MASTER THESIS

Order fulfillment of spare parts during the end-of-life phase

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Management summary

In the past decades, the rate of technological innovation has increased significantly. Additionally, customer preferences are continuously changing nowadays. As a consequence, product life cycles are shorter and making end-of-life inventory decisions to ensure spare part availability during the end-of-life phase has become more critical. In this research different solutions for the end-of-life phase are analyzed in order to determine how order fulfillment of spare parts in the end-of-life phase can be improved. A case study on this topic has been done at Company A.

Current situation

Currently, the company uses the last time buy method to fulfill all the expected demand during the end-of-life phase. For some of the parts, the end-of-life phase already starts two years after start-of-sales. This means that the company keeps many spare parts on stock for a long time period. The company does not have a standard protocol in case the last time buy quantity turns out to be too low to fulfill all spare part requests during the end-of-life phase. Instead, they solve shortage problems on a case by case basis by searching for alternative materials or if this is not possible, they buy back the original product at a depreciated price. However, it happens more often that the ordered last time buy quantity was too large than too small. As a result, the company has a lot of obsolete stock, namely 1.8 million euros of the total spare part stock value that equals 6.5 million euros is regarded as obsolete. Besides that, shortages are expected for 410 SKUs out of the 1745 SKUs that are in the EOL phase. There is clearly a need for a standardized protocol for order fulfillment during the end-of-life phase.

Research objective and scope

The objective of this research is formulated as follows:

“Developing a suitable spare parts management process for the end-of-life phase in order to improve order fulfillment of Company A Engineered Parts”

The scope of this research project is limited to the Company A Engineered Parts as these can only be obtained through Company A and there are no parts from other suppliers that could be used as a replacement. All the other parts can be ordered elsewhere. These parts are therefore regarded as less critical and left out of the scope of this research project.

Methodology

In this research, different solutions for the fulfillment of spare part requests during the end-of-life phase are gathered from literature and practice. From the list of alternative solutions that were found, those that might be applicable to Company A can be summarized with the following list:

1. Last time buy
2. Use an alternative part that is not in the end-of-life phase
3. Offer discount on a new version of the product
4. Buyback the original product

These solutions are analyzed from a legal, customer service, and cost perspective in order to determine what the best approach would be for the Company A Engineered Parts.

There are multiple methods to calculate the last time buy quantity. From the methods that were gathered from literature, two approaches were selected for further analysis. The first approach is the formula of Teunter and Fortuin (1999) that has been proven to determine the last time buy quantity that minimizes the total expected discounted costs. The second approach is to determine a certain service level, which is defined as the probability of facing no shortage during the end-of-life phase, and determine the last time buy quantity based on this service level.

Taking into account the legal regulations, both approaches are analyzed from a customer service and cost perspective in order to determine the best method to calculate the last time buy quantity. The second approach requires the company to select a certain service level. In the analysis a broad range of service levels was used to provide insight into the impact on the achieved customer service level and costs.

For this analysis, a mathematical model was formulated that calculates the total expected discounted costs and the fill rate, which is defined as the percentage of spare part requests that is fulfilled with an original spare part during the end-of-life phase, for a certain last time buy quantity. In these calculations we need to know the actual spare part demand. A Monte Carlo simulation is done to generate the actual spare part demand in many iterations such that we can determine what the expected number of shortages or overstock is for a particular last time buy quantity. As some of the input parameters of the mathematical model are based on assumptions, a sensitivity analysis is done as well to measure the impact of any differences within these parameters.

Results

For the parts of commodity groups 1 and 2, it was determined that the last time buy should be used as the main solution for the end-of-life phase. If the last time buy quantity turns out to be insufficient, another solution must be used. If a warranty request cannot be fulfilled, the company is obligated to buy back the original product from the customer. For all other spare part requests holds that the company could also use an alternative part to fulfill the spare part request, offer the customer discount on a new version of the product, or buy back the original product at a depreciated price.

The best end-of-life solution for the other Company A Engineered Parts is to make use of alternative spare parts that are not in the end-of-life phase yet. If this is not possible or if the alternative spare part is not in line with the legal warranty requirements, the last time buy option should be used to fulfill (a part of) the spare part requests in the end-of-life phase.

Regarding the last time buy quantity, it has been concluded that the company should set a minimum required service level. If the recommended service level, defined as the probability of facing no stockout during the EOL phase, of the formula of Teunter and Fortuin (1999) is higher than the minimum required service level, the last time buy quantity should be determined with the formula of Teunter and Fortuin (1999). Otherwise, the last time buy quantity should be determined with the minimum required service level. An Excel tool has been developed which automatically calculates the last time buy quantity. The company only needs to provide the required input data of the formula and the minimum required service level. It is possible to set different service levels for different parts and/or customers with this approach.

Recommendations

The developed tool determines the last time buy quantity for the different materials with a predetermined minimum required service level. In order to optimally use this tool it is important that the inserted data of the input parameters is accurate. Therefore it is recommended to regularly evaluate the input parameters and improve their accuracy.

The most important input parameter is the spare part demand forecast over the end-of-life phase. An analysis of the current forecasting methods has shown that these could certainly be improved. Because of the time limit of this research project, it was not possible to do extensive research in this field. Some improvements have been made to the current forecasting methods through incorporation of more historical demand data and installed base information. However, it is recommended for future research to look into further improvement of the spare part demand forecasts by performing an extensive analysis of multiple demand forecasting methods and testing these with the available data.

Preface

In September 2019, I started my journey at Company A. I was welcomed with open arms to perform research for my graduation assignment of the master's degree Industrial Engineering and Management at the University of Twente. The company had just started a new project on spare parts and gave me the opportunity to improve the demand forecasting and inventory management processes. I was given a lot of responsibility and had the freedom to ask questions to anyone within the company, from the shop floor to the executive board.

First of all, I would like to thank Armin Landgraf who gave me the opportunity in the first place to work at Company A as a graduate intern. Besides that, I would like to thank Tobias Adomeit and Thomas Baumann for reviewing my draft versions and always challenging me to find more data and deepen my analyses.

My special thanks goes out to Christian, who served as my daily supervisor. He helped me get all the information I asked for and made me laugh so much that it was never a dull day. Furthermore, I would like to thank Matthieu van der Heijden and Engin Topan as my supervisors from the university for their constructive feedback and support. Their ideas gave me new insights for my thesis, which made this thesis as it is today.

I look back with great pleasure at my time within this dynamic and innovative company and look forward to my next adventure.

Nikki Leijnse

Koblenz, January 2019

List of figures

List of tables

List of abbreviations and definitions

Abbreviations

Abbreviation	Definition	Introduced on page
AM	Additive Manufacturing	31
CEP	Company A Engineered Parts	10
EOL	End-of-Life	10
EOP	End-of-Production	17
LTB	Last Time Buy	10
MAD	Mean Absolute Deviation	24
MAPE	Mean Absolute Percent Error	24
MOQ	Minimum Order Quantity	17
MSE	Mean Squared Error	24
OEM	Original Equipment Manufacturer	10
SKU	Stock Keeping Unit	13
SOS	Start of Sales	19

Definitions

End-of-life phase:
The end-of-life (EOL) phase starts once the production of a part has been terminated and ends when the last spare part request of this part has been received by the company.

Warranty requests:
Warranty requests are spare part requests that are placed in the first two years after the original product has been bought and are in line with the legal warranty regulations. The customer does not have to pay for these spare parts.

Guarantee requests:
Guarantee requests are spare part requests that are placed in the first six years after the original product has been bought and are in line with the company's guarantee regulations. The customer does not have to pay for these spare parts.

Other spare part requests:
All spare part requests that are not in line with the legal warranty or the company's guarantee regulations.

Content

Chapter 1 - Introduction

In the past decades, the rate of technological innovation has increased significantly. Additionally, customer preferences are continuously changing nowadays. As a consequence, product life cycles are shorter and final production orders are now typically placed within a year after the product has been introduced in the market (Hong et al., 2008). This intensifies the pressure on inventory management, especially with regard to maintaining appropriate stock levels of spare parts. Once the production of a product has been terminated, the production of spare parts will generally be terminated soon after that as well. This is often long before the warranty period expires. Hence, an end-of-life inventory decision must be made.

End-of-life (EOL) means that the original equipment manufacturer (OEM) has decided that the useful lifespan of a product has come to its end. After this point in time, the manufacturer will not market, sustain or sell the product anymore (Reliant Technology, 2019). A common method used in practice when the end-of-life phase of a product is reached, is the last time buy (LTB). This is basically a final production order of which the amount should cover the total expected future demand after the production has been shut down. In this case, there exists a trade-off between spare part unavailability costs and spare part obsolescence costs (van der Heijden & Iskandar, 2012).

Quite some research has been done on EOL decisions but most of the literature is based on business-to-business environments, especially components of expensive capital goods. The literature on EOL decisions for consumer goods is rather limited. Pourakbar (2011) developed a model that determines the optimal final order quantity of spare parts as well as the optimal time to switch to an alternative repair policy. In this case the regular policy is to repair the defective part of the product. If the defective part cannot be repaired, it is replaced by a new part. Van der Heijden and Iskandar (2012) developed methods for the joint decision of repair/replacement of products and the optimal LTB quantity for these product replacements. Other stochastic models on the LTB decision are proposed by Hong et al. (2008), Teunter and Klein Haneveld (2002), and Li (2007).

The contribution of this thesis lies in proposing an approach of how to cope with spare part order fulfillment during the end-of-life phase in direct selling business-to-consumer environments. The research for this thesis has been conducted at Company A to examine and validate the proposed approaches.

The remainder of the chapter contains the following information. First, Company A is briefly introduced in Section 1.1. Next, the problem context and the core problem of the company regarding spare part inventories are described in Section 1.2 and Section 1.3 respectively. Section 1.4 contains the problem solving approach. The scope and the design of the research are specified in Section 1.5 and Section 1.6. Finally, the structure of this report is explained in Section 1.7.

1.1 Company A

Instead of working with wholesalers or retailers as an intermediary, Company A applies the direct selling concept. Their products can be ordered online or in the showroom located next to the company itself. The legally required warranty is two years but besides this, Company A offers a six-year guarantee on the Company A Engineered Parts (CEP). Besides selling end products, Company A also sells an assortment of components so their customers can keep the original product in top condition by themselves. Because of the highly competitive market, topnotch customer service and innovation are key.

New models and technologies are introduced frequently. However, the products are designed such that they can be used for at least six years, which is equal to the guarantee period. As the main product is quite expensive, it is crucial for customer satisfaction that spare parts can be ordered throughout the entire lifetime of the product in case of damage or breakage of components. Nonetheless, holding inventory of these slow-moving goods, that might not even be produced anymore, is costly and must be limited as it is more efficient to use this space for fast moving (new) products. Hence, finding a balance in this matter is imperative.

In 2017, Company A hired an external consultancy firm to analyze the current after sales practices and to propose a strategy for spare parts management. The company came up with concepts to improve spare parts demand forecasting, facility usage and inventory allocation. Besides that, they reported how to integrate this in the organization and its IT systems. However, most of these plans were never fully implemented and employees just continued to work in the same way as before. Now, two years later, the company still copes with a lot of problems regarding after sales services and decided it is time to fix this.

1.2 Problem context

In the current situation, a couple of problems arise regarding inventories of spare parts at Company A. On the one hand, there is redundant inventory of parts of previous models. This is a waste as these take up expensive storage space whereas there are no customers that buy the items anymore. On the other hand, Company A receives phone calls and complaints from customers who cannot get the part they need to repair or maintain the original product. Reasons for this are that the item is out of stock, it is not produced anymore, or the customer cannot find it on the website.

The first two cases clearly indicate a misfit between supply and demand, which is caused by improper inventory management. There could be multiple reasons for this, such as inaccurate demand forecasting and planning, poor inventory monitoring and control, wrong registration of items, unclear processes, etc. The root cause is however unknown. According to the manager it is most likely a combination of such problems.

The fact that customers cannot find the spare part they need on the website is related to data, content, and website design problems. One of the causes is that the spare part is simply not available on the website. Currently, Company A is only able to put a small selection of the spare parts online. The reason for this is a lack of master data and structural quality issues in the available master data such as incomplete and/or incorrect data. Due to an unstable, low performing, and non-standardized product and spare part definition process, there is not enough data available about the spare parts that is needed for the web shop. Besides that, there are some underlying hardware and software problems.

Another cause for the problem that customers cannot find the spare part they need on the website could be that the customers have a lower level of expertise and need more information about the components than is currently provided on the website.

To provide a clear overview of these problems at Company A, a problem cluster is shown in Figure 1 on the next page.

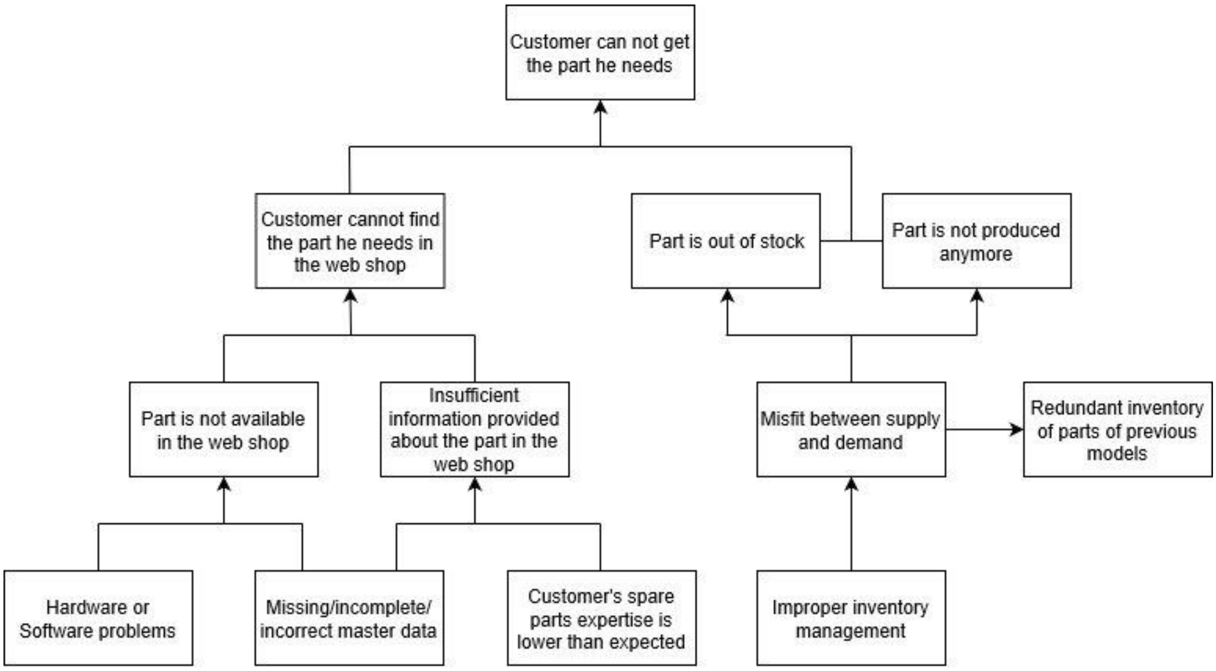

Figure 1: Problem cluster

1.3 Core problem

According to the managerial problem-solving approach described in the book *Geen Probleem*, written by Hans Heerkens (2012), the core problem can be found in the problem cluster by following these rules of thumb:

1. The problem cluster may only contain problems that really matter and have a relation with the other problems in the cluster.
2. The core problem should be a problem that has no other cause in the cluster.
3. The problem must be solvable, otherwise it cannot be the core problem.
4. If multiple problems are left, the core problem is the problem with the highest priority of solving it.

The problem cluster shows four problems that fulfill the first three rules of thumb, namely:

- *"Hardware or software problems"*
- *"Missing/incomplete/incorrect master data"*
- *"Customer's spare parts expertise is lower than expected"*
- *"Improper inventory management"*

The first two problems require a high level of expertise of the IT systems used within the company. The master data problems can be solved by providing an overview of the data needed and making sure that the data can be obtained from the system in that way. A team from within the company is already looking into these two problems and searching for solutions. The third problem can be solved relatively easy with a customer survey and some data analysis on the search engine input and output. The most pressing problem is the last problem, namely improper inventory management, which involves demand forecasting as well as inventory monitoring and control.

At Company A, the spare parts can be divided into two categories, the CEP and OEM parts. The difference is that the CEP can only be obtained through Company A and the OEM parts can be ordered elsewhere as well. This means that if the CEP are out of stock, the customer cannot get the parts. If an

OEM part is out of stock however, there might be other suppliers that have the part and can fulfill the customer order. In general, the out of stock impact is thus bigger for CEP than OEM parts.

As the number of stock keeping units (SKUs) of spare parts is enormous and the scope must be kept feasible, the focus is put on the CEP only. The problems for OEM parts are similar. The solution space for OEM parts is a bit larger than the solution space for CEP because the OEM parts can be obtained elsewhere. Aside from that, the parts are similar. The alternative solutions for CEP can thus also be used for OEM parts. Therefore, in accordance with the internal supervisors, the core problem of this project is formulated as follows:

"Improper inventory management of Company A Engineered Parts"

1.4 Scope of the research

The research took place at the headquarters of Company A in Germany. However, Company A also has a holding in the USA. Both locations are taken into consideration in this research project. The scope is limited to the Company A Engineered Parts, which are approximately 4000 SKUs, as the consumer can only obtain these parts through Company A. Because of the time limit, it is not possible to analyze each of these SKUs in detail. Therefore, in some of the analyses the SKUs are aggregated. Besides that, the scope is limited to the already existing IT systems in the company. The focus of this research project is put on the EOL phase but in some cases the methods used in other phases of the product lifecycle are explained as well for better understanding of the situation.

1.5 Problem solving approach

The managerial problem-solving approach by Heerkens (2012) is used as a guideline to find a solution to the core problem. This approach exists of seven phases:

1. Problem identification
2. Problem solving approach
3. Problem analysis
4. Formulate alternative solutions
5. Decide on the best solution
6. Implementation
7. Evaluation

In order to solve the core problem, more information is needed. First, the current situation is analyzed in depth. Next, knowledge is acquired through literature studies, data analysis and benchmarking. Based on this information, alternative solutions are formulated. Together with the company, the best solution is selected and implemented.

The current situation is analyzed in depth through observations and interviews with employees within the demand forecasting, inventory monitoring and control, purchasing, and maintenance departments. These employees provide insight into the tasks performed within their department and the methods used. Besides that, data analysis is done to obtain quantitative information about the current performance with regard to demand forecasting and inventory monitoring and control of CEP.

Furthermore, a literature study is done to gain more information about spare parts management in the EOL phase. Alternative solutions are investigated in case parts are no longer in inventory and the production has already stopped. Also, the IT systems used by Company A are analyzed to determine the possibilities and opportunities. In addition, benchmarking is done to exploit ideas from other industries. Based on all this information, the alternative solutions are determined and examined.

1.6 Research design

As mentioned before in Section 1.3, the core problem is: *"Improper inventory management of Company A Engineered Parts"*. By solving this problem, the company has more insight into its demand and supply processes and more control over the availability of parts. The focus in this research is put on the EOL phase. The objective is therefore formulated in accordance with the internal supervisors as follows:

"Developing a suitable spare parts management process for the end-of-life phase in order to improve order fulfillment of Company A Engineered Parts"

First, more information is obtained about the current situation at Company A regarding the EOL phase and CEP inventory management by answering the following questions:

1. What does the current situation at Company A look like?
    a. *Which departments are involved in CEP management?*
    b. *What does the EOL decision-making process look like?*
    c. *Which alternatives are used if a part is no longer available?*
    d. *What does the CEP demand forecasting and planning process look like?*
    e. *What does the CEP inventory monitoring and control process look like?*
    f. *How does Company A perform on CEP demand forecasting and inventory control considering quantitative measures such as demand forecasting errors and obsolescence?*
    g. *Which IT systems are used for demand planning and inventory control?*
    h. *In which areas can we find potential for improvement?*

The answers to above questions are gathered through interviews with employees from different departments within Company A. Besides that, data analysis is done to measure the performance of CEP demand forecasting and inventory control on KPI's that are chosen in consultation with the internal supervisors. In this way a better perspective of the problem context is obtained.

Next, information is gathered about spare parts management in the EOL phase, by answering the following questions:

2. What can be found in literature about spare part management in the EOL phase?
    a. *What solutions exist to fulfill spare part demand in the EOL phase?*
    b. *What methods are recommended to determine the last time buy quantity?*

Above questions are answered using online scientific articles, books from the study program and other scientific resources.

