Thesis

A new decision support system for managing spare parts: avoiding unplanned downtime.

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A new decision support system for managing spare parts: avoiding unplanned downtime

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PREFACE

Dear reader,

This report contains the research with the title ‘A new decision support system for managing spare parts: avoiding unplanned downtime’. I have done this research for my bachelor thesis of Industrial Engineering and Management at the University of Twente. This research has been executed at the company ETC in Almelo from September 2021 to February 2022

At ETC it was nice to meet new people which were always available to help you. It was a nice experience to see a high-tech production company. So I would like to thank the company for this opportunity. The maintenance team helps me a lot to get more knowledge about the technique of the machines and they give me more information about the development of the company. I especially want to thank my supervisor Stijn Hulshof for his help. I also want to thank John Kruithof and Emiel Robers who were always available for any question.

I also want to thank my supervisor of the university, Engin Topan. He gives me structured feedback to improve the process of the thesis at any time. Also, I wanted to thank Ipek for the quick responses and the help to construct the research questions at the beginning of the process. Finally, I want to thank my friend and family for supporting me during the process.

Niek van der Wijst

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SPECIFIC PRODUCT INFORMATION IS LEFT OUT.

MANAGEMENT SUMMARY

Introduction

The report describes a research that is done at Enrichment Technology Company (ETC) Almelo and it is part of the bachelor Industrial Engineering and Management at the University of Twente. ETC has the problem that there is a lack of overview in spare parts management. This lack of overview leads to unplanned downtime during a failure. This downtime is caused by the time it takes to deliver the spare part that is needed to solve the failure.

A problem cluster is created to gives an overview of the possible causes of this unplanned downtime. At ETC there is no clear spare part policy, so the purchase of the spare parts is not structured. Next to that, the company has no clear insights into the lead time of the spare parts. These problems lead to the main research question 'How to control spare part supply to avoid unplanned downtime during machine failures'. This question will be answered during this thesis. The product of this thesis is a new spare part policy for ETC.

Context analysis

A failure analysis is conducted which gives the possible situation when a machine gets a failure. If the decision is made to take a spare part in stock, the machine can operate again after a repair. If the spare part is not in stock the production needs to wait until the needed spare part arrives, unless there is another machine that can take over the production. The failure data of ETC is taken from the ERP system. This data gives information about the spare parts that are used during a repair for a machine. This information is used to determine the demand. This is done by counting the uses of the spare parts during the years.

Some data instances of the ERP data were missing or incomplete. Therefore, the decision was made to only use the data instances that are complete because this makes it more easy to compare the instances with each other.

Literature

For this research, a literature review regarding different inventory models was carried out. From this review, it became clear that the base stock level (S, S-1) applies to the situation at ETC. This is because the demand is small, resulting in a stock possibility of 0 or 1. To calculate the fraction of time the spare part is needed, but is not available the Erlang Loss Function is used. This function makes it possible to calculate the service level and the total costs of the spare parts of a machine. This function will be part of the decision support system which gives the output to the company. This output contains a list of spare parts that are advised to keep in stock, based on this Erlang Loss Function.

Solution design

The spare part policy will be conducted by the use of a model. This model consists of input variables that refer to the Erlang Loss Function and output variables that are used for the decision support system. The most important input of this model is the spare part data of a machine that is bought. These spare parts contain information about the price and the delivery times. The demand data is added by giving the spare part a certain category. This category (for example bearings) is determined in consultation with the company and contains the average demand which is based on the historical data of the company. This demand is Poisson distributed which makes the demand memoryless.

This demand makes it possible to calculate the possibility of a request for the spare parts during its lead-time. This is used as input for the Erlang Loss function.

The model uses as input the holding costs, which are available when a part is in stock. These costs consist of occupancy costs, opportunity costs, and depreciation costs. The model uses the emergency costs, which are induced when the part is not available. In that case, the machine is down which gives downtime costs and a rush order needs to be placed.

The decision to take spare parts in stock is influencing the holding and emergency costs. To model will be optimized to find the optimal value for two input variables. The total costs need to be as low as possible within a limited spare part budget and minimize the budget to reach a certain service level.

Results

The list of spare parts that are advised by the supplier is compared with the outcomes of the policy that is created by the model. This outcome shows us that it is possible to increase the service level by 3,68%. The total expected costs per year can be lowered by 61,27%. If the same service level is targeted there will be 77,38% less budget needed and the total costs will be 10,77% lower. These results can be seen in Figure 1. The other outcome is the list of spare parts that meet these outcomes.

	First service pack	Budget based	Service level based	Differences BB	Differences SLB
Reached service level	90,48%	93,81%	90,97%	3,68%	
Used budget	€ 9.402,40	€ 9.402,40	€ 2.126,82		-77,38%
Total expected costs per year	€ 27.883,04	€ 10.799,10	€ 24.880,04	-61,27%	-10,77%

Figure 1: Results: Spare part control

Conclusions and recommendations

The policy makes it easier to convince the company of a higher budget that is needed to reach a certain service level. The results of the increase of the service level and the decrease of the service level are promising to optimize the spare parts.

The policy makes it possible to make better-informed decisions to determine which spare parts there need to be in stock. The policy will not replace the experience of the employees and the recommendations of the supplier, but it gives a starting point for well-funded spare part management.

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TERMS AND DEFINITIONS

ERP = Enterprise Resource Planning. This system manages and integrates business processes through a single system.

ETC = Enrichment Technology Company. This is the company where the thesis is conducted.

Lead time = latency between the initiation and completion of a process.

MPSM = Managerial Problem-Solving Method. A methodological concept with seven different steps to come to a solution for knowledge and action problems.

Reorder point = Specific level at which your stock needs to be replenished.

Safety stock = inventory that is kept in stock to avoid a stockout.

SAP = The brand of the Enterprise Resource Planning system

Service level = probability of meeting the demand.

Paternoster = warehouse system which makes it easy to store a lot of items.

1 INTRODUCTION

In this chapter the company is introduced and a journey to find, analyze, solve and reflect on the problem will be described. Also, the problem approach will be briefly explained.

1.1 Company background

Enrichment technology company (ETC) is producing confidential high-speed gas centrifuges to enrich uranium for nuclear energy and medical applications. The confidentiality is caused because of the developed unique technique of these centrifuges. The company is a joint venture between Urenco and Orano. ETC operates from sites in four European countries: Germany, The Netherlands, The United Kingdom, and France. Most of the high-speed centrifuges are developed and produced at the site in Almelo. ETC uses 450 different machines to produce almost all parts to assemble the centrifuges.

1.2 The problem

The problem of the company is described in this section. Section 1.2.1 describes the action problem. The current situation and the core problem are described in section 1.2.2. The research questions that support the core problem are given in section 1.2.4. The deliverables of this thesis are given in section 1.2.6.

1.2.1 Current situation and action problem

To identify the possible action problems of the company, informal interviews were conducted. The outcomes of these interviews were that there is currently a lack of overview of the spare parts which is caused by the decrease in production. This has a historical background that will be explained in this section.

Due to the Fukushima nuclear disaster in 2011, the demand for new centrifuges is declining very fast. Challenges appear for the company because a lot of machines and workers were not needed anymore. The cause of the lack of overview is inferable to this disaster. The situation before and after 2011 will be described to better understand the cause of this lack of overview.

Before 2011, the period when the production was at the highest point the company has a warehouse manager that was responsible for the spare parts management. This employee did the check-in and check-out of the spare parts and stored them correctly in the paternoster (warehouse organizing system) and the ERP system (system companies use to manage and integrate their core business processes). This high amount of production has a strict schedule to full fill the demand. An unexpected failure can be catastrophic when it is not fixed quickly. For that reason, the company decided to take a lot of spare parts in stock because it was more important to fix machines as quickly as possible than the costs of these spare parts.

After 2011, the position of the warehouse manager was removed and the mechanics need to do the administration in the ERP system by themself. The mechanics are not structured enough to do the check-in and check-out of the spare parts according to the same method. So during the years, it becomes unclear which spare parts there are in stock and which are not. If an unexpected failure occurs it is not sure anymore if the spare part is available. Despite the ERP system saying that the needed part is available.

This lack of overview gives the possibility that a spare part is not available during a failure while it is necessary. The situation of an available part and an unavailable part need to be explained to understand the consequences.

When a failure occurs a spare part may be needed for repair. If the spare part is available, the repair can be done at the moment that a mechanic is available. This process can be seen in Figure 2.

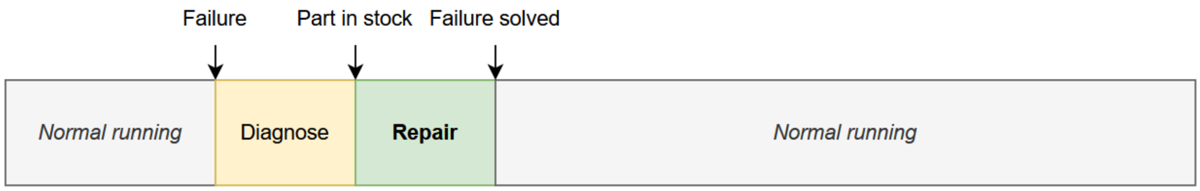

Figure 2: Timeline machine failure - Part in stock

When a pare part is not available an order needs to be placed. This order causes extra downtime for the machine because of two reasons:

- The purchaser needs to place an order. Before this order can be placed different people within the company need to give their approval. This costs several days.
- The spare part has a certain lead time which exists of the delivery times of the supplier and the processing time at ETC to make the part available for the maintenance department.

The process of the repair where an order needs to be placed can be seen in Figure 3. The combination of the purchase process and the lead time gives the unplanned downtime waiting for spare parts.

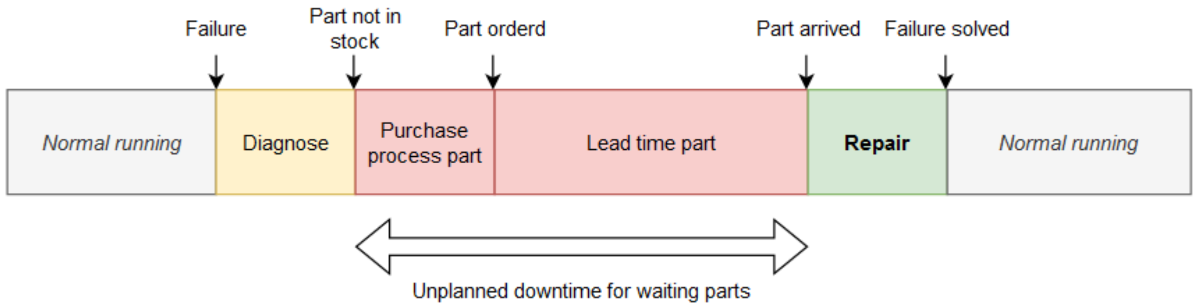

Figure 3: Timeline machine failure- Part not in stock

The unplanned downtime needs to be decreased during this research and therefore identified as an action problem. Because it is more important nowadays to have a more cost-saving production process it is not possible to take all spare parts in stock. Choices within a certain budget need to be made to get the best result. An alternative solution needs to be found.

1.2.2 Core problem

The Managerial Problem Solving Methodology (MPSM) (Heerkens & Van Winden, 2012) was used to create a problem cluster with all possible problems. According to this methodology, problems can be divided into controllable and uncontrollable problems. An example of an uncontrollable problem is bad weather.

Unplanned downtime refers to unexpected waiting times for a part that is not available at the time when the machine broke down. The unavailability of a part can have the following reasons. See Figure 4.

1. *Supply uncertainties:* The supplier can make a mistake during the delivery of the part, which cannot be influenced at that time. The only possibility is to search for new suppliers. ETC has many machines which are specially made for them. This makes it difficult to switch to another supplier. For the smaller, not unique, parts it is possible to switch to another supplier.

However, it also can be a problem that the delivery times are unknown. If a part has an expected lead-time of two weeks, but it is taken three weeks in reality the machine has an extra downtime of one week. The lead-time is longer than expected. The delivery times of the different spare parts are uncertain.

2. *Machines are outdated, parts are obsolete:* The machine needs a spare part to repair, but it is not available anymore because the machine is too old. So the parts become obsolete. Machines will operate for at least 8 years according to their decrepitation period. But in practice, they will work for at least 15 to 20 years. If the machine is at the end of its lifespan it will be more difficult and more expensive to buy spare parts of these machines. At a certain point, the replacement of a machine can be cheaper than ordering a new part. Or it is possible to rebuild the machine and implement a new software system.
3. *No policy for spare parts control:* The company has no policy for purchasing spare parts. The mechanics and the purchaser look together at the machines and determine on experience which parts are needed in stock or a list of spare parts that are advised by the supplier are bought. Historical data learns that there are many parts in stock which are not been used for at least five years. Another problem is that some parts have an expiring date. So it is important to look beforehand (when buying a new machine) how many spare parts need to solve failures without unnecessary downtime.

Summarized ETC lacks an overview of the needed spare parts and an overview of the lead times. This bachelor assignment aims to develop a new inventory control system.

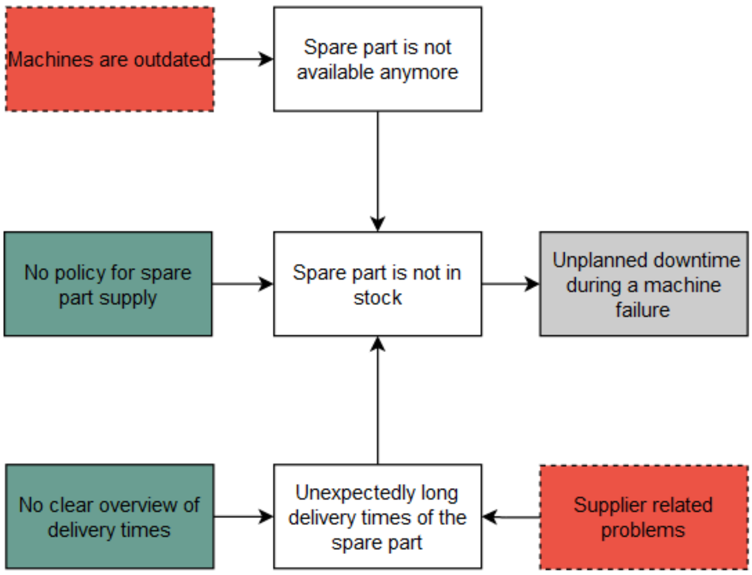

Figure 4: Problem cluster ETC

1.2.3 Norm and reality

To compare the norm and reality it is important to choose variables that can easily show the difference between the old and the new situation (Heerkens & Van Winden, 2012). The variable that can show the difference between the unplanned downtime in the old and new situation is time. It is hard to measure the exact time that a machine is down because this data is not registered the right way by the mechanics. For that reason, the variable 'service level of the spare parts' will be used to measure the difference in unplanned downtime. To convince the company to adopt this new inventory policy it is useful to show the cost-effectiveness. Another variable will be the cost of having fewer spare parts in stock, this variable will be in euros. For the costs, the target is to reduce the spare part control by at least 20%. The target for service is to increase it by 3%. These values are set in consultation with the company.

1.2.4 Research questions

To understand the current situation and to collect data, research questions are formulated. These research questions will help to find the solution for the main question. Because it is hard to solve the question directly.

The main research question is:

'How to control spare part supply to avoid unplanned downtime during machine failure?'

The research questions will be categorized into the following topics: current situation, literature research, field research, policy, evaluation.

