainly dictated by the market demand at the operational location, the decision has been made to make this variable non-controllable and thus fixed. This allows for the method to focus on cost minimisation and operational maximisation through running hours. As a result, the model will only supply a target output for running hours. The second reason for this is that the method will supply a target for tugmoves which is higher, but does not scale the running hours accordingly. Additional conditions describing the relationship between running hours and tugmoves may fix this issue in the future, however this is recommended for future research due to the increased complexity this brings to this research.

As elaborated in chapter 6, the DEA has been applied to four different scopes; fleet, port, tug type and sister vessels. In addition, the choice was made to attempt to perform DEA for these scopes for both yearly averages and evaluation of each individual year for each tug, which is addressed as 'evaluation by year' from here on.

Prior to presenting the results, a number of conclusions have been made regarding the implementation of the method and the results presented below. The first conclusion concerns itself with the evaluation of tugs within the scopes of the entire fleet and port. In the case of evaluation by year, numerous vessels haven't had any dry docking occurrences within that year. The DEA method requires all input- and output variables to be accounted for and thus required exclusion of data, which is not desirable as this reduced the strength of discriminating capabilities of the DEA method. As a result of the method requiring all input- and output variables to be accounted for, DEA is unable to compare tugs with no dry docking costs. This issue often occurs when performing evaluation by year. It has therefore been decided to not include the results for evaluation by year as the absence of dry docking data would only result in an evaluation of running repair maintenance costs while including the dry docking costs is also desired. This also is the case when evaluating at port level. In addition, the shifting of vessels between different ports within the given year resulted in increased complexity for the DEA model and resulted in unfair evaluation of tug performance due to the large differences in maintenance cost and operational hours within that port. The additional challenge of RHrs not being linked to a specific port, for which a temporary solution was made, has lead to the choice of abandoning the port scope evaluation. The results have been presented in appendix K.3, but are considered unsound to base any conclusions on regarding the maintenance efficiency of tugs within each port.

Secondly, as a result of the stepwise regression analysis performed in section 10.1, it was found that the repair cost can be described by vessel characteristics and utilisation. The evaluation of tugs compared to the entire fleet does not take into account technical differences, therefore performance analysis may be considered unlogical and unfair as it can be expected that vessels with a larger installed power operate at a higher cost per running hour or tugmove. Therefore, it is concluded that efficiency scoring can not be done purely based on evaluation of the entire fleet and including the results of the other DEA results is suggested. The extensive results are presented in appendix K, appendix K.2 and appendix K.3.

DEA: Result Summary

To illustrate the use and result from the DEA method, the top 20 lowest maintenance efficiency scores are shown in table 10.14. An extensive list can be found in appendix K.1.

It is found that when evaluating the tugs within their respective sister group, a lot of vessels are considered to be efficient, viewable by the efficiency scores of 1.00. The reason for this is that there aren't enough DMUs to be able to discriminate between different tugs. Sister groups with a larger number of vessels, such as sister group 012, shown in appendix K.5.11 allow for a better evaluation due to the higher number of DMUs. Introducing the DEA efficiency calculation on different tug types increases the amount of tugs to compare to, leading to more inefficiencies. This also helps understand in what respect tugs are deemed inefficient. For example, Tug 6 in table 10.14 shows an efficiency value of 1 when comparing it to the Tug 7, however when comparing it to other ASD tugs, the tug is deemed inefficient. This leads to the conclusions that the sister group, consisting of Tug 6 and Tug 7, are less efficient than other ASD tugs. Tug 7 can also be found within table 10.14 which strengthens this conclusion. The small differences between these two vessels was also found through the Power BI model as well as their lower performance compared to tugs of similar type. The reason for inefficiency may be a result of older age. Tug 6 and 24 are 21 and 22 respectively. Or is may be due to different systems installed. This is one of the downsides of the DEA method, as there is no opportunity to link the reason behind the lower efficiency in other aspects than used for the DEA calculation. Therefore, it is suggested that this method should not be used solely for the evaluation of maintenance efficiency but should be complemented by more detailed business intelligent models, such as the Power Bi Mode, which show underlying fundamentals resulting in these lower efficiencies.

The addition of fleet evaluation in table 10.14 further increases the amount of tugs to compare to, leading to more discrimination and changes in efficiency score. For example, looking at the maintenance performance of RTs in table 10.12a, it is found that the average efficiency performance is 0.88. Comparing the RTs with the rest of the fleet, showing an average efficiency score of 0.39, shows that the RTs show a lower average efficiency. As shown in the Power BI model and through stepwise analysis, it is expected that the efficiency of the RTs is lower as a result of higher maintenance costs due to increased number of components and larger bollard pull. This can also be concluded based on the efficiency difference between tug type evaluation and fleet evaluation in DEA. This makes RTs the worst performing tug type with the lowest average maintenance efficiency within the fleet. The choice was made to incorporate the RT Hybrid with the RTs to be able to compare them to the normal RTs. It is of interest to see whether these perform better. The results are shown in

Table 10.11: DEA results for RT tug types.

Name	Tug Type	Efficiency Score
Tug 13	RT Hybrid	1.00
Tug 15	RT Hybrid	1.00
Tug 16	RT hybrid	1.00
Tug 17	RT	1.00
Tug 19	RT	1.00
Tug 36	RT	1.00
Tug 34	RT	0.83
Tug 14	RT	0.78
Tug 18	RT	0.46
Tug 20	RT	0.37

Table 10.12: Summary of efficiency results for DEA evaluation of tug types and entire fleet.

(a) Fleet and Tug Type efficiency of ASD Tugs.

	Fleet	Tug Type
Nr. of tugs	36	36
Mean	0.49	0.50
Max	1.00	1.00
Min	0.13	0.13
Stdev	0.30	0.30

(b) Fleet and Tug Type efficiency of ATD tugs.

	Fleet	Tug Type
Nr. of Tugs	7	7
Mean	0.82	0.94
Max	1.00	1.00
Min	0.52	0.60
Stdev	0.21	0.14

(c) Fleet and Tug Type efficiency of Conventional tugs.

	Fleet	Tug Type
Nr. of Tugs	2	2
Mean	0.87	0.92
Max	1.00	1.00
Min	0.75	0.84
Stdev	0.13	0.08

(d) Fleet and Tug Type efficiency of RT tugs.

	Fleet	Tug Type
Nr. of Tugs	10	10
Mean	0.45	0.84
Max	1.00	1.00
Min	0.27	0.37
Stdev	0.21	0.23

(e) Fleet and Tug Type efficiency of VSP tugs

	Fleet	Tug Type
Nr. of Tugs	5	5
Mean	0.62	0.93
Max	0.91	1.00
Min	0.42	0.63
Stdev	0.17	0.15

table 10.11, in which it can be clearly seen that RT hybrids outperform the normal RTs. This may be a result of the vessels being younger of age, however the Tug 13 is about the same age as Tug 20, Tug 18, Tug 34 and Tug 36. The same results can be found in fig. 10.16 as a result of DEA. The RT hybrids perform better in RR cost/RHr compared to the normal RT.

As a result of the larger number of ASD tugs and improved discrimination between tugs, the average efficiency score is almost the same when evaluating tug type efficiency and fleet efficiency. The standard deviation is also larger due to the larger number of tugs with a large variation in age and bollard pull.

Table 10.12 further shows a higher average efficiency for ATDs. This corresponds with the lower maintenance cost per running hour found within the Power BI model. The technical department of JV have supplied a possible reason for the higher performance of ATDs, which may be due to ATDs being less favourable for escort activity and more for berthing and unberthing, as a result of a hull design less capable of indirect towage manoeuvres. These tugs perform shorter operating with shorter constraining loads on engine, drivetrain etc. and thus stay in better condition opposed to tugs which perform escort tasks and have to perform heavily loaded manoeuvres.

Within the department of JV, the question arose whether VSPs where more costly compared to ASDs. table 10.12 that the VSPs have a higher average efficiency compared to ASDs. Results form the Power BI model show that ASDs are generally higher in running repair costs, while VSPs are higher with respect to dry docking cots. It is found that this may be due to the higher average bollard pull and thus installed power of ASD tugs, 63t for ASD compared to 42t for VSP. The increased complexity of VSP leads to the higher dry docking costs for VSP.

Comparing the top 10 underperforming tugs, resulting from DEA and the Power BI model, shown in table 10.13, it is found that there are many similarities between the two methods, 70%. The main reason for the differences between the two is may be due to the fundamental difference in how DEA calculated efficiency scores for the tugs. In contrary to performance indicators which show a ratio, in this case maintenance cost RHr, the DEA approach scores the respective tug based on their slack or room to improve.

According the maintenance performance indicator, Tug 29 is underperforming due to its high MR cost/RHr (€129). Appendix K.4.1 shows that, even through Tug 29 has a relatively high yearly average dry docking costs, there is no slack based on peer tugs and thus an efficiency of 1 is granted. This is a result of the relationship between running repair costs, dry docking costs and RHrs. Wheer Tug 29 operates at almost the lowest running repair cost per RHr (€16). Looking at dry docking, Tug 29 is underperforming with a cost of €111.71 per RHr. DEA calculates the available slack for the underperforming dry docking cost per RHr. The slack for dry docking affects the ratio between running repairs and the RHrs. As the ratio between running repair costs and RHrs is already considered to be as low as possible, the tug is operating at its most efficient state according to DEA. It seems that this is one of the flaws in the use of DEA for this case.

One may also argue, as concluded in section 10.1, that as a result of RHrs not being correlated with dry docking costs, the use of a relation between dry docking costs as input and RHrs as output is questionable. It would therefore be recommended to split the evaluation the running repair- and dry docking costs into two separate DEA models. It would be advised to look for other variables which impact/affect dry dockings and perform similar DEA with the respective variables.

Table 10.13: Top 10 underperforming tugs from PBI model and DEA tug type evaluation.

Top 10 PBI	Top 10 DEA	DEA Efficiency Score
Tug 26	Tug 26	0.13
Tug 27	Tug 27	0.14
Tug 6	Tug 22	0.18
Tug 41	Tug 6	0.24
Tug 35	Tug 30	0.24
Tug 7	Tug 39	0.27
Tug 29	Tug 59	0.28
Tug 30	Tug 35	0.28
Tug 25	Tug 25	0.29
Tug 34	Tug 41	0.29

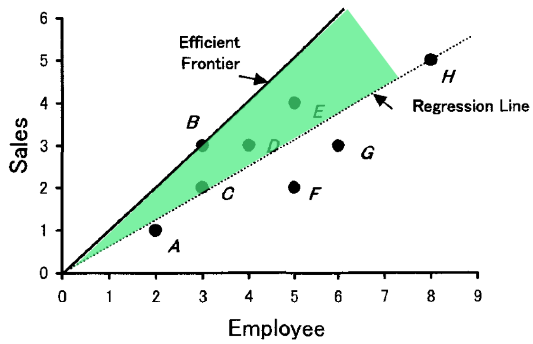


Figure 10.40: Performance region between DEA efficienct frontier and regression line.

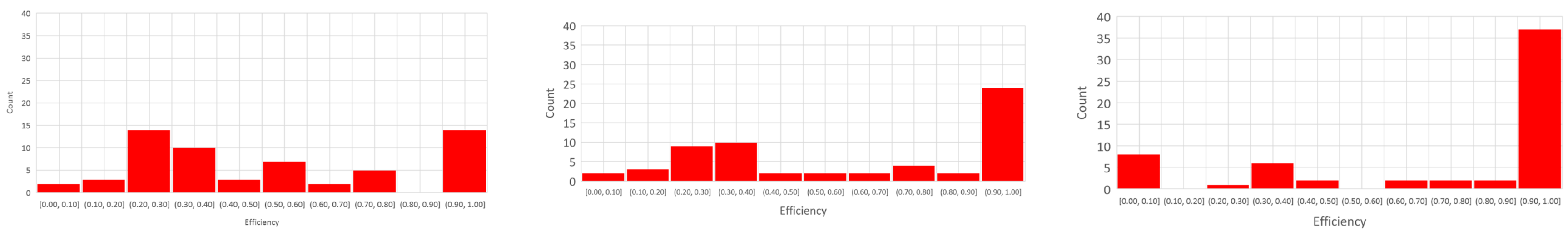
The basic DEA method utilised in this research shows that is capable of measuring maintenance performance between the different vessels. It allows for the determination of underperforming vessels based on multiple variables rather than on one indicator, such as maintenance cost per running hours. However, due to the nature of maintenance which is dependent on various factors and probability of failure, the DEA method shows flaws. Evaluation at fleet level and port level does not take into account technical differences between the tugs. This leads to results that larger tugs, prone to increased maintenance cost, or tugs which are notorious for higher maintenance costs could achieve far lower target maintenance costs which can be considered unfeasible in practice. Nonetheless, the DEA approach can be used to effectively identify underperforming tugs, similar to the Power BI model. Moreover, the model may be to simplistic in describing the full maintenance process. However, this basic model shows the capabilities of DEA which allow for quick peer evaluation and determining of targets based on room for improvement. It is concluded that DEA is an interesting addition and complements the Power BI model, but can not be used individually as it misses detailed data to understand the underlying effects of the efficiency results. From a management perspective, the method of DEA bears fruit as it allows for fast evaluation.

Based on the current available data used to construct and perform DEA, it is concluded that the results for the determining of efficiencies holds. However, the targets resulting from the DEA hold less strength as a result of low data quality and the assumed relationship between RHrs and dry docking costs.

The resulting targets from the DEA can also be used to some extent. As discussed in section 6.2, DEA supplies an efficient frontier, which may seem unfeasible due to limitations of the basic model, but may still be used to create a performance region as shown in fig. 10.40. The resulting targets from DEA form the 'optimal' maintenance performing position, while the regression line can be considered a 'target' to perform below this value. Maintenance results which situate the vessel outside the area between the regression line and the efficient frontier can be labelled as underperforming. Seen as only an equation describing the running repair costs could be established through regression analysis, only individual targets can be established for running repair. Targets for dry docking costs are not presented as no equation could be established through stepwise regression. The resulting targets and optima for each individual vessel are presented in section 10.5.

Table 10.14: Summary of top 20 DEA results for fleet, tug type and sister vessel evaluation.

Input							DEA: Fleet				DEA: Tug Type				DEA: Sister Vessels			
Name	Type	Sis Code	RR Costs [x €1,000]	DD Costs [x €1,000]	RHrs	TM	Efficiency Score	RR Costs [x €1,000]	RR Costs [x €1,000]	RHrs Target	Efficiency Score	RR Costs [x €1,000]	DD Costs [x €1,000]	RHrs Target	Efficiency Score	RR Costs [x €1,000]	DD Costs [x €1,000]	RHrs Target
[redacted]	ASD	008	71.51	94.59	791	500	0.13	10.90	5.98	791	0.13	10.77	6.69	791	0.34	22.64	37.56	791
	ASD	008	215.75	142.71	2,703	1,885	0.14	31.05	19.96	2,703	0.14	30.99	20.31	2,703	0.47	63.42	127.46	2,703
	ASD	018	116.64	99.94	2,015	1,690	0.16	21.31	12.31	2,089	0.18	26.46	17.54	2,384				
	ASD	006	70.46	162.27	1,938	1,538	0.22	20.04	11.86	1,938	0.24	24.07	15.95	2,169	0.76	57.63	100.52	1,938
	ASD	009	107.80	110.86	2,627	2,564	0.24	38.20	24.63	3,506	0.24	40.15	26.61	3,618	1.00	107.80	110.86	2,627
	ASD	012	45.29	38.72	1,311	1,043	0.27	13.53	7.98	1,311	0.30	16.32	10.82	1,471	0.30	16.32	10.82	1,471
	ASD	012	36.94	233.50	1,769	1,739	0.27	9.42	85.75	1,861	0.27	9.42	85.75	1,861	0.40	27.22	18.04	2,453
	ASD	016	94.66	122.66	2,769	2,709	0.27	40.99	26.66	3,740	0.28	42.41	28.10	3,822	1.00	94.66	122.66	2,769
	ASD	007	85.34	72.60	2,466	1,906	0.28	25.94	15.82	2,466	0.30	29.84	19.77	2,689	1.00	85.34	72.60	2,466
	ASD	012	43.72	275.33	2,167	2,089	0.28	11.32	103.03	2,237	0.28	11.32	103.03	2,237	0.41	32.71	21.68	2,947
	ASD	008	28.93	154.82	1,367	1,776	0.29	9.63	87.61	1,902	0.29	9.63	87.61	1,902	0.29	9.63	87.61	1,902
	RT	003	101.38	217.13	2,476	1,470	0.29	37.11	20.19	2,476	0.83	93.73	143.59	2,525	0.83	93.73	143.08	2,520
	ASD	006	125.70	144.66	2,515	1,337	0.29	42.67	23.35	2,515	0.29	42.42	24.80	2,515	1.00	125.70	144.66	2,515
	ASD	007	106.28	75.16	2,197	1,290	0.29	33.54	17.40	2,197	0.30	33.10	19.95	2,197	0.64	77.02	62.54	2,574
	ASD	009	43.37	159.47	1,758	1,678	0.29	9.09	82.74	1,796	0.29	9.09	82.74	1,796	1.00	43.37	159.47	1,758
	RT	001	158.35	73.14	2,140	848	0.30	45.75	23.89	2,140	0.52	92.64	24.94	2,140	1.00	158.35	73.14	2,140
	ASD	006	53.04	101.30	1,986	1,653	0.30	20.59	11.78	2,029	0.34	25.87	17.15	2,332	1.00	53.04	101.30	1,986
	ASD	012	84.07	32.17	2,102	1,974	0.31	26.80	16.31	2,550	0.34	30.91	20.49	2,786	0.34	30.91	20.49	2,786
	ASD	012	65.96	98.83	2,272	2,226	0.31	31.66	19.86	2,958	0.32	34.85	23.10	3,141	0.32	34.85	23.10	3,141
	ASD	008	78.48	184.32	2,794	2,716	0.31	41.12	26.76	3,752	0.31	42.52	28.18	3,831	1.00	78.48	184.32	2,794



(a) DMU efficiency distribution for entire fleet DEA evaluation.

(b) DMU efficiency distribution for tug type DEA evaluation.

(c) DMU efficiency distribution for sister vessel DEA evaluation.

Figure 10.41: DMU efficiency distribution for different DEA scopes.

	(a)
Mean	0.55
Max	1.00
Min	0.13
Stdev	0.29

	(b)
Mean	0.66
Max	1.00
Min	0.13
Stdev	0.34

	(c)
Mean	0.84
Max	1.00
Min	0.04
Stdev	0.37

10.5. Benchmark Targets

One of the goals of this research was to see whether it would be able to determine possible improvement for individual vessels. Using eq. (10.1), results from the Power BI model and targets from DEA analysis the following benchmarking targets are established for individual vessels and thus room for improvement are determined. These are referred to as upper- and lower bound, respectively. The actuals shown in table 10.15 are the yearly averages used for the calculation within DEA. The upper- and lower bounds presented below are yearly maintenance cost per vessel for the year 2019.

It has been concluded in previous section that the lower bound for dry docking, resulting from DEA, are considered weak as a result of low data quality. Therefore, the use of the lower bound is not advised. The DEA results for running repair costs are considered to be sound and are therefore found to be capable of describing a performance region. Both the results of DEA and the calculations using eq. (10.1) are presented in table 10.15 for the year 2019. The actual costs are the yearly average costs for the years 2016-2018.

Table 10.15: Summary of maintenance targets and optima for running repair costs.

Name	Tug Type	Actual	Upper bound	Lower bound
		RR Costs [x €1,000]	RR Costs [x €1,000]	RR Costs [x €1,000]
Tug 1	ATD	37.84	46.42	37.84
Tug 2	Conv	-	59.18	-
Tug 3	ASD	58.17	64.00	58.17
Tug 4	ATD	-	-	-
Tug 5	ASD Hybrid	-	17.29	-
Tug 6	ASD	107.80	80.83	40.15
Tug 7	ASD	43.37	61.33	9.09
Tug 8	Conv	76.95	67.77	64.67
Tug 9	ASD Hybrid	-	15.49	-
Tug 10	RSD	-	-	-
Tug 11	VSP	-	66.52	-
Tug 12	ASD	-	-	-
Tug 13	RT Hybrid	87.12	101.07	87.12
Tug 14	RT	70.77	91.49	68.92
Tug 15	RT Hybrid	76.50	66.45	76.50
Tug 16	RT Hybrid	48.82	82.76	48.82
Tug 17	RT	98.71	106.58	98.71
Tug 18	RT	151.09	98.84	78.41
Tug 19	RT	169.65	108.30	169.65
Tug 20	RT	158.35	97.51	67.28
Tug 21	ASD	52.67	75.86	31.35
Tug 22	ASD	116.64	61.74	26.46
Tug 23	ASD	48.48	98.17	48.48
Tug 24	ASD	33.37	45.67	30.97
Tug 25	ASD	28.93	53.28	9.63
Tug 26	ASD	71.51	41.80	10.77
Tug 27	ASD	215.75	81.39	30.99
Tug 28	ASD	32.58	47.66	32.44
Tug 29	ASD	26.15	51.66	26.15
Tug 30	ASD	70.46	112.30	24.07
Tug 31	ASD	33.05	51.83	33.05
Tug 32	ASD	65.96	62.69	34.85
Tug 33	ASD	45.29	53.95	16.32
Tug 34	RT	101.38	96.38	93.67
Tug 35	ASD	43.72	62.10	11.32
Tug 36	RT	94.45	97.69	94.45
Tug 37	ASD	53.04	113.40	25.87
Tug 38	VSP	39.16	46.58	39.16
Tug 39	ASD	36.94	53.75	9.42
Tug 40	ASD	84.07	59.22	30.91
Tug 41	ASD	125.70	126.25	42.42
Tug 42	VSP	55.12	47.50	37.06
Tug 43	ASD	-	84.68	-
Tug 45	ASD	74.85	57.00	33.31
Tug 45	Conv	55.20	59.62	55.20
Tug 46	ATD	44.10	72.33	44.10
Tug 47	ATD	29.05	64.47	29.05
Tug 48	VSP	40.09	55.47	40.09
Tug 49	ASD	56.82	69.22	56.82
Tug 50	ASD	60.67	69.89	60.67
Tug 51	VSP	27.10	41.83	27.10
Tug 52	VSP	88.16	58.51	88.16
Tug 53	ASD	78.50	90.75	44.20
Tug 54	ASD	106.28	77.27	33.10
Tug 55	ASD	-	107.19	-
Tug 56	ASD	85.34	82.90	29.84
Tug 57	ASD	83.93	86.37	39.83
Tug 58	ASD	-	108.35	-
Tug 59	ASD	94.66	84.43	42.41
Tug 60	ASD	-	80.40	-
Tug 61	ASD	14.37	85.89	14.37
Tug 62	ASD	78.48	80.19	42.52
Tug 63	ASD	76.69	84.88	31.43
Tug 64	ASD	77.17	82.88	52.82
Tug 65	ASD	40.30	43.66	39.00
Tug 66	ATD	25.67	49.81	25.67
Tug 67	ATD	-	59.54	-
Tug 68	ATD	39.85	57.33	26.49
Tug 69	ATD	28.73	61.44	28.73
Tug 70	ATD	17.56	70.41	17.56
Tug 71	ATD	-	60.89	-
Total		**3,983.11**	**4,860.30**	**2,547.63**

Seen as the table 10.15 contains blanks for various tugs, the resulting totals can't be compared. Therefore, they are normalised by calculating the average cost per tug and multiplying this by the total number of vessels. The results are presented below.

Table 10.16: Summary of upper and lower bounds for running repair costs of the entire fleet.

	Actual	**Upper bound**	**Lower bound**
	[x €1,000]	[x €1,000]	[x €1,000]
Avg per tug	66	73	44
Fleet total	4,713	5,150	3,118

In order to improve the quality of the DEA results and its possibility of supplying lower bound for individual tugs, the main recommended improvement is to improve data quality. For dry docking it would be advised to use a dataset with at least a full maintenance cycle, which is at least 5 years, for each vessel. This ensures that the data includes both intermediate surveys and special surveys. Secondly, as stated in previous section, it may be advised to split DEA evaluation of running repair and dry docking into to separate model.

In section 8.4.5 the best practice benchmark table presented by Gulati [2013] was presented and adopted for the first evaluation of the model (fig. 8.7). As it was stated that best practice benchmark are different for every market. Therefore, for future maintenance evaluation of tugs, a new best practice table has been constructed which resembles Gulati his table but with the MPIs for which sound quartile values could be obtained. The proposed quartiles are presented in table 10.17. These values can be used to determine whether tugs require a more detailed evaluation of either their running repairs or dry docking activity for that year.

Table 10.17: Best practice quartiles for maintenance performance indicators, based on the dataset.

		Quartile		
	Unit	I	II	III
Maintenance and Repair - Running Repair Cost				
Total Average Running Repair Cost	K€	35	69	89
Running Repair Cost per Running Hour	€/RHr	24	32	50
Running Repair Cost per Tugmove	€/TM	33	65	113
Running Repair Cost as % of Asset Replacement Value (ARV)		0.45%	0.88%	1.15%
Maintenance and Repair - Dry Docking Cost				
Total Average Dry Docking Cost	K€	72	218	304
Dry Docking Cost per Running Hour	€/RHr	37	102	183
Dry Docking Cost per Tugmove	€/TM	78	163	307
Dry Docking Cost as % of Asset Replacement Value (ARV)		0.92%	2.80%	3.90%
Maintenance and Repair - Total Cost				
Total Maintenance and Repair Cost	K€	106	287	393
Total Maintenance Cost per Running Hour	€/RHr	61	134	233
Total Maintenance Cost per Tugmove	€/TM	111	228	420
Total Maintenance Cost as % of Asset Replacement Value (ARV)		1.37%	3.68%	5.05%
Maintenance and Repair - Maintenance Process				
Preventive and CBM/PdM Time as % of Total Running Repair Time		60%	40%	20%
Availability		93.27%	95.03%	97.57%

10.6. Intermediate Conclusions Chapter 10

This chapter has presented the results from stepwise regression analysis performed on known variables associated with maintenance. Moreover, this chapter has presented results and conclusions regarding maintenance with use of the Power BI model on the case study of JV. Furthermore, this chapter contains results and conclusions on an alternative way of performance analysis through DEA. Within this chapter, the following conclusions were made.

Stepwise linear regression analysis in section 10.1 has resulted in knowledge concerning the relationship between different variables. From this an equation was formed which is able to describe the running repair costs within the dataset with acceptable statistical accuracy, presented in eq. (10.2), which is a function of running hours, age and bollard pull. The establishing of an equation describing dry docking was unfruitful.

$$\text{Running Repair Costs} = 20.760 * \text{RHrs} + 1569.609 * \text{Age} + 1620.280 * \text{BP} - 97203.077 \tag{10.2}$$

With this knowledge an evaluation of the statement made by Stopford [2009], which states that the average annual maintenance costs increase by about 2.2 between the age of 0-5 and 16-20. Figure 10.10 presents the differences in running repair costs by age for different running hours and bollard pull. It was found that the assumption made by Stopford accurate to some extent. However, it is been found that this increase is also dependent on various other factors as stated by Stopford.

With use of the Power BI model, various findings and conclusions were made regarding the maintenance performance of the fleet in the JV scope which could be useful for management within Boskalis Towage. Table 10.1 presents a summary of the historical data of yearly average running repair- and dry docking costs as well as values for the maintenance performance indicators; maintenance RHr intensity (€/RHr) and -TM intensity (€/TM). With this information the management is able to compare future maintenance performance of the entire fleet with historical performance. Furthermore, this information can be used to substantiate the minimal price required to operate at cost price.

As found in this chapter, the maintenance costs and indicators discussed above are not equal across the entire fleet as stepwise regression has shown that these are a function of bollard pull, RHrs and age. And due to the fact that different tugs operate at different ports, this has shows that variations at these ports can be lead back to an underperformance of a specific tug, type of tug with increase average costs, while taking into account port specifics. Figure 10.11 in an exemplary table which shows port performance. Detailed evaluation of fuel oil performance per tugmove can be made. However, this is not the focus of this research as it aims to increase the understanding of maintenance and its performance. Tug type evaluation in fig. 10.16 has found and presented the difference in average running repair costs between different tug types as a reason for differences in performance of ports.

Furthermore, the Power BI model has presented the top five cost- and process drivers within the dataset. These have been and presented in fig. 10.18. Interesting to see is that various critical systems, discussed in section 3.3, re-emerge as cost- and process drivers. These can be labelled by management as systems which require extra consideration in order to be managed.

The same was done for dry docking activity where similar cost- and process drivers were found. However, as the cost allocation for dry docking is not in detailed and assigned to one or two SFI Group Codes, the results found here hold little merit. However, the technical department of JV could confirm the increased importance of 'Propellers, transmission and foils' when it comes to dry dockings.

Moreover, this chapter presents historical benchmarking values for dry docking of both different dry docking types (table 10.5) and tug types. In table 10.4 it was shown that VSPs are considered to be most costly when it comes to yearly average costs for dry dockings and per dry docking, followed closely by ASDs. Further detailing of dry docking data will improve the capability of making definitive conclusions regarding dry docking differences across tug types.

The capabilities of the model have been presented through various elaborations of underlying reasons for variations in maintenance performance. Differences in cost performance for three critical systems have been discussed and presented. Conclusions were made on the underperformance in running repairs of main engines; Caterpillar 3516B-HD DITA, 3512C and 3516C-HD. Additionally, underperformance of auxiliary engine Caterpillar C9 was found and confirmed by the technical department of JV. A detailed evaluation of the difference in RPM of main- and auxiliary engines on running repair costs have resulted in an estimated increase for main- and auxiliary engines of 6.47 and 3.89 per RPM, respectively. Moreover, conclusions where made on the increased costs of CPP vs FPP due to their increased complexity and it being more prone to debris. From detailed thruster analysis, it was found that the Schottel SRP 1515 CP is an underperforming thruster with higher yearly average running repair costs.

In order to validate the model, five tugs were selected based on their underperformance in total maintenance cost per running hour (€/RHr). These five tugs; Tug 26, Tug 27, Tug 6, Tug 41 and Tug 35. Through the use of the Power BI Model, these five tugs have been elaborated upon and underlying reasons for their underperformance have been presented. Relaying these findings back to the technical department of JV has lead to the confirmation of many of these found reasons for underperformance.

Whether these five tugs are truly the top five underperforming within the fleet, according to the technical department, is relative as individual opinions may determine a different top five. However, based on the data and the confirmation of underlying reasons for underperformance, it can be concluded that the model has presented underperforming tugs with capability of determining its reason.

The proposed alternative performance analysis to business intelligent evaluation of indicators, DEA, has shown promise. The method has been able to effectively determine underperformance in tugs. Based on the fundamental difference in how DEA calculated the efficiency of tugs, differences have been found between the top 10 underperforming tugs found within the Power BI model and DEA. Moreover, the method has shown similarities is the determination of performance differences between tug types.

However, the method shows flaws when handling data with low quality. As a result, the targets resulting from DEA regarding dry docking are considered to be unsound and are not recommended for use. Furthermore, due to the re-allocation of tugs to different ports and the fix which divided the RHrs of tugs to respective ports based on TM, it is suggested that the results for the evaluation of the tugs within a port is also unsound. Detailed assigning of RHrs of a tug within a specific port may lead to results which can be used for evaluation of performance.

As a result, the capabilities of DEA have been proven to be useful in the quick evaluation of maintenance performance. However, it is advised to split both running repair and dry docking evaluations in two as it has been shown that a tug achieving efficiency in respect to running repairs will not lead to improvements needed in dry dockings. Secondly, it was found through stepwise regression that the available variables and dry docking costs don't have a strong relationship in the first place. Therefore, it is advised to look into other variables which may be able to portray dry docking costs with a higher degree of certainty. Finally, it is advised to use DEA as an additional traditional business intelligent models, such as the Power BI model, as DEA does not allow for the determining of underlying reasons for underperformance.

The results of DEA found for running repair have been used together with eq. (10.2) in order to establish a performance region for each individual tug in order to establish an upper- and lower bound in this the tug is considered to be performing well (table 10.15). As data quality doesn't allow for the determining of running repair costs for the entire fleet, this has been normalised in accordance with the total number of tugs in the fleet. As a result, the upper- and lower bound for running repair costs for the entire fleet have been suggested at €5.15 million and €3.12 million.

11 Conclusions

Transport by sea is one of the most crucial means of global freight transport. 90% of all trade is transported by ships. Through numerous joint ventures, Boskalis contributes to the global transport by supplying harbour towage services around the world. As a result of increased competition in the handling of ships and the consolidation of shipping liners, Boskalis Towage aimes to increase margins through more cost effective delivery of service. To achieve this, Boskalis has turned to business intelligence to help with decision-making.

As part of this improvement plan, the goal was to increase knowledge in both financial and operational aspects from different joint ventures, in order to analyse cost and operational performance. Maintenance and repair was one of the areas in which large variations were seen between the joint ventures as well as within the respective joint ventures. However, the reasons for the deviations were yet unclear due to the lacking of available detailed information and the complexity of benchmarking maintenance.

The maintenance performance model, as presented in chapter 9, constructed within Microsoft Power BI has shown to effectively use detailed information on cost and operational data to perform maintenance performance monitoring of tugs. This was only possible through the establishing of the 'multi-criteria hierarchical function specific' framework on which it is based. The framework portrays the ideal scenario of a model which is able to monitor all key maintenance processes and resulting equipment- and cost performance. With use of available data, a preliminary model has been constructed which is capable of monitoring the maintenance operations. The results from 10.2 and its validation in section 10.3 demonstrate the capabilities of the model to determine underperformance. Difference in port performance have been traced back to specific tug type, tugs or operations and the model has shown the ability to identify efficiency differences between tug types and specific system manufacturers and types.

However, data management and quality has shown to be lacking in various areas. Firstly, a general improvement in the automated registration of maintenance data is a must in order to structure and standardise registration. This alone will lead to improvement in data quality and thus quality of conclusions made. Secondly, the frame of mind within the business needs to change when it comes to data management. Throughout the organisation, the added value of correct documentation and registration of critical information needs to be relayed. Automation will lead the way in the registration of such said data. However, in this transition period human factor is key for both development and quality.

Alongside the maintenance performance management model, an alternative method for performance analysis has been presented. DEA, used for determining inefficiency in production processes, shows promise in the determining of maintenance inefficiencies and benchmarking targets. Although this is a preliminary research in the capabilities of using this method for performance analysis, it has been found that the method and model constructed has potential. The constructed Slack-Based Measure (SBM) model is however a basic model which is a simplistic way of performance analysis of maintenance. Further development and addition of variables, constraints and extensions may prove fruitful in more accurately representing the maintenance function and performance analysis of tugs with different technical specifications and locations.

Through the proposed the multi-criteria hierarchical function specific framework and the erection of the maintenance performance model, this research has shown a way of constructing a maintenance and repair management model for the monitoring of maintenance investments within the current business structure. Moreover, the model allows for the determination and identification of potential areas of improvement across a set case scenario which is a simplification of business structure of joint ventures. This leads to the confirmation that the main research question has been answered. The main research question is repeated below.

> *Can a maintenance and repair management model on costs and performance be constructed to monitor maintenance investments and identify potential areas of improvement across the joint ventures of Boskalis Towage and how will this be shaped, given the current performance management system and business structure?*

The construction of the maintenance performance model and the addition of a performance analysis method, have given Boskalis Towage increased capability of identify potential maintenance and repair improvements through performance monitoring with a high level of detail and has increased their knowledge regarding maintenance and repair. Moreover, the model has presented underperforming tugs as well as cost- and process drivers. The combination of the Power BI model and DEA have resulted in upper- and lower bounds on running repair costs for individual tugs and new quartile values of Maintenance Performance Indicators (MPIs) for future benchmarking purposes.

Further improvements are possible through the increase of data quality. Nonetheless, this research has been able to increase the monitoring capabilities of maintenance investments and as a result can be used to identify areas of improvement. It is therefore found that the research has achieved the research objective, which is stated below.

> *The main goal of this thesis is to increase the possibility to perform detailed monitoring of maintenance and repair expenses and performance of tugs, through which possible improvements can be determined.*

Through the answering of the main research question, whether a maintenance performance model can be established to monitor investment in the current business structure, and this research meeting its objective, increasing the possibility of maintenance performance monitoring, the problem statement has been solved. The problem statement is reproduced below.

> *Currently, Boskalis is not able to effectively use the knowledge of the different joint ventures to identify potential maintenance and repair improvements due to a lack of performance monitoring with sufficient level of detail. This is due to consolidated data and a non-standardised way of performing maintenance.*

As this research aims to identify potential improvements when it comes to maintenance and repair, it also aims to supply possible improvements and/or recommendations for future research. These are discussed in chapter 12.

12

Recommendations for Future Research

A common thread throughout this report has been the search for improvement. This also holds following this research. Therefore, the recommendations for further research discussed in this chapter will include; recommendations on improvement which will help with the current established maintenance and repair performance model, recommendations on the future development of said performance model, and improvements which will allow for the development of the DEA method of performance analysis.

General improvements

Stated at various occasions through this research, data quality is important to be able to effectively perform maintenance performance analysis. In order to increase the completeness of data and therefore increasing data quality as a whole, it is recommended to explore the benefits of an integrated system which simplifies and automates the registration of maintenance and operational data. Through this improvement not only will data be completer, it will also standardise the format in which data is stored. This simplifies the use of this data for analysis. As this research has had great difficulty with the structuring of data from different file formats, it is believed that investing in said data systems will greatly enhance capabilities of data analysis.

Furthermore, it is important to relay the added value of correct and accurate documentation of this information to the respective employees. As not all can yet be automated, it is imperative that the business awareness, when it comes to quality of data, is increased.

As a result of these improvements, the author of this research believes that the model constructed could be linked to a so called dynamic database in which queries are automatically requesting data when maintenance analysis is required or requested from viewpoint of Boskalis Towage.