Furthermore, it is interesting to know how other companies handle spare part demand during the EOL phase. Useful insights could be gained in this way. At most companies this information is confidential. However, a couple of the companies that have been approached for this research project agreed to an interview if the company name would be left out of the publication. The questions asked are:

3. What do the EOL decision-making and spare parts inventory management processes look like at other companies?
    a. *What does their spare parts inventory management process look like?*
    b. *What solutions do they use to fulfill spare part demand during the EOL phase?*
    c. *How do they cope with shortages during the EOL phase?*
    d. *How do they cope with (the risk of) obsolescence?*

In order to answer these questions, benchmarking is done to gain insight into the EOL decision-making processes and spare part inventory management methods used by other companies, which might be applicable to Company A as well.

After collecting all above information, a solution is formulated by answering the following questions:

4. How should the company cope with spare parts management during the EOL phase?
    a. *Which EOL solutions are applicable to Company A?*
    b. *Which EOL solution or combination of solutions provides the best results?*
    c. *How should the last time buy quantity be determined?*

The answers to these questions are formulated using the information found with regard to all previous questions. By combining the literature review, data analysis, benchmarking and company insights, possible solutions are formulated and tested. After selecting the best solution, there is one final question left:

5. How should the EOL solution be implemented in the company?

The implementation process is developed together with the internal supervisors. Their knowledge about the organizational standards and processes is used to work out an implementation plan that fits the company. All concerned departments are involved in this process to make sure everyone is on the same page and to ensure a smooth implementation phase.

1.7 Structure of the report

The structure of this report follows the research design and answers the questions in chronological order. Basically, the report can be divided into five parts:

1. Analysis of the current situation
2. Information gathering
3. Determining the best solution
4. Implementation
5. Conclusions and recommendations

In Figure 2 on the next page, a graphical representation of the report structure and the corresponding chapters is given. The analysis of the current situation is given in Chapter 2 and answers the first research question and its sub-questions. Next, the gathered information is provided in Chapter 3 and Chapter 4. Chapter 3 includes a literature framework to answer the second research question and its sub-questions. The third research question and corresponding sub-questions are answered in Chapter 4 based on some benchmarks. The process of determining the best solution is described in Chapter 5 and Chapter 6. Different solutions for order fulfillment in the EOL phase are formulated and analyzed in Chapter 5 and in Chapter 6 it is determined how the last time buy quantity should be determined. Together, these chapters provide an answer to research question 4. Chapter 7 describes the implementation process and therefore answers the final research question. The report ends with conclusions and recommendations in Chapter 8.

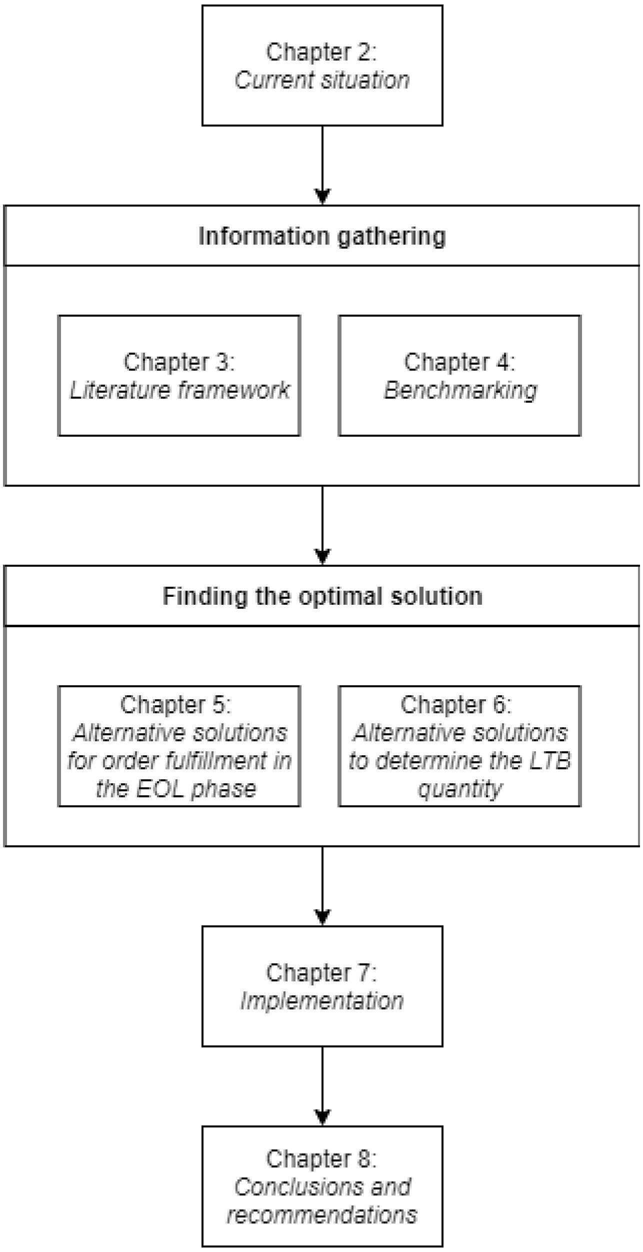

Figure 2: Report structure

Chapter 2 - Current situation

This chapter describes the current situation at Company A with regard to the EOL phase and CEP inventory management. There is a difference between the processes that take place at the headquarters in Germany and the holding in the USA.

The technical service department, which is located at the headquarters, carries the main responsibility of making the demand forecasts of all CEP. This also includes the forecasts for the holding in the USA. Stock keeping, assembling the end products and carrying out repairs is done at the headquarters itself. The holding in the USA on the other hand uses third parties for these steps. Only the final check before sending out orders to customers is done by the holding in the USA herself. In case of shortage problems, the holding in the USA sends out requests to the headquarters. Depending on the inventory levels and needs at the headquarters, these requests are fulfilled or not.

The purchasing department at the headquarters is responsible for ordering the CEP from the suppliers. Once the end-of-production (EOP) time is announced by the supplier, they communicate this to the technical service department such that the final order quantities can be determined. The EOP is also the start of the end-of-life (EOL) phase. This phase ends when the last spare part request has been received by the company.

The chapter is structured as follows. In Section 2.1, the current EOL decision-making process is described. Section 2.2 explains how the LTB quantities are determined and describes the demand forecasting methods. In Section 2.3 the results of a quantitative analysis on the performance of the current situation are presented. Section 2.4 describes the CEP inventory monitoring and control processes. After that, the improvement potential is described in Section 2.5 and the chapter is concluded in Section 2.6.

2.1 EOL decision-making process

Based on the EOL decision-making moment, the CEP can be divided into two groups. Due to capacity restrictions of the suppliers, the order quantities of the parts in the first group must be determined upfront, for the spare parts and the parts required for assembling the end product together. After that, only minor adjustments in the order quantities can be made during the production period. The parts that belong to this group are typically produced with the same specifications for one or two years. However, it is often not known for sure upfront, whether these parts will be produced with the same specifications for a second year.

The parts that belong to the second group are used in multiple models and several generations of the end product. The specifications of these parts change after a longer time period. Reordering is possible in this case, but one should take into account the minimum order quantity (MOQ). The EOL decision of these parts takes place at a later stage.

For the first group of parts Company A uses a common EOL solution, namely the last time buy (LTB), which is also known as the final order quantity. As the company needs to provide a rough capacity plan upfront for these parts and does not always know at that time whether the parts will be produced with the same specifications for a second year, they immediately need to determine the total order quantity to cover the guarantee period of six years. However, for these parts it is possible to slightly adjust the order quantities once the production is already running. Besides that, the production of these parts is meant for spare part usage as well as assembly of the end products. Therefore, at the beginning of the production of end products, the technical service department only wants to receive the amount of spare parts to cover the spare parts demand in the first year. They want to receive the rest of the spare parts at the latest moment, namely after the last moment that the supplier of these parts accepts adjustments in the order quantities. This enables them to change the initial order quantity if necessary and thus to postpone the LTB decision. Depending on the production period of these parts at the supplier, this may give enough time to figure out whether the parts are produced with the same specifications for a second year. If they are, the actual LTB can be postponed even further.

In principle, this method should cover the spare part demand over the six-year guarantee period. If it turns out that the LTB quantity was too low, an alternative solution is used to cover the remaining demand. This alternative solution is to use a newer or more expensive version. This part does however have different specifications. In the worst-case scenario, Company A needs to buy back the original product from the customer because he does not accept the alternative part with different specifications.

When the EOL phase has been reached of the CEP that belong to the second group, a decision is made based on the following four criteria: expected future demand, MOQ, usability of the part in future models, and available alternative parts. If the MOQ is lower than the expected future demand, the LTB quantity is determined and ordered. The same is done if the MOQ is higher than the expected future demand but the part can be used in future models as well. Otherwise, it is determined whether alternative parts can be used to fulfill the future demand. If this is not the case, the MOQ is ordered even though this means that the company will probably end up with obsolete stock. In case of shortages during the EOL phase, alternative parts are searched first. If these are not available, it might be possible to replace a larger part of the end product with a spare part. Again, the worst-case scenario is that Company A needs to buy back the original product from the customer.

In the next section it is explained how the LTB quantity is determined for the different parts.

2.2 Demand forecasting and LTB quantities

For all CEP holds that the LTB quantity is based on the global demand forecast. The technical service department simply determines the expected future demand of the remaining guarantee period, subtracts the current inventory levels, and uses this as the LTB quantity. Other factors such as holding costs, disposal costs, and shortage costs are not taken into consideration. The expected future demand is a point forecast so uncertainty in demand during the remaining guarantee period is not taken into account either.

The technical service department does consider the current inventory levels when determining the LTB quantity. This is rather complicated as the spare parts inventories at the headquarters are spread over two locations, namely at the warehouse at the showroom of Company A where it is clear what the spare parts are and at the main warehouse at the factory of Company A where no distinction is made between spare parts and parts meant for the assembly line. If all parts are always delivered in the right amount and at the right time by the suppliers, this would not be such a big problem. Unfortunately, this is not the case. The suppliers are quite unreliable and send reconfirmations on the number of parts that will be supplied all the time. The question is therefore: what happens if the supplied amount is not enough to fulfill the total amount ordered for the assembly line and after sales and service matters? Right now, the company does not have a standard protocol for this. As a consequence, there is no way of telling what the actual amount of spare part inventory is at the main warehouse and the department can only use the information they have from the warehouse at the showroom of Company A. For the holding in the USA, the current inventory levels need to be retrieved from the third party responsible for their stock keeping.

In the remainder of this section, it is explained how the demand forecasts are made. The demand forecasts of the CEP are partly dependent on the forecasts of the end product. Therefore, the demand forecasting and planning method of the end product is first described in Section 2.2.1 before the methods regarding the CEP are explained in Section 2.2.2.

2.2.1 Demand forecasting and planning of the end product

The Business Intelligence department carries the responsibility of the demand forecasts of the end products. In 2016 a demand forecasting process was set up in collaboration with the Otto Beisheim School of Management. The key element of this process is the so-called "Obermeyer" meeting that takes place three or four times a year. One of these meetings takes place in September to make the forecast of the total sales for each model of the end products, in each possible size and color combination, in the next fiscal year. At Company A the fiscal year starts in October and ends in September. For example, in September 2019 the forecasts were made for the expected sales from October 2020 till September 2021, known as fiscal year 2021. This gives the company approximately a year to order all parts and assemble most of the end products before the start of sales (SOS) as the lead time of the CEP is approximately 120 days.

The forecasts are made as follows. The Business Intelligence department prepares the meeting by collecting information on key performance indicators (KPI's) and factors that could influence demand. Once a new model is introduced, it can be preordered online immediately, even if the production of the product has not started yet. The number of preorders is one of the leading KPI's in the Obermeyers meant for adjustments. Other examples of KPI's and factors are previous sales numbers of similar models, promotions, events planned, etc. These KPI's and factors are shared with a group of experts who then individually forecast the total sales in the next fiscal year for each model with different sizes and colors. In this phase, the KPI's and forecasts are not discussed with each other yet.

During the Obermeyer itself, the Business Intelligence department and experts are present to discuss the numbers. For each product, the average over all forecasts of the experts is taken as a starting point. Next, discussions take place until all attendees come to an agreement on the forecast. Finally, these forecasts are then used by the Business Intelligence department to make the monthly demand planning together with the sales managers of the different product families.

2.2.2 Demand forecasting and planning of CEP

At Company A there are three types of spare part demand, namely warranty requests, guarantee requests, and other requests. The legal warranty period is two years so the warranty requests can occur up to two years after the product has been sold. The guarantee period of Company A equals six years so the guarantee requests can occur up to six years after the product has been sold. The last type includes all other spare part requests, such as crash replacements and other damage that is not covered by the warranty or guarantee regulations.

As mentioned before, the CEP can be split into two groups based on the EOL decision-making moment. The first group consists out of two different types of parts, from now on referred to as commodity group 1 and commodity group 2. For each of these type of parts a different demand forecasting and planning method is used. Within the second group of CEP there is no clear distinction between parts with regard to demand forecasting and planning methods and from now on we refer to these parts as the "other CEP". In all cases, Company A works with point forecasts and does not determine a bandwidth or standard deviation. Forecasting is done with help of Excel spreadsheets and registered in SAP afterwards.

Spare parts demand forecasting of commodity group 1

The spare part demand forecasts of commodity group 1 are based on the demand forecasts of the end product and the expected failure rate of the individual parts of commodity group 1. The expected failure rate is defined as the expected percentage of parts that need to be replaced and is based on the following information:

1. The expected failure rate of the part of a comparable previous model of the end product

2. The differences of the consecutive end product models that could have an impact on the parts within commodity group 1 (development improvement)
3. The material the part is made of
4. The expected type of usage of the end product

If a comparable previous model of the end product exists, its expected failure rate of the part is taken as a basis. Looking at the differences of the consecutive models, it is then determined what the expected failure rate of the new part should be. This is done on model level and not on SKU level. It is assumed that the failure rate is the same for all different sizes and colors of the model. No formal methods from theory are used but it is rather based on expert opinions from the technical service department. If there is no comparable previous model, the failure rate is based on the type of material, the expected type of usage of the end product, and expert opinions from the technical service department.

The spare part demand forecasts of commodity group 1 are then calculated by multiplying the demand forecast of the end products that contain the part by the expected failure rate of the part. This is done on SKU level, so for each color and size combination. In most cases, this results in a non-integer number. The technical service department decides for each non-integer solution whether it should be rounded up or down. This forecast is supposed to cover all spare part demand over the six-year guarantee period. The LTB quantity is then this forecasted quantity minus the parts that have already been ordered and delivered between the start of production (SOP) and the LTB moment. As the spare part demand after these six years is really low, any requests that occur are then solved on a case by case basis.

Spare parts demand forecasting of commodity group 2

Based on experience and limited historical data analysis, the technical service department determined that the number of failures of commodity group 2 parts equals approximately fifty percent of the number of failures of the corresponding commodity group 1 parts. Therefore, for each model of the end product the number of commodity group 1 spare parts is taken and divided by two. Again, this forecast is supposed to cover all spare part demand over the six-year guarantee period. The LTB quantity is in this case also the forecasted quantity minus the parts that have already been ordered and delivered between the start of production (SOP) and the LTB moment.

Spare parts demand forecasting of other CEP

Approximately 80% of the other CEP do not have a demand forecast. For those that have a forecast, it is based on historical data. Again, no formal methods from theory are used but it is rather based on expert opinions. The historical data for these parts is richer as the parts are typically used in different models of the end product and over several years. However, for these parts the suppliers have a MOQ which must be taken into account. If a final order is placed, the LTB quantity equals the MOQ or the expected demand in the remaining guarantee period if this is higher than the MOQ.

For the parts that do not have a forecast, Company A simply orders the MOQ and reorders the parts when they run out of stock. If they get into trouble with these parts during the replenishment time, they borrow items from the assembly line or search for alternative parts. If this is not possible, they just wait until the part is replenished. If a final order is placed, the LTB quantity equals the MOQ.

2.3 Quantitative analysis

Company A basically uses two solutions for the EOL phase, namely the LTB and using alternative materials. In general, the LTB solution is preferred. If the LTB quantity turns out to be too low, alternative materials are used to fulfill the request. However, when the expected demand in the EOL phase is significantly lower than the MOQ and there is a suitable alternative part available, this option is used instead. This is mainly the case for the smaller and less expensive parts of the end product.

When choosing for the LTB method in the EOL phase, two problems can occur. Either the final order quantity was too low such that the demand cannot be fulfilled anymore, or the final order quantity was too high such that the company is left with obsolete stock. The cause for these shortage and obsolescence problems is demand forecasting errors.

When alternative materials are used to fulfill the demand of spare parts in the EOL phase, it becomes a matter of inventory control and adjusting demand forecasts of the alternative materials.

In the remainder of this section a quantitative overview of the obsolescence and shortage problems is given in Section 2.3.1 and Section 2.3.2 respectively. Besides that, the general performance of the demand forecasting methods is analyzed in Section 2.3.3. It should be noted that Company A started working with the Enterprise Resource Planning system SAP in September 2015. Data from before that time is not available anymore. Besides that, the company only started forecasting demand for some spare parts in 2017. Because the guarantee period is six years, it is not possible to do an analysis over a full cycle.

2.3.1. Obsolescence

In order to determine the obsolete stock, two different approaches were used. In the first approach the obsolete stock is defined as parts that have shown no movement within the last three years and are not needed anymore for guarantee or warranty cases. Three years of no movement is taken here, because in some cases a part might not be used in the next model but is reintroduced in the model after that. If a part has not been used at all in the last three years however, the probability that the part will be reintroduced, is assumed to be neglectable by the company.

In the second approach, the potential obsolete stock is determined by subtracting the expected future demand from the current inventory level. The expected future demand is based on a weighted moving average over the years, where more weight is put on the more recent years.

The analysis only covers the two plants of the headquarters that are designated to spare parts. These inventories do however include some production leftovers from the past as well, which cannot be distinguished from the spare parts anymore. In both analyses, the same data set is used which includes CEP as well as OEM parts. This means that parts that were introduced for the first time in 2018 or 2019 are not included in either of the approaches. The data of these parts is too limited to make valid conclusions, so any potential obsolescence of these parts is not included.

In Table 1 below, an overview is given of the number of SKUs and value in euros of the total inventory and the obsolete stock of both approaches.

Table 1: Obsolescence overview September 2019

	Total inventory	**Obsolete stock Approach 1**	**Obsolete stock Approach 2**
Number of SKUs	6465	2215	3549
Value in euros	€6.500.447	€1.820.210	€3.354.845

The obsolete stock value of Approach 2 is almost twice as large as the obsolete stock value of Approach 1. The difference between the two approaches is that in Approach 1 only items are included that have shown no movement in the last three years, whereas in Approach 2 all items with or without movement are included. For example, an item of which the demand was only one in the last three years and had an inventory level of one hundred would be left out of the analysis in Approach 1 whereas it would show a high level of obsolete stock when Approach 2 is used. Therefore, if the expected future demand is calculated accurately, Approach 2 gives a better indication of the true excess stock value.

In order to obtain more insight into the obsolete stock, pareto diagrams were made of the obsolete stock for both approaches on the commodity group level. These can be found in Figure 3 and Figure 4 respectively. The diagrams only include the commodity groups with an obsolete stock value greater than €10.000. For both approaches the sum of the stock values of the commodity groups included in the diagram entail approximately 96% of the obsolete stock value. From both diagrams it can be concluded that the parts of commodity group 1 (spread over five categories, namely A through E) and commodity group 2 have the largest contribution. In Approach 1 they are responsible for 91,6% of the obsolete stock value and in Approach 2 for 88,5%.