Current situation

1. What is the current situation for ETC concerning the control of spare parts in combination with unexpected failures?
    a. When does a failure occur?
    b. What causes unplanned downtime during a failure of the machines?
    c. What is the demand for spare parts?
    d. What are the current lead times for (critical) spare parts?

Question 1 includes all the information about the current situation. This question is specified into four sub-questions. The ERP system will be used to obtain the data. There is a lot of information available, but to answer this question the information needs to be combined. This will be explained in chapter 1.

Literature research

2. Which inventory policies are available to control spare parts?

There are a lot of ways to control spare parts. Before the start of the research more knowledge is needed about the ways to control the need for spare parts. This information is needed to defend the choices for a certain strategy. This will be explained in chapter 3.1.2.

3. How can parts be classified and what inventory policies fit best for each class?

Every machine has different sorts of parts. For example a hydraulic pump, bearings, pressure sensor, etc. Categories will be created of different types of spare parts. This will be explained in chapter 3.1.3.

Field research

4. How to control spare parts at ETC?

This is one of the core elements of the research. After the research on the different control sorts of spare parts, a decision about how to control spare parts needs to be taken. Different classified spare parts can use different policies. So in the strategy can differ per spare part. This will be explained in chapter 4.

5. Which parts need to be in stock, based on lead times, categorization, and service level?

Use the information from questions 1, 2, 3, and 4 as input for the policy. This policy is based on maximum downtime, lead times, and failure analysis. In combination with the chosen spare part control, the policy can be created. This policy will be used to tackle the action problem. This will be explained in chapter 4.

Evaluation

6. What is the benefit of using the new inventory policy in terms of savings and downtime during a failure?

After the development of the policy, it needs to be implemented for the new machines. The service level of the spare parts and the total costs of the new and old situation will be compared. The model will be created to use for future machines that are bought in the future. This will be explained in chapter 5.

The product of this research will be an inventory control system that is written as a policy which is substantiated with an overview of the decrease in costs and downtime during failures.

1.2.5 Problem-solving approach

The Managerial Problem Solving Method (MPSM) (Heerkens & Van Winden, 2012) is a problem-solving method that will be used during this thesis. The MPSM consists of seven phases that are given in Figure 5.

First, the problem needs to be defined. The interviews with the maintenance engineer and the purchaser help to create a problem cluster for the company. The solving approach can be defined by the use of the MPSM cycle (Heerkens & Van Winden, 2012).

To analyze the problem there is more knowledge needed. A literature study is used to get more information about the control of spare parts. Also, more information about machine failures and categorization is obtained. This information is grouped into a theoretical model which is used to determine the current inventory policy of the company. The new policy can be determined and the start of the data mining can be made. The different data sets need to be combined and the information about lead times and demand rates is created.

The possible solutions can be based on this available data. The formulas which are obtained during the literature research are used to define a new inventory policy. The demand and the lead times are determined for the categories and the model is created which can present the results. The input variables 'service time' and 'euros' are implemented into the model.

The solution can be obtained by comparing the current situation with the newly optimized policy. This information is used to make the policy useable for other machines.

The policy is presented to the company and they give some feedback which is used to improve the model and get more realistic results. In the end, the recommendations and the discussion are written to give more information about the deficiencies and further research.

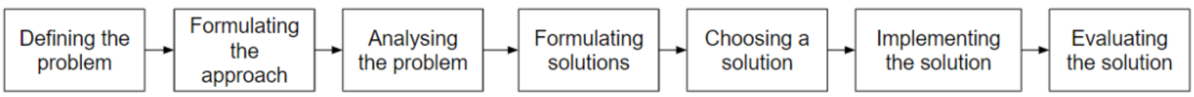

Figure 5: MPSM cycle by Heerkens & Van Winden (2012)

1.2.6 Deliverables

To reduce the unplanned downtime waiting for a part during a failure. A general policy of inventory management will be developed. Based on the policy, the company can decide to get a spare part on stock or not. The following criteria are used.

- The restricted budget that is available.
- The service level of spare parts.

The variables that will influence these constraints.

- The lead time of the spare part.

- Chance of a critical failure of the part in the machine.
- The necessity of the machine.

This policy will be mainly developed for future machines. Which allows ordering the needed spare parts directly when a new machine is purchased. This is expected to lead to a cheaper purchasing process.

The policy will also be written for the current machines if the right data is available. At this moment, there are a lot of spare parts of these machines in stock and it would be illogical to throw away parts that can be used in a later stadium.

To reinforce the research there will be added an overview of the 'increased service level' and the 'cost reduction' comparing the current situation with the new policy.

1.3 Research design

1.3.1 Research types and subjects

The methodology that is used for this thesis is the Managerial Problem Solving Method (MPSM) (Heerkens & Van Winden, 2012) is used to solve the main problem. This is described in section 1.2.5.

The type of research that will be used is prescriptive research, quantitative research, and qualitative research. Prescriptive research is used to define the policy that is created in this thesis. In this research, there are two research objects. Firstly, the spare parts that are used for the analysis. The information about these spare parts is obtained by the use of quantitative research. Second, the maintenance employees that are involved in the research because of the input about the different sort of categories. Quantitative research attempts precise measurements of something (Cooper & Schindler, 2013), so that will be used to obtain information or feedback from the employees.

1.3.2 Boundary condition and scopes

Time: The bachelor assignment will take up to 10 weeks

Business-unit-scope: To create an inventory policy that determines which spare parts for new machines are needed in stock. The policy can also be used for current machines if the right data is available. At this moment, there are a lot of spare parts of these machines in stock and it would be illogical to throw away parts that can be used in a later stadium.

Forecast scope: The policy will help the purchaser and maintenance engineer to make better-informed choices when buying new spare parts. A higher service level can be reached with the same amount of budget.

1.3.3 Validity and reliability

Before it is possible to say something about the validity and the reliability the definition of both needs to be defined. The definition of both are closely related, so reliability is part of validity. Reliability means that the outcomes of the research will always be the same if the researcher repeats his search. Validity means the question about the measurements. Are the measurements as expected? (Heerkens, 2017).

The validity of the research will be tested internally because the data which is used is classified. The outcomes of the policy will be compared with the initial bought spare parts. The policy will be tested for several machines and the outcomes will be presented to the maintenance engineer. The results will be validated as logical in that case.

The external validity will be tested by changing different values on the dashboard of the policy. This will simulate the changes that can be made by other companies to represent their situation.

Reliability is tested to use the same policy in the dashboard several times and compare the outcomes when optimizing the spare pare part management.

1.4 Summary and conclusions

The action problem of this thesis is the unplanned downtime during a failure caused by the lack of overview in spare parts management. There is no clear policy for buying new spare parts and the overview of the lead time is missing. This thesis will conduct a new policy where the variables 'service level' and 'costs' are used.

2 CONTEXT ANALYSIS

In this chapter, the context analysis for this bachelor is described. This is done by answering the first research question: What is the current situation for ETC concerning the control of spare parts in combination with unexpected failures? The difference between the downtime in case the part is in stock is compared with the case that a spare part is not in stock. After that, the available data is explained and the transformation to more useful data is given. In the end, the limitations of these transformations are described.

2.1 Failures

In section 1.2.1 it is described that the unplanned downtime is caused by waiting for a part during failure. For this thesis, it will be important to analyze these failures. More information about the causality of a failure and the possible solutions is needed.

2.1.1 Definition of a failure

A failure is an incident where a part of the machine is not working anymore. This failure can have several causes. According to (Westrom, 2021) the most common causes of machine failure are:

- *Operator error*. The user of the machines does not properly use the machine. This can cause a failure. For example, the operator does not know how to adjust the machine for a specific product.
- *Wrong amount of maintenance*. To maintain the machines it is important to do maintenance. When maintenance is not done in the right way this can cause a failure. For example, if there is too little maintenance the wearing of a part cannot be checked.
- *Physical wear and tear*. Some parts in a machine are made to wear over time. When those parts are not working anymore they cause a failure. An example of this part is a bearing.
- *Reliability culture failings*. When the production capacity is pushed too hard (or for our company too low) the machine can get a failure. For example, if the machine is not working frequently mechanical grease can accumulate which causes failures.

The consequences of the dysfunctionality of a part differ per situation because not all the parts in a machine have the same criticality. Sometimes it is still possible to produce after a small repair, but the part still needs to be replaced in short term. It is also possible that the machine cannot produce anymore and needs to wait for a replacement for the part that broke down. In that case, the part can be in stock or not. When it is in stock the repair can be done directly and after that, the machine can operate again. When the part is not available the mechanic needs to wait until the new part arrives at the company. These different situations will be explained in section 2.1.2

2.1.2 Downtime during failure

When a machine has failure there are different scenarios possible to restart the production. These scenarios and the corresponding influence on the unplanned downtime are shown in Figure 6.

		Spare parts	
Production machine		*Spare part not in stock*	*Spare part in stock*
	Machine cannot produce	Unplanned downtime with additional excess downtime for waiting part.	Unplanned downtime but no downtime for waiting part.
	Another machine can produce after modification	Unplanned downtime with additional excess downtime till modification is finished.	Unplanned downtime with no downtime for waiting part.
	Another machine can take the production	Unplanned downtime with additional excess downtime for set up machine.	Unplanned downtime with no downtime for waiting part.
	Machine can produce	Planned downtime with no downtime for waiting part	Planned downtime with no downtime for waiting part.

Figure 6: Failure possibilities and spare parts in stock or not

In some situations, the machine is not able to produce anymore because a critical part broke down. When the part is in stock the machine will operate again after it is replaced. If the part is not in stock the company needs to wait until the part arrives and after the replacement, it is operating again. Sometimes it is possible to modify or set up a comparable machine which will shorten the downtime when this takes less time than waiting for the part.

2.2 Data gathering

In this subsection, the different sources of data are explained. For this thesis, there is data needed about the current failures, demand per spare part, and the lead times. This data is gathered from the ERP system SAP. SAP is the brand of the ERP system that ETC is using. In consultation with the ERP system specialist data is combined which results in a set of data. The data is collected from 2011 to 2021. Data before 2011 is not usable because the registration of this data is not complete. The following sections will explain how this data is gathered.

2.2.1 Failure data

When a machine broke down notification is made into the ERP system. This notification gets a failure form with a specific number and all the further actions are noted down into this form. If a part is needed this is also registered in this form. So in an ideal situation, all the spare parts that are used to solve a failure are registered in the system and are linked to the failure where it was needed.

But the data about failures of the different spare parts are in our situation not completed. For example, not all spare parts of a machine are registered in the system. Only the parts that are ordered to put in stock get a spare part number. Parts that are ordered because of failure are not registered all the time. This makes it difficult to understand earlier decisions about which parts ETC took in stock.

The registration of a part is time-consuming because a lot of information must be put into the system. So when a spare part is bought once, it will not get registered. Another problem appears when spare parts are bought in batches and are not registered individually. This happens a lot when a new machine is bought. The incomplete registration of the spare parts gives disadvantages. Because they did not register it in a recognizable way it is almost impossible to analyze this data by subtracting it from the ERP system.

It is hard to say something about the demand for spare parts that are not registered because it is not possible to see when this same part is ordered again (which means another demand). So for this thesis, only the data about the registered parts will be used to determine demand.

The failure data that is subtracted from the ERP system is presented in Figure 7. The 'order' number corresponds with a failure that is registered in the system. For each order, a specific part is used to solve this failure. The part that is used is registered with 'part number'.

Art.doc.	AJaar	Part number	Order	Srt	YEAR	MONTH	Date spare part taken from stock
4948253479	2021	3906172	3092205	C2	2021	12	6-12-2021
4948252756	2021	3901161	3090629	M2	2021	12	2-12-2021
4948252755	2021	3901061	3090629	M2	2021	12	2-12-2021
4948248662	2021	3900986	3092164	C2	2021	11	24-11-2021
4948248585	2021	3900632	3091728	M2	2021	11	24-11-2021
4948248009	2021	3907377	3092029	M2	2021	11	23-11-2021
4948247840	2021	3906634	3092149	C2	2021	11	22-11-2021
4948244429	2021	3900555	3092111	C2	2021	11	15-11-2021
4948243829	2021	3901869	3092090	M2	2021	11	12-11-2021
4948243632	2021	3907585	3091731	M2	2021	11	12-11-2021
4948242602	2021	3908581	3092047	C2	2021	11	10-11-2021

Figure 7: Failure data subtracted from SAP

2.2.2 Demand data

To determine the demand of the different registered spare parts the failure data is used. This makes it possible to count the number of parts and machines that used a specific part during the year. This is presented in Figure 8.

Part number	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	SUM	Different machines
3906173	11	16	19	11	18	10	5	4	6	2	4	106	49
3900672	3	14	19	26	8	8	1	4	1	1	0	85	5
3906172	3	7	9	6	5	5	3	4	0	5	2	49	16
3903251	11	11	8	6	2	0	0	1	0	1	1	41	9
3901725	7	9	14	6	2	1	0	0	0	0	0	39	3
3906138	5	11	13	5	2	0	0	2	0	1	0	39	5
3900416	8	9	4	3	3	0	5	4	2	0	0	38	4
3901685	9	4	8	9	3	2	0	0	0	0	0	35	3

Figure 8: Failure data to determine demand subtracted from SAP

2.2.3 Lead time data

The lead time is not frequently updated in the ERP system. To determine the lead time the dates of the purchase document and the received document are compared.

The purchaser creates a purchase document when he orders a part at a supplier. This document number can be seen in 'purchase document number' and the corresponding date in 'order date'. When the part arrives at the company a received document is created, the number of this document can be found in 'receive document number' and the corresponding date in 'receive date'. This can be found in Figure 9.

Purchase document number	Part number	AJaar	Order date	Receive document number	Receive date	Lead time in days
4374844	3906172	2012	6-7-2012	5400717937	21-6-2012	15
4387975	3906172	2013	11-7-2013	5400883501	14-6-2013	27
4396562	3906172	2014	13-2-2014	5400999881	28-1-2014	16
4410282	3906172	2015	7-5-2015	5401255972	2-5-2015	5
4416981	3906172	2016	18-5-2016	5401353998	11-5-2016	7
4422559	3906172	2017	10-4-2017	5401483175	3-4-2017	7
4442435	3906172	2020	27-8-2020	5401763618	6-8-2020	21
4444666	3906172	2021	24-2-2021	5401794164	7-1-2021	48

Figure 9: Lead time data subtracted from SAP

2.2.4 Limitations and assumptions of the data

As not all spare parts were registered it was decided that only the completed registered data will be used during this thesis. So it is assumed that the completed registered data give a reflection of all the data of the company.

The following assumptions are made for this data.

- The demand per machine is calculated to divide the total demand by the number of machines where it is used during repairs.
- The complete available data will be used to define demand. There is a lot of incomplete data which is hard to analyze. For example, the spare parts that are not registered. For this data, it is not clear in which machines this part can be used and if it gets an order for the second time.
- The parts can only be used in the machines where it is registered. When a spare part gets a number in the system it also gets linked to the machines which contain this part. The list of machines where a part can be used is not complete because of the lack of administration. But to do calculations it will be assumed that the complete list of machines where a spare part can be used is available.

2.3 Conclusions and summary

Unplanned downtime is caused when a failure occurs, the machine cannot produce anymore and the spare part is not available. Failure data from the ERP system is used to determine the demand for spare parts. This thesis only uses complete data, because the incomplete data is hard to compare.

