Downtime reduction by an inspection based maintenance service contract

de Nijs, T.J.

Award date:
2014

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Downtime Reduction by an Inspection Based Maintenance Service Contract

by

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Student Identity number 0761837

In partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

Supervisors:
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MBA ing. J. Hendrikx, Bosch Rexroth BV
TUE. School of Industrial Engineering.
Series Master Theses Operations Management and Logistics

Subject headings: Availability, Classification, Decision Support Software-Tool, Downtime, Inspection Based Maintenance, Optimization Heuristic.
It should be noted that all the numbers used in this master thesis are fiction.
I. Abstract
This master graduation report presents a decision support software-tool for the optimization of an inspection based overhaul service of large hydraulic cylinders manufactured and maintained by Bosch Rexroth. A conceptual model is designed to minimize the downtime costs resulting from overhauls during a classification period. A mathematical model is designed corresponding to this conceptual model, calculating the expected costs for customers. An optimization heuristic which optimizes the number and timing of inspections is designed. The mathematical model and optimization heuristic are integrated in a software-tool. The software tool is designed to be user-friendly and as flexible as possible, this enables the tool to optimize a variety of scenarios.
II. Acknowledgements

This report is the result of seven months of research performed at Bosch Rexroth for the graduation of the master program Operations Management and Logistics at the Eindhoven University of Technology. As every graduation project, the project had its ups and downs, however, I enjoyed working on this challenging project.

Firstly, I would like to express my gratitude to my first supervisor S.D.P. Flapper for guiding and mentoring me during the project. I thank him for his time, critical yet constructive feedback, and the meetings we had, which gave me new insights to effectively guide me through the project. Constructing a research scope proved to be challenging sometimes, but together with Mr. Flapper and the people from Bosch Rexroth we constructed an appealing and relevant project for my graduation.

Next, I would like to point out my appreciation for all the time and help of Jeroen Hendrikx. I thank Jeroen for the opportunity he gave me to perform my master thesis at his department. I realize it was not always easy to find time to discuss my research project, but Jeroen always managed to make time for me. When I needed input from Bosch Rexroth Jeroen could introduce me to the right people.

Also thanks to all my other colleagues at Bosch Rexroth, especially within the specialized service department. The informal working environment at Bosch Rexroth was a pleasure to work in, and my colleagues were always friendly and helpful.

Finally, I would like to thank my girlfriend, family, and friends for their support during my graduation. Also thanks to my fellow students/friends for the great time during my entire study.

Thomas De Nijs

September 2014
III. Management summary

This report is the result of a Master graduation project at Bosch Rexroth. Availability of the rigs of Bosch Rexroth’s offshore customers is of key importance. The system of the rig-owner can only generate revenue when their system is available for operation. Every 5 years the rigs need to be classified by a classification bureau, this is required by law. During this classification the rig is unavailable for operation, therefore classifications cause downtime. The rig-owners have a planned classification period. When the overhaul of the hydraulic cylinders has a longer lead-time than the planned classification period, the cylinders overhaul period causes additional downtime. In case Bosch Rexroth would perform inspections to evaluate the condition of the cylinder in advance of the classification it enables Bosch Rexroth to predict the required overhaul activities. The prediction of the required overhaul activities enables Bosch Rexroth to plan the overhaul activities, which could decrease the overhaul period. The decrease in expected overhaul lead-time decreases the expected downtime caused by overhauls. However, the inspections cause downtime and costs for the customer. Therefore, there is a trade-off between the costs due to inspections and the downtime costs caused by overhauls. An inspection based maintenance service only has value if it decrease the expected costs, therefore the assignment for this research project is:

“Develop a service contract decision support software-tool that calculates the potential added-value of an inspection based maintenance service contract for large hydraulic cylinders in the offshore in terms of expected maintenance and downtime costs.”

This software-tool should be able to support the sales department of Bosch Rexroth in the negotiation of an inspection based maintenance service contract with the customer.

A conceptual model is developed to determine the potential added-value of an inspection based maintenance service. The conceptual model is designed to adequately model the inspection based maintenance service, and provides insight in the influence of the number and timing of inspections. When an inspection is performed closer to the classification, the required overhaul activities have a greater probability of being detected. However, it also leaves Bosch Rexroth with less time to plan the overhaul activities. A situation with more inspections could benefit from a higher detection probability. However, more inspections cause more inspection costs.

A mathematical model is developed for the calculation of the total relevant expected costs for a customer. This mathematical model uses the input distributions; overhaul activity requirement probability, overhaul activity detection probability, and overhaul activity lead-time, and input parameters for the scenario in hand.

An optimization heuristic is developed to obtain the lowest expected costs for the customer by changing the number of inspections and the timing of the inspections.

The software-tool that is developed is based on the mathematical calculation of the expected downtime and inspection costs for the customer. Approximations of the equations from the mathematical model are used for the calculations to reduce the computation time to an acceptable level. The software-tool uses the optimization heuristic to obtain the optimal number and timing of the inspections.

The software-tool is parameterizable to deal with different scenarios. The parameters can be filled in, in the software-tool. The variable distributions (requirement probability, detection probability, and
lead-times) up on which the calculations are based, are obtained by fitting statistical distributions to estimations of hydraulic cylinder experts. The distributions can be adapted with the software-tool, either manually or with an estimation fitting procedure. The user can also add or delete overhaul activities from the overhaul activities that are considered. The ability to alter the parameters and adapt the input distributions ensures a flexible tool which can be used for different customers.

A set of scenarios is optimized to give an indication of the potential added-value of the inspections based overhaul service. From the tested scenarios there can be concluded that an inspection based overhaul service can decrease the expected overhaul lead-time up to 40% in the case of 1 inspection, an even greater reduction can result from more inspections. The highest reduction in the expected system overhaul lead-time found in the tested scenarios is 55%.
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<th>Definition</th>
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<td>Some information is classified information of Bosch Rexroth, when there are values which are classified Bosch Rexroth information there will be CI displayed instead of the actual values.</td>
</tr>
<tr>
<td><strong>Classification</strong></td>
<td>Validation by an classification bureau that a construction is according to the technical standards of the construction.</td>
</tr>
<tr>
<td><strong>Classification bureau</strong></td>
<td>Non-governmental organization that establishes and maintains technical standards for the construction and operation of ships and offshore structures</td>
</tr>
<tr>
<td><strong>Classification period</strong></td>
<td>The period in which a rig is at shore for classification</td>
</tr>
<tr>
<td><strong>Cylinder</strong></td>
<td>A hydraulic cylinder that is a mechanical actuator that is used to give unidirectional force.</td>
</tr>
<tr>
<td><strong>Cylinder overhaul lead-time</strong></td>
<td>The time it takes to overhaul a cylinder</td>
</tr>
<tr>
<td><strong>Downtime</strong></td>
<td>Time during which a system is unavailable for production</td>
</tr>
<tr>
<td><strong>Failure</strong></td>
<td>Termination of the ability of a cylinder to give an unidirectional force of a given altitude</td>
</tr>
<tr>
<td><strong>Failure Distribution</strong></td>
<td>The probability density function for description of the time-to-failure</td>
</tr>
<tr>
<td><strong>Fault discovery process</strong></td>
<td>The procedure through which the cause of a system failure or overhaul requirement is identified</td>
</tr>
<tr>
<td><strong>Field repair</strong></td>
<td>Repair of a cylinder at the customer’s location</td>
</tr>
<tr>
<td><strong>Maintenance strategy</strong></td>
<td>The strategy that dictates which maintenance activities are performed at which time</td>
</tr>
<tr>
<td><strong>Mean Time To Failure</strong></td>
<td>The mean time of a cylinder to be able to remain functional under given operating conditions</td>
</tr>
<tr>
<td><strong>Mean Time To Repair</strong></td>
<td>The times it takes to bring a system back to its satisfactory working conditions</td>
</tr>
<tr>
<td><strong>Mean Time To Support</strong></td>
<td>The period from a failure report until the start of a reactive maintenance action performed to restore the functionality of a system after system failure</td>
</tr>
<tr>
<td><strong>Original Equipment Manufacturer</strong></td>
<td>The company that originally manufactured the product</td>
</tr>
<tr>
<td><strong>Operation period</strong></td>
<td>The period in which a rig is planned for operation</td>
</tr>
<tr>
<td><strong>Overhaul</strong></td>
<td>Take apart the customer’s cylinder at a Bosch Rexroth plant in order to examine it and repair if necessary</td>
</tr>
<tr>
<td><strong>Overhaul activity execution lead-time</strong></td>
<td>The time it takes to execute an overhaul activity</td>
</tr>
<tr>
<td><strong>Overhaul activity lead-time</strong></td>
<td>The time it takes to plan and execute an overhaul activity</td>
</tr>
<tr>
<td><strong>Overhaul activity planning lead-time</strong></td>
<td>The time it takes to acquire the required part, people, and tools for an overhaul activity</td>
</tr>
<tr>
<td><strong>Overhaul activity requirement</strong></td>
<td>The requirement to perform an overhaul activity in order to pass a classification</td>
</tr>
<tr>
<td><strong>Overhaul concluding activities</strong></td>
<td>The activities performed for the conclusion of an overhaul</td>
</tr>
<tr>
<td><strong>Overhaul preparation activities</strong></td>
<td>The activities performed for the preparation of an overhaul</td>
</tr>
<tr>
<td><strong>Planned services</strong></td>
<td>Planned services involve all activities that contribute to the avoidance of unexpected costs due to failures of the equipment.</td>
</tr>
</tbody>
</table>
Reliability | The ability of a cylinder to give an unidirectional force of a given altitude under stated conditions for a specified period of time
--- | ---
Reliability centered maintenance | Systematic approach for designing a scheduled-maintenance program
Rig | An offshore oil platform, used to extract and process oil and natural gas
System overhaul lead-time | The period of time in which the cylinders of a rig-owner are overhauled, starting when the classification period starts, ending when all (required) cylinder are overhauled and reinstalled.
Unplanned services | Unplanned services involve corrective maintenance resulting from unpredictable product failures
Uptime | Time during which a system is available for production

**Abbreviations**

CI | Classified Bosch Rexroth Information
MTTF | Mean Time To Failure
MTTR | Mean Time To Repair
MTTS | Mean Time To Support
OEM | Original Equipment Manufacturer
1. Introduction
This is the master thesis report for a research project that is conducted at Bosch Rexroth BV. In this chapter an introduction to Bosch Rexroth BV and their services and products is given. In the second chapter the problem statement is defined, the corresponding research question is defined and the structure of the research project and report is further specified.

1.1. Deliverables
A set of deliverables are specified for this research project. Below the deliverables for the research project are listed:

- A service contract decision support tool, implemented in a software tool.
- User manual
- Final report and presentation of research project and service contract decision support tool.

The detailed explanation of the support tool is given later in this report.

1.2. Bosch Rexroth
This paragraph gives some general information on Bosch Rexroth and their products. Bosch Rexroth BV is part of Bosch Rexroth AG, a German based company.

1.2.1. History
The company Rexroth dates from 1795 when the family Rexroth took over the corporation Höllenhammer in Elsavatal, in 1850 Rexroth took over the ironworks Steinschen in Lohr am Main. Currently the headquarters of Rexroth is stationed in this city. In 1952 Rexroth started the production of standardized hydraulic components. The product-portfolio broadened in the years 1972-2000 with axial piston pumps, motors, gearing, coupling, linear technology and pneumatic by the acquisition of; Hydromatik GmbH, Bruehninghaus GmbH, Lohmann & Stolterfoht GmbH, Deutsche Star GmbH. In the same period (1976), Rexroth becomes a wholly owned subsidiary of Mannesmann AG and goes further under the name Mannesmann Rexroth AG. In 2001 was the spinoff of the Automation Technology group of Robert Bosch GmbH & merger with Mannesmann Rexroth AG, forming a new company called Bosch Rexroth AG.

1.2.2. Organization
Economical, precise, safe, and energy efficient: drive and control technology from Bosch Rexroth moves machines and systems of any size. The company bundles global application experience in the market segments of Mobile Applications, Machinery Applications and Engineering, Factory Automation, and Renewable Energies to develop innovative components as well as tailored system solutions and services. Bosch Rexroth offers its customers hydraulics, electric drives and controls, gear technology, and linear motion and assembly technology.

1.2.3. Specialized Service
The project has been executed within the “Specialized Services” department of Bosch Rexroth Boxtel. Specialized Services is responsible for the service regarding engineer-to-order cylinders and systems, which are being engineered and produced in Boxtel. Specialized service operates in different branches; Offshore, Marine Dredge, Motion Simulation, Special Systems, and Large Hydraulic Cylinders. This research will focus on cylinders in the Offshore, this is decided by Bosch Rexroth. Specialized service sells maintenance and spare parts, and they also upgrade cylinders. The
maintenance activities consist of inspections, field repairs, overhauls, and operation and maintenance training.

1.3. Hydraulic cylinder
A hydraulic cylinder is a mechanical actuator that is used to give unidirectional force. A hydraulic cylinder consists of a cylindrical barrel, piston and piston rod. The piston is inside the cylindrical barrel. The cylinder bottom cap (also called butt), and the cylinder head cap (also called gland), closes the barrel. The bore is the inside diameter of the barrel. The piston has a piston seal to keep the pressure from bypassing to the other side. The piston is attached to the piston rod. The piston rod starts moving outwards, as the hydraulic fluid is pumped into the bottom side of the hydraulic cylinder. In the reverse process, the hydraulic fluid is pushed back into the reservoir by the piston. The pressure in the cylinder is the ratio of unit force per unit piston area. The pressure generated in the piston rod chamber is the ratio of the unit load per the difference in the unit piston area and unit piston rod area. This calculation is used when the hydraulic fluid is let into the piston rod chamber as well as the fluid flows smoothly (without pressure) from the piston area to the reservoir. In this way, the expansion and retraction (push and pull) action of the hydraulic cylinder is generated. The stroke of the cylinder is the distance traveled by a piston in a hydraulic cylinder. Figure 1-1 gives a cross-cut of a hydraulic cylinder.

![Cross-cut hydraulic cylinder](image-url)
The numbered items in Figure 1-1 are the following:

1. Piston rod  
2. Wiper ring  
3. Cylinder head cap / gland  
4. Rod sealing  
5. O-ring + Back-up ring  
6. Oil connection  
7. Cylinder barrel  
8. Piston sealing  
9. Piston bearing  
10. Oil connection  
11. Cylinder bottom / butt  
12. Piston  
13. O-ring  
14. Rod Bearing  
15. Bearing Bush  
16. Stop tube  
17. Minimess coupling  
18. Sealing bush  
19. Drain plug

The cylinders have several seals to keep pressure in the bottom and head chamber:

- Piston seals to prevent leakage from one side to the other  
- Rod seal to prevent leakage from the rod end  
- Static seals to prevent leakage from joints between the barrel and end caps  
- Wiper ring to stop dirt being drawn inside with the rod

The cylinders also have several bearings that constrain relative motion and reduce friction between moving parts to only the desired moving parts. These bearing are:

- The piston rod bearing, this takes the side loads on the rod and ensures lubrication and reduces wear. It also prevents the seal distortion and leaking.  
- The pistons bearings take the sideways forces and reduce wear.

A hydraulic cylinder can either be single acting or double acting. In single acting cylinders the fluid is pressurized from only one side of the cylinder during both the expansion as well as the retraction process. A spring or an external load is used to return the cylinder top to its original position when pressure of the fluid is cut off. In the double acting cylinders, the pressure from the fluid is applied in both directions. In the large hydraulic cylinders of Bosch Rexroth an external load is used. Single cylinders that consist of springs are not used in large stroke applications because there are inherent mechanical problems associated with the spring. The double acting cylinders could be of two types: single rod cylinder and double rod cylinder. The double rod cylinder has a second piston rod that allows equal force and speed in both directions. In the double acting cylinders, the pressure from the fluid is applied in both the directions.
1.4. Offshore market

The cylinders produced by Bosch Rexroth for the offshore are almost completely engineered-to-order. There are some standard components but all the cylinders are unique. Some of the cylinders are made in batches because the rig requires a couple of the same cylinders. Table 1-1 gives the number of cylinders installed in the offshore per cylinder type (first column the cylinder type, second column the number of installed cylinders). The direct customers for these cylinders are Original Equipment Manufacturers (OEM’s). Although the OEM is the direct customer, they are considered as partner by Bosch Rexroth. Together they define the functional requirements of the cylinders, and Bosch Rexroth designs and manufactures the cylinders. The end-users considered in this research are the end-users from the offshore. These end-users are rig-owners, and are typically providers of equipment and components used in oil and gas drilling and production operations, oilfield services, and supply chain integration services to the upstream oil and gas industry. The rig-owner owns and operates rigs that drill oilfields. The oil and gas industry use the services of the rig-owner to drill for oil and gas. See Figure 1-4 for the supply chain of the hydraulic cylinders of the offshore.

<table>
<thead>
<tr>
<th>Cylinder type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Line tensioner</td>
<td>950</td>
</tr>
<tr>
<td>Direct riser tensioner</td>
<td>498</td>
</tr>
<tr>
<td>Jack up cylinder</td>
<td>202</td>
</tr>
<tr>
<td>Hoist cylinder</td>
<td>164</td>
</tr>
<tr>
<td>Drillstring compensator</td>
<td>142</td>
</tr>
<tr>
<td>Guide line tensioner</td>
<td>137</td>
</tr>
<tr>
<td>Pin cylinder</td>
<td>137</td>
</tr>
<tr>
<td>Heave compensation cylinder (other)</td>
<td>100</td>
</tr>
<tr>
<td>Cantilever skidding system</td>
<td>96</td>
</tr>
<tr>
<td>Active heave compensator cylinder</td>
<td>82</td>
</tr>
<tr>
<td>Heavy compensator cylinder</td>
<td>49</td>
</tr>
<tr>
<td>Lifting cylinder</td>
<td>35</td>
</tr>
<tr>
<td>Y-Drive cylinder</td>
<td>32</td>
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<tr>
<td>Locking cylinder</td>
<td>26</td>
</tr>
<tr>
<td>Crown mounted compensator cylinder</td>
<td>17</td>
</tr>
<tr>
<td>Standardized large hydraulic cylinder</td>
<td>16</td>
</tr>
<tr>
<td>Vertical Caster Cylinder</td>
<td>7</td>
</tr>
<tr>
<td>A-frame cylinder</td>
<td>6</td>
</tr>
<tr>
<td>Spannzylinder</td>
<td>4</td>
</tr>
<tr>
<td>Active in-line compensator cylinder</td>
<td>3</td>
</tr>
<tr>
<td>Amplifier Control Cabinet</td>
<td>2</td>
</tr>
<tr>
<td>Travelling block compensator</td>
<td>2</td>
</tr>
<tr>
<td>Offshore replenishment system</td>
<td>1</td>
</tr>
<tr>
<td>X-Y-Drive cylinder</td>
<td>1</td>
</tr>
<tr>
<td>Other</td>
<td>271</td>
</tr>
</tbody>
</table>

Table 1-1; Type and number of cylinders in installed base (Source: IBase; 03-2014)
Hydraulic cylinders are used in several offshore applications; heave compensation, skidding, deck mating, and jacking.

Heave compensation is a technique used on lifting equipment to reduce the influence of waves upon offshore operations. Active heave compensation differs from passive heave compensation by having a control system that actively tries to compensate for any movement at a specific point. Figure 1-6 gives a picture of a heave compensation system.

Installation and decommission vessels are highly complex ships with advanced systems for positioning, heave and anchoring to bring offshore modules on shore/offshore. Heavy duty load out skidding systems are an efficient way to shift complete modules and structures on and off barges. Deck-mating systems are used to position topside on their jackets, with hydraulic cylinder movements and vessel ballasting technology. Figure 1-7 gives a picture of a skidding and deck-mating system.

Jacking systems are used for self-elevating platforms (SEP’s). Hydraulic rack & pinion systems, in the range of 500 to 2,000 tons per leg, contain in-house fabricated motors, gearboxes, cylinders, power units using standard or tailor made components. Figure 1-5 gives a picture of a jacking system.
2. Problem statement

The end-users of the hydraulic cylinders considered in the research project are rig-owners. The rig-owners are hired for oil and gas drilling operations. The rig-owner charges from €200.000 up to €800.000 per day for their services. This means that downtime can cost from 200.000 up to €800.000 per day. The hydraulic cylinders downtime depends on the probability of failure, how easy, safe and economic it is to perform maintenance, how effective the administrative routines are for scheduling, planning, and executing maintenance, as well as availability of spare parts, expert assistance, repair tools, etc. (Kumar, Markeset, & Kumar, 2004). Uptime is the antonym of downtime and is measured by the availability of the equipment. The availability of the cylinders depends on their reliability and maintainability characteristics, as well as an effective and efficient operational and maintenance support system (i.e. supportability). The reliability of a cylinder is defined as the ability to function under stated conditions for a specified period of time (O’Conner, 2002).

Every 5 years the equipment of the end-user has to be classified by a classification bureau. This is required by law. When the classification bureau does not approve the condition of the equipment, the equipment needs to be overhauled. When the classification bureau requires an overhaul of the hydraulic cylinders, the end-user contacts the OEM. The OEM may outsource the overhaul of the cylinders to Bosch Rexroth. The end-user could also outsource the overhaul of the cylinders to competitors. During the overhaul of the cylinders, the cylinders are not available for operations and therefore cause downtime. Because the cylinders are engineer-to-order the components in the cylinders are different for each customer. The required components for the overhauls are ordered when Bosch Rexroth receives an overhaul-order. The lead-time of the components causes the lead-time of the overhaul to be longer.

Because the downtime if very costly for the end-users of the hydraulic cylinders, it is important for the end-users to keep the downtime to a minimum. As described, downtime is caused by failures and overhauls and other operational reasons. This research project investigates how Bosch Rexroth could increase availability of the end-users’ cylinders by means of an inspection based maintenance service contract. The inspections performed during this service contract are used to evaluate the condition of the cylinders. The condition of cylinders can be used to make decisions on the required preventive maintenance activities and predict and plan the required overhaul activities for the classification of the cylinders. The goal of this is to reduce the probability of failure and reduce the overhaul lead-time which will both decrease the downtime, and thereby increase the availability of the cylinders. In order to convince the customers of the added value of such a maintenance service contract the expected maintenance costs and downtime costs should be calculated. This leads to the following research assignment:

“Develop a service contract decision support software-tool that calculates the potential added-value of an inspection based maintenance service contract for large hydraulic cylinders in the offshore in terms of expected maintenance and downtime costs.”

This model should be able to support the sales department of Bosch Rexroth in the negotiation of an inspection based maintenance service contract with the customer.
2.1. Research questions

From the research assignment the research questions can be derived. To be able to convince the customer of the added-value of an inspection based maintenance service contract, the customer needs more insight in the expected downtime caused by failures and overhauls. Currently, most maintenance services are ad-hoc, which means that Bosch Rexroth is contacted when a failure is detected or an overhaul is required. This gives Bosch Rexroth no time to plan any of the maintenance services which causes the reaction-time and lead-time of the services to be long. An inspection based maintenance service contract could decrease the probability of failures and overhaul lead-time. This results in the following research question:

“What is the expected added-value in terms of expected costs resulting from overhauls and failures of an inspection based maintenance service contract versus ad-hoc based service?”

To answer the research question the expected costs, failures, overhauls, the inspection based maintenance service, and the ad-hoc based service should be specified, this is done in chapter 3, to 6. The next section gives the research methodology that is used to specify the different element of the research question.

