Balancing maintenance efforts at Nederlands Loodswezen

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Summary

Nederlands Loodswezen B.V. or just “Loodswezen” is the company that facilitates maritime pilots in their jobs to guide ships in and out of the Dutch ports. The vessels of the company are designed specifically for Loodswezen, which means there are no vessels in the world that are the same. This has great implications for the optimization of maintenance, as not much data is available.

Loodswezen does most maintenance by its own and is therefore depending on their own judgement considering maintenance and (preventive) maintenance intervals. The result is a fleet-wide technical availability of 97,1% (which is considered high and is higher than the target of 97%). The fleet-wide operational availability is reported to be 87,1%, considerably *below* their target (92%). The management of Loodswezen wants to balance the situation in order to improve operational availability. As the preventive maintenance is the cause of the low operational availability, the company wants to determine whether this can be done differently. An important restriction to this problem is the absence of historical failure data which is typically needed in order to calculate optimal maintenance intervals.

The objective of this research is *developing a method to design a maintenance policy that is capable of reducing the total maintenance time*.

As physical models are not available (yet) to optimize maintenance, a mathematical model needs to be used. In order to calculate optimal maintenance intervals with a mathematical model, one needs to model the failure behaviour with some kind of probability distribution. In this research, a two-parameter Weibull distribution is used from which the parameters are estimated in two different ways:

- Conventional: Least Squares method.
- Proposed: Bayesian expert estimation.

As the conventional method requires historical data, Loodswezen can only use the method for a few components, especially ones in older vessels. In cases where not enough data is available, the Bayesian expert estimation can be used. This method features the following advantages over the conventional method and over the current situation:

- No historical data is required; immediate implementation is possible (*prior*).
- Once historical data is available, the solution can be improved (*posterior*).
- The method is more realistic than the results from the FMECA.
- Maintenance intervals can be optimized with the output of the method.

The disadvantage of the expert estimation method is that the results are less exact than the results of the conventional (*data-driven*) method.

The method is validated by the use of a case study with the dynamo of the Aquila Class C32 engine. The results are presented below. The data-driven method can be seen as benchmark for the other analyses.

Type	Method	MTBF	Optimal replacement interval
Data-driven (benchmark)	Real failure data	607	844
FMECA	Expert elicitation	91	-
Prior	Expert elicitation	932	1397
Posterior	Expert elicitation and real failure data	841	980

Table 0.1: Overview of results for the dynamo.

Currently, Loodswezen uses the FMECA to get an understanding of the failure behaviour of components. However, from the table above, it is clear that the MTBF from the FMECA is not

accurate (is way lower than the data-driven solution). The elicited prior from the Bayesian is way more accurate and when adding the available failure data (posterior) it becomes even better.

In the old situation, no preventive maintenance is done to the dynamo (except for an occasional inspection). In the proposed situation, preventive maintenance (replacement or revision) is advised. This advice is based on the data-driven approach as this is available in this case. The replacement can be done in two ways:

1. Use (administratively speaking) existing maintenance interval of 7000 hours.
2. Add new maintenance interval of 6250 hours.

Using an existing maintenance interval reduces the administrative burden of the change. The first solution features a reduced downtime *of the dynamo* of 2,1%, the second solution reduces the downtime by 2,3%. The low reduction indicates that maintenance *of the dynamo* is already near optimal. The same analysis can be performed for all components on every vessel, in order to design a maintenance policy.

To conclude, the proposed expert elicitation method gives the opportunity to plan maintenance without any historical data which was not possible before at Loodswezen. Especially the starting situation (prior) is not very exact but as failures are observed, the solution improves. This gives Loodswezen the opportunity to design a maintenance policy that is capable of reducing the total maintenance time.

Table of contents

Summary 2

I. List of tables........ 5

II. List of figures 7

III. List of abbreviations and terms 7

1. Research design 9

1.1 Company introduction 9

1.2 Problem description 13

1.3 Position in the trajectory 13

1.4 Objective & projected result 14

1.5 Research questions 14

1.6 Research approach 15

2. What is the current maintenance strategy at Loodswezen? 16

2.1 Loodswezen in depth 16

2.2 Spare parts 22

2.3 Maintenance 24

2.4 Availability of information 26

2.5 Conclusions 27

3. What are in general suitable methods to design a maintenance policy? 28

3.1 The maintenance concept 28

3.2 Maritime sector and data 29

3.3 Corrective maintenance 29

3.4 Preventive maintenance 30

3.5 Replacement strategies 31

3.6 Models & Uncertainty 32

3.7 The Weibull function 34

3.8 Bayesian model & Expert opinion 35

3.9 Conclusions 40

4. How can the failure behavior be characterized? 41

4.1 Historical failure data 41

4.2 The case of the dynamo 44

4.3 Expert opinion 46

4.4 Conclusions 53

5. How can information of failure behavior be translated to a maintenance planning? 55

5.1 Current policy ... 55
5.2 Decision variables ... 56
5.3 Planning maintenance ... 58
5.4 Other necessary optimization methods ... 60
5.5 Conclusions ... 61
6. How can a new maintenance policy be implemented? ... 62
6.1 Starting the project ... 62
6.2 Persons involved ... 63
6.3 Implementation ... 63
6.4 Conclusions ... 64
7. Conclusion, Discussion & Recommendations ... 65
7.1 Conclusion ... 65
7.2 Discussion ... 66
7.3 Recommendations ... 67
8. Bibliography ... 70
A. Appendix – Loodswezen operations: key figures ... 73
B. Appendix – Overview of operations ... 74
C. Appendix – Availability of failure data ... 75
D. Appendix – Gathering and filtering failure data ... 76
E. Appendix - Failure dates Dynamo ... 78
F. Appendix – Data driven failure rate ... 79
G. Appendix – Changing equipment: an overview ... 80
H. Appendix – Designing the experiment ... 82
I. Appendix – Overview preventive maintenance cycles Aquila ... 84
J. Converting optimal calendar times to operating hours ... 85
K. Appendix – Expert elicitation process ... 86

I. List of tables

Table 0.1: Overview of results for the dynamo. ... 2
Table III.1: Abbreviations and terms. ... 8
Table 1.1: Number of pilot trips per region per year (Loodswezen B.V., 2014). ... 10
Table 1.2: Technical and operational availability of the (relevant) fleet. ... 12
Table 1.3: Technical and operational availability of the fleet (Loodswezen B.V, 2013). ... 13
Table 2.1: Fleet overview (Loodswezen, 2014). ... 17
Table 2.2: Fleet distribution. ... 17

Table 2.3: P-class vessel specifications (Loodswezen, 2014). 18
Table 2.4: Maintenance costs for 2014 and the share of work orders for DE propulsion. 19
Table 2.5: Breakdown of actual propulsion maintenance costs of the DE propulsion system in 2014. 20
Table 2.6: Aquila class vessels specifications (Loodswezen, 2014). 20
Table 2.7: Actual maintenance costs for 2014 and the share of work orders for DD propulsion. 21
Table 2.8:Breakdown of actual propulsion maintenance costs of the DD propulsion system in 2014. 21
Table 2.9: Warehouses (van Haperen, 2011). 22
Table 2.10: Criticality of spare parts (van Haperen, 2011). 23
Table 2.11: Severity matrix for spare parts. 23
Table 2.12: Overview stock movements per order strategy. 23
Table 2.13: Spending on maintenance x1000 Euro. 24
Table 2.14: Estimation of type of maintenance per vessel. 25
Table 2.15: Maintenance in numbers. 25
Table 2.16: Preventive maintenance in numbers. 26
Table 2.17: Number of work orders. 27
Table 3.1: Overview of variables for the Bayesian analysis. 36
Table 4.1: Quick overview of the number of components per category. 41
Table 4.2: Example outcome of maintenance instances. 42
Table 4.3: Weibull parameters. 42
Table 4.4: Summarized outcome FMECA Aquila Class C32 Dynamo. 46
Table 4.5: Results from expert ε_{1}. 47
Table 4.6: Results from expert ε_{2}. 48
Table 4.7: Overview of elicited $\mathbf{F}(t_k)$ with lower and upper bound per expert. 48
Table 4.8: Values for analysis of variation. 49
Table 4.9: Overview of the outcomes of different scenarios with different variances. 49
Table 4.10: Prior of expert opinion. 49
Table 4.11: Outcomes of the iteration process based on 10.000 runs. 52
Table 4.12: Overview of the different parameters. 52
Table 4.13: Summary of outcomes. 53
Table 5.1: Aquila C32 PO-plan time intervals. 56
Table 5.2: Downtime associated with maintenance scenarios. 58
Table 5.3: Overview of planning. 59
Table 5.4: Downtime and improvement under the assumption of the data-driven Weibull parameters. 59
Table A.1: Number of pilot trips of all regions and ports over time (Ecorys Nederland B.V., 2014). ... 73
Table C.1: Overview of most used components. 75
Table D.1: Example of booking data. 76
Table D.2: Example relevant orders. 77
Table E.1: Overview of failure dates of Dynamo. 78
Table E.2: Overview of life times measured in calendar time and operating hours. 78
Table F.1: Input for regression based on calendar life times and without preventive maintenance. .. 79
Table F.2: Input for regression based on operational life times and without preventive maintenance. 79
Table I.1: Preventive maintenance cycles Aquila Engines. 84
Table J.1: Running hours of Aquila equipment. 85

Table K.1: Overview of input variables for the Monte Carlo Simulation (prior). 86
Table K.2: Overview of input variables for the Monte Carlo Simulation (posterior). 86

II. List of figures

Figure 1.1: Share of regions in pilot trips in 2013 (Ecorys Nederland B.V., 2014). 10
Figure 1.2: Relation between operational and technical availability (Loodswezen B.V., 2013). 12
Figure 2.1: The pilotage business at a glance. 16
Figure 2.2: P-class deployment strategy. 19
Figure 4.1: Failure rate function based on calendar time. 43
Figure 4.2: Survival rate functions based on calendar time. 44
Figure 4.3: Survival rate of different priors. 50
Figure 5.1: The ratio of corrective and preventive maintenance effort. 57
Figure A.1: Share of ports in pilot trips in 2013. 73
Figure B.1: Map of operations. 74
Figure G.1: Different engines for each position. 80
Figure G.2: Different positions for each engine. 81
Figure H.1: Example drawing cumulative failures. 82

III. List of abbreviations and terms

Abbreviation/term	Explanation
ACM	Consumer & Market Authority (Autoriteit Consument & Markt)
BCM	Business Centered Maintenance
CBM	Condition Based Maintenance
CDF	Cumulative Distribution Function
CM	Corrective Maintenance
Dinalog	Dutch Institute for Advanced Logistics
Elicitation	Gathering of subjective information (ontlokken van informatie)
Eurogeul	A deep water route on the North Sea for ships with a depth of more than 20 meter.
Failure mode	The way in which equipment or a part fails (break, fire, bend, etc.)
Failure rate	The rate at which failures occur over a period (failures per unit)
FME(C)A	Failure Mode and Effects (Criticality) Analysis
FLC	Fast Launch Craft (Jol)
LBM	Load Based Maintenance
Maasgeul	Continuation of the Eurogeul in front of the Port of Rotterdam. For ships with a depth of more than 14 meter.
MaSeLMa	Integrated Maintenance and Service Logistics Concepts for Maritime Assets
Mode	Value that appears most often in a data set (Modus)
MTBF	Mean Time Between Failure (statistical quantity)
NLBV	Nederlands Loodswezen B.V. (Dutch piloting organization)
NLC	Nederlandse LoodsenCorporatie (Dutch Pilot Corporation)
NTV	Nautisch Technisch Vlootbeheer (Nautical Technical Fleet Management)
OEM	Original Equipment Manufacturers
PDF	Probability Density Function

PM	Preventive Maintenance
PM-plan	Preventive Maintenance plan (PO-plan). A standard plan to perform preventive maintenance to a certain equipment.
Port	Bakboord, links
Position	Functieplaats (part of a vessel where work orders can be booked on)
PSV	Pilot Station Vessel
RCM	Reliability Centered Maintenance
SLA	Service Level Agreement
Starboard	Stuurboord, rechts
SWATH	Small Waterplane Area Twin Hull
TBM	Time Based Maintenance
TPM	Total Productive Maintenance
UBM	Usage Based Maintenance
USBM	Usage Severity Based Maintenance

Table III.1: Abbreviations and terms.

In order to increase the readability of this research, it is decided to not translate Dutch names of cities, waters and other places (e.g. 'Flushing' is just 'Vlissingen'). In the report, NLBV, Nederlands Loodswezen (B.V.) and Loodswezen are used to indicate the same organization.

With this report, an Excel file is included (Balancing maintenance efforts attachment.xlsx) that is capable of:

- Calculating Weibull α and β from Lifetimes (Least Squares).
- Perform all expert opinion analysis in order to get the expert elicited Weibull α and β.
- Calculating optimal maintenance time with Weibull α and β.

1. Research design

In this first chapter, an outline of the research will be presented. First the company Loodswezen1 will be introduced. The problem will be described in detail, the objective is presented together with the projected final result. To reach this objective, a plan is constructed. This plan consists of questions that need to be answered and a description on how to answer these questions.

1.1 Company introduction

First the work of pilots is described. Then the company that facilitates (NLBV) their work is presented. Finally, the relevant department of NLBV is introduced.

1.1.1 The pilots

Maritime pilots are people who guide sea going vessel to and from ports. A pilot is (officially) not in charge of a ship but gives advice to the captain in order to navigate through pilotage waters. Large civil ships are obliged to use a pilot while visiting all Dutch ports. There are different rules for this obligation in different ports in the Netherlands. For instance in the region Rotterdam-Rijnmond, ships do not need to have a pilot if the overall length is less than 75 meter. Until 95 meter they can request an exemption. In addition, some ports also have these kinds of restrictions concerning the depth of a ship. Regardless the size of the ship, any ship with dangerous cargo needs a pilot (Rijksoverheid.nl, 2014).

Depending on the size (depth) of the ship, the ship needs more or less expertise from the pilot. Some ships are very large and need to be guided from deep sea of the port or back. In these cases a pilot is brought to the ship by helicopter. In addition, the helicopter is used when the weather condition is very bad. Most ships however, are supplied with a pilot by the use of a vessel of Loodswezen.

The pilots are member of the Dutch pilot corporation (Nederlandse Loodsencorporatie – NLC), an organization that guarantees the education and quality of the pilots. Together with 'Nederlands Loodswezen B.V.', this corporation forms the backbone of Dutch pilotage.

1.1.2 The facilitator

Nederlands Loodswezen B.V. is a company that offers the service to support the pilots in the Dutch waters. The vessels that NLBV facilitates will bring the pilots to a ship at sea where they will guide the ship inside (all Dutch seaports and partially Antwerp) or the other way round. The company is responsible for the maintenance of the fleet, but is also responsible for the collection of fees and the administration. The company core values are safety, continuity and orientation towards the future (Loodswezen, 2012).

Three types of vessels are used:

- Tender. A relatively small boat (~22 meter) that is used to transport pilots. The company has different types of tenders.
- Pilot Station Vessel (Loodsboot). These ships are large (~81 meter) and serve as waiting station for pilots. There are three of these ships from which two are roughly permanently outside, at the coast of Rotterdam and Vlissingen. Pilots are transported to and from this ship by either a tender or an FLC. The pilots of course have to be transported from the PSVs to ships coming into Rotterdam or the other way round.
- FLC (Jol). These boats (~8 meter) are located at the PSVs. The boats are used to transport pilots between ships and the PSVs. The FLCs are lowered in to the water by using a Davit. This

[1] 'Loodswezen' can be replaced with 'Het Loodswezen', 'Loodswezen B.V.', 'Nederlands Loodswezen B.V. or 'NLBV': all meaning the facilitating company.

vessel only covers short distances as the PSVs are usually located centrally between incoming and outgoing ships.

Loodswezen also uses SWATH's, a catamaran used as a tender, in the region Scheldemonden.

The company is active in different areas of the Netherlands but the center of gravity of operations is in region Rotterdam-Rijnmond (around 60% of movements). The region Scheldemonden cooperates with the Flemish pilots which resulted in a division of work between the Dutch and Flemish pilots. The Dutch pilots guide 27,5% and Flemish pilots 72,5% of the ships to Flemish ports located on the Schelde.

Because of the continuous upscaling of the size of ships and the increasing capacity sharing between shipping companies, the number of movements is declining for years. This trend is expected to continue (in general) in the future. For 2014, the growth of ports in the region North is expected to compensate the decline in this year. In Table 1.1, an overview of the size of operations through the years is given. In Figure 1.1, one can see the regional division of work. The extended versions of both of these tables can be found in appendix 8.

Year	Dutch Ports	Scheldevaart	Total	Change (tot.)
2009	84.383	9.069	93.452	-
2010	87.600	9.656	97.256	4,1%
2011	88.403	9.958	98.361	1,1%
2012	84.893	9.353	94.246	-4,2%
2013	82.034	9.020	91.054	-3,4%
2014	N/A	N/A	93.350	2,5%

Table 1.1: Number of pilot trips per region per year (Loodswezen B.V., 2014).

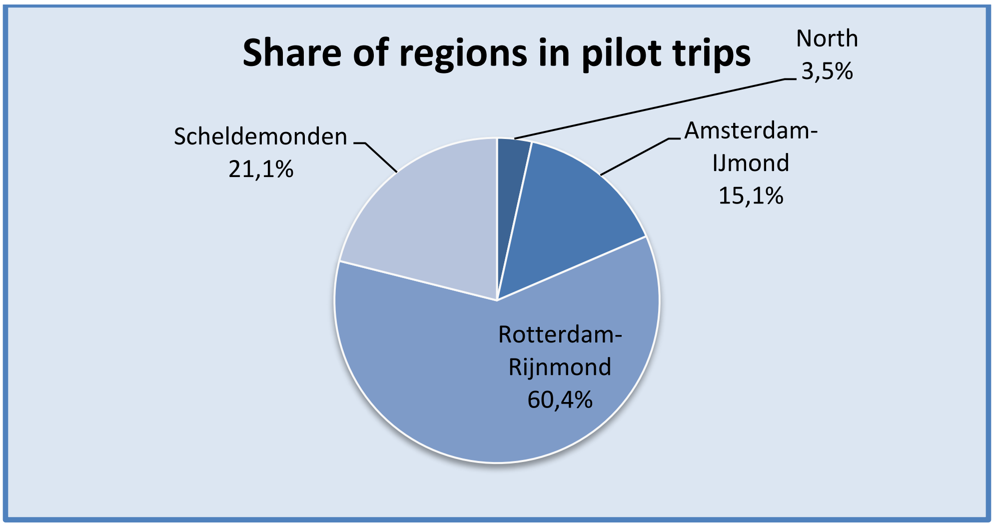

Figure 1.1: Share of regions in pilot trips in 2013 (Ecorys Nederland B.V., 2014).

Loodswezen is a privately owned company (by the pilots). The company used to be public until 25 years ago and still is highly restricted by the government because of the national interest; the company is an essential facilitator in the largest ports (Rotterdam, Antwerp, Amsterdam) in Europe (aapa.com, 2011). These facts have a large effect on Loodswezen. The company is under supervision of the Autoriteit Consument & Market (ACM), an organization that protects consumers and business. This organization assesses the height of the fees that are set by Loodswezen. Loodswezen makes a budget in which the total costs and investments of a year are estimated and the number of pilot trips is estimated. This leads to cost per trip, this is basically the fee for the ships. This means that the amount of income the company gets is more or less set beforehand. Loodswezen and the ACM discuss the finances every year. The goal of the ACM is to make sure Loodswezen does not misuse the monopoly position they have. Loodswezen needs to have enough income because deficits have to be *paid by* the most important stakeholder of all: the pilots. One can imagine that the pilots are not pleased if this happens. Of course, profits are also *paid to* the pilots. This is undesirable for the ACM, as they protect 'the market'. Making a (large) profit suggests misuse of the monopoly position Loodswezen has. The ACM does not offset profits or losses that are caused by more or less traffic. They do however compensate for investments that are either made or not made unexpectedly. This all means that making (unexpected) profit or losses is undesired as this will have cause changes in next years' budget. Therefore Loodswezen wants to control their (budgeted) costs instead of making large cost improvements.

For almost twenty years, discussion has been going on to further privatize the sector, making an end to the monopoly position Loodswezen has. This was finally bound to happen in 2019, until in 2011 the government decided to renounce that idea. They had come to realize there was no support from the pilots nor from Loodswezen, that the national interest of steady piloting operations was too great and that Loodswezen already is transparent and cost conscious. The latter is usually a reason to introduce competition in a market. The government set conditions for Loodswezen under which the company is allowed to operate in a monopoly position (Haegen, 2011).

1.1.3 Fleet Management

The department Vlootbeheer (Fleet Management) is responsible for the supply of the right equipment to the different regions. Each of the four regions indicate its needs regarding the vessels. Vlootbeheer facilitates all regions with regard to the requested fleet. The department makes the (long term) fleet plan, determines the location of vessels in the country and is responsible for the maintenance of vessels.

In order to perform this task, the department works with two performance indicators and one specific goal. These points are Vlootbeheer specific and are an addition to the company's core values (safety, continuity and orientation towards the future). The goal to control costs applies to both Vlootbeheer and the company as a whole.

- Technical availability (≥97%). The technical availability is the part of time that the vessels are (technically) not unplanned out of service. This percentage is calculated by 100% - unexpected down time.
- Operational availability (≥92%). The operational availability is defined as: 100% - (% expected down time + % unexpected down time). In other words, it is the part of time that a vessel can be used effectively.
- Controlling costs (5% under budget to 2% over budget). Loodswezen sets the tariffs for ships as a result of predictions for their financial situation in the future. The reason for this goal is, as already explained in section 1.1.2, that both 'profits' and 'losses' are undesirable. This goal however is way less important than aspects like availability and safety.

The difference between technical and operational availability is the expected downtime which roughly is the amount of time a vessel is in preventive (planned) maintenance (hence the operational availability is always lower than the technical availability). In Figure 1.2, a rough overview is given of the relation between operational and technical availability and maintenance. Part three is what affects the operations; this part should be as small as possible. If it is assumed that a vessel is directly in 'maintenance' when it is not operational, the downtime is made up of preventive maintenance and corrective maintenance or in other words expected and unexpected maintenance. This notion is important because the total maintenance effort is the result of the interplay between the two maintenance types. As the size of area three is to be decreased, corrective and preventive maintenance needs to be balanced. From a mathematical point of view, there should be at least one optimal balance that minimizes area three. In reality however, not all combinations are acceptable, for instance because executing corrective maintenance also introduces safety hazards as this is usually introduced by a failure during operations. The vessels are considered operational during training because if needed, the vessels can be used if needed.

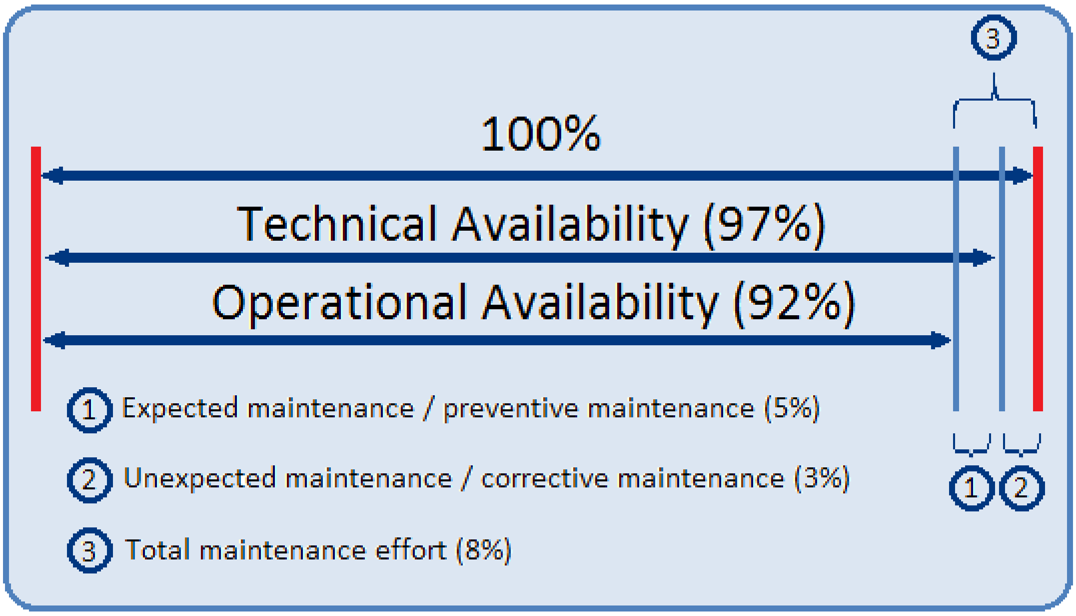

Figure 1.2: Relation between operational and technical availability (Loodswezen B.V., 2013).

The theoretical framework as described above lead to the actual availability numbers. In Table 1.2, a brief overview of the availabilities is shown. The percentages are the averages of the ships available. In case of the P-class, the numbers are only from the Polaris and Pollux from the moment it came available. Unfortunately, although the Aquila class vessels entered service in 2010, data is hard to compare from before 2013 due to both bad quality and a change in definitions. The technical availability of the *whole fleet* (tenders and SWATHs) was 95,8% in 2013 and the operational availability was 87,1% in the same year. In Table 1.2 it can be seen that the *Aquila* performed better than average on technical availability, but way worse on operational availability. In the first nine months of 2014, the technical availability of the tenders and SWATHs increased to 97,1% while the operational availability did not change. Especially the operational availability at the P-Class vessels is higher than the availability of the tenders, because (planned) maintenance generally does not require downtime. P-Class vessels will usually remain at sea and available.

	2013	2014
Total Fleet Technical	95,8%	97,1%
Total Fleet Operational	87,1%	87,1%
Aquila Technical	97,2%	94,5%
Aquila Operational	75,3%	80,6%
P-Class Technical	99,8%	100,0%
P-Class Operational	98,0%	99,7%

Table 1.2: Technical and operational availability of the (relevant) fleet.

1.2 Problem description

Each year Loodswezen sets goals in order to justify their budget for next year. To do this, the company sets goals for their technical and operational availability and cost control. In the past, when primarily breakdown maintenance (replace when broken) was executed, the technical availability was around 90%. The company has had a transition towards a preventive maintenance strategy since 2011 (maintenance according to makers' manual). The strategy worked, as the technical availability increased to values above target. However the increased maintenance efforts did not lead to an increase in operational availability. The company seeks for a better balance between the technical and operational availability under the condition that safety is guaranteed and costs controlled. However, the research has to be performed under the circumstance of having a small installed base: there are only three PSVs and three Aquila-class tenders. This means that there are few units of every component. In addition, the vessels are all fairly new, so there is little historic data.

	Technical	Operational	Preventive maintenance	Corrective maintenance
Before transition	~90%	~85%	~5% *(90%-85%)*	~10% *(100%-90%)*
2013 year average	~99%	~86%	~13% *(99%-86%)*	~1% *(100%-99%)*
Target	≥97%	≥92%	~5% *(97%-92%)*	≤3% *(100%-97%)*

Table 1.3: Technical and operational availability of the fleet (Loodswezen B.V, 2013).

The target of the technical availability is based on calculations that were made to be able to use the vessels of Loodswezen the way they want to. The target for operational availability is based on the technical availability and the fact that a certain balance between corrective and preventive maintenance is best for the company. In this case this is assumed to be 30% corrective and 70% preventive maintenance (Loodswezen B.V., 2013).