3 LITERATURE REVIEW

In this chapter, the literature research questions will be answered. For the literature, systematic literature research is done which helps to search for usable articles. The main goal is to find information about spare part policies, ordering systems, and applied distributions. At least information about spare part categorization and failures is given.

3.1 Theoretical framework

For the theoretical framework, systematic literature research is used to answer two knowledge questions. The theoretical research questions will be answered to support the solution design.

3.1.1 Systematic literature research

The literature questions that will help to get an answer to the main question are:

1. Which sorts of inventory policies are available to control spare parts?
2. How can spare parts be classified and what inventory policies fit best?

The used search strings, inclusion and exclusion criteria, and the concept matrix can be found in APPENDIX A – SELECTION OF LITERATURE.

3.1.2 Which sorts of inventory policies are available to control spare parts?

To search for the different policies in spare part control the inventory policies need to be investigated. But it is also important to identify 'spare parts'. Where do they differ from production inventory?

It is possible to compare spare part management with 'normal' inventory management But there are some differences between them. The differences between these types of inventory are (Miranda, Roda, Macchi, & Montera, 2014):

- The spare part management is in most of the cases dependent on the 'function': how are machines utilized and how are they maintained, while the key decision variable remains the same for all the inventories. So it is important to look at the EOQ of the order for spare parts. This is the same for both situations.
- The demand for spare parts is lumpy with a high variable. This makes it less predictable than 'normal' inventory.

3.1.2.1 Inventory models

There are a lot of inventory models. The most used models are given in the following overview. There is a difference between a continuous review and a periodic review will be given. The following list collects the majorly used or cited models (Miranda, Roda, Macchi, & Montera, 2014):

- The continuous review, with fixed reorder point (s) and fixed order quantity (Q), referred to as (s,Q).
- The periodic review, with fixed ordering interval (R), with fixed re-order point (s) and fixed order quantity (Q), referred to as (R,s,Q).
- The periodic review, with fixed ordering interval (R) and order-up-to-level (S), referred to as (R,S).
- The continuous review, with fixed reorder point (s) and order-up-to-level (S), referred to as (s,S).
- The periodic review, with fixed ordering interval (R), with reorder point (s) and order-up-to-level (S), referred to as (R,s,S).
- The continuous review and with order-up-to level (S) in a one-for-one replenishment mode, referred to as (S-1,S). This is the base stock policy.
- The continuous review, with re-order point (s) one or zero policy that resolves the main spare part problem: stock or not.

There are two types of replenishment policies:

- *Continuous review*. The inventory is continuously tracked and an order of lot size Q is placed when the inventory declines to the reorder point (ROP).
- *Periodic review*. The inventory level is checked at a regular periodic interval. The order is placed by order an amount that will reach the order-up-to point.

3.1.2.2 Control parameters and

After analyzing the different sorts of inventory policies the company is currently using the base stock policy (S-1, S). This policy places an order when the stock gets zero. The base stock S is in this example 1. So of $S-1\ =0,$ there will be placed an order of $S=1$. This policy can also be seen as a special case of the well-known (s, S) policy according to (Anbazhagan, Wang, & Gomathi, 2013). Because of the 0 or 1 policy, this system works the same as the (s, Q) system because the standard order quantity will be one.

The control parameter of the policies (s, S) and (s, Q) will be used to give the parameters which will be used for this bachelor assignment.

Policies with a fixed order quantity (Q) and an order op to level (S) have a point where the new order needs to be placed. This is called the reorder point. At this point, a batch of Q quantities is ordered. To determine the reorder point the safety stock needs to be calculated with equation (1). According to (Silver, Pyke, & Thomas, 2017).

$$ss = k * \ \sigma_L \tag{1}$$

Where $k = safety\ factor\ \ L = Lead\ time$ and $\sigma_L = standard\ deviation\ of\ the\ lead\ time$

The ROP is calculated with equation (2):

$$Reorder\ point\ s = ss + \ \hat{x}_L \tag{2}$$

Where $ss = safety\ stock$, $\hat{x}_L = demand\ during\ lead\ time$

The inventory policy with order up to level (S) has also a reorder point (s). At this reorder point there will be another quantity Q which makes to total inventory equal to S. The Order Up to Level (OUL) can be calculated with equation (3) according to (Silver, Pyke, & Thomas, 2017)

$$Order\ up\ to\ level = D * (T + L) + ss \tag{3}$$

Where $D = Demand, L = Lead\ time, T = time\ of\ a\ period$ and $ss = saftety\ stock$

3.1.2.3 Slow-moving demand

For slow-moving demand where an emergency order is placed when no spare part is available will use the Erlang loss probability to determine which fraction of time the server (spare part) is available or not. (Van Houtem & Kranenburg, 2015). For this problem, a certain total cost formula is given. This formula forms the basis for the total cost formula which will be implemented into the model.

The average costs per time unit for SKU i ($C_i(S_i)$ are calculated with equation (4) (Van Houtem & Kranenburg, 2015):

$$C_i(S_i) = \ c_i^h S_i + m_i(1 - \ \beta_i(S_i))c_i^{em} \tag{4}$$

Where

$Holdingcosts\ per\ year = c_i^h$

$Average\ costs\ per\ time\ unit\ for\ SKU\ i = C_i(S_i)$

$Cost\ for\ an\ emergency\ order = c_i^{em}$

$Average\ demand\ per\ year = m_i$

$Fraction\ of\ time\ that\ spare\ part\ is\ not\ available\ with\ order\ up\ to\ level\ S = \beta_i(S_i)$

To determine the costs of the different situations the erlang loss probability will be used. When using this formula the probability of a 'busy' server is calculated. A busy server means in this case that a spare part is not available. The number of servers describes the number of spare parts that are in stock. When a part is not available an emergency order is placed. The Erlang loss system is described as a $M|G|c|c$ queue. In this assignment, the stock level is 0 or 1. So this Erlang loss system has 1 or 0 servers with arrival rate λ (demand per year) and mean service time μ (lead time/days per year). This is corresponding with the fraction of time that there is at least one server available in the Erlang loss system. The arrival rate and service time are given with the variables and are implemented in equation (5):

$Arrival\ rate = m_i$
$Mean\ service\ time = t_i$

$i = Stock\ Keeping\ Unit\ (SKU)\ i$

$$\rho_i = m_i * t_i \tag{5}$$

The arrival rate is the demand for a part. This is calculated per year. The mean service time is given by the number of products that can be bought during the year (when ordering one per time). This is given by $\frac{Lead\ time\ (days)}{Days\ per\ year\ (days)}$

The Erlang loss probability is given with equation (6), where $S_i$is equal to the order-up-to-level. So this will be 1 or zero.

$$\beta_i(S_i) = 1 - \frac{\frac{1}{S_i!}\rho_i^{S_i}}{\sum_{j=0}^{S_i}\frac{1}{j!}\rho_i^j} \tag{6}$$

3.1.3 How can spare parts and machines be classified and what inventory policies fit best?

The control characteristics of the parts (Huiskonen, 2001). :

- *Criticality*: The criticality of the part is related to the consequences of a failure. To determine the critically there is no need to make exact calculations. The criticality must be based on a few degrees. For example, the three degrees: Immediately correctness, tolerated long term. Another aspect of criticality that is not related to the consequences of a failure or shortage but rather to the possibilities to control is called control criticality. The control criticality includes the availability of spare part suppliers, lead times, etc. It is important to know how much time there is to react to the demand need and when it is needed. If the demand is immediately needed a local safety stock is the only way to cover this demand.

- *Specificity*: There are two sorts of parts. Standard parts can be bought at different suppliers. The availability of these parts is usually good. There are also user-specific parts. The supplier is unwilling to stock a lot of them. So these parts are worse available.
- *Demand pattern*: The demand pattern includes the aspects of volume and predictability. Most of the spare parts have a very low and irregular demand. The predictability of demand is related to the failure process of a part and the probability of a failure. The predictability of a part can be divided into two categories: parts with random failure and parts with a predictable wearing pattern.
- *Value of parts*: High value makes it non-attractive to stock a part. If the parts have a high value it is mostly better to put it as far as possible back in the supply chain.

The criticality of a part is specified in high, medium, and low critical parts. High means that in case of a failure the part is immediate and medium means that there is some lead time allowed. Low has been left out of the examination. The criticality and specificity are dichotomous and the demand pattern and value of the parts have a continuous scale. But those continuous scales can also be translated into a discrete expression by making a qualitative discussion.

During the classification of the spare parts from a maintenance viewpoint, the classification criteria: Machine failure, lead times, supplier's reliability and item criticality can be used. These classifications can broadly be divided into two categories: process criticality and control criticality (Antosz & Ratnayake, 2019).

3.1.3.1 Stock keeping possibilities

Alternative options for spare part management for critical high-value parts is to take it not in stock. In this case, other strategies are possible to keep the high service level of the machines. An option is to outsource the spare part by searching for a company which is specialized in spare parts. Another option is to have a cooperative stocking pool with companies that uses the same machines. The part will be more expensive to buy, but in this case, the company does not have stock costs. These options also need to take into account when determining if the part needs to be in stock or not.

For medium critically it is mostly the efficient way to push back all the user's stock backward in the chain to the supplier or service provider. For medium critically parts with a small value it can be better to take them on stock because it has no big influence on the finance and it will take more work to get the parts from an external company (Huiskonen, 2001).

3.1.3.2 Criticality

To calculate the system reliability a Failure Mode, Effect and Criticality Analysis (FMECA) can be used. The FMECA helps to get a systematic view of the system failures, get insight into failure combinations and track down the weak spots (Topan, 2021). A bottom-up analysis will achieve this. So the possible failures need to be described, this is time-consuming but it gives a structured overview. The quality analysis is based on a tree structure where the following things need to be described:

- The function of the component
- Failure mode: description of a fault and characterize the fault
- Possible causes
- Effects: direct or indirect
- Symptoms

The critically can be calculated with: $\alpha_i \times \lambda \times S_i$ where α_i is the failure mode ratio, λ the failure rate and S_i the severity level. The criticality of a machine can be calculated by adding up the criticality.

3.1.3.3 Decision support system

To advise the company that spare parts are needed on the stock there will be a Decision Support System (DSS). This DSS advises on how many products the company needs to take in stock. (Akçall, et al., 2001). The DSS is based on a chosen inventory policy. The inputs for this policy are:

- Unit costs per part
- The volume of de demand is based on historical data. The gamma distribution can help to model the demand.
- Specify the service level

3.2 Summary and conclusion

After analyzing the stock policies, the (S, S-1) policy will be used for the policy. Slow-moving demand uses the Erlang Loss probability to calculate the fraction of time that a part is not available. Spare parts can be categorized on different control characteristics: Criticality, specify, demand pattern, and value of the parts. These characteristics are not directly reflected in the spare parts, but these are applied to the machines. The different machines get a criticality that influences different costs. A decision support system will be created by the use of the model. This decision support system can give useful advice based on calculations. But this model will always need a critical look by an expert.

4 SOLUTION DESIGN

In this chapter, the different input & output variables will be described. The demand distribution will be determined and the expression of the lead time will be explained. The formulas and the calculation of the different costs are described. At least the total costs formula and the system to solve the constraints are given.

4.1 Conceptual model

To create the inventory policy in the form of a decision support system a model is used to implement the variables. This model makes it possible to easily change variables or implement other input data. The concept of this model is described in this section.

4.1.1 The goal of the model

The goal of the model is to minimize the unplanned downtime waiting for a spare part. This waiting time is caused by a part that is not in stock. This can be based on a service level that the company wants to reach or the limited budget that is available for spare parts. The model and the corresponding optimization will look at the best possible solution to keep the costs at low as possible or the service level as high as possible.

The model will work by using the spare part data of a (new) machine. This data needs the description, delivery times, amount in the machine, and unit price.

4.1.2 Input and output variables

The input and output variables are the input and output of the model. The input variables that are used for experimenting will be the limited budget or the service level that ETC wants to reach. Other input variables are used to determine the base input. For example the number of days in a year or the production capacity in a year. The output variables will for example be the costs of the different decisions. The variables can be found in Figure 10.

Input variables	**Output variables**
Maximum budget spare parts	Total costs
Service level	Spare parts to buy
General information	Service level
Spare part price	
Delivery times	
Spare part description	
Production amount	
Category of machine	
Holding costs	
Emergency costs	

Figure 10: Input and output variables

4.1.2.1 Input variables

Maximum budget

The maximum budget is the maximum amount of money that is available to spend on spare parts. This is one of the input variables where the model is used to determine the parts which need to be bought.

Service level

This is the service level that is used to target. This service level gives the service level of the spare parts, not the service level of the machine because a machine can also have downtime that is not caused by waiting for apart. For example when a machine is down for maintenance, and this time is not included). The service level for the experiment in our model will vary between 90 – 99 %.

General information

These input variables can be determined at the beginning of the experiments and do not have to be changed because the users put them in the system as fixed values. For the model, the general information includes the number of days in a year, depreciation period, and the total value of the spare parts (at ETC).

Delivery times

These inputs are the fixed values of the delivery time of the supplier and the processing time of ETC when they receive a package until the moment that the spare part is available. The supplier will give the mean values of the delivery times. The delivery times of the supplier means the time between the order and the receiving in the warehouse of ETC.

Production amount

This input is the number of centrifuges that are produced during the year. This is a fixed value for every experiment.

Category of machine

The machine needs to get a category based on criticality.

Holding costs

The holding costs give the cost when a part is in stock.

Shortage costs

The shortage costs are caused when a part is needed but is not in stock. In that case, the machine is not able to produce anymore.

Emergency costs

The emergency costs are caused when a part is not in stock, but it is needed to repair. In that case, the part needs to be ordered in an emergency.

4.1.2.2 Output variables

Total expected costs

The total expected costs consist of the sum of the holding costs, shortage costs, and emergency costs

Spare parts

The list of parts that needs to be bought for a certain service or the high possible service level with a limited budget. The model will mark the spare parts with the binary system (0 or 1).

Reached service level

This is the service level that is reached with the decision of the different spare parts.

4.1.3 Limitations

When constructing the model it is important to determine the limitations which are applied in the model. These limitations exist in the assumptions and simplifications of the model. Assumptions are used to fill the gap in knowledge (Robinson, 2014). Simplifications help to avoid too complex situations make the model more transparent and improve the development of the model (Robinson, 2014). The following assumptions and simplifications are used:

4.1.3.1 Assumptions

1. The company needs to decide to take spare parts in stock when they bought a new machine. So at the beginning of the period, the decision is made which spare parts need to take in stock.
2. As described in section 2.2.2 the demand is based on the failure rates. Normally the failure rate of a part is changing because of the changing failure mode. For this model, we will assume that the failure mode keeps a constant which gives a constant failure rate.

4.1.3.2 Simplifications

1. It can also be possible that de demand can be one during the lead time of the part. In the real world, this fraction is extremely small because the fraction of time that one part is taken is also very small. So for this simplification, we want to suggest that the demand during the planning period cannot be more than one.

4.2 Data construction

Information about the lead times and the demand is necessary to make those calculations. The results of those determinations will be presented in a dashboard where the machine builder delivers the data about the spare parts. When the data of the machine builder is not available this model will use averages of old data to complete the data.

The use of the old data means that the data from the past estimate demand. For example, the spare parts that are available in the warehouse at this moment will be labeled with a certain category, sensors. These inputs can be used to make an estimation

4.2.1 Demand distribution

For the demand distribution, we want to use the Erlang Loss function which is described in chapter 3.1.2.3. Before this function can be applied it needs to be proved that the demand has a Poisson distribution. After that, the Erlang Loss function will be applied to our problem.