2.2. Research methodology

In a design process it is important to allow for iteration especially when there are multiple stakeholders. To obtain iteration there will be made use of the Deming cycle and the regulative cycle (van Strien, 1997). The Deming cycle, i.e. PDCA (plan-do-check-act), is an iterative four-step management method which is used in business for controlling and continuously improving processes and products (Sokovic, Pavletic, & Kern Pipan, 2010). The regulative cycle is a combination of a problem analysis phase, a design process which results in a design and the implementation and evaluation of the design (Kerssens-van Drongelen, 2001). For this project the Deming cycle is implemented in the regulative cycle in order to obtain the best substantiated and thoughtful concept solutions for Bosch Rexroth’s Service contract calculation software-tool, see Figure 2-1. More precisely, the Deming cycle is implemented between each phase in the regulative cycle so that the iterative steps (plan-do-check-act) can enable optimization and refinement of the final design. For this project the Deming cycle will be conducted in the following manner: Between each phase a plan will be made based on how to approach the subsequent phase. This plan will be implemented and the actual process executed, i.e. the plan will be done and problems will be encountered. The problems need to be solved so that the phase can be finished. Problems found will be discussed with all the stakeholders and reported while performing the check step. The last step is acting accordingly, identified problems will be solved and corrective actions on significant differences between actual and planned results will be taken.

Figure 2-1; Regulative Deming Cycle (van Strien, 1997) (Sokovic, Pavletic, & Kern Pipan, 2010)
2.2.1. Problem definition
During the problem definition phase the motivation and objective of the project is determined. Also, the required project activities are identified and planned. This process will be completed with an agreement of all stakeholders.

2.2.2. Diagnosis
The diagnosis phase starts with examining the situation. The services that Bosch Rexroth provides for their customers are investigated and then reported. By examining the situation the research assignment is further specified and the required data and information is defined. Thereafter the data collection starts. The historical data on failures, corrective maintenance and preventive maintenance in terms of frequency and duration are investigated. Also the experts on hydraulic cylinders are interviewed for their view on the appropriate maintenance strategy. When all the data is gathered and compared, this can be used as input for the conceptual model. The conceptual model is used to understand and simulate the maintenance strategy in the service contract that will be proposed. When the conceptual model is developed the diagnosis phase ends, and is used in the design phase.

2.2.3. Design
After the diagnoses the design phase starts. Using the conceptual model as input the maintenance strategy for the service contract is designed. This is used to develop the mathematical model for the calculation of the expected costs for both Bosch Rexroth and the customer. For the calculation to be constructive an optimization is required. The optimization will be designed to optimize the maintenance strategy that is developed. The calculation model and optimization needs to be verified and validated. When the model is verified and validated a software tool is made. This software tool uses the mathematical model to calculate the expected costs for both Bosch Rexroth and the customer, and the optimization to minimize these costs. The collected data from the diagnosis phase will be used as the input for the calculations.

2.2.4. Intervention
After the diagnosis and design, the service contract decision software-tool can be implemented at Bosch Rexroth, this is the intervention phase of the regulative cycle. In this phase all employees of Bosch Rexroth who will be using the tool will receive a manual of the service contract calculation software-tool and training will be organized.

2.2.5. Evaluation
Eventually, when the model is implemented, the design is evaluated. The conformation of the initial problem and the solution is checked. Furthermore, the effectiveness of the design process is evaluated.
3. Situation description
Currently the services that are provided for the offshore-customers are reactive. This means that Bosch Rexroth reacts when there is a demand of the customer for either failure-rectification or overhaul for classification. A failure is defined as the termination of the ability of a cylinder to perform its required function (O’Conner, 2002). The function of a hydraulic cylinder is to give a unidirectional force of a given altitude. This chapter describes how the failure-rectification and overhaul service is currently executed by Bosch Rexroth.

3.1. Cylinder failure
When a cylinder failure occurs the hydraulic cylinder is unable to give the required unidirectional force of a given altitude. Failures modes are the result of different. Appendix I gives the different failure modes, failure causes, failure effects, and rectification activities. Appendix I is systematically derived at by exploring the historical warranty claims (from 2000 to 2007) with the hydraulic cylinder experts and deducting the different failure modes, causes, failure effects, and rectification activities from the claim settlements. Failures occur during the operation period of the rig (see Figure 3-2 for the failure rectification process). The operation period is defined as the period in which the rig-owner is operating the rig for oil or gas drilling commissioned by the oil/gas-field owner. Every 5 years the rig needs to be reclassified, this is required by law. Between two operation periods there is a classification period, see Figure 3-1.

![Figure 3-1; Operation and classification periods](image)

For a schematic overview of the failure rectification see Figure 3-2 on the next page.
When a failure is detected, the customer can choose to either contact the Original Equipment Manufacturer (OEM) or a competitor. When the customer contacts the OEM and the OEM or the customer has a spare-cylinder, this spare-cylinder could be used to replace the failed cylinder. The customer can
than either choose to use this cylinder or to repair the failed cylinder and use this. When a spare-cylinder is used the failed cylinder is transported to Bosch Rexroth Boxtel to overhaul the cylinder and the spare cylinder is installed in the rig. When no spare cylinder is used, the customer chooses (with the help of a recommendation of Bosch Rexroth) to either do a field repair or an overhaul. Bosch Rexroth does this recommendation on the basis of an inspection on the cylinder. When it has been decided to do a field repair the required tools, people, and parts are acquired and send to the customer, then Bosch Rexroth repairs the failure at the customer’s site. When it has been decided to do an overhaul, the cylinder is transported to Bosch Rexroth. Simultaneously the required tools, people, and parts are acquired. Thereafter, the cylinder is overhauled and sent back to the customer. When the cylinder is repaired, the cylinder is installed back into the rig. The decision to either choose between an overhaul or to do a field-repair is based on the severity of the failure and the possibility to do a field repair. The downtime caused by the cylinder failures depends on the failure mode and the severity of the failure. Appendix I gives the different failure modes, failure causes, failure effects, and failure rectifications.
3.2. Cylinder classification

During the classification period the cylinder is classified. For a schematic overview of the cylinder classification process see Figure 3-3.

![Cylinder classification process diagram](image-url)
When a cylinder is not in the required condition the cylinder needs to be overhauled. The customer either contacts the OEM or a competitor for the overhaul of the cylinder. The OEM contacts Bosch Rexroth for the overhaul. The cylinder is sent to Bosch Rexroth and thereafter the required tools, people, and parts are acquired. When the cylinder arrives at Bosch Rexroth and the required tools, people, and parts are available the cylinder is disassembled and the components overhauled. When the cylinder components are overhauled, the cylinder is reassembled and sent back to the customer. The OEM installs the cylinder back into the rig. The cylinders are now in the required condition, the classification organization examines the cylinders and thereafter the cylinders are ready to be used again.

3.3. Conclusion
Availability of the system for the rig-owner is of key importance since operating their system to drill for oil and gas is their source of income. When the system of the rig-owner is unavailable no money can be made. Unavailability is measured by the downtime of the system, downtime of the system of the rig-owner can have two cause; failures or classification. As described earlier, when a failure is detected it means there is a termination of the ability of a cylinder to give an unidirectional force of a given altitude. The amount of downtime caused by a failure depends on the severity of the failure the reaction time of Bosch Rexroth, and the availability of the required maintenance people, tools, and parts. The expected number of failures during the operation period depends on the reliability of the cylinders. The reliability of a cylinder is defined as the ability of the cylinder to give an unidirectional force of a given altitude under stated conditions for a specified period of time.

During the classification period the system of the rig-owner is unavailable. The amount of downtime caused by the classification depends on whether an overhaul is required and what the lead-time is of the overhaul. A prudent service provider will adopt broad strategies that create incentives that foster customer satisfaction and retention, therefore the research scope is on inspection based maintenance that reduces the downtime caused by failures and classifications (i.e. overhauls).
4. Service Contract

A service contract is defined as an agreement between a service provider and an equipment owner about the maintenance activities performed by the service provider for a given price (Jackson & Pascual, 2008). A prudent service provider will adopt broad strategies that create incentives that foster customer satisfaction and retention. Because the downtime cost for the rig-owner is high, the focus of a maintenance service contract for these customers should be on reducing the downtime. In this research project an inspection based maintenance service contract is introduced that minimizes the downtime of the hydraulic cylinders of the rig-owner. The service provided is this inspection based maintenance service contract and the added-value for the customer is clarified in the next chapter “research scope”. The duration of the service contract is the time of one operation period, see Figure 4-1.

![Figure 4-1; Contract Period](Image)

The contract period is the period of one operation period and not for multiple operation periods. The contract period is not for multiple operation periods because the rig-owners don’t want to have long term commitments with maintenance service providers because they don’t know where (in the world) they will be operating in the future and may want to use local maintenance service providers for their equipment in the future.

During the contract period inspections are done. The service contract states the number of inspections and the time at which these inspections will be performed. The maintenance activities that are recommended, by means of the inspections, have a separate invoice. This means that the service contract price has a fixed price and necessitates Bosch Rexroth to do an agreed upon number of inspections at a specified time, the maintenance activities that follow from these inspections will only be paid if the customer gives an approval of the proposition of the recommended maintenance activities and price. The maintenance activities are not part of the service contract invoice because the customers want to have the opportunity to make a decision during the operation period on whether to do maintenance activities during the classification.
5. Research scope

Since availability is of key importance of the rig-owner, the maintenance strategy for their equipment should minimize the downtime of the equipment. In this research project an inspection based maintenance service contract is introduced that increases the expected availability of the hydraulic cylinder. Smets et al. (2012) introduced a holistic framework called “Design for Availability” that uses the principles of Lean, Six Sigma and Design for X to cost-effectively optimize the availability of capital goods throughout their entire lifetime (Smets, van Houtum, & Langerak, 2013). Manufacturers require such a framework because users of capital goods increasingly insist on high system availability levels against reduced lifetime costs, as is the case of the rig owners. Two crucial steps in the implementation of Design for Availability are the analysis of the current status of system availability, and the analysis of the lifetime costs associated to the current status of system availability. Figure 5-1 gives a holistic outline of system availability principles (Smets, van Houtum, & Langerak, 2013), the framework does not only distinguishes Mean Time To Failure (MTTF), Mean Time To Support (MTTS), and Mean Time To Repair (MTTR), but additionally shows that the system availability is dependent on the design and development, production, and installation activities (categorized under “Design and Delivery”) as well as on its after-sales activities when the system is already operational at the customer (categorized under “Operations”).

5.1. Mean Time To Failure

Mean Time To Failure (MTTF) refers to the ability of a system to remain functional under given operating conditions. More specific; the ability of a cylinder to give an unidirectional force of a given altitude under stated conditions for a specified period of time (O’Conner, 2002)(Heiserman, 2003). The MTTF is defined as the average life of a non-repairable system or the average time before the first failure of a repairable system (Kumar, Crocker, Knezevic, & El-Haram, 2000). The MTTF can be improved by increasing the system reliability and through reliability centered maintenance according to Smets et al. The system reliability is a design parameter. Since the design optimization is not taken into account, the system reliability is used as an input parameter for this research. Reliability-centered maintenance is a systematic approach for designing a scheduled-maintenance program, which ensures that the optimum reliability capabilities of a system are realized (Nowlan & Heap, 1978). As stated before, the rig-owners are obligated to have planned maintenance by law every five years. Planned, scheduled and executed maintenance before a breakdown occurs can contribute to better system performance and will therefore be considered in the proposed service contract for the rig owners.
5.2. **Mean Time To Support**

The Mean Time To Support (MTTS) covers the period from a failure report until the start of a reactive maintenance action performed to restore the functionality of a system after system failure (Kumar, Crocker, Knezevic, & El-Haram, 2000). For the overhauls (described in section 0) this is the period from a detecting the requirement till the start of the overhaul. MTTS is closely related to system downtime at the customer caused by the loss system performance, failure or overhaul requirement. MTTS can be optimized by improving the fault discovery process and the commercial and technical service.

The fault discovery process refers to the procedure through which the cause of a system failure or overhaul requirement is quickly identified. The conceptual model proposed in this research optimizes the fault discovery process by identifying upcoming failures and detecting upcoming overhaul requirement by means of system inspections.

The acceleration of the fault discovery process by gathering and opening up information about a system’s failure and overhaul requirement allows for timelier customer support (Blanchard, Verma, & Peterson, 1995). This concept is stated as “Commercial and Technical Support” in the holistic framework of Smets et al. In this research project the fault discovery is used to schedule and plan parts, people, and tools for the failure rectification and overhaul processes.

5.3. **Mean Time To Repair**

Mean Time To Repair (MTTR) is the time it takes to bring the system back to its satisfactory working condition (Thompson, 1999). MTTR indicates the ability of a system to be maintained, retained or restored and is dependent on the ease of system disassembly, the management of maintenance actions, and the composition of spare/repair packages (Smets, van Houtum, & Langerak, 2013).

The difficulty and duration of maintenance actions is to a large extent determined by the complexity of the system. Disassembly is part of the maintenance actions of an overhaul, the ease of system disassembly is a function of the complexity of the system. However, the design of the cylinders is not a decision parameter and the ease of disassembly is therefore an input parameter for the research project.

The management of maintenance actions corresponds to the decisions about whether to replace or to repair a broken part on- or off-site, as well as considerations on monitoring maintenance actions. These decisions are influential for the MTTR (Blanchard, Verma, & Peterson, 1995).

Providing customers with spare/repair packages containing the right and sufficient number of parts is crucial for a system to be repaired immediately after failure (Smets, van Houtum, & Langerak, 2013). Yet it is unnecessary to provide the customer with too many spare/repair parts resulting in redundant inventory costs (Smith & Knevevic 1996). In this research project the inventory policy is not a decision parameter. The scheduling and planning of the required parts for failure rectification and overhauls are within the scope of this research project, an optimization of the inventory levels of the spare/repair parts is not proposed.
5.4. Availability principles to be used
Downtime due to cylinder unavailability is caused by failures, and classifications (i.e. overhauls). The aim of this project is to propose an inspection based service contract by which the availability for the customer increases.

Reliability-centered maintenance uses the “Fault Discovery” and the “Maintenance Actions” principles to systematically design a scheduled-maintenance program that will prevent failures. Section 5.5 describes how this is realized. The commercial and technical support uses the “Fault Discovery” and the “Maintenance Actions” to reduce the overhaul lead-time. Section 5.6 describes how this is realized.
5.5. Failure prevention

The probability of failure during operation can be reduced by detecting an upcoming failure in advance. See Figure 5-3 for a graphical representation of the trade-off between the costs made by inspections and failures, note that the lengths of the activities in the figure do not represent the real time it takes.

![Figure 5-3; Inspection versus failure trade-off](image)

When an upcoming failure is detected, preventive maintenance activities can be performed, which could reduce the probability of failure depending on the failure behavior of the cylinder. An upcoming failure can be detected by means of an inspection. These inspections and maintenance activities require that the cylinder is put out of use at that moment, therefore the inspections cause downtime. However, when these inspections and maintenance activities prevent a failure from happening, the downtime resulting from failures could be reduced. When the expected costs of downtime and corrective and preventive maintenance resulting from an inspection based maintenance service is lower than the expected costs of downtime and corrective maintenance resulting from a reactive based maintenance service, it could be profitable to have an inspection based maintenance service contract for the rig-owner.

To make the trade-off between the inspection based service and reactive service, the expected costs need to be calculated. The expected number of failures is an important factor for this trade-off since this partially determines the expected failure costs. From experience, Bosch Rexroth knows that their cylinders could fail due to misuse of the equipment or incorrect specifications of the system. Misuse of the equipment is defined as not operating the equipment as it should. Incorrect specifications of the system are defined as a misalignment of the required specifications and the specifications to which the system is engineered. Because these specifications are not inline, the system is unable to cope with the actual working conditions. Incorrect specifications occur when somewhere between
the defining of the customer’s requirements and the design of the system an inadequate translation-step is made. The extent of misuse and incorrect-specifications cannot be quantified because there is no data on this. Also, there is no data on the failures of the equipment and the downtime caused by these failures. Therefore, the expected costs of downtime and maintenance for an inspection based service or reactive service during the operation period cannot be calculated. To effectively increase the availability of the cylinders during the operation period the reliability should be increased by eliminating the misuse of the cylinders. Bosch Rexroth can provide their customers with operation training, ensuring an understanding of the operating personnel of the required working condition. This could lead to a situation in which the reliability of the cylinders is not diminished by inappropriate use of the cylinders. Because there is no data on the extent of misuse of the cylinders of the customer or the unconsciousness of the customer of the proper use of the cylinders it is hard to make an appropriate estimation of the effect of operation training. Since the effects of operation training or inspection based maintenance is not quantifiable in terms of expected reliability or availability, it will not be part of the scope of the research and will therefore not be further discussed in this research project.
5.6. Overhaul lead-time reduction

The activities that are executed during an overhaul can be divided in three groups. See Figure 5-4 for the graphical representation of the activities that are performed during an overhaul.

Figure 5-4; Overhaul activities

The first group contains the preparation activities. These activities are always done in an overhaul and are done first. The preparation activities are comprised out of, transport to Bosch Rexroth, disassembling and cleaning the cylinder and the accumulator, thereafter an inspection of the components is performed and an inspection report is made.

The second group contains the actual overhaul activities. These activities are done simultaneously and are comprised out of two groups; the overhaul activities that are always executed and the activities that are only executed if required. The overhaul activities that are always executed are; renewal of the seals, renewal of the bearings, renewal of the bolts and screws, and shot blast and paint the cylinder and accumulator. The overhaul activities that are only executed if required are; Renewal of the accumulator nickel layer, the renewal of the rod coating, honing of the cylinder barrel and overhauling the safety valve. Different rod-coatings are used, all having different renewal lead-times.

When all overhaul activities are performed the last group of activities is performed, the concluding activities. The cylinder and accumulator are reassembled and conserved, thereafter a pressure test is performed under supervision of the classification bureau and the customer, and finally an overhaul report is made and the cylinder is prepared for transportation, and transported back to the customer.
Inspections can be used to reduce the overhaul lead-time during the classification, the planning activities can be done during the operation period. Figure 5-5 gives an example of an ad-hoc overhaul service and an inspection based overhaul service. The lead-times of the different activities in the figure do not correspond to actual lead-times but are purely as example.

When inspections are done before the classifications the required repairs and renewals during the classification maybe could be predicted. Based on this prediction Bosch Rexroth can give a proposal on what should be done during the overhaul. When the customer approves the proposition the
repair actions can be planned, the spare-parts can be acquired, and the required tools and people can be planned. This plan reduces the lead-time of the overhaul which could result in a reduced classification period and therefore a decreased down-time.

In the ad-hoc overhaul service, Bosch Rexroth is contacted after the classification of the cylinders. The cylinder is transported to Bosch Rexroth. Thereafter the required tools, people, and parts are acquired, this is “planning of the overhaul activities” in the Figure 5-5. In this example there are five overhaul activities; renew rod-coating, overhaul valve, hone cylinder barrel, renew seals, and renew bearings. After the cylinder is disassembled and the required tools, people, and parts are acquired the overhaul activities are performed. When all overhaul activities are performed the cylinder is reassembled and sent back to the customer.

In the inspection based overhaul service one or more inspections are done before the classification. In the example in Figure 5-5 one inspection is done. During the inspection the cylinder is unavailable. During the inspection there has been detected that the five above mentioned overhaul activities need to be executed during the overhaul of the cylinder. The planning of these overhaul activities can be done in a manner that enables Bosch Rexroth to do the overhaul activities immediately after transportation and disassembly of the cylinder. When all overhaul activities are performed the cylinder is reassembled and sent back to the customer.

The overhaul lead-time is reduced in the example, as shown in Figure 5-5. This means that the classification period is shorter and the downtime is therefore less. However, additional costs are made with the inspection which also leads to downtime. To demonstrate the potential added value of the inspection based maintenance service, the costs of the ad-hoc service have to be compared with the costs of the inspection based maintenance service.
5.6.1. Customer costs

The expected costs that are made during the service contract depend on the costs of the overhaul activities and the probability that they are performed, the lead-time of the overhaul activities, and the detection probability of the overhaul activities. See Figure 5-6 for an overview of the customer costs.

![Figure 5-6; Overhaul service costs for the customer](image)

5.6.1.1. Transportation and assembly costs

The transportation costs are the costs that are made to get the cylinder to Bosch Rexroth. The transportation costs depend on where in the world the cylinder is and how the cylinder is transported to Bosch Rexroth. The disassembly costs of the cylinder are the costs to disassemble and clean the cylinder in order to perform the required overhaul activities. Because the transportation and disassembly costs are only made when an overhaul is actually executed the expected transportation and disassembly costs depend on the probability that the overhaul activities are required.

When all the required overhaul activities are executed the cylinder is reassembled and transported back to the customer. Because the reassembly and transportation costs are only made when an overhaul is actually executed the expected transportation and reassembly costs depend on the probability that the overhaul activities are required.

5.6.1.2. Acquisition costs

The acquisition costs are costs of acquiring the required tools, people, and parts. These costs depend on the required tools, people, and parts for the overhaul activities. Because these costs are only made when the overhaul activity is actually executed the expected acquisitions cost depend on the probability that the overhaul activities are required and executed.

5.6.1.3. Overhaul execution costs

The actual execution of the overhaul activities also generates costs; these are the overhaul activity costs. The expected overhaul activities costs depend on the probability that the overhaul activities are required.
5.6.1.4. **Downtime cost**
The downtime cost is the cost of not having the cylinders available for operation. The downtime cost is the product of the unavailability cost per time unit and the expected overhaul lead-time and inspection time. The overhaul lead-time is the time from transportation to Bosch Rexroth till the cylinder is back to the customer. The length of the overhaul lead-time depends on the transportation lead-time, disassembly lead-time, reassembly lead-time, the planning lead-time, the overhaul activities lead-time, and the probabilities of the overhaul activities being required. Also the detection probability and the time of detection determines the overhaul lead-time since the earlier the overhaul activities are detected the earlier the planning of the overhaul activities can be done. The inspection time is the time that it takes to inspect the cylinders, during this time the cylinders are also unavailable for operations. The more inspections are performed, the more downtime due to these inspections.

5.6.1.5. **Inspection costs**
The inspection costs are the cost for the customer to have an inspection performed by Bosch Rexroth. The inspection costs are the cost of service engineers traveling to the customer, inspecting the cylinders, reporting the inspection, and make a recommendation on the overhaul for the upcoming classification.

5.6.2. **Bosch Rexroth Costs**
The costs for Bosch Rexroth are comprised out of the same elements as for the customer except for the downtime costs. See Figure 5-7 for an overview of the costs for Bosch Rexroth.

![Figure 5-7; Overhaul service costs for Bosch Rexroth.](image)

The costs for Bosch Rexroth are the same as for the customer except for the downtime costs, because the overhaul service does not generate downtime for Bosch Rexroth. The transportation, assembly, acquisition, execution and inspections also generate costs for Bosch Rexroth, the difference in these costs for Bosch Rexroth and the Customer is the profit margin of Bosch Rexroth.
5.7. Conclusion

As stated before, reliability-centered maintenance is a systematic approach for designing a scheduled-maintenance program, which ensures that the inherent reliability capabilities of a system are realized (Nowlan & Heap, 1978). Since the effects of operation training or inspection based maintenance is not quantifiable in terms of expected reliability or availability, it will not be part of the scope of the research and will therefore not be further discussed in this research project. However, the classifications that are required by law every five years are a form of scheduled-maintenance and are used as starting point for the MTTS reduction. The fault discovery process refers to the procedure through which the cause of a system failure or overhaul requirement is quickly identified, which reduces MTTS. The conceptual model utilizes the current fault discovery capabilities of the service engineers to detect overhaul activity requirements in advance. The information about the overhaul requirements allows for timelier customer support and is stated as “Commercial and Technical Support” in the Holistic Framework of system availability principles of Smets et al. The decisions about whether to replace or to repair a broken part on- or off-site, as well as considerations on monitoring maintenance actions, and dealing with deficiencies are responsibilities of Bosch Rexroth and their customers and are decided upon within the proposed service contract. Providing customers with spare/repair packages containing the right and sufficient number of parts is crucial for a system to be repaired immediately after failure or at an overhaul (Smets, van Houtum, & Langerak, 2013). Yet it is unnecessary to provide the customer with too many spare/repair parts resulting in redundant inventory costs (Smith & Knevevic 1996). In the conceptual model the inventory decision is not a decision parameter. The conceptual model optimizes the scheduling and planning of the required parts for overhauls, but does not propose an optimization of the inventory levels of the spare/repair parts. See Figure 5-8 for the arrangement of the availability principles from the holistic framework of Smets et al. that are used.