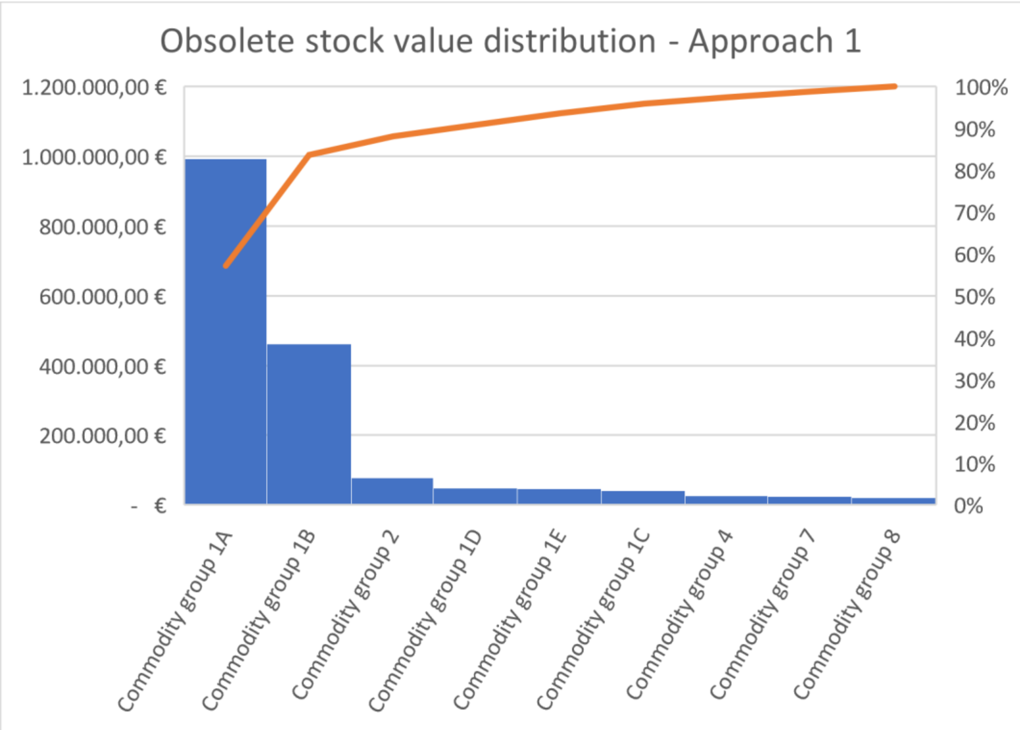

Figure 3: Obsolete stock value distribution Approach 1

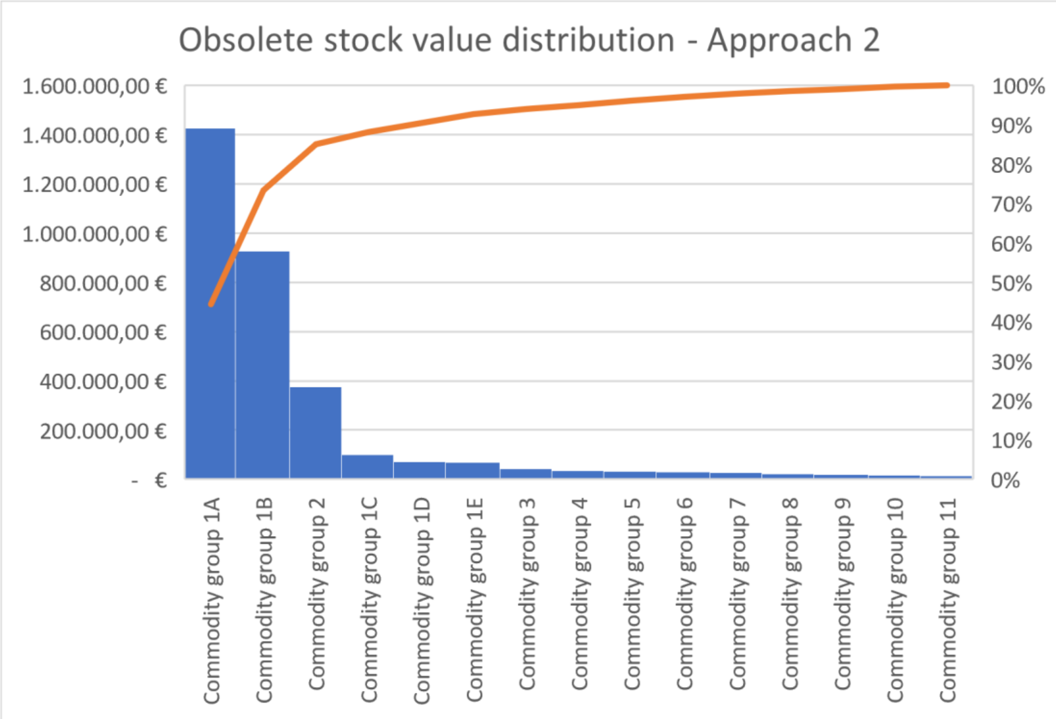

Figure 4: Obsolete stock value distribution Approach 2

2.3.2. Shortages

In case of shortages, Company A searches for alternative parts that can be used to fulfill the demand. At the service workshop, they do not keep track of these events. If an alternative part is used to fulfill a customer order, this is not registered properly. Therefore, it cannot be traced back unfortunately if there was a difference between the requested part and the part used to fulfill the order with the available data in the system.

However, with Approach 2 that was used to determine potential obsolescence we can also detect potential shortages. The same weighted moving average over the years is used to determine the expected future demand. In this case we are only interested in the parts that cannot be reordered and are thus in the EOL phase. Of the 6465 SKUs that are on stock, 1745 are already in the EOL phase and cannot be reordered anymore.

If the current inventory level is subtracted from the expected future demand, it turns out that 410 SKUs will potentially end up with shortages. The expected shortage for these SKUs in total is 88.889 items with a total value of €505.609. These include OEM parts as well as CEP. An overview of the CEP with the largest shortages on a commodity level is given in Table 2 below.

Table 2: Overview of CEP shortages on a commodity level

Commodity group	Number of expected shortages	Value of expected shortages
12	9238	€12.087
13	3581	€4.708
14	1408	€16.571
11	828	€11.638
5	484	€14.515
3	308	€1.744
1B	81	€16.605
2	63	€4.348
1A	29	€10.144

2.3.3. Performance of the demand forecasting methods

The previous sections already gave an overall indication of the performance of the demand forecasting methods. In this section, we take a closer look at the performance of the different forecasting methods.

Forecast errors of commodity group 1

As mentioned before, it is not possible yet to determine the forecast error over a full forecasting cycle. The oldest forecast available is those of model year 2018. The production of these parts and end products started in 2016 and 2017. This means that the spare part usage data of these parts covers two to three years until now. Of each SKU within commodity group 1, the production quantity of the end products and the spare part usage data was retrieved. With this information the actual failure rate until now could be determined with the following formula:

$$Actual\ failure\ rate\ until\ now = \frac{number\ of\ spare\ parts\ used}{number\ of\ end\ products\ produced}$$

These outcomes were compared to the expected failure rates as determined by the technical service department, using standard forecast error measures. This was done for the case that each SKU has the same weight in the analysis and for the case that the weight of the SKU equals the percentage of end products that contain the SKU. The analysis includes 396 SKUs in total. The (weighted) average expected failure rate, actual failure rate until now, and the resulting forecast error measures are summarized in Table 3 below. As the failure rates are in percentages, the error measures are presented in percentage points, except for the MAPE.

Table 3: Forecast error measures of model year 2018 of commodity group 1

Error measure	Equally weighted SKUs	Differently weighted SKUs
Average expected failure rate	3,4%	3,5%
Average actual failure rate until now	3,7%	2,7%
Bias	4,01 percentage point	-5,23 percentage point
Standard deviation of the forecast error	5,63 percentage point	5,23 percentage point
MSE	0,16 percentage point	0,29 percentage point
MAD	2,51 percentage point	9,35 percentage point
MAPE	165%	1446%

Looking at the results in the table, it can be concluded that the forecast errors are really high. The bias and the standard deviation are larger than both the average expected failure rate and the average actual failure rate until now. Besides that, the MAPE shows quite extreme values. This holds for both the cases that the SKUs are weighted equally and that the SKUs are weighted based on the percentage of end products that contain the SKU.

If the SKUs are equally weighted, the bias has a positive value which means that the actual failure rate until now is on average higher than the expected failure rate. This would mean that the company could expect a lot of shortages in the near future as the spare parts have already been ordered but there are still some years left that need to be covered with the spare parts on stock. On the other hand, in the calculation where the SKUs are weighted, a negative bias is obtained which means that on average the expected failure rate is higher than the actual failure rate until now and there must thus still be spare parts left to cover (a part) of the spare part requests in the future.

A forecast error can occur in two ways. Either the actual demand is lower than the expected demand or it is the other way around. In Table 4 on the next page, an overview is given of the proportions until now.

Table 4: Actual failure rate until now versus expected failure rate

SKUs	Quantity	Percentage
Actual failure rate until now > expected failure rate	162	41%
Actual failure rate until now < expected failure rate	234	59%
Total	396	100%

If the actual failure rate until now is higher than the expected failure rate, this means that right now the actual spare part demand has already exceeded the expected spare part demand. Somehow, the company was able to obtain the additional required spare parts or took parts from the inventory meant for the assembly line to fulfill this extra demand. However, as the production of these SKUs has already stopped at the present, there will most likely be shortage problems in the future.

If the actual failure rate until now is lower than the expected failure rate, this means that future spare part demand can still be fulfilled right now. However, it is hard to tell at this stage if there will still be a shortage later on or that the company will be left with obsolete stock. More information is needed about the spare part demand distribution over time for this.

Forecast errors of commodity group 2

As mentioned before, the technical service department determines the forecasts of these parts by taking the forecasts of the corresponding part of commodity group 1 and dividing this number by two. This method is analyzed by comparing the actual failure rates until now of the parts of commodity group 2 with the actual failure rates until now of the corresponding parts of commodity group 1. The actual failure rate until now of the parts of commodity group 2 is calculated with the same formula as was used for the parts of commodity group 1. With the actual failure rates until now, the ratio between the parts of the two commodity groups can be determined with the following formula:

$$Commodity\ ratio = \frac{actual\ failure\ rate\ until\ now\ of\ the\ part\ of\ commodity\ group\ 2}{actual\ failure\ rate\ until\ now\ of\ the\ part\ of\ commodity\ group\ 1}$$

As a part from commodity group 2 can be used in combination with multiple parts from commodity group 1, the ratios are analyzed from a platform level. A platform consists of multiple models of the end product with different size and color combinations of the part from commodity group 1. Within a platform, the number of parts from commodity group 2 and the specification differences are limited. In Table 5 below, a summary is given of the commodity ratios.

Table 5: Summary of commodity ratios

Measure	Performance
Average	276,9%
25th percentile	59%
Median	107%
75% percentile	268%

From the results in Table 5 it can be concluded that the current forecasting method does not work. The commodity ratio of the 25th percentile is already higher than 50%. The range between the 25th and 75th percentile is quite large, especially between the median and the 75th percentile. This means that the commodity ratios are spread over a wide range and it does not make sense to take one ratio that holds for all platforms as this leads to high forecasting errors.

A full overview of the actual failure rates until now of the parts of both commodity groups and the corresponding ratios of each of the twenty-four platforms that were analyzed, can be found in Appendix A.

Forecast errors of the other CEP

As 80% of the other CEP do not have a forecast, the data for this analysis is limited. An analysis is done on the forecasts of parts of commodity group X, Y, and Z for the year 2018. In Table 6 below, an overview is given of the number of forecasted SKUs, the average actual demand per SKU and the average forecasted demand per SKU for the three different parts.

Table 6: Actual versus forecasted demand of parts of type X, Y, and Z

Parts	Number of SKUs analyzed	Average actual demand	Average forecasted demand
Commodity X	38	125	175
Commodity Y	96	38	36
Commodity Z	14	158	171

Each of these SKUs were analyzed and a summary of the forecast errors of these items can be found in Table 7 below.

Table 7: Summary of forecast error measures of parts of commodity group X, Y, and Z

Overview of forecast error measures				
Commodity X	**Average error**	**Standard deviation of forecast error**	**MSE**	**MAD**
Average	4,15	11,05	489,12	10,53
25th percentile	-1,42	3,03	10,40	2,52
Median	-0,29	5,82	36,71	4,63
75th percentile	2,19	14,17	319,83	14,27
Commodity Y	**Average error**	**Standard deviation of forecast error**	**MSE**	**MAD**
Average	-0,17	3,07	20,04	2,63
25th percentile	-1,44	1,36	2,40	1,06
Median	-0,58	2,48	7,00	1,96
75th percentile	0,10	4,10	20,69	3,44
Commodity Z	**Average error**	**Standard deviation of forecast error**	**MSE**	**MAD**
Average	1,09	10,75	239,72	8,41
25th percentile	-1,31	2,90	8,85	1,71
Median	-0,04	6,68	60,29	6,04
75th percentile	1,92	16,92	290,00	12,54

For each of the forecast error measures holds that we want them to be as close to zero as possible. The median of the average error is quite close to zero for all the materials. The average of the average error of the parts of commodity group X is much higher than the 75th percentile. This means that there are some extreme outliers. For the parts of commodity groups Y and Z holds that the average error lies within the boundaries of the 25th and the 75th percentile so the outliers are less extreme in this case.

Looking at the size of the actual demand (see Table 6), it can be concluded that the average standard deviation of the forecast error and the average MAD are almost 10% of the size of the actual demand for the parts of commodity groups X and Y. For the parts of commodity group Z it is a bit lower but still quite high. Overall, the standard deviation of the forecast error is quite high considering the low quantities of the actual demand of these materials. Besides that, the median of the MAD is also quite high in comparison to the actual demand. Therefore, it can be concluded that these forecasts should be improved.

2.4 CEP inventory monitoring and control

Inventory control plays a big role in the EOL phase. In this phase, it is not possible anymore to place reorders. Therefore, it is important to keep track of the inventory levels of the parts that have reached this phase and the alternative materials that can be used to fulfill the demand if the inventory of the original part is depleted. Besides that, at the end of the EOL phase there might be obsolete stock of which the company must take care of. This might need to happen earlier as well with excessive stock.

Right now, inventory control of CEP is a reactive process at Company A. As mentioned before, inventories of spare parts are kept at two locations but the technical service department only has full insight into the inventories at the warehouse at the showroom. If they need parts from the main warehouse, they need approval of the purchasing department for an internal shipment of materials from the main warehouse to the warehouse at the showroom. However, these requests for internal shipments are only placed after the technical service department has received a customer order that they cannot fulfill from the warehouse at the showroom. There is no routinely inventory monitoring in between to check proactively if internal shipments should take place in order to fulfill future demand. In the EOL phase, backordering is not possible, so if the main warehouse does not have the part either, the technical service department searches for an alternative part that can be used to fulfill the customer demand.

Looking at the general performance of inventory control, considering all products instead of only those in the EOL phase, it can be concluded that the performance is quite poor. In Table 8 below an overview is given of the average fill rates and average number of backorders of the service workshop and other customer orders in 2019. The other customer orders come from the web shop, call center and emails.

Table 8: Average fill rates and number of backorders in 2019

	Average fill rate (per month)	Average number of backorders (per month)
Service workshop	75%	131
Other customer orders	52%	715

The average fill rates are low and the average number of backorders are high, especially for the other customer orders. Of the latter an analysis has been done on the order fulfillment time as well, which can be found in Table 9 below. The data includes all the customer orders, not only those that cannot be fulfilled immediately. For the service workshop there was insufficient data available to do this analysis.

Table 9: Order fulfillment times in 2019

Measure	Order fulfillment time (in days)
Average	7
75th percentile	8
90th percentile	17

The targets of the executive board are that 90% of the orders should be fulfilled in 9 working days and 75% in 5 working days. The gap between this target and the current performance as illustrated in Table 9 is quite large. Significant improvements must be made to reach the target.

Regarding obsolete stock, Company A does not have a clear procedure but when possible, the obsolete stock is sold to carbon, steel, and aluminum recycling companies. Reviewing stock for obsolescence is not done periodically but rather sporadically when higher management requests an overview.

Equal to demand forecasting, the technical service department makes use of Excel spreadsheets and SAP for inventory control.

2.5 Improvement potential

The current situation at Company A provides quite some room for improvement regarding shortages and obsolescence in the EOL phase. The solution set in the EOL decision-making process is limited to three options, namely the LTB, using alternative materials, and buying back the original product. The latter is however used as a last resort, because this is a very expensive solution if it is used too often. The solution of the company for any obsolete stock is to try and sell the stock to other companies who might be able to recycle the materials.

Shortages and obsolescence are due to errors within demand forecasting and or inventory monitoring and control. Previously in this chapter it became clear that these areas could also be improved significantly. In the sections below, the improvement potential is described for both areas separately.

2.5.1 Demand forecasting improvement potential

Quite some effort is already put in the spare part demand forecasting of parts of commodity group 1. It is the most expensive part of the end product. The difficulty of this part is that the spare part demand must be forecasted before the end products are physically on the market and that reordering is a really big challenge. Adjustments in the quantity can only be made during the production period, so the forecasts are completely dependent on the forecasted sales numbers of the end products and expected failure rates of the parts. The determination process of the expected failure rate of the parts has the highest improvement potential as these are mainly based on so called expert opinions instead of formal forecasting methods.

The spare part demand forecasting method for the parts of commodity group 2 is to simply take the spare part demand forecast of the corresponding part from commodity group 1 and divide the forecast by two. As shown in Section 2.3.3 this results in high forecast errors so it would be better to make separate forecast for these parts.

For most of the other parts, demand forecasts are not even made. If a forecast is made, it is simply an estimation based on usage quantities in the past and the current inventory levels. As shown in Section 2.3.3, the current method results in large forecast errors.

Furthermore, the LTB quantity is only based on the expected demand during the EOL phase and the current inventory levels. Other factors such as holding costs, disposal costs, and shortage costs are not taken into consideration.

Moreover, there is no documented procedure for making these forecasts. There are only two people in the company that work on the forecasts. If they are gone, nobody could take over as the method is not registered properly.

Therefore, improvements could be made by creating a standardized forecasting protocol, that provides a clear overview of the forecasting methods and is easy to understand. Besides that, the demand forecasts could be improved by making better use of the available historical data and making real calculations instead of using estimations and so called expert opinions. In addition, the company should make better use of the installed base information by tracking the sales numbers of the end products and adjusting the spare part forecasts accordingly when this is still possible.

2.5.2 Inventory control improvement potential

The area of inventory control shows plenty of room for improvement. Right now, the organization has a reactive attitude and only takes action in case problems occur. Besides that, they do not have enough insight into the spare part inventory levels.

A current complication needs to be solved first. A clear digital distinction must be made between the production and spare parts inventories in the main warehouse at the factory of Company A. The company must know which amount of the inventory is meant for production and which amount is considered as spare parts. If in the end, less end products are produced than was initially planned, the parts that are left over could be used as spare parts as well. However, this only works properly with good collaboration between the production and spare parts teams.

Additionally, the company needs a transparent protocol in case the supplier cannot deliver the total requested amount. It needs to be clear what the consequences are for the inventory meant for the assembly line and spare parts so the corresponding departments can adapt their plans accordingly. Furthermore, the company could benefit from a clear protocol for obsolete stock.

2.6 Conclusion

This chapter provided an analysis of the current situation at Company A with regard to CEP inventory management. It answers the first research question: *"What does the current situation at Company A look like?".* The following conclusions are drawn:

1. Three solutions are used in the EOL phase: the LTB, replacement by alternative parts, and as a last resort buying back the original product.
2. The method to determine the LTB must be improved and other EOL solutions must be explored.
3. The parts of commodity groups 1 and 2 have a spare part demand forecast but approximately 80% of the other CEP do not have a spare part demand forecast.
4. CEP demand forecasting need to be standardized and made more reliable by reducing the so-called expert opinion input and introducing formal forecasting methods.
5. The inventory monitoring and control processes must be standardized and incorporate proactive interventions.

Before improvements can be made to the current situation, more information is needed on the EOL-decision making process. It would be interesting to know what options exist for the EOL phase and which option works the best in what kind of situation. Based on a literature review, some relevant information is given in the next chapter.

Chapter 3 - Literature framework

As concluded in the previous chapter, more information is needed about the EOL-decision making process. This chapter provides insight into alternative solutions a company could choose from when an EOL decision must be made. Besides that, different methods to calculate the LTB quantity are discussed that could be used to improve the current method used by Company A.

The chapter is structured in the following way. Section 3.1 provides an overview of the alternative solutions that could be used in the EOL decision-making process. In Section 3.2 several methods are discussed to determine the optimal last time buy quantity. The conclusions of this chapter are presented in Section 3.3.

3.1 Alternative solutions in the EOL decision-making process

An efficient spare part inventory management system takes into account the life cycle of the parts and is adjusted accordingly. The life cycle of spare parts is not necessarily identical to the life cycle of the related product but generally follows it with a time lag (Pourakbar, 2011). It starts when the product is introduced to the market. At this time there are no historical data, which makes it hard to forecast the demand. Despite, the demand is typically quite low in the beginning and it is easy to adapt to fluctuations by simply adjusting the production rates. In the maturity phase, the production is running, and historical data are available to forecast demand behavior such that standard inventory management principles can be implemented. The final phase is reached as soon as the production is terminated and ends when the last service (or warranty) contract expires (Teunter and Fortuin, 1999). This phase is generally the longest. Because of the considerable increase in innovation in the past decades, some products may go through all three phases within a very small period of time. As a consequence, the EOL decision must be made in a relatively early stage.