4.2.1.1 Distribution prove

For this model, the assumption of the demand being Poisson distributed must be proven with a statical test. The assumption is made because in most cases a failure occurs randomly and this can be implemented into the Erlang loss function which will be used. Another characteristic of a Poisson distribution is that is memoryless (Axsäter, 2006) This is also the case for parts in a machine because they can also break down after it is replaced recently. To test the Poisson demand assumption distribution we apply the goodness of fit test to test our assumption within a 95% confidential interval. This is tested with equation (7). A sample of spare parts will be used to achieve this. Unfortunately, it is not possible to determine the distribution of all the data because a lot of spare parts it been only used once in the last 10 years. Therefore, we test our assumption only for seven parts for which we have sufficient data. We assume that his assumption holds for the rest. Yet this assumption makes sense because the lower demand shows the given characteristics of the distribution. The demand during the year is divided per moths to get more useful data points.

The number of uses is given in the column ‘count’. After that, the theoretical Poisson distribution with the mean of the historical data is used to determine the cumulative density function (CDF).With the determination of the expected value the comparison with the real data is done.

$$Test\ statiscs\ X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{7}$$

Where $O_i = Observed\ value$ and $E_i = Expected\ value$

Spare part 3906187 will be used to analyze. The values of the mean, count, CDF, PDF, and test statistics are given in Figure 11: Test statistics part 3906187

3906187	Mean (λ)	0,17424		
Bin	**Count**	**CDF**	**PDF**	**TEST**
0	114	110,892	110,8923042	0,08709
1	13	130,214	19,32214392	2,06859
2	5	131,898	1,683368599	6,53454
3	0	131,996	0,097771409	0,09777
4	0	132	0,004258982	0,00426
5	0	132	0,000148419	0,00015
			Sum of errors	8,7924
			Chi-Square test	**11,0705**

Figure 11: Test statistics part 3906187

Since the sum of the errors of the test statistics is smaller than the given value of the Chi-Square test (with a 95% confidence interval). This means that the assumption the demand is Poisson distributed cannot be rejected with a confidence interval of 95%.

For all of the 7 tested spare parts, the poison distribution fits after grouping some bins to get less influence of outliers. One of the spare parts will be shown in this chapter. The other six distributions will be placed in APPENDIX B – DATA, HISTOGRAM, AND TEST STATISTICS. The histogram of spare part 3906187 is shown in Figure 12.

Because all the tested spare parts give the same outcome it is assumed that for all spare parts the Poisson distribution will be used.

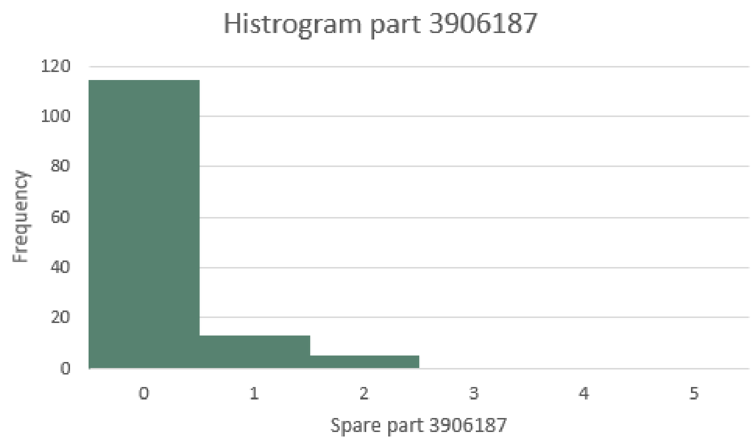

Figure 12: Histogram spare part 3906187

4.2.1.2 Demand probabilities

To determine the costs of the different situations the Erlang loss function will be used. The definition and the characteristics can be found in chapter 3.1.2.3. The Erlang loss probability is given with equation (8), where S_i is equal to the order-up-to-level.

$$\beta_i(S_i) = 1 - \frac{\frac{1}{S_i!}\rho_i^{S_i}}{\sum_{j=0}^{S_i}\frac{1}{j!}\rho_i^j}$$

(8)

Where,

$Arrival\ rate = m_i$
$Mean\ service\ time\ = t_i$

$\rho_i = \ m_i * \ t_i$

(9)

For our model, it means that the order-up-to-level is equal to zero or one. When using these values the formula will be simplified. The calculation of $S_i = 0$ can be seen in equation (10).

$$\beta_i(0) = 0$$

(10)

This means that the servers are always occupied. This is a logical conclusion because in the case of zero stock there will be no servers at all. So every arrival at the system will always transform into a lost sale. This lost sale gives extra costs because of the shortage of this product and the extra costs that need to be made to order the product.

The situation where one server is available is given in equation (11).

$$\beta_i(1) = 1 - \frac{\rho_i}{1 + \rho_i}$$

(11)

Because it is important that we can estimate the fraction that a zero server system gets a request. The assumption for this model will be made that the fraction of time that a zero server system gets a request will be the same as the fraction of time that one server system gets a request.

4.2.2 Lead time

The lead time is already explained in section 1.2.1. For the model, the delivery times of the supplier must be known. The procurement time will be equal to zero in our model because in the case that a part needs to be ordered caused by a failure it will always get an emergency order. To calculate the lead times of the different spare parts equation(12) is used.

$$Lead\ time\ (days) = \ delivery\ time\ (days) + procurement\ time\ (days)$$

(12)

The lead time and the demand are independent variables. So if the demand is low it will automatically not mean that the lead time is high. So if the lead time is given by the supplier it does not influence the demand that is determined by the categorization. The demand and the corresponding lead times are noted in a scatterplot in Figure 13. The data points in the scatterplot correspond with the different spare parts.

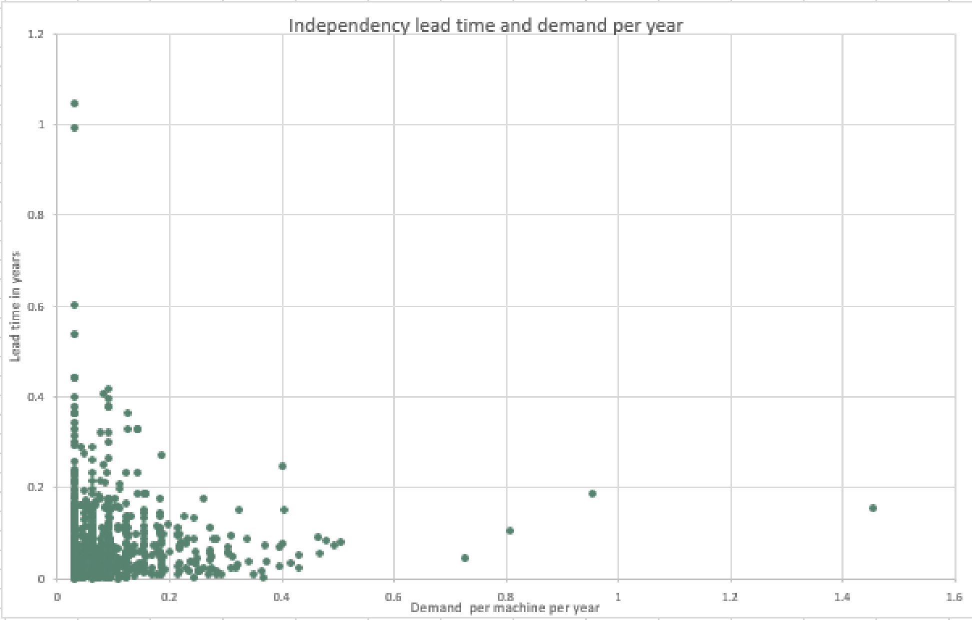

Figure 13: Scatterplot independency demand & lead time

4.2.3 Holding costs

Holding costs consist of the sum of occupancy costs, opportunity costs, and depreciation costs. These costs are caused when a part is in stock. These are yearly costs. When a part arrives the part needs to be stored in the warehouse with a certain risk that it broke down and get useless. Another opinion is that the money that is invested in spare parts cannot be spent on other projects. For example, a new machine cannot be bought when an expensive spare part is bought to keep in stock. The holding costs are calculated with equation (13).

$$Holding\ costs\ per\ year\ c_i^h\ (\%) = Occupancy\ costs\ (\%) + Opportunity\ costs\ (\%) + Depreciation\ costs\ (\%)$$

(13)

4.2.3.1 Occupancy costs

The occupancy costs consist of the warehouse costs. To determine a percentage the total value of the spare parts needs to be known. The occupancy costs are calculated with equation (14).

$$Occupancy\ costs (\%) = \frac{Warehouse\ costs}{Total\ value\ of\ spare\ parts}$$

(14)

4.2.3.2 Opportunity costs

The opportunity costs exist of the costs that are based on the possible profit that can be made with the amount of money. On one side the interest rate of the banks influences these costs. On the other side, the revenues of other investments cannot be done anymore. The opportunity costs are calculated with equation (15).

$$Opportunity\ costs = Return\ on\ not\ chosen\ option - Return\ on\ chosen\ option$$

(15)

4.2.3.3 Depreciation costs

The depreciation costs are the costs that give the actual decrease of the value of the spare parts. The finance department is depreciating the machines in a specific amount of years. The depreciation costs are calculated in equation (16).

$$Depreciation\ costs\ (\%) = \frac{100\%}{Year\ of\ depreciation} \tag{16}$$

4.2.4 Emergency costs

When a part is not available there are emergency costs. In this model, the emergency costs consist of two parts: shortage costs and rush order costs. The shortage costs are caused when a machine is down and can not produce anymore. The rush order costs are made because a fast order is placed. The emergency is calculated in equation (17).

$$Emergency\ costs\ c_i^{em}(j)\ = Shortage\ costs\ + Rush\ order\ cost \tag{17}$$

Where $j = criticality\ of\ the\ machine\ for\ 1, 2\ and\ 3$

In the model the distinction between three sorts of criticality will be used:

- *Category 1*: Alternative production facility not available. When the machine is down it is not possible to produce any more
- *Category 2*: Alternative production facility available after modifications
- *Category 3*: Alternative production facility available. When a machine is down, but another machine can produce the same product without any time-consuming modifications or new needed qualifications

4.3 Implementing model

In this section, the implementations of the different variables will be described.

4.3.1 Demand

For the model, the average demand for the spare parts will be used. The demand will reflect the failure rate of a part because when a part broke down it needs to be replaced by another part. In that situation, the demand will get one. So the failure rate is in our situation the same as the demand frequency. It will be explained how the demand per spare part is gathered and which categories are created for determining the average demand per category.

4.3.1.1 Processing data for categories

The demand per category needs to be determined. First, the demand per spare part needs to be known. Chapter 2.2.2 it is described how the data is subtracted from the ERP stem. It was only possible to analyze the parts with an article number because for single-bought spare parts the description was not clear enough to categorize it structurally. In that case, every single part needs to be analyzed which is too time-consuming for this research.

After that, the maintenance data with a linked article number is used for determining the demand. This link means that a spare part was used during the repair. For determining the demand the data of corrective and preventive maintenance is included. The decision is based on the following situations:

- When a part is replaced during preventive maintenance it could be the case that the part was already broken but has not caused a failure. If the maintenance was planned on another date the part was replaced during corrective maintenance. So if the preventive maintenance is not included in the demand data the demand will be unreal.

- If a part gets replaced during preventive maintenance and it is not included in the data of the demand then it will cause a wrong interpretation of the demand. Figure 14 shows the influence of not registering a part during predictive maintenance. In that case, the mean time between failures gets higher and the demand during this period gets two instead of three. Because the demand determination of the model needs to be as accurate as possible the predictive maintenance data will also be included.

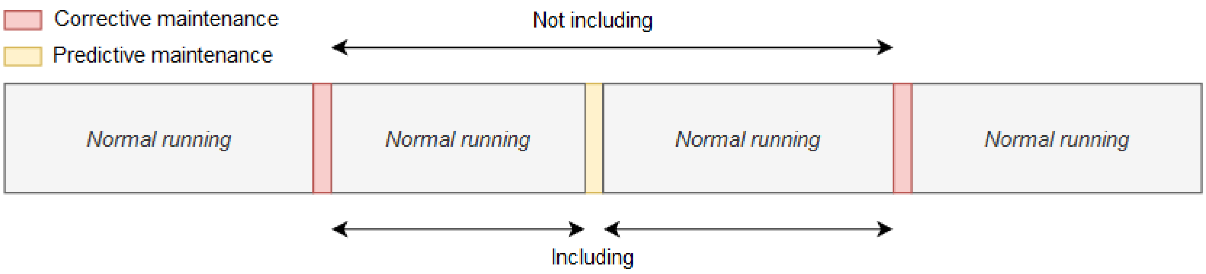

Figure 14: Spare part replacement

The demand for the different spare parts is correlated to the number of products that ETC produced because in the first years the demand for spare parts is higher than in the last year. See Figure 15 for the visualization. Around 2011 they produced 142.976 products per year, after the downscaling they only produced 4.085 products per year. Logical there were fewer machines needed and fewer machines means fewer failures. But another problem occurs on the existing machines. Those machines were developed and designed to produce at a constant rate with an almost constant amount of products. It is possible to fluctuate within this range, but when it drops with a high amount the machine will not be able to produce like its specification. For that reason, machines get issues that they did not have. Because the company decided to produce in batches the machine will get more planned downtime. During this downtime, the machine will not run and caused problems like bad bearings and lubrication problems.

Part/Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
3906173	11	16	19	11	18	10	5	4	6	2	4
3900672	3	14	19	26	8	8	1	4	1	1	0
3906172	3	7	9	6	5	5	3	4	0	5	2
3903251	11	11	8	6	2	0	0	1	0	1	1
3906138	5	11	13	5	2	0	0	2	0	1	0

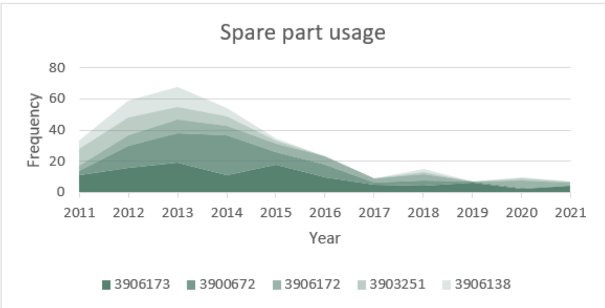

Figure 15: Decreasing of the demand over time

To compare the demand values of the different production amounts there is a need for a value that makes it relative. The years are categorized into two groups with different production capacities. The spare part demand at the years that the production was at his max, so the production of 142.976 products and the groups where the production is at its current level 4.085 products. To determine the relative values the total budget of the planned and unplanned is used.

Year	Production	Production ratio	Total maintenance costs	Costs ratio
2013	142.976	35	20,14 mil	2.9
2020	4.085	1	6,94 mil	1

Figure 16: Relative ratios different demands over time

So the demand during the years, 2011, 2012, 2013, and 2014 will be divided by 2.9 to compare this data with the years 2015 to 2021. This ratio is based on the total maintenance cost in the different years. It can be seen that the maintenance costs are not linear to the number of products. This is caused by the fact that the standard maintenance keeps the same.