Figure 5-8; Arrangement of the conceptual model in the holistic framework of Smets et al.
6. Conceptualization

As described in section 5.6.1 & 5.6.2 the costs for the customer are divided into 5 groups; transport and assembly, acquisition, downtime, and inspection costs. In essence, the main objective of the inspection based maintenance is to minimize the overhaul lead-time. The influence of inspections on the transport and assembly, acquisition, and execution costs will not be considered because the probability of an overhaul activity being executed is not dependent of the inspections. For this reason only the inspection and downtime costs are taken into account in the conceptualization of the inspection based maintenance service contract. First the assumptions of the model are described, thereafter the model is described.

### 6.1. Assumptions

Several assumptions are made in the conceptual model. These assumption are described below:

- The overhaul of an component is assumed to bring the component back to a “good as new” state. Either the component is renewed or completely revised, therefore the overhaul of an component can be assumed to bring the component to its original specifications and is “good as new”

- The lead-time of the preparation and conclusion activities of the overhaul is assumed to be constant. This lead-time is not dependent of the decision variables (number and timing of the inspections), making this lead-time variable in the model will only make the model needless complex. Also, the preparation and conclusion activities lead-time is only a small part of the overhaul lead-time and the variance on the preparation and conclusion lead-time is therefore negligible.

- The requirement of an overhaul activity can only be detected if the overhaul activity is actually required. This assumption is made because the detection is done by a visual inspection of damage to the components, when there is damage to a component the overhaul of that component will always be required.

- The overhaul activities are only planned if the overhaul activities requirement is detected. This assumption is made because the customers will not accept that unnecessary overhaul costs are made by doing unnecessary overhaul activities.

- During the operation period only field repairs are executed if there is a failure. According to the service engineers and the sales managers of the specialized service department of Bosch Rexroth the probability of an overhaul being required during the operation period is negligible. The field repairs are assumed to be minimal repairs which do not cause the overhaul probability distribution to change. When there is a failure during the operation period the rig-owner want to have the cylinders back in working-condition as fast as possible and therefore only the essential maintenance activities that are required to bring the cylinders back in working condition are performed.

- The execution of an overhaul activity can start as soon as the planning activities (and preparation activities) for that overhaul activity are finished.
6.2. Downtime caused by overhaul

The downtime that is caused by overhaul is dependent of several lead-times, see Figure 6-1.

Figure 6-1; Downtime caused by overhaul lead-time
The model in Figure 6-1 is explained in the section 6.3.1 to 6.3.8. The downtime due to “system overhaul lead-time” is dependent of the “planned classification period” and the system overhaul lead-time, see section 6.3.

The “system overhaul lead-time” is dependent of the “cylinder overhaul lead-time” of the cylinders in the system, see section 6.3.1.

The “cylinder overhaul lead-time” is dependent of the “overhaul preparation activities lead-time”, the “actual overhaul activities lead-time” of the different overhaul activities, and the “overhaul concluding activities lead-time”, see section 6.3.2.

The “actual overhaul activities lead-time” is dependent of the “overhaul activity lead-times”, see section 6.3.3.

The “overhaul activity lead-time” is dependent of “actual planning lead-time” and the “execution lead-time”, see section 0.

## 6.3. Down-time

The downtime that is caused by the overhaul of the cylinders is dependent of the lead-time of the overhaul of the cylinders and the lead-time of the planned classification period, see Figure 6-2.

![Figure 6-2; Downtime due to system overhaul lead-time.](image)

Figure 6-2 gives a graphical representation of the downtime caused by the overhaul of the system. The “planned classification period” is the period planned to classify the rig and do all required maintenance activities to the rig, overhauling the system is one of these maintenance activities. The “system overhaul lead-time” is the time it takes to overhaul all cylinders that require an overhaul. When the lead-time of the overhaul of the system is longer than the planned classification period the classification period has to be extended. This means that during this extension of the classification period the rig is not available for operation and therefore causes additional downtime.

### 6.3.1. System overhaul lead-time

The rigs have several cylinders that determine the “system overhaul lead-time”, see Figure 6-3.

![Figure 6-3; System overhaul lead-time and cylinder overhaul lead-times](image)
Figure 6-3 gives an example of a customer with four cylinders that are overhauled. The “Cylinder overhaul lead-time” is the time it takes to overhaul the cylinder. The cylinder which has the longest lead-time determines the system overhaul lead-time because the overhaul period is finished if all cylinder overhauls are finished. The lead-time of the overhaul of the cylinders is not constant, see Figure 6-4 (the values do not correspond to actual lead-times).

Figure 6-4; Cumulative probability cylinder and system overhaul lead-time

Figure 6-4 gives the cumulative probability graph of the lead-times of the cylinder overhauls. The colored lines give the probability that the overhaul of a cylinder is executed is equal or lower than X days. The product of the cumulative overhaul lead-time probability functions of the different cylinders gives the probability that all cylinder overhauls are finished and thus the system overhaul lead-time, this is given by the black line. The black line (system overhaul lead-time) is always equal or lower than the colored lines (cylinder overhaul lead-time), because the overhaul period is only finished if all cylinder overhaul are finished.

For example, there is 50% probability that the lead-time of cylinder 1 is between 0 and 40 days, 34% for cylinder 2, 7% for cylinder 3, and 25% for cylinder 4. The probability that the system overhaul lead-time is between 0 and 40 days is the probability that all cylinder overhaul lead-times are between 0 and 40, thus; $50\% \times 34\% \times 7\% \times 25\% = 0.298\%$
6.3.2. **Cylinder overhaul lead-time**

As described in section Figure 5-6 the overhaul of a cylinder can be divided in three groups of activities; preparation activities, actual overhaul activities, and concluding activities, see Figure 6-5.

![Figure 6-5; Overhaul activities lead-time](image)

Figure 6-5 gives an example of the lead-time of the overhaul of a cylinder. The lead-time of the cylinder is the sum of the lead-time of the preparation activities, the overhaul activity that has the longest lead-time, and the concluding activities. The lead-time of the preparation activities and concluding activities are assumed to be constant (see assumptions). The lead-time of the actual overhaul activities is not constant, see Figure 6-6 (the values do not correspond to actual lead-times).

![Figure 6-6; Cylinder and overhaul activities lead-time](image)

Figure 6-6 gives the cumulative probability graph of the lead-time of the overhaul of cylinder 3 (green line) and the cumulative probability graph of the lead-time of the actual overhaul activities (brown line). The difference between the cylinder overhaul lead-time and the actual overhaul activities lead-time is the lead-time of the preparation and concluding activities. For example, there is a 31% probability that the actual overhaul activities have a lead-time equal or lower than 40 days. The preparation activities lead-time is 5 days and the concluding activities lead-time is also 5 days. Thus, the cylinder overhaul lead-time is than 40 + 5 + 5 = 50 days. Thus, there is a probability of 31% that lead-time of the overhaul of cylinder 3 is equal or less than 50 days.
6.3.3. **Actual overhaul activities lead-time**

There are several overhaul activities that determine the actual overhaul activities lead-time, see Figure 6-7.

![Diagram of Actual overhaul activities lead-time](image)

**Figure 6-7; Actual overhaul activities lead-time**

Figure 6-7 gives an example of the overhaul cylinder for which four overhaul activities are executed. The overhaul activity which has the longest lead-time determines the “actual overhaul activities lead-time”, because the “actual overhaul activities lead-time” is finished if all overhaul activities are finished. The lead-time of the overhaul of the cylinders is not constant, see Figure 6-4 (the values do not correspond to actual lead-times).

![Overhaul activities lead-time graph](image)

**Figure 6-8; Overhaul activities lead-time**
Figure 6-4 gives the cumulative probability graph of the lead-times of the overhaul activities. The colored lines give the probability that the overhaul activity is executed is equal or lower than X days. The product of the cumulative overhaul activity lead-time probability of the different overhaul activities gives the probability that all overhaul activities are finished and thus the “actual overhaul activities lead-time”.

For example, there is 99.3% probability that the lead-time of cylinder 1 is between 0 and 40 days, 41.2% for cylinder 2, 97.7% for cylinder 3, and 76.8% for cylinder 4. The probability that “actual overhaul activities lead-time” is between 0 and 40 days is the probability that all cylinder overhaul lead-times are between 0 and 40, thus; 99.3% * 97.7% * 41.2% * 76.8% = 31%

The example of Figure 6-4 gives the scenario that 4 overhaul activities need to be performed. However, not all overhaul activities are always required. In the case of the hydraulic cylinders of Bosch Rexroth 8 overhaul activities can be performed. Therefore, there are different scenarios in which different overhaul activities are required, each scenario having a certain probability. An example is given in Appendix II.
6.3.4. **Overhaul activity lead-time**

The “Overhaul activity lead-time” is the sum of the “actual planning lead-time” and the “execution Lead-time”. See Figure 6-9.

![Figure 6-9; Overhaul activity lead-time](image)

The “actual planning lead-time”, in Figure 6-9, is the time it takes to do the planning of the overhaul activity after the “preparation activities”, see next section. The “execution lead-time”, in Figure 6-9, is the time it takes to actually execute the overhaul activity. Summing up the “actual planning lead-time” and the “execution Lead-time” gives the “Overhaul activity lead-time”. See Figure 6-10 for this summation.

![Figure 6-10; Actual planning and execution lead-time](image)

<table>
<thead>
<tr>
<th>Actual planning lead-time</th>
<th>Probability</th>
<th>Execution Lead-time</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30.1%</td>
<td>0%</td>
</tr>
<tr>
<td>10</td>
<td>39.9%</td>
<td>0%</td>
</tr>
<tr>
<td>20</td>
<td>24.2%</td>
<td>0%</td>
</tr>
<tr>
<td>30</td>
<td>5.4%</td>
<td>0%</td>
</tr>
<tr>
<td>40</td>
<td>0.4%</td>
<td>0%</td>
</tr>
<tr>
<td>50</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>60</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>70</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>80</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>90</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>100</td>
<td>0.0%</td>
<td>0%</td>
</tr>
</tbody>
</table>
The “actual planning lead-time” and the “execution Lead-time” are not constant; the lead-times can have different values. Figure 6-10 gives the calculation of the probability that the overhaul activity lead-time is 70 days. The probability that the “overhaul activity lead-time” is 70 days is the probability that the sum of the “actual planning lead-time” and the “execution lead-time” is 70. In the example in Figure 6-10 this is the following:

\[
(0 \times 0) + (0,008 \times 0) + (0,036 \times 0) + (0,109 \times 0,004) + (0,213 \times 0,054) + (0,266 \times 0,242) + (0,213 \times 0,399) + (0,109 \times 0,301) = 19,4\%
\]

The same calculation can also be done for other values of the “overhaul activity lead-time” to get the “overhaul activity lead-time” probability density function.

### 6.3.5. Actual Planning Lead-time

The “actual planning lead-time” is the part of the “planning lead-time” that is within the “overhaul activity lead-time”, see Figure 6-11.

![Figure 6-11; Actual planning lead-time](image)

When an inspection is done and the overhaul activity requirement is detected Bosch Rexroth can start with the planning of the overhaul activity. The “actual planning lead-time” is than the “planning lead-time” minus the part that is done during or before the “preparation of the overhaul”. Thus the “actual planning lead-time” is the “planning lead-time” minus the “overhaul preparation activities lead-time”, the “classification lead-time” and the “time till classification”. When two inspections are done there are 4 scenarios for the “actual planning lead-time”, see Figure 6-12.

![Figure 6-12; Actual planning lead-time and time till classification at moment of detection](image)
In the first scenario in Figure 6-12, the overhaul activity requirement is detected at the first inspection, the largest part of the planning is done during or before the “overhaul preparation activities”.

In the second scenario in Figure 6-12, the overhaul activity requirement is not detected at the first inspection and detected at the second inspection, a part of the planning is done during or before the “overhaul preparation activities”.

In the third scenario in Figure 6-12, the overhaul activity requirement is not detected at the first or second inspection, the “actual planning lead-time” is equal to the “planning lead-time.”

The overhaul activity does not have to be planned or executed if the overhaul activity is not required. In the fourth scenario the overhaul activity is not required and the “planning lead-time” as well as the “actual planning lead-time” is therefore zero.

Figure 6-13 gives the probability density function of the “actual planning lead-time” for the different scenarios. Figure 6-13 does not correspond with the other examples but is given as example for the different actual planning probability density functions depending on the scenario.

![Actual Planning Lead-Time PDF](image)

*Figure 6-13; Actual planning lead-time probability density function for the different scenarios.*
6.3.6. Detection probability

The closer an overhaul activity performed to the classification the greater the probability of detecting the requirement of the overhaul activity, see Figure 6-14.

![Detection Probability](image)

**Figure 6-14; Detection Probability**

In the example in Figure 6-14 there are two inspections. The probability that the overhaul activity requirement is detected at inspection 1 is 50%. When the overhaul activity requirement is detected a second inspection is redundant since the planning of the overhaul activity can already be done. Thus the probability that a second inspection is performed is 100%-50%=50% (1-probability that inspection 1 has detected the overhaul activity requirement = probability of performing inspection 2). When the second inspection is performed there is a probability of 86% that the overhaul activity is detected, thus there is a probability of $(100\%-50\%) \times 86\% = 43\%$ that the overhaul activity is detected at the second inspection. The probability that the overhaul activity is not detected during the additional inspections is $(100\%-50\%) \times (100\%-86\%) = 7\%$.

The overhaul activity is only executed if required therefore the probability that the overhaul activity is required needs to be accounted for. If the requirement probability of the overhaul activity would be 80% the following would apply;

- The probability that the overhaul activity is required and detected at inspection 1 (thus scenario 1 in Figure 6-12) is: $80\% \times 50\% = 40\%$
- The probability that the overhaul activity is required and not detected at inspection 1 and is detected at inspection 2 (thus scenario 2 in Figure 6-12) is: $(100\%-50\%) \times 86\% \times 80\% = 34.4\%$
- The probability that the overhaul activity is required and not detected at inspection 1 or inspection 2 (thus scenario 3 in Figure 6-12) is: is \((100\% - 50\%) \times (100\% - 86\%) \times 80\% = 5.6\%\)
- The probability that the overhaul activity is not required (thus scenario 4 in Figure 6-12) is: \(100\% - 80\% = 20\%\)

6.3.7. Overhaul execution dependency
Some of the overhaul activities are always executed if any of the overhaul activities are required. If the requirement of any of the overhaul activities is detected at the first inspection the overhaul activities that are always executed if any of the overhaul activities are required can be planned after the first inspection. When none of the overhaul activities’ requirement is detected at the first inspection but any of the overhaul activities’ requirement is detected at the second inspection, the overhaul activities that are always executed if any of the overhaul activities are required can be planned after the second inspection. Thus, as soon as any of the overhaul activities’ requirement is detected, the overhaul activities that are always executed if any of the overhaul activities are required can be planned. The example in Appendix II gives the implications of the overhaul execution dependency.

6.3.8. Requirement probability
The probability that a component overhaul is required is dependent of time since the last renewal of the component.

![Figure 6-15; Overhaul activity requirement probability.](image-url)

The component’s age (see Figure 6-15) is 10 years at the start of the service period, since the component is not overhauled during the operation period the component can either be overhauled directly after the service contract period (in classification period) or later. The probability of the overhaul being required in the classification period is thus the green area in Figure 6-15 divided by the sum of the green and purple area in Figure 6-15.
7. Mathematical model
This chapter gives the mathematical model for the conceptual model described in chapter 6. First the variable descriptions are given, thereafter the calculations are given.

7.1. Variable descriptions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{IN}$</td>
<td>Cost of an inspection</td>
</tr>
<tr>
<td>$CP_{k(1,s_1),(2,s_2),...,(l-1,s_{l-1}),(l,s_l)}$</td>
<td>Case probability of cylinder $k$ and scenario $s_i$ (for all overhaul activities)</td>
</tr>
<tr>
<td>$c_{D,IN}$</td>
<td>Downtime costs due to inspection per day</td>
</tr>
<tr>
<td>$c_{D,SO}$</td>
<td>Downtime costs due to extended classification period per day</td>
</tr>
<tr>
<td>$c_{IN}$</td>
<td>Cost of inspection</td>
</tr>
<tr>
<td>$DP_i(TTC_r)$</td>
<td>Requirement detection probability of overhaul activity $i$ at $TTC_r$</td>
</tr>
<tr>
<td>$E[C_D]$</td>
<td>Expected downtime costs for the customer</td>
</tr>
<tr>
<td>$E[C_T]$</td>
<td>Expected total costs for the customer</td>
</tr>
<tr>
<td>$E[DT_{IN}]$</td>
<td>Expected downtime resulting from an inspection</td>
</tr>
<tr>
<td>$E[DT_{SO}]$</td>
<td>Expected downtime due to the system overhaul</td>
</tr>
<tr>
<td>$E[L_{IN}]$</td>
<td>Expected lead-time of an inspection</td>
</tr>
<tr>
<td>$i$</td>
<td>Overhaul activity ($\forall i \in I$)</td>
</tr>
<tr>
<td>$I$</td>
<td>Total set of overhaul activities</td>
</tr>
<tr>
<td>$i_a$</td>
<td>Overhaul activity that is always performed if an overhaul is executed ($\forall i_a \in I$)</td>
</tr>
<tr>
<td>$i_o$</td>
<td>Overhaul activity that is only performed if required ($\forall i_o \in I$)</td>
</tr>
<tr>
<td>$k$</td>
<td>Cylinder ($\forall k \in K$)</td>
</tr>
<tr>
<td>$K$</td>
<td>Total set of cylinders in the contract</td>
</tr>
<tr>
<td>$L_{CO_{k(1,s_1),(2,s_2),...,(l-1,s_{l-1}),(l,s_l)}}(.)$</td>
<td>Cumulative distribution function of cylinder overhaul lead-time of cylinder $k$ in scenario $s_i$ (for all overhaul activities)</td>
</tr>
<tr>
<td>$L_{CO_k(.)}$</td>
<td>Cumulative distribution function of cylinder overhaul lead-time of cylinder $k$</td>
</tr>
<tr>
<td>$LP_{OC-A_{k,(i,s_l)}(.)}$</td>
<td>Cumulative distribution function of overhaul activity $i$ of cylinder $k$ in scenario $s_i$ and the preparation and concluding activities</td>
</tr>
<tr>
<td>$L_{CA}$</td>
<td>Lead-time of concluding activities</td>
</tr>
<tr>
<td>$L_{I}$</td>
<td>Lead-time of inspecting and reporting back to customer</td>
</tr>
<tr>
<td>$L_{PA}$</td>
<td>Lead-time of preparation activities</td>
</tr>
<tr>
<td>$L_{SO(.))$</td>
<td>Cumulative probability function of system overhaul lead-time</td>
</tr>
<tr>
<td>$l_{E_i(.)}$</td>
<td>Probability density function of execution lead-time of overhaul activity $i$</td>
</tr>
<tr>
<td>$l_{P_i(.)}$</td>
<td>Probability density function of planning lead-time of overhaul activity $i$</td>
</tr>
<tr>
<td>$l_{AP_{k,(i,s_l)}(.)}$</td>
<td>Probability density function of actual planning lead-time of overhaul activity $i$ of cylinder $k$ in scenario $s_i$</td>
</tr>
</tbody>
</table>
- \( I_{OA_{k,i}} (.) \) Probability density function of overhaul activity lead-time of overhaul activity \( i \) of cylinder \( k \) in scenario \( s_i \)
- \( I_{SO}(.) \) Probability density function of system overhaul lead-time
- \( PCP \) Planned classification period
- \( POS_{k,(i,s_i)} \) Scenario probability of scenario \( s_i \), for overhaul activity \( i \) of cylinder \( k \)
- \( PRQ_{k,i} \) Probability density function of requirement of overhaul activity \( i \) for cylinder \( k \)
- \( r \) Inspections (\( \forall r \in R \))
- \( R \) Total set of inspections
- \( RQ_{i} \) Requirement of overhaul activity \( i \) for cylinder \( k \)
- \( s_i \) Detection/Requirement scenario of overhaul activity \( i \) (\( \forall s_i \in S_i \))
- \( S_i \) Total set of scenarios for the requirement/detection of overhaul activity \( i \)
- \( SCP \) Service Contract Period
- \( TSR_{k,i} \) Time since last renewal of overhaul activity \( i \) for cylinder \( k \) at start of inspection based overhaul service contract
- \( TTC_{r} \) Time till classification at the start of inspection \( r \)

**Table 7-1: Variable descriptions**

### 7.2. Calculations

As described in section 5.6.1, the expected costs for the customer dependents on the costs of the inspections and the downtime costs, see equation 1.

\[
E[C_T] = E[C_D] + C_{IN} \tag{1}
\]

The relevant expected cost can be calculated by the sum of the expected downtime costs and inspection costs. The inspection costs are a function of the number of additional inspections and the cost of inspections, see equation 2.

\[
C_{IN} = (|R| - 1) \ast c_{IN} \tag{2}
\]

When there is an overhaul there is always an inspection, this inspection is performed during the overhaul preparation activities and does therefore not cause additional inspection costs. The cost of the inspection is the product of the cost per inspection and the number of inspections. The downtime costs are calculated with equation 3.

\[
E[C_D] = E[DT_{SO}] \ast c_{D,SO} + E[DT_{IN}] \ast c_{D,IN} \tag{3}
\]

The cost of downtime is the product of the downtime and the downtime cost per time unit. The downtime is the summation of the expected downtime due to inspections and the expected downtime due to the overhaul period. For the downtime due to inspections see equation 4, for the downtime due to the overhaul see equation 5.

\[
E[DT_{IN}] = (|R| - 1) \ast E[L_{IN}] \tag{4}
\]
The expected downtime due to inspections is the product of the number of inspections minus one and the expected lead-time of an inspection. There could be a difference in the agreed upon inspections and the actual performed inspections, because when all overhaul activities’ requirement are already detected there is no need for more inspections. However, the customer plans the rig to be down for the planned inspections and also plan other maintenance activities during this period. Therefore, there will be downtime during the period during which the inspections are planned irrespectively on whether the inspections are done. When there is an overhaul there is always an inspection, this inspection is performed during the overhaul preparation activities and does therefore not cause additional downtime. The expected system downtime due to the overhaul period is given by the equation 5.

\[
E[DT_{SO}] = \int_{PCP}^{\infty} l_{SO}(x) \times (x - PCP) \, dx
\]  

The “downtime due to the system overhaul” is the “system overhaul lead-time” minus the “planned classification period”. Integrating the probability density function of the “system overhaul lead-time” multiplied by the “downtime due to the system overhaul” gives the expected downtime due to the system overhaul.

### 7.2.1. System overhaul lead-time

The “system overhaul lead-time” probability function is given in equation 6.

\[
l_{SO}(x) = \frac{d}{dx} L_{SO}(x)
\]  

The “system overhaul lead-time” probability density function is the differential of the “system overhaul lead-time” cumulative probability function. The “system overhaul lead-time” cumulative probability function is given in equation 7.

\[
L_{SO}(x) = \prod_{k \in K} L_{CO_k}(x)
\]  

The “system overhaul lead-time” cumulative probability function is the product of the “cylinder overhaul lead-time” cumulative probability function of all cylinders. The “cylinder overhaul lead-time” cumulative probability function gives the probability that the overhaul lead-time of the cylinder \(k\) is \(x\) or lower. Multiplying this probability for each cylinder gives the probability that all “cylinders overhaul lead-times” are \(x\) or lower, and thus gives the probability that the “system overhaul lead-time” is \(x\) or lower.

