Spare parts inventory management by a supplier of a capital good

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Spare Parts Inventory Management by a Supplier of a Capital Good.

by

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Abstract

This study investigates how a supplier of a module of a capital good can determine the spare parts re-order levels at the global warehouse of the capital good’s manufacturer and make efficiency improvements and cost reductions. The multi-item, single location inventory model of Kranenburg & van Houtum (2014) is used for taking spare parts inventory related decisions. With the model, the supplier can replicate the original situation and subsequently propose various efficiency improvements, based on the supplier’s insights. Inefficiencies can be improved by introducing emergency shipments or realizing shorter lead-time for instance.

The multi-item, single-location model has been tested in a business case in which first is tested whether the model can accurately replicate the original situation and subsequently investment costs between the original situation and possible improvements are compared. The model in this study is able to determine quantitative outcomes of supply chain modifications and can subsequently be compared with the costs of the modifications in order to make improvements with regard to the spare parts inventory.

Keywords: Maintenance, Spare Parts, Inventory Control, Capital Goods, Linear Programming, Queuing theory, Greedy Algorithms
Management Summary

A significant part of the total costs of ownership (TCO) of a capital good are deemed to be related to service-like activities, such as maintenance, downtime or spare parts. Furthermore it is evident that an optimization of these service activities can lead to large cost reductions, especially for manufacturers of capital goods.

These two reasons lead to the initiative where VDL ETG is appointed by a main customer to take over several service supply chain responsibilities with regard to the product VDL ETG manufactures. First, because the main customer focuses on the total service grade and not on the specific (VDL ETG made) sub-modules. Second, because VDL ETG might be able to realize supply chain improvements with its in-house knowledge of the concerned product.

In the future, VDL ETG faces the problem of being able to propose service supply chain improvements in order to reduce supply chain costs. Among many, one of the aspects of this service supply chain is the spare parts inventory held by the main customer (the manufacturer of the capital good). In order to be able to assess possible improvements, it is key for VDL ETG to gain understanding of how stock keeping works and how it can be influenced or optimized by internal changes. Because of the absence of knowledge at VDL ETG about how spare parts inventory, particularly used for service purposes in the field, is determined, this study concentrates on how the spare parts supply chain works, how stock levels can be determined and how VDL ETG can assess possible internal improvements that might be able to improve the overall service supply chain efficiency.

For the year 2013, an analysis shows several different spare parts streams. Most importantly, since it can be economical for expensive spare parts to repair them, a distinction is made between repaired parts and new parts.
This insurance stock, readily available when problems occur in the field, is distributed over several dozens of local warehouses over the world in order keep stock geographically close to the installed base. It is furthermore observed that these local warehouses are served by a global distribution center (GDC) where, by worth, about a quarter of the parts is stored. This GDC acts as a fast replenishment source towards the local warehouses. Demand at these local warehouses is based on user information and since the manufacturer is responsible for the service in the end by means of a service contract, it is best to keep the manufacturer responsible for the spare parts stock in the local warehouses. On the other hand it could be beneficial to improve the stock levels in the GDC.

Since all demand is fulfilled by the GDC, the combined demand of the local warehouses is observed at the GDC, the multi-item, single-location inventory model of Kranenburg & van Houtum (2014) is used to determine stock levels at the GDC, based on various parameters like procurement lead-times, demand rates, scrap rates, etc. The model can both for a system approach (all stock keepin units (SKU) together) or for a unit approach (per SKU) determine the optimal stock levels in order to achieve various types of key performance indicators (KPI). These KPI’s are defined by the manufacturer and should be achieved in order to realize the admired performance of the service supply chain.

**Conclusions**

The multi-item model that has been used in this research, aims at minimizing the investment costs with regard to the spare parts inventory in the GDC, while taking various parameters, like lead-times, demand rates and holding costs into account.

First, the model was compared to the original situation, where the manufacturer define the stock levels for spare parts in the GDC. The results can be seen in table below. Two different KPI have been used. In the original situation a sample of items in the GDC realized a fill rate (percentage of the demand that can directly be fulfilled) service measure of 58.84%. The model discussed in this research is able to realize the same fill rate with about 6% less investment costs. Furthermore, the original expected number of backorders per year (EBO) is considered to be 25.42. When using the KPI as a constraint for the model, a cost reduction of about 11% is realized.

<table>
<thead>
<tr>
<th>Fill Rate model</th>
<th>Total initial investment</th>
<th>Total Holding Costs</th>
<th>Actual Fill Rate</th>
<th>Actual EBO</th>
<th>Mean Waiting time</th>
<th>Total Items</th>
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<tr>
<td>% improvement</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Fill Rate model</td>
<td>6.3%</td>
<td>6.3%</td>
<td>+0.0%</td>
<td>+63.5%</td>
<td>+63.5%</td>
<td>-29.6%</td>
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<tr>
<td>% improvement</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>EBO model</td>
<td>11.6%</td>
<td>11.6%</td>
<td>-15.4%</td>
<td>-0.1%</td>
<td>-0.1%</td>
<td>-3.4%</td>
</tr>
<tr>
<td>% improvement</td>
<td></td>
<td></td>
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</table>
Considering a 6% cost reduction under the same input parameters, one could conclude that the model approximates the original model. The difference in costs could be due to the fact that only a portion of the total number of SKU’s is used as a reference. Using the EBO KPI, a much larger cost improvement is realized. The EBO measure is calculated in a different way than the fill rate service measure, since also the lead-time aspect is taken into account when determining the EBO. Mean waiting time for parts is in practice more important than the number of items directly delivered from on hand stock. It is therefore that the EBO and the mean waiting time for parts KPI’s are more applicable for this spare parts optimization problem.

Next, since it is important for VDL ETG to be able to decrease costs of the spare parts supply chain, a sensitivity analysis has been performed to determine how several parameters react on changes and how this affects the total investment costs. These finding are shown in the table below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Average</th>
<th>Incremental parameter increase</th>
<th>Percentage parameter decrease</th>
</tr>
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<tr>
<td>Average lead time</td>
<td>69.9 working days</td>
<td>1.9% increase in investment costs per extra day</td>
<td>8.8-9.0% decrease in investment costs per 10% decrease</td>
</tr>
<tr>
<td>Procurement lead time</td>
<td>86.7 working days</td>
<td>0.67% increase in investment costs per extra day</td>
<td>4.5-5.5% decrease in investment costs per 10% decrease</td>
</tr>
<tr>
<td>Repair lead time</td>
<td>36.6 working days</td>
<td>1.0% increase in investment per extra day</td>
<td>2.5-3.6% decrease in investment costs per 10% decrease</td>
</tr>
<tr>
<td>Demand Rate</td>
<td>8.3 items per year</td>
<td>Increases 1.7-4.6% increase in costs per extra item/year</td>
<td>8.8% decrease in investment costs per 10% decrease</td>
</tr>
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Since the model that was used holds promise for implementation and further use at VDL ETG, a decision-support tool (software) has been developed, which is based on this model. This tool can be used by logistics planners, service employees and purchasers to both determine optimal spare parts stock levels at the GDC or a single warehouse, or to assess possible parameter improvements for their effects on the supply chain’s performance.

**Recommendations**

Based on the conclusions, the following recommendations are given to VDL ETG

**Implementation of the decision-support tool:** VDL ETG should be able to search for optimal spare parts stock values in order to understand the supply chain better. In this research, a multi-item, single location optimization model has been developed to determine the optimal stock levels such that investment costs can be determined. Furthermore this model can be used to validate proposed parameter changes.

**Investigate internal cost parameters:** This research mainly concentrated on how input parameters should change in order to realize a certain cost-down in investment costs. On the other hand it is very important to determine what costs are incurred when changing these parameters.
Investigate supply chain redesign possibilities with the proposed model: When more is known about costs for internal parameter changes, it is recommended to search for improvement opportunities with the decision support tool.

Research optimization of end-of-life products: As has been discussed before, VDL ETG will be responsible for the production of spare parts for 10 years after a certain product goes end-of-life. When a product is end-of-life, this has a significant impact on the production price of spare parts, mainly because there is no regular flow of new-build parts anymore. Since it can still be beneficial to maintain a stock of spare parts for end-of-life product, it is recommended to investigate how VDL ETG should make the transition from regular spare parts inventory to end-of-life spare part inventory and how the production of end-of-life spare parts during this 10 year period should be produced.

Discuss the customer service approach with the manufacturer: In the case study section, it was observed that a different approach towards the service measure resulted in different obtained inventory solutions. Knowing that the mean waiting time for parts is a more appropriate KPI for spare parts, where time is a very important factor, VDL ETG should discuss on which type of KPI is wants to be reviewed by the manufacturer.
Preface

Eindhoven, September 8th, 2014

This report is the result of my Master thesis project, which I conducted in partial fulfillment for the degree of Master in Operations Management and Logistics at Eindhoven University of Technology in the Netherlands.

I conducted this project from March to September 2014 for VDL ETG in Eindhoven. It was an incredibly instructive and, above all, fun experience to put all the knowledge I gained the past five years into practice. The high-tech environment at VDL ETG, which affects all of us in our everyday lives, is very inspiring and made me feel significant in a sense.

During the project, I had the pleasure to work with inspiring people from both VDL ETG and from Eindhoven University.

From VDL ETG, I would like to thank my daily supervisor William van der Put. William is a very inspiring and committed guy. There is no problem he will shy away from or won’t go to the bottom of understanding to get it solved. I got to know him as a very friendly person, who was always prepared to support me and share his experience.

Furthermore, I thank Bram Corbijn, the initiator of this project. Although Bram is now pursuing new challenges at another company, it wouldn’t be without him, seeing the opportunity of this project, that I would have had the privilege to work for VDL ETG.

Thanks go to Theodoor Scheerder, my secondary supervisor. His experience, commercial focus and professional approach helped me working towards the right direction and taught me the ins and outs of working in a company environment.

Finally I owe thanks to everyone else who made time in his or her hectic day to provide me with time, information and a fun time.

From the university, I thank Arun Chockalingam, my mentor and primary supervisor. Discussions about the project, and especially about other topics, were always fun. Many thanks for the constructive way you guided me in my project and for always supporting me in the decisions I made.

Furthermore, as my second supervisor, I would like to thank Joachim Arts for his time, his critical reviews of my work and for sharing his outstanding expertise in all scientific knowledge I needed to know to perform this project.

This project concludes my years as a student, which I have enjoyed incredibly. I thank my friends for their support, their great companionship and all the fun we shared and will share in the future. Special thanks go to my parents, who always act in my best interests, regardless of their busy lives. Last but not least I would like to thank my girlfriend, Milou. In good times and in bad times, I could always count on you. For sure, starting my adult live together with you is my greatest achievement of all. Thank you so much for your love and support.

Jack Aelmans
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1. Introduction

This study investigates spare part inventory management in the high tech manufacturing industry. The optimal production, procurement and control of inventory levels of spare parts for capital goods, like airplanes, oilrigs, baggage handling systems or container ships, can be very complex. Though, not only these operations should be optimized, also the responsibilities within this spare parts supply chain to be taken by different parties should be examined and optimized. Moreover, optimal control of production, procurement and inventory levels of spare parts depend on how responsibilities are distributed within this supply chain.

The main motivation of this study is the initiative of a manufacturer and supplier of a capital good to transfer several supply chain responsibilities from the manufacturer to the supplier, referred to as the transfer initiative. Subsequently this leads to several questions with regard to the supply chain performance, which will be covered in this report.

The spare parts supply chain of a high tech module, which is assembled by VDL ETG and subsequently integrated by the final manufacturer (VDL ETG’s customer) in a capital good, is considered as a case example. The independent module is a completely functional module that VDL ETG assembles for the manufacturer. Since the functionality of this module is decisive for the functionality of the entire capital good, the installed base has to be supported by a fast-response safety-stock strategy, assuring high usability in the field. The supply chain is subject to a rapidly advancing environment and spare parts therefore have a relatively high risk of obsolescence, while the relative value of these spare parts is high. Additional complicating factors are the low demand, long lead-times and reparability of spare parts.

1.1 Project context

The final manufacturer of the capital good currently has an extensive logistics network that can provide customers with their service supply needs. With this network, where and how spare parts are stored and how servicing and repair are committed to customers is regulated. Furthermore, this network ensures that (possibly) defective parts return to the respective manufacturer for research in order to positively affect the R&D process and to investigate warranty claims. The total spare parts stock consists of 399 different ‘module-specific’ parts and 78 common parts (shared with other modules in the capital good) kept in stock at different warehouses in order to react quickly to failures in the field. In the current situation, the manufacturer determines re-order levels with its own policy and generates demand forecasts, which take installed-base, engineering-technical, and service contract related parameters into account. Furthermore the manufacturer decides when a spare part needs refurbishment or has to be re-ordered.