A better balance first of all means that the technical availability should be at least 97% and the operational availability at least 92%. As stated earlier, the difference between the two numbers is roughly the time that a vessel is being preventively maintained. This means that, theoretically speaking, if the technical and operational availabilities are on target, there will be just ~5% time (97%-92%) for preventive maintenance where the company currently needs ~13% time (99%-86%) for preventive maintenance. Although the company has a very conservative maintenance plan (change parts that are still in good shape) it is easy to understand that certain combinations of the two availabilities are not (yet) possible as they are related. Therefore a better balance also means a feasible balance. To address these issues, Loodswezen joined the MaSelMa project in which other maritime companies and universities are present in order to lower cost of ownership of their maritime assets. For this project, a baseline-study will be conducted. This study is somewhat more elaborate than chapter two of this research (but overlaps greatly) and is published separately.

1.3 Position in the trajectory

Some years ago, Loodswezen started a trajectory to decrease the unexpected downtime of their vessels. The reason for this was that the low technical availability lead to reduced safety (technical problems at sea) and reduced operational flexibility. As exactly these two factors are the very important in piloting, Loodswezen decided to change their maintenance method. The company introduced a preventive maintenance method, making using of the makers' manual. This maintenance method turned out to be very conservative: maintenance is done too soon. The new method increased the technical availability, but because of the increased maintenance efforts, the operational availability decreased.

The last is the starting point of this research. Loodswezen needs a less conservative preventive maintenance plan without additional safety risks (read: unexpected downtime). The goal is to decrease the total expected and unexpected downtime. This research will focus solely on the propulsion system of two vessel types: the Diesel-Electric system for the PSVs and the Diesel-Direct system for the Aquila tenders. To develop a method to reach the goals, FMEAs and RAM results are used as starting point.

1.4 Objective & projected result

The objective of this research is developing a method to design a maintenance policy that is capable of reducing the total maintenance time. To get to this point, the policy needs to be able to reach feasible balance between technical and operational availability while meeting the targets that were set by Vlootbeheer (technical availability, operational availability, budget control). It also needs to guarantee safety, continuity and future orientation.

In order to do this, there is a need to gain knowledge about the failure behavior of parts on the vessels. This means that by using FMEAs and for instance supplier information, the MTBF and failure rate functions can be estimated. This then leads to the ability to introduce more clever maintenance.

The output of this research is a guideline for Loodswezen specific, to generally deal with the lack of information concerning failure rates, failure behavior, historical data, experience etc.. The research will focus on the propulsion systems of PSVs and Aquila tenders (see chapter 0). The guideline should be such that Loodswezen is able to do the same for other systems and other vessels. Part of the research will also be a recommendation on how to implement the new maintenance policy.

1.5 Research questions

In order to know how to reach the goals, a systematic approach is needed. Therefore, some research questions have been made. After answering these questions, there is a great understanding of what is happening and why the performance differs from the norm.

1. **What is the current maintenance strategy at Loodswezen?** *(chapter 2)*
   This can be seen as the description of the current situation (zero-measurement) with all necessary background information. Questions that are answered in this part are for instance how often is a vessel in maintenance? What kind of maintenance? How is the maintenance organized? In addition, the way Loodswezen operates is also treated extensively.

2. **What are in general suitable methods to design a maintenance policy?** *(chapter 3)*
   Currently, Loodswezen has the feeling they are replacing the different components too soon because they don't have the information with regard to the lifetime of the components. In this part, a (theoretical) overview of the aspects involved in the trajectory to design a maintenance policy is given. The focus in this chapter is on the gathering and analysis of data about the failure behavior of components.

3. **How can the failure behavior be characterized?** *(chapter 4)*
   Failure behavior can be described by physical and mathematical models. In this report, mathematical models are chosen. This question will solve the problem of the lack of available data to use mathematical models.

4. **How can information of failure behavior be translated to a maintenance planning?** *(chapter 5)*
   Chapter 4 gives the opportunity to see how the failure behavior of a component looks like. This can be used to calculate the optimal time to do maintenance. In this chapter, different ways of ways of doing this are discussed.

5. **How can a new maintenance policy be implemented?** *(chapter 6)*
   The new maintenance policy will most likely be a policy that is less conservative, meaning that parts are renewed less often. In addition, the gathered information is partially subjective (i.e.

gathered from people) and may therefore be not very exact. Both these issues introduce a safety hazard as it is needed to be absolutely sure that there will be no unwanted breakdowns. Therefore, testing in practice needs to be done very carefully. In addition, the results of the new policy, either positive or negative, will take some time to reach emerge (up to years). This chapter will give a roadmap to implementing the new system.

To conclude, the first question is the current situation, the second question is the theoretical solution to the problem while the third question makes this more tangible. Question four and five can be seen as practical translation of the information found. This can be seen as a validation of the method described in this research. The final question can be viewed as a useful extension to the research because designing a new maintenance policy is useful, but is has to be implemented somehow. This is the final step to improvement.

The project will be performed on the propulsion system of two different systems:
- Diesel-Electric (P-class pilot Station Vessels)
- Diesel-Direct (Aquila class tender)

The propulsion system consists of different components, divided in modules.

1.6 Research approach

The process of improving the maintenance policy has started some years ago. During the past years a lot of knowledge is already gathered using FMECAs and comparable analysis methods.

The first research question contains background information (the current situation or baseline study) and is constructed by using expert opinion, FMECA reports, observation and sources within the company. The second question is answered primarily by literature research. In order to map the possibilities, external sources are needed. In order to determine what is and what is not suitable for Loodswezen, of course, some expert opinions are needed.

The third question is meant as bridge to connect the literature to the reality. To answer this question, the FMECAs that already have been done are very useful. In addition, experts are used and data is gathered using SAP. With these sources, the failure behavior is modeled.

Also the fourth question is answered by looking both at literature as well as looking internally. This question tries to translate the findings of the previous questions into an actual maintenance schedule. The goal of this research question is to create practicability and effectiveness for the company.

The final question will describe the trajectory that Loodswezen can follow in order to implement the proposed solution in a safe way.

The report ends with a conclusion, discussion (limitations, assumptions, etc.) and recommendations for the company.

2. What is the current maintenance strategy at Loodswezen?

This chapter consists of a somewhat deeper understanding of what Loodswezen does.

2.1 Loodswezen in depth

Nederlands Loodswezen B.V. offers services to the pilots that involve operations. In addition, the pilots are member of the NLC. This corporation is committed to aspects like quality, safety and education. The pilots are shareholders and non-managing *partner* of Loodswezen B.V. and are *member* of the NLC. It is important to understand that the pilots, although being the owner of the company, do not run operations, NLBV does. This interplay summarizes the pilotage business as can be seen in Figure 2.1. All three actors are essential in the process (NLBV, 2014).

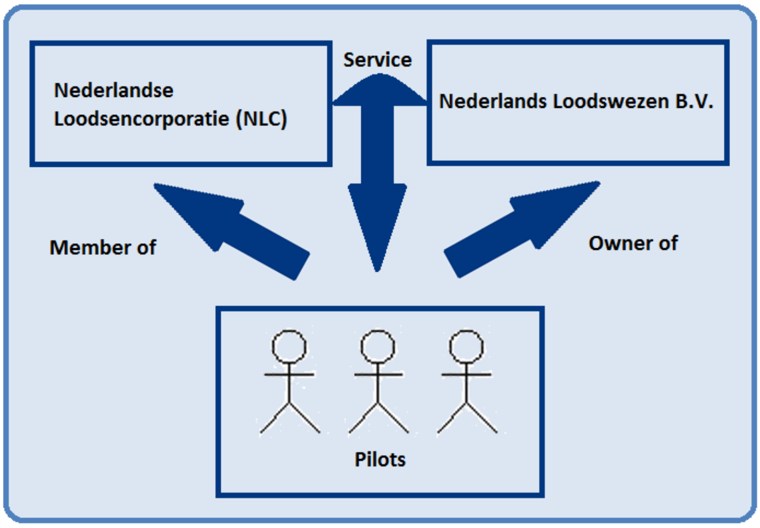

Figure 2.1: The pilotage business at a glance.

The company itself states in their mission statement for 2012-2015: "*Nederlands Loodswezen B.V. fully supports all Dutch pilots in their occupation and business, now and in the future. Nederlands Loodswezen B.V. stands for safety, continuity and focus on the future.*" (Loodswezen, 2012). With this, they indicate that they are a service provider for the pilots which makes the pilots the customer of NLBV.

The reason the pilots are considered consumers is because the vessels are there, in the first place to facilitate their jobs. The use of all vessels is explained in sections 2.1.2 and 2.1.3. It can be seen that Loodswezen does not have a large number of vessels of one single type. This has to do with different needs in different regions and the current transition towards a modern fleet. Currently the Lynx-class is growing to the size of five in 2016 while the Discovery class fleet will decrease until retired completely.

Type	Class	Fleet	Description
Pilot Station Vessel	P-class	3	The largest vessels of Loodswezen
Fast Launch Craft	(On the) P-class	8	Small aluminum, jet driven boat, stationed at the PSVs
Tender	Conventional	2	Polyester conventional tenders
	Discovery Class	7[2]	Aluminum and jet driven (being retired)
	Aquila Class	3	First edition of new, aluminum, jet driven series
	Lynx Class	3	Improved edition of Aquila Class
	Hercules Class	2	New steel tender with screw, designed for icy conditions
	SWATH[3]	2	Vessels to be used in seas with high swell
Helicopter	Helicopter (leased)	1	Eurocopter AS365N3 Dauphin

Table 2.1: Fleet overview (Loodswezen, 2014).

The vessels of Loodswezen are all located in the Netherlands. However, this involves the whole coast line. In Table 2.2, the projected size of the fleet is shown. The actual number of vessels in a region is not this steady because some ships are at a shipyard and are temporarily replaced by spare vessels.

Region	Tenders [SWATH]	P-Class
Scheldemonden (Vlissingen)	3 [2]	2
Rijnmond (Rotterdam)	5 [0]	1
IJmond (IJmuiden)	3 [0]	0
Den Helder	2 [0]	0
Harlingen	2 [0]	0
Eemshaven	2 [0]	0
Total	17 [2]	3

Table 2.2: Fleet distribution.

For the Aquila Class specific, currently the Aquila is in Rotterdam, Draco in IJmuiden and Orion is in repair because of damage it has, that was caused by a fire. If Orion returns to Rotterdam, the Aquila Class is at its dedicated positions again. The PSVs are always in Rotterdam (1) and Vlissingen (2). The Aquila class is built to last for 20 years with a revision ('dokking plus') after 10 years. The P-class vessels are built to last 30 years. It depends on the part of the propulsion system how long a certain system will last. The propeller for instance should be able to last for 30 years, while most bearing will never make it to this age.

2.1.1 Contracts

Loodswezen does not have full service contracts. Although the company wants these kinds of contracts in the future, the market is not ready to supply these kinds of contracts. The reason for this is the lack of knowledge of both suppliers and Loodswezen, about the failure behavior of components and the effect of different usage on the very specific maritime fleets. This way, either the supplier or the customer is saddled with an unknown risk. Usually, the customer pays the provider of full service contracts to cover a certain risk, but as this risk is unknown, no agreement on this can be reached. Fortunately, Loodswezen has a lot of expertise to do maintenance themselves so full service contracts are not necessary, but it could potentially take away risks.

There are however, large framework contracts with important suppliers Datema (safety equipment), Northrop (radar) and PON (engines). In these contracts, pricing agreements are made and the maintenance intervals are agreed on. In case of PON for instance, Loodswezen can buy some components cheaper under the condition that is replaces the component on the time PON requires.

[2] Fleet in 2015, excluding Columbia.
[3] SWATHs are very different from the other tenders in terms of technology but are used nearly the same way.

In addition to pricing and maintenance intervals, the conditions of the service and the storage of certain components are dealt with. Again for PON, this means for instance that delivery times are set.
In addition to this large framework contracts, Loodswezen has smaller contracts with nearly all suppliers. These contracts are mainly about pricing conditions of components and man hours.

2.1.2 Pilot Station Vessels

On request of Loodswezen, Barkmeijer Shipyards built three, so-called, Pilot Station Vessels (PSV). These ships are used as waiting station at sea for pilots. This means that there are permanently 17 people (maximum) on board, operating the ship in order to receive, send and provide service to pilots. The crew changes every week, the ship itself returns to the port every three weeks for supplies. Once operating, the PSVs are located at a central location at sea that doesn't change significantly during the time they are there. This means that these vessels have a relatively light task i.e. they don't sail enormous distances, are not always sailing, etc.. In the design of the vessels, this fact has been taken into account (hence, the two different engines C18 and C32). The vessels are the largest ships of Loodswezen with the following specifications:

Type	Pilot Station Vessel
Ships	Polaris (2012), Pollux (2013), Procyon (2014)
Length	81,2 meter
Width	13,3 meter
Depth	4,8 meter
Crew	17
Power	5100kW
Speed	16 knots
Engine	4x Caterpillar C32 Acert, 2x Caterpillar C18
Propulsion	Diesel-electric, 2x propeller, 2x bow thruster

Table 2.3: P-class vessel specifications (Loodswezen, 2014).

As can be seen in the table above, the ships are new. The ships are custom made and identical. This means that there are only three of these vessels in the world. Both these facts make it urgent to gather data for Loodswezen specific, as no other company (or historical data) can help us. The PSVs use the Diesel-Electric propulsion.

The usage of the Pilot Station Vessels is fairly equal, measured in operating time. As already introduced earlier, there are three PSVs. One is always at sea in Rijnmond (A), one is always at sea in Scheldemonden (B) and one is always in the port in Vlissingen (C). Vessel A returns to the port of Hoek van Holland (Berghaven) every five weeks to supply. This is usually on a Thursday between 08:00 and 14:00. Vessel B and C (both in Vlissingen) change position every week. Because the vessels need to be used equally, the Rotterdam vessel will change position with one of the Scheldemonden vessels twice a year.

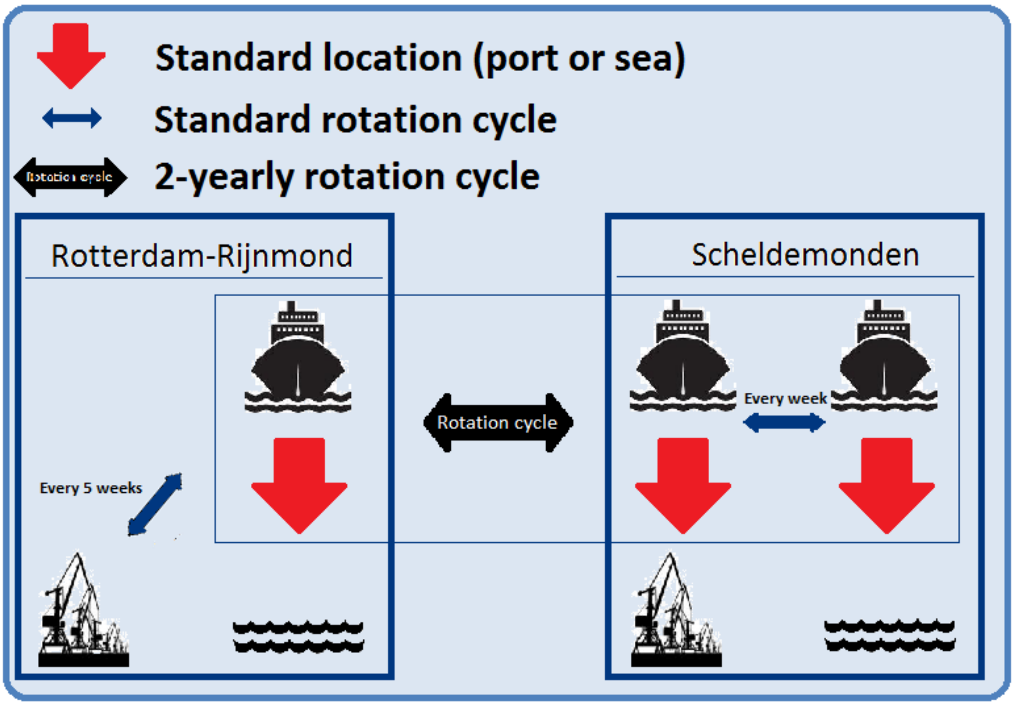

Figure 2.2: P-class deployment strategy.

Table 2.4. Shows the costs as a percentage of the total costs. As seen in the table the propulsion systems together with the generators are the main cost drivers.

System	Share of Costs	Work orders	Share of Work orders
General	23%	183	12%
Propulsion	1%	94	6%
Generators	30%	321	20%
Technical systems	4%	223	14%
Safety equipment	15%	64	4%
Navcom, IT, Alarm & Monitoring	6%	127	8%
Casco	6%	153	10%
Deck machinery	10%	257	16%
Ballast tanks	0%	15	1%
Consumables	1%	4	0%
Electronics	2%	48	3%
Climate	1%	68	4%
Engine Cooling	1%	17	1%
Other	0%	4	0%
Total	100%	1578	100%

Table 2.4: Maintenance costs for 2014 and the share of work orders for DE propulsion.

The orange parts above (propulsion and generators) are defined as the propulsion system of the P-class vessels. In Table 2.5, these parts are brought to a lower level (called ‘modules’ here). It is clear that the motors are the most important part of the propulsion system, with 81% of the costs and 58% of the work orders. In addition, the generators are important. Because Loodswezen has problems with the amount of downtime due to maintenance, it is interesting to see where the most work orders occur. This way, the focus in an improvement program can be on the modules that can give the biggest improvement. Unfortunately, there were not enough recorded failures to give a detailed view of the amount per module or even per system.

Module	Share of Costs	Work orders	Share of Work orders
General Propulsion	0%	1	0%
General Generators	0%	6	1%
Motors	81%	239	58%
Generators	15%	68	16%
Bow thruster	1%	13	3%
Axis	1%	6	1%
Main Electric Motor	0%	16	4%
Propeller	0%	17	4%
Steering	1%	35	8%
Emergency engine	0%	8	2%
Gears	1%	6	1%
Total	100%	415	100%

Table 2.5: Breakdown of actual propulsion maintenance costs of the DE propulsion system in 2014.

2.1.3 The Aquila tenders

Tenders are smaller vessels, used to transport pilots. The way these boats are used is very different from the PSVs. Instead of lying still at sea, these boats sail large distances all day, every day. The boats operate at a relatively high speed (PSVs do not) and in high swell and (most likely) wear faster than the PSVs. The aluminum waterjet driven Aquila vessels are built in Seattle. Their sisters, the L-class (Lynx, 2012, Lyra, 2013, Lacerta, 2014) are similar from the outside, but different from technical point of view. The L-class ships are built by Barkmeijer Shipyards, just like the PSVs.

Type	Tender
Aquila-1	Aquila (2010), Draco (2010), Orion (2010)
Length	22,9 meter
Width	6,8 meter
Depth	1,2 meter
Crew	17
Power	2x 970kW
Speed	28,5 knots
Engine	2x Hamilton 651 waterjet
Propulsion	Diesel (direct)

Table 2.6: Aquila class vessels specifications (Loodswezen, 2014).

This class uses a Diesel-Direct propulsion system with a (water) jet engine. Jet engines are safer to operate, especially for a company like Loodswezen. This is, because people cannot be injured by a propeller when falling in the water. These tenders are very different from the PSVs, both in the way they are used and the way they are driven.

The usage of the tenders differs heavily in both time and intensity. The reason for this has multiple dimensions. First of all, there are spare vessels. This means that not every vessel is constantly in use but just berthed waiting for service. Second, at different locations, there are different usage intensities. In appendix A, one can see that the difference between Den Helder (305 trips in 2013) and Rotterdam (almost 55.000 trips in 2013) is huge (factor 180). Of course, there are not 180 times more vessels in Rotterdam than there are in Den Helder. In fact, there is one tender in Den Helder while there are only four tenders in Rotterdam. This means that a specific tender in Rotterdam is involved in 45 times more pilot trips than in Den Helder.

The different locations also make the intensity of the trips different. One can imagine that the swell for instance is different everywhere (Wadden sea, Westerschelde or North Sea). Of course, the swell can change at a certain location too and not every vessel at one location necessarily has to be used an equal amount of time. Loodswezen also has vessels that are designed especially for icy conditions, they have a steel hull instead of aluminum and they are propeller driven (H-Class). Because these conditions occur mostly in the northern region, these vessels are usually located in Eemshaven and Harlingen. Both the ice in the water and the different vessel specifications make the wear for the ships in this region different.

The usage of the ships is tracked (engine running hours) in order to make sure they are as equal as possible, the future usage and maintenance is adjusted likewise. The vessels are not rotated between regions like the PSVs. There are a lot of changes in regions but this happens when a tender breaks-down and has to be temporarily replaced.

Table 2.7. Shows the costs as a percentage of the total costs. As seen in the table the propulsion systems together with the generators are the main cost drivers.

System	Share of Costs	Work orders	Share of Work orders
General	10%	16	2%
Propulsion	40%	299	33%
Generators	2%	75	8%
Technical systems	20%	57	6%
Safety equipment	3%	57	6%
Navcom, IT, Alarm & Monitoring	3%	114	13%
Casco	19%	131	14%
Deck machinery	1%	29	3%
Certification	0%	8	1%
Consumables	0%	2	0%
Electronics	2%	62	7%
Climate	1%	39	4%
Engine Cooling	0%	8	1%
Other	0%	7	1%
Total	100%	904	100%

Table 2.7: Actual maintenance costs for 2014 and the share of work orders for DD propulsion.

The numbers for the Aquila tenders are not very different from the P-class. For this class, only the system 'propulsion' is considered to be the propulsion system (as opposed to the P-class). 40% of money is spent on the propulsion system and 33% of the work orders are propulsion related. This makes it by far the most important part of the vessel.

Module	Share of Costs	Work orders	Share of Work orders
General	0%	3	1%
Axis	0%	7	2%
Motor	91%	205	69%
Waterjet	8%	51	17%
Gears	0%	33	11%
Total	100%	299	100%

Table 2.8:Breakdown of actual propulsion maintenance costs of the DD propulsion system in 2014.

In Table 2.8, one can see that the motor accounts for 91% of the costs and 69% of the work orders.

2.2 Spare parts

Spare part management is a subject that Loodswezen does not prioritize. Therefore, not a lot of information about spare parts is known. In this section, a short introduction of spare parts at Loodswezen is given.

2.2.1 Warehousing

The spare parts are stocked in many different locations. In Table 2.9, the situation concerning the different warehouses is shown. In Appendix B, the information on the physical locations can be found.

Type	Number	Location	Type of parts
Central warehouse	1	Hoek van Holland (Berghaven)	All
Local warehouse	5	Vlissingen, IJmuiden, Den Helder, Harlingen, Delfzijl	Basic[4]
Mobile warehouse (van)	5	Mobile	Basic On demand[5]
Floating warehouse (PSV)	3	Rijnmond (sea), Vlissingen (sea, port)	Basic Planned maintenance[6]
External warehouse (PON)	(1)	The Netherlands	Engines

Table 2.9: Warehouses (van Haperen, 2011).

In the central warehouse, nearly all spare parts that are stored by Loodswezen are present. The company is owner of every part in its warehouses. Because engines are big equipment, companies like PON (Caterpillar) store engines for Loodswezen. These are also owned by Loodswezen. There are more companies delivering these kinds of services, but for this project, only PON is relevant. In the local warehouses there is just basic inventory like windscreen wipers. More is not needed because the operators in the region don't perform other maintenance tasks than these basic ones. For more complicated maintenance, a mobile technician will go to the regions with a van. They have some basic spare parts in the bus and the components that are needed for a specific task. On the PSVs, there are also storages. The inventory there is meant to make sure the vessels are operational and all preventive maintenance for the time at sea can be performed. These are the largest warehouses after the central warehouse.

The inventories and flows of parts are monitored at all locations, except for the local warehouse. This means that Loodswezen formally does not know the amount of spare parts in the regional warehouses. The local warehouses contain only a couple of thousand Euro worth of materials like oil, windscreen wipers and lighting.

2.2.2 Criticality

Loodswezen has been subject of a spare parts research before. In that research, the criticality of the spare parts is investigated and divided into three categories. The three categories are based on the consequence of failure to operations and the lead time. In Table 2.10, the two indicators are explained. The consequence of failure and lead time combined give the final judgement A, B or C. How these two criteria lead to the final judgement can be seen in Table 2.11. For instance 'immediate downtime' (1) in combination with a short lead time (3) leads to severity B ('critical'). The longer the downtime and/or lead times, the more critical a component is.

[4] Anything that can be changed by a tender-crew, like oil and windscreen wipers.
[5] (Nearly) all components, but they are only loaded into the vans only when the components are needed in the region.
[6] As the (P-class) vessels are nearly always at sea, most planned maintenance is done over there. Components are moved to the ship when it arrives in the port to prevent the problem of having to move components larger distances.

Measure	Category	Conclusion
Consequence of failure	1	Immediate downtime
	2	Expected downtime (< 7 days)
	3	No downtime
Lead time	1	≥ 8 days
	2	4-8 days
	3	<4 days

Table 2.10: Criticality of spare parts (van Haperen, 2011).

	Lead time T cat. 1	Lead time T cat. 2	Lead time T cat. 1
Consequence cat. 1	Very critical	Critical	Critical
Consequence cat. 2	Critical	Critical	Non-critical
Consequence cat. 3	Critical	Non-critical	Non-critical

Table 2.11: Severity matrix for spare parts.

In Table 2.11, the judgement of a component can be seen. If for instance the consequence of failure from Table 2.10 falls in category 2 and the lead time in category 1, the component will be "critical". Approximately 41% of the components is very critical, 44% is critical and 14% is non-critical.
It can be seen that a large amount of the spare parts is very critical. Only 14% of all parts are not critical at all, suggesting that spare part management is very important in order to increase the operational availability at the company. Obviously a vessel cannot be repaired if the needed spare part is not available. Only new parts are assessed considering the criticality. The old parts are stocked the way they were before, however, this will also change in the future.

Loodswezen has information on the reliability of their suppliers in terms of punctuality and whether it is the right part or not. What can be seen is that deliveries are nearly always right (99,99%), but is just 38% of the instances on time.

2.2.3 Key numbers

In the table below, one can see an overview of the different items in stock at Loodswezen. There were 2933 items with a stock movement in the period from 06-2000 to 03-2013. This means that 2933 unique items have been bought or used in that period. From 09-2009 to 11-2014, 2797 unique items were ordered with a total value of € 28.979.831. This was 4,3 million liter of fuel, oil and lubricants. The order produced an inflow of 83.838 pieces in five years.

Type	Replenishment	Number	share
V1	Reorder level	1404	48%
ND	On demand manual	767	26%
PD	On demand automatic	36	1%
Other	Unknown	726	25%
Total	-	2933	100%

Table 2.12: Overview stock movements per order strategy.

As ND and PD components are ordered on demand, only V1 components are present in the warehouse. There are 3990 unique items in stock with a value of €2,4 million. The holding costs are estimated to be around € 364.000. An improvement plan that has been performed that takes into account item criticality. Loodswezen is planning to put the new method for critical spare parts in operation in the future. This would lead to a high service level for the most critical (category 1) components of over 99,6% and a service level of around 50% for less critical (category 2) components. The service level is defined as the percentage of demand that can be fulfilled from stock. The least critical components (category 3) are not in stock anymore and therefore have a service level of 0%. The new method would lead to a decrease in holding costs of around € 37.000 (van Haperen, 2011).

The current service level of all stocked components is approximately 92% and will probably decrease in the new system. However, if the system works properly, the performance of the maintenance (for example the duration of the maintenance and the total down time of a vessel) will not change or improve.