### 7.2.2. Cylinder overhaul lead-time

The cylinder overhaul lead-time depends on the lead-time of the preparation activities, actual overhaul activities, and concluding activities. The distribution of actual overhaul activities lead-time depends on the time at which the overhaul requirement is detected, this is called the “scenario” of the overhaul activity, see table below.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Overhaul activity required:</th>
<th>Detection time:</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s_i = 1)</td>
<td>Required</td>
<td>Detected at first (additional) inspection ((r = 1))</td>
</tr>
<tr>
<td>(s_i = 2)</td>
<td>Required</td>
<td>Detected at second (additional) inspection ((r = 2))</td>
</tr>
</tbody>
</table>
Each overhaul activity can be in a different scenario. The probability that overhaul activity $i$ is in scenario $s_i$ for every overhaul activity is called the case probability, see equation 8.

$$CP_k((1,s_1),(2,s_2),...,(l,s_l),(l,s_l)) = \prod_{i \in I} POS_{k,(i,s_i)}$$ (8)

The case probability is thus the multiplication of the scenario probabilities of all overhaul activities of cylinder $k$.

As described in section 6.3.7, there are two types of overhaul activities; the overhaul activities that are executed if required, and the overhaul activities that are always executed if any of the overhaul activities are required. As soon as any of the overhaul activities’ requirement is detected, the overhaul activities that are always executed if any of the overhaul activities are required are planned, see equation 9.

$$L_{COA,k}((1,s_1),(2,s_2),...,(l,s_l),(l,s_l)) = \prod_{i \in I} L_{POC,A_k,(i,s_i)} \prod_{i \in I} L_{POC,A_k,(\min(s_1,s_2,...,s_{i-1},s_i))}$$ (9)

The probability that the cylinder overhaul lead-time is $x$ or less (in the case of: $((1,s_1),(2,s_2),...,(i,s_i),..., (l-1,s_{l-1}),(l,s_l))$) is the probability that the sum of the overhaul activity lead-time, the preparation activities lead-time and the concluding activities lead-time is, for all overhaul activities, is $x$ or less. The scenario of the overhaul activities that are executed if required ($\forall i \in I_o$) is only dependent on their own scenario. The scenario of the overhaul activities that are executed if any of the overhaul activities are required ($\forall i \in I_a$) depends on the first detection point of any of the overhaul activities and is therefore the minimum of $(s_1; s_2; ...; s_{i-1}; s_i)$.

To get the cumulative distribution function of the cylinder overhaul lead-time of cylinder $k$ the product of the “case probability” and the “the case cumulative distribution function” has to be summed up for every case, see equation 10.

$$L_{COA,k}(x) = \sum_{s_1=1}^{S_1} \sum_{s_2=1}^{S_2} ... \sum_{s_l=1}^{S_l} \sum_{s_{l-1}=1}^{S_{l-1}} \sum_{s_i=1}^{S_i} L_{COA,k((1,s_1),(2,s_2),...,(l,s_l),(l,s_l))}(x) \times CP_k((1,s_1),(2,s_2),...,(l,s_l),(l,s_l)) $$ (10)

The cumulative distribution function of the cylinder overhaul lead-time in equation 10 gives the probability that cylinder overhaul lead-time is $x$ or less.
7.2.3. Preparation, overhaul, and concluding activities

The lead-time of the preparation, overhaul, and concluding activities depends on the scenario of the overhaul activity, see equation 11.

\[
L_{POC-A, k(i_{(s_i=1)})}(\psi) = \begin{cases} 
\int_{0}^{\psi-(L_{PA}+L_{CA})} l_{OA_{k_1}}(\beta) d\beta, & \psi \leq L_{PA} + L_{CA} \\
0, & \psi > L_{PA} + L_{CA}
\end{cases}
\]

\[
L_{POC-A, k(i_{(s_i=2)})}(\psi) = \begin{cases} 
\int_{0}^{\psi-(L_{PA}+L_{CA})} l_{OA_{k_2}}(\beta) d\beta, & \psi \leq L_{PA} + L_{CA} \\
0, & \psi > L_{PA} + L_{CA}
\end{cases}
\]

\[
L_{POC-A, k(i_{(s_i=S_i-1)})}(\psi) = \begin{cases} 
\int_{0}^{\psi-(L_{PA}+L_{CA})} l_{OA_{k_{S_i-1}}}(\beta) d\beta, & \psi \leq L_{PA} + L_{CA} \\
0, & \psi > L_{PA} + L_{CA}
\end{cases}
\]

\[
L_{POC-A, k(i_{(s_i=S_i)})}(\psi) = 1
\]

In the scenario that overhaul activity is required \((s_i < S_i)\), the lead-time the preparation, overhaul, and concluding activities is the sum of the lead-time of these activities. The cumulative probability function (in these scenarios) of the preparation, overhaul, and concluding activities is the cumulative distribution function of the overhaul activity lead-time shifted with \(L_{PA} + L_{CA}\) to the right. The cumulative distribution function of the overhaul activity lead-time is the integral of the probability density function of the overhaul activity lead-time. When the scenario is \(S_i\) the overhaul activity is not required and therefore the probability that the preparation, overhaul, and concluding activities execution is finished is always 1.

7.2.4. Overhaul activity lead-time

The overhaul activity lead-time is the sum of the “actual planning lead-time” and the “execution lead-time”, see equation 12.

\[
l_{OA_{k_{(S_i)}}}(\beta) = \int_{0}^{\beta} \left( l_{AP_{k_{(S_i)}}}(\varphi) * l_{E_{S_i}}(\beta - \varphi) \right) d\varphi
\]
### 7.2.5. Actual planning lead-time

The actual planning lead-time depends on the time at which the overhaul activity’s requirement is detected (and thus the scenario), see equation 13.

\[
l_{AP_{k(i(s_i = 1))}}(\varphi) = \begin{cases} 
    \int_0^{TTC_1 + L_{PA} - L_I} l_{P_1}(\phi) \, d\phi, & \varphi = 0 \\
    l_{P_1}(TTC_1 + L_{PA} - L_I + \varphi), & \varphi > 0 
\end{cases}
\]

\[
l_{AP_{k(i(s_i = 2))}}(\varphi) = \begin{cases} 
    \int_0^{TTC_2 + L_{PA} - L_I} l_{P_1}(\phi) \, d\phi, & \varphi = 0 \\
    l_{P_1}(TTC_2 + L_{PA} - L_I + \varphi), & \varphi > 0 
\end{cases}
\]

... 

\[
l_{AP_{k(i(s_i = s_i - 2))}}(\varphi) = \begin{cases} 
    \int_0^{TTC_{s_i - 2} + L_{PA} - L_I} l_{P_1}(\phi) \, d\phi, & \varphi = 0 \\
    l_{P_1}(TTC_{s_i - 2} + L_{PA} - L_I + \varphi), & \varphi > 0 
\end{cases}
\]

\[
l_{AP_{k(i(s_i = s_i - 1))}}(\varphi) = l_{P_1}(\varphi)
\]

In the scenario that overhaul activity’s requirement is detected at an additional inspection \((s_i \leq s_i - 2)\), the “actual planning lead-time” is the “planning lead-time” minus the “overhaul preparation activities lead-time”, minus the “time till classification” plus the “inspection lead-time”, see section 6.3.5. In the scenario that the overhaul activity is required but not detected at the additional inspections the actual planning lead-time” is equal to the “planning lead-time” ”, see section 6.3.5 and Figure 7-1.

![Figure 7-1; Actual planning lead-time](image)

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7.2.6. Scenario probability

The scenario probability gives the probability of a certain scenario, there are 3 types of scenario’s; overhaul activity required and detected at an additional inspection, overhaul activity required and not detected at an additional inspections, and overhaul activity not required. See equation 14.

\[
POS_{k,i,(s_l = 1)} = PRQ_{k,i} \times DP_l(TTC_1)
\]

\[
POS_{k,i,(s_l = 2)} = PRQ_{k,i} \times DP_l(TTC_2) \times (1 - DP_l(TTC_1))
\]

\[
\vdots
\]

\[
POS_{k,(i,s_l)} = PRQ_{k,i} \times DP_l(TTC_{s_l}) \times \prod_{r=1}^{s_l-1} (1 - DP_l(TTC_r))
\]

\[
\vdots
\]

\[
POS_{k,(i,s_{l-1} - 2)} = PRQ_{k,i} \times DP_l(TTC_{s_{l-2}}) \times \prod_{r=1}^{s_{l-1}-1} (1 - DP_l(TTC_r))
\]

\[
POS_{k,(i,s_{l-1} - 1)} = PRQ_{k,i} \times \prod_{r=1}^{s_{l-1}-1} (1 - DP_l(TTC_r))
\]

\[
POS_{k,(i,s_{l-1})} = 1 - PRQ_{k,i}
\]

The probability that the overhaul activity is required and detected at an additional inspection \((s_l \leq S_l - 2)\) is the product of the requirement probability \((PRQ_{k,i})\), the probability of detection at inspection \(r \left( DP_l(TTC_{s_l}) \right)\), and probability of no earlier detection \(\left( \prod_{r=1}^{s_l-1} (1 - DP_l(TTC_r)) \right)\). The probability that the overhaul activity is required and not detected at an additional inspection is the probability that the overhaul activity is detected during the classification period \((s_l = S_l - 1)\) and is calculated by the product of the requirement probability \((PRQ_{k,i})\), and the probability of no detection during additional inspections \(\left( \prod_{r=1}^{S_l-2} (1 - DP_l(TTC_r)) \right)\). The probability that the overhaul activity is not required \((s_l = S_l)\), is one minus the probability of requirement.
### 7.2.7. Requirement probability

The requirement probability is given in equation 15.

\[
PRQ_{k,i} = P(TSR_{k,i} < RQ_i \leq TSR_{k,i} + SCP | RQ_i > TSR_{k,i})
\]

\[
PRQ_{k,i} = \frac{P(TSR_{k,i} < RQ_i \leq TSR_{k,i} + SCP)}{P(RQ_i > TSR_i)}
\]

\[
PRQ_{k,i} = \frac{P(RQ_i \leq TSR_{k,i} + SCP) - P(RQ_i \leq TSR_{k,i})}{1 - P(RQ_i \leq TSR_{k,i})}
\]

\[
PRQ_{k,i} = \frac{\int_0^{SCP+TSR_{k,i}} RQ_i(\tau) d\tau - \int_0^{TSR_{k,i}} RQ_i(\tau) d\tau}{1 - \int_0^{TSR_{k,i}} RQ_i(\tau) d\tau}
\]

(15)

The requirement probability is the probability that overhaul activity \( i \) of cylinder \( k \) its requirement arises during the service contract, and not after the service contract, given that the overhaul activity was not required at \( TSR_{k,i} \). Thus that the requirement probability arises after \( TSR_{k,i} \) and before \( TSR_{k,i} + SCP \) given that it arises after \( TSR_{k,i} \). This completes the mathematical model.
8. Optimization heuristic

The objective of the model described in section 6 and 7 is to minimize the expected costs for the customer \( E[C_T] \). As described the costs are dependent of the number of additional inspections \( R \) and the time till classification of the inspections \( TTC_r \).

The optimization heuristic consists of three modules. The first module is given in Figure 8-1 and has 5 steps.

**Step 1** sets the number of inspections to one \( R = 1 \), this inspection is executed at \( TTC_1 = 0 \). This is the inspection during the overhaul.

**Step 2** saves the current settings (i.e. number of inspections and TTC of inspections) and calculates the expected costs for the customer \( E[C_T] \).

**Step 3** adds another inspection \( R := R + 1 \). The moment at which the inspection takes places is determined in the next step.

**Step 4** optimizes the \( TTC \) of inspection so that the expected costs for the customer are minimal given the number of inspections determined in step 3 (see next page). Then the expected costs are calculated for the settings derived from step 3 and the optimization of the \( TTC \) of the inspections.

When the expected costs in Step 2 are lower than in Step 4 the expected costs are not decreased by adding an extra inspection (step 3) and thus the settings in step 2 should be used (step 5). When the expected are decreased by adding an extra inspection (step 3) than go to Step 2 again.

**Step 5** when the expected costs in step 2 are lower than in step 4 the settings as in step 2 give the optimal settings for the decisions variables and should be used.

**Figure 8-1; Expected cost optimization**
In step 4 the TTC of the inspections are optimized, Figure 8-2 describes how this is done.

**Step 4.1** sets the initial values of the TTC of the inspections. Inspection $R$ is the in inspection during the classification period and therefore $TTC_R = 0$. $TTC_R$ should always be lower than $TTC_{R+1}$ therefore $TTC_R \leq TTC_{R+1} - \Delta$. $\Delta$ is the minimum distance between two inspections.

In **step 4.2** the settings of the TTC of the inspections is saved and the expected costs are calculated.

In **step 4.3** the TTC of the inspections are adapted by adding $\alpha$ to the TTC of the different inspections. The adaption that results in the greatest decrease in the expected costs is used in step 4.4. Step 4.3. is further specified on the next page.

In **step 4.4** the expected costs are calculated with the adaption of the settings given in step 4.3.

When the expected costs in Step 4.2 are lower than in Step 4.4 the settings as in step 2 should be used (step 4.5). When the expected costs in Step 4.4 are lower than in Step 4.2 the settings as in step 2 should be used, in this case go back to step 4.2

**Step 4.5** when the expected costs in step 4.2 are lower than in step 4.4 the settings as in step 4.2 give the optimal settings for the TTC of the inspections, given the number of inspections.

*Figure 8-2; TTC optimization*
Step 4.3 gives the adaption of the TTC of the inspections which results in the smallest expected costs for the customer, see Figure 8-3.

In step 4.3, the $TTC$ is added with $\alpha$ for all inspections. The smaller $\alpha$ the higher the accuracy of the optimization, $\alpha$ can be chosen by the software-tool user (see section 9.5) and is done manually. The inspection for which this adaption gives the lowest expected costs is the optimal adaption. When $TTC_r + \Delta + \alpha < TTC_{r+1}$ the adaption is performed, if $TTC_r + \Delta + \alpha > TTC_{r+1}$ than the adaption is not performed because the inspection $r$ should always be before $r + 1$. For the first inspection the adaption is always performed because it is not constraint by an earlier inspection. See Figure 8-4 for a schematic overview of the optimization heuristic.
9. Software-tool

The calculations described in section 7.2, and the optimization heuristic described in section 8 are used as input for the service contract decision support software-tool. The software tool is made in excel-VBA. Section 9.1 describes which type of cylinder is selected for implementation in the software-tool. Section 9.2 describes how the input distributions are derived. Section 9.3 describes how the software-tool works. Section 9.4 gives the verification of the expected cost calculation. Section 9.5 gives the verification of the optimization heuristic. Section 9.6 gives the results of some tested scenarios. Section 9.7 describes how the software-tool is implemented.

9.1. Hydraulic cylinder selection

Different types of hydraulic cylinder are used in offshore. These different types have different applications and specifications, and are also used in different environments. The different types of hydraulic cylinders have a different reliability due to the differences in specifications and operating environment. The mathematical model as described in chapter 7.2, can be used for all the hydraulic cylinder types, however there are differences in the values of the input variables. For the calculation and the software tool one type of hydraulic cylinder type is selected. The selection of the type of hydraulic cylinder that is used for the implementation is done with two selection criteria. The first criterion is the quantity of the type of hydraulic cylinder in the field. This criterion is used because if the quantity of the type of hydraulic cylinders is higher the calculation model can be applied for more customers. The second criterion is the accuracy in which the hydraulic cylinder experts can estimate the input distributions. This criterion is used because low accuracy of input distributions results in low accuracy of the output.

<table>
<thead>
<tr>
<th>Cylinder type</th>
<th>Quantity</th>
<th>Percentage of total</th>
<th>Average Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Line tensioner</td>
<td>950</td>
<td>31.88%</td>
<td>11.1</td>
</tr>
<tr>
<td>Direct riser tensioner</td>
<td>498</td>
<td>16.71%</td>
<td>7.1</td>
</tr>
<tr>
<td>Jack up cylinder</td>
<td>202</td>
<td>6.78%</td>
<td>8.7</td>
</tr>
<tr>
<td>Hoist cylinder</td>
<td>164</td>
<td>5.50%</td>
<td>9.4</td>
</tr>
<tr>
<td>Drillstring compensator</td>
<td>142</td>
<td>4.77%</td>
<td>16.0</td>
</tr>
<tr>
<td>Guide line tensioner</td>
<td>137</td>
<td>4.60%</td>
<td>24.0</td>
</tr>
<tr>
<td>Pin cylinder</td>
<td>137</td>
<td>4.60%</td>
<td>9.4</td>
</tr>
<tr>
<td>Heave compensation cylinder (other)</td>
<td>100</td>
<td>3.36%</td>
<td>13.2</td>
</tr>
<tr>
<td>Cantilever skidding system</td>
<td>96</td>
<td>3.22%</td>
<td>10.3</td>
</tr>
<tr>
<td>Active heave compensator cylinder</td>
<td>82</td>
<td>2.75%</td>
<td>7.3</td>
</tr>
<tr>
<td>Heavy compensator cylinder</td>
<td>49</td>
<td>1.64%</td>
<td>4.4</td>
</tr>
<tr>
<td>Lifting cylinder</td>
<td>35</td>
<td>1.17%</td>
<td>1.4</td>
</tr>
<tr>
<td>Y-Drive cylinder</td>
<td>32</td>
<td>1.07%</td>
<td>1.0</td>
</tr>
<tr>
<td>Locking cylinder</td>
<td>26</td>
<td>0.87%</td>
<td>6.0</td>
</tr>
<tr>
<td>Crown mounted compensator cylinder</td>
<td>17</td>
<td>0.57%</td>
<td>5.2</td>
</tr>
<tr>
<td>Standardized large hydraulic cylinder</td>
<td>16</td>
<td>0.54%</td>
<td>12.0</td>
</tr>
<tr>
<td>Vertical Caster Cylinder</td>
<td>7</td>
<td>0.23%</td>
<td>6.0</td>
</tr>
<tr>
<td>A-frame cylinder</td>
<td>6</td>
<td>0.20%</td>
<td>8.0</td>
</tr>
<tr>
<td>Spannzylinder</td>
<td>4</td>
<td>0.13%</td>
<td>16.0</td>
</tr>
<tr>
<td>Active in-line compensator cylinder</td>
<td>3</td>
<td>0.10%</td>
<td>17.0</td>
</tr>
<tr>
<td>Amplifier Control Cabinet</td>
<td>2</td>
<td>0.07%</td>
<td>12.0</td>
</tr>
<tr>
<td>Travelling block compensator</td>
<td>2</td>
<td>0.07%</td>
<td>Unknown</td>
</tr>
<tr>
<td>Offshore replenishment system</td>
<td>1</td>
<td>0.03%</td>
<td>16.0</td>
</tr>
<tr>
<td>Other</td>
<td>271</td>
<td>9.09%</td>
<td>12.9</td>
</tr>
</tbody>
</table>

Table 9-1; Cylinder types (Source: IBase; 03-2014)
Table 9-1 gives the cylinder types found in the installed base list downloaded from IBase. The first column gives the different types of cylinder, the second column the number of cylinders that installed in the field, the third column the percentage of number of cylinder type of the total installed base, and the fourth column the average age of the cylinder type installed in the field. The “Wire Line Tensioner” is the most common cylinder in the field. The experts also think that the overhaul requirement and overhaul detection probability is the easiest to estimate for this type of cylinder. Therefore, the “Wire Line Tensioner” is selected for the mathematic model in the software tool. Appendix III describes what a “Wire Line Tensioner” is.

9.2. Input distributions

Three input variables are described in section 6 and 7, requirement probability, detection probability, and lead-time of the overhaul activity execution and planning. Distribution estimations are done by expert estimations. Historical data has not been used for the estimations because the available data is assumed to be invalid and incomplete. The distribution fitting procedures can be found in Appendix V.

The validity of the input distributions can be distinguished in face-validity and technical validity. Face-validity is proven when the input variables are expected to correspond to the real-world. Technical validity is proven when the input variables correspond to real data (Law & Kelton, 2000).

9.2.1. Face-Validity

The requirement and detection probability distributions are estimated by the experts. The different estimations are used to find a combined estimation and fit a statistical distribution. The distributions that is fitted to the estimations are discussed with the experts. The distributions that are fitted to the estimations are labeled as valid by the customer on the basis that it looks reasonable. Therefore, it can be concluded that the input variables for the detection and requirement probability have face-validity.

The lead-time distributions of the overhaul activities are also estimated by experts. The experts formed an estimation upon which they all agreed. This naturally proves the face-validity of the lead-time distributions of the overhaul activities.

9.2.2. Technical Validity

The technical validity can be proved by comparing real data with the statistical distributions. The requirement probability distribution could be compared with the time till executing of the overhaul activities in the past, however, as described in section 5.5 the data that is available is assumed to be unreliable. Information on the time till executing of the different overhaul activities should be gathered in the future and compared with the distributions fitted to the estimations to prove the technical validity.

The detection probability distribution should be compared with the real data of inspections to prove the technical validity. However, since the concept of performing inspections in order to predict overhaul activities’ requirement is new to Bosch Rexroth, there is no historical data of inspections performed by Bosch Rexroth. Information on inspections, overhaul recommendations and actual overhaul requirements should be gathered in the future in order to prove the technical validity of the statistical reliability functions used for the detection probability.
The lead-time distributions are fitted to estimations. The estimations are based on historical overhauls, and therefore correspond to the real-world lead-times.

9.3. **Software-tool process**

The software-tool contains three modules, each having its own Excel-workbook. The first module contains the input and output of the tool. The second module is the optimization heuristic. The third module contains the cost calculation.

![Software-Tool Process Flowchart](image)

Figure 9-1 gives the flow of the processes through the 3 modules of the software-tool.

9.3.1. **Open software-tool**

After the user opens the software-tool the user can go directly to “input contract information”.

9.3.2. **Input contract information**

In the “input contract information” process the user is asked to fill the required information of the contract, this contains the following:

- The user name
- The customer name
- The project name
- The date of the start of the operation period (i.e. service contract)
- The date of the end of the operation period (i.e. service contract)
- The length of the classification period in days
- The expected downtime that is caused by one inspection
- The lead-time of the overhaul preparation activities
- The lead-time of the overhaul concluding activities
- The lead-time of inspecting and reporting
- The cost of one inspection
- The cost of downtime per day due to inspection
- The cost of downtime per day due to overhaul
- The number of cylinders

Screenshots of the “input contract information” processes can be found in the manual in Appendix VIII.

9.3.3. View and or adapt input distributions
When the user goes to the “view and or adapt the input distributions”, the user finds charts of the requirement probability density function, the detection probability function, the planning lead-time probability density function, and the planning lead-time probability density function. The user can select the overhaul activity for which overhaul activity the charts have to be displayed. The distributions can also be adapted, either manually or with an estimation fitting procedure. When the user knows the distribution and the parameters of the distribution these can be filled in. The user can also put in estimations of the distributions and let the software tool fit a distribution to the estimations. The user can also add or delete overhaul activities from overhaul activities list. When the user wants to add an overhaul activity, the user is asked for the name of the overhaul activity and subsequently the requirement probability density function, the detection probability function, the planning lead-time probability density function, and the planning lead-time probability density function can be filled in. The user also has to fill in whether the overhaul activity is only executed if required or also if any other overhaul activity to the same cylinder is required. This can also be changed later. Screenshots of the “view and or adapt the input distributions” processes can be found in the manual in Appendix VIII.

9.3.4. Input cylinder information
When all this information of the contract is filled in, the user goes to the “input cylinder information”, here the user has to fill the rod-coating of the cylinders. The user also has to fill in the time since last renewal of the different component for all the cylinders in the contract. Screenshots of the “input cylinder information” processes can be found in the manual in Appendix VIII.