After the relative factor has been put in the formula the average demand per year per machine is calculated in equation (18).

$$AVGD_i \; (per\ machine\ per\ year) = \frac{\frac{(D_{2011} + D_{2012} + D_{2013} + D_{2014})}{2,9} + D_{2015} + D_{2016} + D_{2017} + D_{2018} + D_{2019} + D_{2020} + D_{2021}}{M * 11}$$

(18)

Where:

$AVGD_i = Average\ demand\ per\ machine\ per\ year\ for\ spare\ part\ i$

$D_{yyyy} = Total\ demand\ of\ spare\ part\ during\ year\ YYYY$

$M = Total\ amount\ of\ machines\ where\ spare\ part\ i\ is\ used\ during\ the\ years$

4.3.1.2 Categorization

The demand of the parts is determined based on the demand which is calculated per category. In collaboration with the maintenance department, the categories are given to the parts which are given by the supplier of the new machine. This is one of the steps that ETC needs to take by hand in the future to use the model again in another situation. If a part is more than once available the machine needs to be counted. The demand is calculated in equation (19).

$$Total\ demand\ part\ X = demand\ per\ part * parts\ in\ machine$$

(19)

In consultation of the maintenance depart the following main groups are created:

1. Electronic components
2. Mechanical components
3. Pneumatic and hydraulic components
4. Vacuum components
5. Heating and cooling components
6. Laser equipment
7. Oil/soda/liquids
8. Production tooling

After that, the subgroups are created within these main groups. All of the registered spare parts were given one of the created labels. Those labels are used to combine the data that contains almost the same components. The complete list of subgroups can be found in APPENDIX C - CATEGORIZATION SPARE PARTS. These sub-groups correspond with an average demand that is used in the model.

After sorting the data per subgroup it was seen that some subgroups have fewer data points. For some subgroups, it is necessary to group the data because of the lack of data points. If a category has more data points the mean demand will be more accurate. The disadvantage of the grouping of these parts is that the demand determination will be less specific for that kind of part in comparison with a specific subcategory. The subgroups that had fewer data points and are grouped with other groups are:

- Safety parts (grouped with the other category)
- Time chain (grouped with timing belt)
- Gear (grouped with the other category)
- Overig electrical components (grouped with small electric components)

In some cases, it is not possible to combine the data because the spare part is too specific. When grouping this kind of data it will give too much difference between the real and category data. An example of a part where it is not possible to group it is the 'spindle' and all the vacuum parts.

Simplifications for data

The parts are divided equally over the machines where it was used for the last 11 years. The data get too complicated for the model if the number of parts in a specific machine was included. For example, it can be possible that a part was used 12 times in the last 11 years. One time in machine 1, two times in machine 2, and nine times in machine 3. Our determination of demand will give an average demand of four parts per machine.

4.3.2 Lead time

The lead times are directly derived from the supplier. The procurement time is determined on 1 day in consultation with the maintenance controller so the lead time is calculated with equation (20).

$$Lead\ time\ (days) = \ delivery\ time\ (days) + 2 \tag{20}$$

As already described in all the parts will be seen as parts that need to be ordered when a machine is completely not working. When the machine is down this will lead to big losses and a negative influence on the production planning. The assumption is made that orders will always be placed by emergency order.

As described in chapter 2.2.4 the time between the observation of a failure and the order of the needed part cannot be measured with the available data. So the assumption will be made that the time between the observation and the order is equal to zero.

4.3.3 Holding costs

As described in chapter 4.2.3 the holding costs can be calculated with equation (13). This equation exists of three different parts. These parts are explained in the following sections.(4.3.3.1 & 4.3.3.2 & 4.3.3.3)

4.3.3.1 Occupancy costs

Most of the spare parts are kept in a paternoster. This is a stock-keeping machine which makes it possible to store a lot of spare parts in a small area. Because of this small area, the electricity and square meter costs are negligible. Some parts are too big to store in the paternoster, for these parts, there is a small warehouse at the company. For this case, the assumption is used that the parts that are kept in the paternoster have the same costs per part if it is compared with the parts from the warehouse. The company has three paternosters and 1 warehouse. The total cost will be seen as the cost to have four paternosters. For that case, the occupancy costs per year will be based on the buying price and the maintenance costs during the deprecation period. The occupancy costs are calculated with equation (21) and are described in Figure 17. The deprecation will be explained in chapter 4.2.3.3.

$$Occupancy\ costs(\%) = \frac{Warehouse\ costs}{Total\ value\ of\ spare\ parts}$$

(21)

Occupancy costs	
Costs of paternoster	€ 118.598,76
Maintenance cost per year per paternoster	€ 37.452,24
Depreciation period	10 years
Total costs per year	€ 156.051,-
Total value of spare parts	€ 6.001.962,-
Occupancy costs (% p/y))	2,6%

Figure 17: Occupancy costs

4.3.3.2 Opportunity costs

The interest rate is at the moment 0,01% [1] the potential revenue is determined at 2% because the money can also be invested in other machines, this 4,5% reflects the revenue of these investments. This is determined in consultation with the finance department. The opportunity costs can be calculated with the following formula. The opportunity costs are calculated with equation (22) and are described in Figure 18.

$$Opportunity\ costs = Return\ on\ not\ chosen\ option - Return\ on\ chosen\ option$$

(22)

Opportunity costs	
Interest rate (% p/y)	0,01 % (100,01% - 100% = 0.01%)
Potential revenue (% p/y)	4,5%
Opportunity costs (% p/y))	4.51 %

Figure 18: Opportunity costs

4.3.3.3 Depreciation costs

The depreciation costs are the costs that give the actual decrease of the value of the spare parts. The finance department is depreciating the machines in 10 years. Because of the assumption that the parts can only be used for a specific machine the value of the parts will also be depreciated within 10 years. The depreciation costs are calculated with equation (23) and are described in Figure 19.

$$Depreciation\ costs\ (\%) = \frac{100\%}{Year\ of\ depreciation}$$

(23)

Depreciation costs	
Value when buying a product	100%
Value at the end of the depreciation	0%
Depreciation period	10 years
Depreciations costs (% p/y)	10 %

Figure 19: Depreciation costs

[1] https://www.rabobank.nl/particulieren/sparen/alles-over-rente/actuele-rentes

4.3.3.4 Total holding costs

The total holding costs per year c_i^h are calculated with the equation (24). The following percentage is based on the value of the spare part.

$$Holding\ costs\ c_i^h\ (\%) = 2{,}6\% + 4{,}51\% + 10\% = 15{,}11\%$$

(24)

4.3.4 Emergency costs

Emergency costs are not always the same because not every machine has the same criticality in the production process. The machine that is down is crucial for the whole production process. But not every machine is crucial in the production process, it can also be possible to use another machine to make the product. The machines can be categorized into three divisions. If ETC uses this model to determine the parts that must be bought, the indispensability needs to be determined. The categorization of (Huiskonen, 2001) is used to create the categories.

4.3.4.1 Category 1: Alternative production facility not available

Category 1 means that the machine is unique and is necessary for the production process. When the machine is down it is not possible to produce anymore. So the shortage costs will be 100% of the possible shortage costs. The Emergency costs are calculated with equation (25).

$$Emergency\ costs\ c_i^{em}(1) = Lead\ time * Profit\ per\ day +\ rush\ order\ cost\ (ROC_i)$$

(25)

Where

$ROC_i = rush\ order\ cost\ with\ \ ROC_i =$ €144,21 if $u_i <$ €144,21 $ROC_i = c_i^{em} *\ u_i$ if $u_i \geq$ €144,21

$$u_i = unit\ price\ spare\ part$$

The shortage costs for ETC are based on the revenues that are missed during the period that a machine is not able to produce (during the total lead time). The shortage costs can be seen in Figure 20. The shortage costs are related to the time that a machine is not able to produce. In this assignment, this is caused by the fact that the part is not available in stock. Because of the emergency order, the time of the purchase process can be removed because the purchase process will be done during the lead time. So the profit per day is calculated with the formula (26).

$$Profit\ per\ day = \frac{production\ amount * margin\ per\ product}{360}$$

(26)

Shortage costs	
Production amount (products per year)	7821 products
Margin per product	€ 1.534,33
Profit per day (euros per day) = c_i^{sh}	€ 33.333,33

Figure 20: Shortage costs

The margin per product cannot be given exactly because of the ‘need-to-know’ policy of ETC. But in consultation with the finance department, an estimate is made which is close to the actual value. This actual value is hard to determine because ETC also gets revenues if the machines are working at the site of the customers. Since these machines will work for 20 years the influence in margin can be calculated with a lot of factors, but this estimate will give shortage costs which are useful for this model.

The rush order costs start at €144,21because a courier needs to pick up the part and bring it directly to ETC. It makes no difference if the part is €10 or €100 because the driver still makes the same costs. If the part gets more expensive (and more unique) the emergency costs will be higher because the factory must set up their machines, especially for ETC. In consultation with the finance department, the emergency costs are set at 20% of the value of the part. So if the part is more expensive than €750 the formula $0,2 * u_i$ will be used, otherwise, the rush order costs are €150

The emergency costs of category 1 are given in equation (27) or (28):

$$Emergency\ costs\ c_i^{em}(1) = LT * €\ 33.477,54\ if\ u_i < €750 \quad (27)$$

$$and\ \ Emergency\ costs\ c_i^{em}(1) = LT * €\ 33.333,33\ + 0,2 *\ u_i\ if\ u_i \geq\ €750 \quad (28)$$

4.3.4.2 Category 2: Alternative production facility available after modifications

Category 2 means that a machine is down, but another machine can do the same work after some modifications. This will take some time, material, and labor costs. In consultation with the maintenance engineer, it is determined that takes 21 days to make a machine operational. This is caused because the machine needs a quality qualification before it can produce a certain product. These strict protocols are caused by the accuracy of the products that are needed to build the centrifuge, a very small deviation can have big effects on the final product. It is for the company only useful to do modifications if the lead time if for at least 28 days, otherwise, it is not worth it investments of time and labor.

For part with LT <, 28 days equation (29) *is used,*

$$Emergency\ costs\ c_i^{em}(2) =\ Emergency\ costs\ c_i^{em}(1) \quad (29)$$

For parts with a LT > 28 days. (Take LT = 21) equation (30) or (31) is used.

$$Emergency\ costs\ c_i^{em}(2) = €\ 700.144,14\ if\ u_i < \ €750 \quad (30)$$

$$and\ \ Emergency\ costs\ c_i^{em}(2) = €\ 699.999,93\ + 0,2 *\ u_i\ if\ u_i \geq\ €750 \quad (31)$$

4.3.4.3 Category 3: Alternative production facility available

Category 3 means that a machine is down, but another machine can produce the same product without any time-consuming modifications or new needed qualifications. For example, the winding machines can produce two different sizes of centrifuges. This machine has the qualification to produce both, so in case one of the machines fails and needs a spare part with a long lead time the factory can easily adjust the machines to produce the other side of the centrifuge. Because of the small changes, it takes on average 1 day to make the machine ready to produce the other product. For these costs equations (32) or (33) are used.

$$Emergency\ costs\ c_i^{em}(3) = €\ 33.477,54\ if\ u_i < \ €750 \quad (32)$$

$$and\ \ Emergency\ costs\ c_i^{em}(3) = €\ 33.333,33\ + 0,2 *\ u_i\ if\ u_i \geq\ €750 \quad (33)$$

4.3.5 Total costs of inventory

The original total cost model has described the costs with a simple formula that is described in chapter 3.1.2.

The average costs per time unit for SKU i $C_i(S_i)$ are given in equation (34):

$$C_i(S_i) = c_i^h S_i + m_i(1 - \beta_i(S_i))c_i^{em} \tag{34}$$

The new total costs model contains a percentage of the holding costs, so this needs to be multiplied by the price of a spare part. The emergency costs depend on the criticality of the machine. The three different sorts are explained in chapter 4.2.3. The new total costs formula is given in equation (35):

$$C_i^*(S_i) = u_i c_i^h S_i + m_i(1 - \beta_i(S_i))c_i^{em}(j) \tag{35}$$

Where

$$c_i^{em}(j) \; depends\ on\ the\ criticality\ of\ a\ machine$$

Assumptions:

Since the shipping costs, handling costs, and ordering costs keep the same per product they will not be implemented in the model. These costs will be the same for regular orders and rush orders.

4.3.6 Optimization

The decision of the spare parts is based on the variables that are described in chapter 1.2.3. This solver looks for the best possible combination of spare parts to meet the given variables.

The solver works in this model as the '0-1 knapsack-model'. The knapsack model describes a model where a sum of products needs to be minimized or maximized by looking for the best possible combination of the different products. In our model, it will for example look at the cheapest combinations of spare parts to achieve the targeted service level.

The (non-)linear problems that need to be solved:

The company has a limited budget and wants to reach less amount of yearly costs. This is given in equation (36).

$$\begin{gathered} Min\ z = \sum_{i=1}^{n} C_i^*(S_i) \\ s.t.\ \sum_{i=1}^{n} S_i * u_i \le b \\ S_i = 0\ or\ 1\ (i = 1, 2 \dots, n)\ where\ n\ is\ the\ total\ amount\ of\ spare\ parts \\ b = maximum\ budget\ for\ spare\ parts \end{gathered} \tag{36}$$

The company wants to reach a certain service level with the lowest value of spare parts in stock. This is given in equation (37)

$$Min\ z = \sum_{i=1}^{n} S_i * u_i$$

$$s.t.\ \prod_{i=1}^{n} S_i + (1 - S_i) * \beta_i(1)\ \geq sl$$

$$S_i = 0\ or\ 1\ (i = 1, 2 \ldots, n)\ where\ n\ is\ the\ total\ amount\ of\ spare\ parts$$

$$sl = service\ level\ that\ need\ to\ be\ reach\ at\ least$$

(37)

The first problem is linear, the second one is a non-linear problem. So the first problem will give an exact answer in determining the optimal level. The second problem will search for the best option within a maximum amount of time.

4.4 Summary and conclusions

The conceptual model describes the variables that are needed for the model. The used budget, total costs, service level, and a list of spare part will be output. The demand is Poisson distributed which means that failures appear randomly. The Erlang Loss function is used to determine the fraction of time that a part is not available. The demand is based on the failure data. The lead time is given by the supplier.

The total holding costs are 15,11% and the emergency costs depend on the criticality of the machine.

The solutions can be found by optimizing the model. This optimization is based on the variables ‘service level’ and ‘available budget’.

5 SOLUTION TEST

In this chapter, the model will be used to search for a new inventory policy for a cleaning machine. The base model will be given and the differences between the old strategy and the advised strategy are given.

5.1 Base model

The spare parts of a new aluminum cleaning machine are used to analyze the model. For this model, the spare parts are implemented into the model and the calculations are made. The maintenance engineer already decided which spare parts will be placed in stock. The analysis will be made between the estimated yearly costs and the available budget and the service level that would be reached with the same budget. With the other constraint, there will be the comparison between the service level that is reached with the spare parts that have been bought and the budget that was necessary to reach these same values.

The data spare part data from the aluminum cleaning is implemented into the model. The results depend on this data.

5.1.1 Minimize the yearly costs

The optimization to minimize the yearly costs which exist of the costs that are explained in sections 4.3.3, 4.3.4, and 4.3.5. This gives an insight that the total costs of spare parts are decreased fast when de budget gets relativity a little bit higher. This is caused because cheaper parts can have a big influence on the availability of the machine. It can also be seen that an optimal budget is reached. After this point, it is not reliable anymore to take more spare parts in stock, because the yearly holding costs will be higher than the expected emergency costs. The optimal solutions can be seen in Figure 21.