A major aspect of life-cycle supply and assuring a high utilization in the field is the availability of spare parts. The demand for spare parts usually comes from the need for machine maintenance, either preventive or when a failure occurs. The demand for spare parts often is difficult to predict due to the fact that breakdowns can occur at any time, therefore an optimal inventory policy on spare parts is difficult to determine. Furthermore, there is a trade-off between the availability of spare parts and the penalty costs for breakdown (Wang & Kang, 2009). Inventory costs will rise when inventory levels are higher, yet the costs of out-of-stock situations will drop when holding more stock and vice versa. Proper planning of spare part inventory and maintenance can reduce the associated costs of life-cycle service supply, making it an interesting issue for optimization.
1.1.1 The transfer initiative

As discussed before, the incentive of this assignment is that VDL ETG will take over part of the manufacturer’s service responsibilities with respect to the capital good, which is in its entirety assembled and partly fabricated by VDL ETG. Hence, the knowledge, expertise, research and design of this product lies for the most part with the supplier VDL ETG, making it a good candidate to individually decide how to organize the spare parts management process. At the end of this process the pieces have to come together perfectly as the effects of failure in the field are enormous. The price of the capital good can be up to tens of millions of euros, which makes a high utilization of this product very important.

For this reason it is crucial to research the consequences and feasibility of transferring supply chain responsibilities thoroughly. Also, as both companies pursue commercial interests, the financial impact of the concerned decisions should be evaluated.

The main idea behind this initiative is to trigger the developing party to improve its performance by awarding performance improvements, such as better design, lower failure rates, production cost reductions etc. This should result in creating an incentive to improve the product (which already meets its current requirements) further and finally result in cost reductions on the service supply chain as a whole. One aspect of this initiative will be a higher level of responsibility for the spare parts stock keeping process. VDL ETG will be able to propose improvements, depending on internal intelligence and will subsequently be awarded for cost reductions.

The initiative can be separated into three sequential phases. Phase one is referred to as ‘transfer as is’. Since VDL ETG produces not all parts and the manufacturer orders spare parts via ‘tier-2 suppliers’, this means that all spare parts will be rerouted via VDL ETG. After phase one, VDL ETG will be the only responsible party for delivery of spare parts towards the manufacturer. Obviously this rerouting will result in increased supplier lead-times and this responsibility entails an increased element of risk. A preliminary provision on top of the part price is meant to compensate this risk and cover extra costs incurred. In phase two VDL ETG aims at improving the spare parts supply chain performance. Examples by which this can be done is by optimizing logistics operations and improved batching production. Finally, phase three is considered as the ‘expansion’ phase. In fact VDL ETG will expand its service responsibilities towards the manufacturer. For example by taking over ownership of stock, or responsibility of availability of parts in a stocking point. Furthermore, depending on research and development, service parts can be combined in order to improve efficiency, known as ‘kitting’.

1.1.2 A rapidly advancing industry

In recent years, machinery products have become more and more complex, while product life cycles have become increasingly shorter. This is especially true in high tech industry sectors, where research and development can hardly keep up with increasing demands and desires of business customers. For this reason, manufacturers of high tech products tend to place more emphasis on their own core competences (Gottfredson, Puryear, & Phillips, 2005), developing and manufacturing their products and outsourcing other non-core activities to subcontractors (Wu, Chien, & Gen, 2012). For example a company closes a large contract that is significantly going to increase the volume of purchasing in a very short period of time. A way to save resources for important, key company activities is to outsource the purchasing activities.
Service supply is rarely a core competence of most manufacturing companies. It is, however, crucial for the life-cycle sustainment of high tech products. Moreover, as competition increases for highly innovative products, a manufacturer can differentiate itself from others with excellent additional services (Wang & Wang, 2010). Considering these two trends, companies within the value chain need to cooperate more closely and divide work more efficiently to create superior value. Service supply might be a very beneficial activity for subcontractors (Aberdeen Group, 2005) as stakes for end users are high and are therefore prepared to pay large sums of money for the life-cycle service supply of high-tech products.

1.2 The organization

The Van der Leegte Group (VDL Group) conglomerate employed over 10,000 people worldwide in August 2014 and had a turnover of 1.81 Billion euros in 2013 (VDL Groep, 2014). The main theme is metalwork, though this description is too narrow at the same time. The product range varies from parts and machines used in chip manufacturing, assembly of complete coaches, roof boxes, solariums and signposting. As to solariums, VDL takes the third place worldwide regarding market share and takes second place within the roof box market. The entire VDL Group is still in ownership of the van der Leegte family, making it one of the most prominent family businesses of the Netherlands.

VDL Enabling Technologies Group BV is a composition of 7 of the 81 operating companies that fall within the VDL Group (Figure 1.1). It was founded by Philips in the year 1900 as Philips machinefabrieken and has grown for more than 100 years in the science and industry sector as a production partner for mechatronic systems. In 2006 the VDL Group acquired the then called Philips Enabling Technologies Group, which resulted in the current name VDL Enabling Technologies Group. VDL ETG is a now tier-one contract manufacturer that is engaged in semiconductor capital equipment, thin film deposition equipment for photovoltaic solar systems, analytical instruments, medical systems, aerospace & defense parts and systems and mechanization projects. Furthermore it is one of the larger companies within the VDL Group with about 2000 employees, depending on the season.

VDL ETG’s goal is: “outperform customer expectations in delivering mechatronic solutions” and the company’s headquarter is located in Eindhoven, Netherlands. Furthermore VDL ETG has facilities in Almelo, Delft (Netherlands), Singapore, Suzhou (China) and Newfields (USA), in order to provide worldwide service and support to customers wherever they have manufacturing facilities.

![Figure 1.1: Organizational chart.](image)
2. Research Approach

The research approach is defined by summarizing the supply chain challenges, stating the problem definition, discussing the research context and explicitly formulating individual research questions.

2.1 Supply chain challenges

The following problem scheme is based on an interpretation of the current supply chain together with the transfer project’s requirements. Figure 2.1 gives the problem scheme, summarizing the main complexities VDL ETG has with regard to spare parts management due to the transfer project.

First of all, the transfer initiative creates the need for a formal inventory management policy. Since VDL ETG is going to be responsible for operational expenditures with regard to spare parts inventory, and VDL ETG will be rewarded for OPEX improvements, an inventory management policy is needed. Furthermore the complexity of the supply chain is such that not all employees understand the reasons for optimizing spare parts inventory management and the benefits and risks that come with that, one could say that this concept is new to VDL ETG. This limited understanding results in both the need for an inventory management policy and in the need for supply chain performance accountability measures also known as KPI’s (key performance indicators). The manufacturer is more familiar with inventory management strategies while this is new for VDL ETG. If VDL ETG wants to seriously be able to define supply chain accountability measures, it needs to understand the way stock keeping can be optimized by an inventory management policy. These undefined performance accountability measures together with the limited understanding of the supply chain lead to unknown opportunity gains, no insight in inventory related costs, limited insight in supply chain related risk and unknown post-transfer performance requirements. Subsequently one could say that there is no thorough insight in the consequences and opportunities with regard to the spare supply chain.

This leads to several problems:

1. The transfer project may not result in supply chain benefits.
2. The transfer project may result in risks that VDL ETG does not want to take.
3. As the transfer project is rolled out, there is no baseline to measure performance against.
4. Due to the lack of insight in costs and risks it is hard to make supply chain improvement decisions.
5. Because of shifting responsibilities there is a potential risk for the sustainability of the workflow and the assurance of current performance.
2.2 Problem definition

At present, 399 SKU’s are kept as insurance stock by the manufacturer, resulting in several millions of operational service expenses and inventory investment costs for the supply chain in 2013. VDL ETG and the manufacturer are considering the shift of several responsibilities within the spare parts supply chain. In other words, responsibilities like ordering, production planning and ownership of spare parts now rest with the manufacturer, though VDL ETG might do a better job at maintaining these responsibilities or at least can provide improvement suggestions by combining the manufacturer’s and VDL ETG’s knowledge.

The specific decision problem to be addressed is the question of what VDL ETG should change internally or externally in order to achieve economic benefits in a post-transfer scenario when several responsibilities within the spare parts supply chain are taken over. This is a multi-aspect decision to be taken by VDL ETG and the manufacturer, which addresses aspects like the ownership of spares, information sharing authorization, stocking, forecasting and order quantity decisions, repair or re-order decisions etc. Furthermore we should evaluate the consequences and feasibility of possible contracting aspects for VDL ETG in technical and financial perspective.

2.3 Research questions

The main research question that summarizes the aims of this research is formulated as:

What internal and external changes should VDL ETG implement with regard to the spare parts supply chain in order to achieve economic benefits by taking over spare parts management responsibilities and ownership?

Next, several sub-questions define the research in a more detailed way:

What exact changes can take place with regard to parameters that affect the supply chain performance in order to achieve economic benefits?

If VDL ETG accepts the responsibility of maintaining spare parts inventory in the GDC, how can VDL ETG optimize their internal production by determining order moments and production quantities for spare parts and smoothening production facility utilization?

What terms should be included in a service contract between the manufacturer and VDL ETG and, depending on the risk of these terms, how should the costs of the improved situation be shared in order to at least realize a break-even situation?
3. Literature Review

As an introduction to spare parts inventory management for capital goods, first the characteristics of a capital good and its lifecycle are explained. Next, the importance of capital good maintenance is underscored whereupon the consequences of downtime of capital goods are discussed. Furthermore several characteristics of the actual maintenance process, like the service contract between manufacturer and user, different types of maintenance, the actual spare parts inventory and occurrence of obsolescence are discussed.

3.1 Capital goods

Capital goods are durable assets that are used by companies to produce their end products or to deliver their services. Examples are oilrigs, roller coaster equipment and lithography machines. Usually a capital good’s life cycle consists of the following five stages as can be seen in figure 3.1. The first stage is tendering and occurs whenever there is an invitation to tender for a specific contract. After a contract has been awarded, the contract execution starts with engineering and procurement. Whenever the developed product meets all requirements, the physical process of manufacturing starts. The fourth stage is maintenance and support. Keeping capital goods up in the field is crucial since end users highly depend on the functioning of capital goods for their core activities. Finally, whenever the good does not meet current requirements, the machine will be disposed or will get a second life if it can meet requirements for other processes.

Because of the high complexity of capital goods, customers are usually inclined to outsource the maintenance and support aspect (after sales) of the machines to the original equipment manufacturers (OEMs). Furthermore there is a long-term trend that end users are getting more interested in purchasing a function rather than a tangible product meaning that after sales responsibilities for OEMs in keeping capital goods properly functioning generally increase (Stahel, 1994; Oliva & Kallenberg, 2003). To be able to fulfill these responsibilities, OEMs keep spare parts inventories geographically as close as possible to their customers in order to react to machine breakdowns and carry out preventive maintenance. These particular capital good spare parts are characterized by the need of a high continuous availability, since downtimes are very costly. Sporadic demand for these service spare parts can be considered another characteristic (Kennedy, Patterson, & Fredendall, 2002). Yet, due to the fact that downtimes are costly, the consideration is always made whether to stock a spare part, just in the rare event there is a demand occurrence.

Figure 3.2: Typical life cycle of a capital good (Hicks, Earl, & McGovern, 2000)

3.2 The importance of maintenance

From both an OEM and a user’s perspective, an important aspect of a capital good’s life cycle is the ongoing maintenance support needed to keep it operational. For a user it is important to minimize downtime as much as possible through a machine’s entire usable lifetime, since downtime of a capital good can cause blockage of an entire plant and entail lost profits. For this reason an OEM has
to be aware that adequate service is key to superior user satisfaction by minimizing the total cost of owning a capital good during its lifetime, which in short is denoted as ‘total cost of ownership’ (TCO). TCO is the most appropriate approach for determining how much a capital good actually costs for its entire usable life as not only procurement and development costs are considered as relevant, but also maintenance and downtime costs. While procurement costs of a capital good seem incredibly high ($5-50 million) and one can imagine that the development process of such equipment incur similarly large investment costs, maintenance and downtime costs are responsible for a significant part of the TCO for a capital good. Research conducted by Öner et al (2007) divides TCO into acquisition costs, maintenance costs and downtime costs and measured the individual costs for an engineer-to-order system. The outcome is given in figure 3.2. Though the actual distribution between these costs can vary per type of capital good and service strategy, it gives an impression that acquisition costs of capital goods is only the tip of the iceberg with regard to TCO. As a consequence, high tech OEM companies are becoming more and more focused on service support for their products, although they consider this not as a key activity. The underestimation of the importance of service is then easily made.

3.3 Consequences of downtime

The primary reason to perform maintenance and service activities is to reduce unscheduled downtime of capital goods as far as possible. As has been discussed earlier, downtime is responsible for a significant part of the TCO for a capital good. Downtime occurs when a capital good in the field is considered not functional, also known as ‘down’. Since the concerned capital goods have moving parts and design complications can occur, failure of parts of the machine is inevitable.