9.3.5. Input optimization parameters
After all the information of the input distributions, the contract, and the cylinders in the contract is filled in, this information is used to find the optimum number and timing of the inspections of the cylinders. The user is asked to fill in the alpha and beta for the optimization process (see section 8). The user can also set a maximum number of inspections. Recommendations on the alpha and beta, and verification of the optimization can be found in section 9.5.

9.3.6. Optimize inspections
The “optimize inspection” process uses the optimization heuristic from section 8 and approximations of the equations in section 7. Recommendations on the alpha and beta, and verification of the
optimization can be found in section 9.5. The approximations of the equations in section 7 used during the optimization are designed to give a fast calculation of the expected costs, however the accuracy of the calculations is low (see section 9.4 and 9.5). Therefore, the expected costs have to be recalculated with more accuracy with the optimized number of inspections and timing of the inspection found with the optimization heuristic.

9.3.7. Calculate costs
As stated above, the expected costs have to be recalculated with more accuracy. This happens in the “calculate costs” process. Approximations of the equations in section 7 are used to calculate the costs. Section 9.4 describes the approximations and the appropriateness of these approximations. The costs are calculated with the optimized number and timing of the inspections, and also for the case in which no inspections are done. Both calculations are performed to show the difference between an inspection based and ad-hoc overhaul service. In addition, the user can specify an alternative scenario where the number and timing of the inspections can be changed with reference to the optimized scenario. This gives the user the ability to specify another scenario and thereby find the effect of changing the timing and number of inspections.

9.3.8. Give output
After the calculations are done the tool displays the expected costs as well as the “system overhaul lead-time” probability density function for both the inspection based, user-specified, and ad-hoc overhaul service. This output together with the input-parameters is given in a PDF-file. This PDF file can be used to negotiate the service agreement with the customer. Screenshots of the output can be found in the manual in Appendix VIII.

9.4. Cost calculation verification
The equations in section 7 are transformed to approximations to calculate the expected costs. Because the software-tool should be able to calculate the expected costs for the scenario with at least 8 (at most 15) overhaul activities, and up to 3 inspections and 20 cylinders, approximations of the equations are used. The transformed equations can be found in Appendix IX.

9.4.1. Computation time
Only the integral and differential equations are transformed. A differential gives the part of change in the dependent variable with respect to changes in the independent variable of a function. The change in the independent variable in this differential is Infinitesimal\(^1\). However, in the approximation of the differentials the change in the independent variable is 1 day. There is chosen for 1 day because the downtime costs are also per day. An integral can be seen as an infinite sum of rectangles of infinitesimal width. Again, instead of infinitesimal width, there has been chosen for a width of 1 day because the downtime costs are also per day. For the integral in equation 12 there has been chosen for another approach.

\[
I_{DA_k,(l_3)}(\beta) = \int_0^\beta \left( I_{AP_k,(l_3)}(\varphi) * I_{E_1}(\beta - \varphi) \right) d\varphi
\]

\(^1\) According to the Oxford English Dictionary the term infinitesimal was originally an ordinal, viz. the “infinitieth” in order; but, like other ordinals, also used to name fractions, thus infinitesimal part or infinitesimal came to mean unity divided by infinity (1/∞), and thus an infinitely small part or quantity.
For the integral in equation 12 there has been chosen to do $X$ sums of intervals (rectangles) instead of an infinite sum of intervals (rectangles) of infinitesimal width. The product in the integral has to be calculated for up to 20 cylinders, 15 overhaul activities, 4 inspections (3 Additional inspection, 1 during classification), 300 days, and $X$ per integral, which is $20 \times 15 \times 4 \times 300 \times X = 360,000 \times X$ intervals. Because of the large number of times the integral has to be calculated, the integral of equation 12 causes the most computations time in the software tool, the larger the number sums of intervals($X$) the higher the computations time. Figure 9-2 gives the number of intervals versus the computations time.

\[
\text{approximation}\left(I_{OA_{k,ir_{i}}}(\beta)\right) = \sum_{\varphi=0}^{X} I_{AP_{k,ir}}(\beta \cdot \frac{\varphi}{X}) * I_{E_{i}}(\beta - \beta \cdot \frac{\varphi}{X}) * \frac{\beta}{X}
\]

Figure 9-2; Computation time of integral

Figure 9-2 gives the lower and upper bound of the computation time versus the number of sums of intervals in the integral of equation 12. The more number of intervals, the more accurate the calculations. When using the $X = 100$ the computation time is between 4 and 12 minutes, which is still not too long. Therefore, $X = 100$ is used in the approximation of the integral. Section 9.4.2 verifies that the approximated calculation corresponds to the exact outcome.

\[9.4.2. \text{ Verification}\]

To verify that the approximated calculation and the exact outcome correspond to each other the case with one cylinder, one inspection, and one overhaul activity are calculated exact and with the approximations. The “planning lead-time” and the “execution lead-time” are exponentially distributed in the calculation. The equation of the exact calculation can be found in Appendix X.

A couple of scenarios are tested, in all of the scenarios the requirement probability of the overhaul activity is 80%, the probability that the overhaul activity requirement is detected at the inspection is 60%, the probability that the overhaul activity requirement is detected during the classification...
period is 20%, the lead-time of the “overhaul preparation activities” is 7 days, and the lead-time of the “overhaul concluding activities” is also 7 days. The timing of the inspection and mean planning lead-time and execution lead-time are enumerated with different values:

- \( \text{Time till classification at moment of inspection (TTC_r)} = [25, 50, 75] \)
- \( \text{Mean } \left( \frac{1}{\lambda} \right) \text{ planning leadtime} = [10, 15, ... , 70, 75] \)
- \( \text{Mean } \left( \frac{1}{\lambda} \right) \text{ execution leadtime} = [10, 15, ... , 70, 75] \)

For all scenarios the “system overhaul lead-time” probability density function is calculated exact and with the approximated calculation. The relative and absolute difference in expected “system overhaul lead-time”, and the relative difference in standard deviation is measured, see Appendix XI. The relative difference in expected “system overhaul lead-time” only exceeds 1% in cases where the mean planning lead-time is much higher than the mean execution lead-time, and does not exceed 5%. The absolute difference in expected “system overhaul lead-time” only exceeds 1 day in cases where the mean planning lead-time is much higher than the mean execution lead-time, and does not exceed 3 days. The relative difference in standard deviation of the “system overhaul lead-time” only exceeds 1% in cases where the mean planning lead-time is much higher than the mean execution lead-time, and does not exceed 3%. The only small differences in the expected “system overhaul lead-time” and its standard deviation verifies the appropriateness of the calculation approximations.

9.5. Optimization verification

The optimization heuristic has to calculate the expected costs several times. The optimization heuristic has to calculate the expected costs from at least 100 to 15000 times, depending on the required accuracy of the user. The calculation with the approximations described in section 9.4 takes from 4 to 12 minutes. This means that the optimization heuristic would have a computation time from 400 to 180.000 minutes. Because this computation time is far from acceptable the expected costs have to be calculated different in the optimization heuristic. As described, the main cause of the computation time is the integral in equation 12, therefore, instead of this integral a two-moment approximation is used to get the “overhaul activity lead-time” probability density function. This two moment approximation is given in Appendix XII.

The two-moment approximation is derived by trial and error. With the two-moment approximation (and the other approximations of the equations from section 9.4) the software-tool can optimize the number and timing of the inspections in 2 up to 5 minutes (instead of 800 to 180.000 minutes). To verify that the optimization heuristic does indeed find the optimal number and timing of the inspections the expected costs for a number of scenarios are enumerated and compared with the optimization heuristic outcome, see Appendix XIII. The optimum value is not found by the heuristic but is 1 to 2 days off in the tested scenarios. However, the difference in expected cost of the real optimal expected cost and the expected cost found with the optimization in the three calculated scenarios is only 0,14%, 0,01%, and 0,02%, see Appendix XIII. This small difference is acceptable.

The optimization process has two input-parameters, \( \Delta \) and \( \alpha. \Delta \) gives the minimum time between inspections, the value of \( \Delta \) must be entered by the user of the software-tool. The value of \( \Delta \) is dependent of the minimum time that the customer wants two have between inspections. The user can also set a maximum number of inspections. The default value of the maximum number of inspections is 3, however, if a customer wants not more than a certain number of inspections this
can be entered in the tool. $\alpha$ represents the accuracy of the optimization. An $\alpha$ of one is recommended, this means that the optimization heuristic is accurate to one day. If the $\alpha$ is set higher the optimization outcome is less accurate but the computation time of the optimization heuristic is also less. See Figure 9-3 for the computation-time versus accuracy graph.

![Computation Time](image)

**Figure 9-3; Computation time of optimization heuristic**

As Figure 9-3 describes the computation time of the optimization heuristic is, even with the highest accuracy (alpha = 1), within a reasonable range. Therefore, an accuracy of $\alpha = 1$ is recommended.

### 9.6. Test results

A set of scenarios is tested to demonstrate the potential decrease in system overhaul lead-time by doing inspections at the time recommended by the optimization heuristic, see Figure 9-4.

![Expected System Overhaul Lead-Time](image)

**Expected System Overhaul Lead-Time**

- Ad-Hoc
- 1 Inspection (optimized timing)
- 2 Inspections (optimized timing)
- 3 Inspections (optimized timing)
Figure 9-4: Expected system overhaul lead-time

Figure 9-4 gives the expected system overhaul lead-time for several scenarios. The x-axis gives the number of cylinders and the y-axis the expected system overhaul lead-time. The expected system overhaul lead-time is calculated with no inspections (ad-hoc service), 1 inspection, 2 inspections, and 3 inspections. The input parameters for the scenarios can be found in Appendix XIV. Figure 9-4 shows that if a customer has more cylinders the expected system overhaul lead-time increases. The relative decrease in expected system overhaul lead-time for the scenarios with inspections versus the ad-hoc service scenario is described in Figure 9-5.

![Expected System Overhaul Lead-Time Reduction](image)

Figure 9-5: Expected System Overhaul Lead-Time Reduction

Figure 9-5 shows that the reduction in the expected overhaul lead-time is higher if more inspections are done. From the figure it can be concluded that an inspection based overhaul service can decrease the expected overhaul lead-time up to 40% in the case of 1 inspection and even further if more inspections are performed. The overhaul lead-time probability density functions of the different scenarios can be found in Appendix XIV.

### 9.7. Implementation

The output of the software-tool should be used by the sales-department to demonstrate the added-value of an inspection based overhaul service to the customer (i.e. rig-owner). A manual is provided containing instructions of the software-tool for the sales department. Training sessions are planned to further clarify the instructions, and engender an understanding of the conceptual model and calculations for the sales-department employees. It is vital for the sales-department employees to have a good understanding of the conceptual model and calculations because this department is going to sell the inspection based overhaul service to the customers. The manual for the software-tool can be found in Appendix VIII.
10. Conclusion and recommendation

This chapter draws up the conclusion of the research project in section 10.1, section 10.2 describes the academic relevance, and section 10.3.3 presents the recommendations for Bosch Rexroth and future research.

10.1. Conclusion

In this research project a software tool has been developed that calculates the expected costs in the scenario of an ad-hoc overhaul service and an inspection based overhaul service which is optimized for the customer. The software-tool allows the answering of the research question:

“What is the expected added-value in terms of expected costs resulting from overhauls and failures of an inspection based maintenance service contract versus ad-hoc based service?”

Availability of the system for the rig-owner is of key importance since operating their system to drill for oil and gas is their source of income. When the system of the rig-owner is unavailable no money can be made. Unavailability is measured by the downtime of the system, downtime of the system of the rig-owner can have three causes; failures, classification, or other operational reasons (weather, rig moves, etc.). The costs caused by classifications can be minimized by minimizing the downtime caused by the overhauls during the classification period. By performing inspections, which evaluate the condition of the cylinders, Bosch Rexroth can predict the required overhaul activities. The prediction of the required overhaul activities enables Bosch Rexroth to plan the overhaul activities, which could decrease the system overhaul lead-time and therefore the expected downtime caused by this lead-time.

The software-tool that has been developed gives a recommendation on how many inspections should be executed and when these inspections should be executed to minimize the costs caused by classifications. The software-tool gives a report of the optimization, presenting the decrease in expected cost when performing inspections at the recommended dates instead of ad-hoc overhaul service. This optimization-report gives the answer to the research question since the added-value of the inspections based service is the decrease in expected costs. However, unavailability is caused by both failures and classifications (i.e. overhauls), but only the classifications are considered in the research. The expected cost calculations are done with approximations and the costs are optimized with an optimization heuristic. The approximations and the optimization heuristic both have proven to give results very close to exact calculations.

The input distributions (requirement probability, detection probability, and lead-times) on which the calculations are based are obtained by fitting statistical distributions to estimations of hydraulic cylinder experts. The distributions can be adapted with the software-tool, either manually or with an estimation fitting procedure. The user can also add or delete overhaul activities from overhaul activities that are considered.

The software tool is parameterizable to deal with different scenarios. The parameters that can be altered are:

- The date of the start of the operation period (i.e. service contract)
- The date of the end of the operation period (i.e. service contract)
- The length of the classification period in days
- The expected downtime that is caused by one inspection
- The lead-time of the overhaul preparation activities
- The lead-time of the overhaul concluding activities
- The cost of one inspection
- The cost of downtime per day due to inspections
- The cost of downtime per day due to overhauls
- The number of cylinders
- The coating of the cylinders
- The time since renewal of the components

The ability to alter the parameters and adapt the input distributions ensures a flexible tool which can be used for different customers.

A set of scenarios is optimized to give an indication of the potential added-value of the inspections based overhaul service. From the tested scenarios there can be concluded that an inspection based overhaul service can decrease the expected overhaul lead-time up to 40% in the case of 1 inspection, an even greater reduction can be the result from more inspections. The highest reduction in the expected system overhaul lead-time found in the tested scenarios is 55%.

10.2. Academic Relevance
A lot of research is done within the field of maintenance strategies. Manzini et al. (2010) discusses the most critical issues concerning the planning, the design, the management, and the control of modern production systems. By this discussion it is possible to identify the role of maintenance in a production system and the capability of guaranteeing a high level of safety, quality, and productivity in a proper way. Once the role of maintenance is identified the appropriate maintenance strategy can be determined, Bevilacqua & Braglia (2000) describe the application of their Analytic Hierarchy Process (AHP) for selecting the best maintenance strategy. The inspection based overhaul service is a type of condition based maintenance strategy. Condition based maintenance is widely discussed topic within the scientific world (Grall, Bérenguer, & Dieulle, 2002), (Besnard & Bertling, 2010), (Tsang, 1995), etc. However, the strategy of applying inspection based maintenance to reduce overhaul lead-time for multi-component, and multi-activities, and mutually dependencies of the activities is new in the scientific world. The inspection based overhaul service is provided to the customer by means of a service contract. Service contracts are described and examined by many researchers including, Lay et al. (2009), Kumar et al. (2004), Wenbin (2009), as well as many others. The detailed description of the inspection based overhaul service contract in this research project is a contribution to the already existing literature on both maintenance strategies and service contracts.

10.3. Recommendations
This section gives recommendations for the utilization and improvements of the software tool, and describes future research opportunities.

10.3.1. Recommendations for utilization of the software-tool
The software-tool should be used as a support tool for the decision process about the number of inspections and the time at which these inspections should be performed. The recommended number and timing of the process is based on the assumptions, input distributions, and input parameters. Only when the assumptions are met, the input distributions are valid, and when the parameters are entered correctly the software gives a reliable output. However, even when the assumptions are met, the input distributions are valid, and the parameters are entered correctly, the
output should still be put in perspective and checked for face-validity. Sensitivity analyses could be used to test the robustness of the results and form an increased understanding of the relationships between the input distributions, parameters and output.

The output of the software-tool should be used by the sales-department to display the added-value of an inspection based overhaul service to the customer (i.e. rig-owner). Not only does this provide an effective overhaul strategy for the rig-owner, it also reveals the pro-active approach of Bosch Rexroth which is a desirable attitude of a service provider.

10.3.2. Improvements of the model

For the development of the software-tool estimations and assumptions are made which limit the reliability of the output, extensions of the tool/model and relaxation of the assumptions could increase the reliability of the output:

- The model assumes that only minimal repair is performed during the operation period, failures during the operation period are assumed to not change the overhaul requirement probability of the cylinder. The probability of failures and their effect on the overhaul requirement probability during the classification could be introduced in the model.
- The lead-times of the preparation and conclusion activities of the overhaul are assumed to be constant. The model could be extended by introducing a variable preparation and conclusion activities lead-time, making the model more accurate.
- It has been assumed that overhaul activities are only planned if the activity is required and detected. An extension of the model could be that certain overhaul activities are also planned if the requirement probability is above a certain threshold. When an overhaul activity requirement probability is high but the probability of detection is low, there could be decided to plan the overhaul although the requirement is not detected. This way, the expected overhaul period could be shorter. However, it could also bring forward extra costs for unnecessary acquisition costs when the overhaul activity is not required.
- The input distributions are based on estimations. More research on these distributions could ensure a more reliable output. The estimations are assumed to be valid, however the estimated distributions of the requirement probability, detection probability, and lead-times should be compared with real-world data. Gathering real-world data of overhaul activity requirements, detections, and lead-times will give the opportunity to examine technical-validity.

10.3.3. Future Research

The main limitation of this research project is the input distributions. Only when the requirement probability, detection probability and lead-times correspond to reality the software-tool can give a valid optimization and expected cost calculation. These input variables have face validity but lack some prove of technical validity. The requirement probability of the overhaul activities are expected to be dependent of not only time but also location and usage. Further research should examine the decisive variables for the probability of an overhaul activity requirement.

The concept of performing inspections in order to predict overhaul activities requirements in a detailed and structured way as described in this research project is new to Bosch Rexroth. Therefore, the estimated detection probabilities cannot be compared with real-life data. In the future Bosch Rexroth should store data on inspections (when inspected, what inspected, what detected) and
overhauls (when overhauled, which overhaul activities executed, which overhaul activities required). This way, Bosch Rexroth could find out what the actual probability of detecting and overhaul activity requirement is.

In this research project an inspection based overhaul service is introduced to increase the availability of the rig-owners. The availability is increased by a decrease in the length of the system overhaul lead-time. The planning of the overhaul activities (requiring people, parts, and tools) accounts for a large part of the overhaul period. When keeping spare-parts this planning period could be reduced even more since the expected lead-time of the acquisition of the spare-parts will be lower. Future research could examine the possibilities of a service contract in which Bosch Rexroth has a spare-part inventory for the cylinders in the contract.

Bosch Rexroth knows that their cylinders could fail due to misuse of the equipment or incorrect-specifications of the system. Future research could examine the root-cause of the misuse and incorrect-specifications and come up with a method to eliminate the causes of misuse and incorrect specifications. In addition to eliminating the causes of misuse and incorrect specifications, inspection based maintenance could reduce the probability of failure when degradation of the cylinders is detected before actual break-down. A good understanding of the reliability and its influential factors is the starting point of such a maintenance strategy and should therefore be examined before anything else.
Bibliography