Secondly, it is recommended to perform an additional stepwise regression analysis for de determining of an adequate equation to describe dry docking costs after determining new variables to describe these costs. Aside from this equation, it may give an opportunity to find relationships between these costs which are more significant than the ones found in this research. A suggestion would be to incorporate duration of dry dockings, as it has been shown that these differ marginally based on type. An alternative method would be to dissect the maintenance activity within dry docking the different maintenance activities, focussed on or linked to survey activities. As a result, based on the expected activities to be performed, one may be able to make a well calculated forecast of the expected dry docking costs.

Future development

Furthermore, this author believes that the model presented in this research is a well functioning model. However, it is expected that a specialist in enterprise information management could construct a more efficient model. The reason for this is that the author has obtained basic understanding of the two programming languages DAX and M within the Power BI program, but is not considered to be an expert.

Moreover, the structuring of the user interfaces have been done from the viewpoint of the author, taking into account user requirements within Boskalis Towage. Experts may be able to construct a more dynamic and user-friendly interface with fewer tabs and other efficient solutions.

The last recommendation regarding the model interface is considering whether the current form should be its final form as monitoring tool. The model has, aside from the goals of monitoring, also been structured to be able to gain knowledge from the data and therefore may be seen as too extensive for the sole purpose of monitoring. Therefore, it should be considered if results and conclusions regarding new benchmarking targets should be taken from this model and used to construct a model which is solely focussed on monitoring.

DEA improvements

The final recommendations concern themselves with DEA. Firstly, it is recommended to research the benefits of splitting the running repair and dry docking costs performance analysis of DEA into two separate evaluations. Together with the recommendation of looking into other variables which may be able to describe dry docking costs, this may give better results when it comes to calculating efficiency scores. It is suggested to still allow for an evaluation of both costs using these newly introduced variables. Based on the assumptions made by Stopford [2009], concerning the ratio between OPEX and CAPEX for maintenance, the addition of a condition or mix between the two should be incorporated in the DEA. The addition of an assurance region or cone-ratio may help with the targeting of the ratio between maintenance OPEX and CAPEX towards a ratio in which these are balanced.

Furthermore, a recommendation would be to see whether dissecting of the consolidated cost would allow for detailed targeting of individual cost categories. For example, dividing costs into spare parts costs, material costs, equipment costs and employee cost may help determine where the highest cost differences are, e.g. slacks, and thus where the most improvements can be made. However, care should be taken in order to not unnecessarily increase complexity of the analysis through the addition of detail.

Thirdly, a recommendation can be made for the improvement of the current DEA model is the addition of categorical variables. Standard DEA models assume continuous, numerical variable values. However, Banker and Morey [1986b] have shown capabilities of incorporating data which is limited to certain discrete values, or are qualitative in nature. This may allow for the addition of a categorical variable which portrays geological and climatic factors for either the influence between RHrs, TM and the resulting costs or for the sake of incorporating the impact of maintenance quality performed at a different location. A second use of categorical variables may be in order to account for technical differences between the respective tugs. Incorporating such a variable will, for example, only make it possible for older vessels to be compared to the similar aged vessels or older. This way older tugs aren't compared to younger tugs with significantly lower yearly maintenance costs. The same can be done for vessels with a higher bollard pull. These two variables have been taken as example as they have been found in this research to be closely related to running repair costs. Further research may show the benefits of the addition of these categorical variables.

Another recommendation would be the addition of maintenance process related variables to the DEA. As data quality was too low to be able to incorporate it in the current DEA model, it is suggested to look into the possibility of adding maintenance process variables to the model. This allows for the inclusions of evaluation of maintenance cost per unit of time between the different tugs. As a result it may be found that certain maintenance actions performed where excessively high in cost or that the vessel had too much downtime as a result of slow MTTR.

Fifthly, one of the downfalls of the current DEA model is that it sets somewhat unpractical lower bound targets for high costing vessels, due to their tug type, bollard pull or age, which may be considered unachievable as a result of being compared to younger tugs. An alternative to the introduction of categorical variable, it may be possible to introduce bounds on the weights which dictate the improvement room for the slacks. This way the DEA limits the maximum slack and thus the room for improvement. However, whether this is a viable option in increasing the fairness of DEA performance analysis needs to be researched.

VI

Appendices

A

Performance Measurement Frameworks

Table A.1: Various performance measurement frameworks with measures and indicators developed by various authors [Parida et al., 2015]

Model/framework	Measures/indicators/criteria	Reference
1. Sink and Tuttle (1989)	Efficiency, effectiveness, quality, productivity, quality of work life and innovation, profitability/budget ability, excellence, survival and growth,	Sink and Tuttle (1989)
2. Du Pont Pyramid	Financial ratios, ROI	Chandler (1977); Skousen *et al.* (2001)
3. PM matrix	Cost factors, non-cost factors, external factors, internal factors	Keegan *et al.* (1989)
4. Results and determinants matrix	Financial performance, competitiveness, quality, flexibility, resource utilization, innovation	Fitzgerald *et al.* (1991)
5. PM questionnaire	Strategies, actions and measures are assessed, extent to which they are supportive? Data analysis as per management position or function, range of response and level of disagreement	Dixon *et al.* (1990)
6. Brown's framework	Input measures, process measures, output measures, outcome measures	Brown (1996)
7. SMART pyramid (Performance pyramid)	Quality, delivery, process time, cost, customer satisfaction, flexibility, productivity, marketing measures, financial measures	Developed by Wang Laboratories. Lynch and Cross (1991)
8. Balanced Scorecard (BSC)	Financial, customer, internal processes, learning and growth	Kaplan and Norton (1992)
9. Consistent PM system	Derived from strategy, continuous improvement, fast and accurate feedback, explicit purpose, relevance	Flapper *et al.* (1996)
10. PM framework for small businesses	Flexibility, timeliness, quality, finance, customer satisfaction, human factors	Laitinen (1996)
11. Cambridge PM process	Quality, flexibility, timeliness, finance, customer satisfaction, human factors	Neely *et al.* (1997)
12. Integrated dynamic PM System	Timeliness, finance, customer satisfaction, human factors , quality, flexibility	Ghalayini *et al.* (1997)
13. Integrated PM framework	Quality, flexibility, timeliness, finance, customer satisfaction	Medori and Steeple (2000)
14. Integrated PM system	Finance, customer satisfaction, human factors, quality, flexibility, timeliness	Bititci (1994)
15. Dynamic PM systems	External and internal monitoring system, review system, internal deployment system, IT platform needs	Bititci *et al.* (2000)
16. Integrated measurement model	Customer satisfaction, human factors, quality, flexibility, timeliness, finance	Oliver and Palmer (1998)
17. Comparative business scorecard	Stakeholder value, delight the stakeholder, organizational learning, process excellence	Kanji (1998)
18. Skandia navigator	Financial focus, customer focus, human focus, process focus, renewal and development focus	Edvinsson and Malone (1997); Sveiby (1997)
19. Balanced IT scorecard (BITS)	Financial perspective, customer satisfaction, internal processes, infrastructure and innovation, people perspective	ESI (1998) as mentioned in Abran and Buglione (2003)

(*continued*)

Model/framework	Measures/indicators/criteria	Reference
20. BSC of advanced information. Services Inc (AISBSC)	Financial perspective, customer perspectiveprocesses, people, infrastructure and innovation	Abran and Buglione (2003)
21. Intangible Asset-monitor (IAM)	Internal structure: *growth, *renewal, *efficiency, *stability, risk (concept models, computers, administrative systems); external structure: *customer, *supplier, *brand names, *trademark and image; individual competence: * skills, *education*experience, *values, *social skill	Sveiby (1997)
22. QUEST	Quality, economic, social and technical factors	Abran and Buglione (2003)
23. European Foundation for Quality Management (EFQM)	Leadership, enablers: people management, policy and strategy, resources; processes, results: people and customer satisfaction, impact on society; and business results	www.efqm.org/ as mentioned in Wongrassamee *et al.* (2003)
24. EN 15341	Maintenance key performance indicators	CEN (2007)
25. Multi-criteria hierarchical framework for MPM	Balanced and considering the strategic, tactical and operational perspectives	Parida and Chattopadhyay (2007)
26. Link and effect model	Technical indicators, like; availability, capacity utilization, etc., at the operational level is linked to strategic level through the tactical level and vice versa	Stenström (2012)
27. Venezuela Norma Covenin 2500-93	Manual for evaluation of maintenance systems through questionnaire and scoresheet	Norma Venezolana (1993)

Note: *Indicates the different internal and external structures
Source: Adapted from Parida and Chattopadhyay (2007)

B

Link and Effect model

Improvement process such as the Plan/Do/Study/Act (PDSA) cycle, also known as the Deming cycle, Shewart cycle or Kaizen cycle, have their basis in a continuous improvement process [Imai, 1986]. The link and effect models is based on the PDSA but emphasises on the key elements of strategic planning. The link and effect model aims to solve some problems encountered in traditional performance measurement system by complementing indicators with the underlying factors responsible for the performance [Stenstrom et al., 2013].

The model consist of two main components: a four-step continuous improvement process and a top-down and bottom-up approach, shown in Figure B.1. The methodology starts by breaking down the objectives, followed by updating the measurement system and aligning of indicators and objectives. Step 4 is analysis of data and finally identification and implementation of improvements. The model is usually used on a yearly cycle as objectives commonly change as a result of annual reporting.

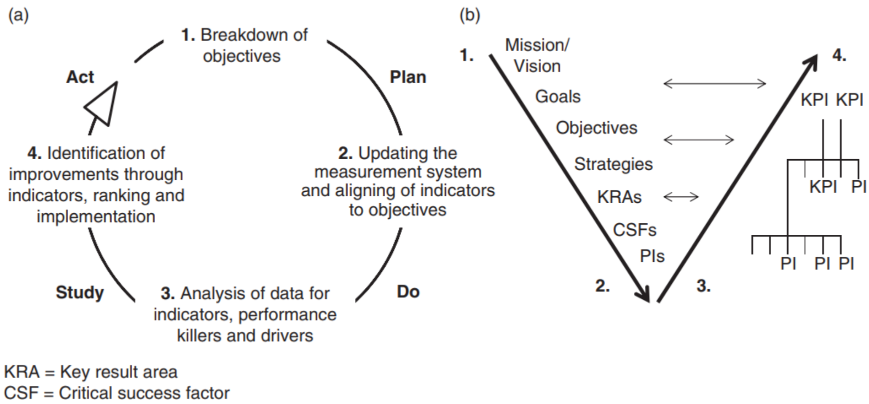


Figure B.1: The link and effect model based on (a) a four-step continuous improvement process and (b) a top-down and bottom-up process. The numbers in (b) represents the steps in (a) [Stenstrom et al., 2013].

Step 1: Breakdown of objectives
The first step focusses on strategic planning. This step also includes gathering stakeholders' objectives and assembling them into a common framework [Stenstrom et al., 2013]. Strategic planning is described as the process of specifying objectives, establishing strategies, and evaluating and monitoring results [Armstrong, 1982]. The definition of strategic planning can differ between organisations and researchers. Therefore, Stenstrom et al. [2013] has established Table B.1 which defines certain elements of strategic planning and assist in understanding the first step of the link and effect model.

Step 2: Updating the measurement system and aligning of indicators
An organisation and its performance measurement system are under constant pressure from strategic planning, organisational changes, new technologies and changes in physical asset structure [Stenstrom et al.,

2013]. Step 2 addresses these challenges as it concerns updating the measurement system based on new stakeholders demands and objectives. This step is shown in Figure B.2.

According to Kaydos [1991], a good performance measurement system does not necessarily require level of precision. It is more important to know the trend of the movement in an indicator and how it compares with historical values. The way that indicators are calculated can change based on the new objectives or organisational changes. It is noted that the trend in a movement can be lost, and therefore the old trend move should be preserved and presented alongside the new calculation for a period, i.e. create an overlap [Stenström et al., 2012].

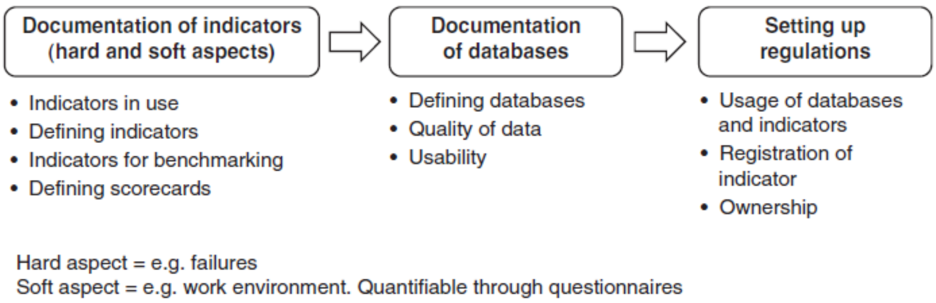
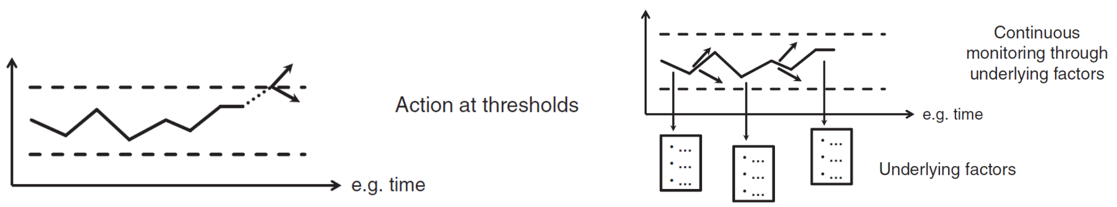


Figure B.2: Key requirements for performance measurement Stenstrom et al. [2013].

Step 3: Analysis of data for indicators, performance killers and drivers
Organisations tend to collect a large amount of data, but are unable to turn the data into information [Davenport et al., 2001, Karim et al., 2009]. Accordingly, step 3 focusses on the developing of analysis methodologies that use various statistical methods to construct PIs and identify performance killers and drivers. This step uses resources, therefore another important aspect in this step is to identify what data is required and what data is unnecessary.

Aggregation is seen as a weakness of traditional performance measurement systems since indicators can be abstract and do not show the underlying factors [Stenström, 2012, Stenström et al., 2012]. The link and effect model complements thresholds with the underlying factors which are responsible for the performance observed. Indicators with a threshold are generally only given attention when they pass the limit, making them reactive in nature. The link and effect model provides the underlying performance drivers and killers, supplying a starting point for improvements. See Figure B.3.



(a) Traditional performance measurement system with thresholds.

(b) Link and effect model complemented with the underlying factors of the indicators.

Figure B.3: Traditional performance measurement system vs link and effect model [Stenstrom et al., 2013].

Step 4: Identification of improvements, ranking and implementation
Step 4 in the link and effect model utilises continuous improvement with the goal of facilitating decision-making, by providing a performance measurement system which is up-to-date. Step 4 includes simulation, re-engineering physical assets and processes, ranking, implementing prognostic techniques and further defining indicators and databases [Stenstrom et al., 2013].

Table B.1: Key elements of strategic planning [Stenstrom et al., 2013].

Term	*Description*
Vision statement	A statement of what an organisation hopes to be like and to accomplish in the future.
Mission statement	A statement describing the key functions of an organisation. Note: vision and mission are set on the same hierarchical level, since either can come first, e.g. an authority has a vision, and gives a mission to start a business; the business can develop its own vision later on.
Goals	A goal is what an individual or organisation is trying to accomplish. Goals are commonly broad, measurable, aims that support the accomplishment of the mission.
Objectives	Translation of ultimate objectives (goals) to specific measurable objectives, or targets assigned for the activities, or specific, quantifiable, lower-level targets that indicate accomplishment of a goal.
Strategy	Courses of action that will lead in the direction of achieving objectives.
Key Result Area (KRA)	Areas where results are visualised, e.g. maintenance.
Critical Success Factor (CSF)	Are those characteristics, conditions, or variables that when properly managed can have a significant impact on the success of an organisation, e.g. high availability.
Performance Indicator (PI)	Parameters (measurable factor) useful for determining the degree to which an organisation has achieved its goals, or numerical or quantitative indicators that show how well each objective is being met.
Key Performance Indicator (KPI)	The actual indicators used to quantitatively assess performance against the CSFs. A KPI is a PI of special importance comprising an individual or aggregated measure.

C

Performance Indicators in Different Industries

C.1. Oil and gas performance indicators

The following table shows the groups in which different performance indicators are grouped for the oil and gas industry, established by Kumar and Ellingen [2000].

Table C.1: Performance indicator for the oil and gas industry Kumar and Ellingen [2000]

Production
Produced volume oil Sm3 [1]
Planned oi-production Sm3
Produced volume gas Sm3
Planned gas-production Sm3
Produced volume condensate Sm3
Planned condensate-production Sm3

Technical integrity
Backlog preventive maintenance [man-hours]
Backlog corrective maintenance [man-hours]
Number of corrective work orders

Maintenance parameters
Maintenance man-hours safety system
Maintenance man-hours system
Maintenance man-hours other systems
Maintenance man-hours total

Deferred production
Due to maintenance Sm3
Due to operation Sm3
Due to drilling/well operations Sm3
Weather and other causes Sm3

[1] **Standard cubic meter**(Sm3) refers to a common condition: Temperature 20°C, Pressure: 1.01325 barA

C.2. Railway performance indicators

The following table shows different performance indicators as a result of a research project for the Swedish rail road transport system, established by Åhrén [2008].

Table C.2: Railway performance indicators for the Swedish rail road transport system [Åhrén, 2008]

Performance indicators
Capacity utilisation of infrastructure
Capacity restriction of infrastructure
Hours of train delays due to infrastructure
Number of delayed freight trains due to infrastructure
Number of disruptions due to infrastructure
Degree of track standard
Markdown in current standard
Maintenance cost per track-kilometer
Traffic volume
Number of accidents involving railway vehicles
Number of accidents per area
Energy consumption per area
Use of environmental hazardous material
Use of non-renewable materials
Total number of functional disruptions
Total number of urgent inspection remarks

C.3. Process and utility industry performance indicators

MPIs identified for a process and utility industry, according to Parida et al. [2005].

Table C.3: Process and utility industry performance indicators [Parida et al., 2005]

Process industry	**Utility industry**
Downtime	System average interruption duration index (SAIDI)
Change over time	Customer average interruption duration index (CAIDI)
Planned maintenance tasks	Customer satisfaction index (CSI)
Unplanned maintenance tasks	Total maintenance cost
Number of new ideas generated	Profit margin
Skill and improvement training	Downtime
Quality returned	Overall equipment effectiveness (OEE)
Employee complaints	Number of unplanned stops
Maintenance cost per ton	Number of emergency work
	Inventory cost
	Number of new ideas generated
	Skill and improvement training
	Number of accidents
	Number of HSE complaints
	Employee satisfaction level

D

Standard Capesize, lifetime maintenance costs (1993 dollar price)

Table D.1: Standard Capesize, lifetime periodic maintenance costs (1993 dollar price) [Stopford, 2009].

	Age of ship 0–5	6–10	11–15	16–20	
Time out of service (days)	**20**	**23**	**40**	**40**	
Time in drydock (days)	**10**	**14**	**23**	**18**	**Total**
Cost Items (USD)					
Dry-dock charges	62,000	68,000	81,500	74,000	285,500
Port charges, tugs, agency	70,000	73,300	92,000	92,000	327,300
General services	80,000	92,000	160,000	160,000	492,000
Hull blast, clean & painting	102,800	128,800	183,600	99,000	514,200
All dry-dock paint	164,100	175,500	207,000	194,100	740,700
All steel replacement	70,000	350,000	1,190,000	840,000	2,450,000
Cargo spaces	22,200	64,200	126,000	150,000	362,400
Ballast spaces	36,400	23,200	26,000	47,400	133,000
Hatch covers & deck fittings	28,000	56,320	60,560	60,560	205,440
Main engine and propulsion	46,000	42,000	48,000	48,000	184,000
Auxiliaries	27,000	34,000	134,000	44,000	239,000
Piping & valves	18,000	37,000	50,000	34,000	139,000
Navigation & communications	9,000	11,000	11,000	11,000	42,000
Accommodation	6,000	8,000	7,000	7,000	28,000
Surveys & surveyors	70,000	78,500	113,000	108,000	369,500
Miscellaneous	100,000	100,000	100,000	100,000	400,000
Spare parts & subcontractors	70,000	100,000	100,000	120,000	390,000
Owner's attendance	23,800	25,600	35,800	35,800	121,000
Estimated total	1,005,300	1,467,420	2,725,460	2,224,860	7,423,040
Averaged annual cost	201,060	293,484	545,092	444,972	
Averaged daily cost	551	804	1,493	1,219	

E

Extensive Fleet List of JV

MMSI	Name	Tug Type	Year Built	Shipyard	GT	BP	FiFi Capacity	L	B	D	Design
					t	t	m^3	m	m	m	
[redacted]	Tug 1	ATD	2018		220	72		24.74	12.63	5.85	ATD 2412
[redacted]	Tug 2	Conv	1991	Rupelmonde	249	40					Conventional
[redacted]	Tug 3	ASD	1988	Rupelmonde	375	45					
[redacted]	Tug 4	ATD	2018	Damen	490	72		24.74	12.63	5.85	ATD 2412
[redacted]	Tug 5	ASD Hybrid	2015	Damen	574	60	1200	28.67	10.43	4.6	ASD 2810 HYBRID
[redacted]	Tug 6	ASD	1997	Armon	496	55		34.75	10.8	4.6	Aarts Marine BV
[redacted]	Tug 7	ASD	1998	Armon	496	55		34.75	10.8	4.6	Aarts Marine BV
[redacted]	Tug 8	Conv	1985	Rupelmonde	323	40		33.13	9.64	4.6	
[redacted]	Tug 9	ASD Hybrid	2018	Damen	574	60	1200	28.67	10.43	4.6	ASD 2810 HYBRID
[redacted]	Tug 10	RSD	2018	Damen	525	75	1500	24.73	13.13	5.5	RSD 2913
[redacted]	Tug 11	VSP	1995	Armon	399	43		30.54	11.52	4.5	VSP
[redacted]	Tug 12	ASD	2017	Damen	652	84		29.1	13.23	5.4	ASD 2913
[redacted]	Tug 13	RT Hybrid	2010	NSR	463	84		31.63	12	5.4	RT 8032
[redacted]	Tug 14	RT	2012	ASL	465	84		32	12	5.95	RT 8032
[redacted]	Tug 15	RT Hybrid	2014	Damen	598	80		32	12.6	6.25	ART 8032 HYBRID
[redacted]	Tug 16	RT Hybrid	2014	Damen	598	80		32	12.6	6.25	ART 8032 HYBRID
[redacted]	Tug 17	RT	1999	ABZ	449	78		31.63	12	5.9	RT 7532
[redacted]	Tug 18	RT	2009	NSR	463	84		32	12	5.4	RT 8032
[redacted]	Tug 19	RT	1999	ABZ	449	78	600	29	12	3.8	RT 7532
[redacted]	Tug 20	RT	2009	NSR	449	84		32	12	6.4	RT 8032
[redacted]	Tug 21	ASD	2013	Damen	453	80		32	12	4.1	ASD 3212
[redacted]	Tug 22	ASD	1998	East Isle	392	52		31	11		ASD Robert Allen 30/60
[redacted]	Tug 23	ASD	2012	Damen	294	60	2400	28	10	4.9	ASD 2810
[redacted]	Tug 24	ASD	2012	Damen	294	60	2400	28	10	5	ASD 2810
[redacted]	Tug 25	ASD	2008	Medmarine	483	65	2700	32	12		ASD RAmpart 3200
[redacted]	Tug 26	ASD	2008	Medmarine	483	65	2700	32	12	5.7	ASD RAmpart 3200
[redacted]	Tug 27	ASD	2008	Medmarine	483	65	2700	32	12	5.7	ASD RAmpart 3200
[redacted]	Tug 28	ASD	2007	Damen	294	58		30	10	4.8	ASD 2810
[redacted]	Tug 29	ASD	1999	Damen	305	52		35	11	4.8	ASD 3110
[redacted]	Tug 30	ASD	2009	Damen	484	95	2800	32	13	5.9	ASD 3213 Big Cat
[redacted]	Tug 31	ASD	2007	Damen	294	58		28	10	4.7	ASD 2810
[redacted]	Tug 32	ASD	2009	Damen	285	60	1300	28	10	4.7	ASD 2810
[redacted]	Tug 33	ASD	2007	Damen	294	60		28	10	4.7	ASD 2810
[redacted]	Tug 34	RT	2011	ASL	377	80		26	11	6.1	RT 8028
[redacted]	Tug 35	ASD	2008	Damen	285	60		28	10	4.5	ASD 2810
[redacted]	Tug 36	RT	2011	ASL	377	80		26	11	6.2	RT 8028
[redacted]	Tug 37	ASD	2009	Damen	484	95	2800	31	13	6.4	ASD 3213 Big Cat
[redacted]	Tug 38	VSP	1996	Armon	399	43		31	11	5.2	VSP
[redacted]	Tug 39	ASD	2008	Damen	289	60		28	10	4.6	ASD 2810

MMSI	Name	Tug Type	Year Built	Shipyard	GT	BP	FiFi Capacity	L	B	D	Design
[redacted]	Tug 40	ASD	2009	Damen	285	60		28	19	4.6	ASD 2810
[redacted]	Tug 41	ASD	2009	Damen	484	96	2800	31	13	6.3	ASD 3213 Big Cat
[redacted]	Tug 42	VSP	1987	Richards in Leight	301	36		30	10	4.6	VSP
[redacted]	Tug 43	ASD	2017	Damen		84	2400	29	13	5.48	ASD 2913
[redacted]	Tug 45	ASD	1991	Rupelmonde	249	39		30	8.8	4.6	ASD
[redacted]	Tug 45	Conv	1991	Rupelmonde	249	39		32	8.7	4.65	Conventional
[redacted]	Tug 46	ATD	1992	St Malo	321	45		30.51	8.7	5.1	ATD
[redacted]	Tug 47	ATD	1992	St Malo	321	45		30.6	9.7	5.1	ATD
[redacted]	Tug 48	VSP	1997	Armon	399	43	2700	31	11	5.1	VSP
[redacted]	Tug 49	ASD	1992	Rupelmonde	290	45		32	10	4.7	ASD
[redacted]	Tug 50	ASD	1993	Rupelmonde	290	45		32	10	4.7	ASD
[redacted]	Tug 51	VSP	1996	Armon	399	43	2700	31	11	5.4	VSP
[redacted]	Tug 52	VSP	1997	Armon	399	43	2700	31	12	5	VSP
[redacted]	Tug 53	ASD	2007	Armon	311	65		26	12	5	Astilleros Armon
[redacted]	Tug 54	ASD	2004	Armon	493	65	2400	34	12	5.6	Cintranaval-Defcar
[redacted]	Tug 55	ASD	2010	Armon	439	80	2400	30	13	5.9	Compact Tug
[redacted]	Tug 56	ASD	2005	Armon	493	66	2400	34	12	5.6	Cintranaval-Defcar
[redacted]	Tug 57	ASD	2007	Dearsan	473	65		32	12	5.6	ASD RAmpart 3200
[redacted]	Tug 58	ASD	2010	Armon	439	80	2400	30	13	5.9	Compact Tug
[redacted]	Tug 59	ASD	2007	Armon	311	65		25	11.6	5.3	Astilleros Armon
[redacted]	Tug 60	ASD	2009	Dearsan	479	64		32	12	5.6	ASD RAmpart 3200
[redacted]	Tug 61	ASD	2007	Dearsan	473	65	2400	32	12	5.6	ASD RAmpart 3200
[redacted]	Tug 62	ASD	2009	Dearsan	479	64		32	12	5.6	ASD RAmpart 3200
[redacted]	Tug 63	ASD	2005	Armon	493	65	2700	34	12	5.6	Cintranaval-Defcar
[redacted]	Tug 64	ASD	2005	Armon	493	65	2700	34	12	5.6	Cintranaval-Defcar
[redacted]	Tug 65	ASD	1992	Rupelmonde	249	39		31	8.8	4.6	ASD
[redacted]	Tug 66	ATD	2014	Damen	229	70		24	12	5.7	ATD 2412
[redacted]	Tug 67	ATD	2014	Damen	229	70		24	12	5.7	ATD 2412
[redacted]	Tug 68	ATD	2012	Damen	229	70		24	12	5.7	ATD 2412
[redacted]	Tug 69	ATD	2012	Damen	299	70		24	12	5.7	ATD 2412
[redacted]	Tug 70	ATD	1982	USA	194	45		29	11	5.4	
[redacted]	Tug 71	ATD	1981	USA		45					

Name	Nr. Engines	ME Maker	ME Type	ME Power	ME RPM	Nr. Aux	Aux Type	Aux Maker	Aux RPM	Nr. Thrusters	Thruster Maker	Thruster Type	CPP/ FPP	Winch Maker	FWD Winch	AFT Winch
				kW											t	t
Tug 1	2	Caterpillar	3516C-TA-HD	4200	1800	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 255 FP				
Tug 2	1	ABC	8MDZC-800	2130	800	2	DS 1160 M	Scania	2200	1	Brusselle	HMS 165R		Brusselle	80	
Tug 3	2	Deutz	SBV8M628	2720	1000	2	DS 11	Scania	2200	2	Aquamaster		FP	Brusselle	45	38
Tug 4	2	Caterpillar	3516C-TA-HD		1800	2	C4.4	Caterpillar		2	Rolls-Royce	US 255 FP	FP			
Tug 5	2	MTU	16V4000M63R	3680	1800	1	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP		Ulstein	60.7	56.8
Tug 6	2	Deutz	SBV8M628	4500	1000	2	D2866 E	MAN	2100	2	Schottel	SRP 1212 FP	FP	Ulstein		
Tug 7	2	Deutz	SBV8M628	4500	1000	2	D2866 E	MAN	2100	2	Schottel	SRP 1212 FP	FP	Rolls-Royce		
Tug 8	2	Deutz	SBV8M628	3534	1000	2	DS 11	Scania	2200	2	Aquamaster			Brusselle	40	37
Tug 9	2	MTU	16V4000M63R		1800	1	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP		Ulstein	60.7	56.8
Tug 10	2	MTU	16V4000M63L	4480	1800	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 255 FP				
Tug 11	2	Deutz	SBV8M628	4080	1000	2	TMD 102A	Volvo Penta	1800	2	Voith Schneider	VSP 28 GII		Brusselle		
Tug 12	2	Caterpillar	3516C-TA-HD	5050	1800	2	C7.1	Caterpillar	2200	2	Rolls-Royce	US 255 P30 FP	FP			
Tug 13	3	Caterpillar	3512C	5296	1800	2	C9	Caterpillar	2200	3	Schottel	SRP 1215 FP	FP			
Tug 14	3	NIIGATA	6L28HX	3308	750	2	D7A-B TA	Volvo Penta	1900	3	Niigata	ZP31	FP			
Tug 15	3	Caterpillar	3512C	5395	1800	1	C18 C9	Caterpillar	2100	3	Schottel	SRP 3000 FP	FP	DMT		
Tug 16	3	Caterpillar	3512C	5395	1800	1	C18 C9	Caterpillar	2100	3	Schottel	SRP 3000 FP	FP	DMT		
Tug 17	3	Caterpillar	3512B		1800	2	3306 DITA	Caterpillar	1750	3	Schottel	SRP 1212 FP	FP			
Tug 18	3	Caterpillar	3512C	5295	1800	2	C9	Caterpillar	2200	3	Schottel	SRP 1215 FP	FP			
Tug 19	3	Caterpillar	3512B	4680	1800	2	3306 DITA	Caterpillar	1750	3	Schottel	SRP 1212 FP	FP			
Tug 20	3	Caterpillar	3512C	5295	1800	2	C9	Caterpillar	2200	3	Schottel	SRP 1215 FP	FP			
Tug 21	2	Caterpillar	3516C-HD	5050	1900	2	C 6.6	Caterpillar		2	Rolls-Royce	US-255 CP	CP			
Tug 22	2	Caterpillar	3516 DITA	2983	1600	2	3306	Caterpillar	2300	2	Rolls-Royce	US 1701/3250				
Tug 23	2	Caterpillar	3516B-TA-HD	3730	1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP		60	58.4
Tug 24	2	Caterpillar	3516B-TA-HD	3730	1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT		
Tug 25	2	Caterpillar	3516B-HD DITA	3840	1600	2	DI 12 62 M	Scania	1800	2	Schottel	SRP 1515 CP	CP		65	60
Tug 26	2	Caterpillar	3516B-HD DITA	3840	1600	2	DI 12 62 M	Scania	1800	2	Schottel	SRP 1515 CP	CP		65	60
Tug 27	2	Caterpillar	3516B-HD DITA	3840	1600	2	DI 12 62 M	Scania	1800	2	Schottel	SRP 1515 CP	CP		65	60
Tug 28	2	Caterpillar	3516B-TA-HD		1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT		
Tug 29	2	Caterpillar	3516B	3132	1800	2	3304	Caterpillar	1800	2	Rolls-Royce	US 2001	FP		53	51
Tug 30	2	Caterpillar	C280-8	5420	900	2	C 9DI	Caterpillar	2200	2	Rolls-Royce	US 285 CP	CP	Rolls-Royce	96.6	89.6
Tug 31	2	Caterpillar	3516B-TA-HD		1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT		
Tug 32	2	Caterpillar	3516B-TA-HD	3730	1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT	63.5	58.3
Tug 33	2	Caterpillar	3516B-TA-HD	3730	1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT		
Tug 34	3	ABC	8DZC-1000	5298	1000	2	D 7A TA	Volvo Penta	1900	3	Schottel	SRP 1215 CP	CP			
Tug 35	2	Caterpillar	3516B-TA-HD	3626	1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT		
Tug 36	3	ABC	8DZC-1000	5304	1000	2	D 7A TA	Volvo Penta	1900	3	Schottel	SRP 1215 CP	CP			
Tug 37	2	Caterpillar	C280-8	5420	900	2	C 9DI	Caterpillar	2200	2	Rolls-Royce	US 285 CP	CP	Rolls-Royce	96.6	89.6
Tug 38	2	Deutz	SBV8M628	3100	1000	2	TMD 102A	Volvo Penta	1800	2	Voith Schneider	VSP 28 GII		Brusselle		
Tug 39	2	Caterpillar	3516B-TA-HD	3678	1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT		
Tug 40	2	Caterpillar	3516B-TA-HD	3626	1200	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 205 FP	FP	DMT		
Tug 41	2	Caterpillar	C280-8	5420	900	2	C 9DI	Caterpillar	2200	2	Rolls-Royce	US 285 CP	CP	Rolls-Royce	96.6	89.6
Tug 42	2	Ruston	RK270		1000	2	6LXB	Gardner	1500	2	Voith Schneider	VSP 28 GII				
Tug 43	2	Caterpillar	3516C-TA-HD	5050	1800	2	C7.1	Caterpillar	2200	2	Rolls-Royce	US 255 P30 FP	FP			
Tug 45	2	ABC	6DZC-1000	2330	1000	2	DS 1160 - M24SV	Scania	1800	2	Schottel	SRP 1010 FP	FP	Brusselle	39	37
Tug 45	1	ABC	8MDZC-800	2130	800	2	DS 1160 M	Scania	2200	1	Brusselle	HMS 165 R	FP	Brusselle	39	
Tug 46	2	Deutz	SBV8M628	2470	1000	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 1401	FP	Kraaijeveld	45	
Tug 47	2	Deutz	SBV8M628	2470	1000	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 1401	FP	Kraaijeveld		
Tug 48	2	Deutz	SBV8M628	3100	1000	2	TMD 102A	Volvo Penta	1800	2	Voith Schneider	VSP 28 GII		Brusselle		
Tug 49	2	ABC	6MDZC-1000	2652	1000	2	DS 1160 - M24SV	Scania	1800	2	Schottel	SRP 1010 FP	FP	Brusselle	47	44
Tug 50	2	ABC	6MDZC-1000	2652	1000	2	DS 1160 - M24SV	Scania	1800	2	Schottel	SRP 1010 FP	FP	Brusselle	47	44