2.3 Maintenance

In this chapter, the current maintenance policy of Loodswezen is investigated in detail. First an overall view of the maintenance is presented. Then the two types of maintenance are discussed: corrective or unplanned maintenance and preventive or planned maintenance. Corrective maintenance is not subject to choices, if a vessel breaks down, you need to repair. Preventive maintenance on the contrary, does introduce choices. The choice here is when to do maintenance and on which components. Depending on these two factors, there are different maintenance rules. These rules are, in order of sophistication: time based, usage based, usage severity based, load based and condition based maintenance.
In the table below, an overview of the financial details on maintenance is given (actual performance), numbers x 1000.

Year	2010	2011	2012	2013	2014
Turnover NLBV	€ 182.367	€188.241	€190.485	€199.139	€193.738
Cost of Maintenance (CoM)	€ 5.064	€ 5.225	€ 5.953	€ 5.761	€ 6.197
% of turnover	2,8%	2,8%	3,1%	2,9%	3,2%

Table 2.13: Spending on maintenance x1000 Euro.

The geographical spread of the company makes it essential to think about how to arrange maintenance. The costs of moving a tender to another port can costs more than € 800 per hour (Loodswezen Vlootbeheer, 2014), depending on the travelling time (primarily because of overtime of travelling expenses of the crew). Therefore, the company needs to keep travelling distances as small as possible and perform maintenance as close to the original port as possible. To illustrate this, travelling from Hoek van Holland to the closest port (IJmuiden, 54 miles) takes three hours. As this is always a two-way transport, this means this activity will cost € 4800. This is the shortest route; travelling to for instance Eemshaven (from Hoek van Holland) can easily exceed € 16.000. It is not hard to calculate that the yearly costs, only from moving vessels, can easily get high. The exact numbers however are not available as the length of these trips is not accurately documented. On average, there are around 12 large trips (to a shipyard, region changes and testing) per month. It is known that a change of regions will cost around 1300 man hours a year and that there are two people on board of a vessel. This 1300 however is not the actual travel time but the time that personnel are unavailable due to a region change so no calculations can be performed with this number. A conservative estimation of the cost of non-operational movements of vessels would be around € 576.000 a year (based on average trip of 5 hours, 12 per month).

For this reason, Loodswezen does the maintenance jobs in the regions as much as possible. There are roughly three different ways maintenance is performed. The extent to which each of the types is performed differs greatly between PSVs and tenders.

1. First of all, maintenance can be done by the crew. For the *Aquila Class* (and other tenders), only basic maintenance is done by the crew, like changing oil and screen wipers. If performed at all, this type of maintenance is performed in the port. On the *PSVs*, this is almost the opposite. These vessels, which are large and have a wide range of spare parts on board and generally have a crew with a higher education level. As the crew does this kind of

maintenance themselves and offshore, it can be done fast and will have little or no effect on operations.
2. If the crew is not able to solve the problem, either because of a lack of knowledge or the lack of spare parts, a mobile technician is sent from Hoek van Holland with the right tools, knowledge and parts. Certain parts are covered by service contracts (e.g. radar systems) or might need activities that cannot be performed by the mobile technician. In these cases the service provider is sent.
3. When the problems still are not solved, the vessel is transported to a place where it can be repaired. As Loodswezen does not have a dock, obviously, maintenance requiring docking facilities needs to be done elsewhere.

Below, an *estimation* of the number of work orders being performed within each of the three types of doing maintenance. The numbers are based on the estimation of the workshop planner.

Type	P-class	Aquila-class
By crew (1)	80%	10%
By mobile technician (2)	10%	80%
By external party (3)	10%	10%

Table 2.14: Estimation of type of maintenance per vessel.

Each of the three basic options can be either a corrective or preventive action.

The goal of Loodswezen was to increase the percentage preventive maintenance from 18% in 2011 to 70% in 2014 (van Haperen, 2011). This is measured in the time that the performance of an order takes. There are two problems with this that need introduction. Obviously, in order to determine the actual percentages, the durations of the maintenance orders have to be documented in a reliable way. This fact reveals the first issue: the durations are not always documented, let alone reliably. The second issue is that some preventive maintenance tasks only occur once every couple of years (max. five years). This means that in order to measure the amount of preventive maintenance accurately, there is a need to look at data from the past five years. This however, is not possible due to a change in the allocation of orders and costs: they used to be (<2013) allocated on a location and are now allocated to vessels. The amount of preventive maintenance is measured both in work orders and in time to get around the problem with the actual durations of orders that are not documented.

The most logical way to determine the preventive and corrective maintenance efforts of the company would be to use the distinction in eight different order types (ZM01 to ZM08) that Loodswezen uses. Each of these order types *should* represent either corrective or preventive maintenance. However in reality, not all eight types are used and most are not used correctly. For this reason a lot of corrective maintenance orders are called "preventive" by this system and vice versa.

Therefore, preventive maintenance orders are defined as orders that have a PM maintenance plan. Corrective maintenance orders are the ones that do not have a PM maintenance plan.

	Total fleet	Tenders + SWATH	PSV	Aquila
% PM order	42%	35%	50%	28%
% CM orders	58%	65%	50%	72%
% PM costs	10%	9%	22%	16%
% CM costs	90%	91%	78%	84%

Table 2.15: Maintenance in numbers.

In the table above it can be seen Loodswezen-wide, 42% of the work-orders were a preventive maintenance order. For the PSVs, this is somewhat higher (50%), while the Aquila is below the average (28%). In terms of costs, preventive maintenance just takes up 10% of the maintenance costs. The absolute value of the costs per order is not particularly useful as this depends on for instance the definition of preventive maintenance, the definition of work orders and the type of asset. The costs however, are useful relative to the other costs. Corrective maintenance is at least two times more expensive than preventive maintenance. At the same time, the maintenance at the PSVs seems relatively cheap. A reason for this could be the fact that these vessels are very new and their maintenance is still relatively simple. The Aquila class, preventive maintenance seems to be relatively expensive.

Preventive maintenance is important and becomes more important for Loodswezen. Currently, Loodswezen performs time based, usage based and condition based maintenance. Unfortunately, the latter is not documented separately (this means it is considered either TBM or UBM). Because CBM at Loodswezen roughly consists of taking oil samples and some visual checks, the share of CBM in the total preventive maintenance would be small.

In the table below, the division between TBM and UBM can be seen. It seems like the division is close to equal. It is noteworthy that usage based maintenance is more expensive than time based maintenance. This most likely has to do with the fact that for instance certifications are time based, one can imagine this being somewhat cheaper than changing some rotating component that is built-in.

	Time based	Usage based
PM-plans	43%	57%
PM-orders	56%	44%
PM-costs	27%	73%

Table 2.16: Preventive maintenance in numbers.

2.4 Availability of information

Overall in the company, a lot of data is available. The data however, is not always documented and is barely documented properly. The quality of the data that is available is generally low. A good example of this is the fault messages and their corresponding work orders. The starting time is documented very precise. However the end time is not documented. This means that a vessel can be artificially unavailable. There are FMECAs available on all vessel types and are updated when new equipment is installed on the vessels. Failure modes are known in detail (component level). However, information on failure mechanisms is not available. Root cause analysis is not performed but an important step is being performed at this moment: spending will be tracked in the future be to 'the third level' (one level lower than the current situation). This will make diagnosis of troublesome parts easier.

The most important factor that plays a role in the availability of information is the lack of failure data. This problem seems persistent in the entire maritime sector. There are a couple of reasons for this. Due to the fact that the number of comparable assets are usually small or even just one (Loodswezen has a fleet of just three Aquila class and three P-class vessels) less comparable failures will occur than with an installed base of hundreds (like airlines). In addition, most maritime companies will not run (critical) components to failure, as this will have a huge effect on safety and ability to operate.

The failure data that does exist are not of the desired quality and has in general two large problems. The first problem is that components are not numbered individually. This means that the lifetime of these components cannot be estimated. This is, because if it is not known which component exactly has failed, it is impossible to calculate how long it has been running properly. The second problem is that failures are reported on a certain location in the vessel where they seem to occur. For instance, when a warning light turns on it indicates there is a problem somewhere in the vessel. However, this might as well be an error in the sensor, the light, the wiring or something else in the vessel that causes the problem at the indicated place. In order to make sure that the failure data of the right components are used, a lot of technological knowledge and manual analysis is needed to prevent mixing up the failed components.

The number of work orders connected for a failure is presented in Table 2.17. There were over 17.000 work orders since 2012 (the start of the new system). The orders shown in the table give an overview of the corrective maintenance orders with tags ZM01, ZM02, ZM04. Because there are corrective maintenance orders *without* these tags and there are preventive maintenance orders *with* these tags the table below can only be used as indication. All numbers are rounded to the nearest equivalent of 50.

Corrective orders	Work orders
Total	8600
Aquila	1500
Aquila propulsion	400
Aquila motors	300
P-Class	1350
P-Class propulsion	250
P-Class motors	150

Table 2.17: Number of work orders.

It seems like there is a lot of data and it is. However, from the for instance 300 work orders connected to the Aquila motors, only a very small fraction is indeed a failure (mostly the work orders are problems with settings or sensors). In addition, a motor has a lot of components. To give an example of this, there are just 15 work orders for the turbo chargers on all six engines of the Aquila class and none of them was a failure of the actual turbo but indicated leakages near the component.

2.5 Conclusions

Loodswezen has a turnover over around € 200 million, from which just a small amount is used for maintenance (around 3%). The maintenance of the vessels does have a lot of implications for the company. As the company's main task is to provide the pilots with services for which they need their vessels, maintenance is very important. There is not a lot of historical data available to be able to plan the preventive maintenance. This is a problem as the company currently spends 42% of their work orders and 10% of their money on preventive maintenance and does this by generally following the guidelines from suppliers.

The two vessel types under investigation are the Aquila Class (tender) and the P-Class (PSV). The two vessels have respectively Diesel-direct and Diesel-electric propulsion. Both are very new and unique in the world, Loodswezen has three of both of them. The tenders are used to transport pilots from the port to the PSVs and vice versa. The PSVs are permanently located at sea.

3. What are in general suitable methods to design a maintenance policy?

This chapter can be viewed as a literature review and research demarcation. There are different steps in determining the right maintenance program. The structure of this chapter is as follows. First, a general introduction is presented in the form of knowledge of maintenance concepts. Then the maritime sector and the chronic lack of failure data are elaborated on. This will give insight in the chosen models and methods. Then the theory behind corrective and all kinds of preventive maintenance is presented. After this, replacement strategies and different ways to model failure behavior are discussed. The chapter ends with the explanation of the proposed model to model the failure behavior.

3.1 The maintenance concept

There is a lot of literature written about the type of problems Loodswezen encounters. The emphasis of most research is on the determination of optimal preventive maintenance intervals. While this is the primary goal of this research, some important assumptions need to be made to come to this point. One can think of the question: which components are going to be correctively maintained and which preventively?

These kinds of questions are derived from a so-called maintenance concept. A maintenance concept reflects the vision on what maintenance should be like and needs of the company in terms of budget, target availability or criticality of systems (Waeyenbergh & Pintelon, 2002).

With the maintenance concept, it can be understood why the company decided to perform preventive maintenance anyway. This is of great importance for this research, because a good balance between corrective and preventive maintenance begins with the understanding of why these kinds of maintenance is performed anyway. In addition, the translation from the methods described in this research to a general way of doing maintenance, is highly depending on this. In fact, the concept is closely related to the set of maintenance rules (Gits, 1992).

Most companies want an acceptable availability of their assets for the lowest price. There are also companies, like airlines, that need a certain availability for nearly any price as unavailability during operations usually leads to disaster. Obviously, airlines care about their operational availability as the aircraft don't gain revenue while not being operated. However in these systems, the owner tries to prevent failure during operations while events happening on the ground are less important: the interval reliability is optimized (Dijkhuizen & Heijden, 1999).

Loodswezen however is not interested in cost reduction, nor in aviation-like safety measures. Because the company never makes any profit or loss, they just want the costs to remain stable. While Loodswezen obviously doesn't want failures during operations like the airline industry, their emphasis is on the availability of the vessels to operate. The company wants the highest operational availability with the current costs.

This elaboration is vital as history has taught us that there is no general maintenance concept for all companies. Instead, we need to learn from literature and design a method to meet our demands (Waeyenbergh & Pintelon, 2002). The exploration of the (optimization) problem above makes clear how other methods can be used to design a suitable approach for the individual company.
RCM was introduced for the airline industry. In RCM, the three basic questions are (1) what, how often and who should do routine maintenance? (2) which components to redesign (3) in which cases is corrective maintenance performed? . This concept is known for reducing preventive maintenance efforts while maintaining or improving (technical) availability (Rausand, 1998). The current policy resembles (Maker's manual) RCM best. The concept uses FMEAs and failure consequence evaluation

techniques to determine the right maintenance tasks (Hipkin & Cock, 2000). This report will go into detail of question one (1) and three (3), concerning planned and unplanned maintenance. Redesigning components is not an issue at this point.

3.2 Maritime sector and data

The MaSeLMa project, where Loodswezen acts as an asset owner, is about maritime assets. This indicates that the 'problems' that Loodswezen has are not unique and are actually pretty common in the sector. It is useful to understand why the maritime sector has these problems, in order to determine from what could be done to solve these problems.

In the past decades, smarter maintenance policies have been introduced in many capital intensive industries like the aviation industry and the semi-conductor business. The implementation of relatively expensive RCM concept and CBM policies have had huge successes in these industries as unexpected failures usually lead to high costs in these industries. Despite the fact that the maritime sector certainly is capital intensive (buying and maintaining the assets worldwide), it is not common for these companies to implement these strategies. Remarkable is that in certain cases (e.g. van Oord), CBM was implemented decades ago. The natural question in this case is why other maritime companies have such difficulties implementing good maintenance policies.

There are at least eleven reasons for this (Mokashi, Wang, & Vemar, 2002) from which the most important is the lack of data (1). Data is usually gathered easily from a large installed base. A good example of this is the airline industry. With many aircraft of the same type, airlines have many data. In addition, the installed base worldwide can be hundreds or even thousands. Maritime companies build vessels especially for a certain project. One can think of dredging companies that build custom vessels for a certain job at a certain depth, in a certain climate and country. In statistics, not much can be done with the very few failure data of vessels that are custom and used only a couple of years. With the low installed base of P-class (three vessels) and Aquila-class (also three vessels) and the fact that they are relatively new, Loodswezen also has these problems. The fact that suppliers of maritime equipment usually are not eager to share FMECAs and underlying data makes it even harder to improve the situation (2). In comparison, the airline industry also has this problem, although government safety regulations force better supply chain integration and more extensive testing as opposed to the maritime sector.

Other reasons that advanced maintenance in the maritime sector is difficult are the lack of training of shipboard personnel (3), overburdened personnel (4), changes in crew (5), changing operating environments (6), mandatory compliance with supplier recommendations during the guarantee period (7), additional requirements from maritime regulatory bodies (8) and the unknown basic condition of equipment (9). Loodswezen also has to deal with these problems to a certain extent. It might be an opportunity for the company that it has no problems with geographical dispersion (10) and has, in contrary to other maritime companies, access to nearly fully redundant systems (11) (Mokashi, Wang, & Vemar, 2002).

3.3 Corrective maintenance

Sometimes, it makes sense to just let a part fail and perform corrective maintenance. There are in general three aspects to take into account in order to determine whether to do corrective maintenance or not.

One condition is that the failure rate is non-increasing over time (i.e. the probability of a components failing becomes smaller or remains the same). These kinds of components should *always* be maintained correctively. A good example of this is most electronics. Most electronic components will either fail early on life or survive for a very long time. Preventive maintenance (in this case replacement) does not make sense here, because the probability of failure of a new electronic component will be the same or higher than of the old one. This can cause bad performance. One can also imagine that replacing components with a constant failure rate does not improve nor worsen the situation and will ‘only’ be a waste of time and money. Any component that does not meet this requirement is maintained correctively whether it is critical or not.

However, if the failure rate is increasing, sometimes there is still chosen for corrective maintenance. This can only be the case if a component is non-critical. One can imagine that a light bulb (non-critical) can just fail, while the cooling of a nuclear power plant (critical) needs to work. But even when a component has an increasing failure rate and is critical, there might be reasons to perform corrective maintenance.

The most important one is costs. Costs can be measured in r in case of Loodswezen in terms of the associated downtime (Gertsbakh, 2000). One has to consider the possibility of preventive maintenance being more expensive than corrective maintenance. If this happens, it does not make sense to do preventive maintenance. For most companies the demand is that the cost of preventive maintenance is *way lower* than the cost of corrective maintenance. For Loodswezen it would be a good assumption to say that the preventive maintenance should *at least be cheaper* than corrective maintenance. This is true because preventive maintenance is usually done more often in the life of a component than corrective maintenance. If preventive maintenance is not cheaper than corrective maintenance, this would lead to way higher costs.
Although cost-related considerations play an important role here, there are more reasons to choose for this strategy (see 3.8.5). Any (preventive) maintenance can cause failures, leading to a lower availability.

3.4 Preventive maintenance

Preventive maintenance is the act of maintaining (replacing, upgrading, painting etc.) before they fail, in order to avoid the unexpected character of failure. The previous part about corrective maintenance immediately implicates that preventive maintenance is performed when the probability of failure increases over time, the component is critical and the costs of preventive maintenance are lower than of corrective maintenance. This seems like there are many requirements, but as Loodswezen has set a high reliability goal, many components are critical.

The optimal maintenance interval is the interval where a component is replaced or maintained just before it fails. Obviously, it is not known when failure will occur. There are roughly five methods to estimate when this will happen. They are introduced below and are ascending in terms of complexity to perform and in terms of performance (Tinga, 2010). This practically means that you pay your good performance with a high complexity. Or in other words, you pay your quality with money.

1. **Time based maintenance.** The most common system is a static system: (calendar) time based maintenance. Usually the OEM makes an assumption on the expected number of operating hours and the expected power settings. From this, a time interval is set in which the maintenance will be done, all the company has to do is watch the calendar. Components that are not used in this time interval are replaced or maintained anyway. In addition, most failure modes are not time dependent (e.g. some corrosion types) but usage dependent (e.g. anything that wears).

2. **Usage based maintenance.** To tackle the problem of components not being time dependent, a dynamic system can be implemented. The usage, at Loodswezen measured in operating hours, gives us a better picture of the situation. However, to determine these time intervals,

one still needs to know the intensity of operations. An engine running at full power will degrade faster than an idling engine.

3. **Usage severity based maintenance.** The latter is tackled by a more sophisticated system: USBM. For this, a lot more information is needed. First of all the data on how long a vessel has been operated on each severity level. Second, the effect of these settings on the degradation process has to be modelled. A severity level could be 'low', 'medium' or 'high' power settings. How this should be defined is another problem. Because the severity is the measurement of input, this still says nothing about the actual output. Despite the increased difficulty of measuring, a big uncertainty remains.

4. **Load based maintenance.** LBM solves this uncertainty. By measuring the actual loads (output) on a certain component, the load on a certain part can be estimated. Measuring is way harder than with USBM as it is not possible to measure this via software and settings (input) but has to be done via hardware only (output). An example of LBM is the measurement of temperature on a component. The upside of this method is that is delivers accurate information on degradation and that there are models for many different failures available. Yet still a model has to be used to determine the degradation.

All the methods introduced above, from which TBM and UBM are the best known offer an insight in the estimated lifetime. However, in order to increase the maintainability it is needed to know when a certain component is bound to fail. For this prognostics is needed (Tinga, 2010). Finally, there is a method that eliminates the risk of computing the state of a system by a certain indicator.

5. **Condition based maintenance.** CBM practically is the monitoring and analyzing of the actual state of certain components in order to know with the least possible uncertainty when a component is bound to fail. Although CBM is used to perform preventive maintenance, the method is considered to be of a different magnitude than other maintenance types.

There is a wide range in which CBM can be performed in the sense that it can be performed with high and low sample rates, with sensors or visual. For instance, checking the paint of a vessel is a visual, cheap and fast way of using CBM. This type of inspection is incredibly useful but as maintenance is not time based, it will be harder to plan it and therefore more expensive. One can imagine that doing maintenance every month is easier to plan than doing maintenance at more random times. Especially clustering of maintenance tasks becomes more difficult. CBM can go as far as monitoring a certain component practically continuously. This way the uncertainty of what happens during the inspection intervals is diminished. These systems however, are usually very expensive, making it suitable only for the most critical components.

3.5 Replacement strategies

There are in general two replacement strategies: block replacement (multiple components) and age replacement (single component or series of single components). In relation to section 3.4, one may note that for instance "age" (in age replacement) can be measured with the unit of time being based on calendar time (TBM) or operating hours (UBM) without the interruption of physical models (Gertsbakh, 2000). One can imagine that in order to determine the critical age in USBM or LBM, one needs to know more what severity or load the system can handle. For this, physical models are necessary.

In age replacement, a component is replaced when it reaches age T or upon failure. This means that if for example a component is 100 days old, it will be replaced. If the component is on failure after 80 days, the next replacement therefore will be 100 days after failure.
In block replacement, all units (in the block) will be replaced at time T, whether a component has been replaced or not. In a clever system, there is a need to make a decision on failure to either replace only the failed component or all units in the block in order to reduce the waste of the system. In general, age replacement will lead to slightly better results in terms of costs (Gertsbakh, 2000). This can be explained by the fact that in block replacement, sometimes fairly new components are changed. Block replacement however should lead to a somewhat lower downtime as maintenance is done in a whole system.

In the example above, the age T is defined as the uptime plus downtime (calendar time), which means it would correspond to 'time based maintenance' (calendars don't stop when the vessel is out of service). This indicated time can also be the operational time only (usage based maintenance), operating hours do of course stop when a vessel is out of service.

The replacement strategies above assume that maintenance can be done at all times. This is not always realistic and can be highly inconvenient. One can imagine that equipment that runs continuously never leaves an opportunity for maintenance. Therefore, once an opportunity does occur, as much maintenance as possible should be done. A maintenance strategy like this is called opportunity based maintenance. In this strategy, less time and money is spent on the maintenance activity itself but money is 'wasted' when component are changed too early. It is therefore important to determine what an opportunity is. Opportunity based maintenance can be seen as an extension of either block or age replacement: the policies remain the same, but now with the restriction that preventive maintenance is performed when the opportunity occurs (Dekker & Rijn, 2003). An opportunity-based age replacement policy can best be used in combination with exponential (i.e. random) times between failures (Dekker & Dijkstra, 1992).

Each of these models assumes either minimal repair, complete renewal or partial renewal. Minimal repair means that after the repair, the machine is 'as bad as old' and in the complete renewal the machine will be 'as good as new'. Obviously, the truth will be somewhere in the middle, that is why models are developed that consider partial renewal. It is important to note that a component is not always 'replaced' as the name of a 'replacement' strategy suggests, the important distinction is whether or not the result is a good as new, as bad as old or something in between. In addition, inspections can be viewed as a class of its own as inspections do not improve the systems life time in any way but have to be used in order to detect 'hidden failures' and the state of the system.

To decide whether or not to replace (service) a component or even a whole block, one needs to know when a component will fail. This can be done by using different kind of models, which will be discussed in the next section.

3.6 Models & Uncertainty

In this section, a short introduction on the different models to model lifetimes of components is given and a suitable model variant is chosen. The influence of uncertainty on the model is discussed with a method to overcome this.

3.6.1 Models

There are two kinds of models to estimate the degradation of components: physical models and mathematical models.

Physical models are models that estimate the state of a component by the failure mechanism of the component. There are models to model for instance fatigue, creep, corrosion and wear. Physical models are relatively new in the sense that not many practical applications have been examined. There has however been much practical research on this topic and these models cannot be used at the moment. A very interesting benefit of these methods however, is that there is no need to collect huge amounts of (failure) data. This is an advantage because the use of this data is only useful if the usage of an asset will be the same in the future and of course because data does not always exist in the maritime sector. The clear disadvantage of the physical models is that a suitable model might not exist (yet), which makes it impossible to evaluate a complete system. The accuracy of these models is better than of mathematical models and evolutionary models, but is also more expensive to implement. A special type of physical models are so-called evolutionary or trending models. These models are used to extrapolate a measured condition into the future. (Tinga, 2010)

The second type, mathematical models, have the broadest (practical) applications. The models primarily use failure data in order to describe the failure behavior of components. Because these models can be used in practice way more easily than the previous two described models, this method is used the most. It is obvious that without failure data, this strategy becomes way more difficult. Another disadvantage is the limited prognostic capability, as one looks into the history to predict the future. The future usage for example, might be different. There are a lot of ways to use this method in order to get a lifetime distribution of components. Because mathematical models are the easiest to implement in practice, it is decided to use a mathematical model. In the next paragraph, some models are presented to solve the specific problem of a lack of failure data.

3.6.2 Uncertainty

When modeling failure behavior, limited historical data, bad quality data or missing data cause uncertainty in the model. There are two ways of uncertainty: model and parameter uncertainty. Model uncertainty means that it is unclear what model to use to model the lifetime of a component. Parameter uncertainty means that the parameters in the model are not known (Jonge, Klingenberg, Teunter, & Tinga, 2015).

Typically the Weibull distribution is assumed as this distribution can model most of the components' lifetimes (this will be used in this report). The Weibull distribution is able to model early wear-out, aging and end-of-life failures (bathtub curve). Although this assumption, like all assumptions, is slightly restrictive, an estimated 85%-95% of all 'life data' can be modeled with a Weibull probability plot (barringer1.com, 2010). As data at Loodswezen is mostly absent and of doubtful quality, it would make sense to make this assumption some grip and this applies to many maritime companies. Recently, methods have been developed to cover this model uncertainty with a so-called Bayesian approach (Jonge, Klingenberg, Teunter, & Tinga, 2015). This topic is getting increasing attention from scientists because development cycles are speeding up in many industries where fast new product introduction became a factor to compete on. Therefore, the scarcity of useful data is increasing fast. The Bayesian approach is suitable when knowledge of the state is incomplete or unknown or when the system behaves randomly (Jones, Jenkinson, Yang, & Wang, 2010).

But even if a certain model is assumed, there is still parameter uncertainty. For the Weibull distribution, these parameters usually consist of a shape (often called β or k) and a scale parameter (often called α, λ or η). In other words, β determines whether or not the failure rate is increasing. A β larger than one indicates an increasing failure rate. This is important because this can be connected to RCM. In an RCM approach, only components with a β larger than one will be preventively maintained. Sometimes a third parameter is considered in the Weibull distribution: the location parameter (Υ). This parameter moves the Weibull function in time and is usually the time of first failure or just set to 0.

A lot of effort is done in the literature to be able to estimate parameters. There are several methods to determine the value of parameters. Two of the most common methods that are able to deal with a small amount of data are covered below. A two-parameter Weibull function with parameters α and β is assumed, more about this in section 3.7. The most common two methods to estimate these parameters while having very few data are 'bootstrapping' and 'Bayesian analysis'. Bootstrapping is a method in which samples are created, using existing data. It is promising in combination with very few data. In order to be able to do this, at least some data is needed. However, at Loodswezen, most components do not have any failure data at all or very little (less than five). This method can therefore only be used at the company for some (single) components and it not suitable to improve the current maintenance schedule.

The use of Bayesian models, in which can be modeled by the use of expert judgement, becomes the only viable option to deal with the lack of failure data. Not only model uncertainty can be dealt with but parameter uncertainty too. In the Bayesian method, expert judgment and data can complement each other. Once more data comes available, the distribution can be updated (posterior distribution). This method can evolve when more data becomes available. The strength of this method is that components that almost never fail can also be part of the analysis.