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<th>Unique ID: Failure mode &amp; Cause</th>
<th>Failure Mode</th>
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<th>Responsible Cylinder Specifications</th>
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<tr>
<td>FC1</td>
<td>Piston Seal Failure</td>
<td>Contaminated oil</td>
<td>Abrasive particles suspended in the fluid can damage the seal and the piston rod surface</td>
<td>Wiper seal Environment (Application and cylinder type) Oil and Filter</td>
<td>pressure loss</td>
<td>Wiper ring</td>
<td>Internal leakage Worn rod seals</td>
<td>Honing of bore Renewal of seals</td>
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<td>FC2</td>
<td>Rod Seal Failure</td>
<td>Contaminated oil</td>
<td>Abrasive particles suspended in the fluid can damage the seal and the piston rod surface</td>
<td>Wiper seal Environment (Application and cylinder type) Oil and Filter</td>
<td>pressure loss</td>
<td>Wiper ring</td>
<td>Leakage Worn rod seals</td>
<td>Renewal of piston rod coating Renewal of seals</td>
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<td>FC3</td>
<td>Barrel failure</td>
<td>Corrosion</td>
<td>Damage to the barrel paint causes corrosion to form</td>
<td>Damage during operation</td>
<td>Corrosion on barrel</td>
<td>Renewal of seals Repaint barrel</td>
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<td>FC4</td>
<td>Piston Seal Failure</td>
<td>Corrosion</td>
<td>Water in the oil causes the barrel to internally corrode</td>
<td>Bore of barrel Conservation Filter</td>
<td>pressure loss</td>
<td>Bore of barrel</td>
<td>Internal leakage Corrosion boring</td>
<td>Honing of seals Renewal of seals</td>
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<td>FC5</td>
<td>Rod Seal Failure</td>
<td>Corrosion</td>
<td>Corrosion of the piston rod can cause seal wear due to friction</td>
<td>Piston rod coating Environment (Application and cylinder type)</td>
<td>pressure loss</td>
<td>Piston rod coating Piston rod seal</td>
<td>Leakage Corrosion of piston rod</td>
<td>Renewal of piston rod coating Renewal of seals</td>
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<td>FC6</td>
<td>Cushioning failure</td>
<td>Cushioning</td>
<td>When the speed and pressure is higher than accepted the piston rod cannot be cushioned properly which causes damage to the cushioning</td>
<td>Wear on the cushioning Misalignment of design requirements and actual environment</td>
<td>Unable to cushion properly</td>
<td>Cushioning</td>
<td>Renewal of cushioning</td>
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<td>FC7</td>
<td>Cylinder head failure</td>
<td>Cylinder head clearances</td>
<td>Leaking from around the gland outer diameter can be caused by o-ring failure, or by having a cracked gland, either which in turn could have been caused by poor clearances</td>
<td>Cylinder head mounting</td>
<td>pressure loss</td>
<td>Leakage from the cylinder head</td>
<td>Renewal of cylinder head</td>
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<td>FC8</td>
<td>Production failure</td>
<td>Dimensions</td>
<td>Inadequate production of cylinder causes the dimensions to deviate from specifications</td>
<td>Production</td>
<td></td>
<td></td>
<td>Deviating dimensions</td>
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<td>FC9</td>
<td>Piston Seal Failure</td>
<td>Extreme Temperatures</td>
<td>Seals that have been overheated or exposed to too low temperatures which causes them to crack and brittle</td>
<td>piston seals Environment (Application and cylinder type)</td>
<td>pressure loss</td>
<td>piston seal</td>
<td>Leakage Cracked and brittle piston seal</td>
<td>Renewal of seals</td>
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<td>FC10</td>
<td>Rod Seal Failure</td>
<td>Extreme Temperatures</td>
<td>Seals that have been overheated or exposed to too low temperatures which causes them to crack and brittle</td>
<td>Piston Rod seals Environment (Application and cylinder type)</td>
<td>pressure loss</td>
<td>Piston rod seal</td>
<td>Leakage Cracked and brittle piston rod seal</td>
<td>Renewal of seals</td>
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<td>FC11</td>
<td>Piston Seal Failure</td>
<td>Extrusion</td>
<td>Bypass of oil at the piston seal due to extrusion causes the seal to fail</td>
<td>Misalignment of design requirements and actual environment</td>
<td>pressure loss</td>
<td>Piston seal</td>
<td>Extreme leakage Worn piston seal</td>
<td>Renewal of seals</td>
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<tr>
<td>FC12</td>
<td>Rod Seal Failure</td>
<td>Extrusion</td>
<td>The result of inadvertent pressure intensification across the piston. A severe meter-out flow restriction at the head end of a cylinder with an oversized piston rod can expose the rod seal to a back pressure equal to twice the system pressure. Continued operation under these conditions can cause rapid seal wear due to excess friction.</td>
<td>Misalignment of design requirements and actual environment</td>
<td>pressure loss</td>
<td>Piston rod diameter Piston rod length Piston Rod Seal</td>
<td>Extreme leakage Worn piston rod seal</td>
<td>Renewal of seals</td>
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<td>FC13</td>
<td>Ballooned barrel</td>
<td>High pressures</td>
<td>Cylinder walls can sometimes get warped out of shape, which results in the escape of high-pressure fluid and a reduction in seal life. This warping can occur due to insufficient wall thickness in the cylinder and/or insufficient material strength.</td>
<td>Misalignment of design requirements and actual environment</td>
<td>pressure loss</td>
<td>Unmovable cylinder Barrel</td>
<td>Leakage Unmovable cylinder Renewal of seals Renewal of bearings</td>
<td></td>
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<td>FC14</td>
<td>Piston Seal Failure</td>
<td>Inside barrel roughness</td>
<td>When the surface roughness on the cylinder bore is too low, the cylinder will not retain lubrication properly. Therefore the seals will not be adequately lubricated, and they will dry out and fail</td>
<td>Bore of barrel Piston seal</td>
<td>pressure loss</td>
<td>piston seal Barrel inside roughness</td>
<td>Worn piston seal</td>
<td>Honing of bore Renewal of seals</td>
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<td>FC15</td>
<td>Oil connection failure</td>
<td>Leak in oil port connection</td>
<td>Failures of oil connection bolts causes the oil connection to leak</td>
<td>Port connection</td>
<td>pressure loss</td>
<td>Port welding</td>
<td>Leakage from the ports</td>
<td>Renewal of oil port</td>
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<td>FC16</td>
<td>Piston Seal Failure</td>
<td>Low pressures</td>
<td>Some elastomeric lip-seals require a minimum pressure level to become fully energized, and only work at full efficiency with back pressures above 30 bar. Below that level, the seal may hydroplane and fail to seal against the bore surface.</td>
<td>Misalignment of design requirements and actual environment</td>
<td>pressure loss</td>
<td>Piston seal</td>
<td>Leakage</td>
<td>Honing of bore Renewal of seals</td>
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<tr>
<td>FC17</td>
<td>Rod Seal Failure</td>
<td>Low pressures</td>
<td>Some elastomeric lip-seals require a minimum pressure level to become fully energized, and only work at full efficiency with back pressures above 30 bar. Below that level, the seal may hydroplane and fail to seal against the rod surface.</td>
<td>Misalignment of design requirements and actual environment</td>
<td>pressure loss</td>
<td>Piston rod seal</td>
<td>The rod runs 'wet', with a collar of oil.</td>
<td>Redesign of system</td>
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<td>FC18</td>
<td>Construction failure</td>
<td>Multiple</td>
<td>Construction is not in line with application</td>
<td>Misalignment of design requirements and actual environment</td>
<td>-</td>
<td>-</td>
<td>Deviating dimensions</td>
<td>System review</td>
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<td>FC19</td>
<td>Position sensor system fail</td>
<td>Position sensor system fail</td>
<td>Not enough or to much voltage of the sensor which causes the sensor system to fail</td>
<td>Environment</td>
<td>Unable to measure position of hydraulic cylinder</td>
<td>None</td>
<td>Unable to measure position of hydraulic cylinder</td>
<td>Redesign of system</td>
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<td>FC20</td>
<td>Position sensor system fail</td>
<td>Position sensor system</td>
<td>Sealing system fails which causes pressure on the position sensor which leads to failure of the position sensor system</td>
<td>Misalignment of design requirements and actual environment</td>
<td>Unable to measure position of hydraulic cylinder</td>
<td>Seals</td>
<td>Unable to measure position of hydraulic cylinder</td>
<td>Renewal of position sensor system Renewal seals</td>
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<td>FC21</td>
<td>Position sensor system fail</td>
<td>Position sensor system</td>
<td>Damage during the mounting of the cylinder which causes the sensor system to fail</td>
<td>Mounting</td>
<td>Unable to measure position of hydraulic cylinder</td>
<td>None</td>
<td>Unable to measure position of hydraulic cylinder</td>
<td>Renewal of position sensor system</td>
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<tr>
<td>FC22</td>
<td>Rod Seal Failure</td>
<td>Rod coating</td>
<td>When the surface roughness on the cylinder rod’s finish is too low, the cylinder will not retain lubrication properly. Therefore the seals will not be adequately lubricated, and they will dry out and fail</td>
<td>Piston rod&lt;br&gt;Piston rod seal</td>
<td>pressure loss</td>
<td>Piston rod coating&lt;br&gt;Piston rod seal</td>
<td>Worn piston rod seal</td>
<td>Renewal of piston rod coating&lt;br&gt;Renewal of seals</td>
</tr>
<tr>
<td>FC23</td>
<td>Side-loading</td>
<td>Side-loading</td>
<td>Cylinders are designed to provide linear force and motion to a guided load. The path which the guided load travels must not impose a significant eccentric load on the rod or the piston rod bearing, or the bearing surfaces will be damaged and fluid leakage and reduced bearing life will result.</td>
<td>Piston Rod&lt;br&gt;Bearings&lt;br&gt;Misalignment of design requirements and actual environment</td>
<td>Unmovable hydraulic cylinder&lt;br&gt;Pressure loss</td>
<td>Piston rod diameter&lt;br&gt;Piston rod length&lt;br&gt;Type of bearings</td>
<td>Leakage&lt;br&gt;Galling of piston rod&lt;br&gt;Rod seals and bearings are worn on one side only&lt;br&gt;Piston rods and cylinder tubes are worn or galled on opposite sides</td>
<td>Renewal of cylinder</td>
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<tr>
<td>FC24</td>
<td>Oil connection failure</td>
<td>split weld on ports</td>
<td>A split weld on the ports may be caused at the original manufacture (or recent repair) by a poor weld failing. It may also be caused by shock loading - or a sudden impact to full pressure (or beyond).</td>
<td>Port welding</td>
<td>pressure loss</td>
<td>Port welding</td>
<td>Leakage from the ports&lt;br&gt;Loss of pressure</td>
<td>Renewal of oil port</td>
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<td>FC25</td>
<td>Stick-slip failure</td>
<td>Stick slip</td>
<td>Stick-slip is the phenomenon of vibration induced by a change in friction force that occurs in the hydraulic cylinder at low sliding speeds</td>
<td>Misalignment of design requirements and actual environment</td>
<td>Stick-slip results in low accuracy and as well as the early fatigue of components</td>
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<td>Vibration</td>
<td>System review</td>
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<td>FC26</td>
<td>Piston Seal Failure</td>
<td>Wear</td>
<td>The piston seal and inside barrel wear due friction over accumulated travel distance</td>
<td>Piston seal&lt;br&gt;Barrel inside roughness&lt;br&gt;Working pressure</td>
<td>pressure loss</td>
<td>piston seal&lt;br&gt;Barrel inside roughness</td>
<td>Leakage&lt;br&gt;Worn piston seal&lt;br&gt;Worn barrel</td>
<td>Renewal of seals&lt;br&gt;Honing of bore</td>
</tr>
<tr>
<td>FC27</td>
<td>Rod Seal Failure</td>
<td>Wear</td>
<td>The piston rod seal wear due friction over accumulated travel distance</td>
<td>Piston rod seal&lt;br&gt;Barrel inside roughness&lt;br&gt;Working pressure</td>
<td>pressure loss</td>
<td>Piston rod seal&lt;br&gt;Worn piston rod&lt;br&gt;Worn piston rod</td>
<td>Leakage&lt;br&gt;Worn piston rod&lt;br&gt;Worn piston rod&lt;br&gt;Renewal of seals&lt;br&gt;Renewal of piston rod coating</td>
<td></td>
</tr>
</tbody>
</table>
Appendix II. Overhaul activity execution dependency

This appendix gives an example of the case of 1 cylinder, 1 additional inspection, and 3 overhaul activities. Appendix II.

Appendix II.I. Overhaul Activity 1

Overhaul Activity 1 is executed if required. The requirement of the overhaul activity can be detected at the additional inspection and at the classification. Therefore there are 3 scenarios for overhaul activity 1:

### Overhaul Activity 1

<table>
<thead>
<tr>
<th>Scenario</th>
<th>When</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detected at inspection 1</td>
<td>$P(\text{Required}) \times P(\text{Detection})$</td>
<td>40%</td>
</tr>
<tr>
<td>Detected at classification</td>
<td>$P(\text{Required}) \times (1 - P(\text{Detection}))$</td>
<td>20%</td>
</tr>
<tr>
<td>Not Required</td>
<td>$1 - P(\text{Required})$</td>
<td>40%</td>
</tr>
</tbody>
</table>

The cumulative distribution function of the different scenarios are the following:

![Overhaul Activity 1 CDF](image-url)
Appendix II. Overhaul Activity 2

Overhaul Activity 2 is executed if required. The requirement of the overhaul activity can be detected at the additional inspection and at the classification. Therefore there are 3 scenarios for overhaul activity 2:

Overhaul Activity 2

<table>
<thead>
<tr>
<th>Scenario</th>
<th>When</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detected at inspection 1</td>
<td>$P(\text{Required}) \times P(\text{Detection})$</td>
<td>70%</td>
</tr>
<tr>
<td>Detected at classification</td>
<td>$P(\text{Required}) \times (1 - P(\text{Detection}))$</td>
<td>10%</td>
</tr>
<tr>
<td>Not Required</td>
<td>$1 - P(\text{Required})$</td>
<td>20%</td>
</tr>
</tbody>
</table>

The cumulative distribution function of the different scenarios are the following:
Appendix II.III. Overhaul Activity 3

Overhaul Activity 3 is executed if any of the overhaul activities is required. The requirement of the overhaul activity can be detected at the additional inspection and at the classification. Therefore there are 3 scenarios for overhaul activity 3:

**Overhaul Activity 3**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>When</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detected at inspection 1</td>
<td>$P(\text{Required}) \times P(\text{Detection})$</td>
<td>70%</td>
</tr>
<tr>
<td>Detected at classification</td>
<td>$P(\text{Required}) \times (1 - P(\text{Detection}))$</td>
<td>10%</td>
</tr>
<tr>
<td>Not Required</td>
<td>$1 - P(\text{Required})$</td>
<td>20%</td>
</tr>
</tbody>
</table>

The cumulative distribution function of the different scenarios are the following:
## Appendix II.IV. Cases Probabilities

Every overhaul activity has 3 scenarios, and there are 3 overhaul activities. Therefore, there are \(3^3 = 27\) different cases. See the table below:

<table>
<thead>
<tr>
<th>Case</th>
<th>Requirement Scenario</th>
<th>Execution Scenario</th>
<th>Scenario Probability</th>
<th>Case Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Detected at inspection 1</td>
<td>Overhaul activity 1: Start planning after inspection 1 Overhaul activity 2: Start planning after inspection 1 Overhaul activity 3: Start planning after inspection 1</td>
<td>Overhaul Activity 1: 40% Overhaul Activity 2: 70% Overhaul Activity 3: 10%</td>
<td>3%</td>
</tr>
<tr>
<td>2</td>
<td>Detected at classification</td>
<td>Overhaul activity 1: Start planning in classification Overhaul activity 2: Start planning after inspection 1 Overhaul activity 3: Start planning after inspection 1</td>
<td>Overhaul Activity 1: 20% Overhaul Activity 2: 70% Overhaul Activity 3: 10%</td>
<td>1%</td>
</tr>
<tr>
<td>3</td>
<td>Not Required</td>
<td>Overhaul activity 1: Not Required Overhaul activity 2: Start planning after inspection 1 Overhaul activity 3: Start planning after inspection 1</td>
<td>Overhaul Activity 1: 40% Overhaul Activity 2: 70% Overhaul Activity 3: 10%</td>
<td>3%</td>
</tr>
<tr>
<td>4</td>
<td>Detected at inspection 1</td>
<td>Overhaul activity 1: Start planning after inspection 1 Overhaul activity 2: Start planning in classification Overhaul activity 3: Start planning after inspection 1</td>
<td>Overhaul Activity 1: 40% Overhaul Activity 2: 10% Overhaul Activity 3: 10%</td>
<td>0%</td>
</tr>
<tr>
<td>5</td>
<td>Detected at classification</td>
<td>Overhaul activity 1: Start planning in classification Overhaul activity 2: Start planning in classification Overhaul activity 3: Start planning after inspection 1</td>
<td>Overhaul Activity 1: 20% Overhaul Activity 2: 10% Overhaul Activity 3: 10%</td>
<td>0%</td>
</tr>
<tr>
<td>6</td>
<td>Not Required</td>
<td>Overhaul activity 1: Not Required Overhaul activity 2: Start planning in classification Overhaul activity 3: Start planning after inspection</td>
<td>Overhaul Activity 1: 40% Overhaul Activity 2: 10% Overhaul Activity 3: 10%</td>
<td>0%</td>
</tr>
<tr>
<td>#</td>
<td>classification</td>
<td>inspection 1</td>
<td>classification</td>
<td>1</td>
</tr>
<tr>
<td>----</td>
<td>----------------</td>
<td>--------------</td>
<td>----------------</td>
<td>---</td>
</tr>
<tr>
<td>7</td>
<td>Detected at inspection 1</td>
<td>Not Required</td>
<td>Detected at inspection 1</td>
<td>Start planning after inspection 1</td>
</tr>
<tr>
<td>8</td>
<td>Detected at classification</td>
<td>Not Required</td>
<td>Detected at inspection 1</td>
<td>Start planning in classification</td>
</tr>
<tr>
<td>9</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Detected at inspection 1</td>
<td>Not Required</td>
</tr>
<tr>
<td>10</td>
<td>Detected at inspection 1</td>
<td>Detected at inspection 1</td>
<td>Detected at classification</td>
<td>Start planning after inspection 1</td>
</tr>
<tr>
<td>11</td>
<td>Detected at classification</td>
<td>Detected at inspection 1</td>
<td>Detected at classification</td>
<td>Start planning in classification</td>
</tr>
<tr>
<td>12</td>
<td>Not Required</td>
<td>Detected at inspection 1</td>
<td>Detected at classification</td>
<td>Not Required</td>
</tr>
<tr>
<td>13</td>
<td>Detected at inspection 1</td>
<td>Detected at classification</td>
<td>Detected at classification</td>
<td>Start planning after inspection 1</td>
</tr>
<tr>
<td>14</td>
<td>Detected at</td>
<td>Detected at</td>
<td>Detected at</td>
<td>Start planning in</td>
</tr>
<tr>
<td></td>
<td>classification</td>
<td>classification</td>
<td>classification</td>
<td>classification</td>
</tr>
<tr>
<td>---</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>15</td>
<td>Not Required</td>
<td>Detected at classification</td>
<td>Not Required</td>
<td>Start planning in classification</td>
</tr>
<tr>
<td>16</td>
<td>Detected at inspection 1</td>
<td>Not Required</td>
<td>Detected at classification</td>
<td>Start planning after inspection 1</td>
</tr>
<tr>
<td>17</td>
<td>Detected at classification</td>
<td>Not Required</td>
<td>Detected at classification</td>
<td>Start planning in classification</td>
</tr>
<tr>
<td>18</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Detected at classification</td>
<td>Not Required</td>
</tr>
<tr>
<td>19</td>
<td>Detected at inspection 1</td>
<td>Detected at inspection 1</td>
<td>Not Required</td>
<td>Start planning after inspection 1</td>
</tr>
<tr>
<td>20</td>
<td>Detected at classification</td>
<td>Detected at inspection 1</td>
<td>Not Required</td>
<td>Start planning in classification</td>
</tr>
<tr>
<td>21</td>
<td>Not Required</td>
<td>Detected at inspection 1</td>
<td>Not Required</td>
<td>Not Required</td>
</tr>
<tr>
<td>22</td>
<td>Detected at inspection 1</td>
<td>Detected at classification</td>
<td>Not Required</td>
<td>Start planning after inspection 1</td>
</tr>
<tr>
<td></td>
<td>Detected at classification</td>
<td>Detected at classification</td>
<td>Not Required</td>
<td>Start planning in classification</td>
</tr>
<tr>
<td>---</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>23</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Not Required</td>
</tr>
<tr>
<td>24</td>
<td>Detected at classification</td>
<td>Detected at classification</td>
<td>Not Required</td>
<td>Start planning after inspection 1</td>
</tr>
<tr>
<td>25</td>
<td>Detected at inspection 1</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Not Required</td>
</tr>
<tr>
<td>26</td>
<td>Detected at classification</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Not Required</td>
</tr>
<tr>
<td>27</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Not Required</td>
</tr>
</tbody>
</table>
Appendix II.V. Case cylinder overhaul lead-time function

Every case has a different cylinder overhaul lead-time cumulative distribution function, see the graph below:

![Cylinder Overhaul Lead-time - CDF](image-url)
Appendix II.VI. Cylinder overhaul lead-time

To get the cylinder overhaul lead-time distribution function is sum of the product of the case probability and the case cumulative distribution function for all cases. The cylinder overhaul lead-time cumulative distribution function is given in the graph below:
Appendix III. Wire Line Tensioner

A “Wire Line Tensioner” is a hydraulic riser tensioner that consists of a hydraulic cylinder with sheaves at both sides. The cylinder is energized by an connection to a number of high-pressure gas bottles via an accumulator. A wire rope is rigged in the cylinder; one end is connected to the fixed part of the tensioner, the other end is connected to the riser (Sparks, 2007). The riser is connected to the drilling guide base on the sea bed and therefore the wire line tensioner must manage the differential movements between the riser and the rig. Tension on the wire lines is directly proportional to the pressure of the stored air. As the rig heaves upward, fluid is forced out of the hydraulic cylinders, compressing the air. As the rig heaves downward, the hydraulic cylinder is allowed to stroke in the opposite direction, forced by the compressed air (Aker Solutions ASA, 2013). If there were no tensioner and the rig moves downward, the riser would buckle; if the rig rises then high forces would be transmitted to the riser and it would stretch and damaged.

Figure III-1; Oil-rig
Appendix IV. Statistical Distributions

The distributions used in the report are the probability density function (PDF), cumulative distribution function (CDF) and the reliability function (R). The PDF is a function that describes the relative likelihood for a random variable $X$ to take on a given value. The CDF describes the probability that a real-value random $X$ variable with a given probability distribution will be found to have a value less than or equal to $X$. Skewness is a measure of the asymmetry of the probability distribution of a real-valued random variable about its mean. The skewness value can be positive or negative, or even undefined. For a distribution, negative skew indicates that the tail on the left side of the probability density function is longer or fatter than the right side – it does not distinguish these shapes. Conversely, positive skew indicates that the tail on the right side is longer or fatter than the left side.

Kurtosis is a measure of the peakedness of the probability distribution of a random variable. Just as for skewness, there are different ways of quantifying it for a theoretical distribution and corresponding ways of estimating it from a sample from a population.

Appendix IV.I. Gamma distribution

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$k &gt; 0$ Shape $\theta &gt; 0$ Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support</td>
<td>$x \in (0, +\infty)$</td>
</tr>
<tr>
<td>PDF</td>
<td>$f_X(x) = \frac{1}{\Gamma(k)\theta^k}x^{k-1}e^{-\frac{x}{\theta}}$</td>
</tr>
<tr>
<td>CDF</td>
<td>$F_X(x) = \frac{1}{\Gamma(k)}\gamma\left(k, \frac{x}{\theta}\right)$ where $\gamma\left(k, \frac{x}{\theta}\right) = \int_0^\infty t^{k-1}e^{-t} dt$</td>
</tr>
<tr>
<td>R</td>
<td>$R_X(x) = 1 - \frac{1}{\Gamma(k)}\gamma\left(k, \frac{x}{\theta}\right)$</td>
</tr>
<tr>
<td>Mean</td>
<td>$k\theta$</td>
</tr>
<tr>
<td>Variance</td>
<td>$k\theta^2$</td>
</tr>
<tr>
<td>Skewness</td>
<td>$\frac{2}{\sqrt{k}}$</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>$\frac{6}{k}$</td>
</tr>
</tbody>
</table>
### Appendix IV.II. Gumbel distribution

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\mu$ location</th>
<th>$\beta &gt; 0$ Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Support</strong></td>
<td>$x \in (-\infty, +\infty)$</td>
<td></td>
</tr>
<tr>
<td><strong>PDF</strong></td>
<td>$\frac{1}{\beta} e^{-(z + e^z)}$ where $z = \frac{x - \mu}{\beta}$</td>
<td></td>
</tr>
<tr>
<td><strong>CDF</strong></td>
<td>$e^{-e^{-(x-\mu)/\beta}}$</td>
<td></td>
</tr>
<tr>
<td><strong>R</strong></td>
<td>$1 - e^{-e^{-(x-\mu)/\beta}}$</td>
<td></td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>$\mu - e^{-e^{-(x-\mu)/\beta}}$ where $\gamma = eulcer's constant$</td>
<td></td>
</tr>
<tr>
<td><strong>Variance</strong></td>
<td>$\frac{\pi^2}{6} \beta^2$</td>
<td></td>
</tr>
<tr>
<td><strong>Skewness</strong></td>
<td>$12\sqrt{6}\zeta(3) \approx 1.14$</td>
<td></td>
</tr>
<tr>
<td><strong>Kurtosis</strong></td>
<td>$\frac{12}{5}$</td>
<td></td>
</tr>
</tbody>
</table>

![Gumbel Distribution Graph](chart.png)

PDF - Gumbel (Location Parameter = 10, Scale Parameter = 2)
PDF - Gumbel (Location Parameter = 10, Scale Parameter = 5)
PDF - Gumbel (Location Parameter = 15, Scale Parameter = 10)
PDF - Gumbel (Location Parameter = 30, Scale Parameter = 15)
Appendix IV.III. Normal distribution

| Parameters | $\mu \in \mathbb{R}$ mean  
|           | $\sigma^2 > 0$ variance |
| Support   | $x \in \mathbb{R}$ |
| PDF       | $\frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$ |
| CDF       | $\frac{1}{2} \left[ 1 + \text{erf} \left( \frac{x-\mu}{\sqrt{2}\sigma} \right) \right]$ |
| R         | $1 - \frac{1}{2} \left[ 1 + \text{erf} \left( \frac{x-\mu}{\sqrt{2}\sigma} \right) \right]$ |
| Mean      | $\mu$ |
| Variance  | $\sigma^2$ |
| Skewness  | 0 |
| Kurtosis  | 0 |
### Uniform distribution

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$-\infty &lt; a &lt; b \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Support</td>
<td>$x \in [a, b]$</td>
</tr>
</tbody>
</table>

**PDF**
\[
\begin{align*}
    f(x) &= \begin{cases} 
        \frac{1}{b - a}, & \text{for } x \in [a, b] \\
        0, & \text{otherwise}
    \end{cases} \\
\end{align*}
\]

**CDF**
\[
\begin{align*}
    F(x) &= \begin{cases} 
        0, & \text{for } x < a \\
        \frac{x - a}{b - a}, & \text{for } x \in [a, b] \\
        1, & \text{for } x \geq a
    \end{cases} \\
\end{align*}
\]

**R**
\[
\begin{align*}
    R(x) &= \begin{cases} 
        1, & \text{for } x < a \\
        1 - \frac{x - a}{b - a}, & \text{for } x \in [a, b] \\
        0, & \text{for } x \geq a
    \end{cases} \\
\end{align*}
\]

**Mean**
\[
\frac{1}{2} (a + b)
\]

**Variance**
\[
\frac{1}{12} (b - a)^2
\]

**Skewness**
0

**Kurtosis**
\[-\frac{5}{6}\]

---

**Graphs**

- **PDF - Uniform (a = 10, b = 90)**
- **PDF - Uniform (a = 20, b = 80)**
Appendix IV.V. Weibull distribution

| Parameters | \( \lambda > 0 \) Scale \n| k > 0 Shape |
| Support | \( x \in (0, +\infty) \) |
| PDF | \[
\frac{k}{\lambda} \left( \frac{x}{\lambda} \right)^{k-1} e^{-\left( \frac{x}{\lambda} \right)^k}, \quad x \geq 0 \\
0, \quad x < 0
\] |
| CDF | \[
1 - e^{-\left( \frac{x}{\lambda} \right)^k}, \quad x \geq 0 \\
0, \quad x < 0
\] |
| R | \[
\begin{cases} 
\frac{e^{\left( \frac{x}{\lambda} \right)^k}}, & x \geq 0 \\
1, & x < 0
\end{cases}
\] |
| Mean | \( \lambda \Gamma \left( 1 + \frac{1}{k} \right) \) |
| Variance | \[
\lambda^2 \left[ \Gamma \left( 1 + \frac{2}{k} \right) - \left( \Gamma \left( 1 + \frac{1}{k} \right) \right)^2 \right]
\] |
| Skewness | \[
\frac{\Gamma \left( 1 + \frac{3}{k} \right) \lambda^3 - 3\mu \sigma^2 - \mu^3}{\sigma^3}
\] |
| Kurtosis | \[
-6\Gamma_1^4 + 12\Gamma_1^2 \Gamma_2 - 3\Gamma_2^2 - 4\Gamma_1 \Gamma_3 + \Gamma_4 \\
\frac{\Gamma_2 - \Gamma_1^2 \Gamma_1^2}{\Gamma_2 - \Gamma_1^2 \Gamma_1^2}
\] |
Appendix V. Distribution fitting

Three input variables were described in section 6 and 7, requirement probability, detection probability, and lead-time of the overhaul activity execution and planning. The distribution estimations have been done by expert estimations. Historical data is not used for the estimations because the available data is assumed to be invalid and incomplete. All values on the horizontal axes of the graphs are deleted in this appendix since this is Bosch Rexroth classified information.