Name	Nr. Engines	ME Maker	ME Type	ME Power	ME RPM	Nr. Aux	Aux Type	Aux Maker	Aux RPM	Nr. Thrusters	Thruster Maker	Thruster Type	CPP/ FPP	Winch Maker	FWD Winch	AFT Winch
Tug 51	2	Deutz	SBV8M628	3100	1000	2	TMD 102A	Volvo Penta	1800	2	Voith Schneider	VSP 28 GII		Brusselle		
Tug 52	2	Deutz	SBV8M628	3100	1000	2	TMD 102A	Volvo Penta	1800	2	Voith Schneider	VSP 28 GII		Brusselle		
Tug 53	2	ABC	8MDZC-1000	3700	1000	2	D9 95 - M03D	Scania	1800	1	Rolls-Royce	SRP 1515 FP	FP	Brusselle	65	60
Tug 54	2	ABC	8MDZC-1000	3700	1000	2	D9 95 - M03D	Scania	1800	1	Schottel	SRP 1515 FP	FP	Brusselle	66	62
Tug 55	2	ABC	12VDZC-1000	5200	1000	2	DI 12 62M - M03D	Scania	1800	2	Schottel	SRP 2020 FP	FP	Brusselle	86	81
Tug 56	2	ABC	8MDZC-1000	3700	1000	2	D9 95 - M03D	Scania	1800	1	Schottel	SRP 1515 FP	FP	Brusselle	66	62
Tug 57	2	ABC	8MDZC-1000	3890	1000	2	D2866 LXE30	MAN	1800	1	Schottel	SRP 1515 CP	CP		66	60
Tug 58	2	ABC	12VDZC-1000	5200	1000	2	DI 12 62M - M03D	Scania	1800	2	Schottel	SRP 2020 FP	FP	Brusselle	86	81
Tug 59	2	ABC	8MDZC-1000	3700	1000	2	D9 95 - M03D	Scania	1800	1	Rolls-Royce	SRP 1515 FP	FP	Brusselle	65	60
Tug 60	2	ABC	8MDZC-1000	3890	1000	2	DI9-74M	Scania	1800	1	Schottel	SRP 1515 CP	CP	Rolls-Royce	65	58
Tug 61	2	ABC	8MDZC-1000	3890	1000	2	DI9-74M	Scania	1800	1	Schottel	SRP 1515 CP	CP	Brusselle	66	60
Tug 62	2	ABC	8MDZC-1000	3800	1000	2	D2866 LXE30	MAN	1800	1	Schottel	SRP 1515 CP	CP	Rolls-Royce	66	60
Tug 63	2	ABC	8DZC-1000	3660	1000	2	D9 95 - M03D	Scania	1800	1	Schottel	SRP 1515 FP	FP	Brusselle	65	62
Tug 64	2	ABC	8DZC-1000	3700	1000	2	D9 95 - M03D	Scania	1800	1	Schottel	SRP 1515 FP	FP	Brusselle		
Tug 65	2	ABC	6MDZC-1000	2330	1000	2	DS 1160 - M24SV	Scania	1800	2	Schottel	SRP 1010 FP	FP		39	37
Tug 66	2	Caterpillar	3516C-TA-HD	4200	1800	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 255 FP	FP	DMT		
Tug 67	2	Caterpillar	3516C-TA-HD	4200	1800	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 255 FP	FP			
Tug 68	2	Caterpillar	3516C-TA-HD	4200	1800	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 255 FP	FP			
Tug 69	2	Caterpillar	3516C-TA-HD	4200	1800	2	C4.4	Caterpillar	2200	2	Rolls-Royce	US 255 FP	FP			
Tug 70	2	Detroit	EMD	2206	0						Niigata	ZP-2A				
Tug 71		Detroit	EMD		0						Niigata	ZP-2A				

F

Exemplary vessel assist evaluation per port

Port Location	Year				
Vessel Type	2015	2016	2017	2018	**Grand Total**
Port A		**15,763**	**53,050**	**34,379**	**103,192**
BULK		652	6,469	3,315	10,436
CAR CARRIER		70	724	190	984
CONTAINER		1,248	13,956	9,043	24,247
CRUISE LINER			20	36	56
DREDGER				2	2
GENERAL CARGO		56	1,736	1,186	2,978
LNG				6	6
OFFSHORE		3	54	86	143
OTHER		6	114	272	392
REEFER		8	871	291	1,170
RORO		1	56	621	678
TANKER		1,492	19,912	16,331	37,735
TUG				1	1
(blank)		12,227	9,138	2,999	24,364
Port B			**929**	**2,867**	**3,796**
BULK			18	160	178
CAR CARRIER			64	220	284
CONTAINER			795	2,257	3,052
CRUISE LINER			15	28	43
GENERAL CARGO			20	15	35
OTHER			8	78	86
RORO			1	81	82
TANKER				6	6
(blank)			8	22	30
Port C		**3,868**	**3,401**	**2,883**	**10,152**
			1,400		1,400
BARGE		11		4	15
BARGE CARRIER			44	4	48
BULK				56	56
BULK CARRIER		906	85	81	1,072
BULK/COAL			8	9	17
BULK/CONT			56	45	101
BULK/METAL			109	127	236
BULK/SCRAP			9		9
CABLE LAYER			2		2
CAR CARRIER		17			17
CHEM/TANKER			40	41	81

Port Location	**Year**				
Vessel Type	2015	2016	2017	2018	**Grand Total**
CONTAINER		1,536	710	485	2,731
CONTAINER/RORO		49	2		51
CRUDE OIL			13		13
CRUISE		11			11
CRUISE LINER				11	11
DREDGER		15		2	17
GC			9		9
GENERAL CARGO		137	86	60	283
HEAVY LOAD CARR		34	6		40
MILITARY			34	40	74
MISCELLANEOUS			20	15	35
NAVAL RORO LOG			3		3
NAVY		33			33
OFFSHORE		2			2
OFFSHORE SUPP			3		3
OTHER		124			124
PASS/RORO		280	125	71	476
PONTOON				2	2
RORO				3	3
RORO/CG			3		3
RORO/FERRY			151	109	260
RORO/GENERAL CARGO		2			2
STONE CARRIER			60	36	96
SUCTION DREDGER			1		1
TANKER		711	421	370	1,502
TANKER/LNG				1	1
VEHICLE			1		1
(blank)				1,311	1,311
Port D		**1,019**	**1,302**	**2,660**	**4,981**
BULK		92	26	30	148
CAR CARRIER				1	1
CONTAINER		282	505	1,484	2,271
CRUISE LINER		28	30	30	88
GENERAL CARGO		34	51	48	133
OFFSHORE			2	2	4
OTHER		3		50	53
REEFER		3	11	136	150
RORO		7	7	19	33
TANKER		200	373	552	1,125
TUG				1	1
(blank)		370	297	307	974
Port Een		**24,746**	**14,494**	**11,577**	**50,817**
			7		7
BULK			54	441	495
BULK CARRIER		914	783		1,697
CAR CARRIER		1,407	86	653	2,146
CHEM/TANKER			10		10
CONTAINER		7,774	7,610	6,156	21,540
CRUDE OIL			9		9
CRUISE LINER			2	1	3
GENERAL CARGO		696	580	295	1,571
LNG			2	20	22
MISCELLANEOUS			22		22
OTHER		37	4	142	183
REEFER			16	92	108
REFRIG		271	200		471
RORO			10	273	283

Port Location	Year				
Vessel Type	2015	2016	2017	2018	**Grand Total**
TANKER		3,759	3,642	2,119	9,520
VEHICLE			1,321		1,321
(blank)		9,888	136	1,385	11,409
Port F		**8,939**	**9,610**	**6,860**	**25,409**
BULK CARRIER		16	21	22	59
CAR CARRIER		5,871	27		5,898
CHEM/TANKER			8		8
CONTAINER		388	483	473	1,344
CRUISE LINER				4	4
GENERAL CARGO		554	552	266	1,372
HEAVY LOAD CARR		8			8
LNG		23	22		45
MISCELLANEOUS			326	109	435
NAVY		4			4
OIL PRODUCTS			2		2
OTHER		287	7	7	301
REFRIG		120	45	18	183
RORO				299	299
RORO/CG			16	13	29
RORO/GC			8		8
RORO/GENERAL CARGO		18			18
TANKER		558	333	474	1,365
TANKER/LPG			5		5
VEHICLE			7,755	5,159	12,914
(blank)		1,092		16	1,108
Port G		**6,913**	**6,852**	**6,838**	**20,603**
BARGE CARRIER			5		5
BULK				114	114
BULK CARRIER		3,416	3,445	2,885	9,746
CAR CARRIER		254	1		255
CHEM/OIL			2		2
CHEM/TANKER			53		53
CONTAINER		33	9	25	67
CRUDE OIL			4		4
GC/CONT			1		1
GENERAL CARGO		711	572	599	1,882
HEAVY LOAD CARR			2		2
MISCELLANEOUS			335	236	571
OIL PRODUCTS			6		6
OTHER		327	3	63	393
REFRIG		12	147	264	423
RORO				16	16
TANKER		2,160	1,940	2,319	6,419
TANKER/LPG			59		59
TUG				1	1
VEHICLE			258	211	469
(blank)			10	105	115
Port H	**2,739**	**4,787**	**4,697**	**3,310**	**15,533**
BULK	346	441	643	518	1,948
CAR CARRIER	335	507	385	77	1,304
CONTAINER	1,602	2,728	2,694	1,622	8,646
CRUISE LINER		12	23	5	40
GENERAL CARGO	23	37	36	5	101
OFFSHORE		1			1
OTHER	10	11	8	161	190
REEFER	4	5	1	1	11
RORO	25	47	61	287	420

Port Location	**Year**				
Vessel Type	2015	2016	2017	2018	**Grand Total**
TANKER	273	404	426	555	1,658
(blank)	121	594	420	79	1,214
Port I	**3,715**	**5,991**	**4,857**	**3,580**	**18,143**
BULK	21	27	14	7	69
CAR CARRIER	2,242	3,782	4,078	2,471	12,573
CONTAINER	1,277	1,996	591	575	4,439
CRUISE LINER	1	1	5	2	9
GENERAL CARGO	6	9	44	12	71
OTHER	71	115	75	221	482
REEFER	79	21	7		107
RORO	2		10	282	294
TANKER	1	19	1	4	25
(blank)	15	21	32	6	74
Grand Total	6,454	72,026	99,192	74,954	252,626

G

R script use for Regression Analyses of Maintenance Cost vs Operational Variables

Multi_regression.R

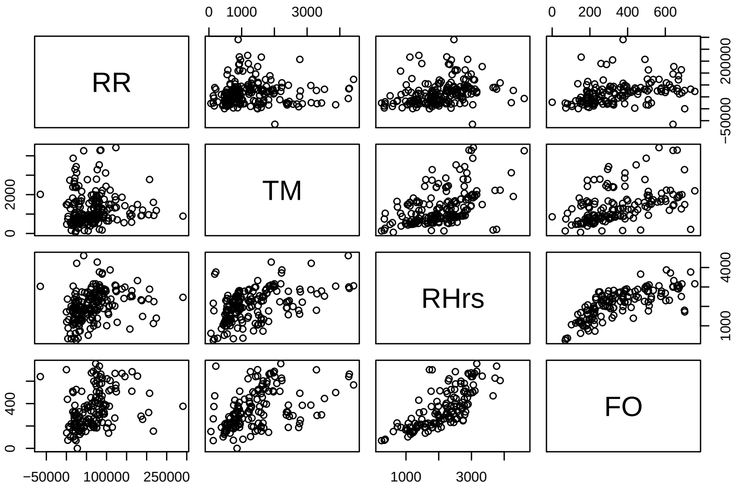
KEDR

2019-06-23

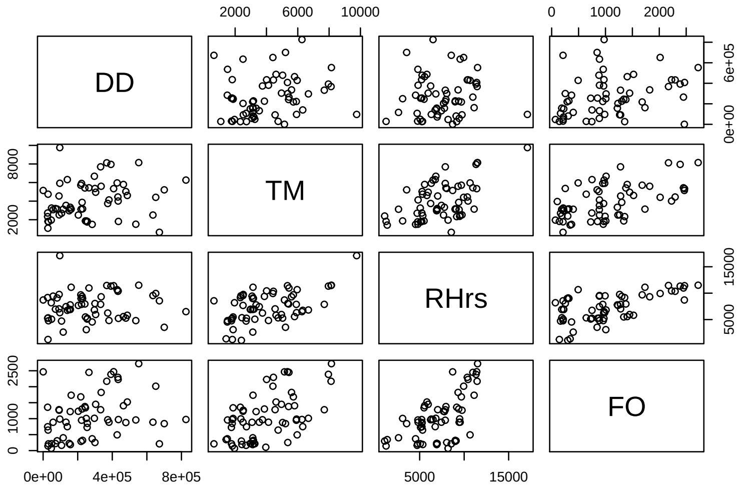
```r
library("readxl")
library("openxlsx")
library("broom")
library("MASS")
library("leaps")
library("caret")
```

```
## Loading required package: lattice

## Loading required package: ggplot2
```

```r
##########################

RR <- read.csv(file=
"D:/Users/KEDR/boskalis.com/Towage Division - Maintenance Strategy/DATA MODEL/DATA/RegData.csv",
header = TRUE, sep=",")
RR = data.frame(RR = RR[4], TM = RR[5], RHrs = RR[6], FO = RR[7])
###

DD <- read.csv(file=
"D:/Users/KEDR/boskalis.com/Towage Division - Maintenance Strategy/DATA MODEL/DATA/RegDataDD.csv",
header = TRUE, sep=",")
DD = data.frame(DD = DD[2], TM = DD[3], RHrs = DD[4], FO = DD[5])

###########

plot(RR)
```


```r
plot(DD)
```




```r
summary(RR)
```

```
##        RR               TM             RHrs            FO
##  Min.   :-65084   Min.   :  61   Min.   : 254   Min.   :  0.0
##  1st Qu.: 28215   1st Qu.: 694   1st Qu.:1540   1st Qu.:215.4
##  Median : 61140   Median : 965   Median :2037   Median :316.9
##  Mean   : 65713   Mean   :1287   Mean   :2069   Mean   :350.3
##  3rd Qu.: 83172   3rd Qu.:1656   3rd Qu.:2579   3rd Qu.:491.5
##  Max.   :290579   Max.   :4421   Max.   :4611   Max.   :756.4
##  NA's   :7        NA's   :9      NA's   :19     NA's   :58
```

```r
summary(DD)
```

```
##        DD               TM             RHrs             FO
##  Min.   :   436   Min.   : 646   Min.   : 1065   Min.   :  69.2
##  1st Qu.: 96449   1st Qu.:2467   1st Qu.: 5275   1st Qu.: 320.4
##  Median :241591   Median :3340   Median : 7028   Median : 950.1
##  Mean   :264210   Mean   :3952   Mean   : 7352   Mean   :1008.0
##  3rd Qu.:386663   3rd Qu.:5352   3rd Qu.: 9389   3rd Qu.:1357.1
##  Max.   :825994   Max.   :9761   Max.   :17109   Max.   :2722.4
##  NA's   :6        NA's   :2      NA's   :4       NA's   :4
```

```r
#### Stepwise Regression RR ##############
RR.lm <- lm(RR~., data=RR)

# Set up repeated k-fold cross-validation
train.control <- trainControl(method = "cv", number = 10)
# Train the model
```



```r
step.model <- train(RR~., data = RR, method = "leapSeq", tuneGrid = data.frame(nvmax = 1:3),
                    trControl = train.control, trace = FALSE, na.action=na.exclude)

# Model Accuracy
step.model$results
```

```
##   nvmax     RMSE  Rsquared      MAE   RMSESD RsquaredSD     MAESD
## 1     1 44071.82 0.2253086 32567.80 17590.93  0.2308861 10196.209
## 2     2 43501.17 0.2341647 32943.26 16962.62  0.2317068  9862.222
## 3     3 43015.94 0.2686439 32202.10 17807.75  0.2389439  9995.008
```

```r
# Final model coefficients

# Summary of the model
summary(step.model$finalModel)
```

```
## Subset selection object
## 3 Variables  (and intercept)
##      Forced in Forced out
## TM       FALSE      FALSE
## RHrs     FALSE      FALSE
## FO       FALSE      FALSE
## 1 subsets of each size up to 3
## Selection Algorithm: 'sequential replacement'
##          TM  RHrs FO
## 1  ( 1 ) " " "*"  " "
## 2  ( 1 ) "*" "*"  " "
## 3  ( 1 ) "*" "*"  "*"
```

```r
# Best model
step.model$bestTune
```

```
##   nvmax
## 3     3
```

```r
# Coeff of best model
coef(step.model$finalModel,3)
```

```
##  (Intercept)           TM         RHrs           FO
## 20903.470251    -8.729863    18.599550    53.002421
```

```r
# Compute model
lm(RR~ TM + RHrs + FO, data = RR)
```

```
##
## Call:
## lm(formula = RR ~ TM + RHrs + FO, data = RR)
##
## Coefficients:
## (Intercept)           TM         RHrs           FO
##    20903.47        -8.73        18.60        53.00
```

```r
summary(lm(RR~ TM + RHrs + FO, data = RR))
```

```
##
## Call:
## lm(formula = RR ~ TM + RHrs + FO, data = RR)
##
```

```
## Residuals:
##     Min      1Q  Median      3Q     Max
## -158736  -27688   -7717   15971  211705
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) 20903.470  12210.567   1.712   0.0892 .
## TM             -8.730      4.927  -1.772   0.0786 .
## RHrs           18.600      8.001   2.325   0.0216 *
## FO             53.002     35.421   1.496   0.1368
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 46330 on 138 degrees of freedom
##   (66 observations deleted due to missingness)
## Multiple R-squared:  0.1516, Adjusted R-squared:  0.1331
## F-statistic: 8.217 on 3 and 138 DF,  p-value: 4.528e-05
```

```
########################################################

#### Stepwise Regression DD ##############
DD.lm <- lm(DD~., data=DD)
DD.lm <- stepAIC(DD.lm, direction = "both", trace = FALSE)
# Set up repeated k-fold cross-validation
train.control <- trainControl(method = "cv", number = 10)
# Train the model
DD.model <- train(DD~., data = DD, method = "leapSeq", tuneGrid = data.frame(nvmax = 1:3),
                  trControl = train.control, trace = FALSE, na.action=na.exclude)
# Model Accuracy
DD.model$results
```

```
##   nvmax     RMSE  Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1     1 175406.0 0.2960345 142127.3 62766.24  0.3679292 49097.38
## 2     2 181496.6 0.1363544 149078.0 59639.66  0.1630828 44344.11
## 3     3 174970.0 0.3158136 141251.7 67309.52  0.3430221 45426.04
```

```
# Summary of the model
summary(DD.model$finalModel)
```

```
## Subset selection object
## 3 Variables  (and intercept)
##      Forced in Forced out
## TM       FALSE      FALSE
## RHrs     FALSE      FALSE
## FO       FALSE      FALSE
## 1 subsets of each size up to 3
## Selection Algorithm: 'sequential replacement'
##          TM  RHrs FO
## 1  ( 1 ) " " " "  "*"
## 2  ( 1 ) "*" "*"  " "
## 3  ( 1 ) "*" "*"  "*"
```

```
# Best model
DD.model$bestTune
```

```
##   nvmax
## 3     3
```



```
# Coeff of best model
coef(DD.model$finalModel,3)
```

```
##  (Intercept)           TM         RHrs           FO
## 168497.68947     16.90876     -4.96442     69.18017
```

```
# Compute model
lm(DD~ TM + RHrs + FO, data = DD)
```

```
##
## Call:
## lm(formula = DD ~ TM + RHrs + FO, data = DD)
##
## Coefficients:
## (Intercept)           TM         RHrs           FO
##  168497.689       16.909       -4.964       69.180
```

```
summary(lm(DD~ TM + RHrs + FO, data = DD))
```

```
##
## Call:
## lm(formula = DD ~ TM + RHrs + FO, data = DD)
##
## Residuals:
##     Min      1Q  Median      3Q     Max
## -382486 -120311  -21045   91099  520885
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 168497.689  85533.115   1.970   0.0539 .
## TM              16.909     16.264   1.040   0.3031
## RHrs            -4.964     12.635  -0.393   0.6959
## FO              69.180     47.385   1.460   0.1500
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 190100 on 55 degrees of freedom
##   (10 observations deleted due to missingness)
## Multiple R-squared:  0.1086, Adjusted R-squared:  0.06001
## F-statistic: 2.234 on 3 and 55 DF,  p-value: 0.09447
```

H

R script Stepwise Regression Analyses of Maintenance Cost, Operational Variables and Vessel Characteristics

Stepwise_regression_ops_+_vessel_char.R

KEDR

2019-07-04

```r
library("readxl")
library("openxlsx")
library("broom")
library("MASS")
library("leaps")
library("caret")
```

```
## Loading required package: lattice
## Loading required package: ggplot2
```

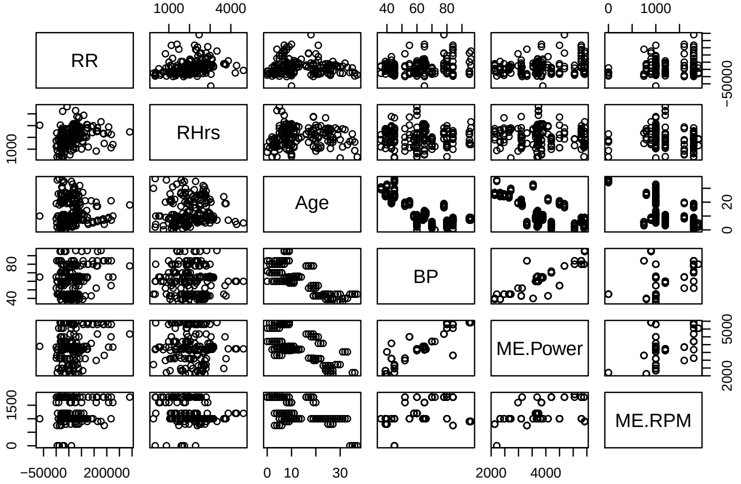
```r
library("car")
```

```
## Loading required package: carData
```

```r
library("lmtest")
```

```
## Loading required package: zoo
##
## Attaching package: 'zoo'
## The following objects are masked from 'package:base':
##
##     as.Date, as.Date.numeric
```

```r
##########################

RR <- read.csv(file=
"D:/Users/KEDR/boskalis.com/Towage Division - Maintenance Strategy/DATA MODEL/DATA/Data.csv",
               header = TRUE, sep=",")
RR = data.frame(RR = RR[3], RHrs = RR[4], age = RR[5], BP = RR[6], MEP = RR[7], MERPM = RR[8])

###

DD <- read.csv(file=
  "D:/Users/KEDR/boskalis.com/Towage Division - Maintenance Strategy/DATA MODEL/DATA/dataDD.csv",
               header = TRUE, sep=",")
DD = data.frame(DD = DD[8], RHrs = DD[6], age = DD[2], BP = DD[3], MEP = DD[4], MERPM = DD[5], FO=DD[7]

###########

plot(RR)
```


```r
summary(RR)
```

```
##        RR              RHrs           Age              BP
##  Min.   :-65084   Min.   : 254   Min.   : 0.0   Min.   :36.00
##  1st Qu.: 28215   1st Qu.:1540   1st Qu.: 7.0   1st Qu.:45.00
##  Median : 61140   Median :2037   Median :10.0   Median :64.00
##  Mean   : 65713   Mean   :2069   Mean   :13.3   Mean   :62.46
##  3rd Qu.: 83172   3rd Qu.:2579   3rd Qu.:20.0   3rd Qu.:72.00
##  Max.   :290579   Max.   :4611   Max.   :37.0   Max.   :96.00
##                   NA's   :12     NA's   :1
##     ME.Power        ME.RPM
##  Min.   :2130   Min.   :   0
##  1st Qu.:3132   1st Qu.:1000
##  Median :3730   Median :1000
##  Mean   :3868   Mean   :1229
##  3rd Qu.:4500   3rd Qu.:1800
##  Max.   :5420   Max.   :1900
##  NA's   :20
```

```r
#### Stepwise Regression RR ##############
RR[RR == 0] <- NA
RR[RR < 0] <- NA

RR.lm <- lm(RR~., data =RR)

# Set up repeated k-fold cross-validation
train.control <- trainControl(method = "cv", number = 10)
```

```r
# Train the model
step.model <- train(RR~., data = RR, method = "leapBackward", tuneGrid = data.frame(nvmax = 1:3),
                    trControl = train.control, trace = FALSE, na.action=na.exclude)
# Model Accuracy
step.model$results
```

```
##   nvmax     RMSE   Rsquared      MAE    RMSESD RsquaredSD    MAESD
## 1     1 49532.03 0.06989065 37178.98  9081.809  0.0825505 4674.207
## 2     2 48472.06 0.14466565 34572.64 10456.033  0.1679256 6175.960
## 3     3 46100.86 0.23575549 32920.35 10863.553  0.1467463 5951.588
```

```r
# Summary of the model
summary(step.model$finalModel)
```

```
## Subset selection object
## 5 Variables  (and intercept)
##          Forced in Forced out
## RHrs         FALSE      FALSE
## Age          FALSE      FALSE
## BP           FALSE      FALSE
## ME.Power     FALSE      FALSE
## ME.RPM       FALSE      FALSE
## 1 subsets of each size up to 3
## Selection Algorithm: backward
##          RHrs Age BP  ME.Power ME.RPM
## 1  ( 1 ) "*"  " " " " " "      " "
## 2  ( 1 ) "*"  " " "*" " "      " "
## 3  ( 1 ) "*"  "*" "*" " "      " "
```

```r
# Best model
step.model$bestTune
```

```
##   nvmax
## 3     3
```

```r
# Coeff of best model
coef(step.model$finalModel,3)
```

```
##   (Intercept)          RHrs           Age            BP
## -113776.64099      18.51529    2288.07125    1841.60269
```

```r
# Compute model
summary(step.model$finalModel)
```

```
## Subset selection object
## 5 Variables  (and intercept)
##          Forced in Forced out
## RHrs         FALSE      FALSE
## Age          FALSE      FALSE
## BP           FALSE      FALSE
## ME.Power     FALSE      FALSE
## ME.RPM       FALSE      FALSE
## 1 subsets of each size up to 3
## Selection Algorithm: backward
##          RHrs Age BP  ME.Power ME.RPM
## 1  ( 1 ) "*"  " " " " " "      " "
## 2  ( 1 ) "*"  " " "*" " "      " "
```



```
## 3  ( 1 ) "*"  "*" "*" " "      " "
```

```r
RR.model <- lm(RR~ RHrs + Age + BP , data = RR)
lm(RR~ RHrs + Age + BP , data = RR)
```

```
##
## Call:
## lm(formula = RR ~ RHrs + Age + BP, data = RR)
##
## Coefficients:
## (Intercept)         RHrs          Age           BP
##   -97203.08        20.76      1569.61      1620.28
```

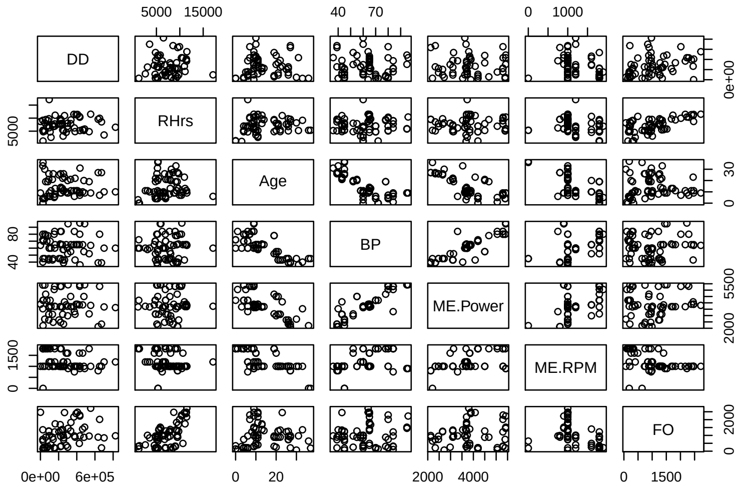
```r
summary(RR.model)
```

```
##
## Call:
## lm(formula = RR ~ RHrs + Age + BP, data = RR)
##
## Residuals:
##    Min     1Q Median     3Q    Max
## -93454 -26064  -4762  17254 181974
##
## Coefficients:
##               Estimate Std. Error t value Pr(>|t|)
## (Intercept) -97203.077  28047.055  -3.466  0.00066 ***
## RHrs            20.760      4.227   4.911 2.02e-06 ***
## Age           1569.609    555.937   2.823  0.00528 **
## BP            1620.280    319.393   5.073 9.65e-07 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 44670 on 181 degrees of freedom
##   (16 observations deleted due to missingness)
## Multiple R-squared:  0.2184, Adjusted R-squared:  0.2055
## F-statistic: 16.86 on 3 and 181 DF,  p-value: 1.058e-09
```

```r
durbinWatsonTest(RR.model)
```

```
##  lag Autocorrelation D-W Statistic p-value
##    1       0.1844602      1.628778   0.006
##  Alternative hypothesis: rho != 0
```

```r
########################################################

#### Stepwise Regression DD ##############
plot(DD)
```




```r
summary(DD)
```

```
##        DD              RHrs            Age              BP
##  Min.   :   436   Min.   : 1065   Min.   : 0.00   Min.   :36.00
##  1st Qu.: 96449   1st Qu.: 5275   1st Qu.: 7.50   1st Qu.:45.00
##  Median :241591   Median : 7028   Median :11.00   Median :64.00
##  Mean   :264210   Mean   : 7352   Mean   :14.06   Mean   :62.13
##  3rd Qu.:386663   3rd Qu.: 9389   3rd Qu.:21.00   3rd Qu.:71.00
##  Max.   :825994   Max.   :17109   Max.   :37.00   Max.   :96.00
##  NA's   :6        NA's   :4       NA's   :2       NA's   :2
##     ME.Power        ME.RPM          FO
##  Min.   :2130   Min.   :   0   Min.   :  69.2
##  1st Qu.:3124   1st Qu.:1000   1st Qu.: 320.4
##  Median :3730   Median :1000   Median : 950.1
##  Mean   :3842   Mean   :1235   Mean   :1008.0
##  3rd Qu.:4275   3rd Qu.:1800   3rd Qu.:1357.1
##  Max.   :5420   Max.   :1900   Max.   :2722.4
##  NA's   :9      NA's   :2      NA's   :4
```

```r
# Define Model
DD[DD == 0] <- NA
DD.lm <- lm(DD~ RHrs + log(Age) + BP + ME.Power + ME.RPM + FO, data =DD)

# Set up repeated k-fold cross-validation
train.control <- trainControl(method = "cv", number = 10)
# Train the model
DD.model <- train(DD~., data = DD, method = "leapBackward", tuneGrid = data.frame(nvmax = 1:6),
```



```r
                    trControl = train.control, trace = FALSE, na.action=na.exclude)
# Model Accuracy
DD.model$results
```

```
##   nvmax     RMSE  Rsquared      MAE   RMSESD RsquaredSD    MAESD
## 1     1 185432.8 0.2407120 151277.1 42531.54  0.1728811 30975.80
## 2     2 190151.1 0.1567244 153263.9 49256.29  0.1286612 34270.12
## 3     3 197899.8 0.1896124 162171.7 49299.46  0.1589309 30521.75
## 4     4 201641.1 0.2142504 165090.3 50683.13  0.1953900 30670.68
## 5     5 203349.3 0.2118369 166081.7 52550.06  0.2243928 32873.52
## 6     6 203962.7 0.2015303 167553.1 52367.95  0.2146061 33055.17
```

```r
# Summary of the model
summary(DD.model$finalModel)
```

```
## Subset selection object
## 6 Variables  (and intercept)
##          Forced in Forced out
## RHrs         FALSE      FALSE
## Age          FALSE      FALSE
## BP           FALSE      FALSE
## ME.Power     FALSE      FALSE
## ME.RPM       FALSE      FALSE
## FO           FALSE      FALSE
## 1 subsets of each size up to 1
## Selection Algorithm: backward
##          RHrs Age BP  ME.Power ME.RPM FO
## 1  ( 1 ) " "  " " " " " "      "*"    " "
```

```r
# Best model
DD.model$bestTune
```

```
##   nvmax
## 1     1
```

```r
# Coeff of best model
coef(DD.model$finalModel,1)
```

```
## (Intercept)      ME.RPM
## 484280.1490   -163.0453
```

```r
# Compute model
lm(DD~ ME.RPM, data = DD)
```

```
##
## Call:
## lm(formula = DD ~ ME.RPM, data = DD)
##
## Coefficients:
## (Intercept)       ME.RPM
##    517636.7       -197.7
```

```r
summary(lm(DD~ ME.RPM, data = DD))
```

```
##
## Call:
## lm(formula = DD ~ ME.RPM, data = DD)
##
```

```
## Residuals:
##     Min      1Q  Median      3Q     Max
## -319550 -124737  -33324   89435  545538
##
## Coefficients:
##             Estimate Std. Error t value Pr(>|t|)
## (Intercept) 517636.67   87509.35   5.915 1.88e-07 ***
## ME.RPM        -197.65      67.59  -2.924  0.00492 **
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 184300 on 58 degrees of freedom
##   (9 observations deleted due to missingness)
## Multiple R-squared:  0.1285, Adjusted R-squared:  0.1135
## F-statistic:  8.55 on 1 and 58 DF,  p-value: 0.004921
```

```r
durbinWatsonTest(DD.lm)
```

```
##  lag Autocorrelation D-W Statistic p-value
##    1       0.2045053      1.560699   0.086
##  Alternative hypothesis: rho != 0
```

I

Port Specifics

This appendix supplies information on port specifics and how these may impact the towage operations of JV. As operation location has been found to be an important in the level of utilisation of a vessel, and thus indirectly impact maintenance, it is important to understand and discriminate between different port characteristics. It is not aimed to incorporate port characteristics into the benchmarking model but use this background information for the evaluation of the results.

H020 - Europoort

The Port of Rotterdam is a large operating port which is well equipment for handling bulk and general cargoes, coal and ores, crude oil, agricultural product, chemicals, containers, cars, fruit, and refrigerated cargoes. It also supplies facilities for ship repair, maintenance and storage [Port of Rotterdam, 2019]. A layout and a summary of the port is shown in fig. I.1 and table I.1, respectively. The port takes in all sized vessels and indicate no restrictions regarding vessel length, beam and air draught. Restrictions are there for the draught, which is a maximum of 22.55 meter [Port of Rotterdam, 2019].

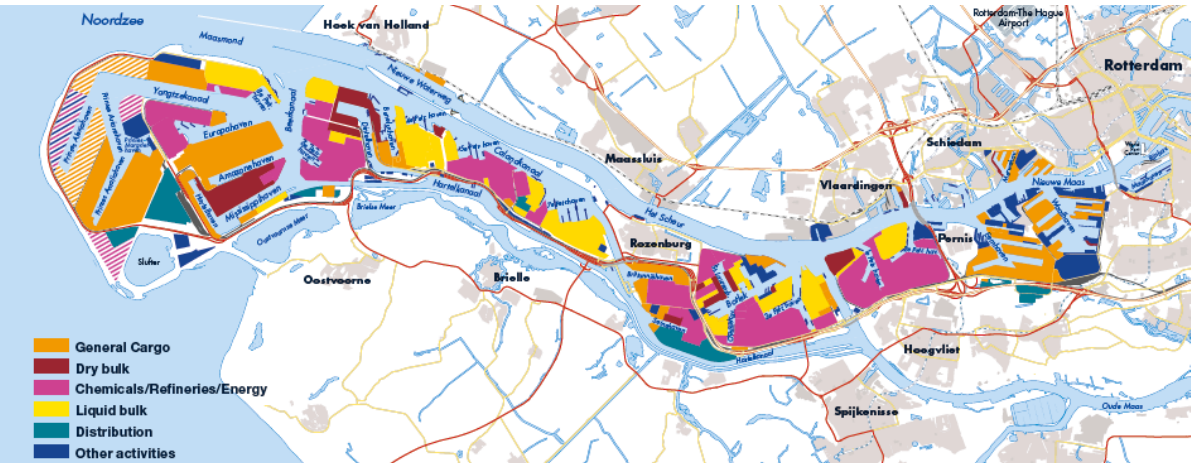


Figure I.1: Graphical layout of the Port of Rotterdam [Port of Rotterdam, 2019]

Table I.1: Summary of main information of Rotterdam Port (2017) [Port of Rotterdam, 2019].

Total port area, including Maasvlakte 2	12,643 ha
Land are	7,903 ha
of which rentable sites	6,046 ha
Water area	4,740 ha
Total length Rotterdam's Port area	42 km
Water depth NAP (max)	24 m
Depth Eurogeul in the North Sea NAP (max)	26 m
Length Eurogeul in the North Sea	57 km
Quay length	74,5 km

The Port of Rotterdam have the following local weather and tidal phenomena which are of interest in towage operations. Regarding wind impact, the Port of Rotterdam note the prevailing winds from the west to south-west which are generally blowing at force 4 or 5. The relative frequency of wind forces greater than Beaufort 7 is around 2% [Port of Rotterdam, 2019].

The tidal conditions within the Port show two high and two low waters within the course of 24 hours, with different amplitudes. A special phenomenon occurs at Hoek van Holland, which has a double low tide with a second low tide lower than the first. In addition, strong and sustained winds from the north-west raise the water levels along the Dutch coast. Winds which are strong and sustained from the south-east have the opposite effect [Port of Rotterdam, 2019].

Other phenomena at sea, is that the wind and tide strongly influence sea conditions when approaching the Maas Entrance. Strom conditions make; "entering the harbour hazardous" [Port of Rotterdam, 2019]. In conditions with storm force winds from the north-west and possible ground swells at Low Water, wave height may exceed 6 meters. Speed reduction in order to let waves run faster than the vessel is recommended in these circumstances.

Unfortunately, no detailed information was found concerning the regulations on the required number of tugs and bollard pull based on vessel specifics and weather conditions.

H048 - Southampton

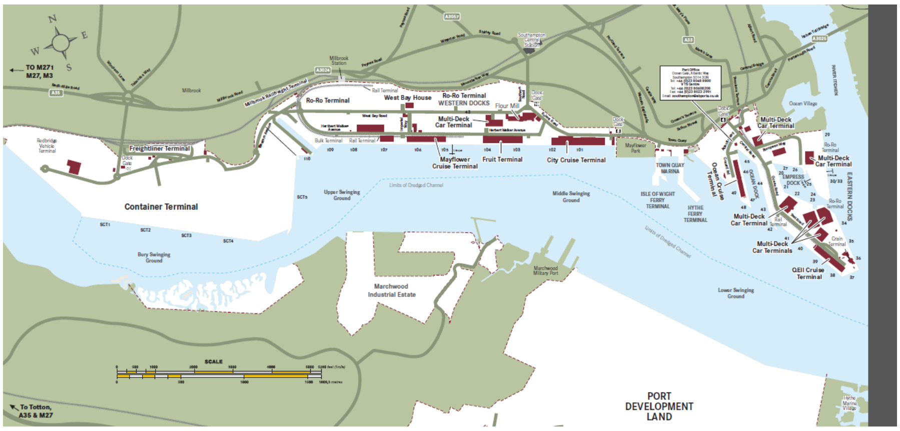


Figure I.2: Geographical layout of the port of Southampton [Port of Southampton, 2019]

The Port of Southampton specifies the following concerning towage information in the port [Port of Southampton, 2019]:

"the towage requirement for an individual vessel remains the responsibility of the Master. The number of tugs required may be increased when unfavourable conditions exist or when the handling characteristics of the vessel are in doubt. The Master may, in appropriate circumstances and with the prior approval of the Pilot and/or Harbour Master, decrease the number of tugs recommended in these guidelines. It should be noted however, that in cases where the vessel's Master refuses to accept the Pilot's, or in advance of the Pilot being embarked, the Liaison Pilot's advice in respect of the number of tugs required to facilitate a safe operation, the Harbour Master may impose the required number of tugs by Special Direction. These tugs will be for the owner's account."