Whenever an extremely expensive capital good is down, missed opportunity costs can be thousands, or even millions per hour depending on the type of machine, the industry and the user. Table 3.1 shows typical costs of downtime for several industries. The concerned module itself performs no activities for the process on its own, though it carries out several important supporting processes needed for the proper functioning of the capital good. This means that whenever the module is down, the entire machine is down. Therefore the module is considered a crucial part of the machine for which downtime should be minimized in a similar way as happens for other crucial parts.
3.4 Service contracts

Depending on the type of capital good (most importantly its newness) and customer preferences a service contract is agreed between the manufacturer and the end user. Since the investments are large for new machines, service contracts are usually agreed per machine individually, though service contracts for groups of machines can occur. Within these service contracts specific parameters with regard to service are agreed between the OEM and user. Most important is the pursued service level of the machine throughout its useful life. Usually this results in a minimal percentage of uptime that has to be realized by the OEM. Furthermore all sorts of aspects of the service process are agreed within this contract. For example the warranty period and warranty conditions and type of spare parts that can be used (new or repaired).

On the basis of this service contract, an OEM can determine its service strategy. A key question is how centralized the spare parts stock should be in order to optimize the performance of the service processes. A more centralized stocking strategy will require less stock in absolute terms, but, since the geographical distance from the customer to the spare part is on average larger, responsiveness will be lower. For a more decentralized stocking strategy this works vice versa.

3.5 Corrective and preventive maintenance

Two types of maintenance can be distinguished. Corrective maintenance is performed whenever an unforeseen defect took place and caused a capital good to go ‘down’. From the moment the machine gives an error code, the clock starts ticking for the servicing company. Maximum downtime can in some cases be as low as one hour! Therefore the manufacturer has a sophisticated rapid response infrastructure close to these customers in order to be able to react quickly to unexpected failures. Preventive maintenance is also considered as downtime, since the machine is not working when performing scheduled maintenance. Significant advantages can be achieved when preventive maintenance is appropriately planned. Since capital goods are so expensive, manufacturers put a lot of effort in optimizing service operations. Therefore usage and reliability of individual parts of capital goods are in general relatively well known. In anticipation of this knowledge, the probability of unexpected failures can be reduced by preventively swapping spare parts with an increased possibility of breakdown.

3.6 Tactical and Operational spare parts inventory

According to Kennedy et al. (2002), spare parts inventory’s primary function is to assist maintenance staff in keeping equipment in operating condition. Furthermore, spare parts inventory differs from regular (work-in-process) inventory as it is not used to smoothen out irregularities in the production flow, but is used for minimizing downtime of capital goods either by preventive or faster emergency parts swapping. The closer spare parts inventory is placed towards the user, the faster will be the responsiveness to unexpected failures. This waiting time can be defined as the ‘mean time waiting for parts’ (MTWFP). Yet the higher will be the capital expenses (CAPEX), as more needs to be invested in spare parts inventory. Again, also the location of capital goods spare parts inventory is a tradeoff between maintenance responsiveness and costs of a more decentralized inventory stock. Intuitively a more pooled inventory strategy would save costs, as the absolute number of spare parts will need to be lower in order to achieve the same availability level of spare parts, though sometimes a faster response is desired for more demanding users. Spare parts inventory can be seen as both a
tactical and an operational measure to ensure performance requirements are met in the field. Operational spare parts inventory is usually kept close to the place where it is needed in order to serve daily operations with necessary spare parts quickly. Furthermore, in the case of a very decentralized operational installed base (for example capital goods with service contracts that are sold worldwide), tactical spare parts inventory could be kept in a central place in order to replenish operational spare parts inventories in their daily needs.

3.7 Obsolescence

Obsolescence is a problem for spare parts that are rarely required and rapidly evolving into newer versions. Although spare part equipment for capital goods can be very costly, critical spare parts need to be available at all times to ensure fast responsiveness when failures happen. For these reasons spare parts stock might become obsolete before it can be used. An obvious way to force the usage of spare parts is to perform preventive (scheduled) downtimes. Bridgman & Mount-Campbell (1993) pointed out that when scheduled downtimes are applied to capital goods, overall less spare part inventory is needed, which as a result reduces stock out costs of an inventory shortage. Another conclusion is that whenever there is a possibility of equipment upgrades, there is an increase of incurring costs due to obsolete inventory. As reference they examined spare parts inventory policies in the context of the space shuttle, where some spare parts could become obsolete due to upgrades of the equipment. Cobbaert & Van Oudheusden (1996) introduced an optimization model that takes obsolescence into account. They improved the economic order quantity model (EOQ) to be able to analyze the risk of “sudden death” obsolescence risk for fast moving spare parts. Several conditions were taken into account: constant obsolescence risk and no shortages allowed, varying obsolescence risk and no shortages allowed and finally varying obsolescence with shortages allowed. Their main conclusion was that ignoring an obsolescence risk of 20% can easily result in an average cost increase of approximately 15%. Although spare parts inventory for capital goods is characterized by slow moving parts (low demand), this still gives an indication of the importance of obsolescence.

3.8 Spare parts inventory management

A huge body of research has been dedicated to spare parts inventory management. Most importantly because spare part inventory is very costly, yet very important for the capital goods life cycle and TCO and improvements can lead to significant cost reductions. The first deliberate attempt to optimize the inventory of expensive spare parts, with low demand at any particular base was by Sherbrooke (1968) with his Multi-Echelon Technique for Recoverable Item Control, METRIC, for the United States Air Force. This method is developed to make optimal procurement decisions in the period of initial demand. It calculates for every spare part item (SKU) a near optimal re-order level depending on different input parameters, like demand rates or scrap costs and different KPI’s, like the service level. Improvements were made by Muckstadt (1973), who introduced the MOD-METRIC method including a hierarchical structure for items with two indenture levels in a two-echelon configuration, and Slay (1984) with the VARI-METRIC method, which takes the variance in pipeline values into account for a better estimation of backorders. (De Kok, 2005)The book of Kranenburg & van Houtum (2014) summarizes, extends and describes several inventory models specifically useful for spare parts inventory situations in real-life. In particular they explain a single-location, multi-item inventory model for spare parts of capital goods, subject to relatively sporadic demand and varying prices.
4. **Analysis of the current supply chain**

In this chapter the Spare parts supply chain from parts supplier to end-user will be discussed. In order to understand the practical complexities of this supply chain a thorough examination is performed, discovering all relevant aspects, which are necessary to be able to implement improvements.

4.1 **Overview of the supply chain**

Figure 4.1 shows an overview of the current pre-transfer supply chain with regard to spare parts. First note that VDL ETG is not the only supplier of the module’s spare parts. Although VDL ETG is responsible for the development, assembly and production of the module, a substantial share of components is purchased from second-tier suppliers. For this reason, the manufacturer orders spare parts directly from those suppliers whereupon suppliers deliver replenishment order to the manufacturer’s central warehouse.

![Figure 4.1: High Level Overview of current Spare Part Supply Chain](image)

The manufacturer’s Spares Logistics (SL) department is responsible for the execution of spare parts exchanges in the field. SL’s main goal is to make sure that downtime in the field is minimized and has therefore the ability to make use of an extensive logistics network, several dozens of warehouses worldwide and on-site service engineers. Furthermore LS is responsible for determining spare parts stock inventory levels in both regional as global warehouses in order to achieve contractually agreed customer satisfaction levels.

Since the SL department regulates all physical spare parts operations, it is the coordinating party within this supply chain. It acts on the basis of information coming from the customer support (CS) department. CS, in turn, communicates with the end user. Problems in the field will be noticed first at CS, and therefore CS is directly responsible for customer satisfaction. On behalf of SL, the Purchasing department places replenishment orders at spare parts suppliers and supervises the replenishment process. This spare parts purchasing is as much as possible combined with the regular purchasing process.
A main global warehouse holds the bulk of all spare parts for the installed base. The central warehouse is used as strategic replenishment source for the regional warehouses where operational service stock is placed to fulfill short-term demand from the field. A relatively small amount of stock is kept at each regional warehouse, as the manufacturer makes sure replenishment time from its global warehouse is short by placing it near an airport hub.

With regard to this assignment, it is assumed that VDL ETG will deliver spare parts to the global warehouse from where the manufacturer takes over further distribution.

4.2 Supply chain processes

4.2.1 Development process

In the current situation VDL ETG is partly responsible for the ongoing development of the module together with the manufacturer of the capital good. The manufacturer sets its requirements and VDL ETG makes sure the product meets these requirements. One aim of the transfer project is to give VDL ETG total responsibility for R&D, transforming VDL ETG from a ‘build-to-print’ manufacturer into an ‘OEM whitebox’ manufacturer who is fully responsible for the functionality of the module and can therefore be judged on the performance achieved. The incentive for VDL ETG to improve performance is then stimulated, as it will directly be rewarded for improvements.

When looking at spare parts, several aspects of the development process are of interest. The most important consequences of ongoing development are risk of obsolescence and risk of design flaws. These two risks can be translated in two different development activities:

- Engineering Changes (EC)
- Field Changes (FC)
  - Immediate
  - On-update
  - On-failure

Engineering changes are changes in the regular production process of the module. This does not always have immediate effects for the installed base, though components might need to be replaced in the long term using on-update or on-failure based field changes, which are defined later on. In the current situation these changes can either come from the manufacturer, the T&D (technology and development) department, the Sustaining department or from another supplier. All these parties can implement changes with their own reasons. Generally, parties have to agree mutually with the changes and the manufacturer has a leading role in the acceptance of engineering changes.

An EC can lead to a field change if there are obsolescence consequences for the current spare parts inventory. If obsolescence is not a problem, current spare parts usually can be phased out with regular spare part demand. Otherwise, if the current inventory becomes obsolete due to an EC, current spare part inventory should either be scrapped or upgraded to a newer version. FCs are changes that take place in the field. Furthermore three different gradations of FCs can be applicable. Most importantly, immediate field changes indicate a flaw in the production or design process that influences multiple machines of the installed base and immediately has to be compensated by a field
change, mostly due to possible safety problems but can also be caused by production problems. Another possible adjustment to the machine happens ‘on update’. This occurs when a design upgrade is sufficiently important to change the component before it fails or is pre-emptively replaced. The manufacturer can also add additional functionalities to the machine during its lifetime, depending on the contract with the user, by implementing changes on-update. Finally, changes on failure are less urgent than immediate and on-update changes. These often regard product updates or design changes, which are not crucial, since the machine functions in a normal way without the update. Important to notice is that the occurrence of a field change often depends on the service contract the manufacturer has with the end user. Some contracts include that the installed based always should have the newest upgraded parts. As a result, components are always swapped whenever an engineering change occurs.

4.2.2 Demand process

Regarding demand for individual parts, a distinction between use for regular production and for service spare parts has to be made. Internal demand (for regular production of new builds) is always planned in advance, depending on the production process of a particular product. On the other hand, external demand for spare parts from the manufacturer’s customer service department can be very erratic as this demand pattern depends on occasional circumstances in the field. Five types of external demand can occur:

- Demand due to a rejection notice
- Demand due to customer forced spares (CFS)
- Demand due to epidemic failures
- Demand due to engineering changes (EC)
- Demand due to re-order level increase

Demand due to a rejection notice occurs when spare parts have been damaged during transport, assembly or disassembly. This means that the part is not usable anymore and therefore will be rejected. Depending on a warranty/non-warranty agreement the costs are charged to the responsible party for the defect (the transportation company or an on-site engineer for example). Either way, a rejected part leads to demand for a new or repaired part.

Customer forced spare parts demand is demand used for commercial use. Usually this is the consequence of a field service defect (FSD). FSDs occur when a machine in the field is down and needs a service part swap. One could argue that this is the regular demand for spare parts for which insurance stock is kept. Because of high costs of downtime, a service part is usually swapped without any further investigation. The only focus of the service engineer is to get the machine working again, no matter how. Subsequently the failed part is always returned to the nearest warehouse for further examination. Usually cheap parts will be scrapped anyway as transportation cost outweigh repair benefits, while expensive parts are assessed for reparability. In some more unusual cases a user demands a new part on the basis of emotionally comforting intentions. A customer could depend heavily on a capital good’s functioning. Even though a part has not a high probability of failing, the customer might want the part exchanged just in order to rule out any problems. This also accounts for commercial use of spare parts.
Spare parts consumed in epidemic quantities as a result of an epidemic failure of a product generate a specific demand pattern. This pattern can be attributed to maturing systems that suddenly need structural part replacements due to design flaws. One could argue that this is similar to an EC as this is the subsequent procedure to address the problem, although epidemic failure are treated as a different demand type because the problem arises epidemically and is therefore more critical than a standard design flaw.