3.7 The Weibull function

As already stated, it is assumed that the failure rate of components can be estimated by a two-parameter Weibull function scale parameter α and shape parameter β. When a component has a failure-free period, the three-parameter Weibull model is assumed, which includes the time parameter (often called γ). With this parameter, the distribution can be moved in time. This parameter is used when there is a 'failure free period' (a period in which no failures occur). In this report it is assumed that the failure free period is zero (i.e. there is no failure free period). This is assumed because adding another parameter complicates the solution and this is not a luxury Loodswezen can afford with so few data. In addition, most components will indeed not have a failure free period. The Weibull distribution can be used with 'few data' and with 'censored' data (e.g. data that is broken because of preventive maintenance).

The basic formula is the probability density function (PDF) which is indicated by f(t) with t being the variable time. As the name 'scale parameter' (α) suggests, this parameter determines the scale of the Weibull model. One can think of this parameter as a measure for the MTBF (but it is *not* the same). As can also be seen in the formulas below, the β determines the shape of the model. The β is what it is all about in this analysis. A value lower than 1 indicates a decreasing failure rate and higher than 1 indicates an increasing failure rate.

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \qquad \text{(Eq. 1)}$$

Then there is the cumulative distribution function (CDF), which is indicated by F(t). The capital F means as much as the primitive of f(t). This function shows the probability that a component has failed before time t.

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \qquad \text{(Eq. 2)}$$

The complement of Eq. 2 is the survival function, which is indicated by $\bar{F}(t)$. This function shows the probability that a component has survived until time t. Sometimes this function is also called R(t).

$$\bar{F}(t) = 1 - F(t) \qquad \text{(Eq. 3)}$$

And finally, the formula for the failure rate function. This function indicates the "*proneness to failure at time t".* This is the function that all the analysis is about, as this function visualizes the failure behavior of a component.

$$\lambda(t) = \frac{f(t)}{\bar{F}(t)} = \frac{\beta}{\alpha}(\frac{t}{\alpha})^{\beta-1} \qquad \text{(Eq. 4)}$$

The parameters α and β can be calculated by using a linear regression (least squares method) if there is enough failure data available. If that is not the case, an expert opinion based Bayesian model can be used.

3.8 Bayesian model & Expert opinion

The Bayesian method is a statistical method that is able to transform expert opinion (prior) to statistical parameters. Usually more objective information is added to the prior, in order to produce the more reliable posterior. For this reason, Bayesian methods are incredibly useful in situations where there is both subjective (experts) and objective (data) is available (Li, Yuan, Peng, Liu, & Huang, 2011).

In the case of the Weibull distribution, the statistical parameters of interest are α and β. Some methods in literature propose direct estimation of these parameters, which is, even for an experienced statistician, very hard. This is true especially because the β parameter of the Weibull distribution is not very transparent to estimate and is very sensitive (a β of 1,20 can make a big difference compared a β of 1,25 in terms of optimal maintenance intervals). Therefore, it is needed to ask experts for information they *can* give and translate it to the needed parameters. For this, a Bayesian analysis can be used.

A lot of different data can be gathered from experts in order to come up with the needed parameters. As stated above, asking for just an α and a β does not make sense. The experts need to be asked observable data (Bousquet, 2010). This could for instance be the actual lifetimes of a component. Such an experiment would lead to obvious problems like where to begin and to where to stop; do we add extreme values like instant failures? In addition, the FMECA has proven that getting a proper MTBF is already very difficult, let alone coming up with multiple failure times.

Fortunately, more clever and systematic methods exist. For instance, there are methods available where experts are asked to choose the most likely of different scenarios (Li, Yuan, Peng, Liu, & Huang, 2011). These methods are limited in the sense that this would require a lot of knowledge beforehand (in order to be able to produce sensible scenarios). In addition, working this way will bias the expert's judgements as the most likely scenarios are assessed.

Therefore, in this research, a method is proposed where not a lot pre-knowledge is needed and that takes into account subjective data that can be delivered by experts without a statistical background (Kaminskiy & Krivtsov, 2005); (Yin, Mu, & Zhao, 2009).

The proposed method elicits information from experts in the form of estimating the probability that a components failure before a certain time. In addition, the experts are asked for an interval in which they think their elicited point fall (which will be used to estimate the variability of their judgement). Each of these points is transformed and then modeled by using the beta distribution. The Beta distribution is used here because it is bounded between 0 and 1 which makes it suitable to estimate probabilities, which is what is actually being done when asking for probabilities at different points in time. With these different points, random samples will be drawn (by Monte Carlo Simulation) that are used to compute the Weibull parameters. Later this can also be updated with real failure data.

This section starts with an explanation of the proposed method (3.8.1). The method introduces some challenges:

- How to model uncertainty (variation) in the obtained expert data (3.8.2).
- How to connect different opinions (3.8.3).
- How to connect opinions to real failure data (3.8.4).

This section ends with a short guideline to perform the elicitation process itself (3.8.5).

3.8.1 The proposed analysis

The proposed (Bayesian) analysis is based on the expert elicitation and updating of the α and β parameters for the *Weibull distribution*. Experts are asked for the percentage of failures that would occur before a certain time (more about this process in 3.8.5). These points can be seen as an *empirical distribution,* this means that somehow, these gathered point have to be converted to parameters of the *Weibull distribution*. Once the points have been gathered, the variation is modeled (3.8.2) and all different opinions are merged to one percentage for each time t_k (3.8.3), the empirical data can be transformed to Weibull parameters that can be used to optimize maintenance intervals.

In order to get from the elicited points to the Weibull parameters, each of the elicited points is transformed to parameters of the Beta distribution and then simulated by a Monte Carlo Simulation. In Table 3.1, the used variables are defined.

Variable	Meaning
k	Index for the k-th point in time (*exposure*)
i	Index for the i simulation run of N runs
t_k	Calendar time in days at exposure k
$\hat{\mathbf{F}}(t_k)$	Elicited % failures until time t_k
$F_i(t_k)$	Simulated % failures until time t_k at run i
$F_i^*(t_k)$	Transformation[7] of $F_i(t_k)$ at run i
$\hat{\boldsymbol{\sigma}}(t_k)$	Elicited standard deviation of the elicited point at t_k
α_i	Scale parameter of the Weibull distribution at run i
β_i	Shape parameter of the Weibull distribution at run i
$c(t_k)$	Parameter of the Beta distribution for exposure t_k
$d(t_k)$	Parameter of the Beta distribution for exposure t_k
N	Number of Monte Carlo Simulation runs
$r(t_k)$	Number of failures observed until time t_k
S	Total number of failures observed until today
$c^*(t_k)$	Updated Beta distribution parameter for exposure t_k ($d(t_k)$ +$r(t_k)$)
$d^*(t_k)$	Updated Beta distribution parameter for exposure t_k ($d(t_k)$ + S)

Table 3.1: Overview of variables for the Bayesian analysis.

Equation 5 gives the definition of the probability density function of the *beta distribution* with parameters c and d. Note that Excel askes for parameters “alpha” and “beta” which respectively represent c and (d – c).

$$f(p) = \frac{\Gamma(d)}{\Gamma(c)*\Gamma(d-c)} p^{c-1}(1-p)^{d-c-1} \quad \text{with } p \in [0,1],\ c>0,\ d\text{-}c>0 \qquad \text{(Eq. 5)}$$

[7] The elicited points and real life times do not move linear with time. In order to perform a (linear) regression, the data has to be ‘linearized’.

The parameters that are needed to generate sample points with the beta distribution can be obtained with equations 6 and 7. Note that the parameters $\widehat{F}(t_k)$ and $\widehat{\sigma}(t_k)$ are input (elicited from the experts).

$$c(t_k) = \frac{\widehat{F}(t_k)^2 * [1 - \widehat{F}(t_k)]}{\widehat{\sigma}(t_k)^2 * [\widehat{F}(t_k)]} - \widehat{F}(t_k) \quad \text{(Eq. 6)}$$

$$d(t_k) = \frac{c(t_k)}{\widehat{F}(t_k)} \quad \text{(Eq. 7)}$$

The parameters $c(t_k)$ and $d(t_k)$ are then used to perform a Monte Carlo Simulation in which N random samples of the beta distribution with parameters c and d are produced. A Monte Carlo Simulation is used in situations where the variation of the starting conditions is very high, unknown or unquantifiable. In other words, the technique is used in cases where many outcomes are possible (as in this situation). By calculating (sampling) many of these outcomes, one can see trends and can try to estimate the most likely value.

The N random samples are denoted by $F_i(t_k)$ (where i=1,…,N) and are first linearized by equation 8. Note that the simulated values of $F_i(t_k)$ must be non-decreasing with t_k as these are values of the *cumulative* distribution function which by definition is increasing. As all k points are randomly generated, it sometimes happens that the simulation gives infeasible results (i.e. $F_i(t_k)$ is decreasing with t_k at one or more points). The infeasible results are simply discarded. Note that this does mean that 10.000 simulation runs do not necessarily produce 10.000 values of α_i and β_i.

$$F_i^*(t_k) = Ln(Ln(\frac{1}{1 - F_i(t_k)})) \quad \text{(Eq. 8)}$$

This then can be used to calculate (i.e. perform a regression) the parameters α and β of the Weibull distribution. With two points, this is represented by equations 9 and 10 which in essence is just a regression, which can be done easily with for instance Excel. Note the index 'i' here, that represents the index of the run. There are N simulation runs so there are N values of α_i and β_i.

$$\beta_i = \frac{F_i^*(t_2) - F_i^*(t_1)}{Ln(\frac{t_1}{t_2})} \quad \text{(Eq. 9)}$$

$$\alpha_i = \exp(Ln(t_1) - \frac{F_i^*(t_1)}{\beta_i}) \quad \text{(Eq. 10)}$$

These points create a cloud of points. At the place where this cloud is the densest, the (most likely) parameters can be found. This point is the mode (the value that occurs most) of the cloud. In order to calculate stable results (i.e. the value does not change each run), lots of simulation runs are needed (i.e. at least more than 100.000). At the same time, the median value does produce stable results, is generally the same or very close to the mode and can be computed easier. Therefore, the median is chosen as way to calculate the (most likely) values of α and β.

With this, the prior distribution has been found and the two-parameter Weibull distribution can be used in order to construct for instance the failure rate of components.

3.8.2 Variation

The answers that experts give will not be extremely accurate. It is important in the model that the variation is estimated. One method to do this is to assume a certain variation and transform this into a coefficient of variation (Kaminskiy & Krivtsov, 2005). This method has two major drawbacks. The first is that one does not know the variation and cannot just assume some value. The second is that by using a coefficient of variation, the variation becomes larger as the elicited value increases, which is only partially true.

Still, some figure for variation has to be estimated in order to quantify the uncertainty. It will take up a whole research to come up with a proper way to deal with this problem and literature is not generous with supplying solutions to the problems. In order to do something with this, two things will be done:

- Ask experts to estimate a lower and upper bound of the percentages given and treat this as a 90% confidence interval for the value, assuming a normal distribution with N (μ,σ^2) with confidence interval [5%,95%].
- Perform a sensitivity analysis with different values of the variability.

Note that the normal distribution is only used here because it gives the possibility to estimate the variation, which the beta distribution does not. Obviously, the points are not modeled by a normal distribution but by the beta distribution which makes this step somewhat inconsistent. However, using the normal distribution to model is justified because:

- Because the normal distribution is well known and easy to understand, it gives experts an opportunity to estimate variation based on a system that they understand. In addition, it was asked to estimate the variation based on the 90% confidence interval of the normal distribution and experts tend to give symmetrical variations around their mean.
- The elicited variations are very uncertain which makes the value of an extremely accurate model to estimate variation low.

3.8.3 Combining different opinions

When working with multiple experts, different opinions will need to be combined. This can be done in many ways. There are in general two ways of aggregating expert opinions: behavioral and mathematical methods (Clemen & Winkler, 1999).

A behavioral method is a way to aggregate multiple opinions by some kind of interaction. When estimating the MTBF in the FMECA, a behavioral method is chosen to reach consensus. The advantage is that it is an easy way to combine the opinions. The largest disadvantage of this however, is that experts can influence each other (Ayyub, 2001). The one with the loudest voice will influence the results, although this will not necessarily be the person with the best knowledge.

A mathematical method would be to take some kind of weighted average (Ayyub, 2001). These methods are usually very easy to implement and likely to give a less biased solution than a behavioral method. However, the problem that arises here is what weight to assign to each opinion. In order to determine the right weights and use them, more advanced mathematical methods are necessary. The question that arises here is whether it makes sense for this research to invest much time in this because (very) simple methods (e.g. mean, median) have shown to give better results (O'Neill, Osborn, Hulme, Lorenzoni, & Watkinson, 2008). Designing a very good method to combine these opinions mathematically could take up a whole other research.

The combination of different expert opinions will therefore be kept simple. As seen in section 3.8.2, the normal distribution is used to model the variance in the opinions. When assuming that experts are independent, the mean of the elicited data of both experts can be averaged. Of course the experts are not independent, but by interviewing them separately, this assumption becomes quite realistic.

Next to the mean of the elicited points, the standard deviations have to be combined. This is done by taking the lowest lower bound and the highest upper bound that the expert elicited. The standard deviation is then calculated as described in 3.8.2. Besides the fact that it is incredibly easy to perform this method, it makes the variation dependent on the degree to which experts agree. As the lower and upper bounds are constructed around the mean, the variation becomes larger as the experts tend to disagree more.

3.8.4 Updating the expert opinion

If one would follow the previous sections, one would end up with the so-called prior distribution of the Weibull function. This prior (based on subjective information) can be updated with real (objective) data. With that, the so-called posterior distribution is created which should in theory always move towards the data-driven solution. This is a very useful feature of this method as the method evolves over time.

The updating of the prior is done by adding the failures $r(t_k)$ to $c(t_k)$ and the total number of observed failures until today, S, to $d(t_k)$. This creates the value for the posterior Monte Carlo simulation that are called $c^*(t_k)$ and $d^*(t_k)$. The values of t_k (with k = 1…S) are the lifetimes of the component upon failure. In order to calculate the values of $c^*(t_k)$ and $d^*(t_k)$ at the points in time a failure occured, one uses the *prior* Weibull parameters to calculate the value of the Weibull distribution at time t_k. A new Monte Carlo simulation run can provide the standard deviation at time t_k (Kaminskiy & Krivtsov, 2005).

Example
The prior (elicited from experts) Weibull parameters are $\beta = 2$ and $\alpha = 10$. A total of two failures have occurred until today, at $t_1 = 2$ and $t_2 = 3$. This means that $r(t_1) = r(t_2) = 1$ and $S = 2$. The value of $c(t_k)$ is updated by adding $r(t_k)$ to it, creating $d^*(t_k)$. The value of $d(t_k)$ is updated by adding S to it, creating $d^*(t_k)$. The value of $c(t_k)$ and $d(t_k)$ depend on the $F(t_k)$ and $\sigma(t_k)$. $F(t_k)$ can be calculated with the prior β, α and t_k The value for the standard deviation $\sigma(t_k)$ can be estimated by Monte Carlo simulation of the prior β and α.

To summarize, the following steps are performed to update the prior distribution:

1. Determine prior Weibull parameters α and β.
2. Determine the lifetimes t_k of the component upon failure.
3. Determine value of the Weibull distribution F(tk) with the prior α and β or Monte Carlo Simulation.
4. Estimate the value of σ(tk) by Monte Carlo Simulation.
5. Calculate the values of $c(t_k)$ and $d(t_k)$ with equation 6 and 7 .
6. Calculate the value of $c^*(t_k)$ and $d^*(t_k)$ by updating with $r(t_k)$ and S.
7. Run new Monte Carlo Simulation with the updated parameters to find the posterior Weibull parameters.

3.8.5 Guidelines for the elicitation process

The actual process of gathering expert opinion is very important. Although this report does not focus on the theory of communication behind the process, some basic question should be answered.

First of all one wants to know who qualifies as an expert. Definitions like “an expert is a very skillful person with much knowledge in a certain field” (Ayyub, 2001) exist, but don’t seem to answer the question. It is still unclear what ‘very skillful’ and ‘much knowledge’ means. A minimum requirement of an expert would be that he has at least basic understanding of the functionalities of the concerning component and vessel. The value of an expert increases when the period working at the concerning vessels becomes larger and the variety of jobs (preventive, corrective, different vessels and locations) is larger.

The experts need to have full knowledge of the assumptions that are made when giving answer to the questions. An example of this, which is the case during the FMECA, is the assumption that no preventive is done. As observable information can be estimated easier by experts (Bousquet, 2010), it makes sense to assume the situation as it is because this is easy to observe. Assumptions that have to be communicated are for instance the performance of preventive maintenance (e.g. is PM performed? what is the effect?) and the use of the components (e.g. do we assume that an engine is always build in a vessel?).

Finally, the experts need to be asked separately in order to avoid the possibility of experts influencing each other (Celeux, Corset, Lannoy, & Ricard, 2005). Obviously, one should limit communication between the experts.

In order to get a good experimental setting, there are roughly six steps to cover (Choy, O'Leary, & Mengersen, 2009).

1. Determine purpose and motivation for expert elicitation.
2. Determine what knowledge is available.
3. Formulate a model.
4. Design effective elicitation.
5. Manage uncertainty.
6. Design an elicitation protocol.

Step one to four are given by the proposed method (Kaminskiy & Krivtsov, 2005). Step five is explained in section 3.8.2, step six can be found in detail in appendix H.

3.9 Conclusions

In order to decide on a trajectory, some extensive choices and assumptions have to be made. Loodswezen has a very specific case in which practically no data is available. One has to be aware that due to this fact, less exact methods have to be used to determine the lifetime distribution of components. For this reason, it is proposed to assume a (two-parameter) Weibull lifetime distribution. For the estimation of the parameters, a Bayesian approach is proposed. This method is well suited to handle a very small amount of data and expert opinions. This process consists of different important steps:

- Elicitation process.
- Managing variability.
- Merging different opinions.
- Bayesian analysis to get prior.
- Update the prior to get a posterior distribution.

With the obtained lifetime distribution of the components, a simple age replacement strategy can be implemented. As stated earlier, due to the small amount of data, this solution will not lead to a huge improvement to the current situation. In order to make optimal use of the information that is available, an opportunity based replacement strategy would be the best way to improve the availability of the vessels.

4. How can the failure behavior be characterized?

The challenge that has to be faced in this chapter is the examination of the failure behavior. For instance, in order to do preventive maintenance on a component, a component has to have an increasing failure rate, or in other words, should be a deteriorating component. The failure rate function is also used to determine *when* to do this preventive maintenance. This chapter will start with the search for a case and the calculation of the failure rate *with* data. Then more information about the case is presented in order to be able to perform the proposed method with expert opinion. Note that for the analyses, calendar time based data (days) is used. This is counterintuitive as Loodswezen typically uses operating hours to plan maintenance. Nevertheless, calendar time is used because experts are not able to perform the expert elicitation process with operating hours but only with calendar time. To keep the outcomes comparable, calendar time is used for all analyses. Later the calendar time will be converted to operating hours.

4.1 Historical failure data

In this section, the gathering and analysis of historical data from Loodswezen is explained. This is the way companies with an abundance of data work. A similar analysis at Loodswezen is used to compare the outcomes of experts with the ‘real’ outcomes in order to validate the proposed expert elicitation method.

4.1.1 Gathering & Filtering

First, there is a need to gather all the (failures) data Loodswezen has. This is important because this process is complicated and time consuming but at the same time necessary to conduct any analysis. A short introduction on how to do this will be given in this section. An extensive analysis of this can be found in appendix D.

Because the number of failures per component is not documented at all, it costs a lot of time to determine which component has most failures as one has to investigate every component. By using data from the bookings in and out of the warehouse, some indication can be given on where to look for often failing components.

Table 4.1 shows a brief overview of the number of replacement data (records) that has been found. These are records from the warehouse in which components are (virtually) booked in and out of the systems every time a component needs corrective maintenance. This number is a fast way to estimate the number of observed failures there are. In other words: 10 records means approximately 10 failures have been observed (approximately because preventive maintenance creates a record, but is not a failure). Table 4.1 shows that only 27 unique components of the Aquila Class and 10 of the P-class offer more than 10 of these records.

Category	Aquila	P-class
All	95	35
>=5 records	33	11
>=10 records	27	10

Table 4.1: Quick overview of the number of components per category.

The full list in appendix C features the whole overview of these records, from which a component can be chosen that fails often. In this list however, there are also filters and other consumables. These are almost always replaced preventively, which does not give failure dates. The same applies to for instance the zinc-rod and zinc anode but also for the v-belts (v-snaar). As the dynamo (Aquila class) is only *replaced* correctively (it *does* receive minor preventive maintenance/inspections which generally consist of cleaning, measuring and if necessary replacing the whole component), this component is chosen to conduct the experiment on.

Now that the dynamo is chosen, the failure data can be retrieved. For this, all dynamo work orders have to be evaluated. These are booked on a position (e.g. starboard engine) and not on equipment (i.e. the physical engine). It is necessary to know what equipment the work order was created for in order to calculate the age of the system. To do that, the work orders should be linked to equipment instead of positions, by looking at the date and position of the work order. When one knows the date and position of the work order (e.g. January 13th 2013 and Aquila Starboard) one can translate this to equipment (e.g. 10003239). In order to translate positions to equipment appendix G is used.

Once it is known which equipment failed on which date, the corresponding hours of operation (draaiuren) need to be added to the dates. The dates of preventive maintenance with the corresponding hours of operation need to be as well. This way, an overview of all times maintenance has been performed on an equipment can be made. An example of this can be seen below (equipment number 10003129). In appendix E, all obtained values can be found.

Time measurement	Entry in service	Failure 1	Failure 2	Time to failure 1	Time to failure 2
Days (calendar)	29-9-2010	18-2-2013	12-5-2014	718	448
Operating hours (usage)	72	5735	8993	5663	3258

Table 4.2: Example outcome of maintenance instances.

Table 4.2 can be read as follows. At 29-9-2010, this equipment had 72 running hours. It failed two times, the running hours below the failure dates correspond to this failure date. The time to failure is in days or in running hours. This equipment produces two failure dates (time to failure) in two formats (days and running hours). These figures can be used in the analysis in next section.

All data that is used from now on in this report will be from the Aquila Class C32 dynamo. To summarize: this component is chosen over other components because:

- It has “many” failure data (needed to do the analysis).
- It does not receive preventive replacement or revisions (this means data is relatively uncensored).
- There is just one dynamo in each engine, so if a dynamo at ‘starboard’ fails, it is exactly known what dynamo it is.

4.1.2 Analysis

With data like in Table 4.2, the actual analysis can be conducted. In Table 4.3, the calculated α and β (by least squares method) are shown. As the β is the parameter that determines whether a failure rate is increasing (>1) or decreasing (<1) and is therefore incredibly relevant to determine whether to do preventive maintenance or run to failure. Also, with these parameters, optimal replacement/maintenance intervals can be determined (chapter 5). Note that the number of 15 failures that were used to calculate these parameters is very minimal. The less points that are used, the more the parameters are influenced by outliers.

Based on	α	β
Calendar time (time based)	667	1,41
Operating hours (usage based)	4430	1,87

Table 4.3: Weibull parameters.

In the table above the results of the least squares analysis is shown for both the age of the dynamo based on calendar time (days) and operating hours. In Appendix F, the whole analysis can be seen. From the β parameter, it can already be concluded that there is a big difference between the ageing of the dynamo when measuring it with a different time unit. Usually, usage based calculations give a somewhat more reliable result as ageing (deterioration) is typically more related to the hours of operation than the calendar time (see section 3.4). This means that in this case, the actual ageing of the dynamo is probably faster than the calendar time analysis suggests. Because experts are not capable of delivering estimates based on operating hours, the calendar time based analysis will be used as an example of what to do with these parameters.

In Figure 4.1, one can see the failure rate function, based on the calendar time. The failure rate functions of the operating hours show a similar pattern as the calendar time above (but with a different scale). The failure rate is defined as "the proneness to failure at time *t*". Note that a constant failure rate, as is assumed in the FMECA, is contradictory to the decision to perform preventive maintenance. One can imagine that if the probability of a component failing as new is just as big as when it is very old, if does not feature any advantage to maintain the component.

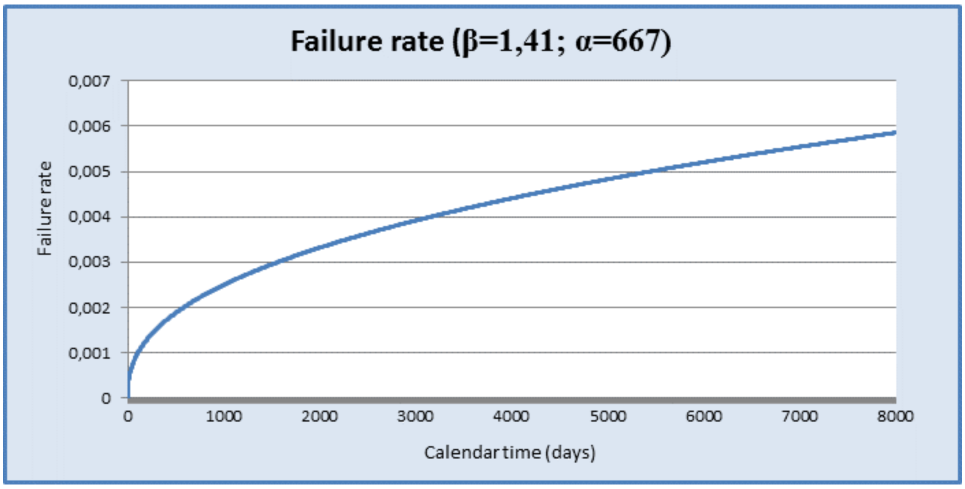

Figure 4.1: Failure rate function based on calendar time.

Although the absolute values in Figure 4.1 might be meaningless to many, two important pieces of information can be retrieved from the graph:

- The failure rate as calculated (calendar time) is increasing with time, therefore preventive maintenance is justified.
- The FMECA- based failure rate ($\beta = 1$) gives results that cannot be used to determine optimal maintenance intervals. Hence this is the main advantage of any method that used Weibull distributions (they are useful to optimize maintenance).

To get a better understanding of what the Weibull-parameters and failure rate actually mean, the survival function of the dynamo, for calendar time is displayed below.

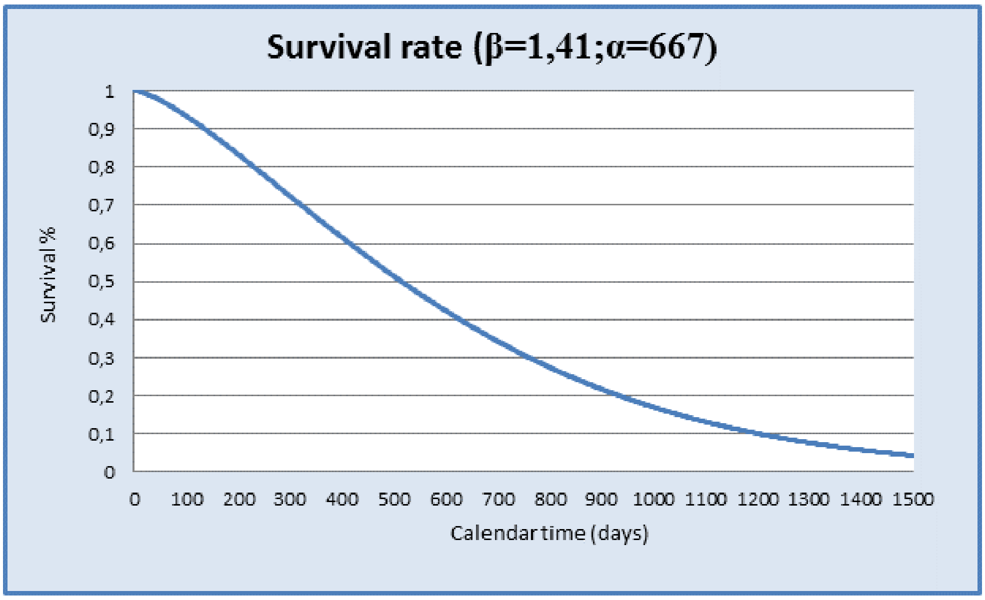

Figure 4.2: Survival rate functions based on calendar time.