Fully or partly laden tankers with excess of 60,000 DWT will be escorted inward and outward. The tug requires a minimum of 60 tonne bollard pull.

Table I.2: Recommended number of tugs to be used for berthing and unberthing in Southampton [Port of Southampton, 2019].

Vessel Type	Vessel Length Overall	No. of Tugs	
		Berthing	Unberthing
High Freeboard/Ferries	>125 m	2	2
High Freeboard/Ro-Ro	>125 m	2	2
	>210 m	3	2
Bulk carriers	125 - 180 m [a]	2	2
	>180 m [b]	3	2
High Freeboard/Ro-Ro and Miscellaneous	125 - 210 m	2	2
	>210 m	3	2
All other vessels except Bulk	125 - 210 m [a]	2	2
	>210 m [a]	3	2
Container Vessels	125 - 240 m	2	2
	>240 m [c]	3	2

[a] Vessels ≥ 20,000 DWT required tugs of a minimum of 30 tonnes bollard pull each.
[b] Vessels ≥ 60,000 DWT require that one tug must have at least 50 tonnes bollard pull.
[c] Vessel ≥ $240m$ LOA require tugs of a minimum of 40 tonnes bollard pull each. One tug must be of a tractor type.

In case of strong beam winds the bollard pull required is dependent on; ship type, draft and windage and handling conditions, reported ship defects, berth location, traffic density, metrological forecast and method of tug assistance [Port of Southampton, 2019].

The port of Southampton is known for unusual tidal phenomenons such as; 'Double High Water', 'Young Flood Stand' and short duration of ebb tide [Port of Southampton, 2019]. The UK Hydrographic Office, Tuanton, Somerset have stated that due to these meteorological effect, predictions can become unbalanced, resulting in higher or lower tides compared to predicted heights.

H050 - Liverpool

As any port, the Port of Liverpool has established towage guidelines. Shown in Figure I.3 is the towage matrix supplied by Peel Ports [2019]. Variation in vessel size, shape, condition, degree of manoeuvring capability, visibility and weather conditions may result in the Master deviating from the recommended number of tugs shown. The towage guidelines also state that inspection of maintenance of towage equipment should be done regularly, including ropes, wires, shackles, messengers, winches and hooks. Tugs are required to have a minimum bollard pull of 30 tonnes.

"It is however recognized that due to the considerable variations in vessel size, shape, condition and degree of manoeuvring capability the recommended number of tugs from the matrix given may be in excess of what is the safe minimum number of tugs for a particular vessel. As a consequence the master of any visiting ship may order the recommended number of tugs as per the towage matrix contained within this document or opt to consult with an authorised Liverpool Pilot where both marine professionals may agree to deviate from the Tug Matrix contained within this document by use of their own professional judgment to set a safe and appropriate level of tug provision for a particular vessel. Likewise, that tug provision may exceed the guidelines in exceptional circumstances, or when directed by the Harbour Master under his statutory powers." [Peel Ports, 2019].

Research within the port has resulted in the following conclusions regarding the suitability of different tug types with respect to operations, under normal port operations at maximum speeds of six to seven knots, and with some reservations [Peel Ports, 2019];

Vessel LOA	Gladstone River Entrance	Langton River Entrance	Alfred River Entrance	12 Quays	CLCT	Tranmere Oil Terminal	Bromborough Wall	Cammell Lairds	Eastham Locks	QEII Lock	Garston
< 95m	-	-	-	1	As per Cruise Terminal Guidelines	As per Tranmere Document	-	1	-	-	-
95m – 120m	1	1	1	2			1	2	1	1	1
120m -140m	2	2	2	2			2	2	2	2	2
140m - 160m	2	2	3	2			2	2	2	2	2†
160m - 180m	2	2	3	2				3	2	2	
180m - 210m	3	2	3	2				3		2	
>210m	3	3						4			

† *Maximum size of vessel for Garston is 152m*

Figure I.3: Towage matrix of the Port of Liverpool [Peel Ports, 2019]

<u>Forward tug towing on a line:</u>
ASD (operating from stern winch)
Combi-tugs
Conventional tugs
ATD and ASD (operating from bow winch)

<u>Stern tug towing on a line:</u>
ATD and ASD (operating from bow winch)
Combi-tugs
Conventional tugs

<u>Operating at ships side:</u>
ASD and ATD
Combi-tugs
Conventional tugs

<u>At speeds over 7 knots:</u>
Escort tugs

Figure I.4: Geographical layout of the Port of Liverpool [Peel Ports, 2019]

H058 - London

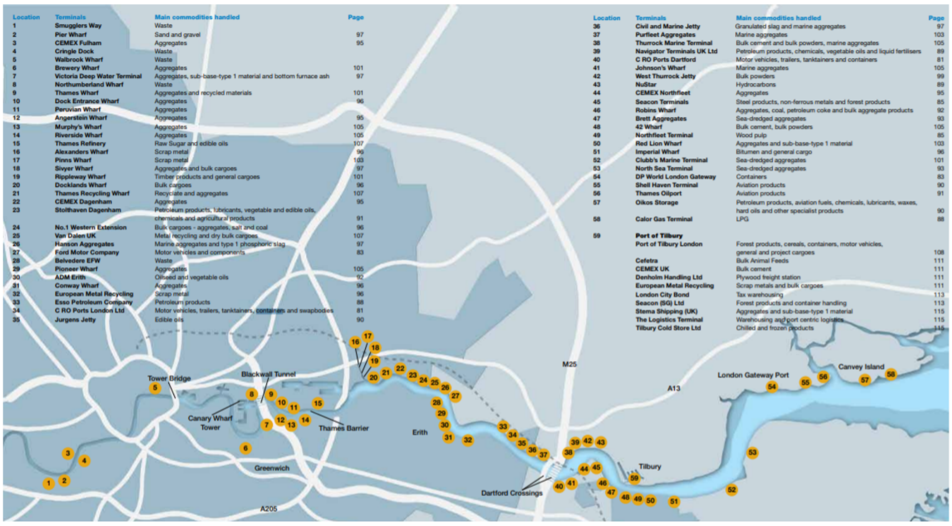


Figure I.5: Geographical layout of the Port of London.

Table I.3: Summary of port specific for inland London Port and London Gateway.

(a) Summary of main information of Port of London (inland) (2017) [UK-ports, 2019].

Max depth	11.4 m
Max size of vessels	
LOA	262.1 m
Beam	32.3 m
Draft	11.4 m
Nr. of berths	30
Berth length	4 km
Nr. of river berths	60

(b) Summary of main information of London Gateway [Gateway, 2019].

Max size of vessels	
LOA	400 m
Draft	16.6 m
Tidal variation	0.6m mean low water springs
	6.1m mean high water springs

Tidal information show low water occurring twice every 24 hours with lows of -0.13m at its lowest and 7.20 m at its highest. Possible surge tides are possible in which the tide exceeds 0.3m above or below predicted levels. It may cause a rise or fall up to 2.5m above or below prediction and may result in closure [of London Authority, 2019]. The Port of London Authority dictate that; "In strong tidal conditions a high percentage of the tug's power may be utilised in maintaining position on the vessel before applying thrust to the vessel. If the tugs are made fast alongside, they are at their most effective with a minimal ship speed through the water."

In the London gateway area, wind speeds are the highest due to larger open areas. An average steady wind will not exceed 30 knots. Predicted winds will not exceed 35 knots gusting [Gateway, 2019]. In this area, two tugs of 80T+ are required for inward vessels when wind is in excess of 20 knots, otherwise one tug. Outward vessels require two tugs above 20 knots. Winds above 30 knots require an additional tug.

Escort operations are also often performed within the Port of London. The port Authority state the following regarding escort operations; "Escorting as a regular operation is becoming common within the port towage industry. It should only be carried out after investigating the suitability of the tug for the operation and the Pilot, Master and Tugmaster(s) agreeing to a plan." This suggests that selective tugs are capable of escort operations and the type of tug should be taken into account.

The requirement of the number of tugs is based on the following matrix tables. These are just three exemplary tables of multiple which differ for different areas of the Thames. Similar to other port, the number of tugs is dependent on the vessel size (LOA and draught), additional manoeuvring aids such as bow thrusters and CPP, and location of operation. Aside from the augmentation shown in fig. I.6d, regulations also state the addition of tugs when performing so called stern-to-tide berthing. This suggests that the tidal influence within the port is significant.

LOA (m)	Maximum Draught (m) Up to 5m	Up to 6m	Up to 7m	Up to 8m	Up to 9m	Up to 10m	Up to 11m	Up to 12m	Above 12m
Up to 99.9	A	A	A	A	-	-	-	-	-
100 to 109.9	B	B	B	B	C	C	-	-	-
110 to 139.9	C	C	C	C	C	D	-	-	-
140 to 149.9	C	C	C	C	D	E	E	E	E
150 to 159.9	D	D	D	D	E	E	E	E	E
160 to 179.9	E	E	E	E	E	E	E	E	E
180 to 199.9	E	E	E	E	F	F	F	F	F
200 to 219.9	E	E	E	F	F	F	G	G	G
220 to 239.9	E	E	E	F	F	G	G	G	G
240 and above	F	F	F	F	F	G	G	G	G

(a) Table 1 - Ship size code for London Port. [of London Authority, 2019]

Manoeuvring Aids	Ship Type Code from Table 1 A	B	C	D	E	F	G
No Manoeuvring Aids	S	T	U	V	W	W	X
Controllable Pitch Propeller and/or Enhanced Rudder	S	S	U	V	W	W	X
Twin Screw, Enhanced Twin Rudder & Bow Thruster (Min1200hp)	S	S	T	T	T	V	W
Bow Thruster - Maximum Power (100hp ≈ 1.1t)							
Up to 499hp (372Kw)	S	T	U	V	W	W	X
500hp to 999hp (745Kw)	S	S	T	U	W	W	W
1000hp to 1499hp (1118Kw)	S	S	T	T	V	W	W
1500hp to 1999hp (1491Kw)	S	S	T	T	U	W	W
2000hp and above	S	S	T	T	U	U	W
Bow and Stern Thruster - Maximum Combined Power							
1500hp (1118Kw) and above	S	S	S	T	U	U	W

(b) Table 2 - Manoeuvring aids allowance code for London Port. [of London Authority, 2019]

Location and Operation		Manoeuvring Aids Allowance Code from Table 2 S	T	U	V	W	X
Tower Bridge Moorings & George's Stairs Tier	Berth	0	0	1	1	-	-
	Berth (S)	0	1	1	2	-	-
	Sail	0	0	1	1	-	-
	Sail (S)	0	1	1	2	-	-
London Bridge to Margaretness	Berth	0	0	1	1	2	-
	Berth (S)	0	0	1	2	2	-
	Sail	0	0	1	1	2	-
	Sail (S)	0	0	1	2	2	-
Margaretness to Sea Reach No. 7 Buoy	Berth	0	0	1	1	2	2
	Berth (S)	0	0	1	2	2	3
	Sail	0	0	1	1	2	2
	Sail (S)	0	0	1	2	2	3

Notes:
1. *(S) = Swing necessary or manoeuvring stern to tide.*
2. *Vessels over 180m swinging into the West India Dock Bellmouth and backing up to Greenwich **must** use 3 tugs, unless fitted with adequate manoeuvring aids and as agreed with the district Harbour Master.*
3. *Tug allocations for ships over 210m LOA navigating above the Thames Barrier are subject to the requirements identified in the associated risk assessment(s). The district Harbour Master must be consulted in such cases.*
4. *See Page 28 for additional requirements at Thames Refinery and Vopak.*

(c) Table 3 - Number of tugs required for London Port. [of London Authority, 2019]

Wind Speed - Constant and/or Gusts	Wind Direction Southerly Quadrant	Northerly Quadrant	Westerly Quadrant	Easterly Quadrant
Less than 25 kts	Tug Allocation Tables Apply		Tug Allocation Tables Apply	
Gusts over 25 kts	Tug Allocation Tables Apply		**Tug Allocation Tables plus 1**	
Gusts over 35kts	**Tug Allocation Tables plus 1**		**Abort Manoeuvre**	
Gusts over 40 kts	**Abort Manoeuvre**		**Abort Manoeuvre**	

Reduction in towage requirement for vessels sailing
The tug requirement can be reduced by one, provided the following conditions are satisfied:
1. The vessel LOA must be less than 225 metres;
2. The wind speed must be less than 15 knots;
3. The vessel must have an operational bow thruster of 1475hp/1100kW or more;
4. The vessel's draught is less than 10 metres;
5. The Vessel must be berthed head down; and
6. If unberthing on the ebb tide from the upper berth, the lower berth must be clear.

(d) Table 4 - Augmentation of towage requirements due to wind conditions. [of London Authority, 2019]

Figure I.6: Tables dictation the required number of tugs for towage operations. [of London Authority, 2019]

Furthermore, based on wind speeds and wind area a total required bollard pull to assist a vessel. This formula is bollard pull (kg) = $0.08 * A * V^2$. As a result, the London Port Authority illustrate that the required bollard pull for a car carrier of 197 meters at wind speeds of 25 knots requires the same amount of bollard pull as a 60,000 dwt loaded tanker at wind speeds of 40 knots [of London Authority, 2019].

To conclude, the London Port seems to heavily impacted by both tidal and weather/wind conditions. The number of locks is limited to mainly the inland ports along the Thames, but do have an impact on towage time. As a result of possible escort operations up the Thames, towage time may be considered longer than average as a result.

H060 - Antwerp

The Zandvlietsluit and the Berendrechtsluis lie 67 nautical miles from the SW Akkaert, which is 14 km of the coast of Ostend where the first pilot is taken on board ships bound for the port of Antwerp [Commissie, 2019]. Distances toe the various important berthing locations around the port are around 65 to 80 nautical miles. An overview of all critical information is shown in table I.4. The port is accessible at all times for ships with a draughts of up to 13.10, with a keel clearance of 12.5% [Commissie, 2019]. Average tidal differences at the Zandvlietsluis are 4.94m. and at the pilots' building on the roads of Antwerp: 5.19m.

Towage services at the Port of Antwerpen are provided by JV Toage and Antwerp Towage when manoeuvring on the Scheldt. Behind the lock, the Port authority's tugs take over towage operations [Port Of Antwerp, 2018].

Figure I.7: Geographical layout of the Port of Antwerp [Port Of Antwerp, 2018]

Table I.5: Mandatory towage requirements of the Port of Antwerp [Port Of Antwerp, 2018]

Jetty	No. of tugs	Mandatory for;
Southern left bank inlet	2	vessels with a draft of more than 11.5m
Southern right bank inlet	1	all seagoing vessels, independent of their dimensions or cargo
Delwaidedock	1	vessels with a width of more than 45m
	1	vessels between 180 and 250m
	1	vessels with a length exceeding 250m and a bow thruster. In all other cases 2 tugs.
	2	vessels when wind force is 6 Beaufort and a length above 250m

Table I.4: Summary of main information of the Port of Antwerp [Commissie, 2019].

(a) Summary of main information of the Port of Antwerp [Commissie, 2019].

Road network	409 km
Rail network	1,061 km
Quay walls	129.9 km
Surface area	13,057 ha
Water area	1,992 ha

(b) Lock information of the Port of Antwerp [Commissie, 2019].

Berendrechtsluit	500m x 68m x 17.75m
Zandvlietsluis	500m x 57m x 17.75m
Boudewijnsluis	360.4m x 45m x 14.50m
Van Cauwelaertsluis	270m x 35m x 14m
Royerssluis	182.m x 22m x 10.58m
Kallosluis	360m x 50m x 16m

The information shows that distance to cover to get to a berthing location is around the 70 nautical miles inland in which part is done with assistance with tugs. The number of locks within the port suggest additional towage duration as a result. This is base on the berthing location within the port itself. Aside from the locks, tidal influences restrict the larger vessels from entering the port around the clock (>13.10m). This restricts the possible entering of larger tankers with an increased draught.

H061 - Zeebrugge

The Port of Zeebrugge is located on the Blegian Coast of the North sea, 22.5 km west off the Scheldt estuary, about 21 km north-east off Ostend. The supervision of the Port of Zeebrugge Authority covers areas from the outer break waters to the northern side fo the Boudewijn Lock. The lock connects the port area to the City of Bruges and inland waterways [Port of Zeebrugge, 2019].

The port of Zeebrgge can be approached from 'The Scheur' which is a deep draught channel and 'Wielingen'- and 'Wandelaar' channels are coastal channels. Additionally, 'Pas van het Zand' is a channel which connects all the channels to the port. It's approximately 2 km long and 600 m wide with a depth of 15.8m over a width of 300 m [Port of Zeebrugge, 2019].

The general wind direction is from the south-west. Weather have a considerable impact on tidal heights, current and available depth [Port of Zeebrugge, 2019]. Sea levels are raised by the north and west winds and lowered by winds from the east. As a result, the breakwaters of Zeebrugge hold traffic lights which dictate the allowing or prohibiting of leaving and entering the port. The tidal range have been presented as;

Mean	+ 4.35 m at HW	+ 0.7 m at LW
Spring tide	+ 4.7 m at HW	+ 0.4 m at LW
Neap tide	+ 3.82 m at HW	+ 1.05 at LW

The outer port is the newest part of the port where access to terminal is direct, time saving and available depth is considerable [Port of Zeebrugge, 2019]. The outer port contains one container terminal, RORO's and LoLo's terminal, one LNG with two jetties- and one cruise terminal. It is noted that not all berths can accommodate maximum size vessels. No detailed information is supplied.

The inner ports are connected with outer through two locks, the Northern Inlet dock and the Southern Canal dock. The main goods unloaded in the inner port are cars, food and breakbulk cargo [Port of Zeebrugge, 2019]. Restriction, when it comes to the inner port, is as result of the max width in the Pierre Vandamme lock and the maximum lengths of the berths.

"The use of tugboats within the port limits of the Port of Bruges-Zeebrugge is not compulsory, except for LNG-carriers and vessels subject to nautical recommendations such as but not limited to large container vessels, towage of pontoons and non-self-propelled units, vessels restricted in manoeuvrability, etc. The Port Authority can impose the use or increase the number of required tugboats. "

Figure I.8: Geographical layout of the Port of Zeebrugge. [Port of Zeebrugge, 2019]

H062 - Ghent/Flushing/Terneuzen (GVT)
In 2017, the ports of Ghent, Flushing (Vlissingen) and Terneuzen fused together to form the North Sea Port [North Sea Port, 2019].

The Port of Vlissingen is accessible for vessels with a draught up to 17 meters. The port areas of Ghent and Terneuzen allow vessels up to a maximum of 12.5 meters. The Westsluis lock in Terneuzen is able to pass vessels up to 92.000 DWT with a maximum length of 265m length, 37m breadth and 12.5m draught. In order to transit towards Ghent, this lock is mandatory [North Sea Port, 2019].

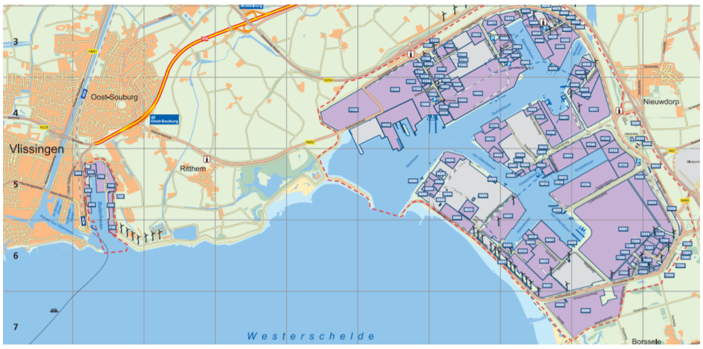


Figure I.10: Geographical layout of the Port of Flushing. [North Sea Port, 2019]

Harbour towage is provided throughout the port areas including the Ghent-Terneuzen Canal [North Sea Port, 2019]. Vessels bound for Vlissingen are required to have tug assistance for entering and manoeuvring in the harbour. “Towage is not compulsory within the port area except for vessels requiring special permission to transit the West Lock” ([North Sea Port, 2019]). Vessels up to 100m are required one tug, while ships over 100m and smaller than 20,000 GT are required two. When leaving ships up to 100m require one tug, vessels over 100m require two and vessels over 20,000 GT, when leaving Ocean Dock South, require three. Some vessels may be exempted if they have powerful bow thrusters and if they are moored with their bows to the north. This as a result of tidal influence [North Sea Port, 2019].

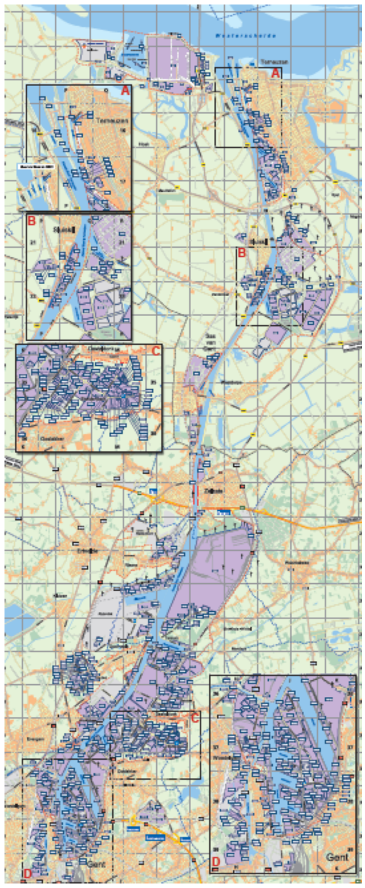


Figure I.9: Geographical layout of the Port of Terneuzen en Ghent. [North Sea Port, 2019]

The port of Vlissingen is a tidal port with direct access and thus more prone to tidal and wind conditions. Ghent and Terneuzen are protected by a lock and allow for a more ideal weather conditions when it comes to tidal. The port of Terneuzen is situated at the Westerschelde and thus more influenced by wind. In that case Ghent is more protected from the environment. However, Both Terneuzen and Ghent require towage assists based on dimensions. As a result the towage duration of Ghent can be considered longest of the three. However, as these three ports are summarised into one port an average of the conditions impacting towage operations is considered.

H084 - Hamburg

The Port of Hamburg lies on the shores of the Elbe about 83 km inland from the North Sea. It is situated about 110 km from the Port of Bremerhaven. The port covers a total of 7.4 hectares. There are about 320 berths using 41 km of quayside. 199 of which are used for handling general and bulk cargo. 83 for coastal shipping, 145 berths at dolphins and 38 berths reserved for container and bulk cargo [World Port Source, 2019].

Alongside depth at the berths are up to 17 meters.

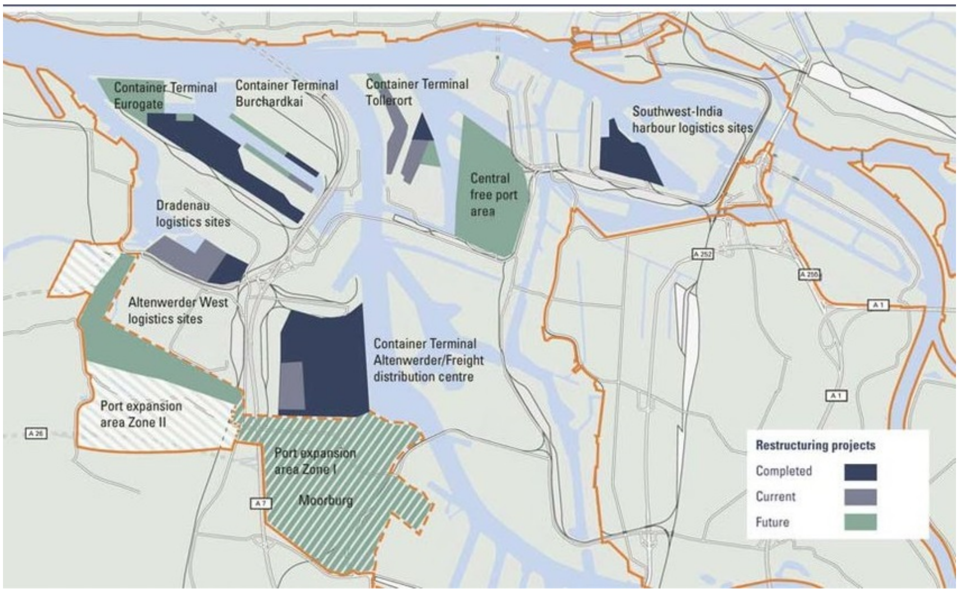


Figure I.11: Geographical layout of the Port of Hamburg. [Port of Hamburg, 2019]

The Port of Hamburg [2019] note that there is a strong tidal current on the River Elbe. Ships with a maximum draft of 12.80 m have access to the Port of Hamburg irrespective of tide. Using the tidal surge it is possible to have ships with a draft of up to 15.10 m going upstream. The other direction allows for a draft of up to 13.80 m [Port of Hamburg, 2019]. On average the difference between water levels, amounts to a mean of 3.66 metres at about 2.5 knots.

Five of the seven tug companies are organized in the 'Port of Hamburg Tugboat Owners' Association' which coordinates tugboats and their deployment. No general obligation to use tugs are in force, but in specific cases the harbourmaster's office can insist on this [Port of Hamburg, 2019]. Tugs are stationed in the centre top of the map. The general pickup point is just on the outside left side of the map, shown in fig. I.11.

It is found that Hamburg is a port which is impacted by tidal conditions through the river Elbe. Wind impact is minimal as the port is situated inland. The towage assist time is on the shorter side as tugs assist the vessels from the start of the port. The berths are all accessible for seagoing vessels without the interference of locks.

H085 - Bremerhaven

The Port of Bremerhaven lies on both banks of the Geest River as it enters the eastern Weser estuary about 70 km from the North Sea [World Port Source, 2019]. The Port is a seaport for the city-state of Bremen. It includes about 33.9 km of quay, 186 km of rail tracks, 56 bridges, 5 locks and 9 km of docks.

The port is, except for the container-, passenger- and part of the fruit terminal, protected by locks. The port has a total of four locks; North-lock, Kaiser-lock and Fischereihafenschleuse, consisting of two locks. Their respective dimensions are; 350m x 42m x 10.4m, 300m x 55m x 10.4m, 181m x 32.5m x 7.8m, 106m x 12m x 5.8m.

Figure I.12: Geographical layout of the Port of Bremerhaven. [Wikipedia, 2019]

Water depth limitations are at 12.2 meters for the channel. 6.1 m for the cargo pier, 9.1 m for the anchorage and 9.1 m for the oil terminal. Entrance restrictions are there due to tidal and overhead limitations.

The port Authority of Bremerhaven supply weather and tidal information [Bremen Ports, 2019]. Mainly, a south-east to west winds occur with a force of 4-5 Bft. The port is generally ice-free, but ice occurs only in extreme periods. Mean high water level is at 4.45m while the mean low water level is at 0.66 m. The tidal range is about 3.8m with the tidal current from 2.5 to 3.5 knots. In the period of 24 hours there are 2 high and 2 low waters. Winds which are strong from the north-west raise water levels along the coast and rivers. Wind from the south-east has the opposite effect. In the case of fog, tankers with a total of cargo > 2,000 mt aren't allowed to proceed on the river when visibility is less than 1,000 m. Smaller tankers need visibility of at least 500 m [Bremen Ports, 2019].

The number of required tugs is selected in agreement with the harbour master, they are not compulsory. Tug lines can be used without extra charge [Bremen Ports, 2019].

It has been found that Bremerhaven is a sea port which is influenced by tidal conditions. Even though some terminals are located outside the locks, the majority of berths are located within the locks, increasing the towage assist time. Tidal windows also dictate busy times within the port as a result. As the port is a sea port, wind conditions play a more important role compared to a more inland port.

J

DEA Script

```r
###########################################################################
####################### LOAD DATA #####################################
###########################################################################

dir <- "D:/Users/KEDR/boskalis.com/Towage Division - Maintenance Strategy/DATA MODEL/DEA/"
setwd(dir)
folder <- "1. Total Fleet/"
# H020 - Europoort / H048 - Southampton / H050 - Liverpool / H058 - London /
# H060 - Antwerp / H061 - Zeebrugge / H062 - GVT / H084 - Hamburg / H085 - Bremerhaven
port <- ""
tugtype <- "" #ASD / ATD / Conventional / RSD / RT / VSP
siscode<- "" #SIS_001/ / SIS_002 .....
location <- paste(dir,"DATA ",folder,port,tugtype,siscode,sep="")
file_list <- list.files(path = location)
file = file_list[1] #avg = 1, FY = 2


#Select 1 for Avg p Year and 2 for Full Year data
DEA.main <- read.csv(paste(location,file,sep=""),header=TRUE,sep=",",
                     fileEncoding="UTF-8-BOM")
DEA <- data.frame(DEA.main)
DEA$Name <- as.character(DEA$Name)

Drydocking <- "YES"

# Data Purging
if (Drydocking == "YES"){
  DEA <- filter_all(DEA, any_vars(DEA$DD >= 8000))
  DEA$RR[DEA$RR < 5000] <- NA
  DEA[DEA < 0] <- NA
}else{
  DEA$DD <- NULL
  DEA$RR[DEA$RR < 5000] <- NA
  DEA[DEA < 0] <- NA
}

#Name Data
if (colnames(DEA[2])=="Year"){
  Name <- data.frame(paste(DEA$Name,DEA$Year,sep="_"))
}else{
  Name <- data.frame(DEA$Name)
}
names(Name)[1] <- "DEA.Name"
Name$DEA.Name <- as.character(Name$DEA.Name)

RR <- data.frame(DEA$RR)
DD <- data.frame(DEA$DD)
RHrs<- data.frame(DEA$RHrs)
TM <- data.frame(DEA$TM)
FO <- data.frame(DEA$FO)

DEA.MASTERDATA <- list(Name = Name, RR = RR, DD = DD, FO = FO, TM=TM, RHrs = RHrs)
```



```r
###########################################################################
################### SELECT DATA AND RUN DEA ANALYSIS ###################
###########################################################################

# Select specific data to analyse
if (Drydocking == "YES"){
  DEA.data <- data.frame(Name, RR, DD, RHrs, TM)
  ni = 2
  no = 2
  inputweight = c(1,1)        #Specify input weight
  outputweight = c(1,1)       #Specify output weight
}else{
  DEA.data <- data.frame(Name, RR, RHrs, TM)
  ni = 1
  no = 2
  inputweight = c(1)          #Specify input weight
  outputweight = c(1,1)       #Specify output weight
}

# Delete all Rows with NA
DEA.data <- na.omit(DEA.data)

# Check rule of thumb
max = max(ni*no,3*(ni+no))
if (nrow(DEA)>=max){
  print("Number of DMUs is large enough for DEA")
}else{
  print("Number of DMUs is not large enough for DEA")
  #stop()
}
```

```
## [1] "Number of DMUs is large enough for DEA"
```

```r
Name <- DEA.data$DEA.Name
RR <- DEA.data$DEA.RR
DD <- DEA.data$DEA.DD
RHrs<- DEA.data$DEA.RHrs
TM <- DEA.data$DEA.TM
FO <- DEA.data$DEA.FO

RTS <- "nirs"  # crs / vrs / nirs / ndrs / grs

# DEA Runs
data_example <- read_data(DEA.data,
                          ni = ni,
                          no = no,
                          #nd_input = 2,
                          nc_outputs = 2)
# SBM Run
result_SBM <- model_sbmeff(data_example,
                           orientation = "no",
                           weight_input = inputweight,
                           weight_output = outputweight,
                           rts = RTS,
```

```
                            selfapp = TRUE, na.action=na.exclude)

###########################################################################
######################## FRONTIER PLOTTING ################################ #benchmarking package
###########################################################################

# Running Plots
dea.plot.frontier(RR, TM, "drs", xlab = "MR Running Costs",
                  ylab = "TM",txt=1:length(RR)[1])
dea.plot.frontier(RR, RHrs, "drs" , xlab = "MR Running Costs",
                  ylab = "RHrs",txt=1:length(RR)[1])

# Dry Docking Plots
if(Drydocking=="YES"){
dea.plot.frontier(DD, TM,   "drs", xlab = "MR Dry Docking Costs",
                  ylab = "TM",txt=1:length(DD)[1])
dea.plot.frontier(DD, RHrs, "drs", xlab = "MR Dry Docking Costs",
                  ylab = "RHrs",txt=1:length(DD)[1])
}


###########################################################################
############################# VIEW RESULTS ################################
###########################################################################

SBM_Eff = efficiencies(result_SBM)
SBM_Slacks = slacks(result_SBM)
SBM_Targets = targets(result_SBM)
SBM_ref = references(result_SBM)

# Write to output Excel
outputlocation <- paste(dir,"OUTPUT ",folder,port,tugtype,siscode,"OUTPUT_",file,sep="")
RESULT <- data.frame(DMU_ID = result_SBM$dmu_eval, Name= result_SBM$data$dmunames,Efficiency = SBM_Eff,
                     InputSlacks = SBM_Slacks$slack_input, InputTarget = SBM_Targets$target_input,
                     OutputSlacks = SBM_Slacks$slack_output,OutputTarget = SBM_Targets$target_output)
write.xlsx(RESULT, file = outputlocation)
```

```
## Note: zip::zip() is deprecated, please use zip::zipr() instead
```

```
# Automatically Save Plots to pdf
if (Drydocking=="YES"){
{pdf(paste(dir,"OUTPUT ",folder,port,tugtype,siscode,"OUTPUT_",file,".pdf",sep=""))

  dea.plot.frontier(RR, RHrs, "drs" , xlab = "Running Repair Costs",
                              ylab = "RHrs",txt=1:length(RR)[1])

  dea.plot.frontier(RR, TM, "drs", xlab = "Running Repair Costs",
                    ylab = "TM",txt=1:length(RR)[1])

  dea.plot.frontier(DD, RHrs, "drs", xlab = "Dry Docking Costs",
                    ylab = "RHrs",txt=1:length(DD)[1])

  dea.plot.frontier(DD, TM,   "drs", xlab = "Dry Docking Costs",
                    ylab = "TM",txt=1:length(DD)[1])
```



```
plot(result_SBM)
dev.off()
}
}else{
  {pdf(paste(dir,"OUTPUT ",folder,port,tugtype,siscode,"OUTPUT_",file,".pdf",sep=""))

    dea.plot.frontier(RR, RHrs, "drs" , xlab = "Running Repair Costs",
                      ylab = "RHrs",txt=1:length(RR)[1])

    dea.plot.frontier(RR, TM, "drs", xlab = "Running Repair Costs",
                      ylab = "TM",txt=1:length(RR)[1])

    plot(result_SBM)
    dev.off()
  }
  print("Excel and PDF showing results and plots have been saved.")
}
```

```
## Press [enter] to continue

## Press [enter] to continue

## pdf
##   2
```

K

DEA Extended Results

K.1. DEA summary of fleet, tug type and sister vessels

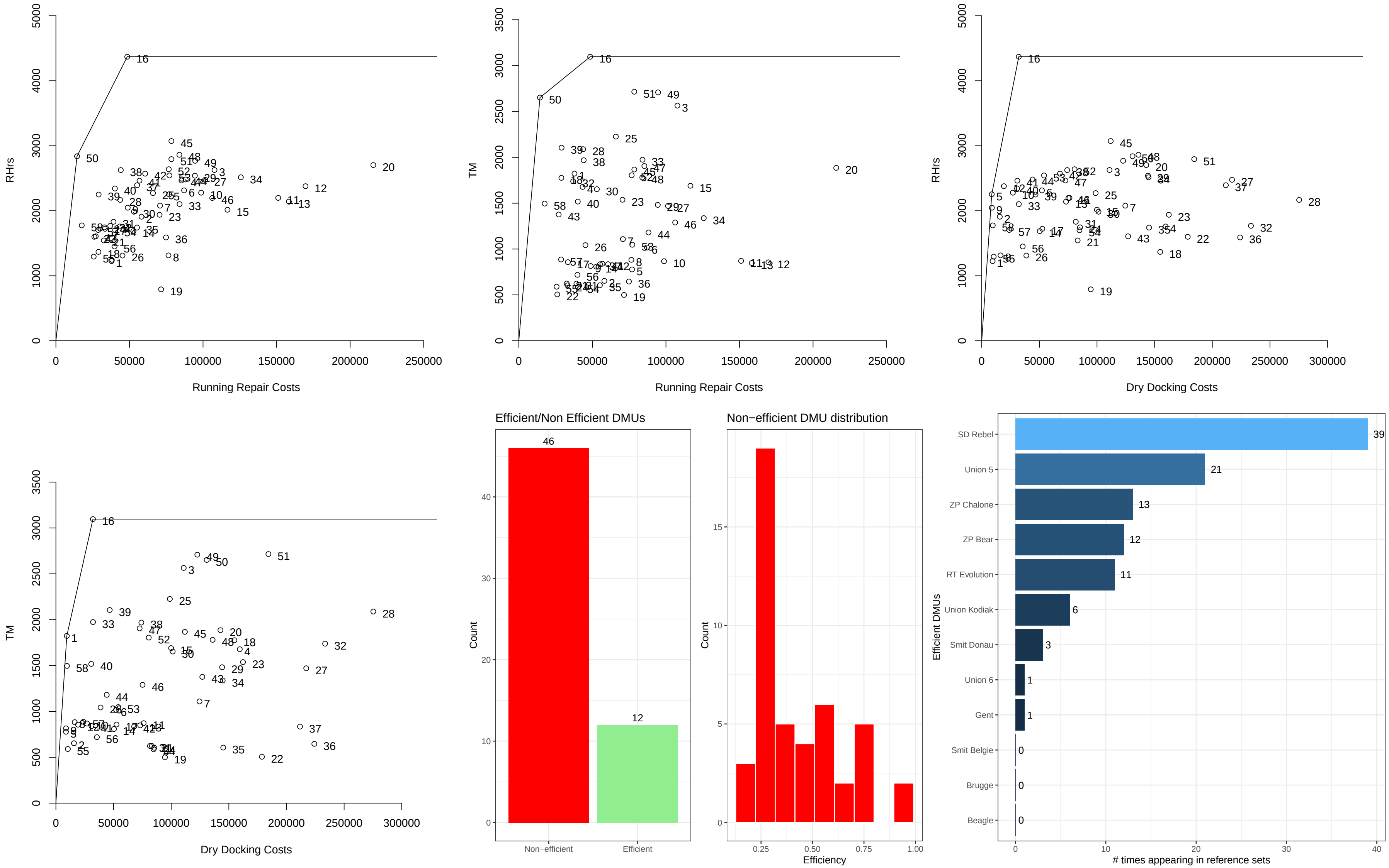
Table K.1: Summary of DEA results for fleet, tug type and sister vessel evaluation.