Whenever an engineering change is carried out, this can have an influence on the demand. This depends on whether an EC results in an FC. If an FC is necessary this means that upgraded parts instead of already existing versions will replace used parts. This results in unusable safety inventory, i.e. obsolete inventory, either causing these parts to be sent in for upgrade or causing a new replenishment order to replace the current inventory, which means that obsolete spare parts will be scrapped.

Finally, the manufacturer can choose to raise its re-order level for specific spare parts. This may be the result of an increase of the installed base, changes in the pool of service contracts, decrease of the average part reliability in the field or problems foreseen in the near future with specific parts. An increase of the re-order level can cause extra demand whenever the new re-order point is not exceeded with current inventory.

Specific for capital goods is that there is a relatively low demand and service level requirements are very high. This results in keeping a lot of stock while there is a reasonable probability that it will stay on the shelf for a long time, perhaps even until it becomes obsolete. This (and the increasing focus on TCO discussed earlier) explains why manufacturers of capital goods focus more on efficient ways to achieve service agreements while keeping as little as possible inventory.

4.2.3 Production process

For parts used in the module there has to be made a clear distinction between parts used to build new machines and service spare parts. In the current situation service spare parts undergo the same production process as regular parts and have the same throughput time. Furthermore a large portion of all parts is procured at second tier suppliers. In general, three different types of service spare parts can be distinguished:

- Repairs
- New parts
- Upgrades

Repairs are processed when a failed part is sent back for repair. This can be the result of a failed part in the field, which is considered eligible for repair or a part that has been rejected, as it does not meet all requirements. Not all parts will be considered as reparable. First of all, cheaper parts will be scrapped anyway as repair and transport costs outweigh procurement costs. But also assessment of expensive parts can indicate the procurement of a new part can be most effective. An average scrap rate per service part indicates what portion of failed parts will be scrapped. Furthermore repair orders are in most times single-item orders, since they concern expensive parts that fail relatively
seldom. Repaired items are considered as equal to new parts when reentering the inventory and will also be accounted on its new value. Furthermore the manufacturer reimburses the repair costs made by VDL ETG with a compensation.

An order for a new service part is placed when the failed or rejected part is considered not eligible for repair and the inventory position drops reaches its re-order level. New parts are in fact the same parts as are used for new modules and undergo the same production or procurement process. While VDL ETG maintains a buffer stock for some parts in order to smoothen work in process, there is no specifically planned inventory for service related demand. Although it may happen that parts from this buffer or even parts from work in process machines are ‘cannibalized’ for critical situations, it is assumed that new service parts always are produced or procured according to the regular process that satisfy agreed supplier lead-times.

Equal to repairs, some parts can be considered upgradable when an EC occurs while some will be scrapped. This all depends on the manufacturer’s analysis of the obsolete parts. A key difference with repairs is that upgrade orders concern mostly larger numbers of items as a whole shelf becomes obsolete. As in fact a repair is a kind of upgrade, ‘upgradables’ are processed similarly to repairs. On the other hand, due to the fact that orders are large (>1) these orders cannot easily be planned without disturbing regular production processes.

4.2.4 Customer support and RS&S

Within VDL ETG customer support is the responsible business unit for customer satisfaction. Since appropriately supplying service spare parts is an element of customer satisfaction, customer support is also accountable for this process.

The RS&S (repair, spares and service) department is the executive party with regard to spare parts. Under the management of customer service RS&S takes care of the processing of service orders forwarded by customer service. In a nutshell RS&S has to make sure a new, repaired or upgraded spare part has to be finished for use within the agreed supplier lead-time and meet all agreed requirements. Furthermore RS&S is responsible for the financial processing of service orders.

4.2.5 Lead-times

Within this service supply chain various waiting times play a role with regard to the supply chain’s performance. The mean downtime (MDT) of capital goods depends partly on the mean lead-time for the delivery of a service part towards the field, also called ‘mean time waiting for parts’ (MTWfP). This MTWfP depends on strategic and tactical decisions with regard to safety stock keeping and therefore falls directly within the scope of this research. Intuitively, a shorter MTWfP means a better performing supply chain as the MDT will be reduced. The way to reduce MTWfP is minimizing backorders by increasing spare parts inventory, which on the other hand comes with more expenses.

Figure 4.2 shows a graphical representation of the capital goods service cycle, where MTBF is the average time between two failures, MTTD is the mean time until a diagnose of the failure is made and MTTR is the mean time until the repair is performed. A servicing organization can also reduce MDT by faster diagnosing or repairing. Furthermore the designing organization can improve MTBF by improving the machine’s reliability. Again there will always be a tradeoff between the improvement costs and the performance increase.
While VDL ETG is not the servicing company in this supply chain, there will be a limited influence on the service cycle between servicing company (manufacturer) and user. On the other hand, at the front of the supply chain, with regard to the supply of spare parts, VDL ETG can exercise more direct influence on the performance. The supplier lead-time of service spare parts is of great influence on the responsiveness of the supply chain. This supplier lead-time consists of the time of all actions taken from order placement until the items are available as safety stock. With regard to the manufacturer and VDL ETG, the supplier lead-time in the current situation can be represented as in figure 4.3.

The manufacturer always places an order whereupon VDL ETG will always make an invoice, which then is send for approval. This indicates that VDL ETG never produces service spare parts on its own initiative and each order has to be checked. After approval the production or procurement process is started after which packaging and transport will follow. This supplier lead-time is restricted for each different SKU in a service agreement between VDL ETG and the manufacturer. In other words, there is an upper limit to how long VDL ETG may take to deliver a replenishment order to the manufacturer’s warehouse. For this reason and for the reason that no data about actual lead-times is available, it is acceptable to assume that the agreed supplier-lead times are the actual lead-times and are fixed, i.e. there is no lead-time volatility effect taken into account. However, it is an option to adjust supplier lead-times in order to optimize the supply chain performance.
4.2.6 End of life support

VDL ETG is required to deliver spare parts up to 10 years after a capital good goes end of life (EOL). EOL occurs when the manufacturer decides to discontinue production of new systems and limits further service by discontinuing technological development. As capital goods can have long lifetimes, on-site support will be needed long after the capital good’s EOL. Therefore the demand for spare parts continues. It makes sense that spare parts increase in price after an EOL. First of all, as manufacturers discontinue regular production of old products, production costs of old spare parts will increase. Furthermore demand will be more incidentally as the installed base shrinks over time, making batching less applicable. Currently there is no strategy to optimize end of life support. The manufacturer simply forwards the demand for an EOL spare part to VDL ETG and production costs will be charged.

4.3 Control Processes

The control structure of the supply chain can be divided in three main processes with each a different planning period (figure 4.4).

![Division of different control processes](https://example.com/figure4.4)

**4.3.1 Strategic control processes**

Strategic control processes are the highest level of processes in the hierarchy. The processes are normally considered once a year for revision and have a multi-year roadmap. Examples of strategic control processes with regard to spare parts inventory is the planning of building new warehouses, closing new contracts with third party logistics parties or suppliers or long term overall objectives with regard to customer satisfaction.

**4.3.2 Tactical control processes**

Tactical control processes have a shorter horizon than strategic processes and are therefore more often reconsidered, though not on a daily basis. The purpose of tactical processes is both realizing strategic decisions as well as making the execution of operational processes possible. They are made to gain a specific objective in the context of an overall strategic plan. A relevant example is the planning of warehouse inventory levels (2-3 times a year) by considering various parameters like the expected demand for the upcoming period, holding costs, etc.

**4.3.3 Operational control processes**

Finally, operational processes are revised on a daily up to a weekly basis. These are the processes that serve to regulate the day-to-day output relative to schedules, specifications and costs. Examples are the planning of repair operations in the field, regulating spare part flow between warehouses and suppliers and invoicing.
4.4 **Information Technology**

4.4.1 **Baan**

Baan is an ERP-system (Enterprise Resource Planning) used by VDL ETG to streamline operations within the organization and improve productivity, maintain operational costs and customer value creation. Baan contains all information about the production parameters of spare parts, costs of spare parts, optimal order quantities, suppliers, order invoices, order status, BOM’s (bill of material) and much more. In fact one could argue that it is a sort of database in order to make information organized and accessible.

On the other hand, Baan does not contain any optimization tools for spare parts inventory planning. Since VDL ETG is at the moment not an active service performing organization, only a limited amount of work-in-process (WIP) parts inventory is kept at stock, which functions as a buffer for the regular production process.

4.4.2 **SAP portal**

In order to communicate with the manufacturer about the status of service requests, VDL ETG can make use of a special portal that gives access to the SAP system used by the manufacturer. This portal can be seen as a link between Baan and SAP in order to streamline information sharing and give both the customer service department of the manufacturer as VDL ETG access to each other’s information, e.g. the status of orders, invoicing status, service requests, etc.

In the current situation, the SAP portal only gives access to operational processes and higher level tactical processes (like demand forecasts, service level requirements and stock levels) cannot be accessed via the portal. In an after-transfer scenario this SAP portal might be used to transfer some tactical information for which VDL ETG will be responsible.
5. **Spare parts inventory planning model**

The global warehouse of the manufacturer is the main stocking point from where regional warehouses are provided with spare parts safety stock. Although this entails organizing complexity for the manufacturer, for VDL ETG the whole spare parts logistics infrastructure can be seen as a single echelon for which it is only responsible for keeping the aggregate stock. In this section a control model will be discussed in order to optimize the stock keeping for this environment, both during a product’s active lifecycle as well as when it has gone end-of-life.

First, a replenishment policy is discussed after which the model for the central warehouse will be explained. After that, the decoupling of the central warehouse from local warehouses is discussed.

### 5.1 Inventory management policy

The backbone for the model will be a continuously reviewed, fixed reorder quantity policy. Otherwise known as the \((s, Q)\) policy (Silver, Pyke, & Peterson, 1998). De Kok (2005) discusses several different widely used ‘one-location, one-product’ inventory policies, which differ upon flexible versus fixed order quantities and continuous versus periodic inventory reviews. The \((s, Q)\) policy is most usable for this case, firstly since the model needs to react quickly upon fairly rare demand occurrences, which make continuously reviewing more appropriate and secondly, since VDL ETG already maintains optimal order quantities for regular production, the implementation of optimal order quantities will most likely lead to cost improvements with respect to the original situation.

As said before, the \((s, Q)\) policy is continuously monitored, i.e. the inventory position \((Y)\) is continuously tested whether it exceeds the so called ‘re-order level’ \((s)\). Since the model is integer constrained (only whole spare parts are processed), the re-order level \('s'\) is the threshold for when a new order of size \('Q'\) should be placed for an SKU in order to achieve the desired service level. Directly when the order is placed, the inventory position increases by \('Q'\), while the net inventory \('X'\) increases by \('Q'\) when the order arrives \('L'\) later. A graphical example of the \((s, Q)\) policy is shown in figure 5.1.

![Figure 5.1: Graphical representation of the \((s,Q)\) policy](image)

5.1.1 **Policy assumptions**

The \((s, Q)\) policy incorporates several relevant assumptions:

1. Delivery times are constant and equal to \('L'\).
2. The reorder quantity is constant and equal to \('Q'\).
3. All demand that cannot be delivered immediately from stock is backordered.
The first assumption needs more explanation. Although VDL ETG and the manufacturer have contractual agreements about supplier lead-times boundaries, this does not mean that there is no lead-time volatility. There might occur unforeseen production problems for instance. It should be noted that in cases where the lead-time volatility is large, the model’s estimation of the supply chain costs might be underestimated, as the lead-time volatility is not explicitly modeled. On the other hand we can assume that contractually agreed supplier lead-times take this volatility into account, as a specified ‘safety margin’ is added to the minimal production or procurement time to make sure the contractual supplier lead-time is always met. In other words, the supplier lead-time can be seen as a target to be met, while the actual lead-time might be smaller than the contractual lead-time. Therefore the supplier lead-time can be assumed to be constant.

The assumption of constant reorder quantities is quite reasonable. Optimal production and order quantities are already used for regular production and, since spare parts are the same parts that are used for regular production, it is acceptable to apply them also for spare parts in order to reduce production and procurement costs.

Finally, the fifth assumption is included to make sure that all demand is met. With regard to this situation this is acceptable, since all service related demand from the manufacturer’s customers has to be met.

5.2 Inventory planning model

A multi-item single-location inventory model with condemnation and batching is proposed for determining the expected inventory related costs over an infinite time horizon. It is possible to use various different service measures and furthermore it can be chosen to realize these service levels on an aggregate focus as well as on an item focus and it is possible to introduce emergency shipments. The parameters used are defined and summarized in appendix B.