The rest of this section is split into two subsections. First, some alternative solutions for the EOL phase, that have been found in literature, are discussed in Section 3.1.1. After that, the applicability of these solutions to Company A is examined in Section 3.1.2.

3.1.1 Alternative EOL solutions from literature

Most of the literature related to EOL inventory decisions focus on repair of defective products through replacement of defective parts by spare parts. Those spare parts may be either new parts or returned items that have been repaired. For capital-intensive goods and their associated spare parts this is a feasible approach. However, for highly innovative technological or electronic consumer goods, it might be wise to consider other approaches because of value deterioration of these products over time (Pourakbar, 2011). Examples of alternatives are using newer versions or more expensive spare parts, offering discount on a new model of the product, or giving a monetary compensation to the customer. Another option is to combine the different approaches.

Instead of covering the spare part demand of the whole final phase of the product's life cycle, Pourakbar (2011) came up with the idea to switch to an alternative solution at some point in time to reduce the quantity of the last time buy. His model obtains the optimal final order quantity and time to switch to an alternative policy for service parts in the final phase of its life cycle, which starts when the production of the part is terminated. The idea was based on the fact that the value of stock deteriorates over time and therefore it might be more cost effective to switch to an alternative solution at some point in time. Pourakbar (2011) assumes that the demand is characterized by a non-stationary Poisson process with a decreasing intensity function and that the repair lead time is negligible. The total costs are discounted back to the beginning of the horizon. The model searches for the breakeven point in this situation.

The model introduced by Van der Heijden and Iskandar (2012) is related to the model of Pourakbar (2011). They focus on the joint optimization of the last time buy quantity and the repair-replacement decision for products with a warranty. In the paper, they developed approximations to estimate the total relevant costs and service levels. Besides that, they show that near to optimal solutions can be found using numerical search. The problem is studied as a stochastic model and dynamic heuristics are used to solve it.

Another solution, that has been discussed more often in the last decade, is making use of additive manufacturing (AM). Additive manufacturing is an automated process in which three-dimensional physical objects are produced layer upon layer based on 3D computer aided design data (Gebhardt, Kessler and Thurn, 2019). The method is suitable for producing parts that are small in volume, complex in structure, and of which the demand is uncertain (Li et al., 2017). A method was developed by Knofius, van der Heijden and Zijm (2016) to determine for which parts additive manufacturing would result into an economically valuable and technologically feasible business case in service logistics. The advantage of using AM is that the parts can be manufactured on demand and closer to the customers (Liu et al., 2014). As a result, the warehousing and transportation costs can be reduced, and obsolescence of parts can be prevented.

Furthermore, a solution could be to postpone the customization processes of the spare parts. These processes would then take place at a stage when more information about the customer's preferences are known. This allows the company to exploit aggregation of spare part demand and therefore to reduce the inventory levels (Chopra and Meindl, 2013). However, the delay of customization processes is only valuable if the information about the customer's preferences can be captured quickly and accurately (Gattorna, 1998).

3.1.2 Applicability of the EOL solutions to Company A

The alternative solutions that were discussed in the previous section can be summarized as follows:

1. Last time buy such that defective parts can be replaced with an original spare part
2. Use returned materials as spare parts, that if necessary have been repaired, or disassemble parts from phased-out systems and use these as spare parts
3. Use an alternative part that is not in the EOL phase (newer versions or more expensive parts)
4. Offer discount on a new model of the product
5. Give a monetary compensation
6. Make use of additive manufacturing

Besides that, postponement of the customization process of the spare parts could also be an option. This is not really a solution for the EOL phase but it may reduce the LTB quantity.

Company A already makes use of options 1 and 3. Option 2 cannot be done on a large scale at Company A. Most of the CEP cannot be repaired or are really expensive to repair. Besides that, only usable components are returned if the original product is bought back from the customer. However, this is only done if the company has no other solution to fulfill the warranty or guarantee requests. Therefore, option 2 is rather considered as an exceptional solution.

Options 4 and 5 are easy to implement and could be interesting solutions for Company A. These options should be analyzed further before conclusions can be drawn. From a commercial perspective option 4 would be preferred over option 5, because in that case the customer buys a new product such that money flows back into the company whereas with option 5 this is not necessarily true and the money flows out of the company. Nevertheless, option 5 is already used as one of the EOL solutions at Company A so it would still be interesting to compare it to the other applicable solutions.

Additive manufacturing does not seem like a realistic option for Company A right now. The company already has a 3D printer for making prototypes. The material used in this printer is biodegradable and not strong enough to be used for spare part production. In order to produce spare parts, the company would need to invest in a laser 3D printer or find a partner to outsource the printing. Additive manufacturing is the most beneficial for low volume, complex structured items of which the demand is uncertain, and the conventional manufacturing method is expensive. Of the CEP, the parts of commodity groups 1 and 2 would be the best candidates. Because of the size of these parts, it would take a week to print them. After that, they need to be painted and varnished as well. This solution thus results in unacceptable waiting times for the customers. However, in the long term, when the additive manufacturing machines are further developed and this method becomes less expensive, it could be interesting to investigate this solution further because it could prevent obsolescence of parts.

Postponing the customization process could be an interesting solution for Company A for the parts of commodity groups 1 and 2. These parts exist in many different sizes and colors. If it would be possible to delay the coloring of these parts, the spare part demand of the part in different colors could be aggregated and therefore probably reduce the number of spare parts needed on stock. Besides that, it would delay the LTB moment as the dimensions of these parts change only after four years or more whereas the color of these parts may change every year. Company A has already done research on this solution before and until now they have not found a (local) partner who can color these parts at a later stage in such small quantities with the same quality as the original part and at a reasonable price. However, the company should keep this option open for a later stage.

3.2 Determination of the optimal last time buy quantity

A more common solution that is used in the EOL phase is the last time buy. There are many methods available to calculate the optimal last time buy quantity. Most models are quite extensive and require high computational efforts. However, Teunter and Fortuin (1999) came up with a relatively simple formula to calculate the near to optimal final order quantity which is described in Section 3.2.1. After that, several other interesting but more complicated approaches are briefly discussed in Section 3.2.2 and the applicability of these approaches to Company A is discussed in Section 3.2.3.

3.2.1 Formula for a near to optimal final order quantity

Teunter and Fortuin (1999) designed a model to seek final order quantities that minimize the accumulated production, holding, removing and shortage costs over the entire end-of-life phase. They consider discounted costs because the length of the EOL period is typically at least three years and often much longer. In their paper they consider two variants. The first variant does not allow stock to be removed before the end of the EOL period. In the second variant this is allowed. They determine this optimal final order quantity using stochastic dynamic programming. Besides that, they calculate a nearly optimal final order quantity using an explicit formula and show that in most cases this quantity is very close to the optimal quantity. The focus is put on this formula without allowing stock to be removed before the end of EOL.

Their model is constructed as follows. The goal is to minimize the total expected discounted cost over the planning horizon, which equals the length of the end-of-life period. The total cost consists of the following elements:

1. Initial purchase cost: the cost of purchasing k spare parts at time $t = 0$ equals ck, where c is the initial provisioning cost.
2. Penalty cost: if at any time $t > 0$ a spare part is needed and there are no spare parts available, a penalty cost p is incurred. This could either be the purchase cost at any $t > 0$ or some penalty paid to the customer for not being able to fulfill the service obligation.

3. Holding cost: if $S(t)$ spare parts are held in stock at time t, then the holding costs in period $[t, t + dt]$ is $hS(t)dt$, where the holding cost rate h is positive.
4. Removing cost: cost of removing k parts equals rk, where r can be positive or negative. If the remaining parts are disposed of, r is positive. If the remaining parts can be recycled or sold, r is negative.

This model also takes into account that products can be returned and that its parts can possibly be used as spare parts. The remanufacturing cost to make this possible is assumed to be negligible. All mentioned costs are discounted with a fixed discounting factor α.

The near to optimal final order quantity is denoted by n. The function $f(n)$ defines the total expected discounted cost in period $[0, L]$. Time is considered as a continuous variable. The parameter M_n denotes the moment at which the n^{th} spare part of the final order is needed and $\Delta f(n) = f(n) - f(n-1)$, which is determined by conditioning on M_n. There are two cases $M_n \leq L$ and $M_n > L$.

If we have $M_n \leq L$ this means for $\Delta f(n)$ that at $t = 0$ one more spare part is purchased/produced, during the period $[0, M_n)$ one more part is held in stock, and at time M_n no penalty is incurred. This is described by the following formula:

$$\Delta f(n) = c + \frac{h}{\alpha} - \left(\frac{h}{\alpha} + p\right) e^{-\alpha M_n} \tag{3.1}$$

If we have $M_n > L$ this means for $\Delta f(n)$ that at $t = 0$ one more spare part is purchased/produced, during the period $[0, L)$ one more part is held in stock, and at time L one more part is removed. This is described by the following formula:

$$\Delta f(n) = c + \frac{h}{\alpha} - \left(\frac{h}{\alpha} - r\right) e^{-\alpha L} \tag{3.2}$$

Combining the cases, this results in:

$$E\big(\Delta f(n)\big) = c + \frac{h}{\alpha} - \left(\frac{h}{\alpha} + p\right) \int_0^L P(M_n = t)\, e^{-\alpha M_n} dt - \left(\frac{h}{\alpha} - r\right) P(M_n > L) e^{-\alpha L} \tag{3.3}$$

For large values of n, the probability is large that $M_n > L$. Moreover, if $M_n \leq L$ then M_n will very likely be close to L. This results in the following approximation:

$$E\big(\Delta f(n)\big) \approx c + \frac{h}{\alpha} - \left(\frac{h}{\alpha} + p\right) P(M_n \leq L) e^{-\alpha L} - \left(\frac{h}{\alpha} - r\right) P(M_n > L) e^{-\alpha L} \tag{3.4}$$

Which can be simplified to:

$$E\big(\Delta f(n)\big) \approx c + \frac{h}{\alpha}(1 - e^{-\alpha L}) - P(M_n \leq L) \times (p + r) e^{-\alpha L} + r e^{-\alpha L} \tag{3.5}$$

If the expected demand D is larger than the expected supply S for all $t \epsilon [0, L]$ then $P(M_n \leq L) \approx P(D - S \geq n)$.

Now, the nearly optimal final order quantity n can be determined for either a continuous or discrete function of the distribution of $D - S$. In the discrete case n is equal to the highest integer for which holds that:

$$P[D - S \geq n] > \frac{c}{p+r} e^{\alpha L} + \frac{h}{\alpha(p+r)}(e^{\alpha L} - 1) + \frac{r}{p+r} \tag{3.6}$$

In the continuous case it is equal to the value of n for which the following holds:

$$P[D - S \geq n] = \frac{c}{p+r} e^{\alpha L} + \frac{h}{\alpha(p+r)}(e^{\alpha L} - 1) + \frac{r}{p+r} \tag{3.7}$$

With this formula it is thus actually determined what the probability of facing a shortage during the EOL phase should be in order to minimize the total expected discounted costs.

As discussed later in the paper of Teunter and Fortuin (1999), one could also look at it from a service level perspective. They define this service level as $\beta = P[D - S \leq n]$ which actually equals the probability of facing no shortage during the EOL phase. In that case, one does not minimize the total expected discount costs but determines the LTB quantity with a predetermined service level. The final order quantity n is then determined for discrete functions such that:

$$\beta < P[D - S \leq n] \tag{3.8}$$

In the continuous case the final order quantity n is then determined such that:

$$\beta = P[D - S \leq n] \tag{3.9}$$

3.2.2 Other approaches to determine the optimal last time buy quantity

Hong et al. (2007) identify four major factors that should be included in any service part forecasting model, namely: product sales numbers, discard rate of the product, failure rate of the service part, and replacement probability of the failed part. Based on these factors, they built a stochastic model that forecasts the demand for a service part on a period-by-period basis. An assumption within their model is that the failed part replacement probability decreases with the age of the product. Reasons for this are that the part may be repaired, the failure may be neglected as it has no significant impact or unauthorized parts are used for replacement. Because of computational limits of the original stochastic model, Hong et al. (2007) also propose an approximate model with constant failure and discard rates. They state that by using the predicted values with respect to the time periods, their model can also be used to aid decision making of the final order quantity. However, the final order quantity is in this case purely based on the expected demand during the end-of-life phase and does not consider any other factors.

Teunter and Klein Haneveld (2002) propose an ordering policy consisting of an initial order-up-to level when the production of the product is discontinued and a subsequent series of decreasing order-up-to levels thereafter until the last service contract expires. They assume that after the initial order, the prices of the spare parts increase. In their model no parts are disposed of before the end of the planning horizon, the moment that the last service contract expires. With their model they calculate the optimal order-up-to times and corresponding levels. The objective is to minimize the total expected undiscounted costs of replenishment, inventory holding, backorder, and disposal.

Li (2007) invented a method for forecasting a spare parts last time buy quantity using a low-pass filter approach. The method uses three types of input data. First, the service lifespan of which the beginning is defined as the end of mass production of the product that contains the spare part. Second, past accumulated production data of the associated product and third a data series of historical spare parts orders. To the latter a low-pass filter is applied to extract components with a low frequency in order to represent a smoothed order data series. A local maximum is sought within this smoothed order data series. When the local maximum has been found, exponential forecasting is used to generate an estimation for the last time buy quantity.

3.2.3 Applicability of the last time buy approaches to Company A

In the previous sections, several approaches to determine the optimal last time buy quantity have been discussed. Besides that, in Section 3.1.1 two approaches were introduced that determine the optimal last time buy quantity in combination with the opportunity to switch to an alternative method.

Looking at the required input data of the approaches and the current means and capacity of Company A, the method of Teunter and Fortuin (1999) seems the most appropriate. Their method can be used to determine the near to optimal LTB quantity from a cost perspective. Besides that, they also explain how to determine the LTB quantity if a certain service level is required. Further analysis is required in order to determine what the best approach is for the different spare parts.

3.3 Conclusion

This chapter provided an overview of alternative solutions to choose from when the EOL decision needs to be made and discussed several methods that could be used to determine the LTB quantity. It answers the second research question: *"What can be found in literature about spare part management in the EOL phase?"*

It can be concluded that the following EOL solutions could be interesting for Company A and need further assessment: last time buy, using alternative parts that are not in the EOL phase, offering discount on a new product, and offering a financial compensation. If the LTB option is used, the approach of Teunter and Fortuin (1999) could help to find the near to optimal LTB quantity. Besides that, the solutions of using additive manufacturing and postponing the customization process of the spare part are not realistic options right now but might be interesting to investigate further in the future.

The information in this chapter is retrieved from research papers and shows methods that are recommended from theory. Most of the methods have been tested based on case studies but it would be interesting to have more information about the methods used in practice. More insight into this is given in the next chapter based on a couple of benchmarks.

Chapter 4 - Benchmarking

As concluded in the previous chapter, it would be interesting to have more information about spare parts management and EOL-decision making processes from practice. This chapter summarizes the information that has been retrieved during interviews with the after sales managers of Distributor B and Company C. Each company is first introduced shortly and after that it is explained how they cope with the EOL phase, spare part demand forecasting, and inventory monitoring and control. This is done in Section 4.1 and Section 4.2 respectively. After that, the applicability of the methods to Company A is discussed in Section 4.3 and the chapter is concluded in Section 4.4.

4.1 Distributor B

Distributor B has been the Dutch headquarters of Company X for approximately fifty years now. They import cars, motorcycles, all-terrain vehicles, outboard motors, and spare parts of these products of Company X and distribute these to approximately two hundred dealers throughout the Netherlands. Distributor B does not sell anything to consumers directly. The warranty on the vehicles is three years or 100.000 km, whichever comes first. According to a comparison research provided by Carchex (2019), this is quite common in the automotive industry.

Spare part demand forecasting and inventory control is done with help of built in modules in SAP. The system makes use of standard forecasting methods that determine the demand based on historical patterns and seasonality. The reorder point is calculated automatically, and the system chooses the best supply option based on time, costs and stock levels. The company only needs to set some basic KPI levels.

The SKU portfolio is determined by Company X. Every month, Distributor B receives an overview of the available SKUs including their price. This is the moment that Distributor B knows whether items have been replaced or taken out of production. They do not receive a warning that items will be taken out of production, so a last time buy is not possible.

As the EOP moment is generally after ten years and Company X replaces the item by an alternative in most cases, Distributor B does not experience a lot of shortage problems during the EOL phase. However, it happens sometimes that an item has been taken out of production whereas there is no alternative available. When demand occurs for these parts, Distributor B searches for other solutions. One example is that they try to get into contact directly with the manufacturer of the Company X products to explore the opportunities. The manufacturer might have an alternative part that could be used. However, this part cannot be sold under the Company X brand then because of legal rights.

Like every company, Distributor B experiences obsolescence issues in the EOL phase. Their solution is to account for a depreciation of 2% per month. After four years the material is then written off to a maximum of 96%. The obsolete material is then disposed of. When possible, the company takes preventive action. An example of preventive action is to sell the items, that will reach the four years in stock within a short period of time, with additional discount to their dealers, who can then still sell these products to the end customers.

4.2 Company C

Company C is a Dutch shipyard building refined superyachts and was founded in 1978. They started out building small polyester yachts but after a few years they switched to building aluminum superyachts. In the beginning, they were able to build yachts up to fifty meters but nowadays this is the minimum size with a maximum of eighty meters. It takes two and a half up to three and a half years to build a yacht. The company has seven dockyards, each containing a yacht in a different stage. The capacity is large enough to work on all yachts simultaneously. Company C aims to deliver four yachts per year. Right now, their installed base is 120 yachts.

The warranty Company C gives is one or two years, depending on the sales negotiations. The staff of the yacht normally includes a couple of engineers who service the yacht. It is common and wise to have spare parts on board such that the cruise does not need to be terminated early in case of trouble. Company C always offers a package of recommended spare parts to their customers about six to twelve months before the delivery date of the yacht. In this way they can make sure that the spare parts arrive in time, before the launch. It is up to the customer if he wants to buy this recommended spare part package or not.

Company C does not have spare parts on stock. Demand forecasting and inventory control of spare parts does not take place. If the customer decided not to take spare parts on board, the waiting time for a spare part equals the supplier delivery time. Depending on the part, this takes two weeks up to four months. If the required part is available in one of the dockyards for production but is not needed immediately, because there is still enough other work to be done until the part is resupplied, the part can be taken out of production and used as a spare part. However, this solution is not standard practice and limited to emergency cases.

In the EOL phase, Company C fulfills customer spare part requests by searching for alternatives. The company does not make use of LTB opportunities because of the high level of customization and high costs of the parts and systems. If a particular part of a system is not available anymore, they look for other suppliers who can deliver a similar part or offer a new version of the system.

Company C does not have any obsolete stock due to spare parts. However, they do experience obsolescence due to production. They try to limit this as much as possible by using the left-over generic parts in yachts that are produced in the future. This cannot be done with customized parts. These are kept in a separate storage space and can then hopefully be sold to scrap dealers. Sometimes also staff bids take place for interior parts such as televisions.

4.3 Applicability to Company A

In the previous chapter it was concluded that the following EOL solutions could be interesting for Company A and need further assessment:

1. Last time buy
2. Using alternative parts that are not in the EOL phase
3. Offering discount on a new product
4. Offering a financial compensation

Besides that, the solutions of using additive manufacturing and postponing the customization process of the spare part are not realistic options right now but might be interesting to investigate further in the future. If the LTB option is used, the approach of Teunter and Fortuin (1999) could help to find the near to optimal LTB quantity.

From this list of EOL solutions, Distributor B and Company C only make use of option 2. However, they do have some other solutions in case this is not possible. Both companies get into direct contact with suppliers to search for alternative materials. For Company A this is quite difficult as the CEP are specifically made for Company A and alternative parts will not fit on the original product. Negotiating with the initial supplier is quite difficult, because Company A is only a small player and the supplier has multiple customers. Besides that, it is hard to find a new supplier on short notice that could produce the parts in a low volume for an acceptable price.