		Input					DEA: Fleet				DEA: Tug Type				DEA: Sister Vessels			
Name	Type	Sis Code	RR Costs [x €1,000]	DD Cost [x €1,000]	RHrs	TM	Efficiency Score	RR Costs [x €1,000]	RR Costs [x €1,000]	RHrs Target	Efficiency Score	RR Costs [x €1,000]	DD Costs [x €1,000]	RHrs Target	Efficiency Score	RR Costs [x €1,000]	DD Costs [x €1,000]	RHrs Target
Tug 13	RT Hybrid	001	87.12	52.23	1,895	1,016	0.49	50.06	14.32	2,314	1.00	87.12	52.23	2,314	1.00	87.12	52.23	2,314
Tug 14	RT	001	70.77	124.55	2,079	1,109	0.40	35.35	18.03	2,079	0.78	68.92	68.42	2,264	1.00	70.77	124.55	2,079
Tug 18	RT	001	151.09	76.10	2,198	871	0.29	50.73	14.60	2,198	0.46	78.41	24.18	2,198	1.00	151.09	76.10	2,198
Tug 20	RT	001	158.35	73.14	2,140	848	0.27	50.03	12.44	2,140	0.37	67.28	17.99	2,140	1.00	158.35	73.14	2,140
Tug 15	RT Hybrid	002	76.50	16.29	1,314	883	0.30	20.04	6.52	1,314	1.00	76.50	16.29	1,314	1.00	76.50	16.29	1,314
Tug 16	RT Hybrid	002	48.82	8.77	1,150	815	1.00	48.82	8.77	2,047	1.00	48.82	8.77	2,047	1.00	48.82	8.77	2,047
Tug 34	RT	003	101.38	217.13	2,476	1,470	0.29	37.11	20.19	2,476	0.83	93.67	141.88	2,531	0.83	93.73	143.08	2,520
Tug 36	RT	003	94.45	144.18	2,539	1,482	0.34	38.85	21.34	2,539	1.00	94.45	144.18	2,539	1.00	94.45	144.18	2,539
Tug 17	RT	004	98.71	27.00	2,278	868	0.58	52.45	19.26	2,278	1.00	98.71	27.00	2,278	1.00	98.71	27.00	2,278
Tug 19	RT	004	169.65	19.24	2,378	856	0.54	69.20	17.05	2,378	1.00	169.65	19.24	2,378	1.00	169.65	19.24	2,378
Tug 21	ASD	005	52.67	50.32	1,687	808	0.51	33.20	11.33	1,687	0.53	31.35	17.89	1,687	-	-	-	-
Tug 30	ASD	006	70.46	162.27	1,938	1,538	0.22	20.04	11.86	1,938	0.24	24.07	15.95	2,169	0.76	57.63	100.52	1,938
Tug 37	ASD	006	53.04	101.30	1,986	1,653	0.30	20.59	11.78	2,029	0.34	25.87	17.15	2,332	1.00	53.04	101.30	1,986
Tug 41	ASD	006	125.70	144.66	2,515	1,337	0.29	42.67	23.35	2,515	0.29	42.42	24.80	2,515	1.00	125.70	144.66	2,515
Tug 54	ASD	007	106.28	75.16	2,197	1,290	0.29	35.38	13.51	2,197	0.30	33.10	19.95	2,197	0.64	77.02	62.54	2,574
Tug 56	ASD	007	85.34	72.60	2,466	1,906	0.28	25.94	15.82	2,466	0.30	29.84	19.77	2,689	1.00	85.34	72.60	2,466
Tug 63	ASD	007	76.69	80.53	2,639	1,805	0.36	31.56	19.58	2,639	0.36	31.43	20.34	2,639	1.00	76.69	80.53	2,639
Tug 64	ASD	007	77.17	54.06	2,543	1,047	0.64	54.11	25.72	2,543	0.64	52.82	29.38	2,543	1.00	77.17	54.06	2,543
Tug 25	ASD	008	28.93	154.82	1,367	1,776	0.29	9.63	87.61	1,902	0.29	9.63	87.61	1,902	0.29	9.63	87.61	1,902
Tug 26	ASD	008	71.51	94.59	791	500	0.13	10.90	5.98	791	0.13	10.77	6.69	791	0.34	22.64	37.56	791
Tug 27	ASD	008	215.75	142.71	2,703	1,885	0.14	31.25	19.58	2,703	0.14	30.99	20.31	2,703	0.47	63.42	127.46	2,703
Tug 57	ASD	008	83.93	135.94	2,862	1,780	0.39	40.10	22.99	2,862	0.39	39.83	24.55	2,862	1.00	83.93	135.94	2,862
Tug 61	ASD	008	14.37	130.78	2,839	2,652	1.00	14.37	130.78	2,839	1.00	14.37	130.78	2,839	1.00	14.37	130.78	2,839
Tug 62	ASD	008	78.48	184.32	2,794	2,716	0.31	41.12	26.76	3,752	0.31	42.52	28.18	3,831	1.00	78.48	184.32	2,794
Tug 6	ASD	009	107.80	110.86	2,627	2,564	0.24	38.20	24.63	3,506	0.24	40.15	26.61	3,618	1.00	107.80	110.86	2,627
Tug 7	ASD	009	43.37	159.47	1,758	1,678	0.29	9.09	82.74	1,796	0.29	9.09	82.74	1,796	1.00	43.37	159.47	1,758
Tug 45	ASD	010	74.85	224.15	1,590	646	0.34	33.31	18.49	1,590	0.34	33.31	18.49	1,590	0.38	43.68	23.77	1,893
Tug 49	ASD	010	56.82	30.92	2,463	840	1.00	56.82	30.92	2,463	1.00	56.82	30.92	2,463	1.00	56.82	30.92	2,463
Tug 50	ASD	010	60.67	67.86	2,571	835	1.00	60.67	67.86	2,571	1.00	60.67	67.86	2,571	1.00	60.67	67.86	2,571
Tug 65	ASD	010	40.30	84.79	1,700	587	0.76	39.03	21.08	1,700	0.76	39.00	21.25	1,700	0.77	39.67	21.58	1,720
Tug 55	ASD	011	-	3.35	2,921	1,827	-	-	-	-	-	-	-	-	1.00	-	3.35	2,921
Tug 58	ASD	011	-	107.55	2,977	2,633	-	-	-	-	-	-	-	-	0.04	-	4.83	4,210
Tug 23	ASD	012	48.48	32.13	4,369	3,097	1.00	48.48	32.13	4,369	1.00	48.48	32.13	4,369	1.00	48.48	32.13	4,369
Tug 24	ASD	012	33.37	52.58	1,723	857	0.75	31.48	14.84	1,723	0.76	30.97	17.82	1,723	1.00	33.37	52.58	1,723
Tug 28	ASD	012	32.58	83.22	1,544	624	0.77	32.44	18.00	1,544	0.77	32.44	18.00	1,544	0.82	27.29	65.16	1,543
Tug 31	ASD	012	33.05	85.26	1,745	604	1.00	33.05	85.26	1,745	1.00	33.05	85.26	1,745	1.00	33.05	85.26	1,745
Tug 32	ASD	012	65.96	98.83	2,272	2,226	0.31	31.66	19.86	2,958	0.32	34.85	23.10	3,141	0.32	34.85	23.10	3,141
Tug 33	ASD	012	45.29	38.72	1,311	1,043	0.27	13.53	7.98	1,311	0.30	16.32	10.82	1,471	0.30	16.32	10.82	1,471
Tug 35	ASD	012	43.72	275.33	2,167	2,089	0.28	11.32	103.03	2,237	0.28	11.32	103.03	2,237	0.41	32.71	21.68	2,947
Tug 39	ASD	012	36.94	233.50	1,769	1,739	0.27	9.42	85.75	1,861	0.27	9.42	85.75	1,861	0.40	27.22	18.04	2,453
Tug 40	ASD	012	84.07	32.17	2,102	1,974	0.31	26.80	16.31	2,550	0.34	30.91	20.49	2,786	0.34	30.91	20.49	2,786
Tug 29	ASD	014	26.15	178.69	1,600	505	1.00	26.15	178.69	1,600	1.00	26.15	178.69	1,600	-	-	-	-
Tug 1	ATD	015	37.84	9.44	1,226	1,823	1.00	37.84	9.44	1,226	1.00	37.84	9.44	1,226	1.00	37.84	9.44	1,226
Tug 66	ATD	015	25.67	10.37	1,294	590	1.00	25.67	10.37	1,294	1.00	25.67	10.37	1,294	1.00	25.67	10.37	1,294
Tug 68	ATD	015	39.85	35.54	1,451	719	0.57	26.76	11.47	1,450	0.60	26.49	15.01	1,450	0.60	26.08	17.02	1,451
Tug 69	ATD	015	28.73	23.84	1,705	887	0.99	28.73	23.09	1,705	1.00	28.73	23.84	1,705	1.00	28.73	23.84	1,705
Tug 53	ASD	016	78.50	111.87	3,073	1,867	0.47	44.38	25.97	3,072	0.47	44.20	26.99	3,073	1.00	78.50	111.87	3,073
Tug 59	ASD	016	94.66	122.66	2,769	2,709	0.27	40.99	26.66	3,740	0.28	42.41	28.10	3,822	1.00	94.66	122.66	2,769
Tug 38	VSP	017	39.16	81.59	1,831	623	0.91	39.16	55.97	1,831	1.00	39.16	81.59	1,831	1.00	39.16	81.59	1,831
Tug 48	VSP	017	40.09	30.65	2,343	1,518	0.72	31.86	15.82	2,343	1.00	40.09	30.65	2,343	1.00	40.09	30.65	2,343
Tug 51	VSP	017	27.10	126.99	1,607	1,377	0.42	11.48	52.63	1,607	1.00	27.10	126.99	1,607	1.00	27.10	126.99	1,607
Tug 52	VSP	017	88.16	44.08	2,481	1,181	0.51	50.04	16.00	2,481	1.00	88.16	44.08	2,481	1.00	88.16	44.08	2,481
Tug 22	ASD	018	116.64	99.94	2,015	1,690	0.16	21.31	12.31	2,089	0.18	26.46	17.54	2,384	-	-	-	-
Tug 42	VSP	019	55.12	145.15	1,741	605	0.56	39.80	21.70	1,741	0.63	37.06	76.31	1,741	-	-	-	-
Tug 46	ATD	020	44.10	74.12	2,626	1,969	0.52	28.18	17.74	2,626	1.00	44.10	74.12	2,626	1.00	44.10	74.12	2,626
Tug 47	ATD	020	29.05	46.69	2,250	2,106	0.68	29.05	19.35	2,754	1.00	29.05	46.69	2,250	1.00	29.05	46.69	2,250
Tug 45	Conv	021	55.20	211.73	2,393	834	0.75	53.75	37.74	2,393	1.00	55.20	-	2,393	1.00	55.20	-	2,393
Tug 3	ASD	-	58.17	15.67	1,909	653	1.00	58.17	15.67	1,909	1.00	58.17	15.67	1,909	-	-	-	-
Tug 8	Conv	-	76.95	8.70	2,254	778	1.00	76.95	8.70	2,254	0.84	64.67	-	2,254	-	-	-	-
Tug 70	ATD	-	17.56	9.57	1,775	1,496	1.00	17.56	9.57	1,775	1.00	17.56	9.57	1,775	-	-	-	-

K.2. Fleet Results

Table K.2: DEA results for the fleet.

INPUT						OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 1	37.84	9.44	1,226	1,823	1.00	37.84	9.44	1,226	1,823
2	Tug 3	58.17	15.67	1,909	653	1.00	58.17	15.67	1,909	653
3	Tug 6	107.80	110.86	2,627	2,564	0.24	38.20	24.63	3,506	2,564
4	Tug 7	43.37	159.47	1,758	1,678	0.29	9.09	82.74	1,796	1,678
5	Tug 8	76.95	8.70	2,254	778	1.00	76.95	8.70	2,254	778
6	Tug 13	87.12	52.23	1,895	1,016	0.35	32.16	15.73	1,895	1,016
7	Tug 14	70.77	124.55	2,079	1,109	0.40	35.35	18.03	2,079	1,109
8	Tug 15	76.50	16.29	1,314	883	0.32	16.25	9.79	1,314	883
9	Tug 16	48.82	8.77	1,150	815	0.46	15.33	7.24	1,150	815
10	Tug 17	98.71	27.00	2,278	868	0.62	71.94	9.86	2,278	868
11	Tug 18	151.09	76.10	2,198	871	0.31	46.95	24.72	2,198	871
12	Tug 19	169.65	19.24	2,378	856	0.54	69.20	17.05	2,378	856
13	Tug 20	158.35	73.14	2,140	848	0.30	45.75	23.89	2,140	848
14	Tug 21	52.67	50.32	1,687	808	0.52	31.85	14.93	1,687	808
15	Tug 22	116.64	99.94	2,015	1,690	0.16	21.31	12.31	2,089	1,690
16	Tug 23	48.48	32.13	4,369	3,097	1.00	48.48	32.13	4,369	3,097
17	Tug 24	33.37	52.58	1,723	857	0.75	31.48	14.84	1,723	857
18	Tug 25	28.93	154.82	1,367	1,776	0.29	9.63	87.61	1,902	1,776
19	Tug 26	71.51	94.59	791	500	0.13	10.90	5.98	791	500
20	Tug 27	215.75	142.71	2,703	1,885	0.14	31.05	19.96	2,703	1,885
21	Tug 28	32.58	83.22	1,544	624	0.77	32.44	18.00	1,544	624
22	Tug 29	26.15	178.69	1,600	505	1.00	26.15	178.69	1,600	505
23	Tug 30	70.46	162.27	1,938	1,538	0.22	20.04	11.86	1,938	1,538
24	Tug 31	33.05	85.26	1,745	604	1.00	33.05	85.26	1,745	604
25	Tug 32	65.96	98.83	2,272	2,226	0.31	31.66	19.86	2,958	2,226
26	Tug 33	45.29	38.72	1,311	1,043	0.27	13.53	7.98	1,311	1,043
27	Tug 34	101.38	217.13	2,476	1,470	0.29	37.11	20.19	2,476	1,470
28	Tug 35	43.72	275.33	2,167	2,089	0.28	11.32	103.03	2,237	2,089
29	Tug 36	94.45	144.18	2,539	1,482	0.34	38.85	21.34	2,539	1,482
30	Tug 37	53.04	101.30	1,986	1,653	0.30	20.59	11.78	2,029	1,653
31	Tug 38	39.16	81.59	1,831	623	0.91	39.16	55.97	1,831	623
32	Tug 39	36.94	233.50	1,769	1,739	0.27	9.42	85.75	1,861	1,739
33	Tug 40	84.07	32.17	2,102	1,974	0.31	26.80	16.31	2,550	1,974
34	Tug 41	125.70	144.66	2,515	1,337	0.29	42.67	23.35	2,515	1,337
35	Tug 42	55.12	145.15	1,741	605	0.56	39.80	21.70	1,741	605
36	Tug 45	74.85	224.15	1,590	646	0.34	33.31	18.49	1,590	646
37	Tug 45	55.20	211.73	2,393	834	0.75	53.75	37.74	2,393	834
38	Tug 46	44.10	74.12	2,626	1,969	0.52	28.18	17.74	2,626	1,969
39	Tug 47	29.05	46.69	2,250	2,106	0.68	29.05	19.35	2,754	2,106
40	Tug 48	40.09	30.65	2,343	1,518	0.72	30.93	17.60	2,343	1,518
41	Tug 49	56.82	30.92	2,463	840	1.00	56.82	30.92	2,463	840
42	Tug 50	60.67	67.86	2,571	835	1.00	60.67	67.86	2,571	835
43	Tug 51	27.10	126.99	1,607	1,377	0.42	11.48	52.63	1,607	1,377
44	Tug 52	88.16	44.08	2,481	1,181	0.54	46.54	25.36	2,481	1,181
45	Tug 53	78.50	111.87	3,073	1,867	0.47	44.38	25.97	3,073	1,867
46	Tug 54	106.28	75.16	2,197	1,290	0.29	33.54	17.40	2,197	1,290
47	Tug 56	85.34	72.60	2,466	1,906	0.28	25.94	15.82	2,466	1,906
48	Tug 57	83.93	135.94	2,862	1,780	0.39	40.10	22.99	2,862	1,780
49	Tug 59	94.66	122.66	2,769	2,709	0.27	40.99	26.66	3,740	2,709
50	Tug 61	14.37	130.78	2,839	2,652	1.00	14.37	130.78	2,839	2,652
51	Tug 62	78.48	184.32	2,794	2,716	0.31	41.12	26.76	3,752	2,716
52	Tug 63	76.69	80.53	2,639	1,805	0.36	31.56	19.58	2,639	1,805
53	Tug 64	77.17	54.06	2,543	1,047	0.64	52.88	29.01	2,543	1,047
54	Tug 65	40.30	84.79	1,700	587	0.76	39.03	21.08	1,700	587
55	Tug 66	25.67	10.37	1,294	590	1.00	25.67	10.37	1,294	590
56	Tug 68	39.85	35.54	1,451	719	0.57	26.76	11.47	1,450	719
57	Tug 69	28.73	23.84	1,705	887	0.99	28.73	23.09	1,705	887
58	Tug 70	17.56	9.57	1,775	1,496	1.00	17.56	9.57	1,775	1,496

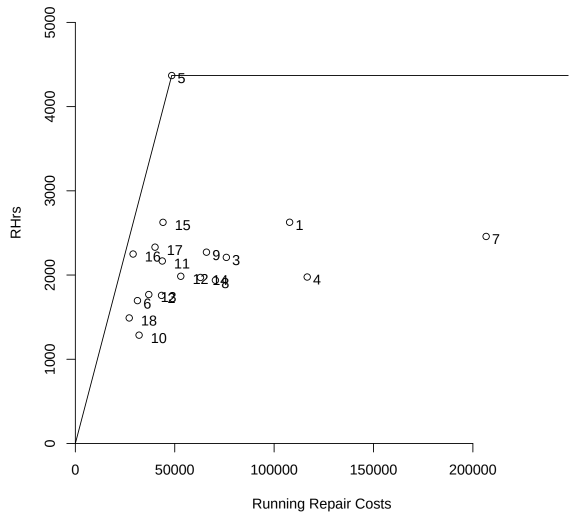

RHrs
Running Repair Costs
TM
Running Repair Costs
RHrs
Dry Docking Costs
TM
Dry Docking Costs
Efficient/Non Efficient DMUs
Count
46
12
Non−efficient
Efficient
Non−efficient DMU distribution
Count
Efficiency
Efficient DMUs
SD Rebel
Union 5
ZP Chalone
ZP Bear
RT Evolution
Union Kodiak
Smit Donau
Union 6
Gent
Smit Belgie
Brugge
Beagle
39
21
13
12
11
6
3
1
1
0
0
0
times appearing in reference sets

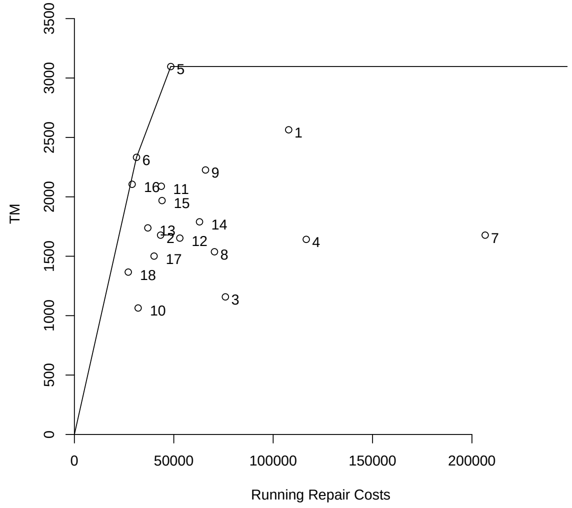
K.3. Port Results

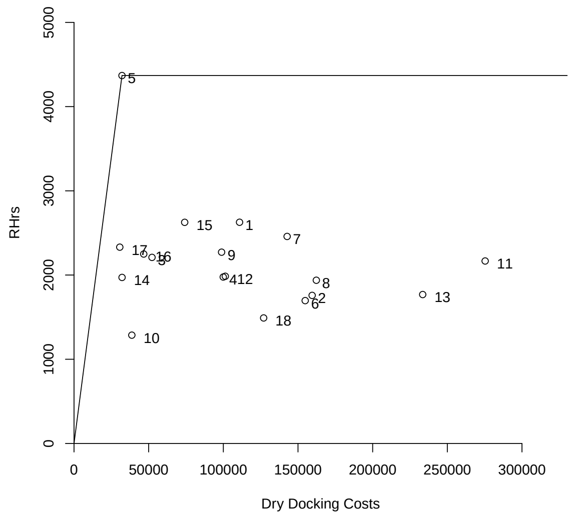
K.3.1. Port A

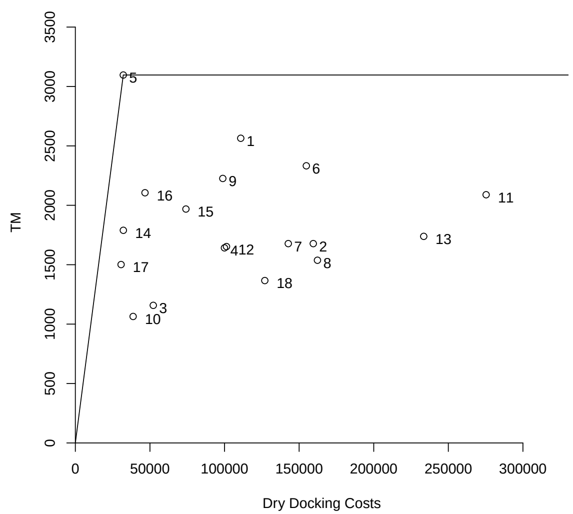
Table K.3: DEA results for tugs within Port A.

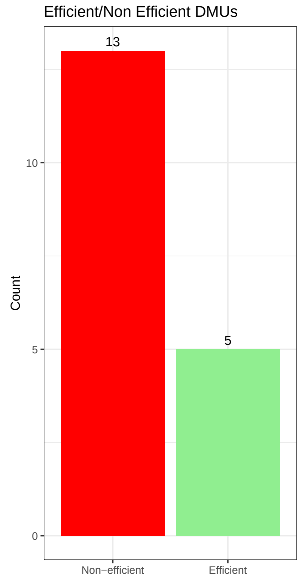
INPUT						OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 6	107.80	110.86	2,627	2,564	0.24	40,148.26	26,607.24	3,618	2,564
2	Tug 7	43.37	159.47	1,758	1,678	0.34	26,266.24	17,407.28	2,367	1,678
3	Tug 13	75.97	52.23	2,210	1,158	1.00	75,966.13	52,228.23	2,210	1,158
4	Tug 22	116.64	99.94	1,977	1,642	0.18	25,707.83	17,037.21	2,317	1,642
5	Tug 23	48.48	32.13	4,369	3,097	1.00	48,482.69	32,130.67	4,369	3,097
6	Tug 25	31.25	154.82	1,696	2,333	1.00	31,248.10	154,819.63	1,696	2,333
7	Tug 27	206.66	142.71	2,458	1,678	0.16	33,376.36	23,871.32	2,458	1,678
8	Tug 30	70.46	162.27	1,938	1,538	0.24	24,074.34	15,954.66	2,169	1,538
9	Tug 32	65.96	98.83	2,272	2,226	0.32	34,851.17	23,096.73	3,141	2,226
10	Tug 33	32.07	38.72	1,286	1,065	0.39	16,666.25	11,045.13	1,502	1,064
11	Tug 35	43.72	275.33	2,167	2,089	0.41	32,706.24	21,675.23	2,947	2,089
12	Tug 37	53.04	101.30	1,986	1,653	0.34	25,874.83	17,147.89	2,332	1,653
13	Tug 39	36.94	233.50	1,769	1,739	0.40	27,221.28	18,040.21	2,453	1,739
14	Tug 40	62.95	32.17	1,972	1,790	0.38	28,019.76	18,569.38	2,525	1,790
15	Tug 46	44.10	74.12	2,626	1,969	0.55	30,822.25	20,426.67	2,778	1,969
16	Tug 47	29.05	46.69	2,250	2,106	1.00	29,048.32	46,688.33	2,250	2,106
17	Tug 48	40.09	30.65	2,331	1,501	1.00	40,085.05	30,650.67	2,331	1,501
18	Tug 51	27.10	126.99	1,490	1,367	0.46	21,397.10	14,180.38	1,928	1,367

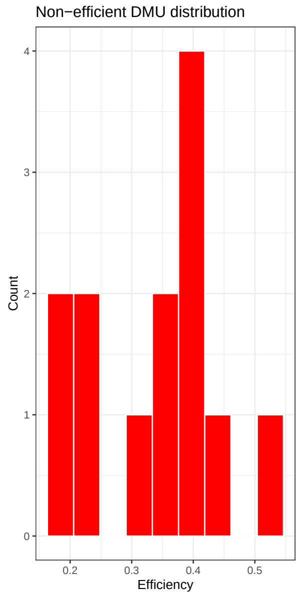

RHrs
Running Repair Costs

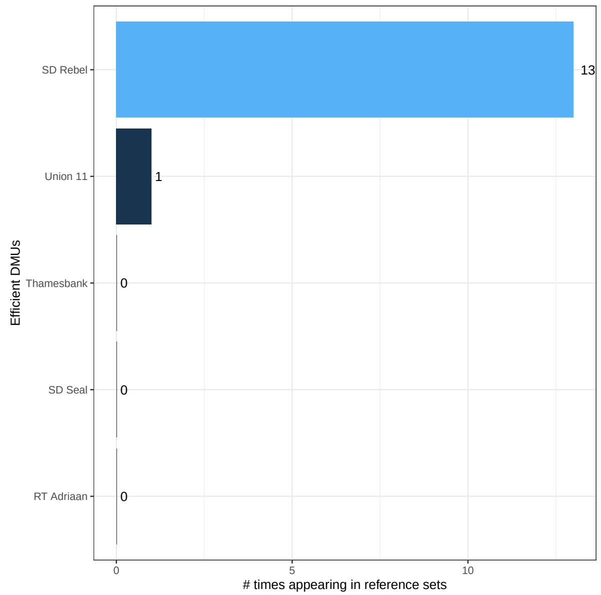

TM
Running Repair Costs


RHrs
Dry Docking Costs


TM
Dry Docking Costs


Efficient/Non Efficient DMUs
Count
13
5
Non−efficient
Efficient

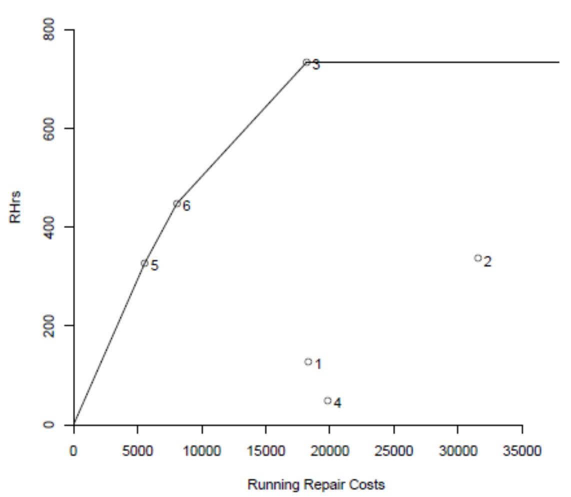

Non−efficient DMU distribution
Count
Efficiency

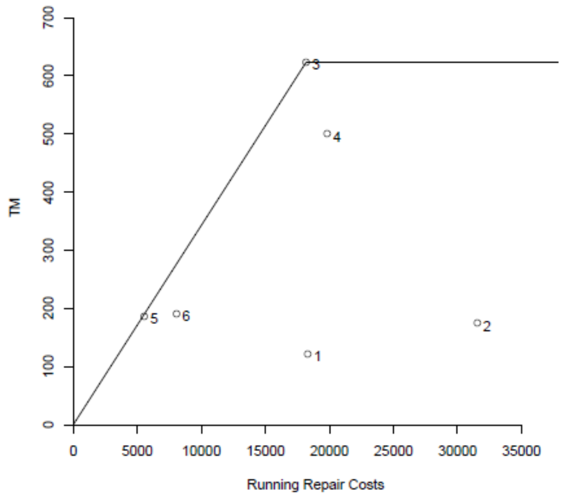

Efficient DMUs
SD Rebel
Union 11
Thamesbank
SD Seal
RT Adriaan
13
1
0
0
0
times appearing in reference sets

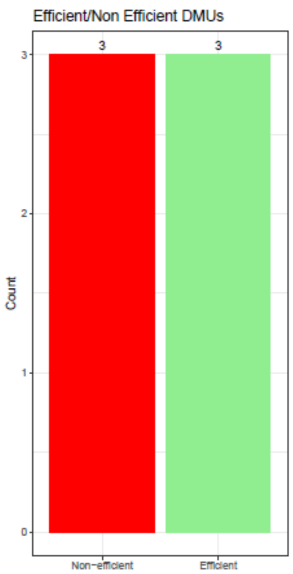
K.3.2. Port B

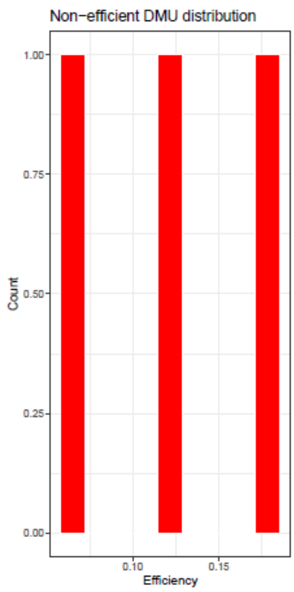
Table K.4: DEA results for tugs within Tug 43.

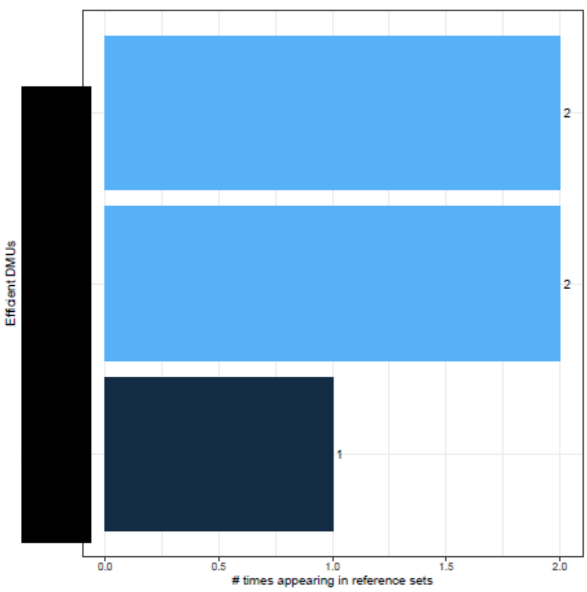
		INPUT				OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 25	18.32	-	128	122	0.12	3.64	-	214	122
2	Tug 26	31.54	94.59	337	174	0.19	5.84	-	337	174
3	Tug 27	18.18	-	734	623	1.00	18.18	-	734	623
4	Tug 33	19.83	-	49	500	0.06	15.28	-	652	500
5	Tug 41	5.55	-	327	186	1.00	5.55	-	327	186
6	Tug 68	8.06	35.54	448	192	1.00	8.06	-	448	192







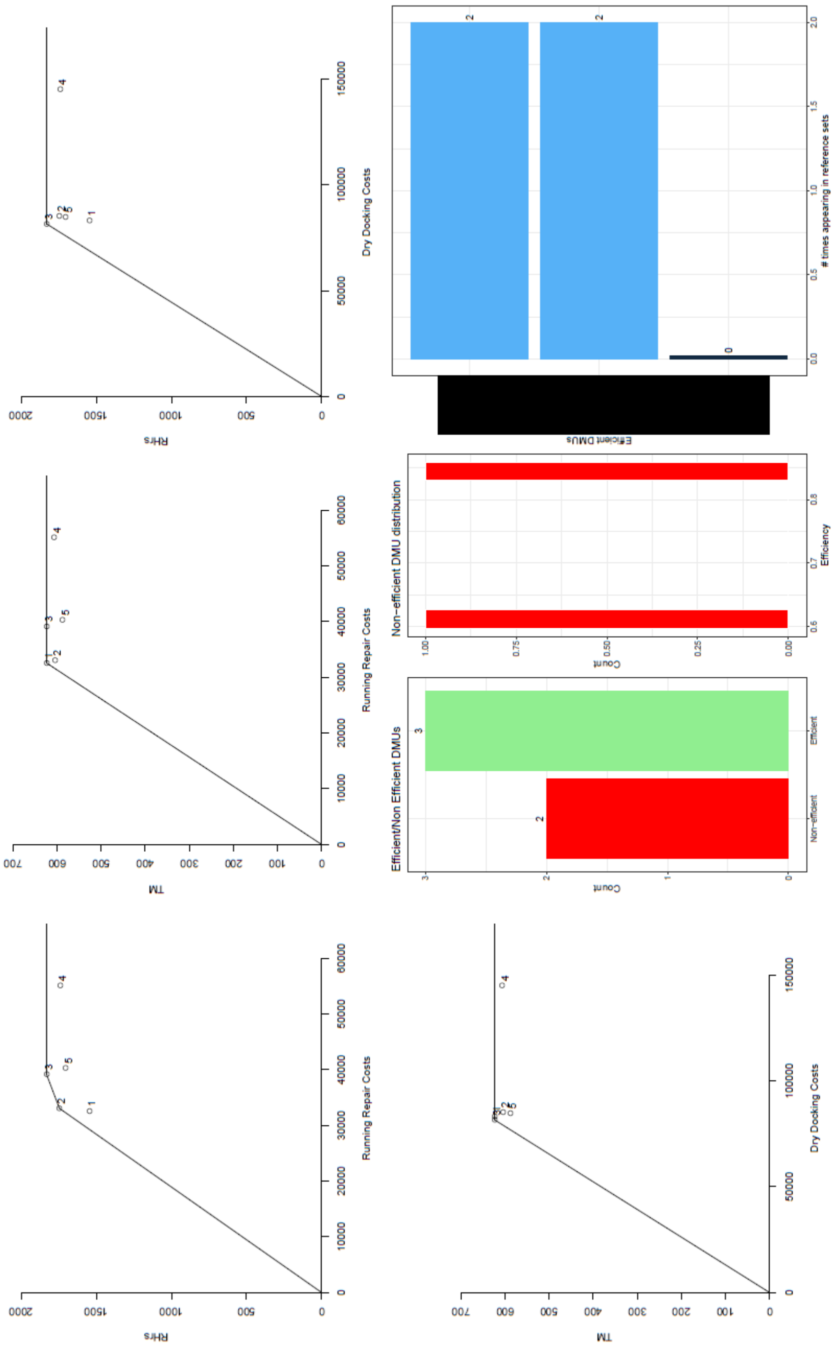




K.3.3. Port C

Table K.5: DEA results for tugs within Port C.