5.2.1 Model description

Consider the multi-item, single-location model of Kranenburg & van Houtum (2014). In the GDC, several spare parts are kept on stock to serve an installed base of capital goods. These spare parts are all critical components in this case example, i.e. when a component fails, the machine will go down at all times. When a spare part fails, it will always be replaced with a spare part from the warehouse. The failed part is subsequently sent to the warehouse and can either be sent immediately back to VDL ETG (and subsequently to its original supplier) for repair or be scrapped whereafter an order for a new spare part is placed at VDL ETG.

The spare parts kept at stock are referred to as stock keeping units (SKU’s). The set of SKU’s is again denoted by $I$ and the number of SKU’s is denoted by $|I|$ ($\in \mathbb{N} = \{1, 2, \ldots\}$). For each SKU $i \in I$, demand from the field occurs according to a Poisson process with a constant rate $m_i (\geq 0)$ where $m_i$ denotes the demand of all machines together. Per SKU $i \in I$ demand is fulfilled immediately if possible, otherwise the demand is backordered and fulfilled as soon as possible and each demand is accompanied by a return of the failed part. Repair and procurement lead-times of different SKUs are assumed to be independent and repair and procurement lead-times of the same SKUs are assumed to be independent and identically distributed (i.i.d). The mean supplier lead-time (towards the GDC) for SKU $i$ is denoted by $t_i (\geq 0)$, where $t_i = \tau_i \cdot t_{i, proc}^{rep} + (1 - \tau_i) \cdot t_{i, rep}^{proc}$. Here $\tau_i (0 \leq \tau_i \leq 1)$ is the scrap rate, $t_{i, proc}^{rep} (\geq 0)$ is the mean procurement time in years and $t_{i, rep}^{rep} (\geq 0)$ is the mean repair time.
for SKU $i$ in years. Note that the first assumption of the $(s, Q)$ policy is violated when $r_i < 1$ or $r_i > 0$. Therefore it is assumed that the model will follow a basestock policy ($Q = 1$) for SKU’s that are not always procured or always repaired. This will be formally discussed in the assumptions section.

Since the $(s, Q)$ policy is applied, a replenishment order of a fixed size $Q_i$ will only be placed when the inventory position $Y_i$ exactly meets the reorder level $s_i \geq -1$ for SKU $i$. The inventory position is defined as the physical stock minus backordered demand plus parts in the repair or procurement process. The acquisition price of a part of SKU $i$ is $c_i^a (> 0)$, this price can vary when a different shipment size ($Q$) is applied. Furthermore, since the model assumes an infinite time horizon, the costs per time period are of interest. The holding costs are the costs to keep an SKU as inventory for a certain time period (in this case one year). Holding costs per year for SKU $i$ is determined by $c_i^h$ and are expressed as a percentage of the acquisition price. The moment of transfer of ownership can be a decision variable, therefore the holding costs can be different for the supplier or the manufacturer.

Looking at the initial supply problem at time instant $t = 0$, the objective is to minimize the total investment subject to a constraint on (for example) the aggregate mean number of backorders. The total initial investment in spare parts of SKU $i$ is given by $C_i(S_i, Q_i) = (c_i)E[Y_i]$ where $E[Y_i]$ is the expected inventory position for SKU $i \in I$ in the GDC and $S_i$ is equal to $s_i + 1$, also denoted as the minimum stock level. Since the concept of an economic ordering quantity is applied, the expected inventory level can be greater than the re-order level. Furthermore note that when the shipment size for SKU $i$ is 1 ($Q_i = 1$), $IP_i = S_i$, otherwise known as the basestock model. The total initial investment for all SKU’s is given by:

$$C(S, Q) = \sum_{i \in I} C_i(S_i, Q_i) = \sum_{i \in I} (c_i)E[Y_i]$$

where $S = (S_1, ..., S_I)$ denotes a vector consisting of all minimum stock levels. Furthermore the solution space is denoted by:

$$\mathcal{S} = \{S = (S_1, ..., S_I) \mid S_i \in \mathbb{N}_0, \forall i \in I\}.$$  

When considering periodic costs, the holding costs are of interest. The periodic holding costs for SKU $i$ is given by $C^h_i(S_i, Q_i) = (c_i^h)E[Y_i]$. Similarly to the total initial investment costs. The total periodic holding costs is then given by:

$$C^h(S, Q) = \sum_{i \in I} C^h_i(S_i, Q_i) = \sum_{i \in I} (c_i^h)E[Y_i]$$

As a service measure, the mean number of backorders of SKU $i \in I$, in steady state, is introduced as $EBO_i(S_i)$. Then the aggregate mean number of backorders, in steady state, is:

$$EBO(S, Q) = \sum_{i \in I} EBO_i(S_i, Q_i)$$

The target level for $EBO(S, Q)$ is given by $EBO^{obj}$. $EBO^{obj}$ is the maximum number of backorders to be expected per time period. Usually this number is determined by the manufacturer in order to meet a certain service level at the end of the supply chain (the local warehouses).
This results in the following non-linear integer programming problem ‘P’, where the initial investment costs are minimized while meeting the $EBO^{obj}$ service measure:

$$(P) \quad \min \quad C(S, Q)$$

subject to $EBO(S, Q) \leq EBO^{obj},$ $S \in S.$

Note that the problem can also be aimed at minimizing the periodic holding costs, but this would not be different from the original problem. Since holding costs depend on the acquisition price, the relationship between initial investment costs and periodic holding costs is linear.

### 5.2.2 Model assumptions

In addition to the $(s, Q)$ policy assumptions, the inventory planning model holds several other assumptions:

1. Demands for the different SKU’s occur according to independent Poisson processes.
2. For each SKU the demand rate is constant.
3. Repair and procurement leadtimes for different SKU’s are independent and repair and procurement leadtimes for parts of the same SKU are independent and identically distributed.
4. SKU’s for which the scrap rate is not equal to 1 or 0 ($r_i \neq 1 \land r_i \neq 0$), a basestock policy is applied. For all other SKU’s an $(s, Q)$ replenishment policy is applied.

In general we can assume that one failure will not lead to another failure in the same machine. SKU’s are composed in such way that the SKU replaces multiple failure sensitive parts by replacing the part as a module. Dependent failures may still exist, although they are always covered by the SKU as a whole. Therefore one could assume that failures occur independently. Furthermore the number of machines served is sufficiently large (several thousands). It is therefore reasonable to assume demand for SKU’s occurs according to Poisson processes. Next, since the warehouse serves a sufficiently large pool of machines and failures occur fairly rare, it can be assumed that demand rates for SKU’s is constant. Furthermore repair and procurement leadtimes can be assumed to be independent for different SKU’s and independent and identically distributed for parts of the same SKU since procurement and repair leadtimes are always planned and agreed with the capital good’s manufacturer.

Finally, it is assumed that an $(s, Q)$ replenishment policy is applied for all SKU’s that are not subject to condemnation or subject to full condemnation. Because of potential cost savings in producing in batches, this is considered the most appropriate policy, especially for the relatively cheap SKU’s. For SKU’s that are partially subject to condemnation, the assumption of a deterministic lead-time required for the $(s, Q)$ replenishment policy is violated.
5.2.3 Model evaluation

Whenever a demand occurs for SKU \(i\), the on-hand inventory \((OH_i)\) decreases by one, with a minimum of zero, unless the on-hand stock is zero. In this case the amount of outstanding backorders \((BO_i)\) increases by one. If for this reason the inventory position \((Y_i)\) drops to the reorder level \(s_i\), the number of items in the pipeline \((X_i)\) increases by \(Q_i\) (remember that \(Q_i = 1\) if parts are partly condemned). Next, when a batch of \(Q_i\) is released from the repair/procurement pipeline, either the on-hand stock will increase by \(Q_i\), if there are no backorders \((BO_i = 0)\), or the amount of backordered demand will decrease by a maximum of \(Q_i\), if there is backordered demand \((BO_i > 0)\), while the on-hand stock will increase by \((Q_i - BO_i)^+\).

According to the properties of Axsäter (2006), when \(t_i\) is deterministic and when making use of an order quantity \(Q_i\), the inventory position at an arbitrary time point is uniformly distributed on the integers \(s_i + 1, s_i + 2, \ldots, s_i + Q_i\).

Now, if the demand during lead-time \(t_i\) is Poisson distributed with mean \(m_i t_i\); \(OH_i(t) - BO_i(t)\) is equal to \(s_i + U_i - X_i\), where \(U_i\) is a uniformly distributed random variable on \(\{1, \ldots, Q_i\}\), and equals 1 if \(t_i\) is not deterministic.

It holds then that:

\[
\begin{align*}
    s_i &= E[Y_i] + OH_i - BO_i - U_i, \\
    E[Y_i] &= s_i + E[U_i] = S_i - 1 + \frac{1 + Q_i}{2}, \\
    OH_i &= (s_i + U_i - E[Y_i])^+, \\
    BO_i &= (E[Y_i] - (s_i + U_i))^+.
\end{align*}
\]

Since \(Q_i\) items are ordered the the inventory position reaches \(s_i\), parts enter the pipeline according to an Erlang renewal process with mean \(Q_i/(m_i t_i)\) and stay a time of \(t_i\) in this pipeline. It can be assumed that this process behaves as a \(M|M|\infty\) queuing system. On the other hand, according to Palm’s Theorem (Palm, 1938) the inventory position behaves as follows:

The inventory position for SKU \(i\) \((Y_i)\) is Poisson distributed with mean \(m_i t_i\):

\[
P\{Y_i = x\} = \frac{(m_i t_i)^x}{x!} e^{-m_i t_i}, \quad x \in \mathbb{N}_0;
\]

The distribution of \(OH_i\) is given by:

\[
P\{OH_i = x\} = \begin{cases} 
\sum_{u=1}^{Q_i} \sum_{y=S_i-1+U_i}^{\infty} P\{Y_i = y\} P\{U_i = u\}, & \text{if } x = 0; \\
\sum_{u=1}^{Q_i} P\{Y_i = S_i - 1 + U_i - x\} P\{U_i = u\}, & \text{if } x \in \mathbb{N}, x \leq S_i - 1 + U_i;
\end{cases}
\]

The distribution of \(BO_i\) is given by:

\[
P\{BO_i = x\} = \begin{cases} 
\sum_{u=1}^{Q_i} \sum_{y=0}^{S_i-1+U_i} P\{Y_i = y\} P\{U_i = u\}, & \text{if } x = 0; \\
\sum_{u=1}^{Q_i} P\{Y_i = x + S_i - 1 + U_i\} P\{U_i = u\}, & \text{if } x \in \mathbb{N};
\end{cases}
\]
And finally the mean backorder positions $EBO_i(S_i)$:

$$EBO_i(S_i, Q_i) = m_i t_i - (S_i - 1 + E[U_i]) + \sum_{u=1}^{Q_i} \sum_{x=0}^{S_i-1+U_i} (S_i - 1 + U_i - x) P(Y_i = x) P(U_i = u), \quad S_i \in \mathbb{N}_0$$

From the expected backorders, the mean waiting time for parts (MTWfP) can easily be obtained when applying Little’s Law (Little, 1961). For a SKU $i \in I$ under re-order level $s_i$, the main waiting time for parts can be determined by:

$$W_i(S_i, Q_i) = \frac{EBO_i(S_i, Q_i)}{m_i}$$

Since it holds that:

$$EBO(S, Q) = \sum_{i \in I} EBO_i(S_i, Q_i)$$

And the aggregate demand rate is denoted by:

$$M = \sum_{i \in I} m_i$$

it holds that the mean aggregate holding time is:

$$W = \frac{EBO}{M}$$

Figure 5.2 shows how the main waiting time for a particular part behaves on increasing the re-order level, for four different order quantities. The higher re-order quantities require a lower re-order level in order to achieve a specific service level. This is due to the fact that on average the stock level will be increased when the re-order quantity is higher, resulting in a lower mean waiting time. Now the average inventory level influences the total costs of the system. Next, figure 5.3 shows how the increase of the stock level for a particular SKU influences the involved costs. A higher stock level results in an exponentially decreasing amount of expected backorders, while it will increase investment costs (linearly). Combining both cost functions, it becomes clear that the optimal position is the optimum of the tradeoff between investment costs and backordering costs.

![Figure 5.2: Typical mean waiting time for parts curve](image)

![Figure 5.3: Typical costs curve](image)
5.2.4 Aggregate fill rate service measure

Instead of using the mean backorder positions as service measure, it may be preferable to set a specific percentage (fraction) of the expected demand to be fulfilled immediately (without backorder) from stock. This service measure is known as the fill rate. The aggregate fill rate is considered the total fill rate of a whole group of items. First, the 'item' fill rate is denoted by $\beta_i(S_i, Q_i)$ for SKU $i$ and contributes relatively to the aggregate fill rate by means of the item’s relative demand rate. This means that the aggregate fill rate can be denoted by:

$$\beta(S, Q) = \sum_{i \in I} \frac{m_i}{M} \beta_i(S_i, Q_i)$$

Where $M = \sum_{i \in I} m_i$.