Furthermore, Company C does not keep spare parts on stock herself but recommends the customer to keep spare parts on board. Later ordered spare parts have a lead time between two weeks and four months, depending on whether the supplier has them on stock or they need to be produced. Because of the really long lead times of the CEP, the solution of Company C would result in many dissatisfied customers at Company A and is therefore not feasible. Besides that, the LTB moment takes place before the end of the warranty period so legally it is also not possible to not keep any spare parts on stock for Company A. It could be interesting however, to make a small spare parts package that contains some screws and other tiny parts that could get lost or break after intensive usage and are easy to replace by the customer. In that case, the customer would have a small spare part package at home and does not have to order and then wait for these small items that prevent him from using the product. This is however not regarded as an actual solution for the EOL phase that could be added to the list.

Regarding obsolete stock, the approach of Company A is similar to Company C, namely to sell the obsolete material to scrap dealers as much as possible. Besides that, Company C uses generic parts that are left over in new yachts. At Company A there are not that many generic parts, but there are parts that could be used as an alternative for other parts. By making better use of this option at an earlier stage, obsolescence could be prevented.

4.4 Conclusion

This chapter provided an analysis of spare part management of two companies in two different industries. It answers the research question: *"What do the EOL decision-making and spare parts inventory management processes look like at other companies?"* The following conclusions are drawn:

1. Both companies do not use the LTB method, instead they make use of alternative materials or solutions to fulfill spare part requests during the EOL phase.
2. Both companies get into direct contact with suppliers to search for alternative materials.
3. Company B does not keep spare parts on stock but recommends the customer to keep spare parts on board.
4. Distributor B writes down their inventory by 2% per month such that any stock that has been laying in the warehouse for four years can be disposed of.
5. Company C tries to sell obsolete stock to scrap dealers as much as possible and also organizes staff biddings for interior parts. If possible, left over parts are used in newer models as well.

Combining the results of the previous chapter and this chapter, the EOL solutions that could be interesting for Company A and need further assessment are: last time buy, using alternative parts that are not in the EOL phase, offering discount on a new product, and offering a financial compensation. This assessment is done in the next chapter.

Chapter 5 – Assessment of the EOL solutions

There are different ways to cope with the EOL phase of spare parts. Multiple alternative solutions from theory and practice were presented in Chapter 3 and Chapter 4. Those that might be applicable to Company A can be summarized with the following list:

1. Last time buy (LTB)
2. Use an alternative part that is not in the EOL phase for replacement
3. Offer discount on a new product
4. Offer a financial compensation (buyback the original product)

The best solution or combination of solutions may differ per item and depends on different criteria. In accordance with the company, the alternative solutions are assessed using the following criteria: legal requirements, customer service level, and total cost.

This chapter is structured as follows. First, the legal requirements are presented in Section 5.1. This is followed by an assessment of the EOL solutions regarding the customer service level in Section 5.2. After that, the EOL solutions are assessed from a cost perspective in Section 5.3. Next, the perspectives are combined in an overall assessment in Section 5.4. Subsequently, a mathematical model is formulated in Section 5.5 to help in the decision-making process. Additional information about the input parameters of the mathematical model is provided in Section 5.6 and the limitations of the model are discussed in Section 5.7. Finally, the chapter is concluded in Section 5.8.

5.1 Legal requirements

The spare part requests of customers can be split into three categories: warranty, guarantee, and other. The warranty has a legal duration of two years after the original product has been sold. Besides the legal warranty, a company can offer an additional guarantee. At Company A the guarantee period lasts six years, starting the moment the product is sold. For both categories holds that the spare parts are free of charge for the customer. The last category ("other") contains all other spare part requests, such as crash replacements and other damage that is not covered by the warranty or guarantee regulations. The customer needs to pay for the spare parts in this case and depending on the type of part, the company must be able to fulfill the request for five up to ten years after the product has been sold.

For warranty cases, a company must provide a spare part with the same specifications as the original part. If this is not possible, the company must buy back the original product from the customer. Depending on the guarantee regulations of the company, it might also be possible to use an alternative solution to fulfill the request. In all other cases, the company may use alternative solutions to fulfill the customer request as long as they can assure safety and a similar quality.

5.2 Assessment of the alternative solutions from a customer service level perspective

The customer service level can be assessed from two dimensions, namely the quality of the solution and the fraction of the demand that can be satisfied with the solution. Based on the company's insight into and experience with its customers, the customer service level is regarded the highest from the qualitative dimension for the solution that the broken part is replaced with a spare part of the original model. After that, the customer would be the most satisfied with an alternative spare part such that he can use the original product again. The customers are the least satisfied with the discount on the new product and the financial compensation. The reason for this is that with these options the customer needs to invest in a new product. For the other dimension it holds that the higher the fraction of demand that is satisfied with the solution, the higher the customer service level. This is also known as the fill rate.

5.3 Assessment of the alternative solutions from a cost perspective

From a cost perspective, it is the best to make use of alternative parts that are not in the EOL phase. However, this is not always possible because there might not be an alternative part available or the alternative part does not fit the legal warranty requirements. In that case, one of the other alternative solutions must be used to fulfill (a fraction of) the spare part demand.

Offering discount on a new product and offering a financial compensation (buying back the original product) are generally quite expensive solutions. Therefore, it only makes sense to consider these solutions for the more expensive parts of the end product, namely the parts of commodity groups 1 and 2, and only in low quantities instead of as a regular solution for all requests in the EOL phase. A better option in this case is to use the LTB option as the regular solution and the discount or financial compensation (buyback) as a last resort in case the LTB quantity was not sufficient to cover the spare part demand during the EOL phase.

The above described approach of how to cope with the EOL phase can be summarized in the decision chart as depicted in Figure 5: Decision chart for the EOL phase.

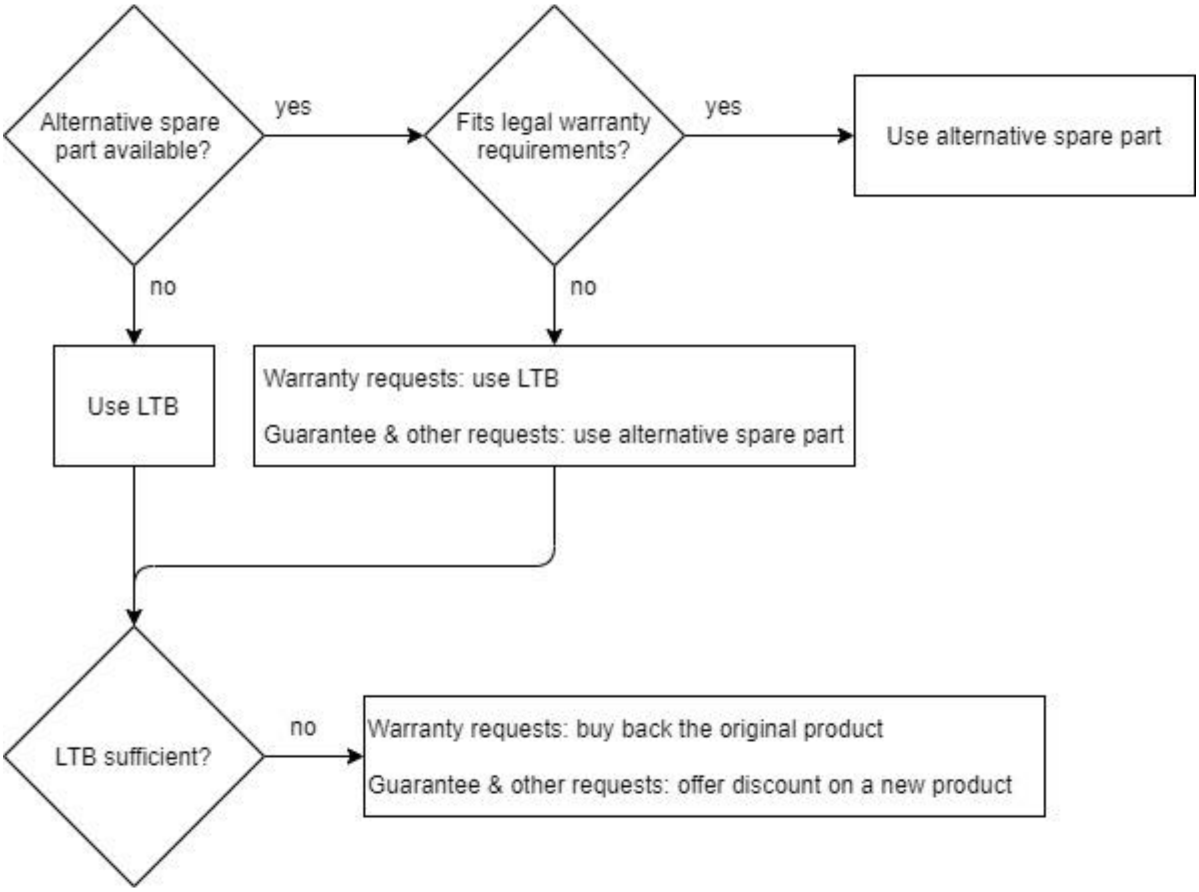

Figure 5: Decision chart for the EOL phase

5.4 Overall assessment of the alternative solutions

In the previous sections it has been discussed what conceptually the best solution for the EOL phase would be purely from the customer service perspective and purely from the cost perspective within the legal framing. However, in order to determine the overall best solution, the two perspectives need to be combined and we need to make sure that the solution is in line with all the legal requirements. As mentioned before, the best solution may differ per item.

First, we have the parts of commodity groups 1 and 2. An alternative part for these items would be their successor but only if the dimensions have not changed. As already explained before, the color of these parts may change with every succeeding model. In most cases, it is therefore not possible to use the successor as an alternative solution for warranty cases as the specifications are different. Besides that, from a customer service perspective, it is a bad idea to fulfill all guarantee and other spare part requests during the EOL phase with an alternative part. If the customer service and the cost perspective are combined, the solution as depicted in Figure 5 does not seem ideal. It would make more sense to use the LTB option as the main solution and find a balance between the customer service level and the total costs in order to determine the optimal LTB quantity. This could be the LTB quantity as determined with Equation 3.7 of Teunter and Fortuin (1999) which minimizes the total expected discounted costs but also the LTB quantity as determined with Equation 3.9 which is based on a certain service level, which equals the probability of facing no shortage during the EOL phase, that has been set by the company itself. In order to determine what the best option is for these parts, it must be determined what the resulting total costs and the fill rates are in both situations. This can be done with the mathematical model that will be introduced in the next section.

Secondly, we have the other CEP. With these parts there are no color issues as these only contain the basic colors black, grey, and white. Besides that, these parts often already have a list of alternative parts that could be used if the item is out of stock. In general, these alternative parts are easily accepted by the customer if the original part is not available anymore. Therefore, it can be concluded that for these parts the company can apply the approach depicted in Figure 5.

5.5 Mathematical model

In order to determine the optimal LTB quantity with respect to the total costs and the customer service level, measured with the fill rate, a mathematical model has been set up. The model contains the same cost factors as were used in the approach of Teunter and Fortuin (1999) as described in Section 3.2.1.

The approach is as follows. Given the length of the EOL phase, LTB quantity, cost parameters, and distribution of the spare part demand during the EOL phase, we want to retrieve the resulting total expected discounted costs and fill rate of every SKU. In order to obtain these results, certain intermediate calculations are required.

First, we need to determine the actual demand during the EOL phase in each time period. With this information, we can determine the stock levels for each time period and also the number of shortages or overstock quantity. These results are then used to determine the total expected discounted costs and the fill rate. These calculations are done for every single SKU.

The actual demand, stock levels, number of shortages and overstock quantity are random variables so the mathematical model is stochastic. Therefore, a Monte Carlo simulation is performed. With this simulation technique, the process is simulated many times and in each iteration different values of the actual demand of every single SKU are generated, such that we obtain more insight into the area of possible outcomes.

Instead of examining the total expected discounted costs and the fill rate of each SKU, the sum is taken over the expected discounted costs of all the SKUs and the average is taken over the fill rate of all the SKUs. These results are examined based on the simulation mean such that conclusions can be drawn from an overall viewpoint. Besides that, we are interested in the range within which the fill rates of the individual SKUs lie. Therefore, the simulation mean of the 10^{th} and 90^{th} percentile of the fill rate of the SKUs are also analyzed.

The approach described above is summarized in Figure 6 on the next page.

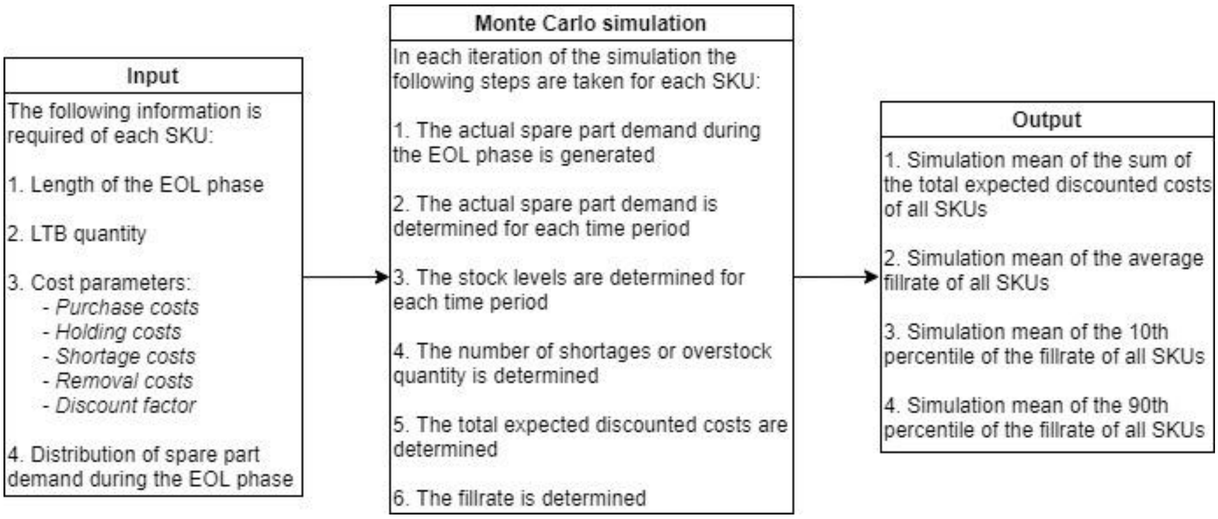

Figure 6: Overview of the mathematical approach

In formulating the mathematical model to determine the total expected discounted costs and fill rate of one SKU, the notation is used as described in Table 10 below. More information about the retrieval of the input data is given in next section.

Table 10: Mathematical notation of the total cost model

Symbol	Description
Parameters	
L	Length of the EOL phase in years
t	Time in years with $t = 0$ is the beginning of the EOL phase and $t = 0, \dots, L$
c	Cost of purchasing one spare part at $t = 0$ in euros
h	Cost of holding one spare part on stock per year as a percentage of the purchase price c
p	Penalty cost in euros, which is incurred at any time $t > 0$ for each spare part request that cannot be fulfilled
r	Cost of removing one spare part at the end of the EOL phase. If the remaining part is disposed of r is positive and if the remaining part can be recycled or sold r is negative.
α	Discount factor per year
LTB	Last time buy quantity
Random variables	
$E[AD_{t-1,t}]$	Expected actual demand in period $[t-1, t]$
$E[S_t]$	Expected stock at the beginning of year t
$E[SH_{t-1,t}]$	Expected number of shortages in period $[t-1, t]$
Output	
$E[TC]$	Total expected discounted cost in period $[0, L]$
C	Total purchase cost
$E[H]$	Total expected holding cost
$E[P]$	Total expected penalty cost
$E[R]$	Total expected removal cost
FR	Fill rate defined as the fraction of spare part demand during the EOL phase that is fulfilled with a spare part of the original model

The total expected discounted costs can be determined with the following formula:

$$E[TC] = C + \mathrm{E}[H] + \mathrm{E}[P] + \mathrm{E}[R] \quad (5.1)$$

The individual cost factors are determined with equations 5.2-5.5 below.

Total purchase cost:

$$C = LTB \times c \quad (5.2)$$

Total expected holding cost:

$$E[H] = \sum_{t=1}^{L} \frac{E[S_{t-1}] + E[S_t]}{2} \times h \times c \times e^{-\alpha t} \quad (5.3)$$

Total expected penalty cost:

$$E[P] = \sum_{t=1}^{L} E[SH_{t-1,t}] \times p \times e^{-\alpha t} \quad (5.4)$$

Total expected removal cost:

$$E[R] = E[S_L] \times r \times e^{-\alpha L} \quad (5.5)$$

Where the stock at the beginning of each year is calculated with:

$$E[S_t] = \begin{cases} LTB & if\ t = 0 \\ E[S_{t-1}] - E[AD_{t-1,t}] & otherwise \end{cases} \quad (5.6)$$

And the shortages in each time period are determined with:

$$E[SH_{t-1,t}] = \begin{cases} 0 & if\ t = 0\ or\ LTB > E[AD_{0,t}] \\ E[AD_{0,t}] - LTB - E[SH_{0,t-1}] & otherwise \end{cases} \quad (5.7)$$

The customer service level can be measured with the fill rate, which tells us what fraction of the spare part demand during the EOL phase is fulfilled with a spare part of the original model. This can be calculated with the following formula:

$$FR = 1 - \frac{E[(AD_{0,L} - LTB)^+]}{E[AD_{0,L}]} \quad (5.1)$$

5.6 Input data of the mathematical model

In this section more information is given about where the required input data is retrieved from. The length of the EOL phase and the purchase costs of each SKU are given information. The actual discount factor is unknown. It is initially set equal to 5% per year. Later on, a sensitivity analysis is done to measure the impact of any differences in this percentage.

The exact holding costs are unknown. According to Stock and Douglas (1987), the standard rule of thumb is to take 25% of the inventory value on hand. Vermorel (2013) confirms that this percentage is commonly accepted. Others, such as Libby (2019), Tradegecko (2019) and Trujillo (2015), state it is somewhere between 20% and 30%. Therefore, the holding costs in this analysis are set at 25%.

The penalty costs may differ per SKU and depend on the policy of the company. It equals the costs of the alternative solution that is used if a request during the EOL phase cannot be fulfilled with the original spare part. If the solution would be to use an alternative part for example, the penalty costs would equal the purchase and holding costs of the alternative spare part. If the solution would be to buy back the original product, the penalty costs would equal the buyback value.

The removal costs are dependent on the material type. Aluminum parts can be recycled and Company A receives approximately one euro per kilo from the scrap dealer for these parts. Parts that are made from other materials such as carbon on the other hand, cannot be recycled that easily and Company A needs to pay for the disposal of these parts.

The LTB quantity and the expected actual demand in each time period $E[AD_{t-1,t}]$ require some additional calculations. It is explained how this is done in Section 5.6.1 and Section 5.6.2 respectively.

5.6.1. Determination of LTB quantity

In order to determine the LTB quantity, the approach of Teunter of Fortuin (1999), as introduced in Chapter 3, is used. In order to calculate the LTB quantity, the standard deviation of the spare part demand during the EOL phase must be known. Company A works only with point forecasts. Therefore, in the analysis we use the normal distribution with the point forecasts as the mean and tested different levels of the standard deviation. Based on the insights of the technical service department, the standard deviation of the spare part demand during the EOL phase is initially set equal to 5% of the mean. As the standard deviation might be higher than this, a sensitivity analysis is done at a later stage to analyze the impact of variability in demand.

As the normal distribution is a continuous distribution, we can either use Equation 3.7 to determine the near to optimal LTB quantity from a cost perspective or define a certain service level β, which equals the probability of facing no stockout during the EOL phase, and calculate the LTB quantity with Equation 3.9.

In the Equation 3.7, the parameter h is expressed in euros, whereas in our notation it is expressed as a percentage of the purchase costs. Therefore, the parameter h in Equation 3.7 of Teunter and Fortuin (1999) is replaced by hc our model. Besides that, there is no supply of spare parts during the EOL phase at Company A. As a result, the formula is adjusted as follows:

$$P[D \geq n] = \frac{c}{p+r} e^{\alpha L} + \frac{hc}{\alpha(p+r)} (e^{\alpha L} - 1) + \frac{r}{p+r} \quad (5.9)$$

The nearly optimal final order quantity n, the LTB quantity in our case, can then be found with the following function in Excel:

$$LTB = n = NORM.INV(1 - P[D \geq n]; \mu;\ \sigma) \quad (5.10)$$

Where μ is the mean and σ is the standard deviation of the demand forecast over time period $[0, L]$.