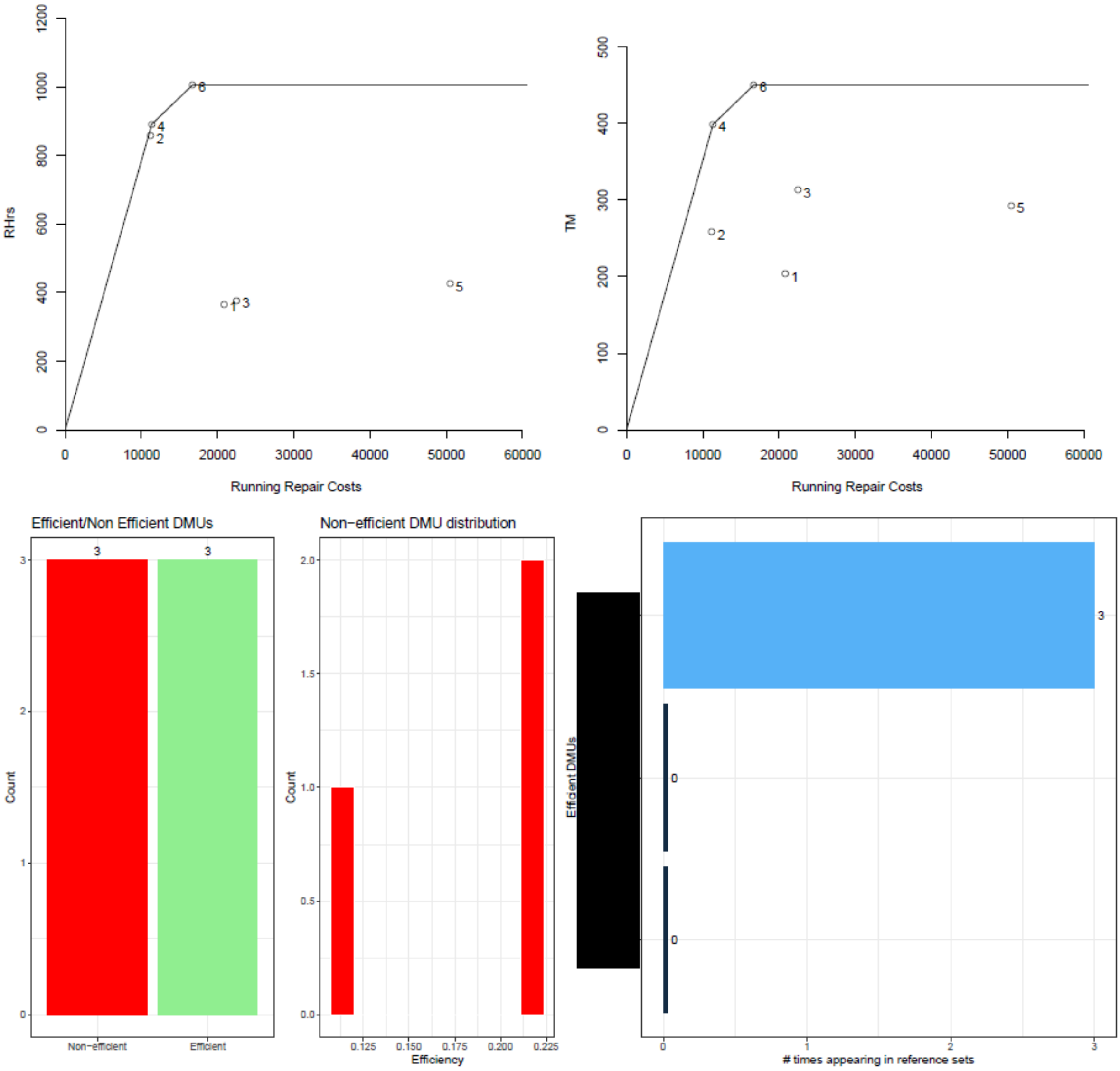
INPUT						OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 28	32.58	83.22	1,544	624	1.00	32.58	83.22	1,544	624
2	Tug 31	33.05	85.26	1,745	604	1.00	33.05	85.26	1,745	604
3	Tug 38	39.16	81.59	1,831	623	1.00	39.16	81.59	1,831	623
4	Tug 42	55.12	145.15	1,741	605	0.60	33.47	85.01	1,751	605
5	Tug 65	40.30	84.79	1,700	587	0.86	32.91	81.79	1,700	587



K.3.4. Port D

Table K.6: DEA results for tugs within Port D.

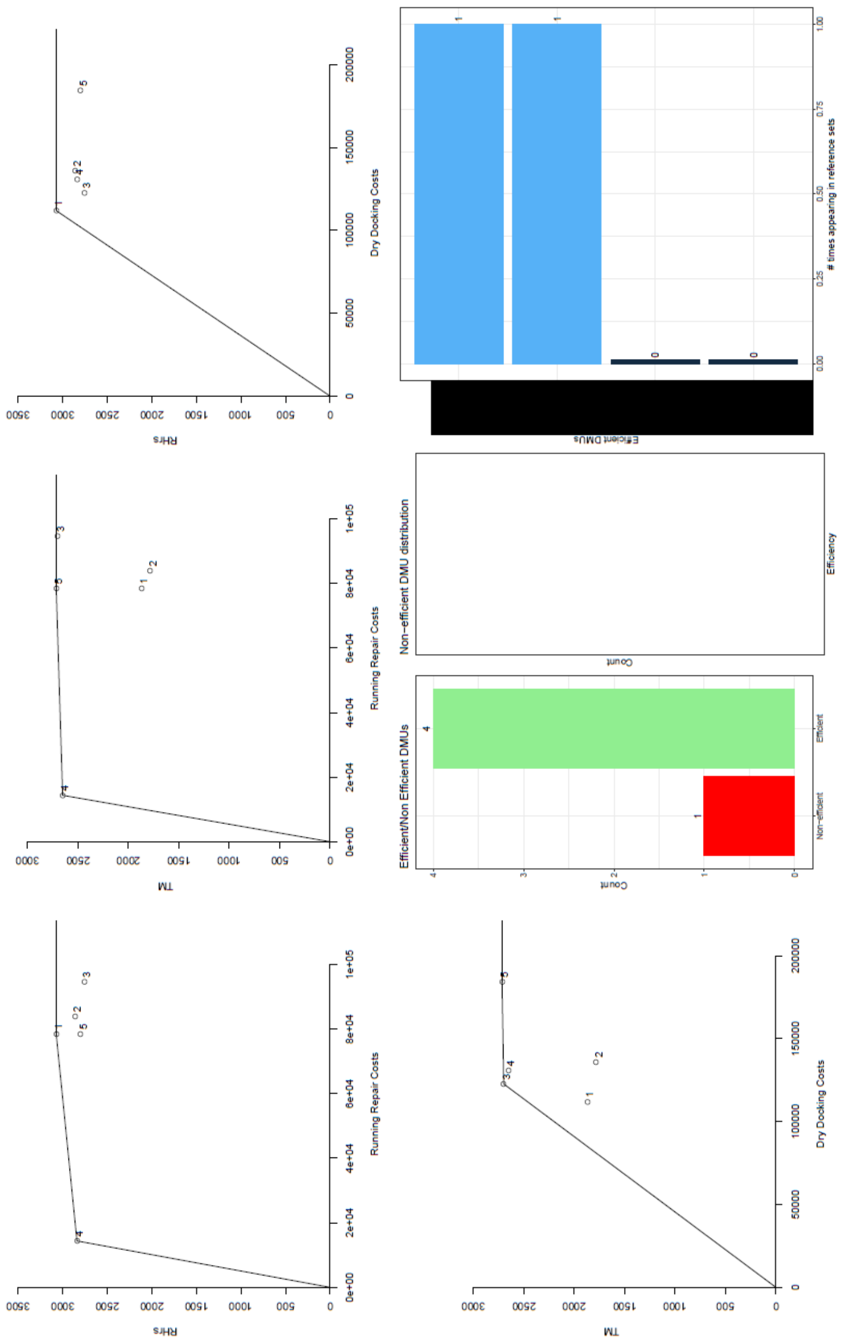
INPUT						OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 13	20.84	-	366	203	0.22	5.79	-	455	203
2	Tug 14	11.20	-	858	258	1.00	11.20	-	858	258
3	Tug 16	22.49	-	377	313	0.21	8.91	-	700	313
4	Tug 21	11.36	-	892	399	1.00	11.36	-	892	399
5	Tug 26	50.48	-	425	292	0.11	8.32	-	654	292
6	Tug 66	16.70	-	1,006	450	1.00	16.70	-	1,006	450



K.3.5. Port E

Table K.7: DEA results for tugs within Port E.

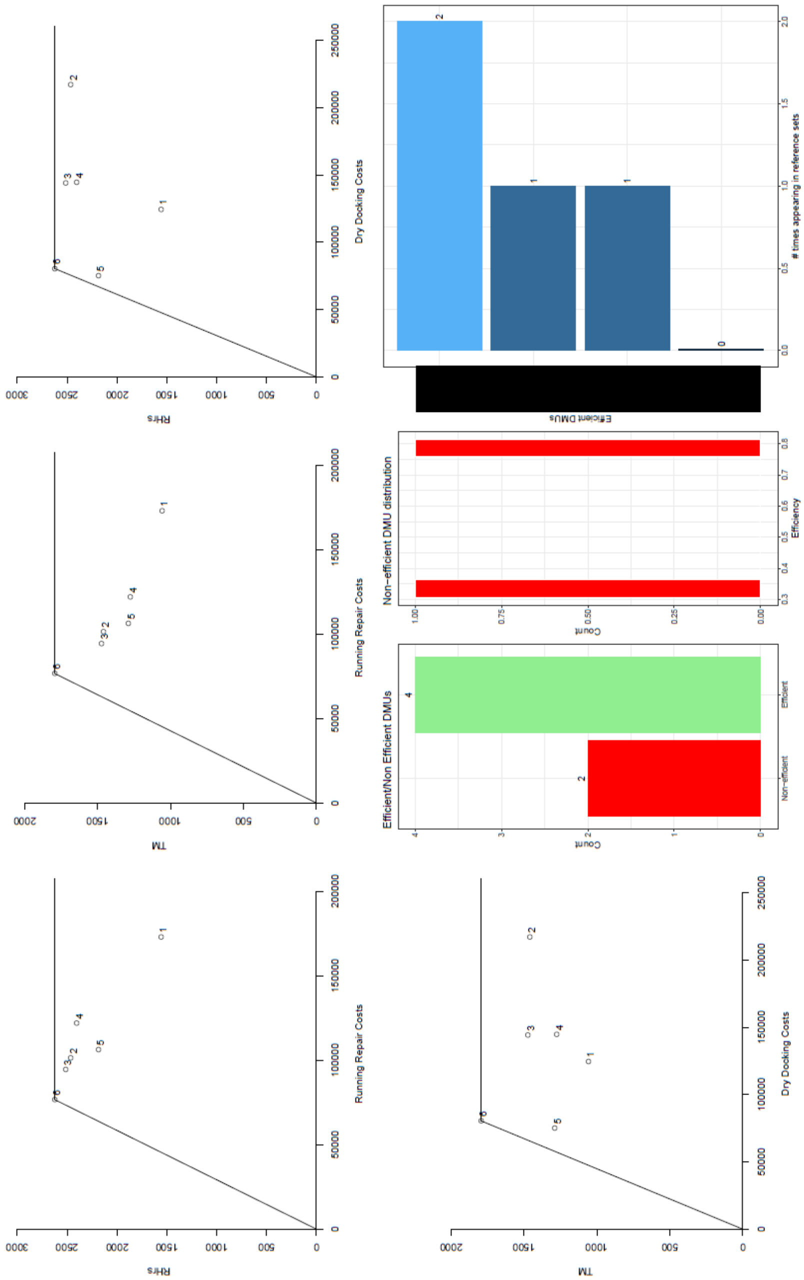
		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 53	78.50	111.87	3,072	1,867	1.00	78.50	111.87	3,072	1,867
2	Tug 57	83.93	135.94	2,860	1,779	0.82	70.51	105.37	2,860	1,779
3	Tug 59	94.66	122.66	2,755	2,698	1.00	94.66	122.66	2,755	2,698
4	Tug 61	14.37	130.78	2,839	2,652	1.00	14.37	130.78	2,839	2,652
5	Tug 62	78.48	184.32	2,794	2,715	1.00	78.48	184.32	2,794	2,715



K.3.6. Port F

Table K.8: DEA results for tugs within Tug 65.

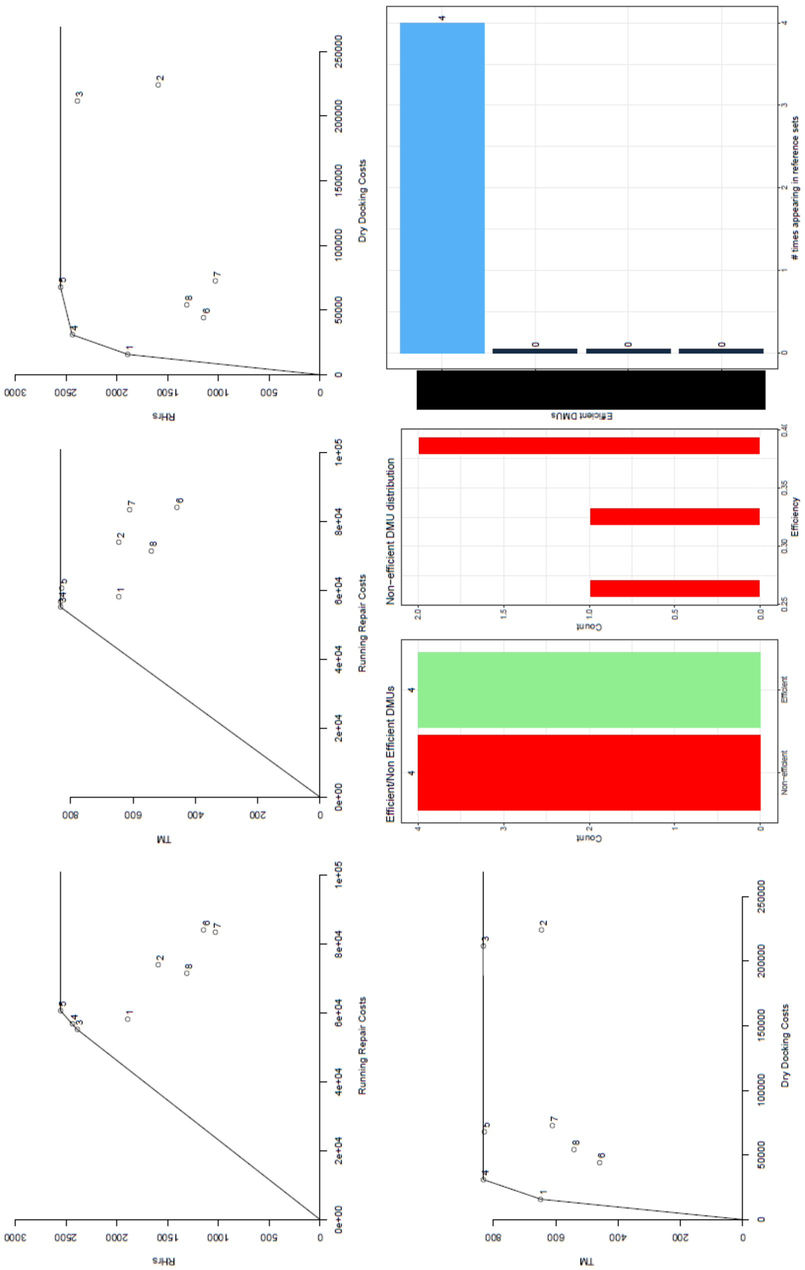
		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 14	172.95	124.55	1,561	1,057	0.31	47.48	48.21	1,561	1,057
2	Tug 34	101.38	217.13	2,461	1,461	0.81	90.42	134.73	2,461	1,461
3	Tug 36	94.45	144.18	2,516	1,469	1.00	94.45	144.18	2,516	1,469
4	Tug 41	122.00	144.66	2,399	1,272	1.00	122.00	144.66	2,399	1,272
5	Tug 54	106.28	75.16	2,189	1,285	1.00	106.28	75.16	2,189	1,285
6	Tug 63	76.69	80.53	2,627	1,795	1.00	76.69	80.53	2,627	1,795



K.3.7. Port G

Table K.9: DEA results for tugs within Port G.

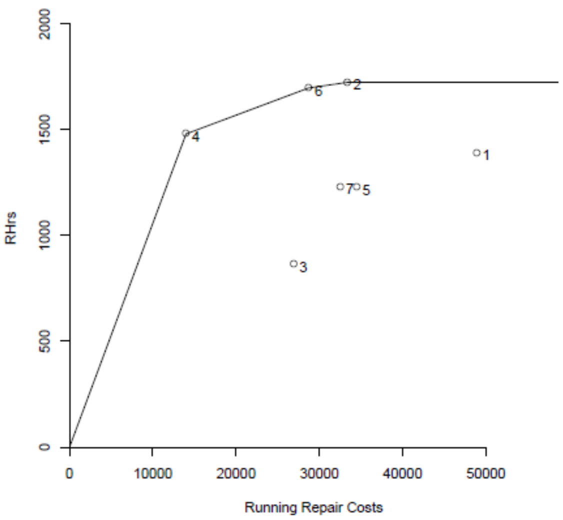
		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 3	58.17	15.67	1,891	647	1.00	58.17	15.67	1,891	647
2	Tug 45	74.00	224.15	1,590	646	0.38	44.10	24.00	1,893	646
3	Tug 45	55.20	211.73	2,389	833	1.00	55.20	211.73	2,389	833
4	Tug 49	56.82	30.92	2,439	832	1.00	56.82	30.92	2,439	832
5	Tug 50	60.67	67.86	2,555	829	1.00	60.67	67.86	2,555	829
6	Tug 52	84.11	44.08	1,141	458	0.32	31.26	17.01	1,342	458
7	Tug 56	83.44	72.60	1,029	611	0.26	41.68	22.68	1,790	611
8	Tug 64	71.49	54.06	1,314	542	0.39	37.00	20.13	1,589	542

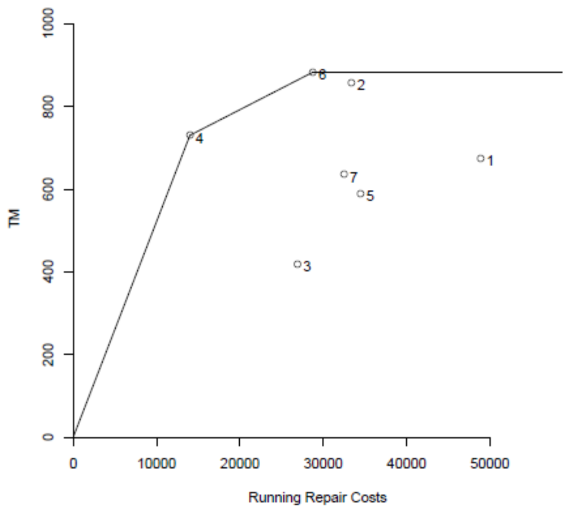


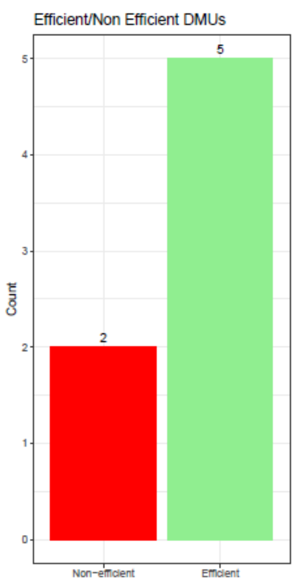
K.3.8. Port H

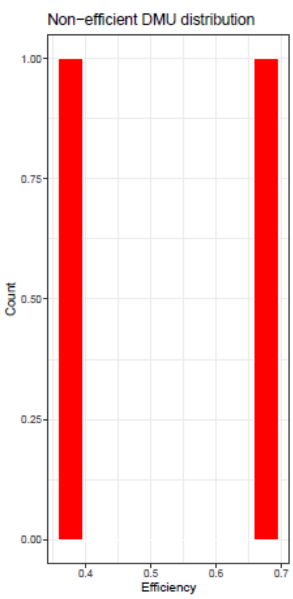
Table K.10: DEA results for tugs within Port H.

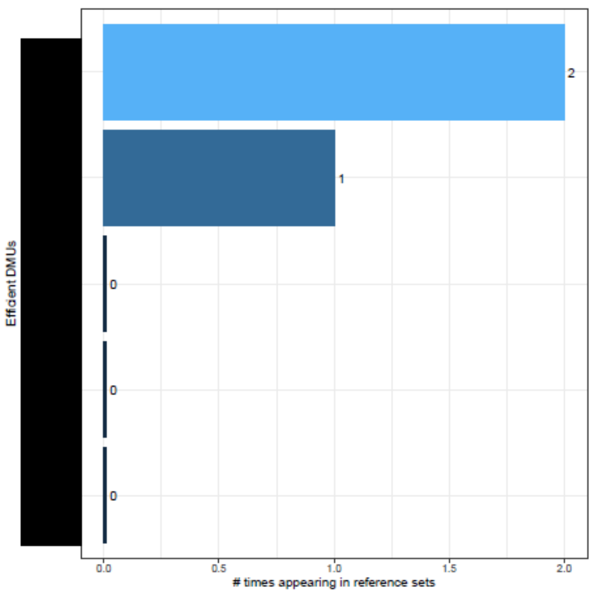
		INPUT				OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 21	48.88	50.32	1,390	675	1.00	48.88	-	1,390	675
2	Tug 24	33.37	-	1,723	857	1.00	33.37	-	1,723	857
3	Tug 66	26.91	10.37	864	419	0.70	18.73	-	864	419
4	Tug 67	14.00	-	1,479	730	1.00	14.00	-	1,479	730
5	Tug 68	34.47	-	1,226	590	1.00	34.47	-	1,226	590
6	Tug 69	28.72	23.84	1,696	882	1.00	28.72	-	1,696	882
7	Tug 71	32.49	-	1,230	634	0.36	12.17	-	1,285	634







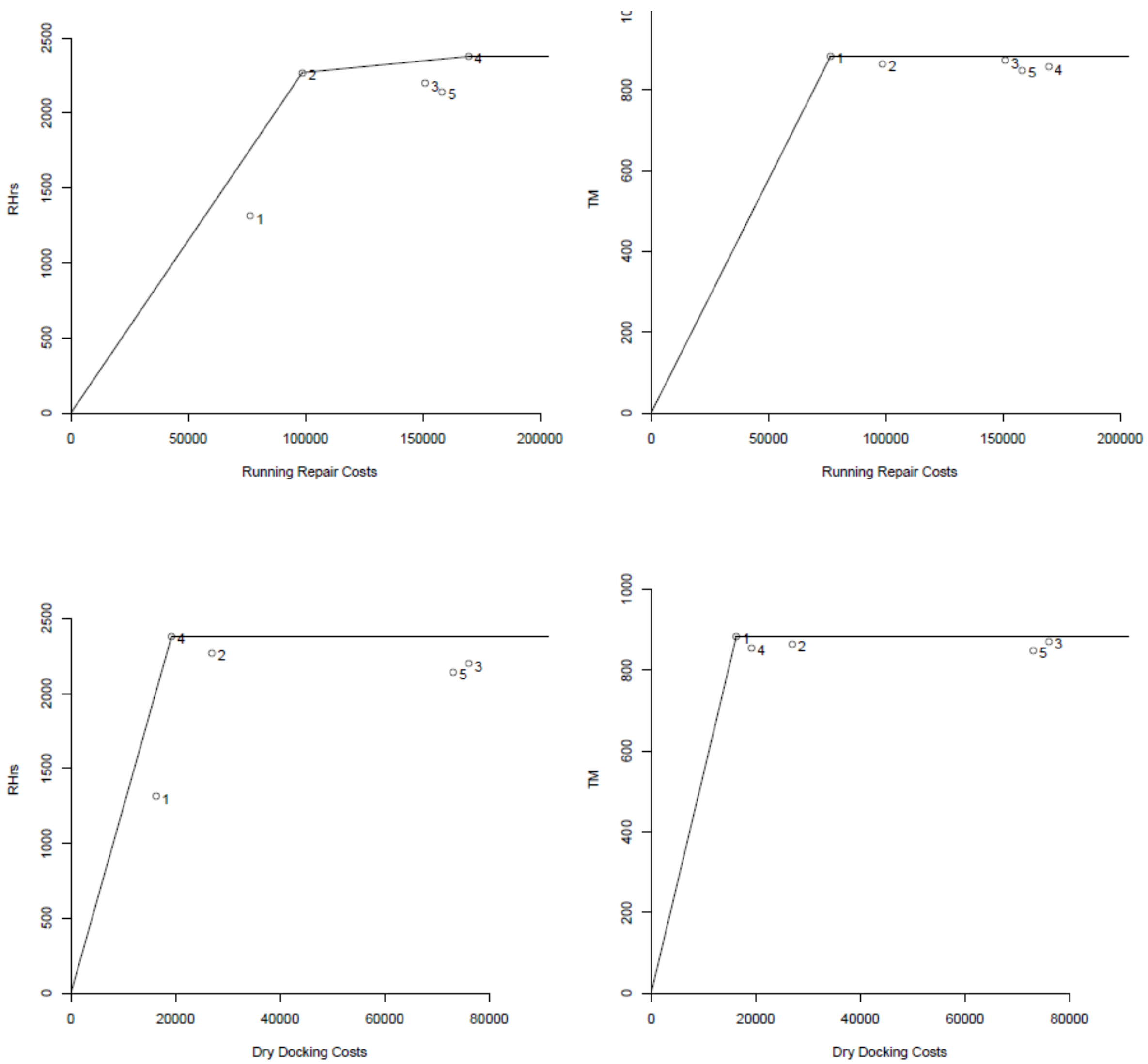




K.3.9. Port I

Table K.11: DEA results for tugs within Port I.

		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 15	76.50	16.29	1,314	883	1.00	76.50	16.29	1,314	883
2	Tug 17	98.71	27.00	2,271	865	1.00	98.71	27.00	2,271	865
3	Tug 18	151.09	76.10	2,198	871	1.00	151.09	76.10	2,198	871
4	Tug 19	169.65	19.24	2,378	856	1.00	169.65	19.24	2,378	856
5	Tug 20	158.35	73.14	2,140	848	0.52	96.80	26.48	2,227	848

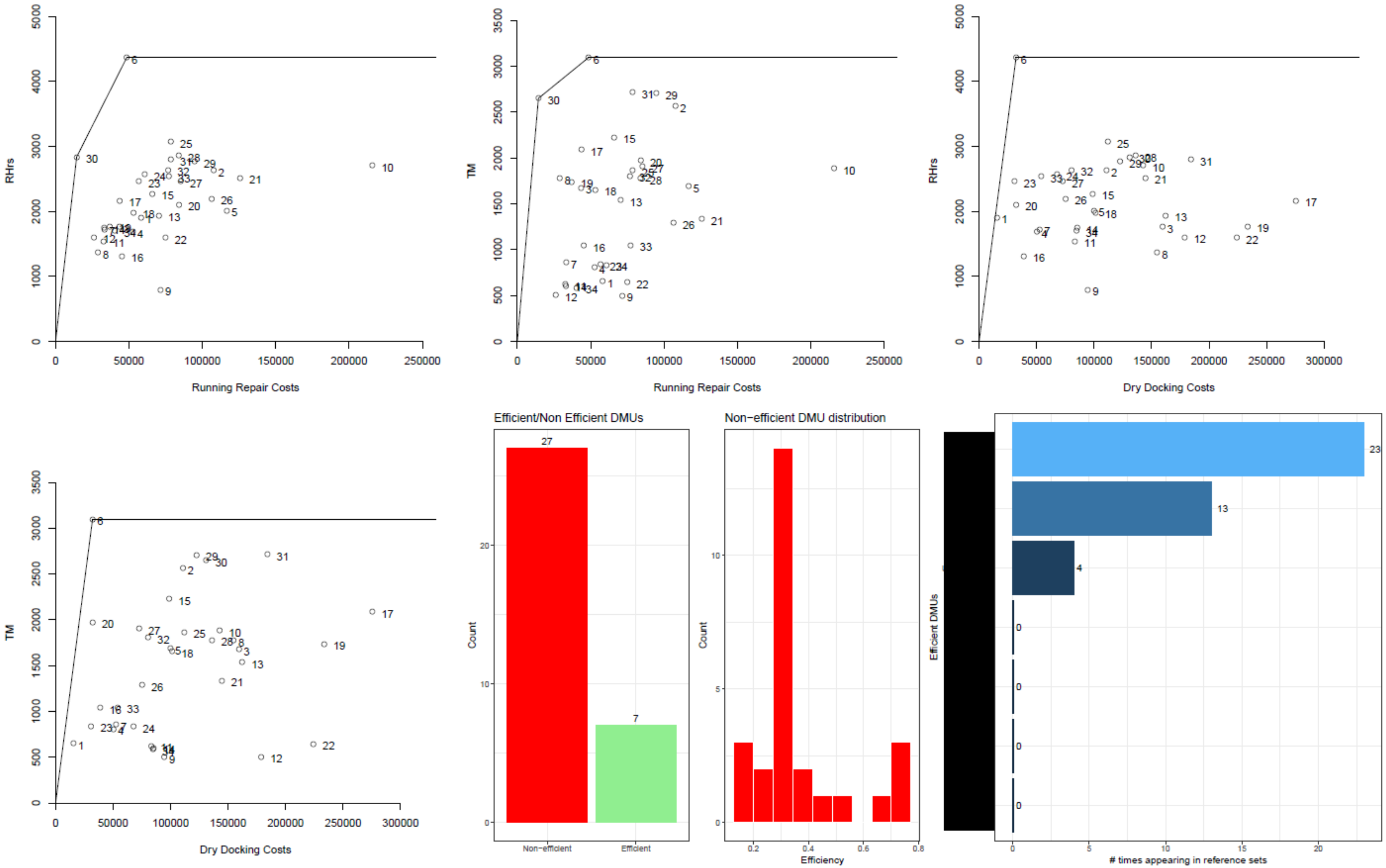


K.4. Tug Type Results

K.4.1. Azimuth Stern Drive

Table K.12: DEA results for ASD tug types.

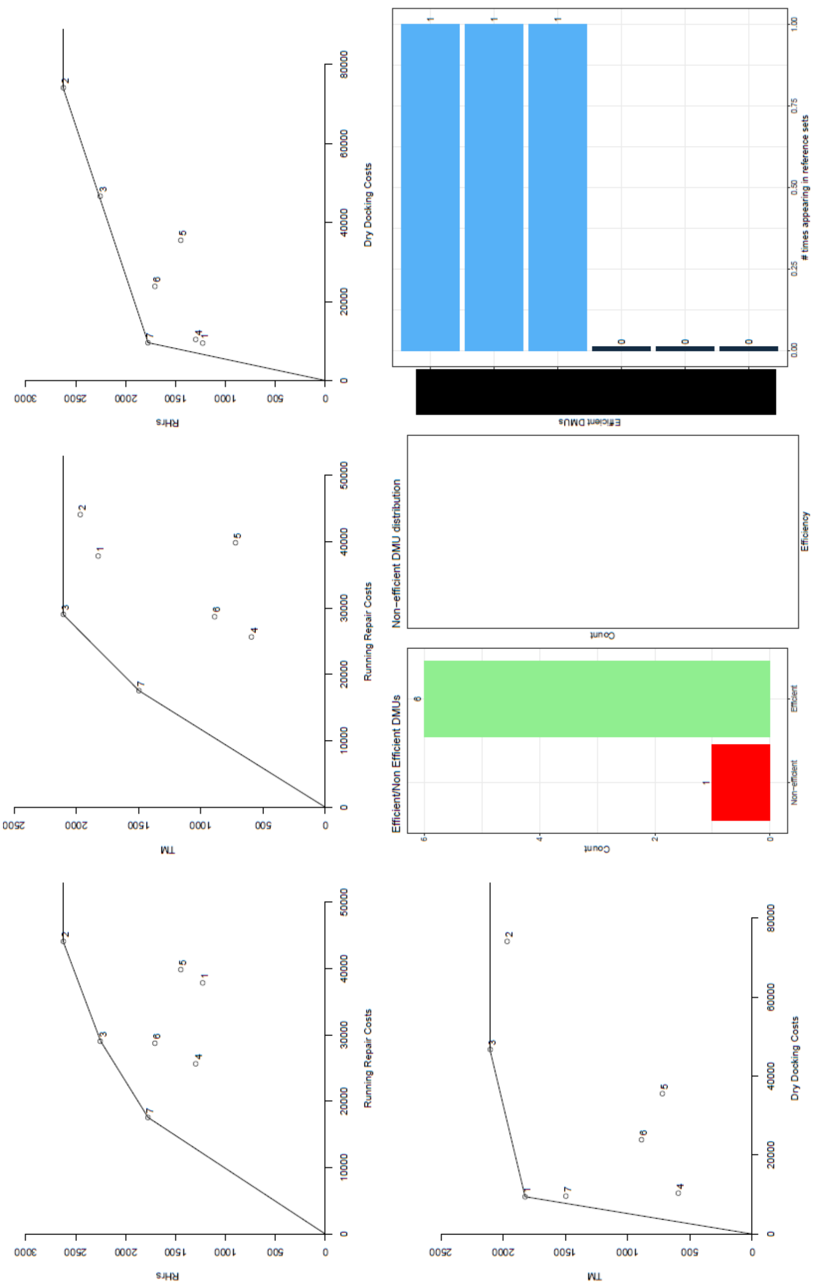
INPUT						OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 3	58.17	15.67	1,909	653	1.00	58.17	15.67	1,909	653
2	Tug 6	107.80	110.86	2,627	2,564	0.24	40.15	26.61	3,618	2,564
3	Tug 7	43.37	159.47	1,758	1,678	0.29	9.09	82.74	1,796	1,678
4	Tug 21	52.67	50.32	1,687	808	0.53	31.35	17.89	1,687	808
5	Tug 22	116.64	99.94	2,015	1,690	0.18	26.46	17.54	2,384	1,690
6	Tug 23	48.48	32.13	4,369	3,097	1.00	48.48	32.13	4,369	3,097
7	Tug 24	33.37	52.58	1,723	857	0.76	30.97	17.82	1,723	857
8	Tug 25	28.93	154.82	1,367	1,776	0.29	9.63	87.61	1,902	1,776
9	Tug 26	71.51	94.59	791	500	0.13	10.77	6.69	791	500
10	Tug 27	215.75	142.71	2,703	1,885	0.14	30.99	20.31	2,703	1,885
11	Tug 28	32.58	83.22	1,544	624	0.77	32.44	18.00	1,544	624
12	Tug 29	26.15	178.69	1,600	505	1.00	26.15	178.69	1,600	505
13	Tug 30	70.46	162.27	1,938	1,538	0.24	24.07	15.95	2,169	1,538
14	Tug 31	33.05	85.26	1,745	604	1.00	33.05	85.26	1,745	604
15	Tug 32	65.96	98.83	2,272	2,226	0.32	34.85	23.10	3,141	2,226
16	Tug 33	45.29	38.72	1,311	1,043	0.30	16.32	10.82	1,471	1,043
17	Tug 35	43.72	275.33	2,167	2,089	0.28	11.32	103.03	2,237	2,089
18	Tug 37	53.04	101.30	1,986	1,653	0.34	25.87	17.15	2,332	1,653
19	Tug 39	36.94	233.50	1,769	1,739	0.27	9.42	85.75	1,861	1,739
20	Tug 40	84.07	32.17	2,102	1,974	0.34	30.91	20.49	2,786	1,974
21	Tug 41	125.70	144.66	2,515	1,337	0.29	42.42	24.80	2,515	1,337
22	Tug 45	74.85	224.15	1,590	646	0.34	33.31	18.49	1,590	646
23	Tug 49	56.82	30.92	2,463	840	1.00	56.82	30.92	2,463	840
24	Tug 50	60.67	67.86	2,571	835	1.00	60.67	67.86	2,571	835
25	Tug 53	78.50	111.87	3,073	1,867	0.47	44.20	26.99	3,073	1,867
26	Tug 54	106.28	75.16	2,197	1,290	0.30	33.10	19.95	2,197	1,290
27	Tug 56	85.34	72.60	2,466	1,906	0.30	29.84	19.77	2,689	1,906
28	Tug 57	83.93	135.94	2,862	1,780	0.39	39.83	24.55	2,862	1,780
29	Tug 59	94.66	122.66	2,769	2,709	0.28	42.41	28.10	3,822	2,709
30	Tug 61	14.37	130.78	2,839	2,652	1.00	14.37	130.78	2,839	2,652
31	Tug 62	78.48	184.32	2,794	2,716	0.31	42.52	28.18	3,831	2,716
32	Tug 63	76.69	80.53	2,639	1,805	0.36	31.43	20.34	2,639	1,805
33	Tug 64	77.17	54.06	2,543	1,047	0.64	52.82	29.38	2,543	1,047
34	Tug 65	40.30	84.79	1,700	587	0.76	39.00	21.25	1,700	587


RHrs
Running Repair Costs
TM
Running Repair Costs
RHrs
Dry Docking Costs
TM
Dry Docking Costs
Efficient/Non Efficient DMUs
Count
Non-efficient
Efficient
27
7
Non-efficient DMU distribution
Count
Efficiency
Efficient DMUs
times appearing in reference sets
23
13
4
0
0
0
0

K.4.2. Azimuth Tractor Drive

Table K.13: DEA results for ATD tug types.