Appendix V.I. Requirement Probability

The requirement probability is the probability that an overhaul activity is required after a specified time. Several experts estimated this probability, see Figure V-1 for an example.

![Requirement Probability - Renewal Seals](image)

**Figure V-1; Example requirement probability renewal seals**

Figure V-1 gives an example of the estimation of the requirement of seals renewal by a cylinder expert. The x-axis gives the time. The y-as gives the probability that the renewal of seals would be required if there would be an classification after a specified time (on the x-axis). The experts were free to choose the length of their step to give the most reliable estimation in their opinion. Several experts are asked for their estimation, for the combined estimations see Figure V-2.
Figure V-2; Example requirement probability renewal seals combined expert estimations

Figure V-2 gives combined expert estimation of the requirement probability of the renewal of the seals. Every expert estimation is given a reliability factor. If an expert has distributed the requirement probability over 1 or 2 points (i.e. number of bars in Figure V-2) his estimation is given a reliability factor of 1, if the if the expert has distributed the requirement probability over 3 or 4 points his estimation is given a reliability factor of 2, if the if the expert has distributed the requirement probability over 5 or more points his estimation is given a reliability factor of 3. The reliability factor of the estimation is given to control for the accuracy of the estimations. The reliability factor and estimations are used to put in Figure V-2 with the following equations:

\[
CRQEst(y) = \frac{\sum_{e \in E} RQEst_{e,i}(y) \cdot RF_e}{|E| \cdot \sum_{e \in E} RF_e}
\]  

Equation 16 is used to get the combined requirement probability estimation of all experts. This estimation can be used to fit a statistical probability function which can be used in the model described in section 6 and 7. Figure V-3 gives an example of the statistical probability function fitting for the seals renewal overhaul activity.
Figure V-3; Cumulative requirement probability estimation and statistical probability distribution.

Figure V-3 gives the cumulative requirement probability, the blue bars are the combined estimations and the red line the distribution that is fitted to the estimations. Several statistical distributions are tested and the distribution with the lowest total absolute error with the combined estimation is chosen to use in the model described in section 6 and 7. The total absolute error with the combined data is the sum of the difference between the blue bars and the red line. Five statistical distribution are fitted; Weibull distribution, Normal distribution, Uniform distribution, Gumbel distribution and the Gamma distribution. Appendix II gives more information on these distributions. In the example of Figure V-3 the Weibull distribution with shape parameter $\beta = 2.44$ and scale parameter $\eta = 6.11$ gives the best fit according to the total absolute error.

Figure V-4; Requirement probability estimation and statistical probability distribution.
In Figure V-4 the combined estimation and weibull distribution is transformed (back) to the probability requirement density function. 0 gives the distributions and parameters of the requirement probability for all the overhaul activities and the estimations for all overhaul activities.

**Appendix V.II. Detection Probability**

The detection probability is estimated in a similar manner as the requirement probability. The estimations of several experts are combined to give the average experts estimation which is used to fit a reliability distribution. See Figure V-5 for an example of the combination of the estimations and the average estimation.

![Detection probability estimation](image)

*Figure V-5; Detection probability estimation (rod coating renewal enduroq 2X00)*

The colored lines in Figure V-5 give the detection probability estimation of the rod coating renewal for the rod coating "enduroq 2X00", the detection probability on the y-axis is dependent on the time till classification on the x-axis. The black line in Figure V-5 gives the average (i.e. combined) estimation for the detection probability.
These estimations are done for every overhaul activity, see Appendix VII. An statistical reliability function is fitted to the combined estimations, which can be used in the model described in section 6 and 7, see Figure V-6 for the example of the enduroq 2X00 rod coating renewal.

\[
CRQEst(y) = \frac{\sum_{e \in E} RQEst_{e,i}(y)}{|E|} \tag{17}
\]

Where:

- \( e = \text{Expert} (\forall e \in E) \)
- \( CDPEst_i(TTC) = \text{Combined detection probability estimation of all experts of overhaul activity i at TTC} \)
- \( DPEst_{e,i}(TTC) = \text{Requirement probability estimation of expert e of overhaul activity i at TTC} \)
- \( TTC = \text{Time Till Classification} \)

Figure V-6; Detection probability estimation and statistical reliability function

Figure V-6 gives the combined estimations for detection probability of the enduroq 2X00 rod coating renewal. The blue line in Figure V-6 gives the combined estimations of the experts and the red line the statistical reliability function that is fitted to the combinations. The line is fitted to give the smallest total difference between the blue line and the red line (i.e. the combined estimations and the statistical reliability function). Several reliability functions are tested for every overhaul activity. The statistical reliability function describes the probability that a real-valued random variable \( X \) with a given probability distribution will be found to have a value bigger than or equal to \( X \). Information on the reliability functions can be found in Appendix II, and the reliability function and the corresponding parameters for the different overhaul activities can be found in Appendix VII.
Appendix V.III. Overhaul activity lead-time
The lead-time of an overhaul activity consists of a planning period and an execution period, as described in section 0. The lengths of these periods are variable. Together, experts have estimated the distribution of the planning period, and execution period of the different overhaul activities based on historical overhauls. The statistical distributions that describe the overhaul planning and execution period are not given in the report because this is classified Bosch Rexroth information.
### Appendix VI. Requirement Distributions

<table>
<thead>
<tr>
<th>Overhaul Activity</th>
<th>Executed if</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renew coating (Ceramax --&gt; Enduroq 2X00)</td>
<td>If required</td>
<td><em>Weibull</em>~<em>(k = CI, λ = CI)</em></td>
</tr>
<tr>
<td>Renew coating (Chrome Nickel)</td>
<td>If required</td>
<td><em>Normal</em>~<em>(μ = CI, σ = CI)</em></td>
</tr>
<tr>
<td>Renew coating (Enduroq 2X00)</td>
<td>If required</td>
<td><em>Gumbel</em>~<em>(k = CI, λ = CI)</em></td>
</tr>
<tr>
<td>Renew coating (Enduroq 3X00)</td>
<td>If required</td>
<td><em>Gumbel</em>~<em>(μ = CI, β = CI)</em></td>
</tr>
<tr>
<td>Hone inside cylinder barrel</td>
<td>If required</td>
<td><em>Gumbel</em>~<em>(μ = CI, β = CI)</em></td>
</tr>
<tr>
<td>Overhaul safety valve (ARES)</td>
<td>If required</td>
<td><em>Weibull</em>~<em>(k = CI, λ = CI)</em></td>
</tr>
<tr>
<td>Renew Bolts and Screws</td>
<td>Never required, if any other required</td>
<td></td>
</tr>
<tr>
<td>Renewal Bearings</td>
<td>If any required</td>
<td><em>Gumbel</em>~<em>(μ = CI, β = CI)</em></td>
</tr>
<tr>
<td>Renewal inside surface Accumulator (nickel)</td>
<td>If required</td>
<td><em>Weibull</em>~<em>(k = CI, λ = CI)</em></td>
</tr>
<tr>
<td>Renewal Seals</td>
<td>If any required</td>
<td><em>Weibull</em>~<em>(k = CI, λ = CI)</em></td>
</tr>
<tr>
<td>Shot blas and paint cylinder and accumulator</td>
<td>Never required, if any other required</td>
<td></td>
</tr>
</tbody>
</table>

See next pages for the different estimations of the experts and the fitted distribution.
Appendix VI.I. Renew rod coating – Requirement Estimations

Ceramax > Enduroq 2X00

Chrome nickel
Enduroq 2X00

Enduroq 3X00
Appendix VI.II. Hone inside cylinder barrel – Requirement Estimations

Appendix VI.III. Overhaul safety valve (ARES) – Requirement Estimations
Appendix VI.IV. Renewal Bearings – Requirement Estimations

Appendix VI.V. Renewal inside surface Accumulator (nickel) – Requirement Estimations
Appendix VI.VI. Renewal Seals – Requirement Estimations
### Appendix VII. Detection Distributions

<table>
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<tr>
<th>Overhaul Activity</th>
<th>Detectable</th>
<th>Reliability Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Renew coating (Ceramax -&gt; Enduroq 2X00)</td>
<td>Yes</td>
<td>$\text{Weibull} \sim (k = CI, \lambda = CI)$</td>
</tr>
<tr>
<td>Renew coating (Chrome Nickel)</td>
<td>Yes</td>
<td>$\text{Weibull} \sim (k = CI, \lambda = CI)$</td>
</tr>
<tr>
<td>Renew coating (Enduroq 2X00)</td>
<td>Yes</td>
<td>$\text{Weibull} \sim (k = CI, \lambda = CI)$</td>
</tr>
<tr>
<td>Renew coating (Enduroq 3X00)</td>
<td>Yes</td>
<td>$\text{Weibull} \sim (k = CI, \lambda = CI)$</td>
</tr>
<tr>
<td>Hone inside cylinder barrel</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Overhaul safety valve (ARES)</td>
<td>Yes</td>
<td>$\text{Weibull} \sim (k = CI, \lambda = CI)$</td>
</tr>
<tr>
<td>Renew Bolts and Screws</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Renewal Bearings</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Renewal inside surface Accumulator (nickel)</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Renewal Seals</td>
<td>Yes</td>
<td>$\text{Weibull} \sim (k = CI, \lambda = CI)$</td>
</tr>
<tr>
<td>Shot bias and paint cylinder and accumulator</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

See next pages for the different estimations of the experts and the fitted distribution.
Appendix VII.I. Renew rod coating – Detection Estimations

Renew rod coating (Ceramax --> Enduroq 2X00)

Renew rod coating (Chrome Nickel)
Appendix VII.II. Overhaul safety valve (ARES) – Detection Estimations

Overhaul safety valve (ARES)

Appendix VII.III. Renewal Seals – Detection Estimations

Renewal Seals
Appendix VIII.  Software-tool Manual

The next pages contain the software manual.
Bosch Group

Inspection decision software support tool - manual

Manual for the inspection based overhaul service

Thomas de Nijs
11-8-2014
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Important Notes
Some important notes on the software-tool:

- Do not move or change the folder in which the tool is.
- Do not change the name of the workbooks.
1. Software-Tool overview
This chapter describes the inspection based overhaul service and the software tool.

1.1. Inspection based overhaul service description
This manual is the result of a Master graduation project at Bosch Rexroth. Availability of the rigs of Bosch Rexroth’s offshore customers is of key importance. The system of the rig-owner can only generate revenue when their system is available for operation. Every 5 years the rigs need to be classified by a classification bureau, this is required by law. During this classification the rig is unavailable for operation, therefore classifications cause downtime. The rig-owners have a planned classification period. When the overhaul of the hydraulic cylinders has a longer lead-time than the planned classification period, the cylinders overhaul period causes additional downtime. When Bosch Rexroth would perform inspections to evaluate the condition of the cylinder in advance of the classification it enables Bosch Rexroth to predict the required overhaul activities. The prediction of the required overhaul activities enables Bosch Rexroth to plan the overhaul activities, which could decrease the overhaul period. The decrease in expected overhaul lead-time decreases the expected downtime caused by overhauls. However, the inspections cause downtime and costs for the customer. Therefore, there is a trade-off between the costs due to inspections and the downtime costs caused by overhauls. An inspection based maintenance service only has value if it decreases the expected costs, therefore the assignment for the research project was:

“Develop a service contract decision support software-tool that calculates the potential added-value of an inspection based maintenance service contract for large hydraulic cylinders in the offshore in terms of expected maintenance and downtime costs.”

This software-tool should be able to support the sales department of Bosch Rexroth in the negotiation of an inspection based maintenance service contract with the customer.

A conceptual model is developed to determine the potential added-value of an inspection based maintenance service. The conceptual model is designed to adequately model the inspection based maintenance service, and provides insight in the influence of the number and timing of inspections. When an inspection is performed closer to the classification the required overhaul activities have a greater probability of being detected, however it also leaves Bosch Rexroth with less time to plan the overhaul activities. A situation with more inspections could benefit from a higher detection probability. However, more inspections also cause more inspection costs.

A mathematical model is developed for the calculation of the total relevant expected cost for a customer. This mathematical model uses the input distributions; overhaul activity requirement probability, overhaul activity detection probability, and overhaul activity lead-time, and input parameters.

An optimization heuristic is developed to optimize the number of inspections and the timing of the inspections, in order to obtain the lowest expected costs for the customer.

The software-tool that is developed is based on the mathematical calculation of the expected downtime and inspection costs for the customer. Approximations of the equations from the mathematical model are used for the calculations to reduce the computation time to an acceptable
level. The software-tool uses the optimization heuristic to obtain the optimal number and timing of the inspections.

The software-tool is parameterizable to deal with different scenarios. The parameters can be filled in the software-tool. The variable distributions (requirement probability, detection probability, and lead-times) on which the calculations are based upon, are obtained by fitting statistical distributions to estimations of hydraulic cylinder experts. The distributions can be adapted with the software-tool, either manually or with an estimation fitting procedure. The user can also add or delete overhaul activities from the overhaul activities that are considered. The ability to alter the parameters and adapt the input distributions ensures a flexible tool which can be used for different customers.

A set of scenarios is optimized to give an indication of the potential added-value of the inspection based overhaul service. From the tested scenarios there can be concluded that an inspection based overhaul service can decrease the expected overhaul lead-time up to 40% in the case of 1 inspection, an even greater reduction can result from more inspections. The highest reduction in the expected system overhaul lead-time found in the tested scenarios is 55%.

### 1.2. Software tool description

The software-tool consist of 5 screen;

- Begin Screen
- Contract Information Screen
- TSR-input screen
- View and adaption input distributions screen
- Calculation screen

In all the screen only the values in the cells that are orange can be changed. The other cells are protected with a password. Every input cell displays an “input message” when selected, this input message gives a description of the input value and the constraint of the input. When the constraint of the input are not met the software tool gives an error and the user has to re-enter the input. The different screens are explained separately in the following 5 chapters. The process that the user has to go through is given in the figure given on the next page.
1.2.1. Open software-tool
After the user opens the software-tool the user can go directly to “input contract information”.

1.2.2. Input contract information
In the “input contract information” process the user is asked to fill the required information of the contract, this contains the following:

- The user name
- The customer name
- The project name
- The date of the start of the operation period (i.e. service contract)
- The date of the end of the operation period (i.e. service contract)
- The length of the classification period in days
- The expected downtime that is caused by one inspection
- The lead-time of the overhaul preparation activities
- The lead-time of the overhaul concluding activities
- The lead-time of inspecting and reporting
- The cost of one inspection
- The cost of downtime per day due to inspection
- The cost of downtime per day due to overhaul
- The number of cylinders

1.2.3. View and or adapt input distributions
When the user goes to the “view and or adapt the input distributions”, the user finds charts of the requirement probability density function, the detection probability function, the planning lead-time probability density function, and the planning lead-time probability density function. The user can select the overhaul activity for which overhaul activity the charts have to be displayed. The distributions can also be adapted, either manually or with an estimation fitting procedure. When the user knows the distribution and the parameters of the distribution these can be filled in. The user can also put in estimations of the distributions and let the software tool fit a distribution to the estimations. The user can also add or delete overhaul activities from the overhaul activities list. When the user wants to add an overhaul activity, the user is asked for the name of the overhaul activity and subsequently the requirement probability density function, the detection probability function, the planning lead-time probability density function, and the planning lead-time probability density function can be filled in. The user also has to fill in whether the overhaul activity is only executed if required or also if any other overhaul activity to the same cylinder is required, this can also be changed later.

1.2.4. Input cylinder information
When all this information of the contract is filled in the user goes to the “input cylinder information”, here user has to fill in the number of cylinders in the contract and the rod-coating of the cylinders. The user also has to fill in the time since last renewal (TSR) of the different component for all the cylinders in the contract.

1.2.5. Input optimization parameters
After all the information of the input distributions, the contract, and the cylinders in the contract is filled in, this information is used to find the optimum number and timing of the inspections of the cylinders. The user is asked to fill in the alpha and beta for the optimization process (see section 8 of the thesis report). The user can also set a maximum number of inspections. Recommendations on the alpha and beta, and verification of the optimization can be found in section 9.5 of the thesis report.

1.2.6. Optimize inspections
The “optimize inspection” process uses the optimization heuristic from section 8 of the thesis report and approximations of the equations in section 77 of the thesis report. Recommendations on the alpha and beta, and verification of the optimization can be found in section 9.5 of the thesis report. The approximations of the equations in section 7 of the thesis report used during the optimization, are designed to give a fast calculation of the expected costs, however the accuracy of the calculations is low (see section 9.4 and 9.5 of the thesis report). Therefore, the expected costs have to be recalculated with more accuracy with the optimized number of inspections and timing of the inspections found with the optimization heuristic.

1.2.7. Calculate costs
As stated above, the expected costs have to be recalculated with more accuracy, this happens in the “calculate costs” process. Approximations of the equations in section 7 of the thesis report are used to calculate the costs. Section 9.4 of the thesis report describes the approximations and the
appropriateness of these approximations. The costs are calculated with the optimized number and timing of the inspections, and also for the case in which no inspections are done. Both calculations are performed to show the difference between an inspection based and ad-hoc overhaul service. In addition, the user can specify an alternative scenario where the number and timing of the inspections can be changed with reference to the optimized scenario. This gives the user the ability to specify another scenario end thereby find the effect of changing the timing and number of inspections.

1.2.8. Give output
After the calculations are done the tool displays the expected costs as well as the “system overhaul lead-time” probability density function for both the optimized inspection based, user-specified, and ad-hoc overhaul service. This output, together with the input-parameters, is given in a PDF-file. This PDF file can be used to negotiate the service agreement with the customer.
2. **Begin Screen**

First the user has to open the workbook “Mainsheet.xslm”

The begin screen is displayed when the software-tool is opened, see Figure 2-1.

![Welcome to the system overhaul lead-time calculation software tool](image)

*Figure 2-1; Begin Screen*

Figure 2-1 gives the begin screen of the tool. The user has to push the button “Start” to go to the “contract information screen”.

---

113
3. Contract information screen

Figure 3-1 gives the contract information screen.

![Contract and Customer Input Table]

The contract information screen is used to fill in the required information on the customer and the contract. As mentioned earlier, only the orange cells have to be filled in.

The **first input** is the name of the user, see Figure 3-2. When the user clicks on the input cell, the cell gives the required input of the cell. The same goes for the other cells.

![Figure 3-2; Name user]
The second input is the name of the customer. The third input is the name of the project (i.e. rig).

The fourth input is the date of the start of the operation period (i.e. start service contract), the fifth input is the date of the end of the operation period, and the sixth input is length of the planned classification period in days, see Figure 3-3.

![Figure 3-3; Contract and classification period](image)

When an incorrect input is given the tool displays the error, see Figure 3-4. A similar error is displayed in other cells that are filled in with incorrect input.

![Figure 3-4; Incorrect input](image)

The seventh input is the downtime caused by one inspection. The eighth input is the inspection report time, this is the time it takes to inspect the cylinders and report back to the customer. The ninth input is the costs of an inspection for the customer. See Figure 3-5.

![Figure 3-5; Inspection and reporting time](image)
The **tenth and eleventh input** is the “preparation activities lead-time” and the “concluding activities lead-time”. The preparation activities lead-time is the time it takes to transport the cylinder to Bosch Rexroth, disassemble and clean the cylinder. The concluding activities lead-time is the time to reassemble and test the cylinder and subsequently sent it back to the customer. See Figure 3-6.

![Figure 3-6; Overhaul activities lead-time](image)

The **twelfth and thirteenth input** is the downtime costs per day during the operation period (due to inspections), and the additional classification period (due to overhaul).

The **fourteenth input** is the number of cylinder of the customer.

When all input cells are filled in the user can either go to the “view and adapt distribution” or to the “input TSR” screen by clicking on the buttons.
4. TSR input

The TSR input screen is used to fill in the coatings of the cylinders and the time since renewal (TSR) of the overhaul activities. See Figure 4-1 for a screenshot.

First the user can enter the coating of the rod. This can either be; enduroq 2X00, enduroq 3X00, chrome-nickel, or ceramax. The user can choose in a dropdown-list, see Figure 4-2.
Next the time since renewal of the overhaul activities can be filled in, see Figure 4-3 for an explanation.

The time since renewal is thus the time between the moment that the overhaul activity was last performed till the beginning of the contract period.
5. View and adapt variables

When the user goes to the “view and or adapt the input distributions”, the user finds the charts of the requirement probability density function, the detection probability function, the planning lead-time probability density function, and the planning lead-time probability density function. See Figure 5-1.

First the user can select the overhaul activity for which the distributions are displayed (orange cell which displays “Renew coating (Enduroq 2X00)” in Figure 5-1).

The requirement probability density function of the selected overhaul activity is displayed in the first graph.

The detection probability function of the selected overhaul activity is displayed in the second graph.

The planning lead-time probability density function of the selected overhaul activity is displayed in the third graph.

The execution lead-time probability density function of the selected overhaul activity is displayed in the fourth graph.

The current settings displays whether the overhaul activity is always executed if there is an overhaul required, or only executed if the overhaul activity itself is required. To change this setting the alternative setting can be chosen with a dropdown-list and changed by clicking on “Use alternative setting”.

A new overhaul activity can be added by clicking on “add an overhaul activity to list”, and deleted by “delete overhaul activity from list”.

Figure 5-1; View and adapt variables
5.1. Requirement distribution

The requirement distribution function is displayed in Figure 5-2. The requirement probability density function gives the probability that the overhaul activity is required after a certain number of years.

![Example Overhaul Activity - Requirement Probability](image)

**Figure 5-2; Requirement distribution**

To change the requirement distribution the user can manually fill in the alternative distribution and click on “Use Alternative Distribution” to change the current distribution. The user can also make an estimation of the distribution by using the scroll bars. When the user has made his estimation the user can click on “Fit Alternative Distribution” to fit a line to the estimations. See Figure 5-3.

![Example Overhaul Activity - Requirement Probability](image)

**Figure 5-3; Alternative requirement distribution**
5.2. Detection distribution

The detection distribution function is displayed in Figure 5-4. The detection probability function gives the probability that the overhaul activity is detected a number of years before the classification.