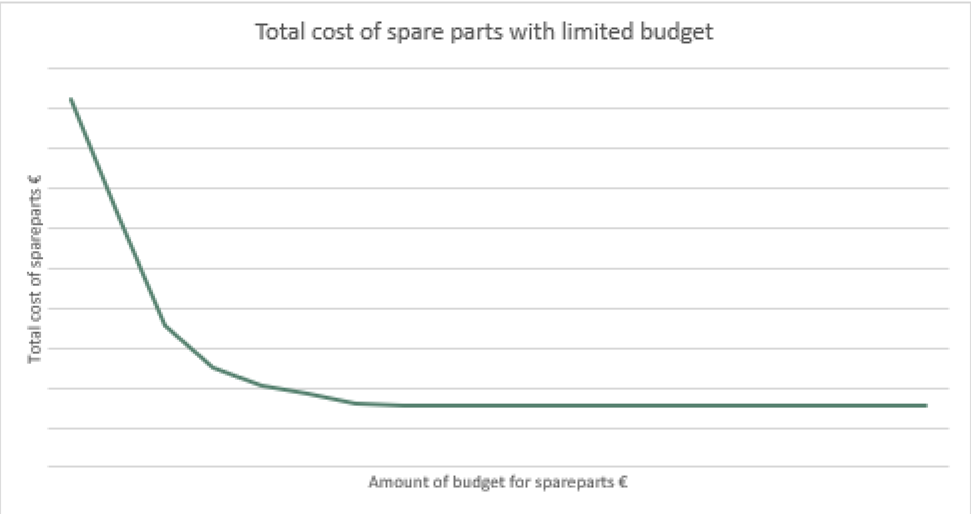

Figure 21: Minimize total year cost with a limited spare part budget.

5.1.2 Minimize budget to reach service level

The optimization to reach a service level search for the cheapest combination of spare parts to get the wanted service level. This solution is found to compare the different solutions with each other and search within a limited time to the best one. It can be seen that the budget does not have to be large to achieve a relatively low service level. The last steps increase the service level from 98% to 99% need more extra budget in compering with the step from 90% to 91%. The optimal solutions of this minimization can be seen in Figure 22.

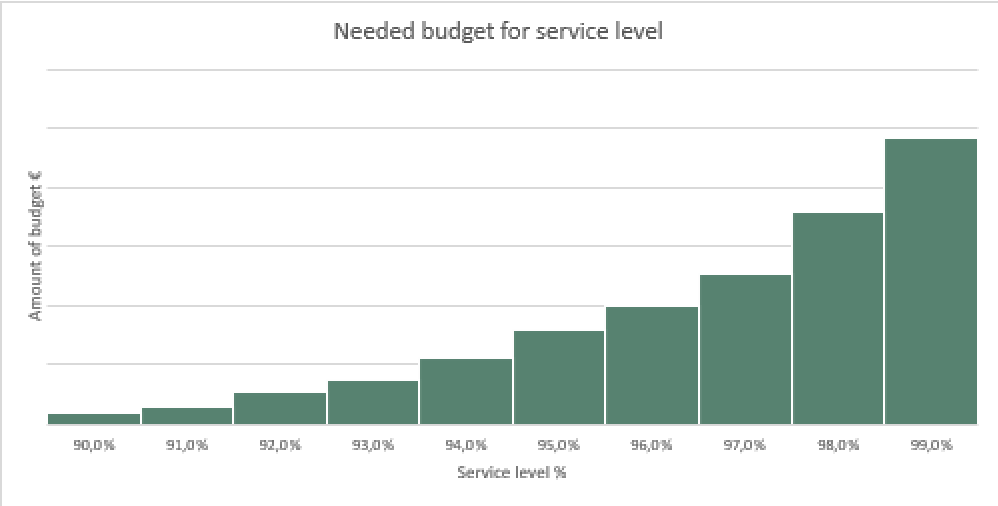

Figure 22: Minimize buying costs with minimal service levels

5.2 Optimize spare part strategy

The company wants to know the optimal strategy for buying spare parts to avoid unplanned waiting times. The best solution will be to take all the spare parts in stock. In that case, the service level will be 100%. This is not possible for the current situation because ETC needs to look at cost-saving measurements.

The available budget or the wanted service level will differ for every machine, for that reason it is not possible to give 'one' general optimal solution for all the situations. The product of this thesis is not the solution itself, but the decision support system that will help to come to the optimal solution. The aluminum cleaning machine will be used to show the working of the system.

The model needs input for the budget constraint and the service level constraint to come to an optimal solution. To make the outcomes comparable with the current situation the list of spare parts that are bought by the maintenance engineer is used. This list exists of the 'first service package', which is advised by the supplier, and some additional spare parts. From here we will call this group of spare parts the 'first service package'

The total list of the spare parts gets put into the model and it is noted down which spare parts a bought according to the 'first service package'. This gives the following output:

- Reached service level = 90,48%
- Used budget = €9.402,40
- Total expected costs per year = €27.883,04

To optimize the spare part strategy the 'used budget' is used to minimize the costs and service level is used to search for the minimum amount of budget to reach the same service level. The outcomes of these optimizations can be seen in Figure 23.

	First service pack	Budget based	Service level based	Differences BB	Differences SLB
Reached service level	90,48%	93,81%	90,97%	3,68%	
Used budget	€ 9.402,40	€ 9.402,40	€ 2.126,82		-77,38%
Total expected costs per year	€ 27.883,04	€ 10.799,10	€ 24.880,04	-61,27%	-10,77%

Figure 23: Spare part control – Aluminum cleaning machine

The differences between the increased service level and the decreased costs are mostly caused by the fact that the 'first service level package' also exists of spare parts that have a total lead time of 3 days.

The model will in this case advise investing the budget in other spare parts because the potential emergency costs are relatively small in comparison to spare parts with a lead time of 14 days.

With the same budget, an service level of 93,81% can be reached. This is an increase of $\frac{93,81-90,48}{90,48} * 100 = 3,68\%$. The total expected cost will be €10.799,10. This is a difference of $\frac{10.799,10-27.883,04}{27.883,04} * 100 = -61,27\%$. So another set of spare parts gives with a lower budget gives a higher service level. These calculations can also be found in Figure 23

Another output of the model is the list of spare parts that are advised to take in stock. The total list of spare parts with the 'first service pack', budget-based and service level based can be seen in Figure 24

Spare parts	First service package	Budget based	Service level based
Part A	1	1	1
Part B	1	0	0
Part C	0	1	0
Part D	0	1	1
Part E	0	0	0
Part F	0	0	0
Part G	0	0	0
Part H	0	0	0
Part I	0	0	0
Part J	0	0	0
Part K	0	0	0
Part L	0	0	0
Part M	0	0	0
Part O	0	0	0
Part P	1	0	0
Part Q	1	0	0
Part R	1	0	0
Part S	0	0	0
Part T	0	0	0
Part U	0	0	0
Part V	0	0	0
Part W	1	1	1
Part X	0	1	1
Part Y	1	0	0
Part Z	0	1	1
Part AA	1	0	0
Part AB	0	1	1
Part AC	1	0	0
Part AD	1	1	0
Part AE	0	0	0
Part AF	0	0	0
Part AG	0	0	0
Part AH	0	0	0
Part AI	0	1	0
Part AJ	0	1	0
Part AK	0	0	0
Part AL	0	0	0
Part AM	0	1	1
Part AN	0	1	1
Part AO	0	0	0
Part AP	1	0	0
Part AQ	1	1	1
Part AR	1	0	1
Part AS	0	1	0
Part AT	1	0	0
Part AU	1	0	0

Figure 24: Comparison of spare parts on stock for different constraints

So if the company decided to take different parts in stock the service level will increase with the same amount of budget. The model makes it also possible to choose a service level that it wanted to reach. In that case, it is also possible to search for the cheapest combination of spare parts to reach this service level.

5.2.1 Sensitivity analysis

The sensitivity analysis shows the influence of the changes that are made in the model. To show this the influence of the different experiments that are used to find the optimal solution. For this sensitivity analysis, the demand and the holding costs are changed to look at the influence of the total costs, used budget, and service level.

5.2.1.1 Total costs

When the holding costs are doubled the costs only differ at the and the of the available budget because the influence is in that stadium the highest. The total costs for the doubled demand are at the beginning very high because the shortage costs become much higher. The influence for the total costs can be seen in Figure 25: Sensitivity analysis total costs

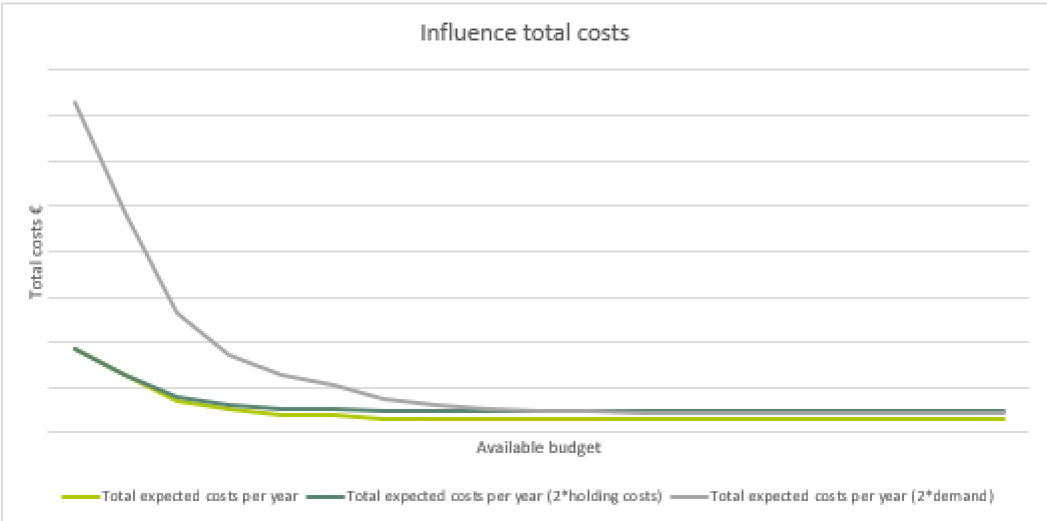

Figure 25: Sensitivity analysis total costs

5.2.1.2 Used budget

When the costs of the demand are doubled there will be used more budget. For some parts, the expected shortage costs become cheaper than the expected holding costs. So at a certain level no more parts will be placed in stock while the budget is still available. The influence of the used budget can be seen in Figure 26: Sensitivity analysis used budget

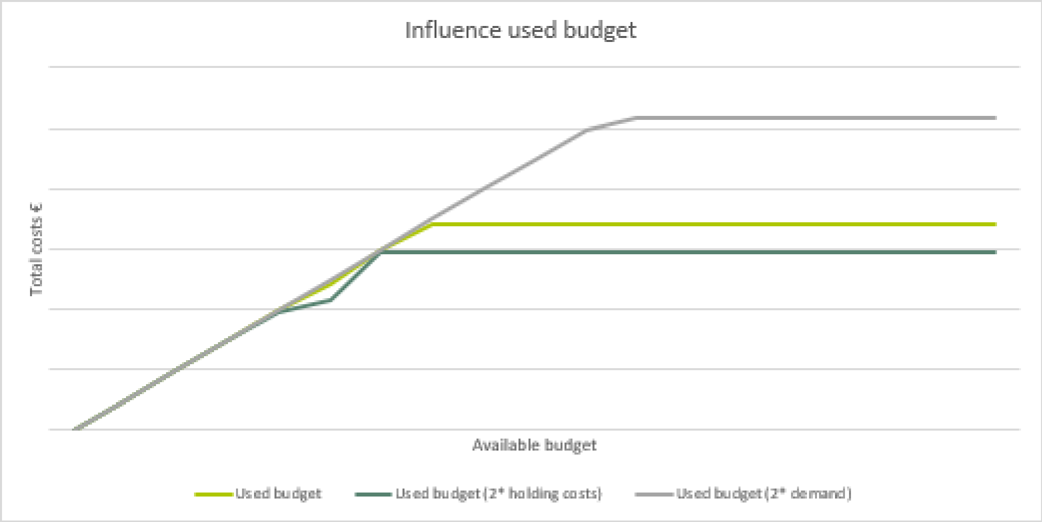

Figure 26: Sensitivity analysis used budget

5.2.1.3 Influence service level

The service level of the spare parts is mostly influenced by the demand. So when the demand is doubled it will have a lot of influence on the service when the budget is very small. The influence of the service level can be seen in Figure 27: Sensitivity analysis service level.

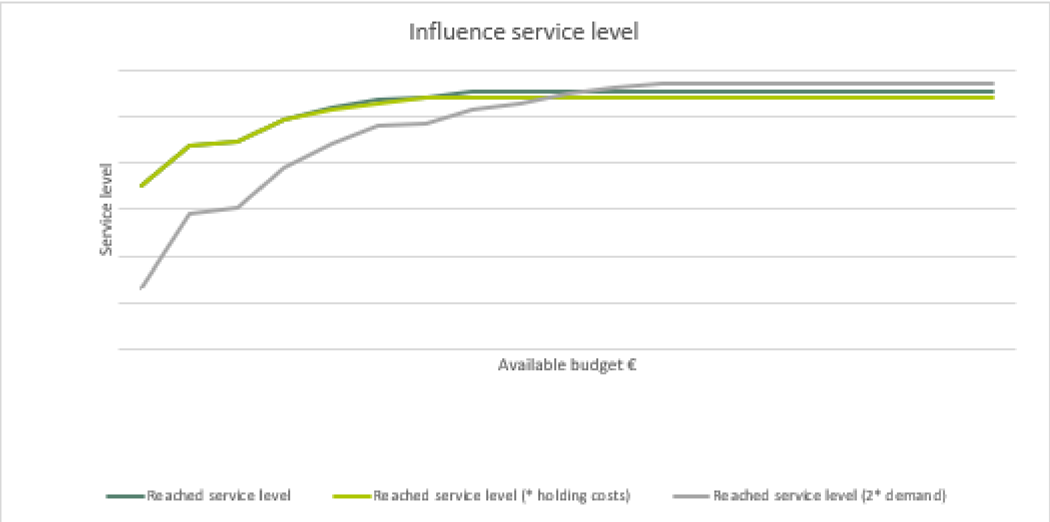

Figure 27: Sensitivity analysis service level

5.2.2 Validation and verification

It is important to look at the validation of the data because the model must use a calculation that reflects the real world.

Section 4.2.1 is already showed that the demand distribution can be seen as a Poisson distribution. Analyzing the data can be proved because the characteristics of a Poisson process are also shown in the data. The lead time can also be validated because it is given by the supplier of the machine. For this model, it is assumed that the lead time is a constant value. This is also explained in section 4.2.2.

In section 5.2.1, it is also shown that the data follows logic patterns. When the demand gets doubled, the expected shortage costs will also be much higher because it is expected that the probability of failure where the part needs to be replaced is higher.

Unfortunately, it is not possible to use old spare part data to validate the outcomes of the system. This is caused by the fact that there is no complete data about the spare part. There is no data available about the spare parts where the decision was made to not take it in stock. So it will not be possible to use the model on an older machine. It is also not possible to get the data from the machine manufacturers because they do not have the right data available.

Because the input data has been validated the right way in consultation with a lot of members of the company (security manager, finance department, maintenance manager, production manager, and mechanics), it is assumed that the outcome data gives values that make it possible to compare different spare part management strategies.