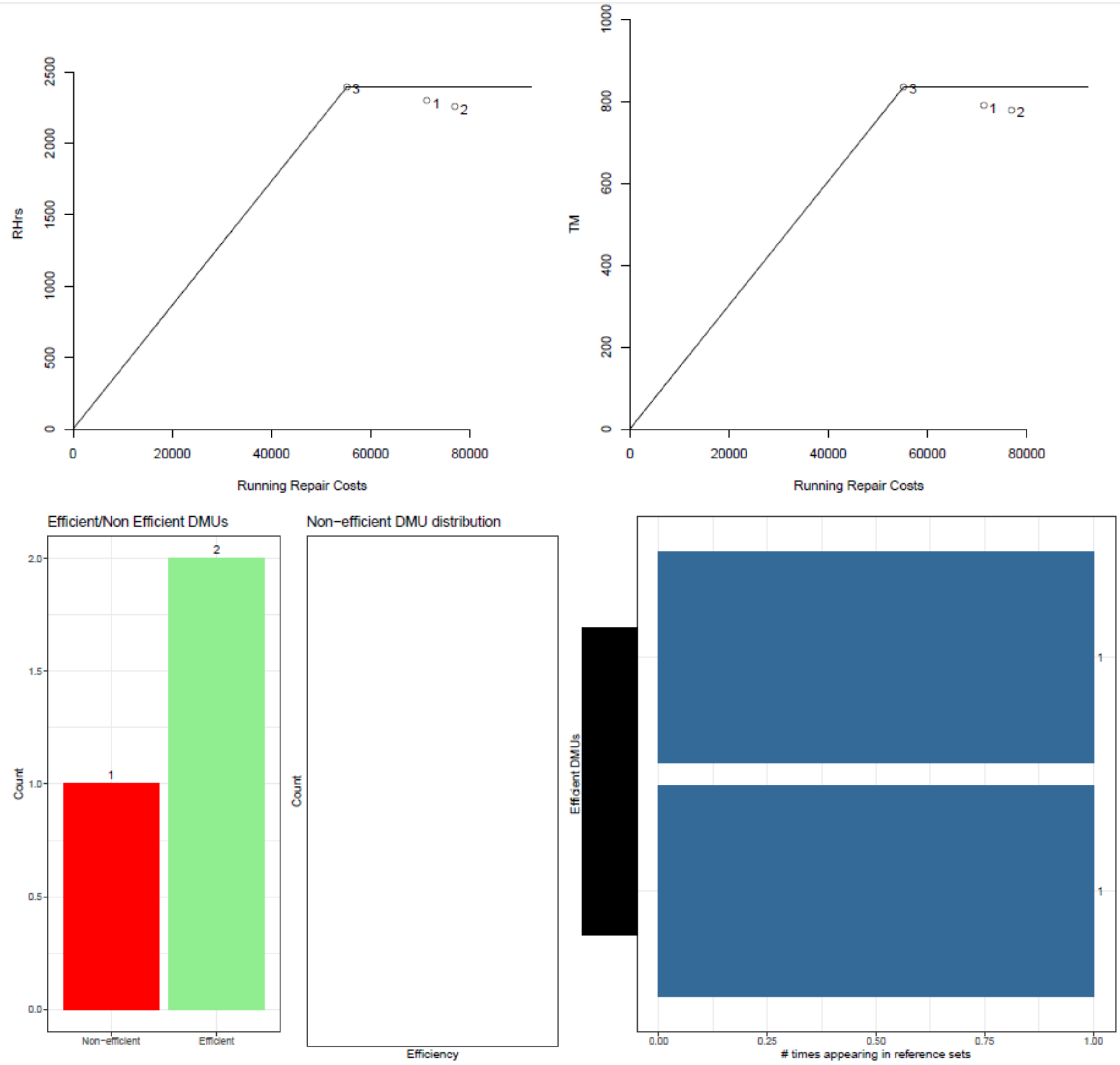
		INPUT				OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 1	37.84	9.44	1,226	1,823	1.00	37.84	9.44	1,226	1,823
2	Tug 46	44.10	74.12	2,626	1,969	1.00	44.10	74.12	2,626	1,969
3	Tug 47	29.05	46.69	2,250	2,106	1.00	29.05	46.69	2,250	2,106
4	Tug 66	25.67	10.37	1,294	590	1.00	25.67	10.37	1,294	590
5	Tug 68	39.85	35.54	1,451	719	0.60	26.49	15.01	1,450	719
6	Tug 69	28.73	23.84	1,705	887	1.00	28.73	23.84	1,705	887
7	Tug 70	17.56	9.57	1,775	1,496	1.00	17.56	9.57	1,775	1,496



K.4.3. Conventional

Table K.14: DEA results for conventional tug types.

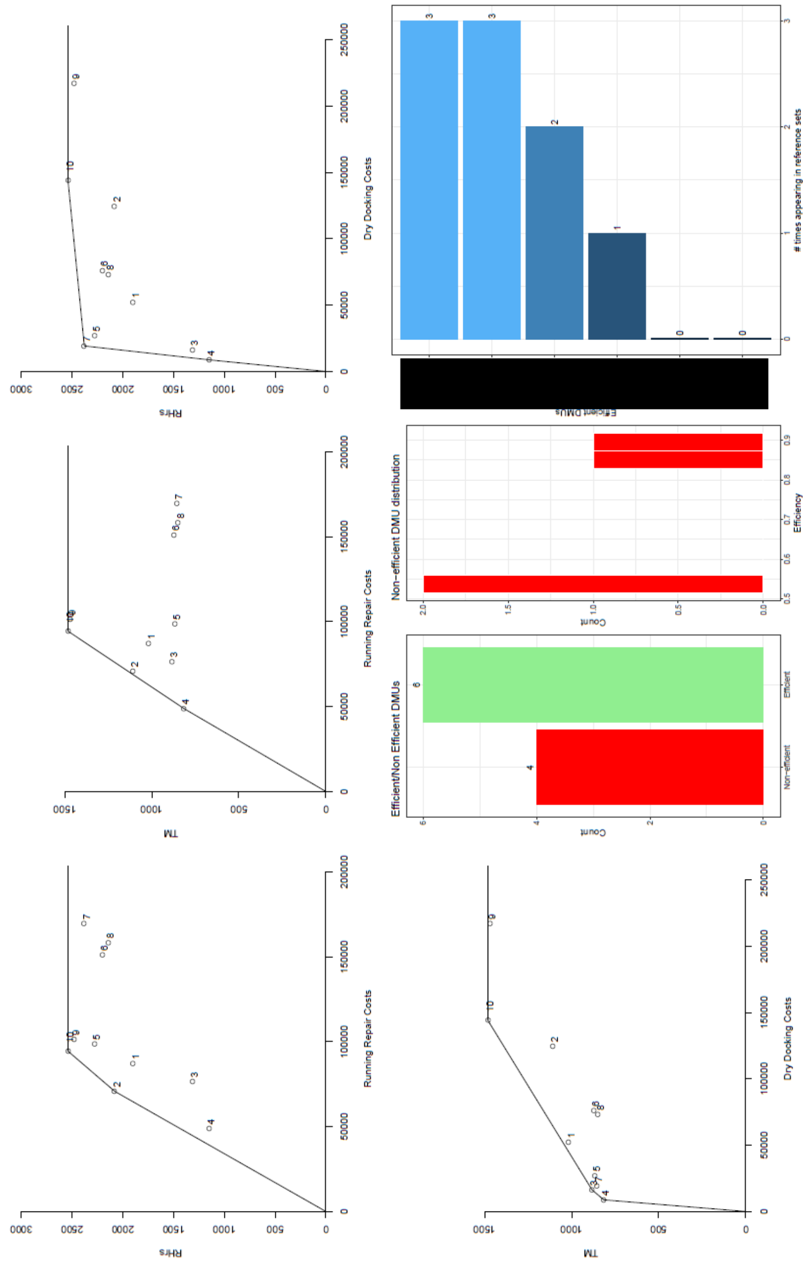
INPUT						OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 2	71.35	-	2,294	789	1.00	71.35	-	2,294	789
2	Tug 8	76.95	8.70	2,254	778	0.84	64.67	-	2,254	778
3	Tug 45	55.20	211.73	2,393	834	1.00	55.20	-	2,393	834



K.4.4. Rotor Tug

Table K.15: DEA results for RT tug types.

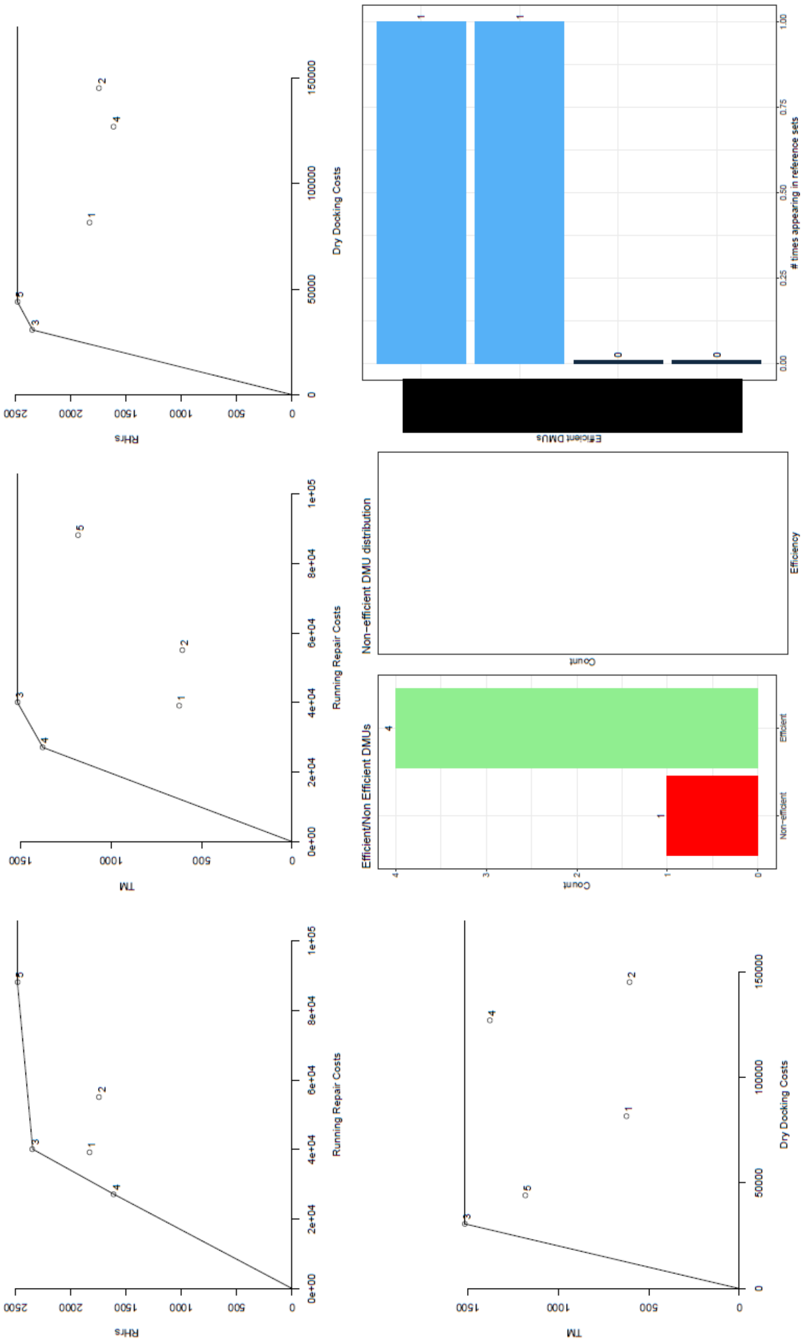
INPUT						OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 13	87.12	52.23	2,314	1,016	1.00	87.12	52.23	2,314	1,016
2	Tug 14	70.77	124.55	2,079	1,109	0.78	68.92	68.42	2,264	1,109
3	Tug 15	76.50	16.29	1,314	883	1.00	76.50	16.29	1,314	883
4	Tug 16	48.82	8.77	2,047	815	1.00	48.82	8.77	2,047	815
5	Tug 17	98.71	27.00	2,278	868	1.00	98.71	27.00	2,278	868
6	Tug 18	151.09	76.10	2,198	871	0.46	78.41	24.18	2,198	871
7	Tug 19	169.65	19.24	2,378	856	1.00	169.65	19.24	2,378	856
8	Tug 20	158.35	73.14	2,140	848	0.37	67.28	17.99	2,140	848
9	Tug 34	101.38	217.13	2,476	1,470	0.83	93.67	141.88	2,531	1,470
10	Tug 36	94.45	144.18	2,539	1,482	1.00	94.45	144.18	2,539	1,482



K.4.5. Voith Schneider Propeller

Table K.16: DEA results for VSP tug types.

		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 38	39.16	81.59	1,831	623	1.00	39.16	81.59	1,831	623
2	Tug 42	55.12	145.15	1,741	605	0.63	37.06	76.31	1,741	605
3	Tug 48	40.09	30.65	2,343	1,518	1.00	40.09	30.65	2,343	1,518
4	Tug 51	27.10	126.99	1,607	1,377	1.00	27.10	126.99	1,607	1,377
5	Tug 52	88.16	44.08	2,481	1,181	1.00	88.16	44.08	2,481	1,181

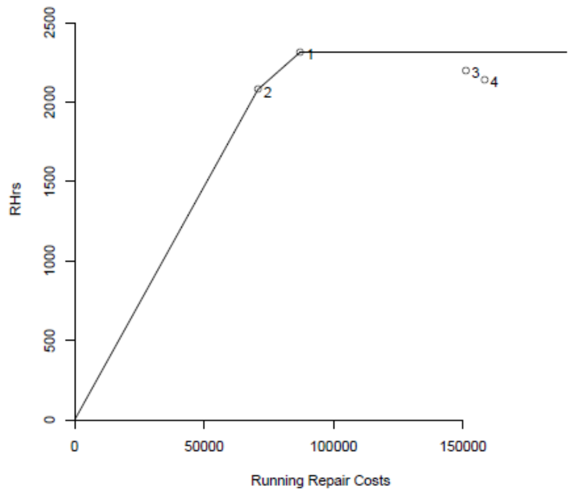


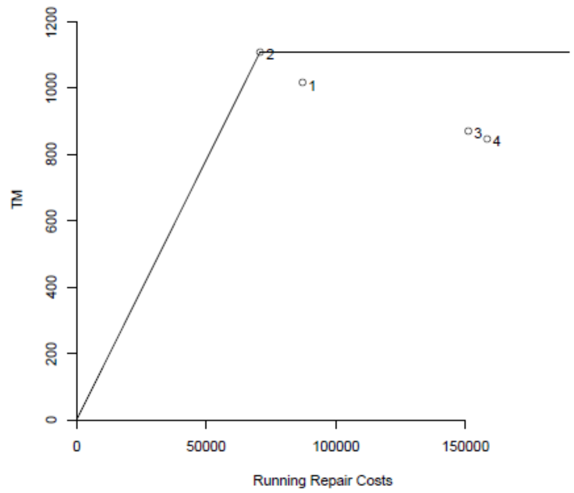
K.5. Sister Groups

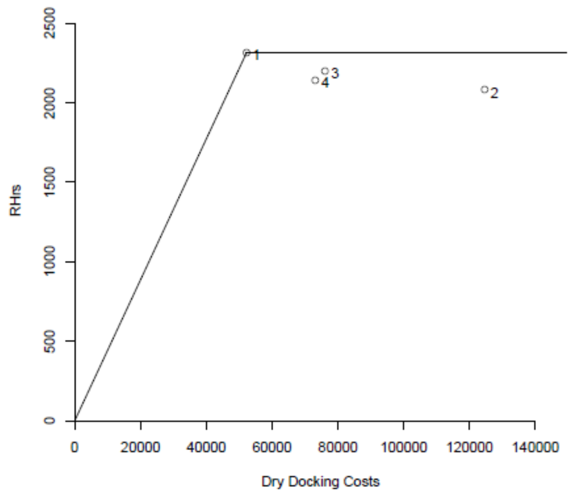
K.5.1. Group 001

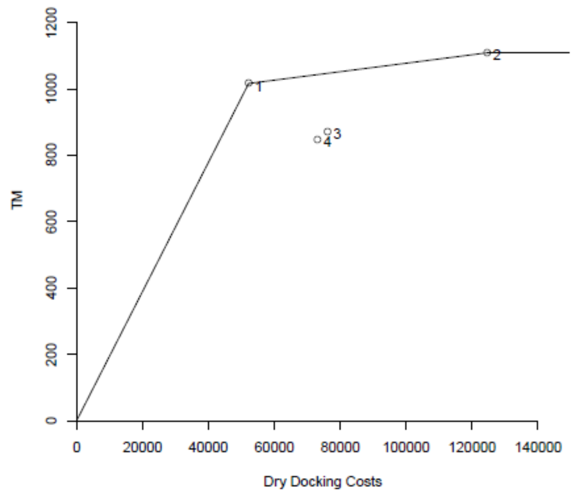
Table K.17: DEA results for sister group 001.

	INPUT					OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 13	87.12	52.23	1,895	1,016	1.00	87.12	52.23	1,895	1,016
2	Tug 14	70.77	124.55	2,079	1,109	1.00	70.77	124.55	2,079	1,109
3	Tug 18	151.09	76.10	2,198	871	1.00	151.09	76.10	2,198	871
4	Tug 20	158.35	73.14	2,140	848	1.00	158.35	73.14	2,140	848





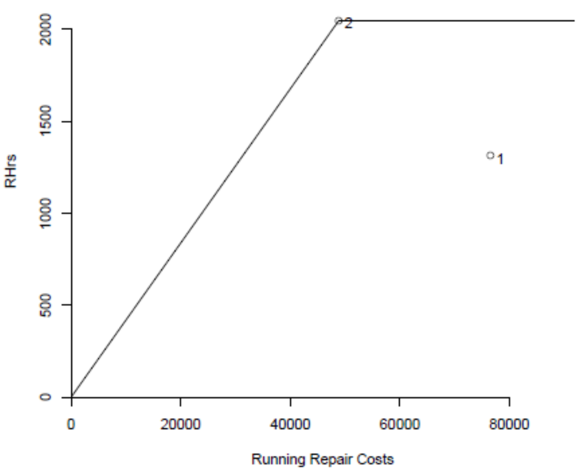


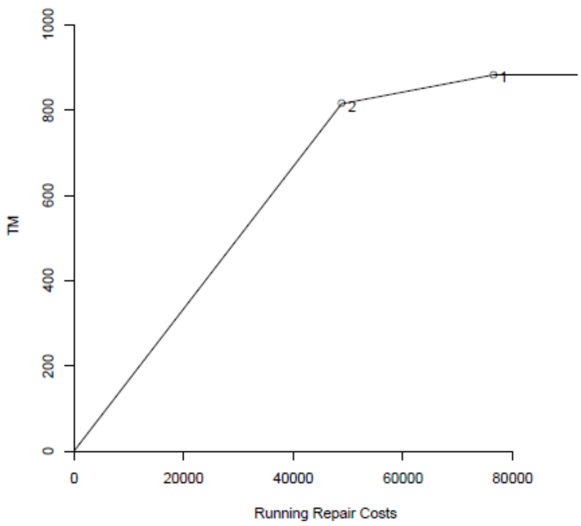


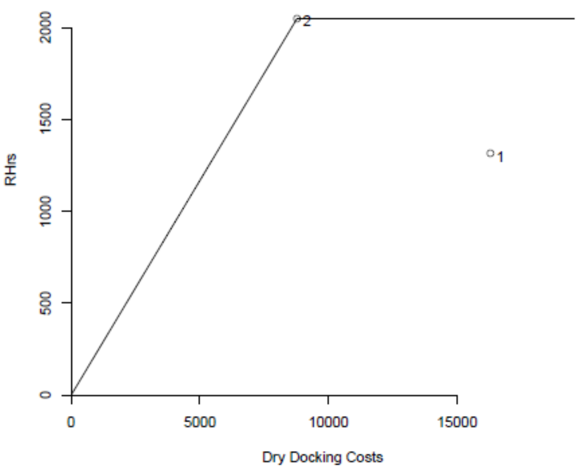
K.5.2. Group 002

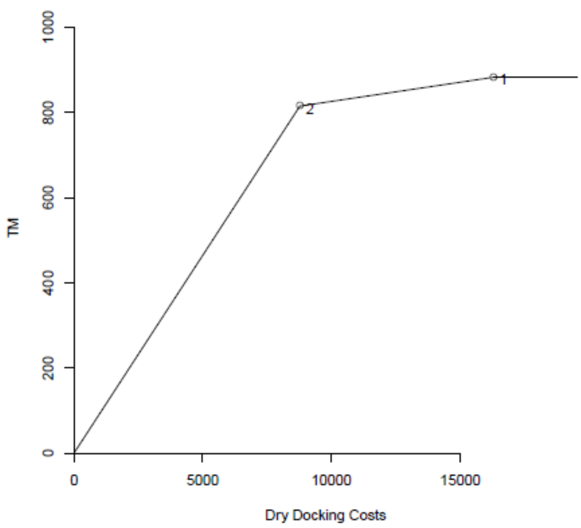
Table K.18: DEA results for sister group 002.

INPUT						OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 15	76.50	16.29	1,314	883	1.00	76.50	16.29	1,314	883
2	Tug 16	48.82	8.77	1,150	815	1.00	48.82	8.77	1,150	815





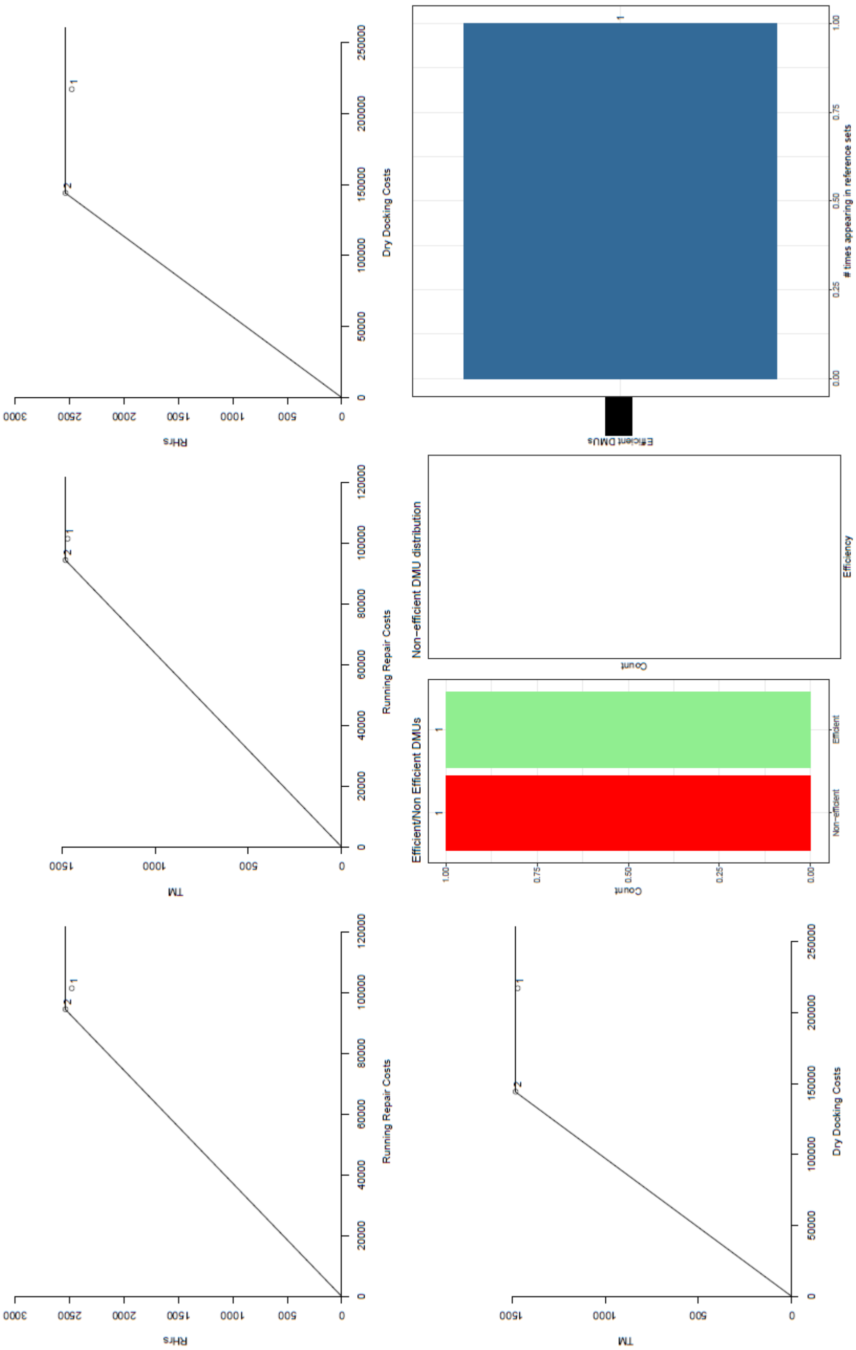




K.5.3. Group 003

Table K.19: DEA results for sister group 003.

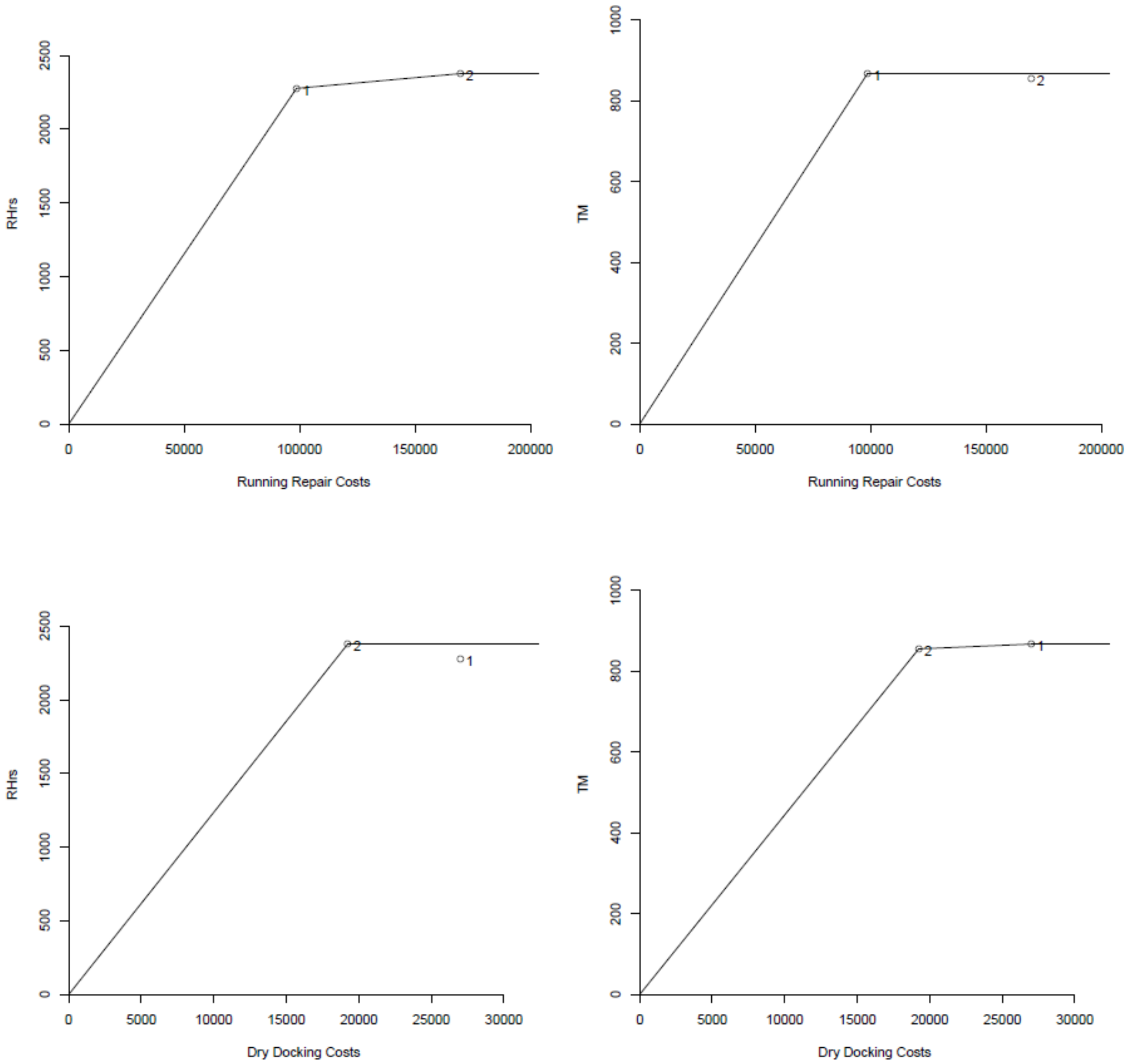
		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 34	101.38	217.13	2,476	1,470	0.83	93.73	143.08	2,520	1,470
2	Tug 36	94.45	144.18	2,539	1,482	1.00	94.45	144.18	2,539	1,482



K.5.4. Group 004

Table K.20: DEA results for sister group 004.

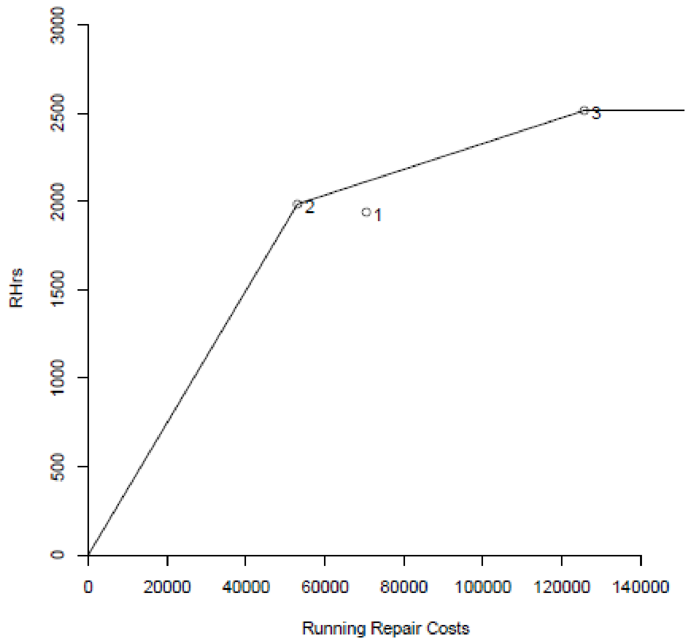
	INPUT					OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 17	98.71	27.00	2,278	868	1.00	98.71	27.00	2,278	868
2	Tug 19	169.65	19.24	2,378	856	1.00	169.65	19.24	2,378	856

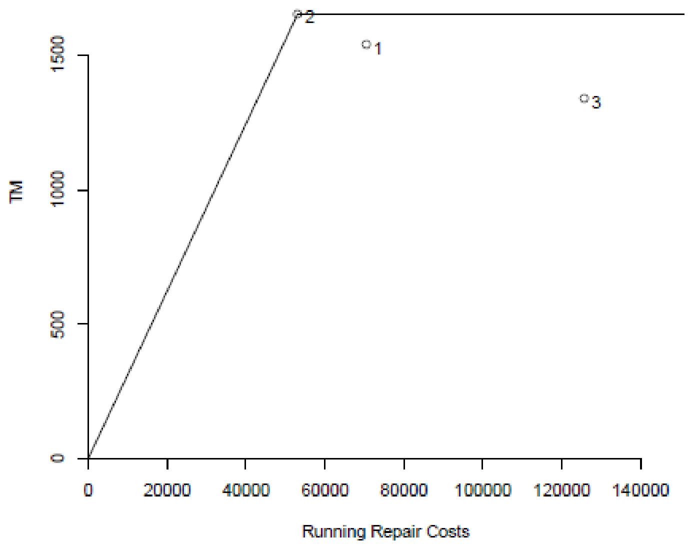


K.5.5. Group 006

Table K.21: DEA results for sister group 006.

		INPUT				OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 30	70.46	162.27	1,938	1,538	0.76	57.63	100.52	1,938	1,538
2	Tug 37	53.04	101.30	1,986	1,653	1.00	53.04	101.30	1,986	1,653
3	Tug 41	125.70	144.66	2,515	1,337	1.00	125.70	144.66	2,515	1,337

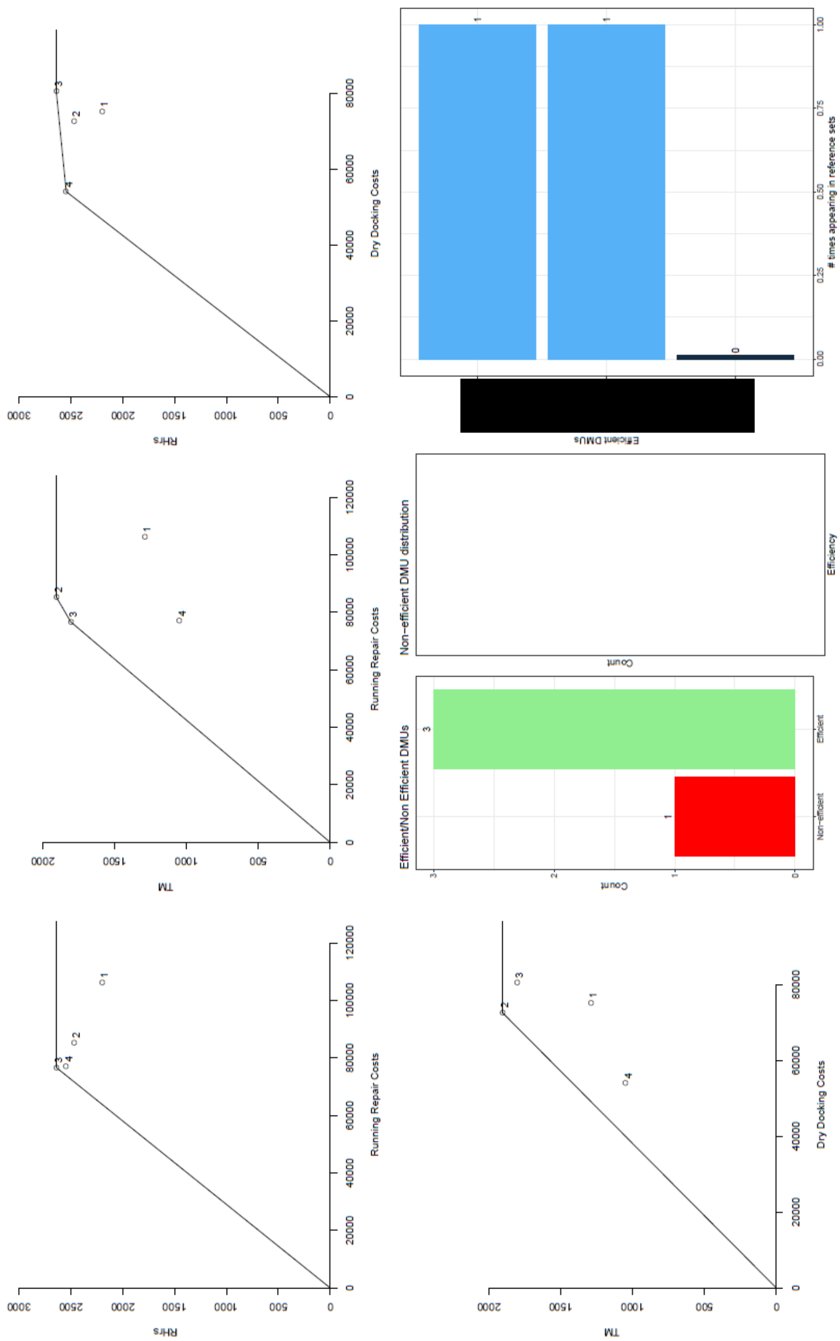




K.5.6. Group 007

Table K.22: DEA results for sister group 007.

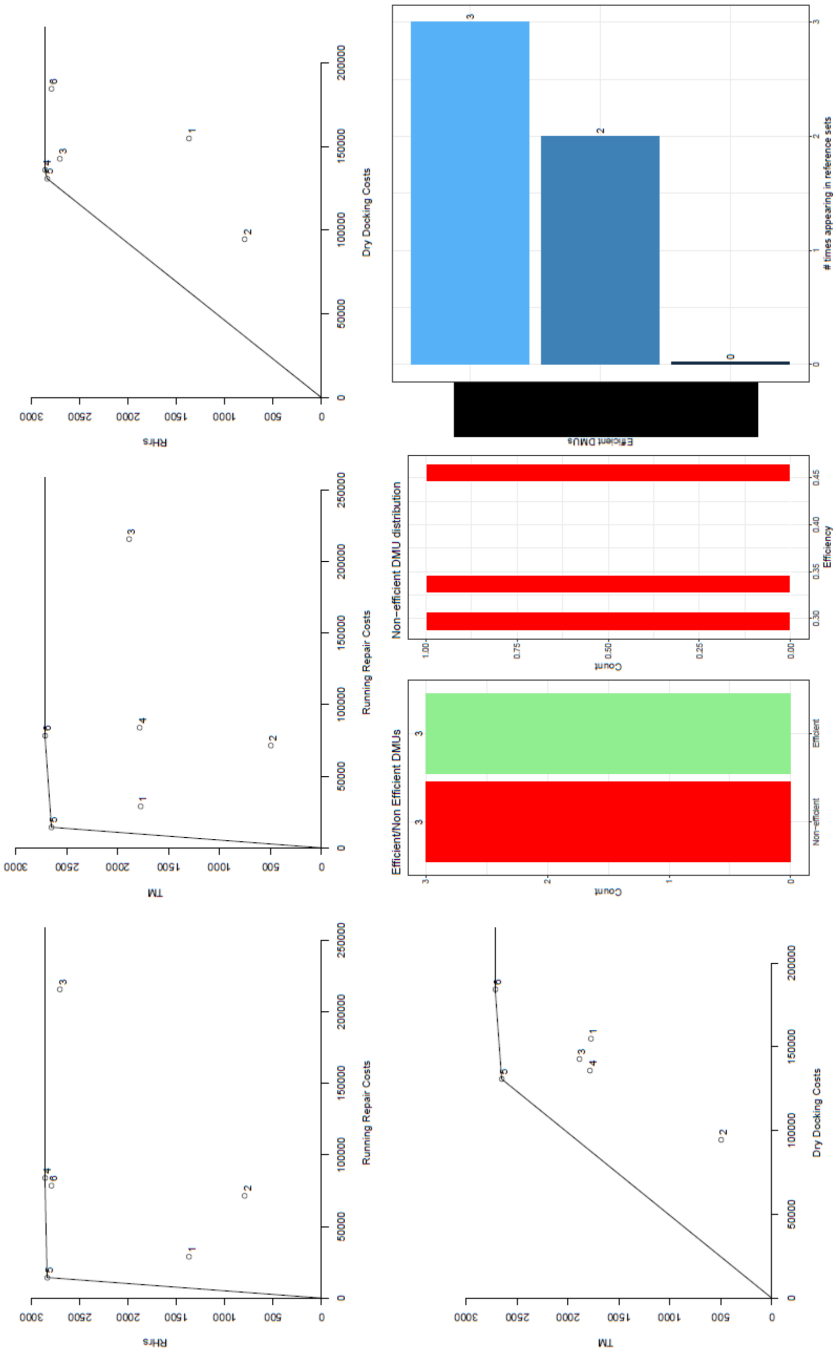
		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 54	106.28	75.16	2,197	1,290	0.64	77.02	62.54	2,574	1,290
2	Tug 56	85.34	72.60	2,466	1,906	1.00	85.34	72.60	2,466	1,906
3	Tug 63	76.69	80.53	2,639	1,805	1.00	76.69	80.53	2,639	1,805
4	Tug 64	77.17	54.06	2,543	1,047	1.00	77.17	54.06	2,543	1,047



K.5.7. Group 008

Table K.23: DEA results for sister group 008.