Instead of using Equation 3.7 which minimizes the total expected discounted costs, one could also define a certain service level β and calculate the LTB quantity with Equation 3.9. As there is no supply of spare parts during the EOL phase at Company A, the equation should be slightly adjusted as follows:

$$\beta = P[D \leq n] \quad (5.11)$$

The LTB quantity can then be found with the following function in Excel:

$$LTB = n = NORM.INV(\beta; \mu;\ \sigma) \quad (5.12)$$

Where μ is the mean and σ is the standard deviation of the demand forecast over time period $[0, L]$.

In the analysis, both methods are used to determine the LTB quantity. Using the approach as summarized in Figure 6, we can then compare the resulting total expected discounted costs and the fill rates of the different LTB quantities to determine which approach is more applicable.

5.6.2 Expected actual spare part demand in each year $E[AD_{t-1,t}]$

The actual spare part demand in each time period is unknown. As this information is needed in order to determine the total costs, a Monte Carlo simulation is done. In this simulation we can generate the actual spare part demand and therefore imitate the real-life situation. In each iteration, the simulation generates one value for the actual spare part demand during the EOL phase. If the number of iterations is high enough, statistical measures can be used to draw conclusions about what could be expected in real-life. In principle, any kind of demand distribution could be used in the simulation but as mentioned in the previous section, we use the Normal distribution with the point forecasts of the technical service department as the mean and a standard deviation that initially equals 5% of the mean in this analysis.

With the Monte Carlo simulation we thus generate the spare part demand over the entire EOL phase so the time period $[0, L]$. If the spare part demand distribution over the years is known, the expected actual spare part demand in each year of the EOL phase $E[AD_{t-1,t}]$ can then be determined. This distribution may differ per spare part request type (warranty, guarantee, other).

At Company A, the exact spare part demand distribution over the years is unknown. As mentioned before, the data of Company A only goes back to the end of the year 2015 and the guarantee period is six years. This means that the data does not cover a full cycle yet. Besides that, with the current means and capacity it was not possible to obtain data about the time between the sales dates and the spare part request dates. However, the customer service and spare part teams of Company A expect that the guarantee and other spare part requests behave according to the curve depicted in Figure 7 below.

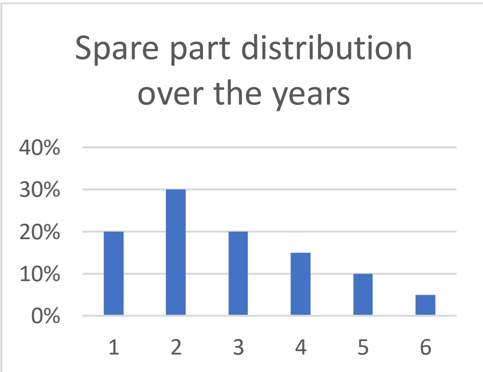

Figure 7: Predicted spare part demand distribution over the years for guarantee and other requests

The warranty requests are only spread over two years. The distribution is expected to be 40% in the first year and 60% in the second year.

However, this information only tells us for each spare part request type that if a certain spare part request is placed what the probability is that it is placed in a certain year after the product has been sold. As the sales period is typically longer than one year, this information alone is not enough.

Given the sales period and the distribution of the sales over this period, we can determine what the fraction of spare part demand is in each year from SOS till the end of the EOL phase. Finally, we can then calculate the expected actual spare part demand in each time period of the EOL phase by determining the fraction of the spare part demand during the EOL phase for each year and multiplying this with the expected actual spare part demand during the entire EOL phase that was generated in the Monte Carlo simulation.

In Table 11 below, an overview is given of the notation that is used in the calculations to determine the actual spare part demand in each year of the EOL phase.

Table 11: Mathematical notation of the actual spare part demand calculations

Symbol	Description
j	Type of spare part request (warranty, guarantee, other) with $j = 1,2,3$
FS^j	Fraction of spare part demand that belongs to type j
t	Time in years with $t = 0$ is the beginning of the EOL phase and $t = 0, \dots, L$
L	Length of the EOL phase in years
$E[AD_{t-1,t}]$	Expected actual spare part demand in period $[t-1, t]$
$E[AD_{0,L}]$	Expected actual spare part demand during the EOL phase generated with a Monte Carlo simulation
d	Year in which the spare part is requested where $d = 1$ is the year in which the original product is purchased and $d = 1, \dots, DP$
DP	Number of years in which spare part demand can be expected after a product has been sold
${SD_d}^j$	Fraction of spare part demand of request type j in year d
s	Time in years where $s = 0$ equals SOS of the end product and $s = 0, \dots, S + DP - 1$
S	Sales period of the end product in years
$FD_{s-1,s}$	Fraction of spare part demand in the period $[s-1, s]$
b	Sales year with $b = 1, \dots, S$
FB_b	Fraction of total sales in sales year b

Based on the demand distribution over the years of the different spare part request types, the distribution over the different spare part request types and the sales distribution over the sales years, it can be determined what the fraction of the total spare part demand is in each year after SOS. The following formula is used:

$$FD_{s-1,s} = \begin{cases} 0 & if\ s = 0 \\ \sum_{j=1}^{J} \sum_{b=1}^{s} {SD_{s-b+1}}^j \times FS^j \times FB_b & if\ s < S \\ \sum_{j=1}^{J} \sum_{b=1}^{S} {SD_{s-b+1}}^j \times FS^j \times FB_b & otherwise \end{cases}$$

Given the actual spare part demand during the entire EOL phase as generated with the Monte Carlo simulation, the expected actual spare part demand in each year of the EOL phase can then be determined as follows:

$$E[AD_{t-1,t}] = \frac{FD_{S+DP-L+t-2,S+DP-L+t-1}}{FD_{S+DP-L-1,S+DP-1}} \times E[AD_{0,L}]\ for\ t = 1, \dots, L$$

In words this equals the fraction of spare part demand in the year after SOS that equals the period $[t-1, t]$ of the EOL phase divided by the fraction of spare part demand during the EOL phase, multiplied by the expected actual spare part demand during the entire EOL phase as generated with the Monte Carlo simulation. The resulting expected actual demand in each time period might not be a whole number but this is not a problem as long as the quantities are not too low.

5.7 Limitations of the analysis

The results of the analysis are highly dependent on the input data. Any changes within the input data might have a significant impact on the total expected discounted costs and the fill rate and could thus lead to different conclusions. Therefore, the impact of changes within the input data must be analyzed through a sensitivity analysis. This includes the following data:

1. Discount factor
2. Distribution over the years of each spare part request type
3. Distribution over the request types
4. Standard deviation of the total spare part demand during the EOL phase

The results of the sensitivity analyses are discussed in the next chapter.

5.8 Conclusion

This chapter provided an overview of the EOL solutions that could be applicable to Company A and determined which combinations of solutions provide the best results for the different CEP. A distinction is made between the parts of commodity groups 1 and 2 and the other CEP. For the latter it can be concluded that the solution for the EOL phase is to use alternative parts that have not reached its EOL phase yet. If this is not possible or if the alternative parts are not in line with the legal warranty requirements, the LTB option should be used.

For the parts of commodity groups 1 and 2 it can be concluded that the main solution for the EOL phase should be the LTB option. However, further analysis must be done in order to determine whether the LTB quantity must be determined with Equation 5.10 which minimizes the total expected discounted costs or with Equation 5.12 which requires a certain service level, the probability of facing no shortage during the EOL phase, that has been set by the company. In this chapter a mathematical model has been set up that determines the total expected discounted costs and gives an indication of the customer service level with the fill rate for a certain LTB quantity. Further analysis is required to find the right balance and to make a decision. As some of the input data is based on assumptions, several sensitivity analyses must be done as well. The focus in the next chapter is on these sensitivity analyses and finding the right balance between the total expected discounted costs and the customer service level in order to determine how the LTB quantity should be calculated.

Chapter 6 – Assessment of approaches to determine the LTB

In the previous chapter it was concluded that the main solution for the parts of commodity groups 1 and 2 should be the LTB option but that further analysis is required to decide how the LTB quantity should be determined. This could either be done with Equation 5.10 which minimizes the total expected discounted costs or with Equation 5.12 which requires a certain service level, the probability of facing no shortage during the EOL phase, that has been set by the company itself. The mathematical model that has been introduced in Section 5.5 can be used to determine the total expected discounted costs and the customer service level expressed with the fill rate for the respective LTB quantities in order to compare the approaches.

This chapter is structured as follows. First, the results of the two approaches are presented in Section 6.1 for the initial values of the input parameters as discussed in Section 5.6. After that, the results of the sensitivity analyses that have been done for the input parameters that are based on assumptions are discussed in Section 6.2. Next, the best solution is determined in Section 6.3 and the chapter is concluded in Section 6.4.

6.1 Analysis of approaches to determine the LTB quantity

The mathematical model of Section 5.5 returns the total expected discounted costs (Equation 5.1) and the fill rate (Equation 5.9) of one SKU. The data of the parts of commodity group 1 of model year 2018 are used as an example in this analysis.

As explained in Section 5.6.2 a Monte Carlo simulation is used to generate the actual demand during the EOL phase. In total 10.000 iterations are done. The actual spare part demand during the EOL phase is only determined once in each iteration for each SKU. This value is then used in the calculations of the total expected discounted costs and fill rate for the LTB quantities determined with Equation 5.10 and Equation 5.12. In this way we can make sure that the same random number stream is used with both equations and thus that the approaches to calculate the LTB quantity are compared to each other under the same circumstances.

It is assumed that once the EOL phase is reached, the LTB option is used as the main solution to fulfill (a part of) the spare part demand during the EOL phase. If the LTB quantity is not sufficient to fulfill all the demand during the EOL phase, alternative solutions must be used to fulfill the demand. For warranty requests this means that the original product must be bought back. For the guarantee and other requests it is also possible to use an alternative part or offer discount on a new product. In accordance with the company six different policies are analyzed. An overview of these policies is given in Table 12 below. The policies are sorted from the highest to the lowest costs for the company in case a spare part request cannot be fulfilled. These policies provide the input for the penalty costs.

Table 12: Policies to be considered if the LTB quantity is insufficient

Policy	Unfulfilled warranty requests	Unfulfilled guarantee and other requests
1	Buyback the original product	Buyback the original product
2	Buyback the original product	Buyback the original product for 80% of the original purchase price
3	Buyback the original product	Offer 60% discount on a new product in the same price range
4	Buyback the original product	Offer 50% discount on a new product in the same price range
5	Buyback the original product	Offer 40% discount on a new product in the same price range
6	Buyback the original product	Use an alternative part for replacement

First, we look at the results if Equation 5.10 is used to determine the LTB quantity. The results are analyzed on the total expected discounted costs and the customer service level, represented by the fill rate, which equals the percentage of requests during the EOL phase that are fulfilled with a spare part of the original model. As a Monte Carlo simulation is used, different results are obtained in each iteration. Therefore, as mentioned before, in the analysis we look at the following results:

1. Simulation mean of the sum over the total expected discounted costs of all the SKUs.
2. Simulation mean of the average over the fill rate of all the SKUs.
3. Simulation mean of the 10^{th} percentile of the fill rate of all the SKUs.
4. Simulation mean of the 90^{th} percentile of the fill rate of all the SKUs.

These results are shown in Table 13 below. Besides that, the table shows the mean of the probabilities of facing no shortage during the EOL phase that have been determined for every single SKU with Equation 5.9.

Table 13: Total costs and fill rate overview of the different policies with the initial simulation settings

Policy	Mean probability of facing no shortage during the EOL phase	Simulation mean of the sum of the total expected discounted costs of the SKUs	Simulation mean of the average over the fill rate of the SKUs	Simulation mean of the 10^{th} percentile of the fill rate of all the SKUs	Simulation mean of the 90^{th} percentile of the fill rate of all the SKUs
1	0,70	€768.641	99,1%	96,5%	100%
2	0,62	€752.098	98,7%	95,4%	100%
3	0,54	€737.514	98,2%	94,2%	100%
4	0,49	€725.803	97,6%	92,9%	100%
5	0,38	€720.887	93,6%	85,7%	100%
6	0,01	€658.040	69,4%	57,3%	97,7%

It can be concluded that the lower the penalty costs, the lower Equation 5.9 will set the probability of facing no shortage during the EOL phase. As a result, the expected total discounted costs are lower but the same holds for the fill rate.

The probability of facing no shortage during the EOL phase is determined for each SKU individually. As a result, the fill rate could vary quite a lot for the single SKUs. In Table 13, the 10^{th} and 90^{th} percentile are given. Based on this information it can be concluded that the fill rates of the single SKUs are quite high for policies one to four. For Policy 5 the range, in which the fill rate of the single SKUs lie, is a bit larger but the levels are still quite high. For Policy 6 on the other hand, the range, in which the fill rates of the single SKUs lie, is large and the mean is significantly lower than those of the other policies.

To gain more insight into the cost structure, an overview of the contribution of each cost factor to the total expected discounted costs is given in Table 14 below for each policy.

Table 14: Overview of the contribution of each cost factor to the total expected discounted costs

Policy	Purchase costs	Holding costs	Penalty costs	Removal costs
1	69,5%	24,9%	5,5%	0,0%
2	69,5%	24,4%	6,1%	0,0%
3	69,3%	23,7%	7,0%	0,0%
4	69,0%	23,1%	7,9%	0,0%
5	65,0%	20,7%	14,3%	0,0%
6	50,0%	11,0%	39,0%	0,0%

It can be concluded that the purchase costs have the highest contribution for each of the policies and that the removal costs are neglectable. Therefore, there is a tradeoff between the penalty costs and the purchase and holding costs in the determination of the LTB quantity.

Instead of using Equation 5.9, the company could also determine a certain service level (β), which equals the probability of facing no shortage during the EOL phase, upfront that is then used for all the SKUs. With this approach the fill rate could be increased but the total costs will also increase. This is especially interesting for Policy 6 as the fill rate is relatively low and in comparison with the other policies the total costs are also low.

In Table 15 below, an overview is given of the total costs and the fill rates of Policy 6 for different probabilities of facing no shortage during the EOL phase (β).

Table 15: Total costs and fill rate of Policy 6 with different probabilities of facing no shortage during the EOL phase (β)

Probability of facing no shortage during the EOL phase	**Simulation mean of the sum of the total expected discounted costs of the SKUs**	**Simulation mean of the average over the fill rate of the SKUs**	**Simulation mean of the 10th percentile of the fill rate of all the SKUs**	**Simulation mean of the 90th percentile of the fill rate of all the SKUs**
Determined with Equation 5.9	€658.040	69,4%	57,3%	97,7%
$\beta = 0{,}10$	€663.415	93,6%	88,2%	99,4%
$\beta = 0{,}25$	€679.912	96,1%	91,0%	100%
$\beta = 0{,}40$	€698.599	97,5%	93,0%	100%
$\beta = 0{,}60$	€729.868	98,7%	95,4%	100%
$\beta = 0{,}80$	€777.704	99,5%	98,1%	100%
$\beta = 0{,}90$	€818.899	99,8%	99,7%	100%
$\beta = 0{,}99$	€926.011	100%	100%	100%

From these results it can be concluded that determining the service level (β) upfront for Policy 6 instead of with Equation 5.9 for every single SKU, could significantly improve the fill rate. Depending on the service level (β) it could however also result in significantly higher costs. In Figure 8 below, the relation between the total costs and the fill rate is depicted for the different service levels (β) in combination with Policy 6.

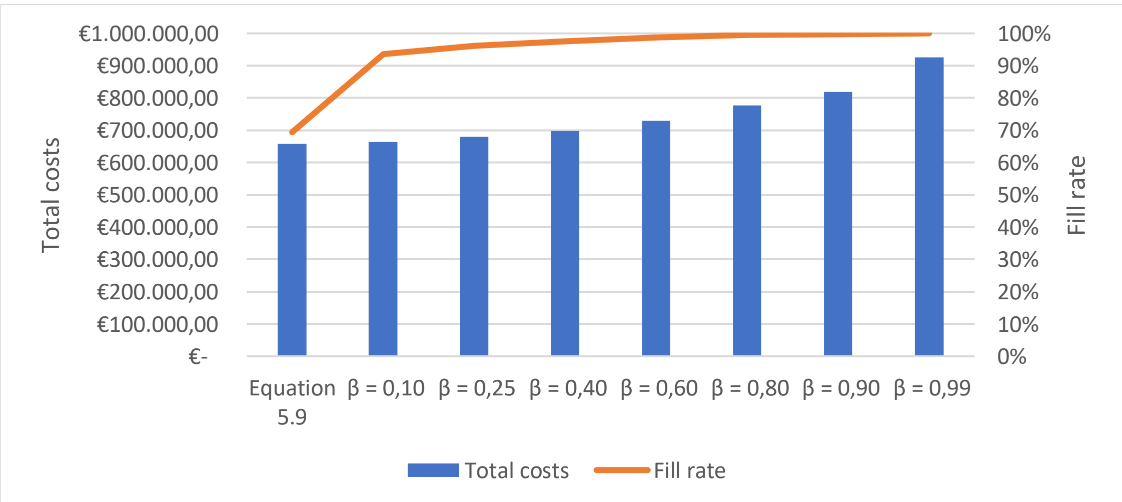

Figure 8: Relation between total costs and the fill rate for different probabilities of facing no shortage during the EOL phase for Policy 6

Switching from usage of Equation 5.9 to determine the service level, that minimizes the total expected discounted costs of each SKU individually, to an equal service level of $\beta = 0{,}10$ for every single SKU only slightly increases the total costs, namely 0,8% which equals €5.375, and significantly increases the mean fill rate namely with 24,2 percentage point. However, as can be clearly seen in Figure 8, switching to a higher service level than $\beta = 0{,}10$ has a more significant impact on the total costs than the fill rate. It holds that the higher the initial fill rate is, the higher the additional costs are to achieve the same increase in percentage points in the fill rate.

The question is whether the increase in the fill rate is worth the additional costs and what the targeted fill rate is. For Policy 6 holds that any unfilled warranty requests are solved by buying back the original product and for any other unfilled requests the customer receives an alternative spare part. If this is regarded as an acceptable alternative solution, one could also argue that it is not necessary to increase the fill rate. It is up to the executive board of the company to find a balance between the total expected discounted costs and the fill rate. They should decide how much the increase in the fill rate is worth the increase in the total expected discounted costs.

The same analysis has been done for the other five policies. In

Table 16 below, an overview is given of the increase in the total expected discounted costs and the increase in the fill rate in percentage points if the service level (β) is determined upfront and set equally for all the SKUs instead of determined with Equation 5.9 for each SKU individually. In this case only one example is given for each of the policies. A similar overview as given for Policy 6 in Table 15, can be found for each of the other five policies in Appendix B. Only the service levels (β) that are higher than the mean of the probabilities of facing no shortage during the EOL phase that have been determined with the Equation 5.9 for every single SKU, are included in the overviews.

Table 16: Comparison of the total expected discounted costs and the fill rate of the different policies between usage of the Equation 5.9 and usage of a predetermined probability of facing no shortage during EOL (β)

Policy	Mean probability of facing no shortage during the EOL phase as determined with Equation 5.9	Predetermined probability of facing no shortage during the EOL phase set equal for all SKUs (β)	Increase in total expected discounted costs	Increase in total expected discounted costs in percentages	Increase in fill rate in percentage points
1	0,70	0,80	€23.214	3,0%	0,4
2	0,62	0,80	€35.865	4,8%	0,8
3	0,54	0,60	€12.049	1,6%	0,5
4	0,49	0,60	€20.287	2,8%	0,9
5	0,38	0,40	€8.988	1,2%	3,9

It can be concluded that the additional costs are quite high for only a slight increase in the fill rate for policies one to four. As the total costs of these policies were already quite high and the simulation mean of the 10^{th} percentile of the fill rate of all the SKUs is 92,9% or higher, it can be concluded that an increase in the fill rate is not worth the additional costs for these policies. Therefore, for these policies the best solution would be to use Equation 5.10 to determine the LTB quantity.

For Policy 5 the increase in the fill rate is a bit higher than for the other policies. However, in comparison with Policy 6 this is only a minor increase in the fill rate for higher additional costs. Here it also holds that the total expected discounted costs are already quite high. Besides that, the simulation mean of the average over the fill rate of the SKUs is already 93,6%. The simulation mean of the 10^{th} percentile of the fill rate of the SKUs is somewhat lower than for the other policies but still quite high.

Therefore, it can also be concluded for Policy 5 that the slight increase in the fill rate is not worth the additional costs and thus that the best solution would be to use Equation 5.10 to determine the LTB quantity.