The outcomes of the optimization are compared with the first service package and are given to the maintenance engineer. He looked at the list of spare parts that are advised to take in stock and some remarks are placed. For some spare parts, the model is suggesting to take these parts, not in stock, but the experience of the maintenance engineer determines that the part can be broken down and causes unplanned downtime. This is the reason that it is not a solution but a decision support system. The outcome can be used to convince the board about the budget that needs to be used for spare parts management to reach a certain service level. It is not possible to implement the experience of an employee into the system, but it can help him to make better-substantiated choices.

5.3 Summary and conclusion

The base model shows budget will have an optimum because the total costs will not decrease to zero. And the model shows that the last percentages of service level provide more budget than the first percentages.

The optimization of the spare parts shows an increase of $3{,}68\%$ in service level if the same budget is spent differently. The total expected costs will differ by $-61{,}27\%$.

The sensitivity analysis is part of the validation of the results. The results are also validated by the maintenance engineer. Differences are available because of experience and knowledge.

Models describe a policy that supports the purchaser and the maintenance engineer. It is not replacing them.

6 VISUALIZATION SOLUTION

This chapter shows the visual part of the solution. This dashboard helps ETC to easily implement the spare part data and change cost influencing values.

6.1 Dashboard guide

The model that is created is visualized into a dashboard. This dashboard can be seen in Figure 28. This dashboard gives the possibility to easily change costs, productions amounts, etc. which are influencing the outcomes and the decision support system.

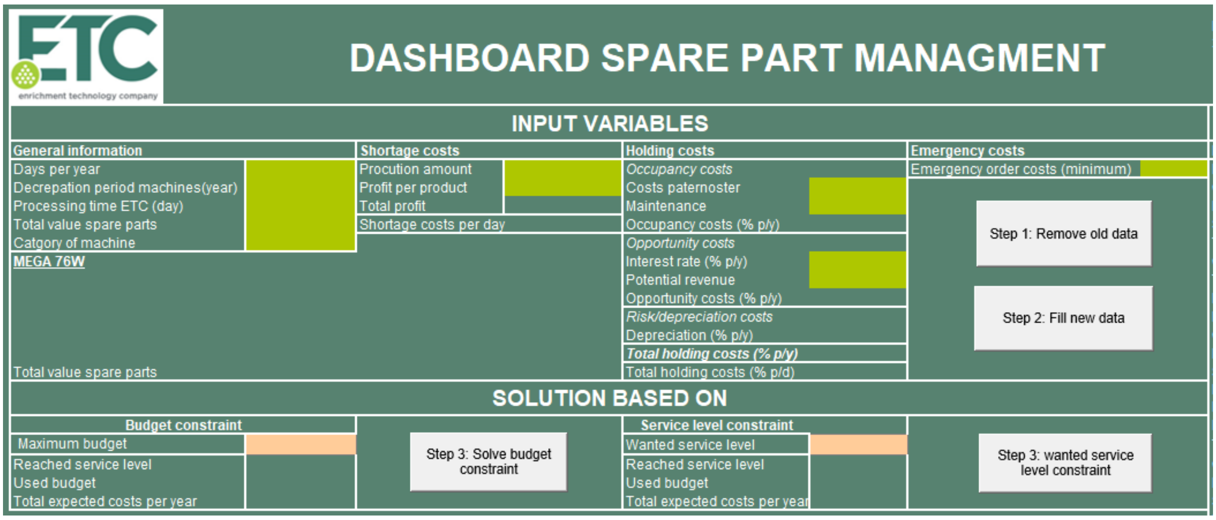

Figure 28: Dashboard spare part management

6.1.1 Step 1: Changes values home screen dashboard

The first step is to change the light green values on the dashboard. The cells that are not marked with a specific color do not have to change. Figure 28 gives the home screen of the dashboard and it exists of several subparts. These parts will be explained in the following sections.

6.1.1.1 General information

The general information can be changed in this part. The delivery times of the supplier need to be changed if the machines come from another supplier and the category of the machine needs to be determined based on the theory described in section 4.3.4.

6.1.1.2 Shortage costs

The production amount and the profit per product can be changed over time. This will probably not be the case in the short term, but if the dashboard is used after some years this part can be important.

6.1.1.3 Holding costs

The (maintenance) costs of the paternoster can be changed if a new paternoster is placed with different costs. It is important to always change the interest rate to the actual value because this influences the holding costs.

6.1.1.4 Emergency costs

The emergency costs of a rush order need to be filled in.

6.1.2 Step 2: Implement spare parts

First, the model needs to be cleared, so the old data must be removed by using the ‘Step 1: Remove old data’ button. After changing the variables the spare part data must be implemented. The description, delivery times, amount in a machine, and unit price must be given by the manufacturer of the machine. The category needs to be determined and the codes of the corresponding category need to be noted. All this data need to be copied to the dashboard. This can be seen in Figure 29

INPUT SPAREPARTS					
Description	Delivery times	Amount in machine	Unit price in	Category	Take in stock
Part A	16	1	€ 52,00	1.1.8	
Part B	2	1	€ 390,00	1.1.1	
Part C	16	1	€ 143,00	3.2	
Part D	16	1	€ 75,00	2.6	
Part E	2	1	€ 110,00	2.6	
Part F	2	4	€ 430,00	5.1	
Part G	2	1	€ 216,00	1.1.6	
Part H	2	4	€ 441,00	1.1.6	
Part I	2	2	€ 153,00	1.1.6	
Part J	9	1	€ 2.093,00	1.1.6	
Part K	16	1	€ 5.088,00	1.1.8	
Part L	2	1	€ 111,00	3.3	
Part M	2	1	€ 53,00	1.1.8	
Part O	2	1	€ 114,00	1.1.8	
Part P	2	1	€ 51,00	2.7.1	
Part Q	9	1	€ 704,00	2.7.1	
Part R	2	1	€ 322,00	1.1.1	
Part S	9	1	€ 173,00	2.6	
Part T	2	1	€ 55,00	2.10	
Part U	2	1	€ 73,00	2.6	

Figure 29: Input spare parts dashboard

6.1.3 Step 3: Optimize policy

The policy can be optimized in two different ways. The limited budget constraint can be found on the left side of the dashboard. The orange cell can be changed to the maximum budget and the button 'Solve budget constraint' can be used to find the optimal solution. The targeted service level can be filled in by changing the orange cell on the right side. This optimal solution can be found by pressing the button 'Solve service level constraint'.

6.1.4 Step 4: Subtract output

The values of the input of the spare parts are changed after optimizing the budget constraint. In Figure 29 the column 'Take in stock' can be seen. After optimizing the policy this column will give a 1 or a 0. The 1 corresponds with 'take in stock' and the 0 corresponds with 'take not in stock'.

6.2 Backhand of dashboard

The input data of the spare parts is transferred to the backhand of the model. In this backhand, the calculations are made to determine which spare parts the company needs to take in stock. When the spare part data is filled the button 'Step 2: Fill new data' can be pressed. This will execute all the formulas in the sheet.

The calculation of the lead time, demand, Erlang loss probabilities, shortage cost, emergency costs, and holding costs are described in chapter 4. The calculations of these costs are given per specific spare part.

These values are calculated based on the decision that the model made to reach the wanted values. The decision of taking a value in stock or not is given in the red column 'decision'.

The values that will be changed by the input of these experiments are also colored orange in the backhand model. The values that show the result of the experiment are colored green and are printed on the dashboard. These values contain and are calculated with the following formula.

- Total cost spare part that needs to be bought.
- Total expected costs per year.
- The estimated service level.

6.3 Summary and conclusions

To use the dashboard, four steps are taken. Step 1: change values, step 2: implement spare parts, step 3: optimize policy and step 4: subtract output.

7 CONCLUSION AND RECOMMENDATIONS

In this chapter, the conclusions and the recommendations of the research are presented. After that, a discussion will be made for this thesis. This research wanted to focus on the following part.

‘Managing spare parts to avoid unplanned downtime for waiting for a part during failure.’

7.1 Conclusions

The research tries to make a policy that can be applied to the spare part list of new machines. At the moment the spare parts are bought based on experiences and data that is given by the supplier of the spare parts. The conclusion is that the policy can give the needed support to the company to make better-informed choices. The policy makes calculations for the holding cots and emergency cots and compares them with each other to come to an optimum combination. It is important to see the policy as a support system and not the replacement of the decision which spare parts need to be in stock.

7.1.1 Same budget, higher service level

If the policy is compared with this list of spare parts that were ordered according to the ‘first service package’ the service level will be 3,68% higher and the costs will be 61,27% lower when using the policy. The targeted values were to reduce the costs with 20% and to increase the service level with 3% with the same budget. Both targets have been met. This is caused by the following facts:

- The first service package also advises keeping spare parts in stock that have a lead time of 2 days. The model calculated the holding costs and the shortage costs and compare them. The emergency costs will be relatively low when the lead time is 2 days. For that reason, the model decided to not take this part in stock.
- The costs are lower because the parts with a longer lead time will take in stock. The expected costs are in most cases high because of the expected emergency costs.

7.1.2 Same service level, lower budget

When the service level of the first service package is applied to the model the budget that is needed to reach this same service level is 77,38 % lower and the costs are 10,77% lower. This is caused by the following facts:

- The model can make a selection of spare parts which influence the service level.

7.1.3 Visualization and calculations of choices

The model will give a decision support system where the spare parts are presented which are advised to buy. An expert must take a look at these outcomes. The outcomes are based on averages in demand, but averages can differ for a specific part so the expert needs to determine which spare parts are needed in stock. Before there was no way of calculating the needed parts. This model will make it easier to convince the board to buy specific spare parts because it is substructures with calculations.

7.2 Recommendations

First, I want to advise the company to use this policy as a decision support system when the spare parts of a new machine need to be bought. The policy makes it possible to make decisions that are based on holding costs and emergency costs. This is something that is not done before. The outcome of this policy is the starting point of the list of spare parts. The experiences of the employees and the recommendations of the supplier make it possible to create a well-found list of spare parts that will decrease unplanned downtime.

This decision support system makes it also possible to convince the board of the company that there is a need for more spare parts when a higher service level wants to be reached. It will be easier to convince them with calculations instead of only basing the arguments on experience.

During the research, I also find a lot of interesting things were the company can also look at. So the list of the following recommendations is made:

- Standardization of spare parts: Why should you have 100 different relays in stock if you can repair 90% of the situations with 10 different sorts?
    - Makes it easier to repair: Always the same part and know where to search.
    - Fewer parts in stock, easier to find parts.
- Implement all spare parts in the system to do better failure analysis.
    - Insight in used parts (also from the parts that you order once)
    - Better overview of parts that can be used in other machines.
    - Disadvantage: time-consuming.
- The naming of the spare parts must be more structured.
    - Add another category: Main group part, subgroup part, part name, part description.

The company is at the beginning of data-driven choices. It is important to make small steps in this process. First, it needs to be clear how the data need to be implemented into the ERP system. This costs a lot of effort of the employees. It is important to convince these employees that their work becomes easier when the data is implemented the right way. If that is reached, the company can start optimizing the different parts.

7.3 Discussion and limitation

In this section, the discussion of the potential shortcomings of the research is presented.

7.3.1 Lack of complete data

During this thesis, it was hard to find the complete data because the company did not register all of its parts in the system. The simplification had to be made to only work with the data that is fully available because otherwise, it was not able to compare this data. So the data of the spare parts that are bought once is not implemented into the model. So the demand ratios are potentially higher than the real values.

7.3.2 Failure

In the model, it is assumed that a spare part that broke down always causes downtime for the machine. In the real world, this is not the case because not all spare parts have the same criticality. For example, if a small rubber ring is leaking it needs to be replaced, but this does not mean that the machine is down until the spare part arrives. It would be possible to add those criticalities into the model, but this is time-consuming when using the model because this needs to be determined for every spare part that is implemented in the model. But because it is a support system, the necessary spare parts can be added before the final decision for the order.

7.3.3 Validation

It was not possible to validate the model for the old machine because the data about the spare parts are not available and the company is not able to get this information. It was already really hard to get the spare part data of the company for the new machines. The validation is only done by concluding that the model is validated because all the inputs are validated.

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APPENDIX A – SELECTION OF LITERATURE

- **Inclusion and exclusion criteria:** the criteria are determined to narrow down the scope. The used criteria can be seen in Figure 30: Inclusion and exclusion criteria.
- **Keywords:** Spare parts management, policy, corrective maintenance, repair, downtime, downtime, spare parts, failure, stock, and failure analysis.
- **Search strings:** The search strings can be found in Figure 31: Search terms. Similar words are used to search for the same subject.
- **Databases:** For this literature research, the literature guide of Industrial Engineering and Management was used. The recommended databases were Scopus, Web of Science and for more business exclusive papers the Business Source Elite. These databases have a lot of useful papers for this bachelor assignment.

Number	Inclusion Criteria	Reason
1.	Keywords: Spare parts management, policy, corrective maintenance, repair, downtime, downtime, spare parts, failure, stock, and failure analysis.	These keywords must be included in the papers. Because these words are used as search terms and are relevant by answering the research questions.
2.	Subjects: Engineering	The research needs to be applicable for a production company that makes use of machines. These machines need maintenance with the use of spare parts. The maintenance is related to engineering.
Number	**Exclusion Criteria**	**Reason**
1.	Non-Dutch or non-English literature	Difficult/impossible to read.
2.	Keywords: Environmental, Aircraft manufacture.	These subjects are not relevant for this research.
	Subject area: Computer science	The spare parts must not relate to computers or other small electronics.
3.	Maintenance strategies and condition monitoring for companies.	For this assignment, the focus is on spare parts management and not on the maintenance strategy.
4.	Specific spare parts management strategies for company's which differs too much from ETC	If the strategy is developed for other types of business, it is not useful for this assignment.

Figure 30: Inclusion and exclusion criteria.

Search string	Database	Scope	No. of entries
"Spare part management" AND policy	Scopus	Article title, Abstract, Keywords	60
Machines AND (repair Or "corrective maintenance") AND ("shutdown time" OR "shut downtime" OR "Downtime" OR "Down time") AND "Spare part*"	Scopus	Article title, Abstract, Keywords	23

"Spare part* management" AND (failure OR breakdown) AND (stock OR inventory)	Scopus	Article title, Abstract, Keywords	25
"Failure Analysis" AND "Spare part*"	Scopus	Article title, Abstract, Keywords	146
"Spare part* management" AND (failure OR breakdown) AND (stock OR inventory)	Web of Science	Topic	25
"Spare part* management" AND (failure OR breakdown) AND (stock OR inventory)	Business Source Elite	Topic	6
Total in Mendeley			**278**
Selection based on inclusion/exclusion			**-215**
Removing duplicates			**-12**
Remove after scanning			**-45**
Include after reading			**+3**
Total selected for research			**9**

Figure 31: Search terms

Nr.	Article & Books	Authors (year)	Relevance
1.	*Strategies in spare part management using a reliability engineering approach*	Sheikh, Callom & Mustafa (1991)	Calculation of failure rate, spare part classification, and ordering strategies.
2.	Criticality analysis of spare parts using the analytic hierarchy process	Gajpal, Ganesh, Rajendran (1994)	Explanation of the AHP in combination with the VAD analysis which is used to categorize spare parts.
3.	Spare parts criticality analysis using a fuzzy AHP approach	Durán (2015)	Extension of the fuzzy approach on the existing AHP analysis.
4.	Spare parts' criticality assessment and prioritization for enhancing manufacturing systems' availability and reliability	Antosz, Ratnayake (2019)	Categorize spare parts on levels of critically. Uses pair-wise comparison (AHP) to determine the prioritization of the spare parts.
5.	On the relationship of spare parts inventory policies with Total Cost of Ownership of the industrial asset	Durán, Macchi, Roda (2015)	Total Cost of Ownership. Explains the different periods during a lifetime. Different stock management controls.
6.	Maintenance spare part logistics: Special characteristics and strategic choices.	Huiskonen (2001)	Categorizing categories in low and high values vs low and high criticality.
7.	A criticality-driven methodology for the selection of spare parts stock management policies: the case of beverage industry company	Miranda, Roda, Macchi, Montera (2014)	Selecting the right inventory policy based on a specific criterion.
8.	A decision support system for spare parts management in a wafer fabrication facility	Akcalt, Davis, Hamlin,	Decision support system which suggests the safety stocks. DSS gives lower and upper bounds

		McCullough, Teyner, Uzsoy (2001)	and leaves the decision to the company.
9.	Managing nuclear spare part inventories: A data driven methodology	Scala, Rajgopal, Needy (2014)	Methodology about spare parts management adjusted to a nuclear energy plant. Describing the inventory policy and shows a simulation with different demands.