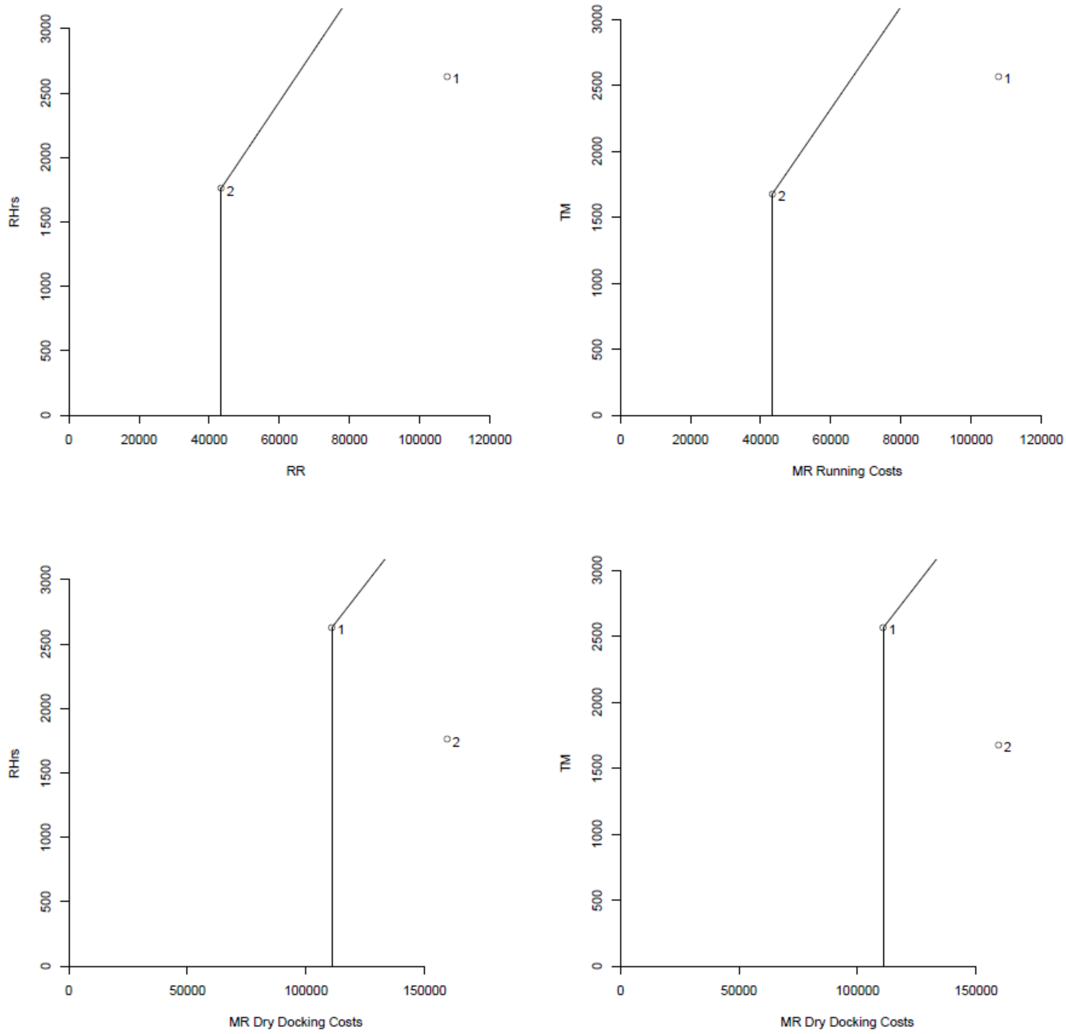
		INPUT				OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 25	28.93	154.82	1,367	1,776	0.29	9.63	87.61	1,902	1,776
2	Tug 26	71.51	94.59	791	500	0.34	22.64	37.56	791	500
3	Tug 27	215.75	142.71	2,703	1,885	0.47	63.42	127.46	2,703	1,885
4	Tug 57	83.93	135.94	2,862	1,780	1.00	83.93	135.94	2,862	1,780
5	Tug 61	14.37	130.78	2,839	2,652	1.00	14.37	130.78	2,839	2,652
6	Tug 62	78.48	184.32	2,794	2,716	1.00	78.48	184.32	2,794	2,716



K.5.8. Group 009

Table K.24: DEA results for sister group 009.

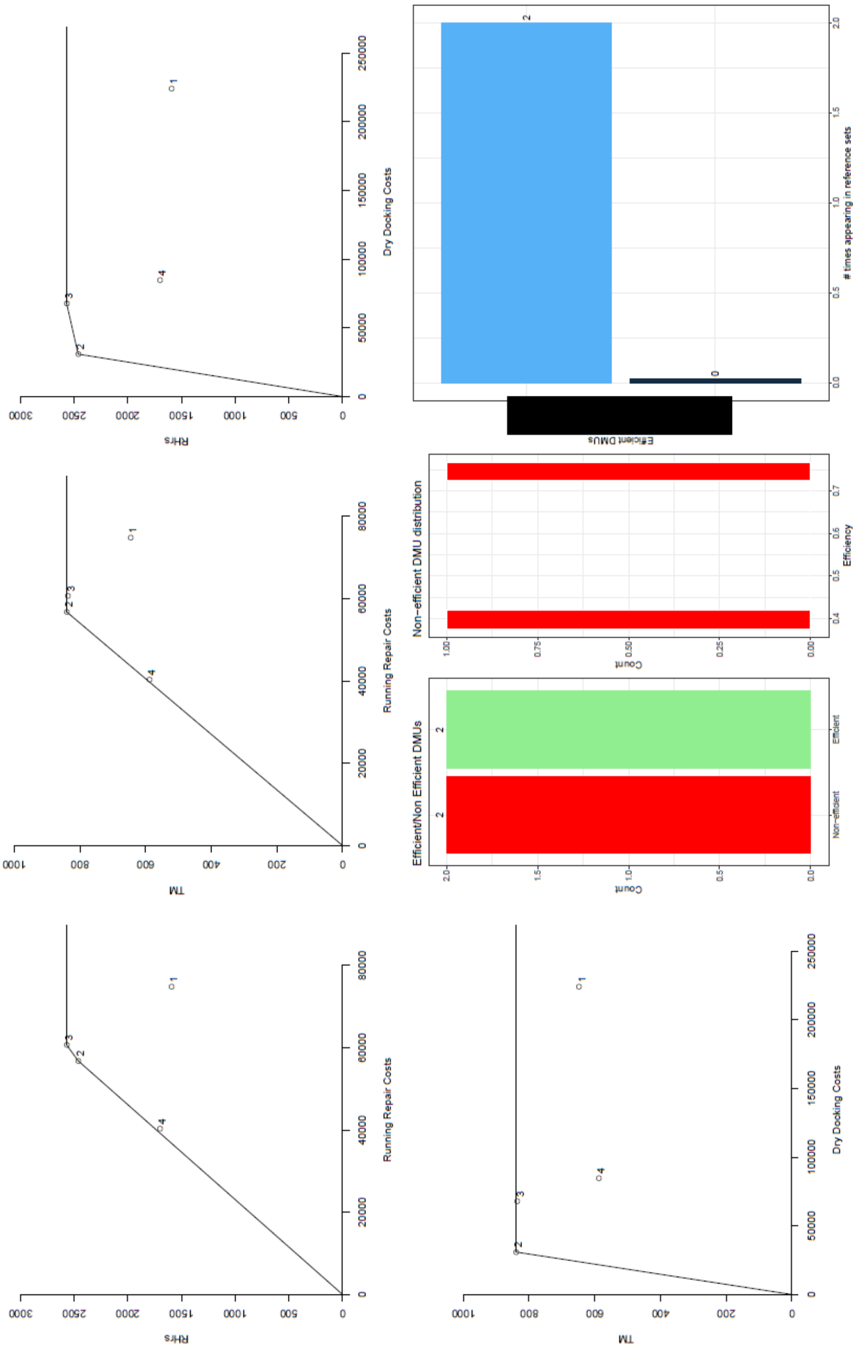
	INPUT					OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 6	107.80	110.86	2,627	2,564	1.00	107.80	110.86	2,627	2,564
2	Tug 7	43.37	159.47	1,758	1,678	1.00	43.37	159.47	1,758	1,678



K.5.9. Group 010

Table K.25: DEA results for sister group 010.

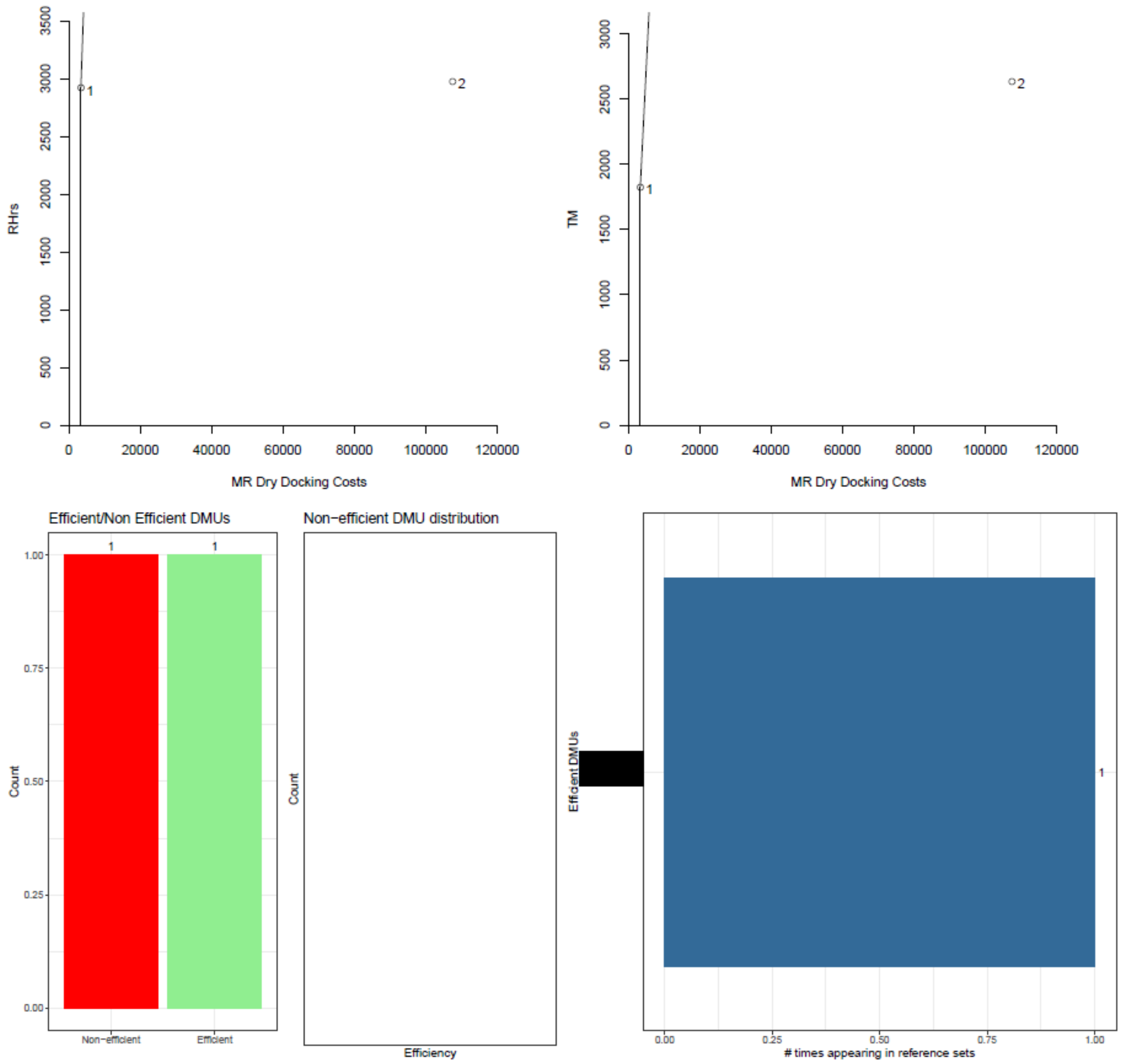
	INPUT					OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 45	74.85	224.15	1,590	646	0.38	43.68	23.77	1,893	646
2	Tug 49	56.82	30.92	2,463	840	1.00	56.82	30.92	2,463	840
3	Tug 50	60.67	67.86	2,571	835	1.00	60.67	67.86	2,571	835
4	Tug 65	40.30	84.79	1,700	587	0.77	39.67	21.58	1,720	587



K.5.10. Group 011

Table K.26: DEA results for sister group 011.

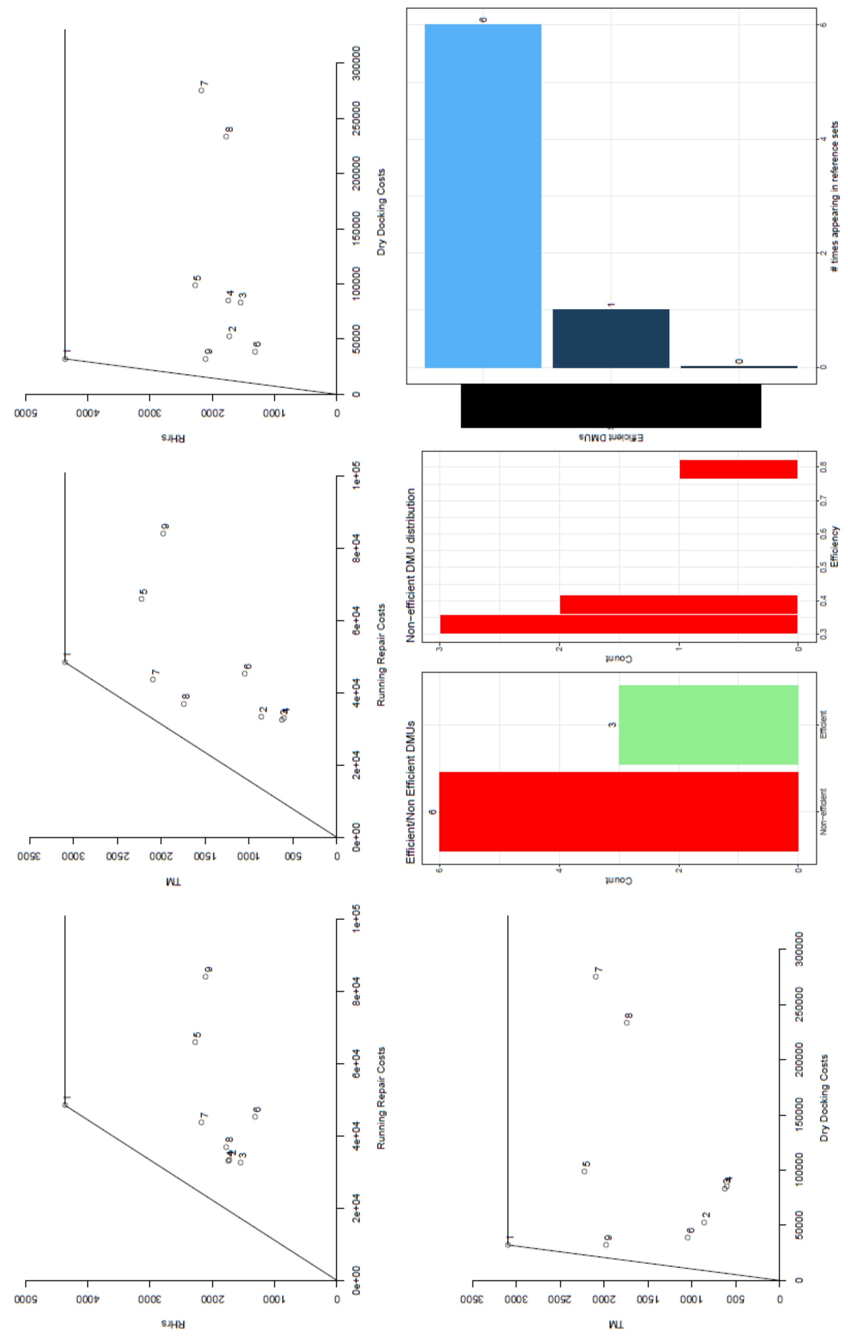
INPUT						OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 55	-	3.35	2,921	1,827	1.00	-	3.35	2,921	1,827
2	Tug 58	-	107.55	2,977	2,633	0.04	-	4.83	4,210	2,633



K.5.11. Group 012

Table K.27: DEA results for sister group 012.

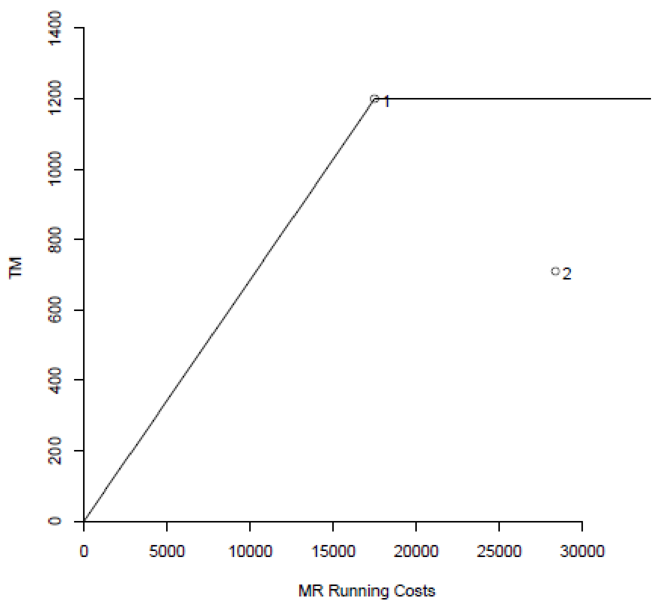
INPUT						OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 23	48.48	32.13	4,369	3,097	1.00	48.48	32.13	4,369	3,097
2	Tug 24	33.37	52.58	1,723	857	1.00	33.37	52.58	1,723	857
3	Tug 28	32.58	83.22	1,544	624	0.82	27.29	65.16	1,543	624
4	Tug 31	33.05	85.26	1,745	604	1.00	33.05	85.26	1,745	604
5	Tug 32	65.96	98.83	2,272	2,226	0.32	34.85	23.10	3,141	2,226
6	Tug 33	45.29	38.72	1,311	1,043	0.30	16.32	10.82	1,471	1,043
7	Tug 35	43.72	275.33	2,167	2,089	0.41	32.71	21.68	2,947	2,089
8	Tug 39	36.94	233.50	1,769	1,739	0.40	27.22	18.04	2,453	1,739
9	Tug 40	84.07	32.17	2,102	1,974	0.34	30.91	20.49	2,786	1,974

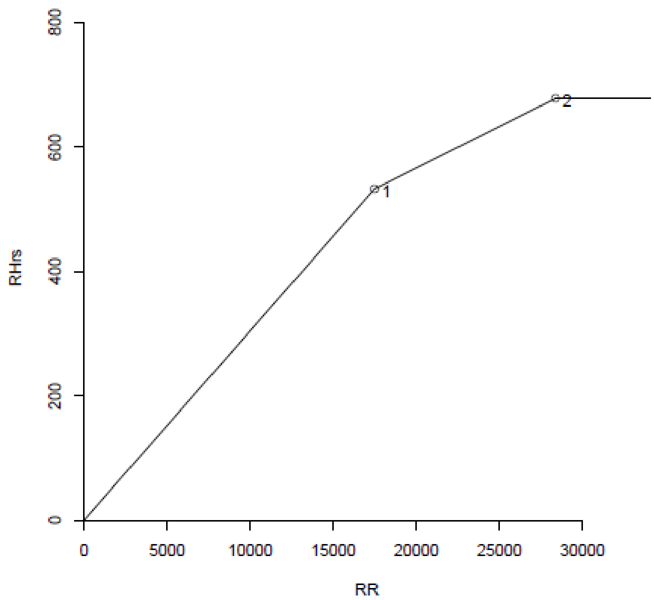


K.5.12. Group 013

Table K.28: DEA results for sister group 013.

		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 5	17.50		533	1,200	1.00	17.50		533	1,200
2	Tug 9	28.37		678	712	1.00	28.37		678	712

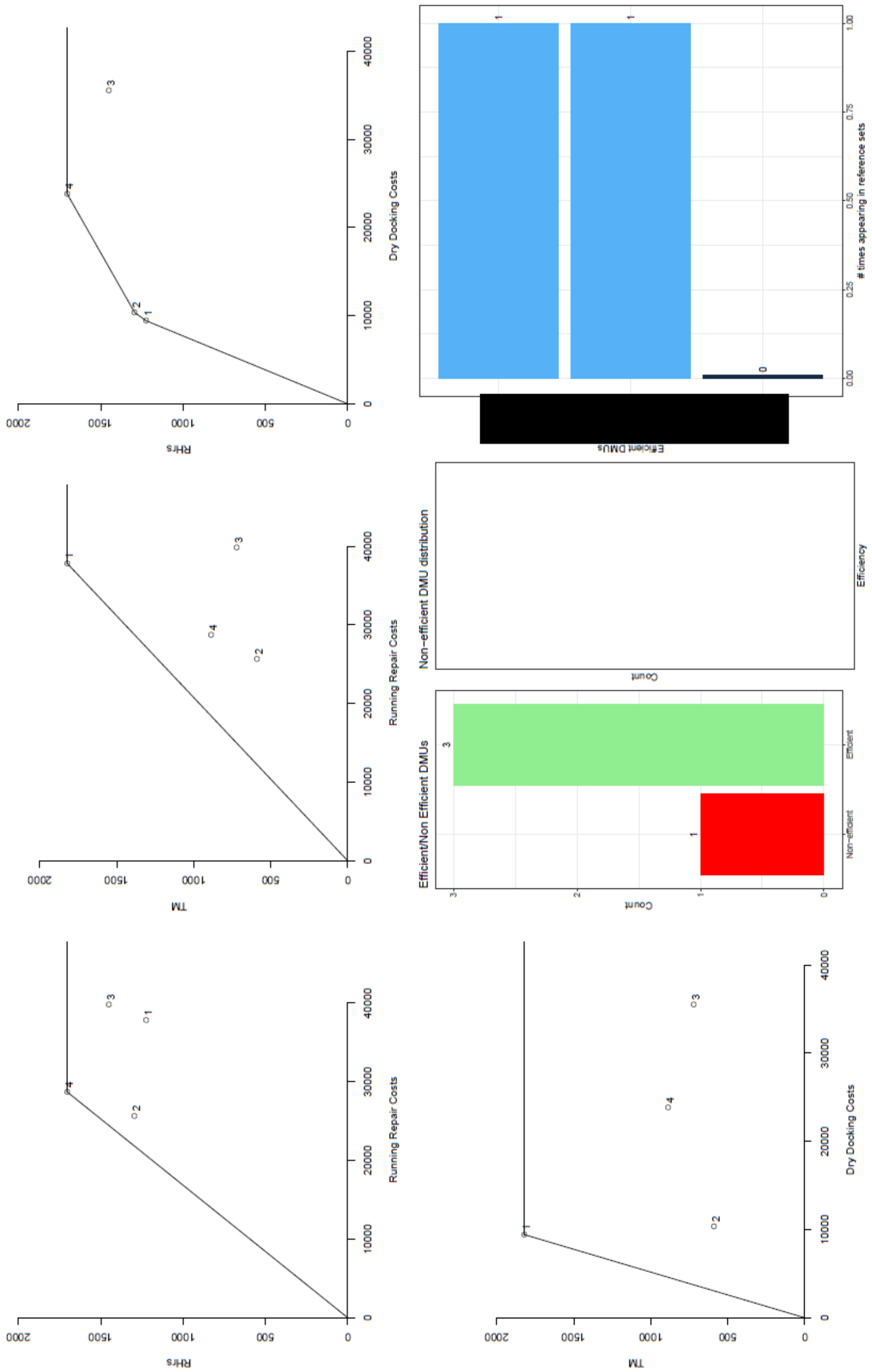




K.5.13. Group 015

Table K.29: DEA results for sister group 015.

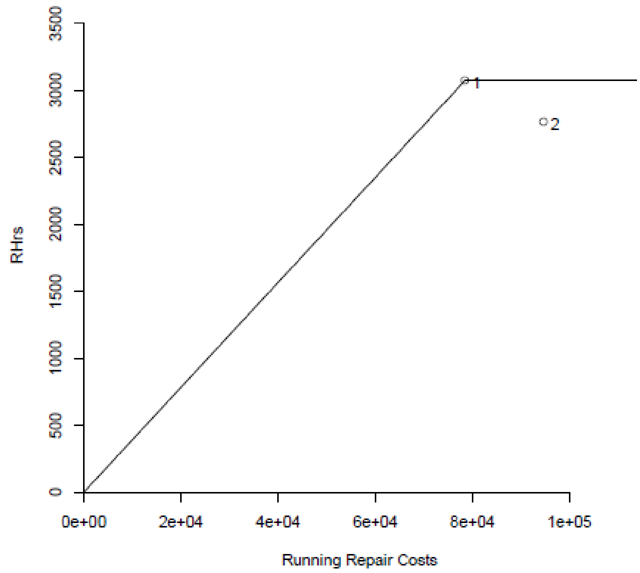
	INPUT					OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 1	37.84	9.44	1,226	1,823	1.00	37.84	9.44	1,226	1,823
2	Tug 66	25.67	10.37	1,294	590	1.00	25.67	10.37	1,294	590
3	Tug 68	39.85	35.54	1,451	719	0.60	26.08	17.02	1,451	719
4	Tug 69	28.73	23.84	1,705	887	1.00	28.73	23.84	1,705	887

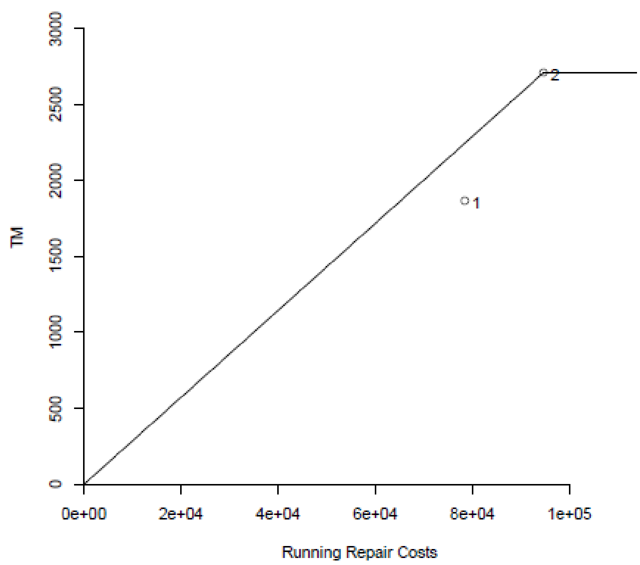


K.5.14. Group 016

Table K.30: DEA results for sister group 016.

		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 53	78.50	111.87	3, 073	867	1.00	78.50	111.87	3,073	867
2	Tug 59	94.66	122.66	2,769	2,709	1.00	94.66	122.66	2,769	2,709

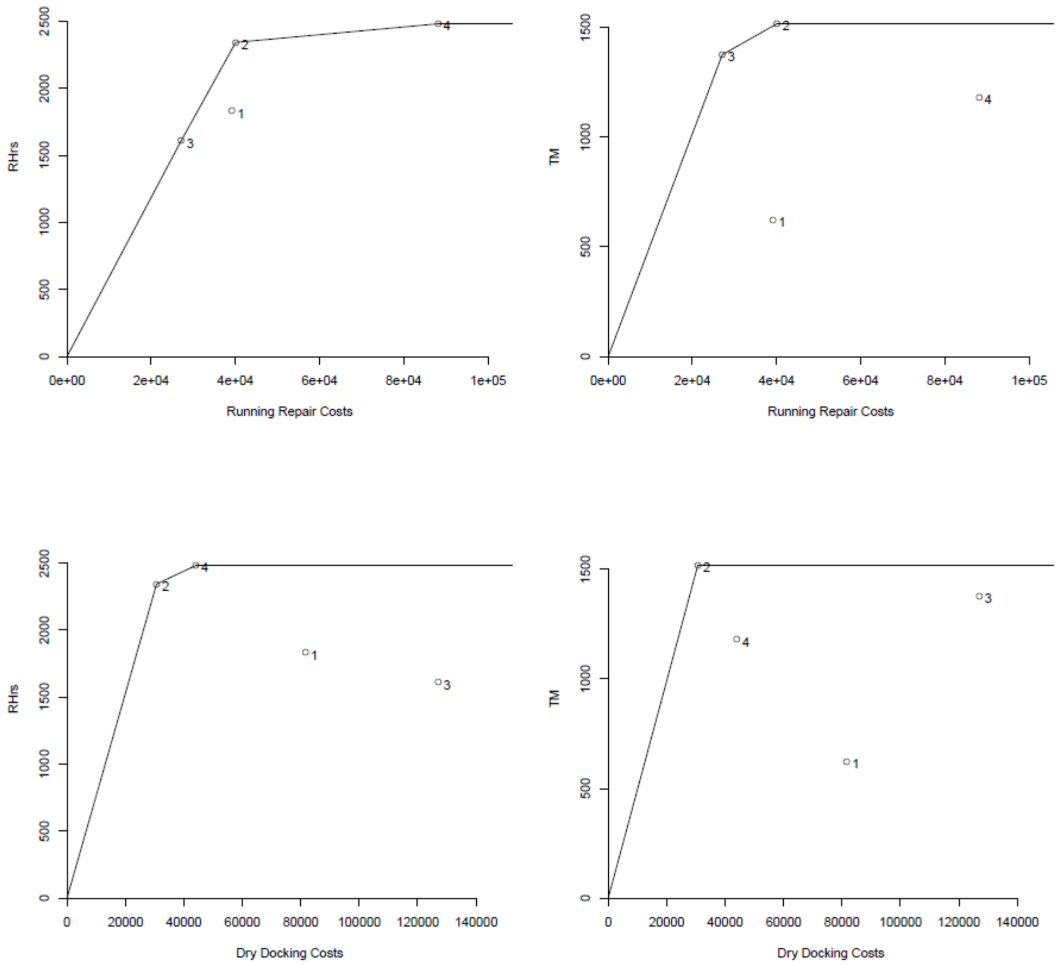




K.5.15. Group 017

Table K.31: DEA results for sister group 017.

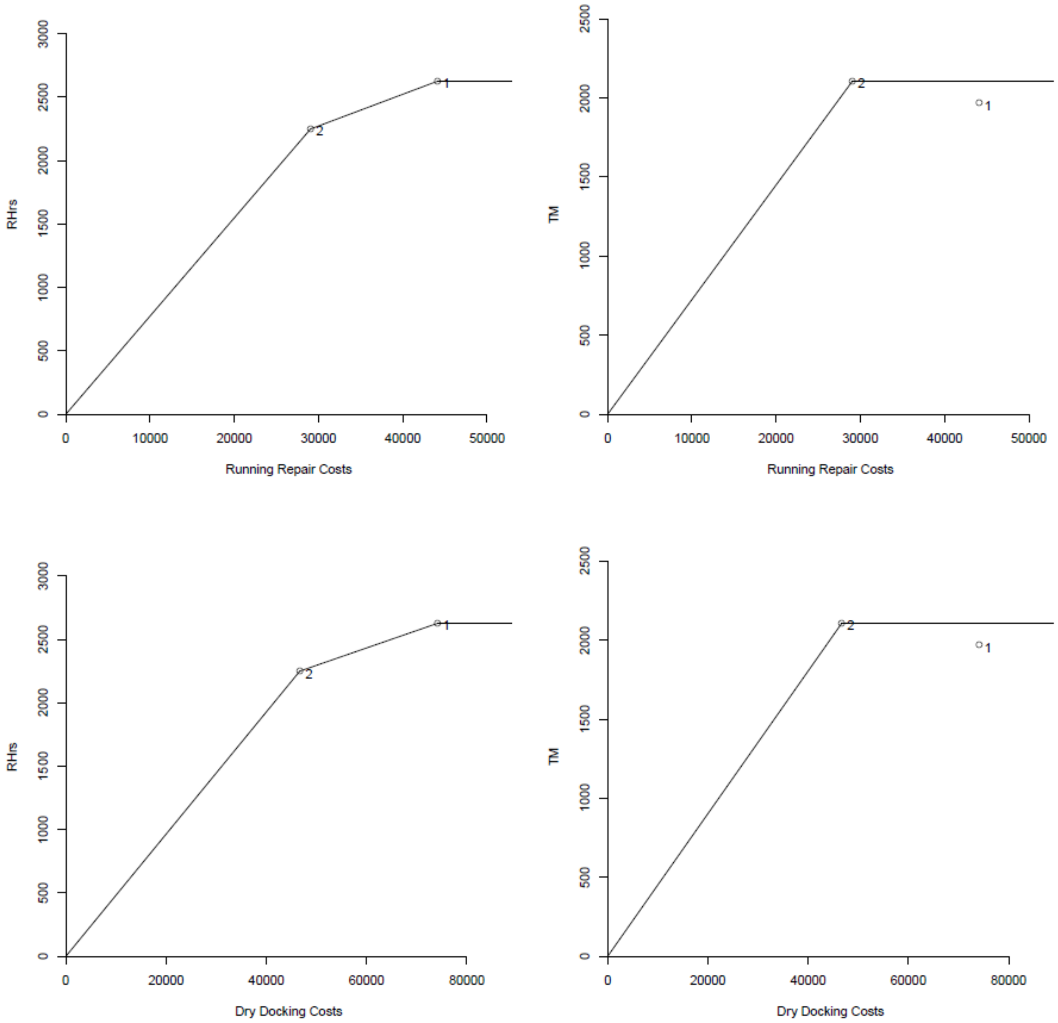
INPUT						OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 38	39.16	81.59	1,831	623	1.00	39.16	81.59	1,831	623
2	Tug 48	40.09	30.65	2,343	1,518	1.00	40.09	30.65	2,343	1,518
3	Tug 51	27.10	126.99	1,607	1,377	1.00	27.10	126.99	1,607	1,377
4	Tug 52	88.16	44.08	2,481	1,181	1.00	88.16	44.08	2,481	1,181



K.5.16. Group 020

Table K.32: DEA results for sister group 020.

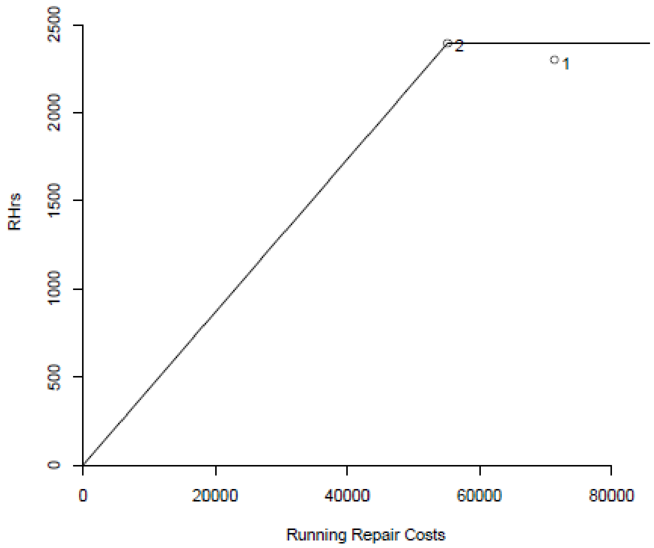
		INPUT				OUTPUT				
DMU	**Name**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs**	**TM**	**Efficiency Score**	**Running Repair Cost** [x €1,000]	**Dry Docking Cost** [x €1,000]	**RHrs Target**	**TM Target**
1	Tug 46	44.10	74.12	2,626	1,969	1.00	44.10	74.12	2,626	1,969
2	Tug 47	29.05	46.69	2,250	2,106	1.00	29.05	46.69	2,250	2.106

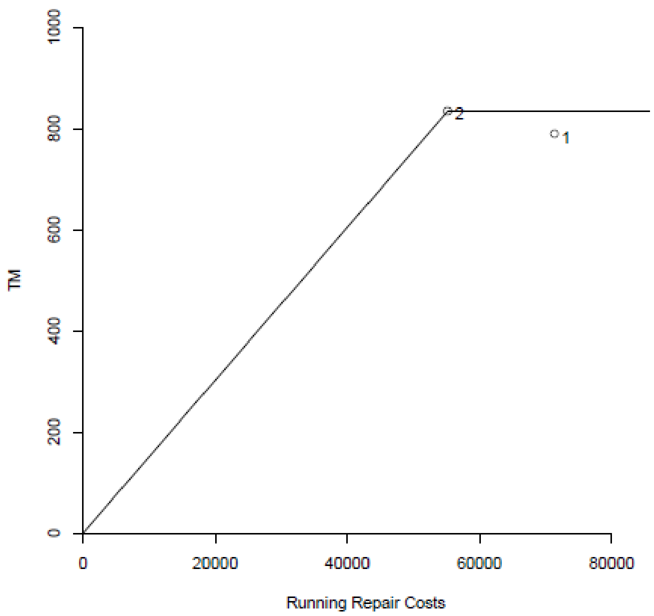


K.5.17. Group 021

Table K.33: DEA results for sister group 021.

		INPUT				OUTPUT				
DMU	Name	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs	TM	Efficiency Score	Running Repair Cost [x €1,000]	Dry Docking Cost [x €1,000]	RHrs Target	TM Target
1	Tug 2	71.35	-	2,294	789	1.00	71.35	-	2,294	789
2	Tug 45	55.20	211.73	2,393	834	1.00	55.20	-	2,393	834





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