---

**Figure 5-4; Detection probability**

To change the detection probability function the user can manually fill in the alternative distribution and click on “Use Alternative Distribution” to change the current distribution. The user can also make an estimation of the distribution by using the scroll bars. When the user has made his estimation the user can click on “Fit Alternative Distribution” to fit a line to the estimations. See Figure 5-5.

---

**Figure 5-5; Alternative Detection probability**
5.3. Planning and Execution Lead-Time

The planning and execution lead-time graphs give the lead-time to respectively plan and execute the selected overhaul activity. The planning lead-time is the time it takes to acquire the required tools, people, and parts and therefore accounts for everything that can be done as soon as the overhaul activity is detected. The execution lead-time is the time it takes to execute the overhaul activity and accounts for everything that can only be done ones the cylinder is disassembled. The distributions give the probability that the lead-time takes a certain amount of days. See Figure 5-6.

![Example Overhaul Activity - Planning Lead-Time Probability](image)

![Example Overhaul Activity - Execution Lead-Time Probability](image)

Figure 5-6: Planning and execution lead-time distributions.
The planning and execution lead-time distributions can be changed in the same way as the requirement and detection distributions. The user can also change the X-axis of the graph by selecting “Short”, “Middle”, or “Long”. For “Short” the X-axis goes from 0 to 30 days, for “Middle” the X-axis goes from 0 to 60 days, and for “Long” the X-axis goes from 0 to 150 days. See Figure 5-7.

Figure 5-7: Adapt X-axis
6. Calculation Screen

All required information is now entered to calculate the system overhaul lead-time probability density function. Three scenarios can be calculated, the Ad-Hoc Service scenario, the optimized inspection based overhaul service scenario, and the user specified inspection based overhaul service. See Figure 6-1.

Figure 6-1; Calculation screen

The Ad-Hoc Service scenario is the scenario without any inspections. This can be calculated by clicking on “Calculate Expected Costs” in the Ad-Hoc Service scenario column. The calculation will take about 1 minute. After the calculation the system overhaul lead-time probability density function, and the expected costs are displayed. See Figure 6-2.
Next the optimized scenario can be found by clicking on “Find Optimal Scenario”. There are three settings of the optimization that can be defined; the “minimum distance between inspection”, the “Accuracy of the optimization”, and the maximum number of inspections. The “Accuracy of the optimization” is the length of the optimization steps in days; if this is 1 the optimization is accurate to 1 day. Maximum number of inspections can be set to 1, 2, and 3, and takes respectively about 1 minute, 2 minutes and 4 minutes. During the optimization the screen from Figure 6-3 is displayed.

After the scenario is optimized the expected costs and system overhaul lead-time probability density function of the optimized scenario can be calculated by clicking on “Calculate Expected Costs” in the optimized scenario column, see Figure 6-4. The calculation can take up to 8 minutes.
Figure 6-4: Optimized scenario calculation
Finally, the user can also define a user specified scenario. The user has to enter the “time till classification” of the inspections. The “time till classification” is the time from the inspection till the end of the operation-period/Classification, see Figure 6-6.

Subsequently the user has to click on “Calculate Expected Costs” in the user scenario column to calculate the expected costs and system overhaul lead-time probability density function, see Figure 6-6.
6.1. Report

Once all calculations are completed the user can make the “inspection based overhaul service” report by clicking on “Make inspection based overhaul service report”. The report contains the following:

- The contract information
- The time since renewal of the components
- The system overhaul lead-time probability density function
- The expected costs in the different scenarios

The following pages contain an example of an “inspection based overhaul service” report.
Inspection Based Overhaul Service

Date: 12-9-2014
Customer: Customer X
Project: Project X
### Contract Information

<table>
<thead>
<tr>
<th>Customer</th>
<th>Customer X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>Project X</td>
</tr>
</tbody>
</table>

| Start operation period, date | 1-1-2015 |
| End operation period, date   | 1-1-2018 |

<table>
<thead>
<tr>
<th>Classification period</th>
<th>Classified Information</th>
</tr>
</thead>
</table>

| Downtime caused by inspection | 1.5 days |
| Cost of an inspection         | € 10,000.00 per inspection |

| Preparation Activities Lead-time | 10 days |
| Concluding Activities Lead-time  | 10 days |

| Downtime costs Inspection       | € 100,000.00 per day |
| Downtime costs Overhaul         | € 100,000.00 per day |

| Number of cylinders on rig | 4 cylinders |

---

### Time Since Last Renewal

<table>
<thead>
<tr>
<th>Cylinder</th>
<th>Coating</th>
<th>Taper seal</th>
<th>Main Seal</th>
<th>Screw in nut</th>
<th>Nut Bolt on Screw</th>
<th>Nut Bolt off Screw</th>
<th>Nut Bolt + Off</th>
<th>Accessory (tubing)</th>
<th>Accessory (tail)</th>
<th>Bosch and Pin</th>
<th>Push Rod and Pin</th>
<th>Push Rod and Pin (tubing)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Enduroq 2X00</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<td>5</td>
<td>5</td>
<td>5</td>
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<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Enduroq 2X00</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Enduroq 2X00</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Enduroq 2X00</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<td>5</td>
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</tr>
</tbody>
</table>

---

Rexroth
Bosch Rexroth Employee: Thomas De Nijs
Date, Time: 12-9-2014 13:18
### Inspections & Overhaul Lead-Time

<table>
<thead>
<tr>
<th></th>
<th>Ad-Hoc Service</th>
<th>Optimized Scenario</th>
<th>User Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspection 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspection 3</td>
<td></td>
<td>68</td>
<td>40</td>
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<td>Inspections</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Expected Overhaul Lead-time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expected Additional Downtime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspection costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspection Downtime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional Overhaul Downtime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total expected Costs</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**System Overhaul Lead-time - Probability Density Function**

- **End Classification Period**
- **Ad-Hoc Service Scenario**
- **Optimized Scenario**
- **User Scenario**

**Classified Information**
Appendix IX. Software-tool expected cost calculations

In software-tool approximations of the equations from section 7.2 are used, this appendix describes these approximations. Only the equation for which approximations are used are given in this appendix.

Appendix IX.I. Equation 5

Exact calculation:

\[ E[DT_{SO}] = \int_{CP}^{\infty} l_{SO}(x) \ast (x - PCP) \, dx \]

Approximation:

\[ \text{Approximation}(E[DT_{SO}]) = \sum_{x=PCP}^{\infty} l_{SO}(x) \ast (x - PCP) \]

Appendix IX.II. Equation 6

Exact calculation:

\[ l_{SO}(x) = \frac{d}{dx} L_{SO}(x) \]

Approximation:

\[ \text{Approximation}(l_{SO}(x)) = L_{SO}(x) - L_{SO}(x - 1) \]

Appendix IX.III. Equation 11

Exact calculation:

\[ L_{POC-A_k(i_s=i_{s1})} (\psi) = \begin{cases} \psi-(L_{PA}+L_{CA}) & 0, \quad \psi \leq L_{PA} + L_{CA} \\ l_{OA_{k,1}} (\beta) d\beta, & \psi > L_{PA} + L_{CA} \end{cases} \]

\[ L_{POC-A_k(i_s=i_{s2})} (\psi) = \begin{cases} \psi-(L_{PA}+L_{CA}) & 0, \quad \psi \leq L_{PA} + L_{CA} \\ l_{OA_{k,2}} (\beta) d\beta, & \psi > L_{PA} + L_{CA} \end{cases} \]

... 

\[ L_{POC-A_k(i_s=i_{s_i})} (\psi) = \begin{cases} \psi-(L_{PA}+L_{CA}) & 0, \quad \psi \leq L_{PA} + L_{CA} \\ l_{OA_{k,i}} (\beta) d\beta, & \psi > L_{PA} + L_{CA} \end{cases} \]

\[ L_{OA_{k,i}} (\psi) = 1 \]
Approximation:

\[
\text{Approximation} \left( L_{\text{POC} - A_k(i,s_1=1)}(\psi) \right) = \begin{cases} 
\psi - (L_{PA} + L_{CA}) & \text{if } \psi \leq L_{PA} + L_{CA} \\
\sum_{\beta=0}^{\psi} l_{OA_{k,i}}(\beta) & \text{if } \psi > L_{PA} + L_{CA} 
\end{cases}
\]

\[
\text{Approximation} \left( L_{\text{POC} - A_k(i,s_1=2)}(\psi) \right) = \begin{cases} 
\psi - (L_{PA} + L_{CA}) & \text{if } \psi \leq L_{PA} + L_{CA} \\
\sum_{\beta=0}^{\psi} l_{OA_{k,i}}(\beta) & \text{if } \psi > L_{PA} + L_{CA} 
\end{cases}
\]

... 

\[
\text{Approximation} \left( L_{\text{POC} - A_k(i,s_1=s_1-1)}(\psi) \right) = \begin{cases} 
\psi - (L_{PA} + L_{CA}) & \text{if } \psi \leq L_{PA} + L_{CA} \\
\sum_{\beta=0}^{\psi} l_{OA_{k,i}}(\beta) & \text{if } \psi > L_{PA} + L_{CA} 
\end{cases}
\]

\[
\text{Approximation} \left( L_{OA_{k,i}}(\psi) \right) = 1
\]

Appendix IX.IV.  Equation 12

Exact calculation:

\[
l_{OA_{k,i}}(\beta) = \int_{0}^{\beta} \left( l_{AP_{k,i}}(\varphi) * l_{E_i}(\beta - \varphi) \right) d\varphi
\]

Approximation:

\[
l_{OA_{k,i}}(\beta) = \sum_{\varphi=0}^{\beta} l_{AP_{k,i}}(\varphi) * l_{E_i}(\beta - \varphi)
\]
Appendix X.  Exact cylinder overhaul lead-time calculation

The table below gives the input variables for the exact calculation

<table>
<thead>
<tr>
<th>What</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning lead-time PDF</td>
<td>( l_P(\varphi) = \lambda_P e^{-\lambda_P \varphi} )</td>
</tr>
<tr>
<td>Execution lead-time PDF</td>
<td>( l_E(\varphi) = \lambda_E e^{-\lambda_E \varphi} )</td>
</tr>
<tr>
<td>Requirement Probability (=execution probability)</td>
<td>( PRQ )</td>
</tr>
<tr>
<td>Time till classification of inspection</td>
<td>( TTC )</td>
</tr>
<tr>
<td>Probability detected at inspection</td>
<td>( POS_1 = DP \times PRQ )</td>
</tr>
<tr>
<td>Probability required but not detected at inspection</td>
<td>( POS_2 = PRQ - PED )</td>
</tr>
<tr>
<td>Probability overhaul activity not required</td>
<td>( POS_3 = 1 - PRQ )</td>
</tr>
<tr>
<td>Lead-time of preparation activities</td>
<td>( L_{PA} )</td>
</tr>
<tr>
<td>Lead-time of concluding activities</td>
<td>( L_{CA} )</td>
</tr>
</tbody>
</table>

Appendix X.I.  Actual planning lead-time

\[
l_{AP_{1,(s_1=1)}}(\varphi) = \begin{cases} 
  \int_0^{TT_{C1} + L_{PA} - L_I} l_{P_1}(\varphi) d\varphi, & \varphi = 0 \\
  l_{P_1}(TT_{C1} + L_{PA} - L_I + \varphi), & \varphi > 0 
\end{cases}
\]

\[
l_{AP_{1,(s_1=1)}}(0) = 1 - e^{-\lambda_P(TT_{C1} + L_{PA} - L_I)}
\]

\[
l_{AP_{1,(s_1=1)}}(\varphi) \text{ (with } \varphi > 0) = -\lambda_P e^{-\lambda_P(TT_{C1} + L_{PA} - L_I)}
\]

\[
l_{AP_{1,(s_1=2)}}(\varphi) = \lambda_P e^{-\lambda_P \varphi}
\]

Appendix X.II.  Overhaul activity lead-time

\[
l_{OA_{1,(s_1=1)}}(\beta) = \int_0^\beta \left( l_{AP_{1,(s_1=1)}}(\varphi) \times l_{E_1}(\beta - \varphi) \right) d\varphi
\]

\[
l_{OA_{1,(s_1=1)}}(\beta) = \int_0^\beta \left( l_{AP_{1,(s_1=1)}}(\varphi) \times l_{E_1}(\beta - \varphi) \right) d\varphi
\]

\[
l_{OA_{1,(s_1=2)}}(\beta) = \lambda_E \lambda_P \left( e^{-\lambda_P(\beta + TT_{C1} + L_{PA} - L_I)} - e^{-\lambda_P(\beta + TT_{C1} - L_I)} \right)
\]

\[
l_{OA_{1,(s_1=2)}}(\beta) = \frac{\lambda_E \lambda_P(\beta - e^{-\lambda_P \beta} - e^{-\lambda_E \beta})}{\lambda_E - \lambda_P}
\]
Appendix X.III. Cylinder overhaul lead-time

\[ l_{SO}(0) = POS_3 \]

\[ l_{SO}(x) \ (\text{with } x > 0) \]

\[ = POS_1 \left( l_{E_1} \left( x - (L_{PA} + L_{CA}) \right) \ast \left( 1 - e^{-\lambda_P(T_{TC} + L_{PA} - L_P)} \right) \right) \]

\[ + \frac{\lambda_E \lambda_P}{\lambda_E - \lambda_P} \left( e^{-\lambda_P(T_{TC} - L_P + x - L_{CA})} - e^{-\lambda_P(L_{PA} + T_{TC} - L_P) - (x - (L_{PA} + L_{CA}) \lambda_E)} \right) \]

\[ + POS_2 \frac{\lambda_E \lambda_P}{\lambda_E - \lambda_P} \left( e^{-\lambda_P(x - (L_{PA} + L_{CA}))} - e^{-\lambda_E(x - (L_{PA} + L_{CA})} \right) \]
Appendix XI. Exact versus approximated lead-times

To verify that the approximated calculation and the exact outcome correspond to each other, the case with one cylinder, one inspection, and one overhaul activity are calculated exact and with the approximations. The “planning lead-time” and the “execution lead-time” are exponentially distributed in the calculation. The equation of the exact calculation can be found in Appendix X.

A couple of scenarios are tested, in all of the scenarios the requirement probability of the overhaul activity is 80%, the probability that the overhaul activity requirement is detected at the inspection is 60%, the probability that the overhaul activity requirement is detected during the classification period is 20%, the lead-time of the “overhaul preparation activities” is 7 days, and the lead-time of the “overhaul concluding activities” is also 7 days. The timing of the inspection and mean planning lead-time and execution lead-time are enumerated with different values:

- Time till classification at moment of inspection ($TTC_r$) = [25, 50, 75]
- Mean $\left(\frac{1}{\lambda}\right)$ planning leadtime = [10,15, ... ,70, 75]
- Mean $\left(\frac{1}{\lambda}\right)$ execution leadtime = [10,15, ... ,70, 75]

For all scenarios the “system overhaul lead-time” probability density function is calculated exact and with the approximated calculation. The relative and absolute difference in expected “system overhaul lead-time”, and the relative difference in standard deviation is measured.

Appendix XI.I. Scenario 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>$PRQ$</td>
<td>0,8</td>
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<tr>
<td>$TTC$</td>
<td>25</td>
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<tr>
<td>$POS_1$</td>
<td>0,6</td>
</tr>
<tr>
<td>$POS_2$</td>
<td>0,2</td>
</tr>
<tr>
<td>$POS_3$</td>
<td>0,2</td>
</tr>
<tr>
<td>$L_{PA}$</td>
<td>7</td>
</tr>
<tr>
<td>$L_{CA}$</td>
<td>7</td>
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</table>
Relative Difference in Expected System Overhaul Lead-time

Relative Difference in standard deviation System Overhaul Lead-time
Appendix XI.II. Scenario 2

<table>
<thead>
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<th>Variable</th>
<th>Value</th>
</tr>
</thead>
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<td>$PRQ$</td>
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</tr>
<tr>
<td>$TTC$</td>
<td>25</td>
</tr>
<tr>
<td>$POS_1$</td>
<td>0,6</td>
</tr>
<tr>
<td>$POS_2$</td>
<td>0,2</td>
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<tr>
<td>$POS_3$</td>
<td>0,2</td>
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<tr>
<td>$L_{PA}$</td>
<td>7</td>
</tr>
<tr>
<td>$L_{CA}$</td>
<td>7</td>
</tr>
</tbody>
</table>
### Appendix XI.III. Scenario 3

<table>
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<tbody>
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<td>PRQ</td>
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<tr>
<td>TTC</td>
<td>25</td>
</tr>
<tr>
<td>POS₁</td>
<td>0.6</td>
</tr>
<tr>
<td>POS₂</td>
<td>0.2</td>
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<tr>
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</tr>
<tr>
<td>L_PA</td>
<td>7</td>
</tr>
<tr>
<td>L_CA</td>
<td>7</td>
</tr>
</tbody>
</table>
Relative Difference in Expected System Overhaul Lead-time

Relative Difference in standard deviation System Overhaul Lead-time
**Absolute Difference in Expected System Overhaul Lead-time**

- **Planning Lead-time Mean**
- **Execution Lead-time Mean**

Legend:
- □ 0,00-0,50
- □ 0,50-1,00
- □ 1,00-1,50
- □ 1,50-2,00
- □ 2,00-2,50
Appendix XII. Overhaul activity lead-time approximation for optimization

\[ l_{OA_{k, (i, \beta)}}(\beta) = \int_0^\beta \left( l_{AP_{k, (i, \beta)}}(\varphi) * l_{E_i}(\beta - \varphi) \right) d\varphi \]

approximation \( l_{OA_{k, (i, \beta)}}(\beta) = P(l_{OA_{k, i}}(adapted) = \beta) \)

\[ P(l_{OA_{k, i}}(adapted) \sim \text{norm}(\mu_{l,r}, \sigma_{l,r}^2)) \]

\[ \mu_{l,r} = \max(E[L_{E_i}], E[L_{E_i}] + E[L_{P_i}] - TTC_r) \]

\[ \sigma_{l,r} = \sqrt{P(L_{P_i} \geq TTC) * \sigma_{l,r}^2 + \sigma_{E_i}^2} \]

Where:

\[ E[L_{E_i}] = \text{Expected execution leadtime overhaul activity i} \]

\[ E[L_{P_i}] = \text{Expected planning leadtime overhaul activity i} \]

\[ \sigma_{E_i} = \text{standard deviation of execution leadtime overhaul activity i} \]

\[ \sigma_{P_i} = \text{standard deviation of planning leadtime overhaul activity i} \]
Appendix XIII. “Calculate cost” process versus “optimize inspections” process.

The expected cost are calculated different in “optimize inspections” process than in the “calculate cost” process from section 9.3. To verify that the optimal timing of an inspection found in the “optimize inspections” process is equal to the optimal timing of an inspection in the “calculate cost” process, 3 scenario's are compared.

Appendix XIII.I. Scenario 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract Duration</td>
<td>5 years</td>
</tr>
<tr>
<td>Inspections</td>
<td>1</td>
</tr>
<tr>
<td>Overhaul preparation activities lead-time</td>
<td>7 days</td>
</tr>
<tr>
<td>Overhaul preparation activities lead-time</td>
<td>7 days</td>
</tr>
<tr>
<td>Inspection lead-time</td>
<td>5 days</td>
</tr>
<tr>
<td>Downtime due to inspections</td>
<td>1 day</td>
</tr>
<tr>
<td>Cost of inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Cost of downtime due to inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Cost of downtime due to inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Classification period</td>
<td>70 days</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>4</td>
</tr>
<tr>
<td>TSR of components</td>
<td>5 years (for all)</td>
</tr>
</tbody>
</table>

Expected Costs

TCC of inspection (Days)

- Calculation Process
- Optimization Process
The “Optimize inspection” process gives another timing of the inspection for the lowest expected cost than the “Calculate Costs” process. However, the difference in expected cost is only in the point where the “Optimize inspection” process and the where the “Calculate Costs” process gives the lowest value is only 0.37% \((\frac{€1,454,009 - €1,451,990}{€1,451,990} = 0.14\%)\).

**Appendix XIII.II. Scenario 2**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Contract Duration</td>
<td>5 years</td>
</tr>
<tr>
<td>Inspections</td>
<td>1</td>
</tr>
<tr>
<td>Overhaul preparation activities lead-time</td>
<td>7 days</td>
</tr>
<tr>
<td>Overhaul preparation activities lead-time</td>
<td>7 days</td>
</tr>
<tr>
<td>Inspections lead-time</td>
<td>5 days</td>
</tr>
<tr>
<td>Downtime due to inspections</td>
<td>1 day</td>
</tr>
<tr>
<td>Cost of inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Cost of downtime due to inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Cost of downtime due to inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Classification period</td>
<td>70 days</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>8</td>
</tr>
<tr>
<td>TSR of components</td>
<td>5 years (for all)</td>
</tr>
</tbody>
</table>
The “Optimize inspection” process gives another timing of the inspection for the lowest expected cost than the “Calculate Costs” process. However, the difference in expected cost is only in the point where the “Optimize inspection” process and the where the “Calculate Costs” process gives the lowest value is only 1,1% \( \left( \frac{€2.486.335 - €2.486.073}{€2.486.073} = 0,01\% \right) \).
### Scenario 3

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contract Duration</td>
<td>5 years</td>
</tr>
<tr>
<td>Inspections</td>
<td>1</td>
</tr>
<tr>
<td>Overhaul preparation activities lead-time</td>
<td>7 days</td>
</tr>
<tr>
<td>Overhaul preparation activities lead-time</td>
<td>7 days</td>
</tr>
<tr>
<td>Inspection lead-time</td>
<td>5 days</td>
</tr>
<tr>
<td>Downtime due to inspections</td>
<td>1 day</td>
</tr>
<tr>
<td>Cost of inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Cost of downtime due to inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Cost of downtime due to inspection</td>
<td>Bosch Rexroth Classified Information</td>
</tr>
<tr>
<td>Classification period</td>
<td>70 days</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>16</td>
</tr>
<tr>
<td>TSR of components</td>
<td>5 years (for all)</td>
</tr>
</tbody>
</table>

### Expected Costs

![Graph of Expected Costs](image-url)

- **Expected Costs**
- **TCC of inspection (Days)**
- **Calculation Process**
- **Optimization Process**
The “Optimize inspection” process gives another timing of the inspection for the lowest expected cost than the “Calculate Costs” process. However, the difference in expected cost is only in the point where the “Optimize inspection” process and the where the “Calculate Costs” process gives the lowest value is only 1,1% \( \left( \frac{\€3,941,742 - \€3,940,760}{\€3,940,760} = 0,02\% \right) \).
Appendix XIV. Multiple inspections cases

Multiple cases are analyzed, all with the input variables given in Table XIV-1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Input</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System Overhaul Lead-Time</strong></td>
<td>Preparation activities lead-time</td>
<td>10</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>Concluding activities lead-time</td>
<td>10</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>Inspection lead-time</td>
<td>5</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>Downtime caused by inspection</td>
<td>1</td>
<td>day</td>
</tr>
<tr>
<td></td>
<td>Length of operation period</td>
<td>4</td>
<td>years</td>
</tr>
<tr>
<td></td>
<td>Time Since Renewal (for all overhaul activities)</td>
<td>5</td>
<td>years</td>
</tr>
<tr>
<td><strong>Optimization</strong></td>
<td>Minimum Distance Between Inspections</td>
<td>40</td>
<td>days</td>
</tr>
<tr>
<td></td>
<td>Alpha</td>
<td>1</td>
<td>day</td>
</tr>
</tbody>
</table>

Table XIV-1: Input variables for multiple inspections scenarios

The cases for the 2, 4, 8, 16, 20 cylinders are optimized with 1, 2, and 3 inspections, the probability density function of the system overhaul lead-time of these cases are given in the following graphs.
Overhaul Lead-Time PDF
(4 Cylinders)

Overhaul Lead-Time PDF
(8 Cylinders)