With this survival function, a better understanding of the failure behavior is obtained. Let's assume that Loodswezen wants to replace the dynamo before the probability of failure reaches 3%. To calculate the time to replace (or maintain) the component the following equation is solved:

$R(t) = e^{-(\frac{t}{\alpha})^{\beta}} = 0{,}97$ with α = 667; β = 1,41

This would mean Loodswezen needs to change the component every 56 days of service. This is impossible as this would lead to enormous downtime and costs. There is a trade-off involved in the decision making between, based on the effort of maintenance. Therefore, in the next chapter (5) methods will be presented to be able to calculate the optimal replacement interval.

Now something is known about this component, but there are a couple of issues to be solved:

- The amount of data of the dynamo is not representative of the amount of other components; therefore it is hard to use this method at this moment. This problem will be addressed in section 4.3.
- The optimal replacement time does not only depend on the amount of failures per time unit, but also on other factors as for instance costs. For Loodswezen, costs are not measured in money but in time. In addition, more clever methods are available to plan maintenance. These aspects will be presented in chapter 5.

Especially with an automatic form to calculate α and β(which is available in Excel), it will costs less than 1 minute to calculate these parameters once all lifetimes are known. The calculation of lifetimes is also a job of minutes. Finding failures with corresponding dates and equipment however, will cost several hours per component. One has to evaluate each order manually and to do this process really exact, help from experts is needed. As SAP is capable of doing this gathering automatically, it is really just a waste of time to do this manually. One could reduce the workload for this data analysis from several hours per component to approximately five minutes by using SAP.

4.2 The case of the dynamo

Before asking experts for their opinion, it is necessary to get a basic understanding of what the component does and what happened to it in the past. This is usually not very spectacular as a component is just used from the start the way it should. The dynamos that are in the C32 engine in the Aquila class vessels do however had some important changes.

There is one dynamo in each engine. With six engines in operation in the Aquila class vessels in total, this means there are six dynamos in total in operation. This also means that with two spare C32 engines, there are also two spare dynamos. This means there are eight dynamos in total. The words 'dynamo' and 'alternator' are used interchangeably although these are two (slightly) different devices. A dynamo is just used to generate power in the form of direct current (DC, *gelijkstroom*), while an alternator generates power with alternating current (AC, *wisselstroom*). In this report, the component is (wrongly) called 'dynamo', but Caterpillar calls it (properly) an alternator. The following preventive maintenance task is advised (Caterpillar, 2010):

"Caterpillar recommends a scheduled inspection of the alternator. Inspect the alternator for loose connections and proper battery charging. Inspect the ammeter (if equipped) during engine operation in order to ensure proper battery performance and/or proper performance of the electrical system. Make repairs, as required. Check the alternator and the battery charger for proper operation."

The required time interval for this task is every 5000 operating hours. For the Aquila Class, this is set to 3000 hours in reality because the vessels are expected to be used more intensive. The actual preventive maintenance that is done every 3000 hours, does not always include this whole check. In addition to this maintenance, before starting the engine, the following inspection is required: "*Inspect the alternator and accessory drive belts for cracks, breaks, and other damage."* This is also performed in practice.

The name of the 3000 hours maintenance in SAP is 'Dynamo inspection/cleaning', which is, as can be concluded from the text above, nothing more than a short *visual inspection*. Cleaning is only done during revisions. Both experts agree that the preventive maintenance task itself does not change the lifetime of the component in the sense that preventive maintenance will not prevent future failures. However, when doing a *thorough inspection*, an error can be found. This would be solved by a revision or replacement. Both revision and replacement will make the dynamo 'as good as new'. Expert ε_2 thinks that the current preventive maintenance (*visual inspection*) should actually be the measuring of the performance of the dynamo (which is also advised by Caterpillar). Because this does not happen (enough), dynamos with improper functionality can live on and fail. Note that Loodswezen does not (always) exactly perform the maintenance that was set by the supplier, although the mechanic indicates that this would be beneficial. Expert ε_2 also stated that preventive replacement/revision would be beneficial. This is currently not standard procedure.

In addition to this relatively complicated maintenance tasks there are two more complicating factors. The dynamos were delivered with some teething problems that were twofold:

- The dynamo that was delivered by Kvichak did not function the way it was supposed to so it was replaced by a slightly different one from a Dutch supplier. This fact has to be neglected because it cannot be traced when this would have happened and in addition the effects of the change are hard to estimate.
- The mounting of the dynamo was not correct in the beginning. For this reason, the forces on the dynamo from the v-belt warped the dynamo, causing the v-belt to slip off. This has also been changed but just like the point above, it cannot be quantified what effects this would have had.

The dynamo in the Aquila class vessels is not used as one would expect. Usually, a dynamo generates power and if it fails, the power is generated by a battery or generator. However, the dynamo in the Aquila class vessels only functions when the battery need to be charged. This situation does not happen if all systems are up and rarely occur during operations. A failure in a dynamo is therefore a hidden failure. It only has to function sporadically. This property also means for Loodswezen that in theory, a vessel is operational, even when the dynamo is on failure (and this is known). This is because the engine will still function properly. If the dynamo would be necessary, the vessel still has another properly functioning engine. In practice, it depends on the crew of the tender whether or not the vessel is in operation.

In Table 4.4, the outcomes of the FMECA are shown. The failure rates are respectively two, one and one per year. This means the failure rate is 4 per year, an MTBF of 365/4 = 91 days.

Failure Mode	Cause	Condition	MTBF	Out of service	Downtime
FM1	Wrong voltage	Hardware failure	0,5 year	No	1 day
FM2	Earth Leakage	Wear	1 year	No	1 day
FM3	Jammed bearing	Wear	1 year	No	1 day

Table 4.4: Summarized outcome FMECA Aquila Class C32 Dynamo.

It is interesting that the estimated MTBF is just 91 days while the data-driven MTBF, with $\beta = 1{,}41$ and $\alpha = 667$ (see Table 4.3) is 607 days. This discrepancy can partially be explained by the fact that the FMECA is built up from failure modes, which makes the overall MTBF of a component non-transparent as the MTBF of different failure modes need to be combined. Nevertheless, the difference between the FMECA based MTBF and the data-drive MTBF is so large that one can question the credibility of the FMECA based MTBFs.
In addition to the MTBFs, the down time mentioned here was 1 day, while changing the dynamo (which is nearly always done when it is on failure) just takes about 2 hours (according to the same expert 6 months later).

4.3 Expert opinion

Determining the failure rate function as was shown in the previous section is usually a data-driven task. Fifteen records like in the analysis in section 4.1 are very few to determine the failure rate and with the low quality of the available data and the fact that the dynamo is the component with the most data, it is likely that this method is not good enough. The lack of data especially becomes problematic when there are even less failure data for a certain component.

As many components have very few or even no failure data at all, one has to come up with a method that can handle this. It makes sense to use the only available source that Loodswezen has: experts. It is important that this process does is not time consuming, not hard to understand but still gives a solution in which the proposed methods in chapter 5 make sense. Such methods exist; a relatively easy method to do this is presented in detail in this section (Kaminskiy & Krivtsov, 2005).
The method consists of many steps and it can be hard to combine the theory in this chapter with what is actually happening in the analysis. To solve this problem, an example of the analysis can be found in appendix J.

4.3.1 The survey & the experiment

Making a good survey is essential. Fortunately, the requirement that the total effort to implement a system like this should be simple and not time consuming makes the survey easy.

The proposed system does not require very difficult data to be gathered. The data that is needed is the probability that a certain component fails at a certain time. So (for example four) dates are taken and (for example two) experts are asked what the probability is that a component (dynamo) has failed. The analysis of section 4.1 or the documents proposed in section 4.3.5 is used to ask for appropriate observation times. Although it does not matter what the chosen time is, it does not make sense to ask for a failure percentage after three years for a component that lasts for a month (the answer would be an unverifiable high percentage). For the experiment, it was tried to ask for both convenient calendar times and operational hours in order to be able to test what gives the best results.

The experts have to answer the question: 'what is the percentage of dynamos that would have failed after the given period?'. The literature does not give information about what preventive maintenance to consider. To experiment with the outcomes, two scenarios are being evaluated:

- In case of no preventive maintenance [1].
- In case of the current preventive maintenance plan [2].

The first experiment was conducted with the workshop manager, from now on called expert ε1. The results can be seen in Table 4.5. LB is the elicited lower bound, UB the elicited upper bound.

t	Period	$\hat{F}(t_k)$ [1]	LB	UB	$\hat{F}(t_k)$ [2]	LB	UB
t_1	0,5 year (183 days)	0,15	0,13	0,17	0,15	0,14	0,16
t_2	1 year (365 days)	0,25	0,23	0,27	0,30	0,29	0,31
t_3	2 years (730 days)	0,40	0,38	0,42	0,50	0,49	0,51
t_4	3 years (1095 days)	0,60	0,58	0,62	0,75	0,74	0,76
ot_1	1000 operating hours	0,30	0,25	0,35	0,10	0,09	0,11
ot_2	2000 operating hours	0,50	0,45	0,55	0,25	0,23	0,27
ot_3	3000 operating hours	0,60	0,59	0,61	0,50	0,48	0,60
ot_4	4000 operating hours	0,70	0,68	0,71	0,70	0,68	0,80

Table 4.5: Results from expert $\varepsilon_{1.}$

The procedure was performed as follows:

- Introduction to the problem, explanation what is to be done.
- Example of what the outcome could be concerning both the failure % ($\hat{F}(t_k)$) and the confidence intervals (Lower bound and Upper Bound).
- Introduction of failure rates, survival functions, the component (dynamo) and assumptions.
- Drawing of the cumulative function.
- Asking the different periods with corresponding failure percentages.

The procedure is discussed in detail in appendix H.

From this first experiment, some conclusions were drawn:

- With and without preventive maintenance is confusing, especially in this case where the preventive maintenance primarily consists of inspections.
- The operating hours were immediately transformed to calendar times. This lead to very bad results. When analyzing the operating hours, β was around 5.
- The confidence of expert ε_1 was way too high. When asked for a 90% interval, the expert thought he would be just 1% off. The literature emphasized the fact that one has to tell the expert his expectations are very uncertain between every step (in this case 16 times). Although this seems a bit overdone, it was tried in the next experiment and this did work.
- Note that expert ε_1 actually predicted that the performance of dynamo would be worse *with* preventive maintenance in case of calendar time. Although the expert really thought preventive maintenance on the dynamo has no positive effects, this expectation seems somewhat inconsistent as the same expert expects that preventive maintenance *does* have positive effects when measuring in operating hours.

Expert ε_2 (mechanic) was not able to give reliable results in case of operating hours which was to be expected after expert ε_1 also was not really able to give reliable results. This time, no distinction was made between preventive and no preventive maintenance. His reflection of reality was the following:

t_k	Calendar time	$\hat{F}(t_k)$	LB	UB
t_1	183 days	0,08	0	0,17
t_2	365 days	0,17	0	0,33
t_3	730 days	0,33	0,17	0,50
t_4	1095 days	0,50	0,33	0,67

Table 4.6: Results from expert ε_2.

The way expert ε_2 got his answers was very clever. His reasoning was as follows: there will probably be one dynamo failure (of six total dynamos) every year. This made the elicitation process very quick as it could be filled in almost automatically. The deviation was gathered by the reasoning that there would be one failure a year but in a good year there would be none and in a bad year there would be two. The data for t_1 was slightly adjusted to meet the reasoning. The reasoning for the first point was "we should not see a failure in the first half year but it might happen", this is translated into the failure percentage of 8% (0,5 of 6 dynamos). One could of course argue that the statement of expert ε_2 should be translated into "0%". Besides the fact that this does not agree with the "one failure a year" statement, this does also introduce problems with the variability and the model, which is not capable of handling "0%".

4.3.2 Combining expert opinion & variation

As the second test with Expert ε_1 was about the "real" situation and the first was "without any maintenance", these data are used to do the analysis. It is still strange that the dynamo would fail more when doing preventive maintenance (according to this expert). In Table 4.7, the elicited percentages (failures until time t; μ) are shown for both experts individually. Also their elicited lower and upper bound are shown.

Time	$\hat{F}(t_k)$ Expert ε_1	LB	UB	$\hat{F}(t_k)$ Expert ε_2	LB	UB
T_1 (0,5 years)	0,15	0,14	0,16	0,08	**0,00**	**0,17**
T_2 (1 year)	0,30	0,29	0,31	0,17	**0,00**	**0,33**
T_3 (2 years)	0,50	0,49	**0,51**	0,33	**0,17**	0,50
T_4 (3 years)	0,75	0,74	**0,76**	0,50	**0,34**	0,67

Table 4.7: Overview of elicited $\hat{F}(t_k)$ with lower and upper bound per expert.

The lower bound and upper bounds as elicited from the experts will be used to determine the standard deviation of the elicited point. First, the opinions have to be combined to one point.

As indicated in chapter 3, it is assumed that the gathered data points are mutually independent and normally distributed with N (μ, σ^2). As been stated, the means (μ) can be found in Table 4.7. Because the points are considered independent, the average of the elicited (failure %) points is also normally distributed. This property means that the average of the two elicited percentages can be taken as combined μ. The lower and upper bounds are combined by taking the most extreme lower and upper bounds (i.e. the lowest lower bound and the highest upper bound) and using them as combined lower and upper bound (see the bold numbers in Table 4.7 and Table 4.8.). This way, the standard deviation will grow with the difference between the two elicited points. In other words: the uncertainty grows as experts tend to disagree.

The combined $\hat{F}(t_k)$, lower and upper bound can be used to calculate standard deviation (σ). Different values for the standard deviation are considered in order to evaluate the sensitivity of the variation. The standard deviation is calculated by solving the formula for the normal distribution with confidence intervals of 99% (1), 95% (2), 90% (3) and 70% (4). With a lower and upper bound that are not symmetrical around the mean, this will obviously lead to two different values of σ from which

always the highest is taken. A for instance 95% confidence interval means that 2,5% of the tail of the distribution is below and 2,5% is above the lower and upper bound.
For instance with the $\hat{F}(t_k)$ of T_1 (0,12) and the lower bound of 0,17 and confidence interval 95%, this means that it is evaluated what sigma must be in order to have 0,17 at the 97,5% level, when the mean is 0,12.

Time	Combined experts $\hat{F}(t_k)$	LB	UB	$\sigma_{99\%}$	$\sigma_{95\%}$	$\sigma_{90\%}$	$\sigma_{70\%}$
T_1 (0,5 years)	0,12	**0,00**	**0,17**	0,04	0,06	0,07	0,11
T_2 (1 year)	0,24	**0,00**	**0,33**	0,09	0,12	0,14	0,22
T_3 (2 years)	0,42	**0,17**	**0,51**	0,10	0,13	0,15	0,24
T_4 (3 years)	0,63	**0,34**	**0,76**	0,11	0,15	0,18	0,28

Table 4.8: Values for analysis of variation.

Scenario	α (days)	β	MTBF (days)
$\sigma_{99\%}$	1128	1,19	1063
$\sigma_{95\%}$	1055	1,30	974
$\sigma_{90\%}$	1020	1,38	931
$\sigma_{70\%}$	863	1,97	765

Table 4.9: Overview of the outcomes of different scenarios with different variances.

The conclusion of Table 4.9 is that α (and with that the MTBF) is not extremely sensitive. Only if the confidence of the elicited values becomes very low, α tends to decrease fairly. The β changes somewhat more than α and becomes larger with the variance.

The calculations in this report are done with the 90% confidence interval (scenario 3) as was decided in during the actual elicitation. In this case, this leads to very good results (i.e. closer to the data-driven solution) as α was elicited too high and β too low. However, the sensitivity analysis suggests that the decision for the confidence interval is not too sensitive in terms of α, β and MTBF. It is known however that especially the β is sensitive itself, when calculating optimal maintenance intervals.

4.3.3 The prior

With the choice of β = 1,38 and α = 1020 (scenario 2), the prior is found. In the table below, one can see the results of the experts separately and combined. One can also compare this with the data-driven value.

Type	α	β	MTBF
FMECA	-	-	91
Data-driven	667	1,41	607
Expert ε_1	896	1,16	851
Expert ε_2	1384	1,38	1264
Combined Experts	1020	1,38	932

Table 4.10: Prior of expert opinion.

The difference between the expert opinion and the actual parameters is still high. The differences can be explained by a couple of factors:

- Overconfidence, especially from expert ε_1, that claimed to have a standard deviation of just 1%. Expert ε_2 was more realistic about this. Both these facts also lead to a tendency of the combined parameters to be in favor of expert ε_2, as the widest range (variance) was taken to combine the two opinions.
- The experts seem to predict the future and recent history, although they were explicitly asked to describe the whole past. The 'real' failure data of course only look at the past. The

prediction of future and recent events is caused by the fact that expert tend to remember recent events more clearly than events further in the past (the performance improved recently). The notion that the future is predicted is backed up by the use of words like "usually" or "typically" that were used by the experts.

- The previous point is even worsened further because the dynamo had design changes and was actually renewed fully to another type of dynamo. Unfortunately this effect has to be neglected as not enough information would be available otherwise. Note that if the recent events form a long-term trend, for instance because the design changed like in this case, the experts might be more reliable than the data-driven approach!
- Expert ε_2 is far away from the data-driven MTBF (also see Figure 4.3). Due to the fact that expert ε_1 gave a good α and expert ε_2 gave a good β, the combined results are still reasonably good. This emphasizes the need to use the opinions of multiple experts.

Expert ε_1 estimated the MTBF of the dynamo to be 91 days during the FMECA and 851 days during the expert elicitation. This can be compared to the data-driven solution for the MTBF of 607 days. It is noteworthy that the expert gave the same quantity (MTBF of dynamo) twice, but with an 835% difference. There are two important reasons for the difference between the FMECA and the expert elicitation answers of this expert:

- The FMECA MTBF is based on different failure modes, while the MTBF of the expert elicitation method is based on the component as a whole. From this, it follows that two different questions were asked which the expert (obviously) answered with two different answers. Answers that are not consistent.
- The overall performance of the FMECA is not very good (e.g. MTBFs and repair times are often wrong), most likely due to the fact that the FMECA was mostly done on just one day of eight hours. This setting leads to a lack of time, motivation and energy to think thoroughly about every component. In addition, the way MTBFs of failure modes are combined to an MTBF of a component as a whole is not transparent and not communicated to the experts.

The survival rates of the different parameters in Table 4.10 is shown in Figure 4.3. On the x-axis the calendar time is displayed, on the y-axis the percentage survived components.

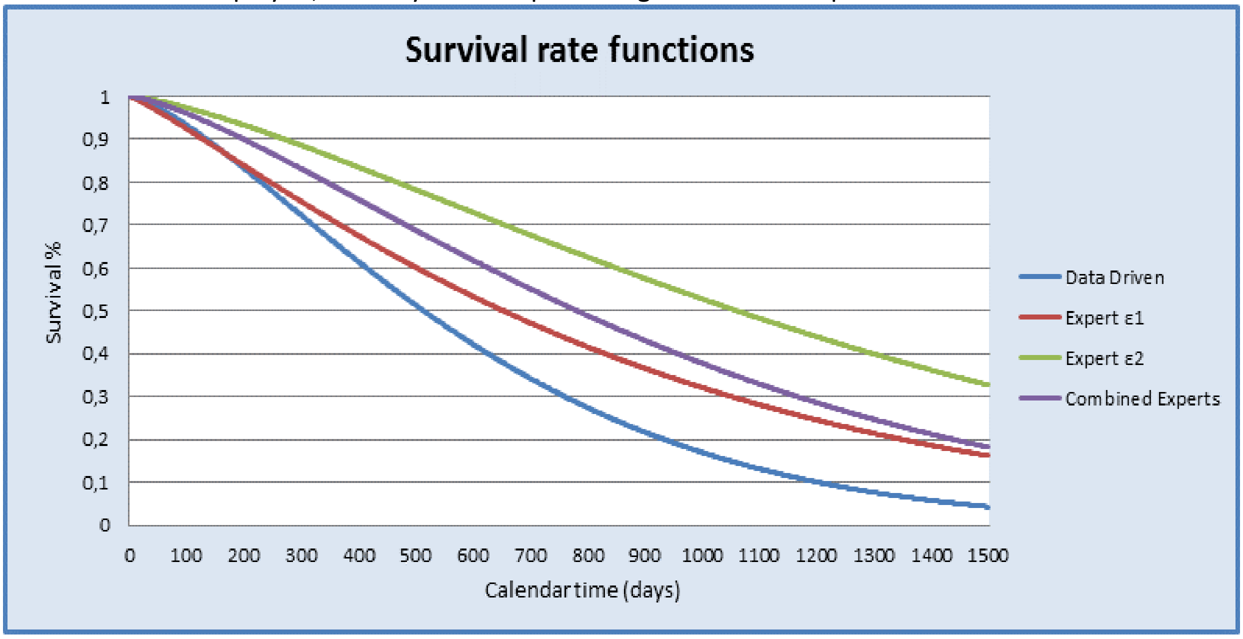

Figure 4.3: Survival rate of different priors.

In the figure, one can see that expert ε_1 is closer to the data-driven survival rate function than expert ε_2 because the estimation of α of expert ε_1 was way better than the one from expert ε_2.

4.3.4 The posterior

The combined expert prior is a good starting point for maintenance optimization. However, the prior can be updated with real failure data in order to improve the solution. For the updating process, the combined expert prior is used (α = 1020; β = 1,38) as starting point.

In order to update the prior to the posterior, first the failures have to be known. The lifetimes are already evaluated in section 4.1.2 and are therefore known (appendix D). There are 15 observed failures at 14 unique ages of the dynamo (two dynamos failed at the same age). The calculated prior will now be updated with these 14 unique lifetimes. Obviously, the failures did not occur exactly at the elicited point (half year, one year, two years, three years), but at 14 other times. In order to update these 14 points, one needs to know two values:

- The value for F(t) at all 14 points t.
- The value for σ(t) at all 14 points t.

The values for $F(t_k)$ at these points can be determined very easily by calculating the value for the Weibull distribution at these exposures with α = 1020 and β = 1,38. The standard deviation is somewhat more difficult. In order to estimate the standard deviations, the original input from the experts (Table 4.8) is simulated again while running the 14 (inferred) points next to it. This time, not the prior α and β are of interest, but the 14 values of the standard deviation that can be used to simulate the updated points.

After this has been done, there are (prior) values of $F(t_k)$ and $\sigma(t_k)$ for all times t_k where there was one or more failure. These are then updated by adding the cumulative number of failures ($r(t_k)$) until time t to the parameter '$c(t_k)$' from the beta distribution ($c(t_k) + r(t_k)$). In addition, the total number of observed failures (S) has to be added to beta distribution parameter '$d(t_k)$' ($d(t_k)$ + S). In this case, S is equal to 15 (15 failures in total).

After the beta distribution parameters have been updated, one can run the simulation and retrieve the posterior Weibull parameters. However, in this case, many of the 14 different lifetimes are close to each other. The values for $F(t_k)$ have to be non-decreasing with time (cumulative functions cannot decrease). Because the values of t are so close, the 14 values of $F(t_k)$ are often not non-decreasing all together. This happens so often that no results are drawn from the analysis, as the results never meets the restriction of being non-decreasing.

This problem can be solved by aggregating two points t_k that are very close as if the two failures occurred at the same time. This is done by first aggregating the two closest failures and aggregating them as if both failures occurred at the highest time t. So if one failure occurred after 334 days and one after 336 days, the two failures are aggregated as if they both occurred after 336 days. The aggregated time t_k is the highest of the two because at this time, both failures were observed.

If this would result in a simulation that does give non-decreasing answers often enough, the aggregation is completed. What is enough is up to the statistician but one has to understand that every aggregation means losing valuable information so this should be left to the minimum. In this case, the analysis was performed with 10 points (so 4 failures were aggregated) because it would be relatively easy to gather at least 10.000 results within 'reasonable' time. Still, only just around 3% of the simulations meet the restriction of being non-decreasing. In this case, the decision to aggregate two of the closest points is made when the Monte Carlo Simulation gives a feasible solution in less than 1% of the times.

This process can be summarized as:

1. Run the updated process with the available lifetimes t_k.
2. If there are enough results, do not aggregate (stop).

3. If there are not enough results, aggregate the two values that are closest together and go back to step 1.

The results of this process can be seen in Table 4.11. With 14 data points, no feasible solutions are found. This means that in all of the 10.000 runs at least on point was decreasing over time. The two closest points in time are aggregated. It can be seen that when there are just 10 points in the analysis, finally more than 1% of the solutions becomes feasible.

	% feasible results
All data	0%
13 points	0,01%
12 points	0,04%
11 points	0,9%
10 points	3%
9 points	7%
8 points	21%

Table 4.11: Outcomes of the iteration process based on 10.000 runs.

As suggested above, the analysis with 10 points would lead to enough feasible points (>1%) to make an analysis in a short time. Note that in order to get 10.000 samples with these 10 points, still more than 300.000 simulation runs are necessary as only around 3% is feasible.

Scenario	α	β	MTBF
Data-driven	667	1,41	607
Prior	1020	1,38	932
Posterior (10 points)	932	1,50	841

Table 4.12: Overview of the different parameters.

Table 4.12 shows that the posterior improves the solution somewhat (in terms of α and MTBF). This is to be expected as the α represents the “center of gravity[8]” of the failures. The data-driven parameters are calculated with the same failure data as the updating process is done with. This means that by definition this “center of gravity” will be the same and therefore should always move the prior α towards the data-driven α parameter.

For the β this is different. The β depends on how many failures occur relative to each other at any point of time. It is based on the idea that more failures occur when time passes (deterioration), so it is relative! Especially in a small data set like this, the β can change rapidly as the parameter can be influenced by short term trends in the data. The same β does not mean that the number of failures is increasing in exactly the same way; it only means that the trend is the same. When updating the prior β towards the data-driven β, one would expect the posterior β to be somewhere near them, but not necessarily in between.

4.3.5 Evaluation of the expert opinions

When asking experts for their opinion, it is necessary to verify the given answers (and the resulting posterior) in order to determine whether or not the results are reliable. In the case of the dynamo, the expert outcomes were simply compared to data-driven outcomes. But when performing the proposed expert elicitation method, this data is never available (otherwise these data would be used). This means that the expert opinions have to be evaluated by other means.

[8] This is a non-scientific term to describe the fact that α always near the MTBF, the point where on average a failure would have occurred.

In order to verify whether the expert elicitation gave 'correct' parameters (i.e. parameters that are close to the actual value), it is important to understand the relation between α and β.
Given the β, the α parameter can be calculated with the eq. 11.

$$\alpha = \frac{\mu}{\Gamma(1+\frac{1}{\beta})} \qquad \text{(Eq. 11)}$$

In the formula, μ represents the mean of the failure data. Some important notes about this equation:

- The gamma function in the denominator can be calculated in Excel by using the e-power of the GammaLN function (exp (gammaln(x)).
- If $\beta = 1$, α will be equal to the mean. If $\beta \neq 1$, α will not be equal to the mean.