In this analysis it has only been shown what the results are if we strictly use Equation 5.10 to determine the LTB quantity and if we strictly use one service level that holds for all SKUs to determine the LTB quantity with Equation 5.12. Another option is to combine the two approaches as follows. The company could determine a minimum required service level (β) such that at least a certain fill rate is achieved for each of the SKUs. Equation 5.9 is then used to determine the recommended service level that minimizes the total expected costs for every SKU. If Equation 5.9 returns a higher service level than the minimum required service level (β), the LTB quantity of the SKU is determined with Equation 5.10. If this is not the case, the LTB quantity of the SKU is determined with the minimum required service level and thus Equation 5.12. In that way, a minimum fill rate is assured for every single SKU whereas the total costs are still minimized as much as possible. It is then still up to the executive board of the company to determine this minimum required service level. The minimum required service level does not necessarily need to be the same for every SKU. It is also possible to set different minimum required service levels for different items and even for customer groups.

6.2 Sensitivity analysis of the input parameters

As some of the input parameters are based on assumptions, sensitivity analyses were done to determine whether any changes in these input parameters would lead to different results. In this section only the relevant conclusions of the analyses are presented and discussed. Additional results of the sensitivity analyses have been included in Appendix C.

6.2.1 Sensitivity analysis of the discount factor

The initial value of the discount factor was set at 5%. In this sensitivity analysis, the discount factor was decreased to 1% and 2% and increased to 7,5% and 10% to analyze the impact on the total expected discounted costs and the fill rate.

If Equation 5.10 is used to the determine the LTB quantity such that the total expected discounted costs are minimized, the following conclusions can be drawn. For the fill rate it holds that the higher the discount rate, the lower the fill rate. Looking at the structure of Equation 5.9 this makes sense, as the formula will return a higher probability of facing a shortage during the EOL phase and as a result the LTB quantity will be lower. This means that less spare part requests during the EOL phase can be fulfilled with a spare part of the original model and thus that the fill rate will be lower. An overview of the fill rates for the different policies with the different discount factors is given in Table 17 below.

Table 17: Overview for the fill rates of the different policies with different discount factors

	Discount factor 1%	Discount factor 2%	Discount factor 5%	Discount factor 7,5%	Discount factor 10%
Fill rate policy 1	99,3%	99,2%	99,1%	98,9%	98,8%
Fill rate policy 2	99,0%	98,9%	98,7%	98,5%	98,2%
Fill rate policy 3	98,6%	98,5%	98,2%	97,9%	96,8%
Fill rate policy 4	98,2%	98,1%	97,6%	96,8%	93,4%
Fill rate policy 5	97,5%	97,1%	93,6%	91,5%	89,7%
Fill rate policy 6	72,8%	72,7%	69,4%	67,9%	66,2%

The impact on the total expected discounted costs is a bit more complicated. Regardless of the value of the discount factor, Policy 6 always returns the lowest total expected discounted costs. However, the remaining order of the policies from a cost perspective changes for the different values of the discount factor. The results are shown in Table 18 on the next page.

Table 18: Overview of the total expected discounted costs of the different policies for different discount factors

	Discount factor 1%	Discount factor 2%	Discount factor 5%	Discount factor 7,5%	Discount factor 10%
Total costs policy 1	€811.698	€800.071	€768.641	€744.995	€723.792
Total costs policy 2	€793.352	€782.403	€752.098	€729.497	€709.074
Total costs policy 3	€777.853	€767.035	€737.514	€715.703	€696.604
Total costs policy 4	€764.960	€754.742	€725.803	€705.025	€711.929
Total costs policy 5	€749.255	€739.161	€720.887	€717.292	€697.249
Total costs policy 6	€672.960	€664.161	€658.040	€653.583	€639.263

The reason for these differences is that changes in the discount factor have an impact on the total expected discounted costs in two ways. First of all, different values for the discount rate result in different outcomes of Equation 5.9 and therefore different LTB quantities and thus in different expected number of shortages or overstock. Secondly, the holding costs, penalty costs and shortage costs are also dependent on the discount factor. The higher the discount factor, the lower these costs. The combination of these effects results in different rankings of the policies from a cost perspective.

If the discount factor is lower than the initial value of 5%, the conclusion that was drawn in the previous section remains the same. The fill rates of policies one to five were already high and are slightly higher in this case. Therefore, it still makes sense to use Equation 5.10 to determine the LTB quantity in order to minimize the total costs. The fill rate of Policy 6 is also slightly higher but the company could still decide to set a minimum required service level in order to achieve a higher fill rate. This will however result in higher total costs than the total costs presented in Table 18 for the different discount factors.

If the discount factor is higher than the initial value of 5%, the fill rates of policies one to five are slightly lower but they are still high. Therefore, it is still recommended to use Equation 5.10 to determine the LTB quantity for these policies such that the total expected discounted costs are minimized. The fill rate of Policy 6 is also somewhat lower in this case. If the company wants the fill rate to be higher, they could decide to set a minimum required service level but this will increase the total costs.

6.2.2 Sensitivity analysis of the distribution over the years of each spare part request type

In the sensitivity analysis the distribution over the years was only adjusted for one type of spare part requests (warranty, guarantee, or other) at the time. For all of them holds that if the distribution over the years is shifted more towards the first couple of years, the total expected discounted costs over the EOL phase decreases. The reason for this is that some of the spare part requests are no longer placed during the EOL phase but already before that time. Besides that, this means that the spare part requests are placed at an earlier stage such that their time on stock is reduced and therefore also the total expected holding costs.

Regarding the fill rate if Equation 5.10 is used to determine the LTB, a different impact is observed for the different types of spare part requests. If the distribution over the years of the warranty requests is shifted more towards the first year, the fill rates of policies one to five are slightly lower or approximately the same. The fill rate of Policy 6 decreases a bit more significantly. If the distribution over the years of warranty requests is shifted more towards the last year, the opposite holds. In Figure 9 on the next page, the original distribution, an example of a distribution that is shifted more towards the first year, and an example of a distribution that is shifted more towards the last year are depicted.

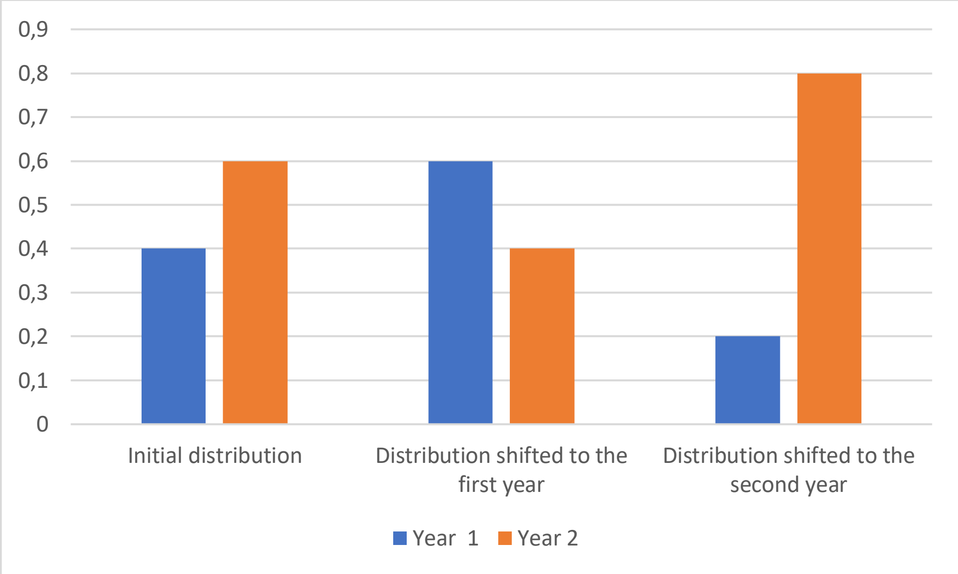

Figure 9: Different distributions over the years for the warranty requests

The resulting fill rates of the different policies with these distributions can be found in Table 19 below.

Table 19: Overview of the fill rates of the different policies for different warranty distributions

	Initial distribution of the warranty requests	Distribution of the warranty requests shifted more towards the first years	Distribution of the warranty requests shifted more towards the last years
Fill rate Policy 1	99,1%	99,1%	99,1%
Fill rate Policy 2	98,7%	98,7%	98,7%
Fill rate Policy 3	98,2%	98,2%	98,3%
Fill rate Policy 4	97,6%	97,5%	97,7%
Fill rate Policy 5	93,6%	92,5%	94,3%
Fill rate Policy 6	69,4%	66,2%	72,7%

Based on these results it can be concluded that changes in the warranty distribution over the years only have a small impact on the fill rates of the policies. Therefore, the conclusion on how the LTB quantity should be determined does not change.

If the distribution over the years of the guarantee or other spare part requests is shifted more towards the earlier years, the fill rates of policies one to three are approximately the same but those of policies four to six are slightly higher. A similar overview as given for the warranty distribution in Figure 9 and below.

Table 19 can be found in Appendix C for the guarantee and other spare part requests. However, the impact on the fill rates of the different policies is even smaller in these cases than was observed for changes in the warranty distribution over the years. Therefore, the conclusion on how the LTB quantity should be determined does not change.

6.2.3 Sensitivity analysis of the distribution over the request types

In the sensitivity analysis more weight was put on one of the three spare part request types at a time. The ratio of the other two request types was kept the same and the weights were converted such that the sum of the weights still equaled one such that the total amount of spare part requests, which includes the spare part requests before and during the EOL phase, remained the same as in the initial setting.

If more weight is put on the warranty requests, the total expected discounted costs decrease. The reason for this is that the warranty requests are only spread over two years so many of the requests are already placed before the EOL phase begins. The guarantee and other requests on the other hand, are spread over six years so a larger portion of these requests are placed during the EOL phase. Compared to the initial settings, now some of the guarantee and other requests have been turned into warranty requests and thus the number of spare parts during the EOL phase has decreased. Besides that, there is also a reduction in the holding costs because the items are kept shorter on stock. If more weight is put on the guarantee or other requests, the opposite holds. The impact is only smaller because interchanging guarantee and other requests does not change anything. Only the warranty requests that have been turned in guarantee or other requests have an impact.

Regarding the fill rate if Equation 5.10 is used to determine the LTB quantity, a different impact is observed for the different types of spare part requests. In Table 20 below, an overview is given of the fill rates of the different policies if the weight of a certain request type is multiplied by 1,5 and the other weights have been adjusted accordingly.

Table 20: Overview of the fill rate of the different policies for different distributions over the spare part request types

	Initial distribution	More weight on warranty requests	More weight on guarantee requests	More weight on other spare part requests
Fill rate Policy 1	99,1%	99,1%	99,1%	99,1%
Fill rate Policy 2	98,7%	98,7%	98,7%	98,7%
Fill rate Policy 3	98,2%	98,4%	98,2%	98,1%
Fill rate Policy 4	97,6%	97,9%	97,5%	97,5%
Fill rate Policy 5	93,6%	95,3%	92,5%	91,8%
Fill rate Policy 6	69,4%	76,3%	65,7%	64,8%

If more weight is put on the warranty requests, the fill rates of policies one to four are slightly higher or approximately the same. The fill rates of policies five and six are increased a bit more significantly. If more weight is put on the guarantee or other requests, the fill rates of policies one to four are approximately the same or slightly lower. The fill rates of policies five and six are decreased a bit more significantly.

As the fill rates of policies one to five are still high in all these cases, the recommendation remains to use Equation 5.10 to determine the LTB quantity that minimizes the total expected discounted costs. Besides that, it still holds for Policy 6 that the company could decide to set a minimum required service level in order to achieve a higher fill rate.

6.2.4 Sensitivity analysis of the standard deviation of the total spare part demand during the EOL phase

In the current forecasting methods, the technical service department only uses point forecasts and does not consider any variability in demand. In the analysis it was therefore assumed that the quantity of the demand is normally distributed with the point forecast as the mean and a standard deviation that equals 5% of the mean. However, as the actual standard deviation of the spare part demand during the EOL phase is unknown it is important to check whether different decisions would have been made if the standard deviation has a different value. Therefore, two sensitivity analyses are done regarding the standard deviation. First, we look at the impact on the results if the standard deviation of the spare part demand during the EOL phase equals 10%, 15% and 20% of the mean. After that, we check for these different levels of the standard deviation of the spare part demand during the EOL phase what the impact is if these deviate from the actual standard deviation of the spare part demand during the EOL phase.

Predicted standard deviation is equal to the actual standard deviation

In general it holds that the higher the standard deviation of the spare part demand during the EOL phase, the higher the total expected discounted costs and the lower the fill rate. This holds for the case Equation 5.10 is used to determine the LTB and the case that the service level (β) is determined by the company itself and Equation 5.12 is used to determine the LTB. In

Table 21 below, an overview is given of the fill rates of the different policies for different values of the standard deviation of the spare part demand during the EOL phase. It is important to note here that the standard deviation of the spare part demand during the EOL phase is one of the input parameters of Equation 5.10 and Equation 5.12 so a different standard deviation of the spare part demand during the EOL phase will also result in different LTB quantities for the SKUs.

Table 21: Overview of the fill rates of the different policies for different levels of the standard deviation of the spare part demand during the EOL phase

	St. Dev. 5%	St. Dev. 10%	St. Dev. 15%	St. Dev. 20%
Fill rate Policy 1	99,1%	98,3%	97,6%	97,0%
Fill rate Policy 2	98,7%	97,6%	96,6%	95,7%
Fill rate Policy 3	98,2%	96,6%	95,2%	93,8%
Fill rate Policy 4	97,6%	95,5%	93,5%	91,7%
Fill rate Policy 5	93,6%	87,5%	83,2%	81,0%
Fill rate Policy 6	69,4%	38,8%	22,4%	21,4%

For policies one to four, the fill rates remain quite high even if the standard deviation of the spare part demand during the EOL phase is increased to a value that equals 20% of the mean. The impact on the fill rate of Policy 5 is more significant but the resulting fill rates are still relatively high. Therefore, the conclusion on how to determine the LTB quantity for these policies does not change.

For Policy 6 it holds that increasing the standard deviation of the spare part demand during the EOL phase has a great impact on the fill rate. Therefore, it is recommended to set a minimum required service level for this policy if the standard deviation of the spare part demand during the EOL phase is expected to be higher than 5% of the mean for a certain SKU. In that way it can be prevented that many of the SKUs end up with a service level of zero and thus a really low fill rate.

In Table 22 on the next page, an overview is given of the resulting fill rates for different service levels (β) and the different levels of the standard deviation of the spare part demand during the EOL phase. As concluded before, the higher the standard deviation of the spare part demand during the EOL phase, the lower the fill rate. Besides that, an increase in the fill rate will result in an exponential increase in the total expected discounted costs as was previously shown in Figure 8.

Table 22: Resulting average fill rates for different values of the service level (β) and different levels of the standard deviation of the spare part demand during the EOL phase

	St. Dev. 5%	St. Dev. 10%	St. Dev. 15%	St. Dev. 20%
$\beta = 0{,}10$	93,6%	87,5%	81,7%	76,1%
$\beta = 0{,}25$	96,1%	92,4%	89,0%	85,8%
$\beta = 0{,}40$	97,5%	95,1%	93,0%	91,1%
$\beta = 0{,}60$	98,7%	97,5%	96,4%	95,5%
$\beta = 0{,}80$	99,5%	99,1%	98,7%	98,3%
$\beta = 0{,}90$	99,8%	99,6%	99,5%	98,9%
$\beta = 0{,}99$	100%	100%	100%	100%

Expected standard deviation differs from the actual standard deviation

In general it holds that the total expected discounted costs are higher and the fill rate is lower if the expected standard deviation of the spare part demand during the EOL phase is lower than the actual standard deviation of the spare part demand during the EOL phase. If the expected standard deviation of the spare part demand during the EOL phase is higher than the actual standard deviation of the spare part demand during the EOL phase, the opposite holds. In Table 23 below, an overview is given of the fill rate of the different policies for an expected standard deviation of the spare part demand during the EOL phase of 10% of the mean and different values for the actual standard deviation of the spare part demand during the EOL phase. In Appendix C some additional results with different settings of the expected standard deviation of the spare part demand during the EOL phase have been included.

Table 23: Overview of the fill rate of the different policies for different values of the expected and actual standard deviation of the spare part demand during the EOL phase

	Expected St. Dev. 10% & Actual St. Dev. 10%	Expected St. Dev. 10% & Actual St. Dev. 15%	Expected St. Dev. 10% & Actual St. Dev. 5%
Fill rate Policy 1	98,3%	97,9%	99,5%
Fill rate Policy 2	97,6%	96,2%	99,0%
Fill rate Policy 3	96,6%	95,2%	98,0%
Fill rate Policy 4	95,5%	94,1%	96,8%
Fill rate Policy 5	87,5%	86,4%	88,6%
Fill rate Policy 6	38,8%	38,8%	38,9%

It turns out that if the expected standard deviation of the spare part demand during the EOL phase is somewhat higher or lower than the actual standard deviation of the spare part demand during the EOL phase, this does not have a significant impact on the fill rate of Policy 6. The impact on the fill rates of the other policies is a bit higher but the fill rates remain high. Therefore, the conclusions on how to determine the LTB quantity for the different policies do not change. For higher levels of the expected standard deviation, the same impact has been observed.

6.3 Selecting the optimal solution

In the analysis six different policies were used to determine what the total expected discounted costs and the fill rate are for the two approaches of determining the LTB quantity. From the analysis it can be concluded that for policies one to five, Equation 5.9 selects a high service level (probability of facing no shortage during the EOL phase) for the individual SKUs and as a result the fill rate is quite high. As the service level is determined separately for every single SKU, the fill rate could vary between the different SKUs. Looking at the simulation mean of the 10th percentile of the fill rate it can be concluded that for most of the SKUs the fill rate is high.

Instead of using Equation 5.9, one could also choose to determine the service level upfront and set this equal for all SKUs. This does however, result in high additional costs. It has been concluded for policies one to five that the additional costs are not worth the slight increase in the overall fill rate.

From the sensitivity analysis it can be concluded that any changes in the discount rate, the distribution over the years of each spare part request type, the distribution over the spare part request types, and the standard deviation of the spare part demand during the EOL phase, do not result in different conclusions for these policies.

For Policy 6, Equation 5.9 selects a low service level (probability of facing no shortage during the EOL phase) for the individual SKUs. In some cases, Equation 5.9 even recommends to select a service level of zero. As a result, the fill rate is significantly lower for this policy than the other policies. Besides that, the differences in the fill rate between the single SKUs is much larger.

From the sensitivity analysis it can be concluded that any changes in the discount rate, the distribution over the years of each spare part request type, and the distribution over the spare part request types could result in slightly lower or higher fill rates but the impact is limited. However, if we work with a higher value for the standard deviation of the spare part demand during the EOL phase, the fill rate decreases significantly.

Therefore, if Policy 6 is used, it is recommended to determine a minimum required service level (β) such that a least a certain fill rate is achieved for every single SKU. This minimum required service level does not have to be equal for every SKU. With this approach it is possible to discriminate between different products and even customers if that is preferred. The company could for example set a higher minimum required service level for their premium customers. The overview of the fill rate for different service levels (β) as presented in Table 22 could help in the decision-making process.

The LTB quantity is then determined as follows. If the recommended service level of Equation 5.9 is higher than the minimum required service level (β), the LTB quantity is calculated with Equation 5.10. Otherwise, the LTB quantity is calculated with Equation 5.12 and thus the minimum required service level. In principle, this approach could also be used for the other policies as in general Equation 5.9 will already recommend a high service level which is most likely higher than the minimum required service level set by the company.

6.4 Conclusion

This chapter provided an analysis of different approaches that could be used to determine the LTB quantity. It answers the research question: *"How should the last time buy quantity be determined?"*. The following conclusions are drawn:

1. If the policy for unfulfilled guarantee and other spare part requests is to offer discount to the customer or to buy back the original product, Equation 5.10 should be used to determine the LTB quantity.
2. If the policy for unfulfilled guarantee and other spare part requests is to use an alternative spare part, a minimum required service level (β) should be determined. If the recommended service level of Equation 5.9 is higher than the minimum required service level (β), the LTB quantity is determined with Equation 5.10. Otherwise, the LTB quantity is determined with the minimum required service level and thus Equation 5.12.

Together with the previous chapter the fourth research question *"How should the company cope with the EOL phase?"* has been answered. Now we need to make sure that the recommended approaches can be implemented properly. In the next chapter it is described how this should be done exactly.

Chapter 7 – Implementation

In the previous two chapters it has been explained how the company should cope with spare part demand during the EOL phase. What is still missing, is an implementation plan which explains how the company should work with the proposed solutions and what this means for the current spare part management processes. This is exactly what this chapter is about.