Demand can only be fulfilled immediately if there is on-hand stock ($OH_i > 0$). In order to determine the fraction of demand that is expected to be fulfilled immediately upon demand, one should determine the probability of a positive on-hand stock ($P\{OH_i > 0\}$), which equals the probability that the inventory position is less than the minimum stock level ($P\{Y_i < S_i - 1 + E[U_i]\}$).

$$\beta_i(S_i, Q_i) = \sum_{u=1}^{Q_i} \sum_{x=0}^{S_i-2+U_i} P\{Y_i = x\}P\{U_i = u\}.$$ 

When optimizing the re-order levels of the set of SKU’s, $\beta^{obj}$ is considered the target service level, i.e. the minimum fraction of the aggregate demand expected to be delivered from on hand stock. Problem P is now reformulated to problem P’ for the fill rate service measure situation instead of the mean number of backordered items service measure situation:

$$\text{(P')} \quad \min \quad C(S, Q)$$

subject to $\beta(S, Q) \geq \beta^{obj}$,

$S \in S$.

With regard to the fill rate service level, figure 5.4 shows how the fill rate generally responds to an increase of the re-order level for a particular SKU. For the same reason as discussed before, a higher re-order quantity results in a re-order level needed to obtain a certain fill rate. Note that the service level increases exponentially at first and then decreasingly rises with the 100% service level as asymptote.

![Figure 5.4: Typical demand fill rate curve](image)
5.2.5 Item-approach model

A difference between a so called system-approach, which was applied before, and an item-approach should be considered. There can be situations where the supplier wants a SKU or a group of SKU’s to meet a service level per item instead of the group as a whole to meet a service level. For example because a customer simply demands some parts to meet specific service levels or when problems occurred in the past, with regard to lead times. In order to meet this requirement, the ‘system-approach’ proposed earlier can be decomposed from aggregate service requirements to item-based service requirements per SKU. This is a so-called item approach.

1. Set a target for the aggregate system \( (EBO^{obj}, \beta^{obj}) \).
2. Divide this over all SKU’s with regard to the relative demand rate, i.e. set a target level per SKU \( i \) depending on the demand rate \( m_i \).
   - \( EBO_i^{obj} = \frac{m_i}{M} EBO^{obj} \)
   - \( \beta_i^{obj} = \beta^{obj} \)
3. Determine for each SKU \( i \) the minimum level \( S_i \) such that the SKU-target level is met.
4. Determine \( EBO(S, Q) \) or \( \beta(S, Q) \) and \( C(S, Q) \).

Note that this is a suboptimal solution with respect to the system approach. Mainly because all \( S_i \) are integer values, the actual \( EBO_i \) can be significantly smaller than the corresponding \( EBO_i^{obj} \) for a SKU \( i \), meaning the model is over-performing and incurs unnecessary costs.

5.2.6 Emergency Shipments

In order to improve the system’s performance further, the supplier can introduce emergency shipments. These emergency shipments come from the original supplier (not always VDL ETG) and can be expensive, due to the extra production and transportation costs, but, since costs of downtime of a capital good can be extremely high, it could be beneficial to introduce emergency shipments to assure faster overall responsiveness. The model discussed in this paper will be able to introduce emergency shipments for specific clusters of SKU’s or for the entire system.

Emergency shipments influence the mean waiting time for parts by making sure backorders are delivered fast. Therefore, when introducing emergency shipments, the waiting time aspect is most appropriate to use as a service measure. Unsatisfied demand will be taken care of by an emergency shipment and is considered ‘lost’ for the formal model. This is called a ‘lost sales model’. A downside of the use of emergency shipments is the restriction of using a basestock replenishment policy instead of an \((s, Q)\) policy, again because of the non-deterministic replenishment lead-times.

The behaviour of parts in the repair/procurement pipeline can now be seen as an \( M|G|c|c \) queue with \( c = S_i \) parallel servers. The reason for this is that the queue in the pipeline is limited to the level of \( S_i \), as demand will be lost after \( OH_i = 0 \). This is also called an Erlang loss system. Subsequently the fill rate can be determined by the Erlang loss probability, which is equal to the fraction of time at least one server is free, i.e. one minus the fraction of time all servers are occupied:

\[
\beta_i(S_i) = 1 - \frac{1}{\sum_{i}^{S_i}} \frac{1}{\prod_{i}^{S_i}}
\]

Where \( \rho_i = m_i t_i \).
In order to be able to assess the performance of such a strategy, the mean waiting time for a part of SKU $i \in I$ to arrive will be used ($W_i(S_i)$). Again, demand can be satisfied immediately, resulting in no waiting time, or an emergency shipment takes place for which it is assumed that the average time for an emergency shipment to arrive is equal to $t_i^{em}$ for SKU $i$. Intuitively, the mean waiting time for a SKU depends on the portion of demand that is satisfied from on-hand stock (the fill rate). The mean waiting time for SKU $i$ can then be denoted by:

$$W_i(S_i) = (1 - \beta_i(S_i))t_i^{em}$$

Where $\beta_i(S_i)$ is the fill rate of SKU $i$ and is determined in exactly the same way as described earlier when $Q_i = 1$ (basestock replenishment policy). Subsequently the aggregate mean waiting time for a part to arrive is again the mean item waiting time relative to the total demand rate.

$$W(S) = \sum_{i \in I} \frac{m_i}{M} W_i(S_i)$$

Now, the required service level can either be set to a maximum mean waiting time ($W^{obj}$) or to a maximum mean fill rate level ($\beta^{obj}$). In order to represent costs of performing an emergency shipment, $c_i^{em}$ is introduced, which denotes the costs of performing an emergency shipment for SKU $i$. It is assumed that $c_i^{em}$ contains the costs for a fast delivery from another location. Subsequently the average emergency shipment costs per time unit for SKU $i$ is equal to $m_i (1 - \beta_i(S_i)) c_i^{em}$. The rest of the periodic cost function remains the same, resulting in the following periodic cost function for the emergency shipment replenishment strategy:

$$C^h(S) = \sum_{i \in I} C_i^h(S_i) = \sum_{i \in I} (c_i^h)S_i + m_i (1 - \beta_i(S_i)) c_i^{em}$$

The initial investment costs $C$ can be determined in exactly the same way as the original strategy. Adapting the optimization problem $P$ to this specific problem gives problem $P''$:

$$\text{(P'') } \min \quad C^h(S)$$

subject to

$$W(S) \geq W^{obj},$$

$$S \in \mathcal{S}.$$
5.3 Decoupling the Central Warehouse

It is assumed that the manufacturer controls service parts in all local warehouses by a base stock policy. Furthermore, it is assumed that demand at a local warehouse is fulfilled immediately (if possible) and immediately a regular replenishment request from the GDC is placed. If the local warehouse does not have the specific SKU on hand, it will try to obtain the part by means of lateral transshipment from another local warehouse, which is able to provide a transshipment, after that a regular replenishment will be ordered towards the local warehouse that delivered the transshipment. In the case that another main local warehouse can’t transship the part, an emergency shipment request is placed at the GDC.

Now, it is clear that three types of demand streams are separated from the local warehouses: regular demand, demand due to transshipments and emergency demand. Figure 5.5 gives a graphical representation of this supply chain mechanism.

Crucial to notice is that the aggregate demand rate for each SKU $i \in I$ from the local warehouse is the sum of all transshipments, regular shipments and emergency shipments for that SKU. This results in the conclusion that the demand observed at the GDC is the aggregate demand of all individual local warehouses. Since this project only aims at regulating the supply chain up to the GDC and emergency demand is in essence not different from regular demand for the GDC, there is no need to take emergency shipments into account. Although, for a multi-echelon analysis, a distinction between these different demand types has to be taken into account, since costs lead-times and shipment priorities differ per type.
5.4 Optimization Algorithm

Kranenburg & van Houtum (2014) furthermore prove that the problem is separable and all individual functions for the expected backorders (expected backorders per SKU) are decreasing and convex on their whole domain. This given, the greedy algorithm is considered as a possible heuristic for obtaining a ‘near-optimal’ base stock level solution (Fox, 1966). Since the problem is considered convex, the greedy algorithm should find the only optimal minimum. The greedy algorithm is an algorithm that follows the problem heuristic of making the locally optimal choice at each stage with the hope of finding the global optimum.

For the expected backorder model, the locally optimal choice per stage is determined by calculating the ratio between the costs of increasing the stock level (investment costs) and the decrease of the total expected backorders for each SKU. This ratio, is denoted by:

$$\Gamma_i := -\frac{\Delta_i EBO(S, Q)}{c_i^a}$$

Where the difference in backorders by increasing the stock level of SKU $i \in I$ by one is denoted by:

$$\Delta_i EBO(S, Q) = \Delta EBO_i(S_i, Q_i) = -\sum_{u=1}^{Q_i} \sum_{x=S_i+1}^{\infty} P(Y_i = x)P(U_i = u) = -\left(1 - \sum_{x=0}^{S_i} P(Y_i = x)\right)$$

The SKU with the highest value for $\Gamma_i$ is then selected and the stock level for this SKU will be increased by one. This will continue until the stop condition is met, i.e. when the total expected number of backorders ($EBO(S)$) is lower or equal than the desired expected number of backorder ($EBO^{obj}$).

The formal procedure is described in Algorithm 1, where $e_k$ is an $|I|$-dimensional unit row vector.

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Set $S_i := 1$ for all $i \in I$, and $S = (1,1,...,1);$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E := {S};$</td>
</tr>
<tr>
<td></td>
<td>$C(S, Q) := \sum_{i \in I}(c_i^a)E[Y_i]$ and</td>
</tr>
<tr>
<td></td>
<td>$EBO(S, Q) := \sum_{i \in I} \left(m_i t_i - (S_i - 1 + E[U_i]) + \sum_{u=1}^{Q_i} \sum_{x=0}^{S_i-1+U_i} (S_i - 1 + U_i - x) P(Y_i = x)P(U_i = u)\right).$</td>
</tr>
<tr>
<td>Step 2</td>
<td>$\Gamma_i := \frac{1}{c_i^a} \left(1 - \sum_{x=0}^{S_i} P(Y_i = x)\right)$ for all $i \in I;$</td>
</tr>
<tr>
<td></td>
<td>$k := \text{argmax} { \Gamma_i; i \in I };$</td>
</tr>
<tr>
<td></td>
<td>$S := S + e_k;$</td>
</tr>
<tr>
<td></td>
<td>$E := E \cup {S}.$</td>
</tr>
<tr>
<td>Step 3</td>
<td>Compute $C(S, Q)$ and $EBO(S, Q);$</td>
</tr>
<tr>
<td></td>
<td>If ‘stop criterion’, then stop, else go to Step 2.</td>
</tr>
</tbody>
</table>

Algorithm 1: Greedy algorithm for aggregate EBO service measure.
With regard to the fill rate service measure, the algorithm works slightly different. The local optimum is similarly obtained by calculation the ratio between the cost increase and the relative fill rate increase. Now this ratio is denoted by:

$$\Gamma_i := \frac{\Delta_i \beta(S_i, Q)}{c_i^a}$$

Where the difference in fill rate for SKU $i \in I$ by increasing the stock level by one is denoted as:

$$\Delta_i \beta(S_i, Q) = \frac{m_i}{M} \left( \beta_i(S_i + 1, Q_i) - \beta_i(S_i, Q_i) \right) = \frac{m_i}{M} \sum_{u=1}^{Q_i} P[Y_i = S_i] P[U_i = u] = \frac{m_i}{M} P[Y_i = S_i]$$

This results in the following formal algorithm:

**Algorithm 2: Greedy algorithm for the aggregate Fill Rate service measure.**

**Step 1**
Set $S_i := \max\{ \lceil m_i t_i - 1 \rceil, 1 \}$ for all $i \in I$;

- $S = (S_1, S_2, ..., S_{|I|})$;
- $\mathcal{E} := \{S\}$;
- Compute $C(S, Q)$ and $\beta(S, Q)$.

**Step 2**
Set $\Gamma_i := \frac{m_i}{M} P[Y_i = S_i]$ for all $i \in I$;

- $k := \arg\max \{ \Gamma_i : i \in I \}$;
- $S := S + e_k$;
- $\mathcal{E} := \mathcal{E} \cup \{S\}$.

**Step 3**
Compute $C(S, Q)$ and $\beta(S, Q)$;
- If ‘stop criterion’, then stop, else go to Step 2.

Finally, emergency shipment optimization is focused on the minimization of waiting time. The difference in mean waiting time for SKU $i \in I$ can be easily obtained by calculating the mean waiting time of the increased stock level:

$$\Delta W_i (S_i, Q) = W_i (S_i + 1) - W_i (S_i)$$

The increase in costs can be determined as the following:

$$\Delta C^h_i (S_i) = C^h_i (S_i + 1) - C^h_i (S_i)$$

Resulting in the following formal algorithm:

**Algorithm 3: Greedy algorithm for the Emergency Shipment focus.**

**Step 1**
Set $S_i := \arg \min\{ c^h_i (S_i) \}$ for all $i \in I$;

- $S = (S_1, S_2, ..., S_{|I|})$;
- $\mathcal{E} := \{S\}$;
- Compute $C^h(S)$ and $W(S)$.