Equation 11 gives a better understanding of the relation between the two parameters and can of course also be used the other way around with Excel's solver.

The mean μ can be found by using either of the following sources:

- Using estimates from the FMECAs.
- Using sources like NPRD (Non-Electronic Parts Reliability Data).
- Available databases (barringer1.com, 2010).
- Software based on each of the above.

Online databases can also be a source for typical values of β.

As stated above, in the dynamo case, verifying the solution was done with observed failure data which are not available in future cases.

4.4 Conclusions

There is very few data at Loodswezen. The dynamo of the Aquila Class C32 was chosen as a case study because this component has a reasonable amount of failure data and only has inspections (no preventive replacements or revisions). Even with this 'ideal' component, just 15 failures could be determined. With these failures and by the expert opinions, the Weibull parameters can be estimated in two ways:

- Conventional Least Squares method (data-driven).
- Bayesian expert elicitation.

The Bayesian method consists of a method to elicit information from experts (prior) and later update this with observed failure data (posterior). In Table 4.13, a summary of the findings shows the outcomes of the FMECA (which is currently used), the data-driven method, both experts individually, combined (prior) and updated (posterior).

Type	α	β	MTBF
FMECA	-	-	91
Data-driven	667	1,41	607
Expert ε_1	896	1,16	851
Expert ε_2	1384	1,38	1264
Prior	1020	1,38	932
Posterior	932	1,50	841

Table 4.13: Summary of outcomes.

A couple of things are notable:

- Expert ε_1 estimated the MTBF during the FMECA. Somehow this expert became way more optimistic in estimations (MTBF from 91 to 851 days).

- Both experts are more optimistic about the performance of the dynamo than the past observations. This can be explained by the facts that expert tend to remember recent event more clearly than earlier events (1) and because they (unconsciously) predict the future (2). Due to design changes, the performance of the dynamo has been better recently.

5. How can information of failure behavior be translated to a maintenance planning?

Chapter 4 has shown ways to gather data and calculate parameters to model failure behavior with the Weibull distribution. With this information, the optimal replacement or maintenance interval can be calculated. There are different ways to give this meaning in practice. These different ways of dealing with maintenance planning will be discussed in this chapter.

In the first section, the current situation is described. In the next section, the decision variables are discussed. The rest of the chapter contains different methods to do planning of maintenance.

Note that in this chapter, the data-driven solution (β = 1,41, α = 667) is used. This is because data-driven solutions (objective) are preferred over subjective solutions (prior/posterior). As in this case the objective information is available, this will be used to plan the maintenance with.

5.1 Current policy

In section 3.5, the theory of different replacement strategies is explained briefly. Loodswezen currently uses an age maintenance policy (i.e. maintain components individually based on their age, measured in for instance calendar time or operating hours). This policy leads to efficient maintenance per component. In order to be able to perform this maintenance at once, the maintenance tasks are clustered and grouped with harmonized maintenance intervals (Gits, 1992). This means the following for Loodswezen:

- PM-plans are made for each second-level system of the vessel (e.g. propulsion system - starboard engine) separately. This practically means some kind of clustering, as maintenance on the engine will have at least some shared set-up time with other maintenance on the engine and this will also be more than the shared set-up time with for instance the radar system. The different second-level systems that are covered in PM-plans are called "*clusters*". In this case, the maintenance of the dynamo is in the cluster "C32 Engine".
- Each cluster contains different grouped activities that might or might not have shared set-up times. The activities are grouped based on time. In this case, the maintenance of the dynamo is in the "*group*" of 3000 hours.
- In addition to this, the groups are harmonized. This means in practice that they are all an integer (*geheel getal*) multiple of the smallest group (250 hours). In this case, the group of the dynamo (3000 hours) is a multiple (12x) of the smallest group.

In this chapter, the following assumptions are made:

- The *cluster* in which components are located can *never change*. Both merging and adding clusters is not allowed. This means that the maintenance of the dynamo will always stay in the *cluster* with the rest of the engine and will never move to for instance the radar system *cluster*.
- Loodswezen uses an age maintenance policy; this will not change to for instance a block maintenance policy.
- The smallest group (250 hours) will always be the same. As the maintenance plan is harmonized, a change to for instance 300 hours would mean the whole cluster and even the whole preventive maintenance of the vessel need to be changed dramatically. The *groups* that are an integer multiple of this smallest group *are* allowed to change.
- Maintenance that involves overhauls (7000 hours, and 28000 hours in particular) is usually at least partially a legal requirement. It is assumed that these can therefore not be changed.
- There are two scenarios available for Loodswezen:
    - The position of components in a group can change to another existing group (section 5.3).

- The position of components in a group can change to another existing group, or a new group can be added with the restriction that the new group must be an integer multiple of 250 hours (section 5.3).

To summarize: there a *clusters* that are based on the equipment. These are assumed optimal and *will not be changed*. Each of the clusters consists of *groups* that represent a certain time interval and specific tasks. The groups are all harmonized according to the smallest group (250 operating hours interval). The groups *can* change.

To get an idea of the amount of groups and their time or usage triggers, a relevant review can be found in Table 5.1. These are the active groups that belong to the cluster C32 engine. Each of the groups includes different tasks and as stated above, they are harmonized. This practically means that when group 4 is executed, groups 1, 2 and 3 are also executed.

The term ‘offset’ means that the maintenance is done ‘in the first hours’ after a large revision (which typically happens every 7000 hours and an overhaul after 28.000 hours). This means for instance that package 16 is only performed 250 hours after the 28.000 maintenance. One can compare maintenance with offset with tightening screws of your furniture, a couple of weeks after assembly. A package with offset is *unique*. This means that the package *28.000* is *different* from the package *28.000 with offset 250*. The observant reader will miss the 28.000 package in the table (only the 28.000 with offset is shown). This is, because the overhaul is outsourced, while the maintenance after 250 is done by Loodswezen itself.

Group	hours	Offset	Group	hours	Offset
[1]	250		[9]	2000	
[2]	500		[10]	7000	
[3]	1000		[13]	14000	
[4]	3000		[16]	28000	250
[5]	4000		[24]	7000	250
[8]	10000				

Table 5.1: Aquila C32 PO-plan time intervals.

As stated earlier, the smallest time interval is 250 hours. This consists of three activities:

- Lubricating oil sampling.
- Lubricating oil change.
- Lubricating oil filter change.

This means that with every maintenance activity, the above activities will be part of the maintenance. A total overview of all groups within cluster C32 engine, can be found in Appendix I.

A final note in this section is about the fact that the maintenance is planned in operating hours and the relevant parameters are all expressed in calendar days. This is, because experts are not able to give (reliable) estimates on failures based on operating hours. Therefore, all calculated calendar days should be converted to operating hours at the end of the analysis. The number of operating hours per day is 7,4 hours on average. This is calculated by taking the average number of running hours per day of all Aquila engines. The whole calculation of this can be found in Appendix J.

5.2 Decision variables

With the parameters and distribution from chapter 4, one can determine the probability that a component has failed after a certain amount of time. Usually however, this probability is not the decision variable because it says nothing about the costs (e.g. time or money) for the company. The costs are usually the criterion for these kinds of problems. Usually, companies have a very simple goal: minimizing costs. Preventive maintenance is usually (way) cheaper than corrective maintenance (as less failures are observed). The company can do multiple times of preventive maintenance for less money than when they would have decided to let a component fail.

Loodswezen does not want to minimize costs, but the effort (measured in downtime) for maintenance. Let's call the effort (cost) for preventive maintenance c_p and the one for corrective maintenance c_c. The decision making has the convenient property that for calculating the optimal replacement time T*, not the actual amount of costs is important, but the ratio $\frac{C_c}{C_p}$ (*cost ratio*). The optimal replacement interval therefore depends on the cost ratio, α and β. This property can be used to determine the optimal replacement somewhat easier: an expert just needs to estimate how much more downtime a corrective maintenance task costs as opposed to a preventive one. In Figure 5.1, one can see that the larger the difference between corrective and preventive maintenance, the faster a component will be replaced preventively. The y-axis shows the optimal replacement interval, which clearly drops when the cost ratio increased. The x-axis shows the cost ratio from 2,5 to 8 to increase the readability of the graph. Below a ratio of 2,5, the graph increases rapidly to infinity while after a ratio of 8, the graphs are just horizontal.

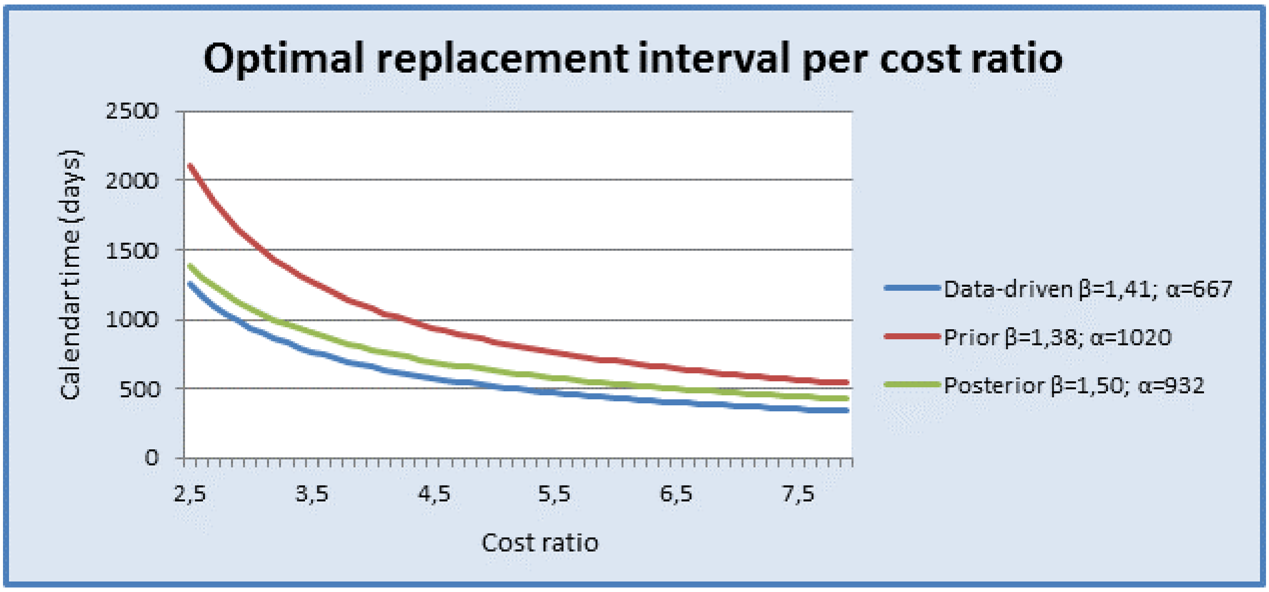

Figure 5.1: The ratio of corrective and preventive maintenance effort.

The value of α determines the height of the optimal replacement time, the β determines the shape.

It makes sense to ask multiple experts a question like *'How much more downtime does a planned maintenance action take, compared to an unplanned maintenance?'*. This question might be easier and faster to answer than the question how much down time each maintenance action will require. After asking expert ε_1 the question above, it became clear why it is so difficult to give exact numbers. A dynamo failure in Hoek van Holland, with spare parts on stock, during office hours, may take just a little more time than preventive maintenance [1]. This extra time is consumed by the diagnosis of the problem, and the possible return to the port (let's assume this takes on average 15 minutes). However, when it is weekend, night, and a failure occurs in Eemshaven, it obviously takes up more time [2], due to unavailable personnel. An illustration (with real estimated (down) times is shown in Table 5.2 for planned maintenance and two extreme scenarios for unplanned maintenance. It is assumed that components that cause immediate down time when being on failure are always on stock.

Activity	Planned	Unplanned [1]	Unplanned [2]
Repair/Replacement	90 min.	90 min.	90 min.
Return to port	None	15 min.	15 min.
Diagnosis	None	30 min.	30 min.
Checking spares	None	30 min.	60 min.
Travel to Hoek v. Holland	None	None	45 min.
Travel to destination	None	None	180 min.
Total	90 min.	165 min.	420 min.
Ratio	1	1,833	4,667

Table 5.2: Downtime associated with maintenance scenarios.

The actual repair or replacement is assumed to always take 90 minutes. The vessel might need to return to the port after a failure occurred at sea. The diagnosis of the problem by telephone is estimated to take about 30 minutes. Then one has to check the availability of spares. This should not take too much time. Then a mechanic needs to travel to the office to get the component (unless he is already there). Then he has to travel to his destination (in scenario [2], this is Delfzijl). To get a rough estimate of the ratio, the average of the two ratios (1,833 and 4,667) is used: **3,25**.

But this is not necessarily a point to stop. Just downtime might be a good decision variable for Loodswezen. However, it might be the case that money is also important, although (way) less than downtime. Relevant for Loodswezen is also safety and can also be a factor in the decision if a way is found to quantify safety (how much safer is not having a failure compared to having a failure?). These factors can be implemented within this ratio rather easily but updating the number with the weight that the company wants to give to for instance: a multi-criteria approach. Because the relation between this ratio and the optimal maintenance time T is not linear (as can be seen in Figure 5.1), this would require some modifications however.

5.3 Planning maintenance

From the analysis in chapter 4, one can very easily calculate optimal replacement times. In this section two similar ways of dealing with this are presented.

1. If the groups should stay the same, for instance because of warranty issues or because this is easier to plan, at least the information created in the previous chapters can be used to change the groups that a certain component is in.
2. The second way is somewhat more radical. Components are not only shifted between groups but also new groups are created (or merge or delete).

The most transparent and easy way to determine when to do preventive maintenance is the so-called age replacement strategy. The idea is that one determines the optimal time to replace a single component. Some companies like Loodswezen then group and harmonize all single components.
In a normal single component age strategy, one would optimize the costs that a company makes. As corrective maintenance is typically way more expensive than preventive maintenance, this will lead to a cost-effective maintenance plan. A short example below will show how this could be done. G(T) has to be solved for every T in order to find the optimal replacement time T*.

$$g(T) = \frac{c_p\overline{F}(T) + c_c F(T)}{\int_0^T \overline{F}(T)dt} \qquad \text{(Eq. 13)}$$

$\overline{F}(T)$ is the survival function that was presented and F(T) the cumulative probability distribution. The integral in the denominator is solved numerical, with use of the trapezoid rule. This is a fast and good estimate of the integral in which the surface of the function is estimated by calculating the surface of very small pieces and adding them. The smaller the steps, the more exact the method is. Steps of 'one' (T = 1, 2, 3…) seem to be enough in order to estimate the integral with an accuracy of hours in a calculation in which the input is in days. This indicates the method is more exact than the input from Loodswezen and therefore is good enough.

Scenario	Real (Mean Least Squares)
α	667
β	1,41
Ratio C_c/C_p	3,25
Optimal T*(calendar)	844 days
Optimal T* (operating hours)	6246 hours
1. Nearest currently existing group [group]	7000 hours [10]
2. Nearest to group to be designed	6250 hours

Table 5.3: Overview of planning.

As can be seen in Table 5.3, when looking at the gathered failure data (only the real ones), assuming C_c/C_p to be 3,25 and 7,4 operating hours per day per engine, the optimal *replacement* moment is after 6246 operating hours. The nearest group that currently exists is 7000 hours, which is a major revision. The replacement (revision) of the dynamo is already in this group now. If one would be allowed to add new groups, a group of 6250 hours could be made to do maintenance optimally. Note that this is the optimal replacement interval. This means that the dynamo should be renewed at this moment. This can mean a new dynamo should be placed or the dynamo should have a revision or another major maintenance. This interval says nothing about maintenance that does not totally (or nearly) renew the component like inspections or cleaning.

The optimal replacement age based on the cost ratio of 3,25 and 7,4 operating hours per day per engine for the prior and posterior is respectively 10338 and 7296 operating hours. The posterior proves to provide a way better answer.

Based on the data-driven parameters (β = 1,41 and α =667), the downtime per time unit (calendar days) can be calculated. This is done by just evaluating the value of g(T) for these parameters α and β and C_c = 90 minutes, C_p = 292,5 minutes. The chosen time T is 946 calendar days (7000 operating hours) for the scenario that only uses existing groups (scenario 1). The time T for scenario 2 is 845 calendar days (6250 operating hours). The value of g(T) in the current situation, in which no preventive maintenance is done is calculated by the value of $g(\infty)$.

	Maintenance/replacement	Downtime due to dynamo	Improvement
Current situation	None	0,482 min./day	-
Scenario 1	Every 7000 hours	0,472 min./day	2,1%
Scenario 2	Every 6250 hours	0,471 min./day	2,3%

Table 5.4: Downtime and improvement under the assumption of the data-driven Weibull parameters.

In Table 5.4, one can see that based on the data-driven Weibull parameters, the expected downtime is almost half a minute per day in the current situation. The expected downtime will decrease slightly (2,3%) as effect of the used method. It can be seen that both the difference between the two scenarios and the improvements compared to the current situation are small. Both these aspects can be explained by the facts that both β (1,41) and the cost ratio (3,25) are relatively low. The higher these two parameters get, the more attractive preventive maintenance is. This means that in this case, preventive maintenance is less favorable and is therefore done relatively late. This fact makes that the optimal solution resembles the current situation in which no preventive maintenance is done.

5.4 Other necessary optimization methods

The goal of this research was to come up with a way to gather information about failure behavior. The proposed method(s) to do this was presented in chapter 4. The question is what can be done with this information. As could be seen in the previous sections, one can plan maintenance by some simple formulas. The formulas presented however, are based on an age replacement policy (replace component when a certain age is reached). An also they assume both corrective and preventive maintenance is 'perfect'. In the sections below, some possible extensions of the simple age replacement model with complete renewal from section 5.3 are discussed briefly.

5.4.1 Block maintenance models

As discussed in chapter 3, there are two basic models: age maintenance and block maintenance models. In an age maintenance model, a component is maintained when it reached a certain age. In a block maintenance policy, a whole block (which would either correspond to a 'group' or a 'cluster' at Loodswezen) will be maintained at once. Maintenance on a certain component is independent on what happened with the component before. In a very extreme case, a new dynamo for instance could be replaced the day after already in such a policy (this won't happen a lot though). For this reason, age maintenance policies have a slightly better performance, at least in terms of costs. Block maintenance policies are however way easier to implement as the history of each component does not have to be recorded. In addition, a block maintenance policy *could* feature benefits in terms of downtime, as one can use shared set-up times more easily.

Loodswezen currently uses an age maintenance policy that is pretty advanced as it is already clustered and harmonized. The main advantage for block maintenance in terms of decreasing downtime is that maintenance activities are put into blocks that are most likely comparable to the current clusters. For this reason, changing to a block maintenance policy would probably not lead to much faster maintenance and lower (expected) downtime.

5.4.2 Partial renewal models & inspections

A more important extension to the model that assumes complete renewal, is models with partial renewal and models that can handle inspections.

When replacing or revising a dynamo, the dynamo is indeed as good as new (complete renewal). When re-attaching the v-belt on the dynamo, the dynamo is functioning again, but still is in a state that is 'as bad as old'. Sometimes however, maintenance consists of tightening screws or cleaning. This will increase the lifetime of the component, but it will not renew it. The current model assumes that all maintenance makes components as good as new, which is not always the case. To solve this problem, there are many models that assume partial renewal. These models can model every result of maintenance between 'as bad as old' and 'as good as new'.

A very important maintenance type that does not change the state of the system is inspections. After an inspection, the system will not be renewed (unless a failure or near-failure is detected). There are also a lot of models to model inspection. The choice where it is all about here is when to do inspections as obviously these also cost time. It could be clever to increase the rate of inspections with the age of the components. As a degrading component becomes older, the probability of failure becomes higher and the probability that the component will survive until next inspection will be smaller. There are models that can model the degradation and decrease the interval between inspections when the degradation reaches a certain point. An interesting question for Loodswezen might be what to do with the results of an inspection. Obviously if the oil has a certain amount of contamination, it will be replaced. But when is a dynamo 'too dirty', when is a screw 'too loose' and when is the alignment of a dynamo not good enough? Even more interesting is the decision to wait with preventive maintenance until next inspection or failure, on what basis is this done?

To conclude, in order to model partial renewal and inspections, many models are available. These models can be as simple and as complicated as one wish.

5.4.3 Opportunistic models

For Loodswezen, opportunistic maintenance models are very promising. Opportunistic maintenance is already done at the company, although the decision is currently based on the judgement of the workshop manager. When a component fails and preventive maintenance is nearing (let's say the engine is at 2800 operating hours and maintenance is planned at 3000 hours), preventive maintenance might be brought forward. This way, the vessel will be in maintenance only once. This should increase availability.

Of course, the decision is quite hard. If this failure occurs at 2800 hours, is that too early to do 3000 hour maintenance? This decision is currently made by a person but with the use of opportunistic models, one could calculate the optimal threshold to use the opportunity of preventive maintenance. There are a lot of these models with a wide variation in complexity. One has to understand that the decision is somewhat more complicated than "shall we do it now or later?". Although chapter 4 provides the parameters needed to calculate this, there are more issues involved. For instance inspections that are needed because of warranty. Bringing forward the preventive maintenance now could then lead to the demand from the supplier to bring forward next preventive maintenance too in order to keep the maximum time interval between two maintenance instances the same. This would then lead to no real benefit. In addition, one has to for instance certifications that have to be done before a certain moment and will be valid for, for instance, one year (so you just move the problem to next year). On top of that, maintenance that is done by external companies cannot (always) be part of such a system. In an opportunistic model, the date that maintenance is done can change every day so no appointments can be made with your service suppliers.

5.5 Conclusions

The Weibull distribution that was found in chapter 4 can be used to determine optimal maintenance intervals. In this chapter, a basic age maintenance method with complete renewal is used to calculate optimal maintenance times. Two ways of giving meaning to these optimal maintenance intervals are proposed:

1. Use existing groups (time intervals) only.
2. Add new groups to the system.

In the dynamo case, the first case means that the dynamo is preventively replaced or revised after 7000 hours, the second case means the replacement is done every 6250 hours. These numbers are based on β = 1,41, α = 667, cost ratio = 3,25 and an engine is used 7,4 hours a day on average.
The 7000 hour interval replacement features a reduction in downtime, caused by the dynamo, of 2,1%. The 6250 hour interval replacement gives a reduction of 2,3%. The benefits of the optimization are rather low in this case because:

- β is relatively low (aging is relatively slow).
- The cost ratio is relatively low.

With this, Loodswezen can build a maintenance planning of its own. In order to make this somewhat more precise and to improve performance, block maintenance models, partial renewal models, models with inspections and opportunistic maintenance models can be used.

6. How can a new maintenance policy be implemented?

One can imagine that extending (or at least changing) maintenance intervals, can lead to dangerous situations as wrongly expert opinions can be the cause of failures at during operations. The accuracy of the proposed methods is not extremely high and fairly experimental in the sense that Loodswezen would be one of the first to use this method. In addition, the past is not always a good predictor for the future. As experts are asked for their experience from the past, it has to be assumed that the future will see the same failure behavior as the past. This assumption is not always justified (Tinga, 2010). Nevertheless, the proposed method is very useful, as it is huge improvement to the current situation, in which the maintenance planning is not based on a model but on the judgement of suppliers. In addition, the method is able to improve over time which makes it both useful today and later. Before implementing these kinds of subjective methods, one has to be aware that these methods do not represent reality but estimate reality.

In this chapter, the recommended trajectory is discussed. This trajectory starts with the choice of suitable additional components. Then the right people have to be selected. Finally, the analysis has to be done.

6.1 Starting the project

The implementation of an expert opinion driven maintenance policy starts with a proper demarcation of the objects of interest. The proposed method is more accurate than the questioning during the FMECA, where only MTBFs where asked and a discussion was conducted until consensus was reached, which was usually after a couple of seconds. The method that is proposed in this report is more time consuming. In fact, one of the key factors to success is taking time and overthinking decisions in an interactive interview between statistician and expert. Every component has (preferably at least two) experts but these will differ between different components. This means that a certain expert has a relatively low burden but a lot of different experts will be needed.

To start the project, one needs to map all components that have failed most or have a lot of preventive maintenance. There are many reasons to do this:

- Because of the time burden described above. It will take a lot of time to perform the analysis on every component.
- These components have most maintenance and are therefore the most relevant to optimize. In terms of maintenance effort, the more preventive maintenance is done, the more can be won. In terms of reliability, the better failing components are managed, the higher the reliability.
- Most knowledge will be known about these components.

The last point above is very important in the start of a project like this. There is no doubt that knowledge that is to be extracted is available in the minds of the experts. The statistician/interviewer has the task to get the information out in usable numbers. One could say that any error in the prediction really is an error in the interviewer's ability to extract the right information. The interviewer needs to practice its skills in order to retrieve the right information when there is no additional information available, for instance, when a component never fails. With component that fails most, one can practice and check the results. The components that fail the most can be seen in Appendix C. The components that have preventive maintenance cannot be automatically reproduced by the SAP system. The overview in Appendix I can be used to manually determine what components these are.

These components form a good starting point of the analysis.

6.2 Persons involved

For the expert elicitation, just three people are necessary: one statistician/interviewer and two (or more) experts.

6.2.1 The statistician/interviewer

This is the person that interviews the expert and is able to do the analysis. The person does not have to be a 'real statistician', however, the person should have basic understanding of:

- Least squares methods for analyzing failure data.
- Bayesian analysis (basic understanding).
- Weibull analysis, understanding of the meaning of α, β and the relation between these parameters and the MTBF.
- How to deal with uncertainty and the CDF that is elicited from the experts.

For the expert elicitation itself, it is important that the interviewer knows what exactly is to be asked and which outcomes are realistic and which are not. The analysis itself is automated in such a way that this is just 'pressing a button', so more than a basic understanding is not necessary. This basic understanding can be gained by reading (and understanding) this report and underlying analyses. Also the sources that are used (chapter 8) can be of help.

The same person will also be the interviewer. With the help of Appendix H, one can set up an experiment. The interviewer needs:

- Basic understanding of what the component in question does.
- The component's preventive maintenance plans, with corresponding time intervals and including inspections.
- Typical failure behavior of the component in order to verify whether the expert is on the right track or not (see section 4.3.5).

The interviewer needs to practice this elicitation with components with the most information, to check its ability to question experts.

6.2.2 The experts

In principle, only one expert is needed. It is however, recommended to use at least two experts (more is better). This way, outliers can be leveled somewhat. One can imagine that if an expert is way off with his prediction, the initial maintenance plan will be wrong. For the dynamo case, two experts were interviewed. Expert ε_1 is workshop manager and expert ε_2 is mechanic for the tenders (*Wal WTK*). Both are actively involved in FMECAs. The latter fact is a good starting point in the search for experts. The search for an expert is not really too difficult. Anyone who knows the history of maintenance of the component is suitable to be an expert. Expert ε_2 made a better prediction than expert ε_1. This could of course be coincidence, but it indicates that maybe someone 'from the field' can give better results than someone who is not. This is an important observation to keep in mind when looking for experts.

6.3 Implementation

When the components of analysis and the statistician/interviewer and experts are chosen one can follow the instructions as can be found in sections 3.8 and 4.3 and Appendix H. The Weibull parameters can now be estimated. If possible, the least squares method can be used (if enough data is available) to calculate the 'exact' α and β, as was done in the case study. With this information, one can compare the results from the experts with the 'real' outcome. In short, the procedure after the elicitation is as follows:

- Combine expert opinions to get one outcome.
- Update the Beta distribution's parameters with real failure data.