In Section 7.1 it is explained how the EOL solution of the parts of commodity groups 1 and 2 should be implemented. After that, Section 7.2 describes how the EOL solution of the other CEP should be implemented. The chapter is concluded in Section 7.3.

7.1 Implementation of the EOL solution for the parts of commodity groups 1 and 2

For the parts of commodity groups 1 and 2 it was determined that the LTB should be used as the main solution for the EOL phase. How the LTB quantity should be determined exactly, depends on the policy for unfulfilled spare part requests during the EOL phase if the LTB quantity turns out to be insufficient. For the warranty requests the policy is in principle to buy back the original product. For the guarantee and other requests the policy is to use an alternative part that is not in the EOL phase, offer discount on a new product, or to buy back the original product.

The following steps must be taken once a part reaches the EOL phase:

1. Determine the policy for unfulfilled guarantee and other requests during the EOL phase.
2. Calculate the penalty costs for the chosen policy.
3. Calculate the probability of facing no shortage during the EOL phase with Equation 5.9.
4. Compare the outcome of the Equation 5.9 with the minimum required service level (β), if applicable:
    a. If outcome Equation 5.9 > minimum required service level (β), use Equation 5.10.
    b. If outcome Equation 5.9 < minimum required service level(β), use Equation 5.12.
5. Determine the LTB quantity.

A tool has been made in Excel that follows these steps and automatically determines the right LTB quantity. The technical service department only needs to insert the required input data for Equation 5.9 and the minimum required service level (β).

As we distinguish between the different spare part request types with the policy of unfulfilled requests during the EOL phase, it is important to keep track of the distribution over the different spare part requests types. This distribution should be updated regularly in order to accurately determine the penalty costs, which is one of the input parameters in Equation 5.9.

Besides that, the demand forecast is a critical input parameter in the calculation of the LTB quantity. Therefore, it is important that this forecast is updated based on the actual spare part demand and the actual sales numbers of the end products. In Chapter 2 it was concluded that this forecasting method needs to be improved by reducing the so-called "expert opinion" input and making better use of the available historical demand data and installed base information. Ideally, multiple spare part demand forecasting methods that have been proven to work successfully in practice would be tested to determine the best fit. Within the time limitations of this research project it was unfortunately not possible to do extensive research in this field. Instead, it was determined how the "expert opinion" input could be reduced in the current method and which historical demand data and installed base information could be incorporated to improve the accuracy of the forecasts.

In order to calculate the LTB quantity, the standard deviation of the spare part demand distribution during the EOL phase must be known. Company A works only with point forecasts. Therefore, in the analysis we used the Normal distribution with the point forecasts as the mean and tested different levels of the standard deviation. However, in order to obtain more accurate results for the LTB quantity, it is recommended that the company does further research to obtain a more accurate approximation of the standard deviation of the spare part demand during the EOL phase.

7.2 Implementation of the EOL solution for the other CEP

It was concluded in Chapter 5 that the solution for the other CEP is in principle to use an alternative spare part that has not reached its EOL phase yet. If this is not possible or if the alternative part is not in line with the legal warranty requirements, then the LTB option should be used to fulfill (a part of) the spare part demand in the EOL phase. This was also depicted in the decision chart in Figure 5. The LTB quantity for these items should be determined with Equation 5.10.

In order for this approach to be successful, it is important to maintain a good overview of the available alternative materials. For most of the other CEP, the company already has a list of available alternative materials that can be used if the original part is not available. This list is already used for shortages during the replenishment lead time. However, this list is not complete yet and should be updated such that there is an overview that contains alternative materials for all of the CEP.

Once a part reaches its EOL phase and an alternative part is used, this means that the demand forecast of the alternative part must be updated. However, it is still important to keep track of the original demand of the different parts for future demand forecasts. This does not only hold for the EOL phase but also in general. If alternative parts are used to fulfill demand of another part, this must be registered properly in the system such that the forecasting team is able to trace back the original demand of the parts.

Also here holds that the demand forecast is a critical input parameter in the calculation of the LTB quantity. In Chapter 2 it was concluded that most of the other CEP do not have a formal demand forecasting method. Besides that, it was concluded that the forecasts that were made could be improved. As explained in the previous section, it was not possible within the time limitations of the research project to do extensive research in this field.

Nevertheless, some literature research has been done to gain more information about spare part demand forecasting methods that make use of installed base information. One relatively simple method has been found, namely the method of Kim, Dekker, and Heij (2017). They introduced a method that requires little computational effort and is easy to understand and implement. Using linear regression, they forecast the future spare part demand based on the historic demand and installed base data and the average age of the installed base.

Another discrete time approach with age-based installed base information is presented by Minner (2011). The framework consists of a product level and a component level. The reason for this is that the age of the product and the component may differ, such that we need to keep track of both. This approach improves the accuracy of the forecasts, but it also significantly increases the computational effort. Especially with a high number of SKUs, this method can become very expensive in terms of computation time and employee efforts. Other more complex methods have been proposed by Jin and Liao (2009) and Jin and Tian (2012) for example but these require a higher level of expertise and involve extensive mathematical calculations.

Especially the method of Kim, Dekker, and Heij (2017) could be interesting for Company A as it is easy to understand and requires little computational effort. As some historical data is needed in order to determine the unknown coefficients that are estimated with linear regression, this method is not really applicable to the parts of commodity groups 1 and 2 but this method could be interesting for the other

CEP as these are used for a significantly longer period of time. It is recommended that the company looks further into this.

7.3 Conclusions

In this chapter it is explained how the different EOL solutions that have been formulated for the different CEP should be implemented in the company and what this means for the current spare part management processes. It answers the final research question *"How should the EOL solution(s) be implemented in the company?"*.

A tool has been developed in Excel that should be used to determine the LTB quantities. For the parts of commodity groups 1 and 2, it is important to determine the applicable policy and the minimum required service level if necessary, before the LTB quantity can be determined. For future research it is recommended to look into the spare part demand forecasting methods for further improvement.

Chapter 8 – Conclusions and recommendations

This chapter contains the conclusions and recommendations of this research project. In Section 8.1 the findings of this research are concluded and in Section 8.2 the recommendations for our findings and further research are stated and discussed.

8.1 Conclusions

The objective of this research project was defined as follows:

"Developing a suitable spare parts management process for the end-of-life phase in order to improve order fulfillment of Company A Engineered Parts"

By means of theoretical and practical research, multiple solutions for order fulfillment during the EOL phase were found. These solutions were examined based on the three criteria set by the company: legal requirements, customer service level, and total costs.

Different solutions were formulated for the different CEP. The best solution for the parts of commodity groups 1 and 2 is the LTB solution. If the LTB quantity turns out to be insufficient, the company must buy back the original part from customers with a warranty request. All other customer requests may also be fulfilled with an alternative part that has different specifications or the company can offer these customers discount on a new product or buy back the original product at a depreciated price.

The best way to determine the LTB quantity for these parts depends on the policy that holds for the unfulfilled guarantee and other spare part requests. The policy for unfulfilled warranty requests is always to buy back the original product. If the policy for unfulfilled guarantee and other spare part requests is to offer discount to the customer or to buy back the original product, Equation 5.10 should be used to determine the LTB quantity.

If however the policy for unfulfilled guarantee and other spare part requests is to use an alternative spare part, a minimum required service level (β) must be determined. If the recommended service level of Equation 5.9 is higher than the minimum required service level (β), the LTB quantity should be determined with Equation 5.10. Otherwise, the LTB quantity should be determined with the minimum required service level and thus Equation 5.12.

The best solution for the other CEP is to use an alternative part that has not reached the EOL phase yet. If this is not possible or the company is not sure that this will be feasible in the future, the LTB option must be used instead. If the LTB quantity turns out to be insufficient, the company needs to buy back the original product or offer discount on a new product. The LTB quantity should be determined with Equation 5.10.

8.2 Recommendations

First of all, it is recommended to Company A to make use of the EOL solutions that have been proposed for the different parts. In order to make optimal use of these solutions, it is recommended that:

1. The company determines minimum required service levels (β) for the parts of commodity groups 1 and 2. This service level does not necessarily need to be equal for all the parts. The company could also choose to differentiation between SKUs and/or customers.
2. The technical service department uses the Excel tool to determine the LTB quantity.
3. Usage of alternative materials to fulfill spare part demand is properly registered such that the forecasting team can keep track of the original demand of the spare parts. In order to achieve this, a label must be added to the form that is filled out in SAP each time a spare part request is fulfilled. Besides that, all employees that fulfill spare part orders must be instructed and reminded regularly that it is of great importance to fill out these forms accurately.

4. The distribution over the spare part request types (warranty, guarantee, other) is updated regularly such that the penalty costs, which are needed in the calculations of the LTB quantity, can be determined accurately. The order fulfillment forms in SAP already have the option to label the request type. So if the employees that fulfill spare part orders register the request type accurately, this information can simply be retrieved from the system by the technical service department.
5. The technical service department makes better use of historical demand and installed base data in their spare part demand forecasts. This can be done by using the actual sales numbers of the end product and the actual number of spare part requests in the calculations of the new failure rate of the part. Together with the technical service department a protocol has been written that provides an overview of which spare part demand forecasts must be made when and how and which information should be retrieved from the system to make the forecasts.
6. The company does further research to obtain a more accurate approximation of the demand distribution, including the standard deviation, of the spare parts.

Secondly, there are some recommendations for further research on this topic in general. In this analysis, only the EOL solutions that were applicable to Company A were included. However, in the literature research more EOL solutions were found. One interesting direction for future research would be to include for example the option of additive manufacturing or postponement of customization as these could lead to different decisions for the LTB quantity. Besides that, this analysis only considered the customer service level and total expected discounted costs but there might be other KPIs that should be taken into consideration as well.

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Appendix A – Ratio analysis

In the table below, a full overview is given of the actual failure rate until now of the parts of commodity group 1 and 2 and the ratio between these two of each of the platforms analyzed.

Platform	Failure rate parts of commodity group 1	Failure rate parts of commodity group 2	Ratio
R22	1,7%	1,0%	56,7%
R25	0,7%	1,0%	148,2%
R28	3,3%	0,3%	8,2%
R32	2,3%	1,6%	68,4%
R33	1,7%	2,0%	117,2%
R34	0,8%	0,5%	65,9%
R36	4,8%	2,4%	51,1%
R39	4,9%	4,2%	86,9%
R45	1,4%	1,0%	73,7%
R46	0,5%	1,5%	279,4%
R49	5,7%	2,5%	43,9%
R50	2,0%	0,0%	0,0%
R51	0,8%	3,1%	404,9%
R52	2,4%	3,1%	125,8%
R54	0,8%	1,5%	190,7%
R55	0,2%	3,1%	1366,2%
R56	0,5%	0,4%	79,5%
R57	0,4%	1,0%	235,3%
R58	0,6%	2,2%	363,8%
R59	2,3%	0,9%	38,5%
R66	1,2%	1,5%	129,3%
R67	2,0%	2,0%	96,8%

Appendix B – Total cost and fill rate overview of the policies

In this appendix, an overview is given for each policy of the total costs and the fill rate when Equation 5.9 is used and when the probability of facing no shortage during the EOL phase is set equal for all SKUs. Only the probabilities that are higher than the mean of the probabilities of facing no shortage during the EOL phase that have been determined with Equation 5.9 for every single SKU, are included in the overviews.

Total costs and fill rate of Policy 1 with different probabilities of facing no shortage during the EOL phase ($\boldsymbol{\beta}$).

Probability of facing no shortage during the EOL phase	Simulation mean of the sum of the total expected discounted costs of the SKUs	Simulation mean of the average over the fill rate of the SKUs	Simulation mean of the 10th percentile of the fill rate of all the SKUs	Simulation mean of the 90th percentile of the fill rate of all the SKUs
Determined with Equation 5.9	€768.641	99,1%	96,5%	100%
$\beta = 0{,}80$	€791.855	99,5%	98,1%	100%
$\beta = 0{,}90$	€824.899	99,8%	99,7%	100%
$\beta = 0{,}99$	€926.435	100%	100%	100%

Total costs and fill rate of Policy 2 with different probabilities of facing no shortage during the EOL phase ($\boldsymbol{\beta}$).

Probability of facing no shortage during the EOL phase	Simulation mean of the sum of the total expected discounted costs of the SKUs	Simulation mean of the average over the fill rate of the SKUs	Simulation mean of the 10th percentile of the fill rate of all the SKUs	Simulation mean of the 90th percentile of the fill rate of all the SKUs
Determined with Equation 5.9	€752.098	98,7%	95,4%	100%
$\beta = 0{,}80$	€787.963	99,5%	98,1%	100%
$\beta = 0{,}90$	€823.252	99,8%	99,7%	100%
$\beta = 0{,}99$	€926.319	100%	100%	100%

Total costs and fill rate of Policy 3 with different probabilities of facing no shortage during the EOL phase ($\boldsymbol{\beta}$).

Probability of facing no shortage during the EOL phase	Simulation mean of the sum of the total expected discounted costs of the SKUs	Simulation mean of the average over the fill rate of the SKUs	Simulation mean of the 10th percentile of the fill rate of all the SKUs	Simulation mean of the 90th percentile of the fill rate of all the SKUs
Determined with Equation 5.9	€737.514	98,2%	94,2%	100%
$\beta = 0{,}60$	€749.563	98,7%	95,4%	100%
$\beta = 0{,}80$	€785.347	99,5%	98,1%	100%
$\beta = 0{,}90$	€822.139	99,8%	99,7%	100%
$\beta = 0{,}99$	€926.240	100%	100%	100%

Total costs and fill rate of Policy 4 with different probabilities of facing no shortage during the EOL phase ($\boldsymbol{\beta}$).

Probability of facing no shortage during the EOL phase	Simulation mean of the sum of the total expected discounted costs of the SKUs	Simulation mean of the average over the fill rate of the SKUs	Simulation mean of the 10th percentile of the fill rate of all the SKUs	Simulation mean of the 90th percentile of the fill rate of all the SKUs
Determined with Equation 5.9	€725.083	97,6%	92,9%	100%
$\beta = 0{,}60$	€745.370	98,7%	95,4%	100%
$\beta = 0{,}80$	€783.720	99,5%	98,1%	100%
$\beta = 0{,}90$	€821.449	99,8%	99,7%	100%
$\beta = 0{,}99$	€926.191	100%	100%	100%

Total costs and fill rate of Policy 5 with different probabilities of facing no shortage during the EOL phase ($\boldsymbol{\beta}$).

Probability of facing no shortage during the EOL phase	Simulation mean of the sum of the total expected discounted costs of the SKUs	Simulation mean of the average over the fill rate of the SKUs	Simulation mean of the 10th percentile of the fill rate of all the SKUs	Simulation mean of the 90th percentile of the fill rate of all the SKUs
Determined with Equation 5.9	€720.887	93,6%	85,7%	57,3%
$\beta = 0{,}40$	€729.875	97,5%	93,0%	100%
$\beta = 0{,}60$	€741.178	98,7%	95,4%	100%
$\beta = 0{,}80$	€782.093	99,5%	98,1%	100%
$\beta = 0{,}90$	€820.759	99,8%	99,7%	100%
$\beta = 0{,}99$	€926.142	100%	100%	100%

Total costs and fill rate of Policy 6 with different probabilities of facing no shortage during the EOL phase ($\boldsymbol{\beta}$).

Probability of facing no shortage during the EOL phase	Simulation mean of the sum of the total expected discounted costs of the SKUs	Simulation mean of the average over the fill rate of the SKUs	Simulation mean of the 10th percentile of the fill rate of all the SKUs	Simulation mean of the 90th percentile of the fill rate of all the SKUs
Determined with Equation 5.9	€658.040	69,4%	57,3%	97,7%
$\beta = 0{,}10$	€663.415	93,6%	88,2%	99,4%
$\beta = 0{,}25$	€679.912	96,1%	91,0%	100%
$\beta = 0{,}40$	€698.599	97,5%	93,0%	100%
$\beta = 0{,}60$	€729.868	98,7%	95,4%	100%
$\beta = 0{,}80$	€777.704	99,5%	98,1%	100%
$\beta = 0{,}90$	€818.899	99,8%	99,7%	100%
$\beta = 0{,}99$	€926.011	100%	100%	100%

Appendix C – Additional results of the sensitivity analysis

In this appendix the additional results of the different sensitivity analyses have been included.

C.1 – Sensitivity analysis of the distribution over the years for the different spare part request types

In table below, an example is given for one distribution which is shifted more towards the first years and one distribution which is shifted more towards the last years for the guarantee requests.

	Initial distribution of the guarantee requests	Distribution of the guarantee requests shifted more towards the first years	Distribution of the guarantee requests shifted more towards the last years
Year 1	0.20	0.250	0.15
Year 2	0.30	0.350	0.25
Year 3	0.20	0.250	0.15
Year 4	0.15	0.075	0.20
Year 5	0.10	0.050	0.15
Year 6	0.05	0.025	0.10

The resulting fill rates of the different policies with the above distributions can be found in the table below.

	Initial distribution of the guarantee requests	Distribution of the guarantee requests shifted more towards the first years	Distribution of the guarantee requests shifted more towards the last years
Fill rate Policy 1	99,1%	99,1%	99,1%
Fill rate Policy 2	98,7%	98,7%	98,7%
Fill rate Policy 3	98,2%	98,2%	98,2%
Fill rate Policy 4	97,6%	97,7%	97,6%
Fill rate Policy 5	93,6%	93,7%	93,1%
Fill rate Policy 6	69,4%	70,0%	69,3%

In the table below, an example is given for one distribution which is shifted more towards the first years and one distribution which is shifted more towards the last years for the other spare part requests.

	Initial distribution of the other spare part requests	Distribution of the other spare part requests shifted more towards the first years	Distribution of the other spare part requests shifted more towards the last years
Year 1	0.20	0.250	0.15
Year 2	0.30	0.350	0.25
Year 3	0.20	0.250	0.15
Year 4	0.15	0.075	0.20
Year 5	0.10	0.050	0.15
Year 6	0.05	0.025	0.10

The resulting fill rates of the different policies with the distributions of the previous table can be found in the table below.

	Initial distribution of the other spare part requests	Distribution of the other spare part requests shifted more towards the first years	Distribution of the other spare part requests shifted more towards the last years
Fill rate Policy 1	99,1%	99,1%	99,1%
Fill rate Policy 2	98,7%	98,7%	98,7%
Fill rate Policy 3	98,2%	98,2%	98,2%
Fill rate Policy 4	97,6%	97,7%	97,6%
Fill rate Policy 5	93,6%	93,7%	93,5%
Fill rate Policy 6	69,4%	70,1%	69,3%

C.2 – Sensitivity analysis of the standard deviation of the spare part demand during the EOL phase

In the tables below, an overview is given of the fill rates of the different policies for different values of the expected and actual standard deviation of the spare part demand during the EOL phase.

	Expected St. Dev. 5% & Actual St. Dev. 5%	Expected St. Dev. 5% & Actual St. Dev. 10%	Expected St. Dev. 5% & Actual St. Dev. 2%
Fill rate Policy 1	99,1%	97,5%	99,7%
Fill rate Policy 2	98,7%	97,1%	99,5%
Fill rate Policy 3	98,2%	96,6%	99,0%
Fill rate Policy 4	97,6%	96,1%	98,4%
Fill rate Policy 5	93,6%	92,4%	94,3%
Fill rate Policy 6	69,4%	69,4%	69,5%

	Expected St. Dev. 15% & Actual St. Dev. 15%	Expected St. Dev. 15% & Actual St. Dev. 20%	Expected St. Dev. 15% & Actual St. Dev. 10%
Fill rate Policy 1	97,6%	96,3%	98,8%
Fill rate Policy 2	96,6%	95,3%	97,9%
Fill rate Policy 3	95,2%	93,9%	96,5%
Fill rate Policy 4	93,5%	92,3%	94,7%
Fill rate Policy 5	83,2%	82,3%	84,2%
Fill rate Policy 6	22,4%	22,1%	22,5%

	Expected St. Dev. 20% & Actual St. Dev. 20%	Expected St. Dev. 20% & Actual St. Dev. 25%	Expected St. Dev. 20% & Actual St. Dev. 15%
Fill rate Policy 1	97,0%	95,8%	98,1%
Fill rate Policy 2	95,7%	94,5%	96,9%
Fill rate Policy 3	93,8%	92,7%	95,0%
Fill rate Policy 4	91,7%	90,6%	92,7%
Fill rate Policy 5	81,0%	80,2%	81,9%
Fill rate Policy 6	21,4%	21,3%	21,6%