Figure 32: Articles description

Concepts					
Source	**Analyze tools**	**Categorization theory**	**Criticality**	**Stock management**	**Failures**
1.		**X**	**X**	**X**	**X**
2.	**X**	**X**	**X**		
3.	**X**	**X**			
4.	**X**	**X**	**X**		
5.				**X**	
6.		**X**	**X**	**X**	
7.	**X**	**X**	**X**	**X**	**X**
8.		**X**		**X**	**X**
9.	**X**	**X**	**X**	**X**	

Figure 33: Concept matrix

Concepts					
Source	**Analyze tools**	**Categorization theory**	**Criticality**	**Stock management**	**Failures**
1.		**Categorize spare parts on the level of costs and criticality**	**Define the spare parts as high, moderate, and low.**	**Use the EOQ calculation to determine the safety stock for the critical parts.**	**Define the failure rates by using historical data or implant engineering statistics**
2.	**AHP is a multi-decision-making tool that uses a pair-wise comparison.**	**Pair-wise comparison. Based on availability, lead times, and alternative production.**	**Define the spare parts with VED: Vital, Essential, and Desirable.**		
3.	**Extension of the fuzzy approach on the AHP.**	**Pair-wise comparison.**			
4.	**Uses AHP matrix to determine the critically**	**Pairwise comparison on availability and reliability of machines**	**Defines characteristics as maintenance and logistics**		

5.				**Describes (Q,r), (s,S), (R,S), (S-1,S), one or zero policy**	
6.		**Criticality, specificity, demand, and value**	**Process and control criticality**	**Cooperative stock pool, push user stocks backward in chain**	
7.	**AHP approach**	**Specificity, price, failure frequently, stockout costs, lead time**	**Uses VED and add Importantly (VEID)**	**Describes (s,Q) (R,s,Q), (R,S), (s,S), (R,s,S), (S-1,S), one or zero policy. Stock policy applicability matrix**	
8.	**Decision Support System (DSS)**	**Fast movers and slow movers**		**EOQ calculation with lower and upper bound of ss and reorder point**	**Use failure rates to determine service levels.**
9.	**AHP approach with ABC analysis.**	**Equipment critically, probability of failure, replenishment number of suppliers, technical specifications, maintenance type. High and low value.**	**Principle Components Analysis (PCA). Inventory and engineering critically.**	**Base stock level**	

Figure 34: Explanatory concept matrix

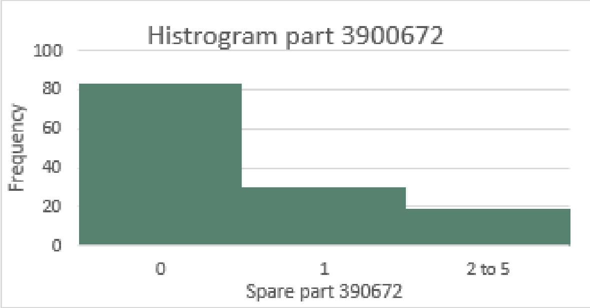
APPENDIX B – DATA, HISTOGRAM, AND TEST STATISTICS

Count	132	3900672	3906172	3903703	3906187	3907384	3900413	3906173
	Mean	0,643939394	0,371212121	0,174242424	0,174242424	0,159090909	0,151515152	0,803030303
Year	Month							
2011	1	0	0	1	0	0	2	0
2011	2	0	0	1	1	0	0	0
2011	3	0	0	0	0	0	0	0
2011	4	2	1	1	0	0	0	0
2011	5	0	0	1	0	0	0	1
2011	6	0	0	0	0	0	1	2
2011	7	1	0	0	0	0	1	1
2011	8	0	1	0	2	0	0	2
2011	9	0	0	0	0	0	1	0
2011	10	0	0	0	0	0	0	1
2011	11	0	1	0	0	0	0	2
2011	12	0	0	0	0	0	0	2
2012	1	1	2	0	0	0	0	1
2012	2	2	0	0	2	0	0	1
2012	3	1	0	0	0	0	0	2
2012	4	1	2	0	0	1	0	4
2012	5	1	1	1	0	0	0	2
2012	6	0	1	0	0	0	0	0
2012	7	0	0	0	0	0	0	0
2012	8	0	0	1	2	1	1	1
2012	9	0	0	0	0	1	2	1
2012	10	1	1	0	0	0	0	2
2012	11	2	0	1	1	1	0	0
2012	12	5	0	0	1	0	0	2
2013	1	2	1	2	1	0	0	2
2013	2	1	0	1	0	0	0	0
2013	3	3	1	0	1	1	0	2
2013	4	0	0	0	0	0	0	0
2013	5	1	4	0	0	0	1	1
2013	6	5	0	0	0	0	0	2
2013	7	1	1	1	0	2	0	1
2013	8	0	0	0	0	0	0	2
2013	9	2	1	0	2	0	0	1
2013	10	2	0	0	1	1	0	4
2013	11	1	1	0	1	0	0	4
2013	12	1	0	0	1	1	0	0

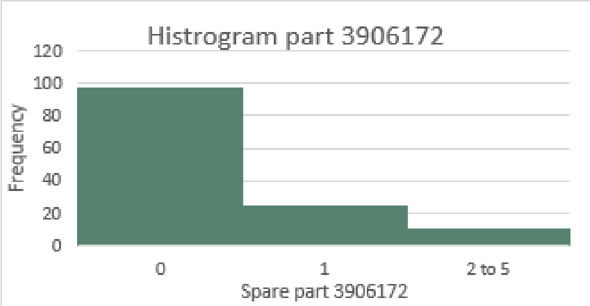
2014	**1**	4	2	1	0	2	1	1
2014	**2**	3	0	0	2	2	0	6
2014	**3**	4	1	0	0	1	0	2
2014	**4**	3	1	0	0	0	1	1
2014	**5**	2	0	1	1	0	0	0
2014	**6**	1	1	0	0	1	0	0
2014	**7**	4	1	0	0	0	0	0
2014	**8**	0	0	0	0	0	0	0
2014	**9**	0	0	0	0	1	0	0
2014	**10**	3	0	0	0	0	0	0
2014	**11**	2	0	0	0	0	0	0
2014	**12**	0	0	0	0	0	0	1
2015	**1**	3	0	0	0	0	0	0
2015	**2**	0	0	0	0	0	0	0
2015	**3**	0	0	0	1	0	0	1
2015	**4**	1	1	1	1	0	0	1
2015	**5**	1	2	0	0	0	0	2
2015	**6**	1	2	1	0	0	0	4
2015	**7**	0	0	0	0	0	0	0
2015	**8**	1	0	0	0	0	0	1
2015	**9**	1	0	0	0	0	0	1
2015	**10**	0	0	1	0	0	1	4
2015	**11**	0	0	0	0	1	0	2
2015	**12**	0	0	0	0	0	1	2
2016	**1**	1	0	0	0	0	0	2
2016	**2**	0	0	0	0	0	0	0
2016	**3**	1	0	0	0	0	0	1
2016	**4**	0	3	1	0	0	1	2
2016	**5**	1	2	0	0	0	1	0
2016	**6**	1	0	0	0	0	0	1
2016	**7**	0	0	0	0	0	1	1
2016	**8**	0	0	0	0	0	0	0
2016	**9**	1	0	0	0	0	0	1
2016	**10**	2	0	0	0	0	0	1
2016	**11**	1	0	0	0	0	0	1
2016	**12**	0	0	1	0	0	0	0

2017	1	0	0	0	0	1	0	1
2017	2	0	1	0	0	0	0	1
2017	3	1	1	0	0	0	0	0
2017	4	0	0	0	0	0	0	0
2017	5	0	0	0	0	0	0	0
2017	6	0	1	0	0	0	0	0
2017	7	0	0	0	0	0	0	0
2017	8	0	0	0	0	0	0	0
2017	9	0	0	1	0	0	0	1
2017	10	0	0	0	0	0	0	2
2017	11	0	0	0	0	0	1	0
2017	12	0	0	0	0	0	0	0
2018	1	0	0	0	0	1	0	0
2018	2	0	0	0	0	0	0	0
2018	3	0	0	0	0	0	0	0
2018	4	1	0	0	0	0	0	0
2018	5	0	1	0	0	0	0	0
2018	6	1	2	0	0	0	0	3
2018	7	1	1	0	0	0	0	0
2018	8	1	0	0	0	0	1	0
2018	9	0	0	0	0	0	0	0
2018	10	0	0	0	0	0	0	0
2018	11	0	0	0	0	0	0	1
2018	12	0	0	0	0	0	0	0
2019	1	1	0	0	0	0	0	0
2019	2	0	0	0	0	0	0	0
2019	3	0	0	0	0	0	0	0
2019	4	0	0	0	0	0	0	0
2019	5	0	0	0	0	0	0	1
2019	6	0	0	0	0	1	0	0
2019	7	0	0	0	0	0	0	1
2019	8	0	0	0	0	0	0	0
2019	9	0	0	0	1	0	0	1
2019	10	0	0	0	0	0	0	0
2019	11	0	0	0	0	0	0	3
2019	12	0	0	0	0	0	0	0
2020	1	0	0	1	0	0	0	2
2020	2	0	0	0	0	1	0	0
2020	3	0	0	0	0	0	1	0
2020	4	0	0	0	0	0	0	0
2020	5	0	0	0	0	0	0	0
2020	6	0	0	1	0	0	0	0
2020	7	0	1	0	0	0	0	0
2020	8	0	0	0	0	0	0	0
2020	9	0	0	0	0	0	0	0
2020	10	0	0	0	1	0	0	0
2020	11	1	1	0	0	0	0	0
2020	12	0	3	0	0	0	0	0
2021	1	0	0	0	0	0	0	0
2021	2	0	0	0	0	0	1	0
2021	3	0	0	0	0	0	0	0
2021	4	0	0	0	0	0	0	1
2021	5	0	0	0	0	0	0	1
2021	6	0	0	0	0	0	0	0
2021	7	0	1	1	0	0	0	1
2021	8	0	0	0	0	0	0	0
2021	9	0	0	1	0	0	0	1
2021	10	0	0	0	0	0	0	0
2021	11	0	0	0	0	0	0	0
2021	12	0	1	0	0	0	0	0

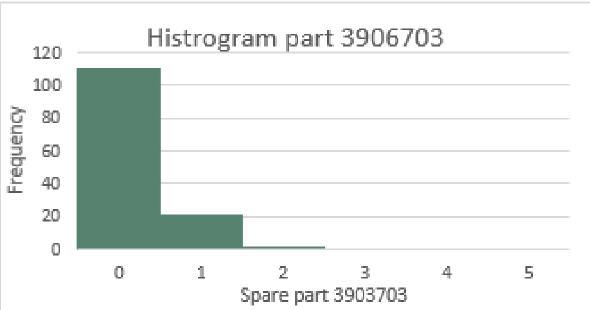
3900672	Mean	0,64394		
Bin	Count	CDF	PDF	TEST
0	83	69,3289	69,32894728	2,69581
1	30	113,973	44,64364029	4,80329
2 to 5	19	131,992	18,01986099	0,05331
			Sum of errors	7,55241
			Chi-Square test	**7,81473**



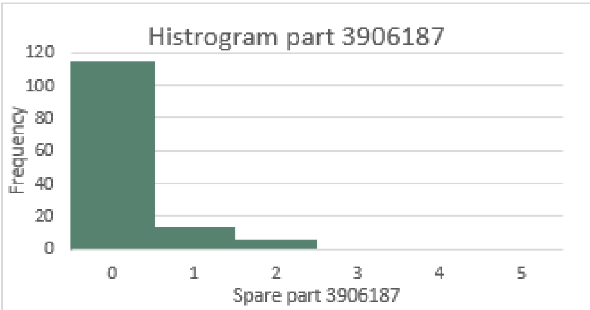
3906172	Mean (λ)	0,37121		
Bin	Count	CDF	PDF	TEST
0	97	91,0665	91,0664811	0,3866
1	25	124,871	33,80498162	2,29338
2 to 5	10	132	7,128187927	1,157
			Sum of errors	3,83698
			Chi-Square test	**5,99146**



3903703	Mean (λ)	0,17424		
Bin	Count	CDF	PDF	TEST
0	110	110,892	110,8923042	0,00718
1	21	130,214	19,32214392	0,1457
2	1	131,898	1,683368599	0,27742
3	0	131,996	0,097771409	0,09777
4	0	132	0,004258982	0,00426
5	0	132	0,000148419	0,00015
			Sum of errors	0,53247
			Chi-Square test	**11,0705**



3906187	Mean (λ)	0,17424		
Bin	Count	CDF	PDF	TEST
0	114	110,892	110,8923042	0,08709
1	13	130,214	19,32214392	2,06859
2	5	131,898	1,683368599	6,53454
3	0	131,996	0,097771409	0,09777
4	0	132	0,004258982	0,00426
5	0	132	0,000148419	0,00015
			Sum of errors	8,7924
			Chi-Square test	**11,0705**



APPENDIX C - CATEGORIZATION SPARE PARTS

	Electric components
	Small electric components
1.1.1	Small electric components
1.1.3	Photocell
1.1.5	Relays
1.1.6	Sensor
1.1.7	Cables
1.1.8	Switch
1.1.9	Auxillary contactor

1.1.10	Connector
1.1.11	Fuse
1.2	Controller
1.3	Control equipment
1.4	Power supply
1.5	Circuit board
1.6	Light
1.7	Coil
	Mechanical
2.2	Spindle
2.3	Motor
2.4	Ball
2.5	Axle
2.6	Bearing
2.7.1	Timing belt/chain
2.8	Gasket
2.9	Filter
2.10	Small components
2.11	Clamps
2.12	Wearing parts
2.14	Rings
2.15	Hoses
2.20	Overig mechanical
	Pneumatic and hydrolic
3.1	Pump
3.2	Cylinder
3.3	Valve/pressure regulator
3.4	Flowmeter
3.6	O-Ring
3.7	Flange
3.8	Spring
3.20	Overig pneumatic/hydrolic
	Vacuum
4.1	Filter
4.2	Valves
4.3	Generator
4.4	Revisonset
	Heating and cooling
5.1	Heating elements
5.2	Heatingshield
5.3	Fans
6	**Laser equipment**
7	**Olien/Zouten/Vloeistoffen**
8	**Production tooling**

Figure 35: Spare part categorization

APPENDIX D – TERMS OF CONDITIONS COMPANY

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