- Perform the analysis (Monte Carlo Simulation).

After the previous three steps, a Weibull function has been created in order to calculate optimal replacement intervals. How this works exactly is elaborated in chapter 5 and is, in addition, fully automated already. The models give answer to the question on when to do maintenance that brings the component back to new state. This means revision or replacement or very thorough maintenance like painting. One can also use the models for maintenance that does not recover the system fully, like replacing or revising a (critical) part within the component but the results will be somewhat less reliable. The models do not give answer (yet) to the question on when to inspections (see 0).

The implementation of maintenance intervals based on expert opinion alone (so without real failure data updating) is very risky and must be done with the greatest caution possible. It is a fact that the experts do not reflect reality. Once the real failure data are added, the method delivers pretty reliable information.

An important note is that, especially during warranty period, the requirements of the supplier have to be met. One could imagine that components that should not be preventively maintained at all have the requirement from the supplier to do so. In these cases there is no other way than do the minimal required preventive maintenance at the longest time interval in order to meet supplier requirements. As soon as warranty is over, one can (hopefully) make better decisions based on the findings in the past.

6.4 Conclusions

The implementation of the method with expert opinion should be done very carefully and with a small start. It will be time consuming and the results can never be as good as a result with real failure data. It is smart to start with a couple of component from which a lot is known. Find a statistician and two experts and start the process. After that, the statistician can again compare the expert elicitation results with the 'real' failure data based information and conclude whether it was done right or not.

7. Conclusion, Discussion & Recommendations

In this final chapter, a conclusion is drawn. After that, the discussion will state the limitations of the research and further research. The final section contains all sorts of recommendations which have not necessarily been mentioned before.

7.1 Conclusion

The research that is conducted has the goal to develop a method to design a maintenance policy that is capable of reducing the total maintenance time. For this, optimal (preventive) maintenance interval should be calculated. In order to do this mathematical models are used to model the necessary Weibull parameters α and β. The proposed methods provide a way to determine the value of these parameters by using:

- Least Squares method (data-driven).
- Bayesian expert elicitation (no historical data needed).

As not a lot of failure data is available, the conventional data-driven method often cannot be used. The Bayesian method can be used in these cases. A case study is conducted in order to evaluate the performance of the Bayesian method as opposed to the data-driven method and the FMECA outcomes. The dynamo of the Aquila C32 engine was the component the case was conducted on. The key findings of the experiment are:

- Experts are capable of (indirectly) estimating α and β with the proposed Bayesian method, although their findings are not very accurate.
- The results of the Bayesian method are of better quality than the results of the FMECA and can, in contrast to the FMECA, be used to optimize maintenance intervals.
- The Bayesian method can be implemented immediately and can be updated in order to create to more accurate parameters and therefore more accurate maintenance planning.

With the estimated Weibull parameters, the maintenance intervals can be optimized. Loodswezen uses an age maintenance policy with harmonized groups, based on operating times. In addition, different equipment has its own cluster (e.g. C32 engine). The base time interval (from which all other time intervals are harmonized) is 250 operating hours. This means that all time groups are an integer multiple of 250 operating hours. Within this context, two options to improve the current planning are proposed:

1. Changing the groups of components to existing groups.
2. Creating new groups in order to optimize the previous step further.

The first option has the advantage that the administrative burden of changing the maintenance program is minimized. The disadvantage obviously is that the solution features a lower improvement in terms of reduced downtime, as it is further away from the optimal maintenance interval.

For the dynamo case, the reduction in downtime caused by the dynamo is 2,1% for the first case and 2,3% for the second case. The differences between the two options are not very large in this case. In addition, an improvement of just over 2% is not much. This is caused by two factors:

- The dynamo ages slowly (low β).
- The cost ratio is low.

To summarize, the maintenance policy that is used here to reduce the total maintenance time consist of two steps:

- Determine Weibull parameters α and β, either by the Least Squares method or by the Bayesian method (depending on the amount of data available).
- Use the Weibull parameters to calculate the nearest existing group to plan the maintenance in (1) or the nearest group that is a multiple of 250 (2).

7.2 Discussion

In this section, an overview of the weaknesses of this research and important facts to take into account is shown. Both are an important first step to start the proposed method and to potentially do additional research.

- The analysis in this report is based on the assumption of total renewal. This means that when maintenance is done, the component will be as good as new after the maintenance. For corrective maintenance, assuming this is usually good enough, as broken parts are often revised or replaced anyway. As can be seen in Appendix I, much of the preventive maintenance involves replacement or revision and can therefore be gathered under total renewal. Also, a large part of preventive maintenance involves for instance cleaning, tightening screws or lubricating. These actions will increase the lifetime but with what factor the lifetime is extended, is unknown. For these situations, partial renewal models are available. This is not part of this report but can be included fairly easily with the Weibull distribution parameters that were found.

- A large part of the preventive maintenance actions are inspections. This report did not come up with a solution for inspections. Inspections obviously do not change the state of the system but only evaluate it. Inspections are needed when the state of the system cannot be observed. This is for instance the case with inspections like oil samples or with the output values of the dynamo. Inspections usually lead either to no actions or a preventive maintenance action. The latter will happen when the component is on failure or in a state from which the mechanic thinks it will not survive until next inspection. There are methods to model the number of inspections in order to get the best result with the least effort.

- A drawback of the use of historical data is that these data are from the past and for instance usage is not the same in the future (Tinga, 2010). When asking experts for their opinion, this problem becomes way more complex. First of all, experts (and any human for that matter) tend to remember recent event more clearly than events that occurred earlier. This is one of the key reasons that the expert opinion gave a way higher α (representation of the MTBF) than the real α; recently performance became better. In this case, this might actually have improved the prediction of the future as performance indeed should be better now. The effect of higher performance can however be temporary. The biggest problem is that this cannot be said with certainty and this effect will be different in every component. The second point is that experts tend to give predictions as ‘it should perform’ instead of how it historically has performed. If changes are made to the design of the component like in the dynamo, this can have positive effect to the quality of the prediction. But again, the problem remains that it is not known whether or not the component has performed ‘as it should’ in the past, nor if it will in the future. Nearly all models feature this problem, which can only truly be solved by monitoring the state of all components.

- The case of the dynamo was chosen because the part did not have preventive maintenance, which is favorable in a case study because this means that failure records are not censored (i.e. they represent actual lifetimes instead of artificially produced ones). The dynamo however, reveals a big problem in any data analysis or expert elicitation method. This problem is that the design or even the whole component can be changed in the meantime. When this happens, any past lifetimes become useless and in addition expert elicitation has to be done again. In the case of the dynamo, both a change in the model of the dynamo and the pulley it joined to are changed.

- In this report, uncertainty has been left to the Bayesian analysis. A lot of random realizations have been made and their mode has been chosen as final α and β for the Weibull distributions. It would be more correct to move this uncertainty to the moment of calculating optimal maintenance intervals. This would mean that the optimal maintenance is not presented as a result of α and β, but are treated as uncertain. This would then result in many different values of optimal maintenance interval. This system could lead to better results.

- The power of the expert elicitation method lies both in the fact that it is more accurate than the FMECA results and can be used (directly) to optimize maintenance intervals. In addition, it can be updated with real failure data. The updating process however, only features updating after failures have occurred. If no failures occur (when the expert were way too pessimistic), no failures will occur and no updating can take place. For this reason, this method can still lead to too much maintenance as a wrongly predicted failure rate by the experts is never updated. One should monitor the performance of the expert elicitation and if there are suspicions that the results were (way) too pessimistic, the process should be done again.

7.3 Recommendations

In this section, the most important recommendations are shown. Obviously the most important recommendation is to start the trajectory as presented in chapter 6. One does have to be careful with this as this could take a lot of time (start small). The recommendations in this chapter might be slightly unexpected, as not all points have been discussed in the report. It would however be a shame if not findings were presented.

- Loodswezen is recommended to investigate the use of models based on physics and not based on failure data, as soon as they come available in the MaSeLMa project. It is likely that physical models will be more accurate than the proposed expert elicitation method while they also don't require failure data. Because of the small amount of vessels and the fact that Loodswezen does not want to let the vessels fail, it is to be expected that failure data will never be available.

- Although using physical models is a good solution to the problems Loodswezen has, it is always wise to have failure data too. The following data are helpful for the analysis if gathered accurately:
    - Exact date a failure was detected.
    - Exact time the repair started.
    - Exact time the repair ended and failure was solved.
    - Exact starting and end time of preventive repairs per task (so not per group as is done now).

All of the above mentioned data should be recorded on the basis of an individual component. This means that if there are multiple components of the same type in one equipment (e.g. cylinders in an engine) each should be mentioned separately. The reason for this is that there is a need to gather information about the lifetimes of all components so it is necessary to be able to exactly identify the component that has failed.

This does definitely not mean that for instance the pulley of dynamo should be treated as separate object. Besides the fact that this would cause an enormous administrative burden, this would also enlarge the problem of a lack of data, as components are split further into smaller components. It is recommended to analyze failure data per equipment that also receives preventive maintenance. In case of the dynamo it is the dynamo that receives the maintenance (not the pulley) and therefore this is the smallest component to document data on.

At this moment the above mentioned data is already being gathered but the quality is rather low. The reason for this lies in three issues:

- Employees do not know the purpose of gathering and therefore are not exact when doing administration. To increase the quality of the gathered data, some awareness is necessary.
- The (time) burden for employees is (too) high. To increase quality of data, filling in data should be made easier. There is a possibility to fill in an almost automatic form on a Tablet, while being at sea, and later upload this data automatically to SAP once on shore. This makes it possible to fill in data fast and very accurate as it can be done on the exact moment an event occurs.
- Often, administration is erroneous due to 'human errors'. The measured operating hours for instance are often misread or filled in wrongly. Aspects like operating hours (if the counter is digital or made digital) can be retrieved automatically by for instance RFID chips, Bluetooth or even internet. Technologies like this do not cost much money, decrease the time burden for employees and make the quality of retrieved data almost perfect.

- In addition to the data requested in the previous point, also the data of vessels being in service and out of service is not accurate. The problem that occurs most often is that vessels are being reported out of service, but are not reported in service as soon as they are. With this information in mind, one can imagine that the actual technical and operational availability are already much higher than currently known.

- Note that SAP is capable of analyzing failure data automatically, once the right information is filled in. The system can for instance calculate mean time to repair, mean time between failures and can at least automatically give an output of all failures with dates and equipment. This would save a lot of time when analyzing failure data (with for instance least squares method).

- In order to make an advanced planning, it would be good for Loodswezen to look at other models to optimize maintenance intervals. This means including at least inspections in the model as these are used regularly. This could however also lead to a total new way of doing maintenance (block maintenance) and/or an opportunistic approach. It is up to Loodswezen how complicated they want to make it. Adding partial renewal and inspections and even implementing an opportunistic model *can* be fairly easy.

Let us finalize this chapter with some observations.

- Some extraordinary observations were made during conversations with many people at Loodswezen. While some components may have up to six-fold redundancies, a vessel is reported out of service once only one of these redundancies fails. Sometimes vessels are reported out of service for a broken (entertainment) radio. It is the captain's call whether or not he or she thinks it's safe to leave the port. While the latter certainly is a good thing, one has to be aware that this sometimes leads to excessive 'out-of-service-reporting' and that this has negative effects on the operational availability. One has to ask the question whether a vessel is really not able to operate with one less redundancy. As long as safety is not at stake, Loodswezen should try to make optimal use of the luxury position of having equipment that is (multiple) redundant.

- Some people indicated that not all preventive maintenance that is announced in theory is actually performed the way it should. For the dynamo this practically means that 'cleaning' is not done while SAP does mention the activity (there is no equipment to clean anyway). This is not strange, as the Caterpillar user manual does not say anything about cleaning. It does say something about measuring output values of the dynamo, which in practice is also not always done. In order to do the analysis in this report in a reliable way, preventive maintenance must be done as stated in SAP and SAP must state the preventive maintenance that is done. Fact is, that cleaning (little effect) is a very different task than measuring output values (no effects, but failures can be detected early).

- It is strange that maintenance on the dynamo is done every 1000 hours at the P-Class and every 3000 hours at the Aquila Class, while the manual recommends every 5000 hours. PON stated that they did their best to customize the maintenance intervals for Loodswezen specific and as the P-Class is used not very heavily, one would assume the intervals to be somewhat relaxed as compared to the usual recommendations. Note that some components age faster when not used actively (this could be the case here). This is something really worth a look at.

- Just like all definitions, the definition of maintenance orders (ZM01 to ZM08) should be mutually exclusive and collectively exhaustive. This means that each ZM order is defined such that it cannot be put under another order type. In addition, all orders together should explain all scenarios. Currently, especially the first point seems to be problematic. For instance, the difference between ZM01 and ZM08 orders is very small and any order that has the property of 'preventively maintaining a broken or nearly broken component' can be either order. For instance a door with rust on it. Is the maintenance a repair-order or a maintenance order? Also the discussion on whether this order is preventive or corrective is a problem. Loodswezen determined that '70% of maintenance should be preventive', but how can this be measured? The definition of the ZM-orders is not correct or at least not carried out correct. At the same time, the definition 'all maintenance with a preventive maintenance plan is preventive' is not complete.

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A. Appendix – Loodswezen operations: key figures

Region	Port	2009	2010	2011	2012	2013	Share (2013)
North	Harlingen	553	504	568	579	602	0,66%
	Delfzijl/Eemshaven	2198	2480	2324	2637	2548	2,80%
	Total	**2751**	**2984**	**2892**	**3216**	**3150**	**3,46%**
	Change		8,5%	-3,1%	11,2%	-2,1%	
Amsterdam-IJmond	Den Helder	199	222	252	252	305	0,33%
	IJmuiden-Amsterdam	13448	13549	13828	13678	13429	14,75%
	Total	**13647**	**13771**	**14080**	**13930**	**13734**	**15,08%**
	Change		0,9%	2,2%	-1,1%	-1,4%	
Rotterdam-Rijnmond	**Rotterdam-Rijnmond**	**58565**	**60451**	**60663**	**56978**	**54965**	**60,37%**
	Change	-8,34%	3,22%	0,35%	-6,07%	-3,53%	0,00%
Scheldemonden	Dutch ports	9420	10394	10768	10769	10185	11,19%
	Flemish ports	9069	9656	9958	9353	9020	9,91%
	Total	**18489**	**20050**	**20726**	**20122**	**19205**	**21,09%**
	Change		8,4%	3,4%	-2,9%	-4,6%	
Total	Dutch ports	84383	87600	88403	84893	82034	90,09%
	Belgian ports	9069	9656	9958	9353	9020	9,91%
	Total	**93452**	**97256**	**98361**	**94246**	**91054**	**100,00%**
	Change		4,1%	1,1%	-4,2%	-3,4%	

Table A.1: Number of pilot trips of all regions and ports over time (Ecorys Nederland B.V., 2014).

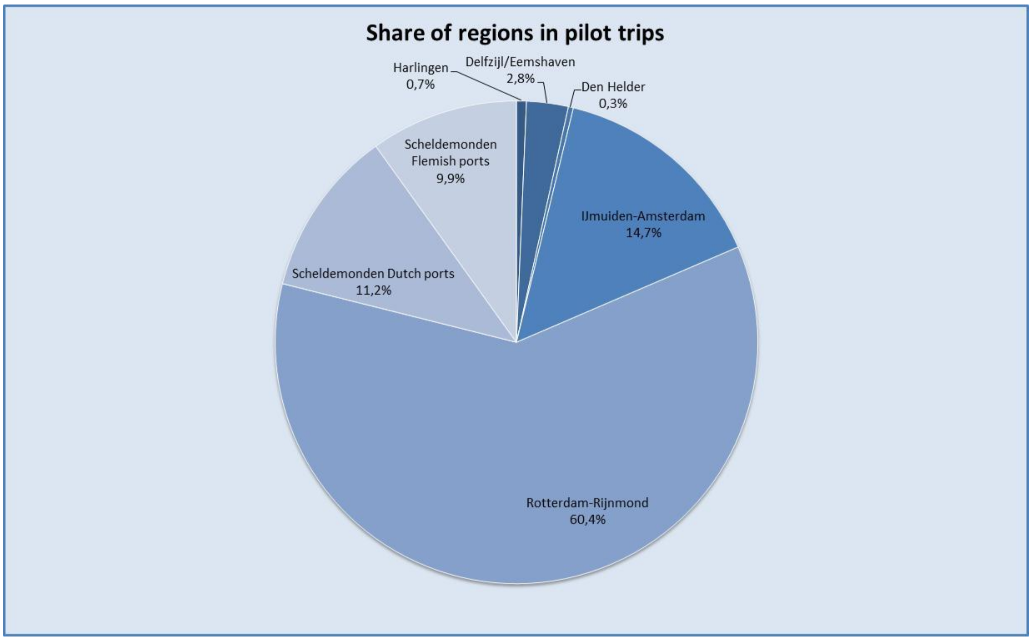

Figure A.1: Share of ports in pilot trips in 2013.

B. Appendix – Overview of operations

On the map below, a geographical representation of the operations is given. At the offices there are also spare parts on stock. There are also two spare vessels for the whole country (in addition to the ones in the regions). This means that the total number of vessels consists of the 14 vessels below and two additional spare vessels (17 in total). The number for Scheldemonden also includes SWATHs. Note that the situation below is not the current situation (October 2014) but the desired situation and that Rijnmond operations are, on paper, divided in a part at the Berghaven and a part at the Pistoolhaven.

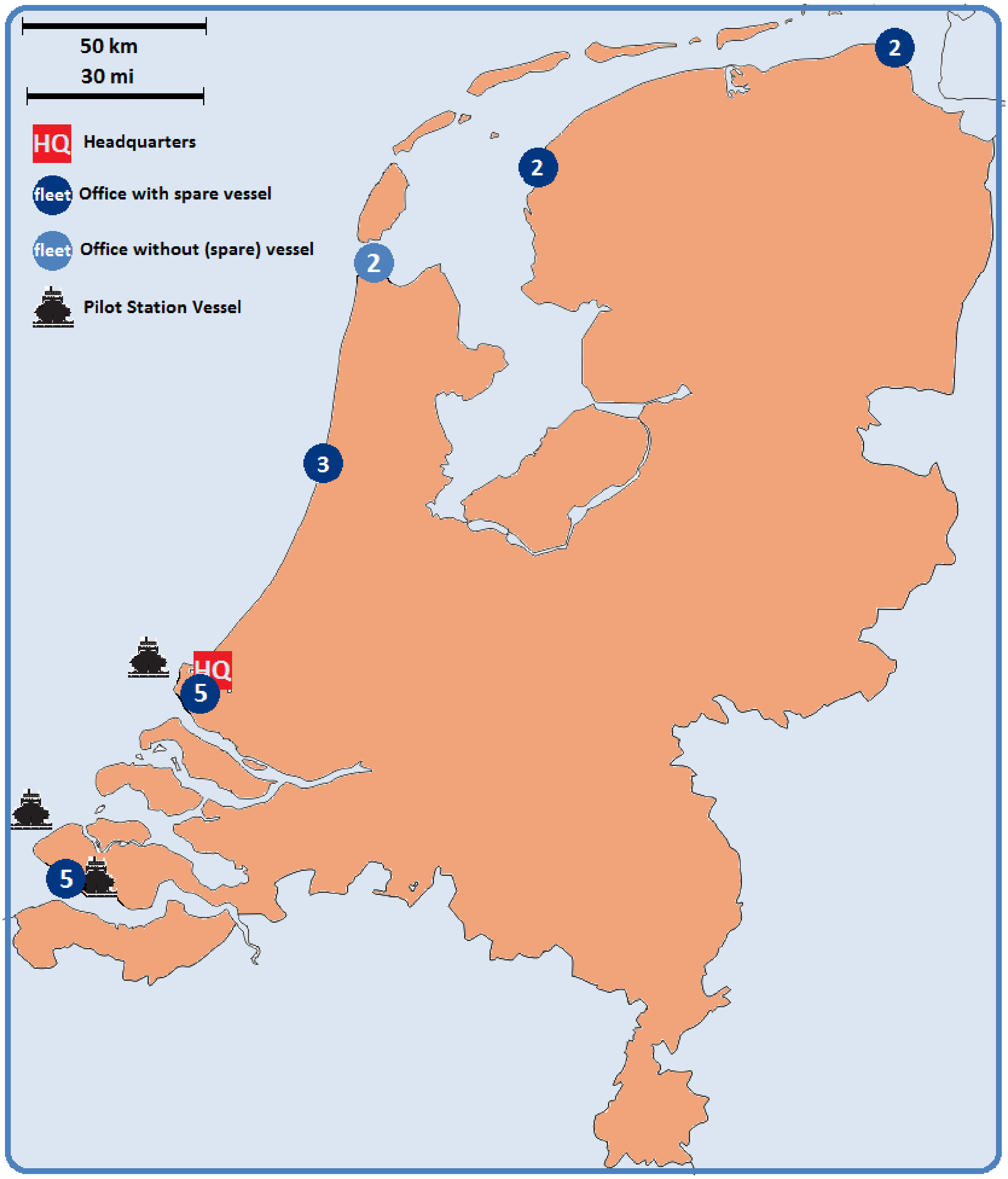

Figure B.1: Map of operations.

C. Appendix – Availability of failure data

The table below features the 30 most used articles based on the number of work orders (N.O.) in the period from 2012 until February 2015. The numbers are based on work orders without a notification (melding) because these are usually orders that are diagnostic and do not involve actual repair actions. Also, only the components from the propulsion system (and generators for P-Class) are taken into account and only components measured in pieces (*stuks*, ST), because meters (e.g. wire) or liters (e.g. oil) does not add any value to the model.

		AQUILA			**P-CLASS**
Article	N.O.	Description	Article	N.O.	Description
112410	121	Smeeroliefilter CAT C18,C32/ 3412E Acert	112410	123	Smeeroliefilter CAT C18,C32/ 3412E Acert
112528	78	Oliefilter M944T (AQ)	110065	93	Brandstoffilter, Racor 30 Mc groot (All)
112493	74	Rod-zinc CAT C32 ACERT / ZF3050 (AQ)	109136	75	Brandstoffilter, Caterpillar,3412E,(DJT)
112425	71	Brandstoffilter CAT C32 Acert (AQ)	115603	72	Carterventilatie filter 274-7913
113206	70	Air Filter Kit Cat C32 Acert (AQ)	115630	37	Air Filter Element - Primary
112423	66	Filter element primary Cat C32 Acert	112425	33	Brandstoffilter CAT C32 Acert (AQ)
112529	51	Brandstoffilter M944T (AQ)	113759	33	Filter element primary C18/3412E (DJT+)
112531	51	Zinc anode M944T (AQ HK LK)	113206	17	Air Filter Kit Cat C32 Acert (AQ)
110065	45	Brandstoffilter, Racor 30 Mc groot (All)	112423	10	Filter element primary Cat C32 Acert
112740	39	Filter Line HM651 (AQ)	112566	10	Dynamo Vsnaar V-belt C32 (AQ)
112724	39	Oil filter element MXR8550 HM651 (AQ)	116528	7	Olie filter tandwielkast AF1163 (PKL)
115135	32	Brandstoffilter, Racor 30Mc klein (All)	112496	4	Seal oring CAT C32 ACERT (AQ)
114976	28	Dynamo Vsnaar ASE M944T (AQ)	112537	4	Seal oring CAT C32 ACERT (AQ)
113205	26	Seal O ring Airfilter CAT C32 Acert (AQ)	113260	4	Seal O ring luchtldng => turbo (3412/C32
112530	25	Luchtfilter M944T (AQ)	112519	3	Aftercooler cover gasket item 8 C32, AQ
113220	25	Raw water pump Impeller kit (M944T)	115135	3	Brandstoffilter, Racor 30Mc klein (All)
112782	24	Filter 30 micron separ 2000/18 UD (AQ)	115636	3	ELC COOLANT EXTENDER ? x 0,946 Liter
112669	21	Oliefilter, gearbox ZF3050 (AQ)	115675	3	Fuel Filter Assy
112566	20	Dynamo Vsnaar V-belt C32 (AQ)	116792	3	Vervallen => zie 112518
112772	20	Filter 30 micron separ 2000/5 U (AQ)	111469	2	Seal lip Cat 3412E (DJT) (AQ)
113203	18	Air Filter Cleaning Kit CAT C32 (AQ)	112491	2	Regulator temperature CAT C32 ACERT (AQ)
111768	12	Seal O ring luchtleidng cooler (3412/C32	115585	2	Gasket (201-4233)
112537	12	Seal oring CAT C32 ACERT (AQ)	115677	2	Air filter
112805	12	Dynamo Vsnaar M944T (AQ)	116527	2	Afdichtingset tandwielkast AF1163 (PKL)
113260	11	Seal O ring luchtldng => turbo (3412/C32	109865	1	Carterdampfilter CCV6000
113572	11	Dynamo, Cat C32 (AQ)	112518	1	Aftercooler cover gasket item 7 CAT C32
114963	10	Raw Water Pump O ring cover (M944T)	113203	1	Air Filter Cleaning Kit CAT C32 (AQ)
112644	9	Reverse Bucketcilinder HM651 (AQ)	113402	1	Coolant conditioner test strips CAT
112533	6	Raw water pump repair kit M944T (AQ)	115581	1	Core Assy Aftercooler
112651	6	Vouwbalg Bucket afm. 60/600 mm. (AQ)	115678	1	Breather assy C9 PKL

Table C.1: Overview of most used components.

D. Appendix – Gathering and filtering failure data

In this appendix, the process of gathering and filtering failure data is investigated thoroughly.

First a position (functieplaats) is chosen for which the analysis will take place. In this case, this will be on the components of AQUI-AANDR, DRAC-AANDR and ORIO-AANDR; the propulsion systems of the three Aquila class vessels.

Before the start, it makes sense to investigate whether equipment has been changed before. This is the case for the engines for example, there are eight for the Aquila class with only six in use. The equipment numbers can be found very easy with the form 'il03': fill in 'AQUI', 'DRAC' or 'ORIO' and navigate to the equipment of interest, in this case the engines. To find the equipment numbers of the engines that are currently not installed in the vessels type 'WERK-PLAAT' and navigate to the structure list again to see the equipment in stock. Now the equipment numbers are known, it is useful to create an overview like in Figure G.1 and Figure G.2 because the dates of failure in a certain position can be from different equipment. These dates can be obtained via 'ie03' in the history of serial information.

Now we are able to link the dates of failure to a certain equipment. For instance if a failure in the port engine of Aquila vessel occurred after 07-02-2013, it can be assumed that the failure occurred in the engine with equipment number 10003129. It is easy to determine the life time of a certain component now this information is available.

The next step is to determine the failure dates. This is a bit more difficult. The most convenient starting point is a list of the *usage of components*. This list consists of many components that are booked from the warehouse and back. It is important to select a component for this analysis and *not filter* on position (functieplaats), as not all bookings are made on the right position but the component is always correct. Most often, we see a virtual booking from the system. It indicates that a certain component might be needed when doing maintenance. If this is not the case, the component will be virtually booked back into the warehouse. This means that the list cannot provide a convenient overview of maintenance. It can however, indicate the exact moments that maintenance on a certain component was *planned.* Note that this list is not useful in case the unit is measured in for instance liters (e.g. oil) or meters (e.g. wire), but only in pieces (stuks, ST).