**Step 2**
Set $\Gamma_i := \frac{\Delta W_i (S_i)}{\Delta C^h_i (S_i)}$ for all $i \in I$;

- $k := \arg\max \{ \Gamma_i : i \in I \}$;
- $S := S + e_k$;
- $\mathcal{E} := \mathcal{E} \cup \{S\}$.

**Step 3**
Compute $C^h(S)$ and $\beta(S)$;
- If ‘stop criterion’, then stop, else go to Step 2.
6. Case Study

In this section, a case study with data from the manufacturer and the supplier will be performed in order to evaluate the model. To be more specific, the study is to compare the manufacturer’s planning concept with the new supplier planning model developed in this project.

First reconsider figure 4.1, where the current supply chain schematically is displayed. In an after-transfer scenario, the supplier (VDL ETG) would coordinate all relevant items that are kept on stock by the manufacturer up to the GDC. Furthermore, the supplier would be responsible for the on-hand stock in the GDC. Figure 6.1 depicts how this supply chain schematically would look like.

![Figure 6.1: After-transfer spare parts supply chain.](image)

Next, in order to make the comparison, the current situation is analyzed. Figure 6.2 represents a schematic flow diagram of the spare parts cycle in 2013 with respect to the capital good’s module. The manufacturer’s cumulative re-order points represent the total amount of items on stock, resulting in several thousands of items on stock. Furthermore the demand is relatively low with respect to the total items on-hand, while still representing a large value. This skewness will be discussed later on in this chapter.

Service departments (Purchasing, CS and SL) process the outward demand further and registered dead-on-arrival (DOA) parts and scrapped parts. Furthermore repair orders and new build orders are placed at suppliers. Subsequently these suppliers report ‘Not OK’ (NOK) parts after revision and these are assumed to be ordered as new build. ‘No fault found’ (NFF) parts after revision are subsequently left out of the system as these parts will enter a different program.

As of March 2014 about 30% of all spare parts are located in the GDC with a little over one third of the total value.
For this case, 353 SKU’s, which are currently in stock in the GDC, are selected. Furthermore, only the GDC will be incorporated as a stock keeping point in this case study. As has been discussed before, the outward demand from local warehouses can be regarded as field demand for the GDC. The price of the most expensive item is about $10^7$ times the price of the cheapest item. These expensive items are though not common with respect to the amount of cheap items. This results in a very skewed distribution of SKU’s in this selection. In table 6.1 the differentiation in price is shown. If this table is considered, this skewness becomes clear as cheap parts (<€1000) represent 71.4% of the total pool of SKU’s. Furthermore note that a relatively small portion of expensive parts is responsible for almost as much demand as all cheap parts combined.

<table>
<thead>
<tr>
<th>Price Range (euros)</th>
<th>Items</th>
<th>Percentage</th>
<th>Responsible for Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition Price &lt; €1000</td>
<td>252</td>
<td>71.4%</td>
<td>36.3%</td>
</tr>
<tr>
<td>€1000 ≤ Acquisition Price &lt; €10.000</td>
<td>80</td>
<td>22.7%</td>
<td>32.8%</td>
</tr>
<tr>
<td>€10.000 ≤ Acquisition Price</td>
<td>21</td>
<td>5.9%</td>
<td>30.9%</td>
</tr>
</tbody>
</table>

Table 6.1: Price differentiation of SKU pool.

<table>
<thead>
<tr>
<th>Demand Range (items/year)</th>
<th>Items</th>
<th>Percentage</th>
<th>Responsible for Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Rate = 0</td>
<td>186</td>
<td>52.7%</td>
<td>0%</td>
</tr>
<tr>
<td>0 &lt; Demand Rate &lt; 1</td>
<td>55</td>
<td>15.6%</td>
<td>2.1%</td>
</tr>
<tr>
<td>1 ≤ Demand Rate &lt; 20</td>
<td>94</td>
<td>26.6%</td>
<td>32.5%</td>
</tr>
<tr>
<td>20 ≤ Demand Rate &lt; 50</td>
<td>12</td>
<td>3.4%</td>
<td>26.5%</td>
</tr>
<tr>
<td>50 ≤ Demand Rate</td>
<td>6</td>
<td>1.7%</td>
<td>39.0%</td>
</tr>
</tbody>
</table>

Table 6.2: Demand rate differentiation of SKU pool.
Table 6.2 shows the differentiation in demand rate within the pool of SKU’s. Most importantly to notice is that just six items are responsible for 39.0% of the total demand, while 186 parts are expected to have no demand for the coming time period. This underlines the idea of a very skewed differentiated pool of SKU’s.

<table>
<thead>
<tr>
<th>Average Lead-Time Range (working days)</th>
<th>Items</th>
<th>Percentage</th>
<th>Responsible for Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-time &lt; 50</td>
<td>47</td>
<td>13.3%</td>
<td>19.7%</td>
</tr>
<tr>
<td>50 ≤ Lead-time &lt; 100</td>
<td>177</td>
<td>50.2%</td>
<td>64.5%</td>
</tr>
<tr>
<td>Lead-time &lt; 150</td>
<td>129</td>
<td>36.5%</td>
<td>15.8%</td>
</tr>
</tbody>
</table>

Table 6.3: Lead-time differentiation of SKU pool.

Finally, table 6.3 depicts the differentiation in average lead-time within the pool of SKU’s. Clearly the SKU’s with medium length of lead-time are responsible for the largest part of the total demand. Furthermore it is observed from the dataset that the difference between the shortest lead-time (20 working days) and the longest lead-time (119 working days) is quite large.

One would now easily conclude that these ‘fast-movers’ items are more important than ‘slow-moving’ items, yet this is not the case. It should be noticed that all parts are critical, i.e. regardless of which part fails the machine will stop function. Therefore it is equally important to have slow-moving parts on stock as having fast-moving parts on stock. Although an important difference is the way these stock levels should be optimized. Van Aspert (2013) proposes a classification strategy for a similar optimization problem, by classifying parts along two axes. For expensive parts with high demand or cheap parts with low demand, the main focus is to balance investment costs and service level. For these parts it is important to choose a reasonable service level that takes the impact on investment costs into account. On the other hand, stock optimization with regard expensive parts subject to low demand is more focused on minimizing investment costs. This is because the high item price has a larger impact on the system performance than the demand. Cheap parts with high demand are then more focused on maximizing service level. Since these parts are relatively cheap, a relatively low investment contributes more to the system performance. Table 6.4 summarizes the part classification focus per item type.

<table>
<thead>
<tr>
<th>Price</th>
<th>Demand Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Focus on minimizing investment costs</td>
</tr>
<tr>
<td>Low</td>
<td>Balance between investment costs and service level</td>
</tr>
<tr>
<td>Low</td>
<td>Balance between investment costs and service level</td>
</tr>
<tr>
<td>High</td>
<td>Focus on maximizing service level</td>
</tr>
</tbody>
</table>

Table 6.4: Parts optimization strategies

This is exactly how the greedy algorithm works as it seeks the relatively most optimal SKU safety stock level to be increased, depending on the price/service level ratio.
6.1 Classification of Spare Parts

Since differences between individual SKU’s with regard to demand and price are very large, it is reasonable to classify SKU’s in different categories with individual target service levels when trying to find an optimal strategy. Furthermore it might be possible that different service target levels are desirable by the manufacturer, the customer, or perhaps for parts of suppliers that caused problems before. The user of the optimization model can decide the exact application of this classification method. Although for this research initially no classification will be used, an example is given. Like the differentiation analysis before, five demand categories will be applied: 0 parts per year, 0-1 parts per year, 1-20 parts per year, 20-50 parts per year and more than 50 parts per year. With regard to price, three categories will be applied: acquisition prices of €0-€1.000, €1.000-€10.000 and >€10.000 per item. This results in 15 different clusters of spare parts (Figure 6.3), for which a different service level has to be achieved.

![Figure 6.3: Example of a cluster distribution.](image)

### Acquisition Price

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Fill Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster 1</td>
<td>98.0</td>
</tr>
<tr>
<td>Cluster 2</td>
<td>98.0</td>
</tr>
<tr>
<td>Cluster 3</td>
<td>99.0</td>
</tr>
<tr>
<td>Cluster 4</td>
<td>99.5</td>
</tr>
<tr>
<td>Cluster 5</td>
<td>99.5</td>
</tr>
</tbody>
</table>

### Fill Rate (%)

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Fill Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster 6</td>
<td>95.0</td>
</tr>
<tr>
<td>Cluster 7</td>
<td>95.0</td>
</tr>
<tr>
<td>Cluster 8</td>
<td>98.0</td>
</tr>
<tr>
<td>Cluster 9</td>
<td>99.0</td>
</tr>
<tr>
<td>Cluster 10</td>
<td>99.0</td>
</tr>
</tbody>
</table>

### Fill Rate (%)

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Fill Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cluster 11</td>
<td>90.0</td>
</tr>
<tr>
<td>Cluster 12</td>
<td>90.0</td>
</tr>
<tr>
<td>Cluster 13</td>
<td>92.0</td>
</tr>
<tr>
<td>Cluster 14</td>
<td>92.0</td>
</tr>
<tr>
<td>Cluster 15</td>
<td>95.0</td>
</tr>
</tbody>
</table>

### Demand Frequency (parts per year)

6.2 Performance evaluation

Parts without any demand expected (demand rate = 0) are in most cases newly released parts for which is no forecasting data available and are, so-called, NPI items (new product introduction). Although the manufacturer keeps a sort of startup part stock, the model described in this project will not be able to determine the stock levels for these parts, since the expected demand rate is a key parameter. In order to get a clearer picture of how the model performs, the rest of this analysis will be concentrated on the ‘released for volume’ parts, for which a thorough forecast is made. This results in a sample of 167 SKU’s used for the analysis.

It is assumed that holding costs for the manufacturer are 15% of the price of a part per year, while these costs are 10% of the price of a part per year for the supplier. Changing the holding costs as parameter theoretically implies that the model calculates the holding costs for when supplier owns the parts in stock. For the initial analysis the holding costs will be assumed to be 15%. VDL ETG’s repair lead-time agreement is always 10 weeks (70 days) for VDL parts when release for volume is applicable (the item has a significantly large installed base). Furthermore it is assumed that the repair item will be the replenishment item, so the manufacturer will not order a new build item when a repair is requested. Emergency shipment costs are assumed to be €1000 per emergency shipment to the GDC and will take 10 working days from order release until delivery. Furthermore procurement lead-time, repair lead-time, scrap rate, acquisition price, demand rate and cluster number are specified per SKU. The general parameters specified are listed in table 6.5 below.
Emergency shipment costs are much higher than regular shipment costs, as regular replenishments are normally consolidated for many parts at once while an emergency replenishment usually contains only one item. It is assumed that regular shipment costs are included in the acquisition price. Several comparisons are made between the original situation and the output of the model under different parameter inputs. The most relevant outcomes are discussed in this chapter; other outcomes can be found in appendix C. In the current situation, the manufacturer realizes a fill rate of 58.84% in steady state and the worth of the total minimum desired stock is approximately €3 million with an approximate total number of 1000 items on stock. For confidentiality issues the exact numbers are left out of scope. First, the base stock levels at the GDC are determined for each service part with the available input parameters.

<table>
<thead>
<tr>
<th>Fill Rate target</th>
<th>Holding costs</th>
<th>$Q$</th>
<th>$t_{em}$</th>
<th>$c_{em}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>95%</td>
<td>15%</td>
<td>1</td>
<td>10 working days</td>
<td>€1000</td>
</tr>
</tbody>
</table>

Table 6.5: Parameters for central warehouse planning

Table 6.6: Comparison between original situation and model output with a fill rate target of 95%.

Table 6.6 shows how the model output performs with respect to the original situation. First notice that the original situation realizes a fill rate level of just 58.84%, much lower than the service level requirement maintained by the model. The model performs way better than the original situation with an increase of the service level of 63.5%, although the total investment costs also increase by 37.6%. Furthermore notice that the number of expected backorders and mean waiting time decrease dramatically.