Below, an example of what can be found:

Article	Description	Order	Notification	Position	Booking	Unit	Date book.
113572	Dynamo, Cat C32 (AQ)	5041475	10029809	AQUI-AANDR-BBMO	1	ST	18.02.2013
113572	Dynamo, Cat C32 (AQ)	5041475	10029809	AQUI-AANDR-BBMO	-1	ST	19.02.2013
113572	Dynamo, Cat C32 (AQ)	5041499		AQUI-AANDR-BBMO	1	ST	20.02.2013
113572	Dynamo, Cat C32 (AQ)	5041499		AQUI-AANDR-BBMO	-1	ST	25.02.2013
113572	Dynamo, Cat C32 (AQ)	5041499		AQUI-AANDR-BBMO	1	ST	20.02.2013
113572	Dynamo, Cat C32 (AQ)	5041499		AQUI-AANDR-BBMO	-1	ST	25.02.2013

Table D.1: Example of booking data.

The article column gives the number of the component, in this case the dynamo. At first, it seems like there are six records. When looking at the 'booking' it can be seen that components are booked out of the warehouse (1) and back in (-1). In addition, only two order numbers are used. It can be concluded that something happened *once* to the port engine of Aquila, at 18 February 2013. In order to see more details, it is needed to look up for order 5041475 and 5041499 in the order overview. This gives the following table:

Order	Type	Date	Description	Position
5041475	ZM01	18-02-2013	Aquila, Dynamo CAT BB defect	AQUI-AANDR-BBMO
5041499	ZM08	19-02-2013	Aquila, Cat Bb reparatie dynamo	AQUI-AANDR-BBMO

Table D.2: Example relevant orders.

One can see that the dynamo apparently malfunctioned at 18 February 2013 and it is repaired the next day. Now we can look at Figure G.1 at AQ-BB. This gives back that the concerning engine was 10003129. Note that orders before 2012 do not have a position and have to be evaluated manually, based on the bookings of the component.

If we perform this procedure for all records, we are able to produce a good overview of all failure dates. The next step is to determine the dates of preventive maintenance. This can be done very easily by the use of 'IW39'. Search for an equipment number and select the date range of choice. Select all orders and press 'taken'. It will show all tasks every performed on the specific engine. In this case we are interested in task '0330' which is defined as dynamo check and cleaning, we can look at when the order is executed to determine the date of preventive maintenance. The number for a certain task can be found using 'IA07', type 'UURBEURT' in 'Routinggroep' and '46' in 'Routinggroepteller' to see all tasks for this the global planning of an engine.

Now all calendar dates are available but we are more interested in the number of running hours of the engines, as this is the decision variable for preventive maintenance. When looking at the equipment 10003129 via 'IE03', one can see the number of running hours in 'meetpunten/tellers', the used measurement is 'Urenteller dieselmotor'. There are no records available for 18-02-2013, so we take the closest record on 25-02-2013, when the engine had 5735 running hours in total.

The actual failures cannot always be determined like in the example above. A couple of examples of assumptions and choices that had to be made:

- Order 5041235 does not determine whether it was a failure on starboard or port. Based on the fact that the port dynamo was changed just a month earlier, it was decided that this would probably be the starboard one.
- The port dynamo from the Draco most likely failed due to leakage of seawater at 03-08-2012 and on 20-08-2012 again. It is assumed that this was actually just one failure at 03-08-2012. Because the failure was externally caused, it makes sense to do the Weibull analysis without taking into account this failure. For this, it has to be assumed that the component would have survived until it's next recorded failure, if it had not failed due to the leakage.
- Order 5044687, 5035411 and 5053725 could not be traced back to an actual dynamo failure.
- Order 5041633 was most likely caused by human error and is not taken into account.
- The first day that the Aquila vessels were used was at the ceremonial ship launching (scheepsdoop) at 29-09-2010. Most engines had less than 100 running hours at that date.
- All corrective maintenance will return the component in an 'as good as new' state. It cannot be tracked whether a component was replaced or repaired, what the repair action was and how this would affect the lifetime of the component.
- The description (korte tekst) is always right.
- No dynamos are replaced preventively.

E. Appendix - Failure dates Dynamo

Equipment	Enter in service	First Failure	Second Failure	Third Failure
3050	29-9-2010	10-9-2014		
3051	29-9-2010	15-10-2012	1-3-2013	
3128	29-9-2010	4-8-2011	13-10-2012	
3129	29-9-2010	18-2-2013	12-5-2014	
3089	29-9-2010	22-11-2011	27-12-2012	17-10-2014
3090	29-9-2010	27-12-2012	17-10-2014	
3225	9-5-2011	18-2-2013		
3239	4-7-2011	10-9-2012	6-11-2012	

Table E.1: Overview of failure dates of Dynamo.

With the help of Appendix G, the equipment was connected to failure dates. In Table E.1 one can see the dates that the engines entered service. 29-09-2010 is the date the Aquila Class vessels entered service. For equipment 3225 and 3239, the first recorded date was chosen as enter in service date (these used to be spare engines). The dynamos in all engines have failed at least once, the dates of all failures (15 have been found) are shown.

Calendar	Operating times
57	576
137	2554
309	2591
401	3165
419	3258
434	3332
436	3333
448	3457
651	3501
659	4035
659	4090
747	4121
820	4883
873	5663
1442	6669

Table E.2: Overview of life times measured in calendar time and operating hours.

If one would subtract the failure dates from each other, one would get the overview in Table E.2. These are the lifetimes of the components. The calendar times are obviously measured in days. The dates and equipment from Table E.1 were also converted to operating hours (the closest record to the date of failure). Note that in Table E.2, lifetimes are not connected to equipment anymore. The lifetimes are ranked from small to large and the calendar time (let's say 57) does not necessarily correspond to operating times (576) in Table E.2. The lifetimes above are input for the least squares method described in appendix F.

F. Appendix – Data driven failure rate

In this appendix, one can learn a little more about how to construct a failure rate by a purely data-driven approach. The two rightmost columns in Table F.1 and Table F.2 is the input for a regression. This regression gives an x-variable and an 'intercept'. The x-variable is the β and $e^{-(\frac{intercept}{\beta})}$ will give the α.

Life Times	Rank	Median ranks	1/(1-MR)	LN(LN(1/(1-MR)))	LN(lifetime)	α	β
57	1	0,045	1,048	-3,068	4,043	**667**	**1,41**
137	2	0,110	1,124	-2,146	4,920		
309	3	0,175	1,213	-1,646	5,733		
401	4	0,240	1,316	-1,292	5,994		
419	5	0,305	1,439	-1,010	6,038		
434	6	0,370	1,588	-0,772	6,073		
436	7	0,435	1,770	-0,560	6,078		
448	8	0,500	2,000	-0,367	6,105		
651	9	0,565	2,299	-0,184	6,479		
659	10	0,630	2,702	-0,006	6,491		
659	11	0,695	3,277	0,171	6,491		
747	12	0,760	4,162	0,355	6,616		
820	13	0,825	5,704	0,555	6,709		
873	14	0,890	9,059	0,790	6,772		
1442	15	0,955	22,000	1,129	7,274		

Table F.1: Input for regression based on calendar life times and without preventive maintenance.

Life Times	Rank	Median ranks	1/(1-MR)	LN(LN(1/(1-MR))))	LN(lifetime)	α	β
576	1	0,045	1,048	-3,068	6,356	**4430**	**1,87**
2554	2	0,110	1,124	-2,146	7,845		
2591	3	0,175	1,213	-1,646	7,860		
3165	4	0,240	1,316	-1,292	8,060		
3258	5	0,305	1,439	-1,010	8,089		
3332	6	0,370	1,588	-0,772	8,111		
3333	7	0,435	1,770	-0,560	8,112		
3457	8	0,500	2,000	-0,367	8,148		
3501	9	0,565	2,299	-0,184	8,161		
4035	10	0,630	2,702	-0,006	8,303		
4090	11	0,695	3,277	0,171	8,316		
4121	12	0,760	4,162	0,355	8,324		
4883	13	0,825	5,704	0,555	8,494		
5663	14	0,890	9,059	0,790	8,642		
6669	15	0,955	22,000	1,129	8,805		

Table F.2: Input for regression based on operational life times and without preventive maintenance.

G. Appendix – Changing equipment: an overview

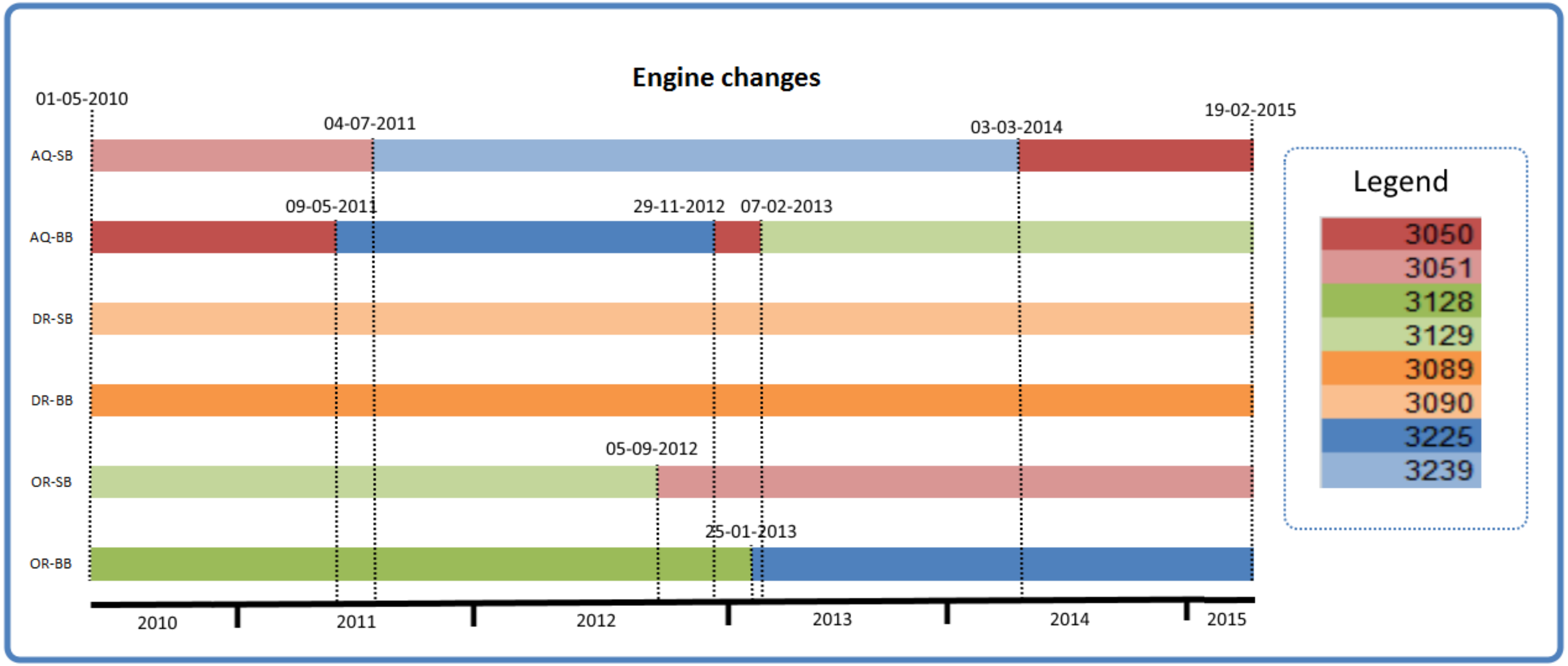

Figure G.1: Different engines for each position.

The abbreviations in Figure G.1 shorter than in the rest of the report due to space restrictions. AQ-SB for instance refers to 'Aquila starboard engine' or as indicated before 'AQUI-AANDR-SBMO'. The first four numbers (always 1000) of the equipment is also left out.

The figure should be used as follows. A work order is connected to a position (functieplaats), for instance Aquila-Starboard (**AQ**UI-**SB**MO). From 04-07-2011 to 03-03-2014 the engine with equipment number 10003239 was in that position. This way, a work order with position and date can be connected to equipment.

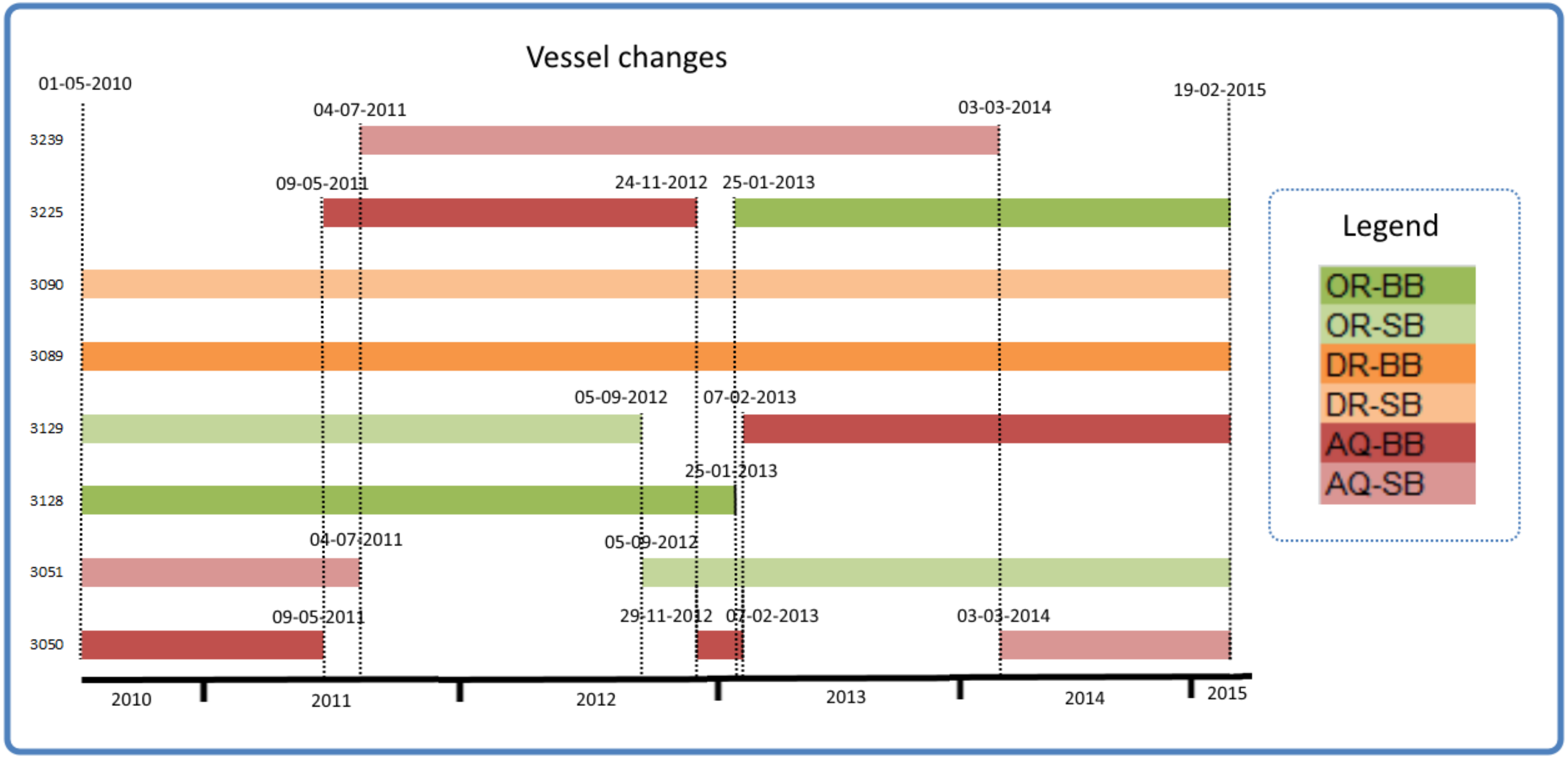

Figure G.2: Different positions for each engine.

The abbreviations in Figure G.2 shorter than in the rest of the report due to space restrictions. AQ-SB for instance refers to 'Aquila starboard engine' or as indicated before 'AQUI-AANDR-SBMO'. The first four numbers (always 1000) of the equipment is also left out.

Figure G.2 can be used in the opposite way from Figure G.1. With this figure, one can see where an engine was, how old it was and when it was replaced.

H. Appendix – Designing the experiment

The execution of this experiment should be done individually with only the 'statistical expert' (the questioner) and a 'technical expert' (the interviewee). The following steps need to be performed, if possible in the form of a presentation.

1. Welcome and introduction on what the intention is.
2. Example of what is going to be asked.
3. Introduction of the component it's assumed failure behavior and preventive maintenance tasks and intervals. In addition, discuss design differences.
4. Agreement on assumptions concerning for instance the preventive maintenance (yes or no, intervals, effects, inspection or maintenance) and what information to gather in the experiment. One of the most important assumptions is that a failed component will never return to the population (even if being repaired). A failure is any situation in which the components cannot fulfill its purpose. The expert needs to estimate the amount of time that an inspection/preventive maintenance takes.
5. Draw Figure H.1 and emphasize that this function can remain equal over time but can never decrease over time.

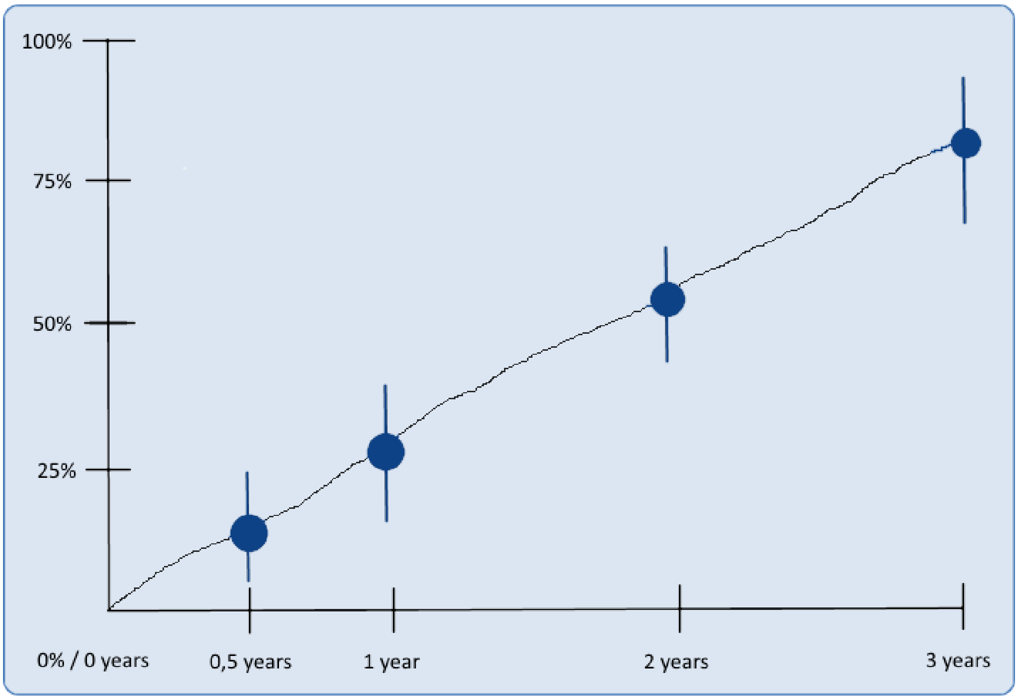

Figure H.1: Example drawing cumulative failures.

The figure is useful as it gives the expert a better understanding what outcomes may be. In addition, the 'variability' lines give a better understanding of what kind of variability we would like to get from the expert. In addition, it can be advantageous to use this diagram in order to visualize the fact that the time interval of 0,5 to 1 year is smaller than from 1 to 2 years. For reference, it can be beneficial for the accuracy to ask at what time the expert expects the full population to have failed. There is also a downside in using this figure, as participants tend to give answers that are close to the given scale (25%, 50% etc.).

6. Perform the actual experiment. Emphasize on the fact that there is a lot of uncertainty, between every single question. This might seem a bit over the top, but this is very important as experts tend to be very overconfident.

   The following questions were asked for all T years and scenarios:
   - How much of the population of 100 dynamos has failed after T years/operating hours?
   - What are lower and upper bounds for the time T as in: in ~90% of the cases, the percentage of fails will be between these bounds.

7. Reflect on the answers the expert gave if possible, in order to give the expert a direction.

As final point, it should be noted that one has to be very careful with non-observable information. It seemed like a good idea to tell the experts that the percentage can be interpreted as 'the number of parts that have failed from a population of 100'. A while after this was noted, the first expert came up with 8 failures (8%) after three years while the actual percentage was over 95%. It seemed he forgot that we were talking about 100 dynamos instead of the 8 that are present in the Aquila fleet. As 100 dynamos are not observable for the expert, it becomes very hard to come up with the right percentages. The solution for these problems is being interactive and giving constant feedback, especially if you suspect that it goes wrong. Repeating the assumptions of the experiment can help.

I. Appendix – Overview preventive maintenance cycles Aquila

In Table I.1, the different active cycle sets with corresponding tasks in Dutch. The values of the cycles are shown in the top row of the table, values times 1000 hours. Note that the cases 28,25 and 7,25 refer to maintenance done in the first 250 hours after the 7000 or 28000 (large) maintenance. Also note that the shortest cycle is 250 hours and that the 28000 maintenance is not specified, although the first 250 hours after are specified. All hours are operating hours. The time intervals (0,25 to 7,25) are times 1000 hours.

Operation	Description	0,25	0,5	1	3	4	10	2	7	14	28,25	7,25
5	Smeerolie monsteren	■										
10	Smeerolie wissel	■										■
14	(Scheepsnaam), preventief onderhoud			■							■	■
20	Smeerolie filters vervangen	■										■
30	Brandstof filters en racors vervangen		■									
45	V-snaren controleren / vervangen				■							
50	Koelwaterinspectie (ELC monster nemen)			■								
70	Luchtfilters inspecteren / reinigen			■								
77	Carterdamp filters inspecteren		■									
120	ELC Koelwater vervangen									■		
140	Uitvoeren TAM-inspectie							■			■	■
180	Vervangen turbo cartridge								■			
220	Uitvoeren endoscopisch onderz.						■					
230	Revisie motor / engine									■		
240	Major revisie(excl bemeten en incl after									■		
280	Uitvoeren topend overhaul								■			
290	Aftercooler drain controleren							■				
300	De- en monteren luchtkoelerelement			■								
310	Motorsteunen controleren				■							
330	Dynamo controleren / reinigen				■							
340	Koelwaterslangen naar delta p sensoren							■				
350	Koelwaterslangen naar murphyswitch							■				
360	Alle slangen op motor controleren			■								
370	Vervangen waterpompen(en)								■			
380	Carterdamp aftap schoonmaken		■									
390	Testen beveiligings apparaten							■				
400	Zink pluggen vervangen		■									
410	Speed timing sensoren controleren,					■						
420	Vervangen buitenbord koelw.pomp					■						
430	Vervangen luchtkoeler element							■				

Table I.1: Preventive maintenance cycles Aquila Engines.

J. Converting optimal calendar times to operating hours

For the convenience of asking experts for their opinion, calendar time was the unit of interest. As stated earlier, when asked for operating hours, experts immediately converted their answer to calendar times and back to operating hours. Because this gives us another uncertainty, it was decided to just ask for calendar times. Of course, most (preventive) maintenance plans are expressed in operating hours rather than calendar times. In order to be able to use the calendar based data a conversion has to be made. This inevitably leads to a major loss in information. To illustrate this, think about the differences between the vessels in terms of running hours because of maintenance or a difference in location.

The conversion will be done in a very straightforward way, but some important assumptions have to be stated. First, the total number of running hours is determined. The dates of entry are around 16-04-2015. Then the date of entering in service (EIS) is determined at 29-09-2010. There were 1660 days between the two.

Equipment	Current Running hours	Running hours start	Difference
3050	5.528	175	5.353
3051	9.469	175	9.294
3128	11.790	72	11.718
3129	11.793	72	11.721
3089	7.237	87	7.150
3090	11.573	87	11.486
3225	10.284	96	10.188
3239	7.294	9	7.285
Total	**34.938**	**773**	**74.195**

Table J.1: Running hours of Aquila equipment.

Now the total difference is divided by 1660 in order to get running hours per calendar day. Again it will be divided by 6 in order to get the operating hours per day per engine. Note that it does not matter whether the engine was installed or not, or did even exist at the time of entering in service of the vessel. What matters is the number of running hours the vessels made per calendar day. On average, an engine makes 7,4 hours per day. This means that all calculated optimal maintenance time T can be multiplied with this number, in order to get the number of operating hours.

K. Appendix – Expert elicitation process

In order to get a better view on the Bayesian analysis, the method is explained in more detail in this appendix. To understand the numbers and characters in this appendix, one needs to have studies chapter 3 and 4 first.

In the table below, the names of variables (both used by the author of the used paper) and the names that were used in this report can be found. The table is filled in as example with T_k in calendar days. The elicited mean cumulative failure percentage $\hat{F}(t_k)$ and standard deviation σ_{t_k} are from the combined expert opinion. With the formulas from chapter 3, one can calculate $c(t_k)$ and $d(t_k)$.

Report name	T_1	T_2	T_3	T_4
T	183	365	730	1095
$\hat{F}(t_k)$	0,12	0,24	0,42	0,63
$\sigma(t_k)$	0,07	0,14	0,15	0,18
$c(t_k)$	2,466122	1,993469	4,1272	3,9025
$d(t_k)$	20,55102	8,306122	9,826667	6,194444
$d(t_k)- c(t_k)$	18,0849	6,312653	5,699467	2,291944

Table K.1: Overview of input variables for the Monte Carlo Simulation (prior).

With the parameters p and p-q above, the random realizations of the Beta distribution is calculated with the following formula: "=beta.dist(rand();c;d-c)". These random realizations are converted to Weibull parameters α and β. From the N random Weibull parameters α and β, the median is set as the most likely value. The simulated values of F(t) must be non-decreasing over time.

This process delivers the prior. Now the 15 failures that were observed can act as update of the prior. Two failures occurred at the same time t so these are immediately aggregated. The other 14 were simulated with the inputs as like in Table K.2. Because the simulated values of F(t) must be non-decreasing over time some more points that were close to each other had to be aggregated as this restriction was never met. 10 points were left as can be seen below.

Var.	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10
T	57	137	309	401	436	651	747	820	873	1442
$\mathbf{F}(t_k)$	0,018	0,060	0,174	0,240	0,266	0,417	0,480	0,525	0,556	0,804
$\sigma(t_k)$	0,036	0,051	0,059	0,072	0,094	0,116	0,132	0,135	0,130	0,137
$c^*(t_k) = c(t_k) + r(t_k)$	1,226	3,242	9,940	12,331	12,551	16,099	18,438	19,643	21,609	20,948
$d^*(t_k) = d(t_k) + S$	82,878	69,141	72,054	66,276	62,211	53,599	53,429	52,429	53,871	41,043
$d^*(t_k)- c^*(t_k)$	81,651	65,899	62,114	53,945	49,661	37,500	34,991	32,786	32,262	20,095
$r(t_k)$	1	2	3	4	7	9	12	13	14	15
S	15	15	15	15	15	15	15	15	15	15

Table K.2: Overview of input variables for the Monte Carlo Simulation (posterior).

In Table K.2, t is the lifetime of the component (dynamo) on failure. $F(t_k)$ is the inferred values of the Weibull function with t , $\alpha = 1020$ and $\beta = 1{,}38$ (the prior). $\sigma(t_k)$ is the simulated standard deviation at these inferred points. The Beta parameters are then updated by adding the number of failures until time T to $c(t_k)$ and the total number of failures to $d(t_k)$.