In order to make a better comparison, the fill rate service level is set to 58.84%. The model output with this service setting is given in table 6.7:

<table>
<thead>
<tr>
<th>Current Situation</th>
<th>Total initial investment (millions)</th>
<th>Total Holding Costs (millions)</th>
<th>Actual Fill Rate</th>
<th>Actual EBO (/year)</th>
<th>Mean Waiting time (days)</th>
<th>Total Items</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€ 3.00</td>
<td>€ 0.450</td>
<td>58.84%</td>
<td>25.42</td>
<td>6.71</td>
<td>1000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aggregate Fill Rate Model</th>
<th>Total initial investment (millions)</th>
<th>Total Holding Costs (millions)</th>
<th>Actual Fill Rate</th>
<th>Actual EBO (/year)</th>
<th>Mean Waiting time (days)</th>
<th>Total Items</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€ 2.81</td>
<td>€ 0.422</td>
<td>58.85%</td>
<td>41.57</td>
<td>10.97</td>
<td>704</td>
</tr>
</tbody>
</table>

Table 6.7: Comparison between original situation and model output with a fill rate target of 58.84%.
The planning model now performs similar to the original situation with regard to the fill rate service target, while costs are decreased by 6.3%. On the other hand the expected amount of backorders is increased by 16 items per year (+63.5%) and mean waiting time by almost 4 days. Therefore it is reasonable to assume that the manufacturer currently uses the fill rate service measure as service target. On the other hand, the expected backorders and mean waiting time service measures might be more applicable for the GDC as a service measure. Although the fill rate represents the expected percentage of demand to be fulfilled from on-hand stock, it does not consider the average duration of the subsequent backorder fulfillment. The optimal way to increase the fill rate is to increase the stock levels of fast-moving SKU’s, yet the mean lead-time of an SKU certainly influences the performance of the total system. In order to reduce the mean waiting time for parts, the lead-time is also taken into account. In other words, the optimal way to reduce the mean waiting time for parts is to increase stock levels for items with the highest lead-time/demand rate ratio. In table 6.8 the model’s results are given when the expected number of backorders is considered as the target service measure with an aggregate optimization focus.

<table>
<thead>
<tr>
<th></th>
<th>Total Initial Investment (millions)</th>
<th>Total Holding Costs (millions)</th>
<th>Actual Fill Rate</th>
<th>Actual EBO (/year)</th>
<th>Mean Waiting Time (days)</th>
<th>Total Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Situation</td>
<td>€ 3.00</td>
<td>€ 0.450</td>
<td>58.84%</td>
<td>25.42</td>
<td>6.71</td>
<td>1000</td>
</tr>
<tr>
<td>Aggregate EBO Model</td>
<td>€ 2.66</td>
<td>€ 0.399</td>
<td>67.92%</td>
<td>25.38</td>
<td>6.70</td>
<td>966</td>
</tr>
<tr>
<td>% Difference</td>
<td>-11.3%</td>
<td>+11.3%</td>
<td>+15.4%</td>
<td>-0.1%</td>
<td>-0.1%</td>
<td>-3.4%</td>
</tr>
</tbody>
</table>

Table 6.8: Comparison between original situation and model output with an EBO target of 25.42.

Looking at service optimization from this perspective greatly improves the performance of the system. The same aggregate mean waiting time can be achieved with a costs reduction of 11.3% with respect to the original situation. A reason for this could be the large differentiation in average lead-time within the pool of SKU’s. Once this parameter is taken into consideration when optimizing, a better solution can be obtained. Surprisingly, the fill rate service level also increases. This means that, when taking the expected backorder service level into account, the model gives a better distribution of stock levels. This can also be recognized in the total items (sum of stock levels). This is more than could be seen in table 6.7, while the investment costs are lower. This is because the model now prefers to stock the cheapest parts and parts with a longer lead-time, resulting in a more skewed distribution of stock levels.

The concept of emergency shipments from the suppliers towards the GDC can add further improvements to these thoughts. As has been discussed earlier, relatively expensive emergency shipments are especially relevant for expensive SKU’s, as the investment costs outweigh emergency shipment costs. If the concept of emergency shipments is applied with the initial parameters, the following results are obtained as can be seen in table 6.9:
With these parameters the model achieves a fill rate level of 95% (61.8% increase) with 31.6% more investment costs (34.3% if emergency shipment costs are included). Note that the investment costs are very similar to the original 95% fill rate outcomes, because there still cannot be more that 5% of total demand shipped as emergency shipments (otherwise as backorder). The small difference is due to the fact that the emergency shipment model is considered to be a ‘lost-sales model’. Emergency shipment lead-times are relatively short with 10 days (average normal replenishment time is 67.9 working days), which makes it possible to reduce the mean waiting time for parts drastically. Note that the emergency shipment model results in more items on stock. The explanation for this is simple. Since emergency shipments are relatively cheap, more expensive parts will make more use of emergency shipments and increasing safety stock levels for cheaper parts then compensates the loss in fill rate. The result is a very skewed distribution of stock levels.

Finally, with a fill rate service level target of 58.84% the emergency shipment model outcomes are given in table 6.10:

<table>
<thead>
<tr>
<th></th>
<th>Total initial investment (millions)</th>
<th>Total Holding Costs (millions)</th>
<th>Emergency Costs (millions)</th>
<th>Actual Fill Rate</th>
<th>Mean Waiting time (days)</th>
<th>Total Items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Situation</td>
<td>€ 3.00</td>
<td>€ 0.450</td>
<td>€ 0</td>
<td>58.84%</td>
<td>6.71</td>
<td>1000</td>
</tr>
<tr>
<td>Emergency Shipment Model</td>
<td>€ 0.891</td>
<td>€ 0.134</td>
<td>€ 0.567</td>
<td>59.00%</td>
<td>5.76</td>
<td>844</td>
</tr>
<tr>
<td>% Difference</td>
<td>-70.3%</td>
<td>-70.3%</td>
<td>N/A</td>
<td>+0.2%</td>
<td>-14.2%</td>
<td>-15.6%</td>
</tr>
</tbody>
</table>

Table 6.10: Comparison between original and model output with a fill rate target of 58.84% and emergency shipments.

It becomes clear that the system heavily relies on emergency shipments, because the percentage of demand that has to be fulfilled from on hand stock is low and the emergency shipment lead-time is relatively short. This results in a cost reduction of 48.2% with respect to the original situation.

In general, the proposed model is able to replicate the original situation (based on the fill rate service measure) and moreover achieve better results by implementing emergency shipments and optimizing through different service measures. Even though the incurred emergency shipment costs and times are just assumptions, the introduction of emergency shipments seems very promising. Bottom line is that a more efficient distribution of safety stock levels per item can result in significant investment costs while maintaining the same or even a higher service level.
6.3 Sensitivity analysis

In this section, a sensitivity analysis is conducted to understand how the output of the planning model behaves in response to the changes in its input. Furthermore, the sensitivity analysis should give an idea of how the transfer initiative influences the supply chain and what changes could be implemented in order to react on these changes. The most important parameters in this case are the supplier lead times, which are usually long for high-tech items, the settings of the target service, emergency shipment parameters and the preferred deliver quantity level. To be more specific, this sensitivity analysis aims to answer the following questions:

- What is the effect of varying several input parameters that are subject to changes caused by the transfer initiative on the planning model’s output?

- What are probable consequences of the transfer initiative on the supply chain performance and what changes should happen to compensate these consequences?

Table 6.11 shows the input parameters that are varied and the values that are assigned to these parameters. Furthermore, only the most relevant outcomes are shown in this analysis; more detailed descriptions can be found in appendix D.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average lead time (days)</td>
<td>-10, -9, ... , 9, 10</td>
</tr>
<tr>
<td>Procurement lead time</td>
<td>-90%, -80%, ... , 90%, 100%</td>
</tr>
<tr>
<td>Repair lead time</td>
<td>-90%, -80%, ... , 90%, 100%</td>
</tr>
<tr>
<td>Fill rate service level</td>
<td>50%, 60%, 70%, 80%, 90%, 95%, 98%, 99%, 99.5%, 99.9%, 99.95%, 99.99%</td>
</tr>
<tr>
<td>EBO service level</td>
<td>50, 40, 30, 20, 10, 5, 2, 1, 0.5, 0.1, 0.01, 0.001</td>
</tr>
<tr>
<td>Emergency shipment costs</td>
<td>€100, €200, €400, €600, €1000, €2000, €5000, €10000, €11000, €15000, €20000</td>
</tr>
<tr>
<td>Emergency shipment time (days)</td>
<td>1, 2, 5, 10, 15, 20, 30, 40, 50, 75, 100</td>
</tr>
<tr>
<td>Preferred deliver quantity</td>
<td>1, 2, 3, 4, 5, 6, 7, 8, 9, 10</td>
</tr>
</tbody>
</table>

Table 6.11: Parameter settings for sensitivity analysis

6.3.1 Change in average lead time

As discussed before, the first phase of the transfer initiative is about re-routing existing second tier supplier replenishment processes via VDL ETG. Obviously, this will cause extra operations, resulting in extra supplier related lead-time. It is important to find out what the consequences of this extra lead time are with regard to the performance of the spare parts supply chain. If again the 95% fill rate service level target with a base stock replenishment policy (Q=1) is assumed, the total investment costs are influenced by the total lead time as is shown in figure 6.4.
The total investment costs clearly increase linearly when the aggregate lead-time is increased. Furthermore notice that the emergency shipment model performs better than the aggregate model without emergency shipments (given the used parameters).

With regard to the transfer initiative, the manufacturer reimburses a commission of a small percentage of the acquisition price. This means that the supplier can at most spend this percentage more on the spare parts supply chain in order to gain benefits or break-even. If only the inventory aspect of spare parts is taken into account, it is concluded that the aggregate mean lead-time increase should not exceed about 2 to 3 extra days in order to stay below this margin in increased costs. On average one day of extra lead-time will result in 1.4% extra investment costs. Still, it is reasonable to assume that several different other costs play a role in the supply chain, when the lead-time is increased, causing this estimate to increase even further.

6.3.2 Change in procurement lead time

An improvement of the mean procurement lead-time is an option to decrease the total costs in the supply chain. If a shorter procurement lead-time can be realized for a particular part, this means that items will be shorter in the pipeline and as a consequence the safety stock level can be decreased. Figure 6.5 shows how the total investment cost behave in accordance with the aggregate procurement lead-time. Again the behavior is almost linear, with respect to the procurement lead-time increase and performs the model that includes emergency shipments better than the standard aggregate model.

The investment costs of the standard aggregate model increase about 4% per 10% procurement lead-time increase, while this is 3.7% for the emergency shipment model.
6.3.3 Change in repair lead time

Another improvement option is to alter repair lead-times. This will mainly affect relatively expensive items, as cheaper items are usually not considered to be repairable. Therefore, and since repair lead-times are shorter than procurement lead-time, one would expect the repair lead-time to have less effect on the total investment costs. Figure 6.6 shows how the total investment costs respond to an aggregate repair lead-time adjustment.

![Figure 6.6: Increase in investment costs by repair lead-time.](image)

The standard aggregate model shows an increase of 3.7% and about 3.2% for the emergency shipment model in investment costs when the repair lead-time is increased by 10%. As was expected, this ration is lower than for the procurement lead-time, though not very much lower. The most intuitive explanation is that more expensive parts (which are repaired in most cases) justify the larger part of the investment costs. For this reason, repair lead-times are still affect the system significantly.

6.3.4 Change in service level

Next, the influence of the fill rate service target on the total investment costs will be examined. Three different model types will be compared, since three different types of model focuses that include a fill rate service strategy were described. This comparison can be seen in figure 6.7.

![Figure 6.7: Increase in investment costs by fill rate service level.](image)

Notice that investment costs drop dramatically for the emergency shipment model when the service measure is decreased. This is because emergency shipment costs are relatively cheap compared to stocking an extra (expensive) item. When the fill rate target is lower, the emergency shipment
strategy will prefer an emergency shipment to extra stock, resulting in substantial cost savings. Furthermore, the emergency shipment investment costs converge with the standard aggregate model, which is logical as there will be less emergency shipments as the fill rate increases. The cost series appear quite linear, although as the service measure increments get ever smaller, costs increase exponentially with the fill rate service target.

The expected backorder service measure cannot be measured for the emergency shipment model, because it is considered as an Erlang loss system (a backorder will be considered as an emergency shipment). Therefore only two models are compared in figure 6.8. Again the total investment costs increase exponentially with the EBO service level and performs the aggregate model better than the item model, especially for low service levels (high amount of backorders allowed).

### 6.3.5 Change in emergency shipment parameters

It is reasonable to assume that emergency shipment parameters are different from the standard parameters used in the performance evaluation section. For example the costs of an emergency shipment could be very different. If the fill rate service model is considered, the expected emergency shipment costs can easily be determined by multiplying the expected amount of out-of-stock situations by the expected demand and the emergency shipment costs \((1 - \text{Fill Rate}) \cdot D \cdot C_{em}\).

On the other hand, when the mean waiting time is minimized, the emergency shipment costs have the following influence (Figure 6.9). An aggregate mean waiting time of 1 day will be set as service target.

![Figure 6.8: Increase in investment costs by EBO service level.](image)

![Figure 6.9: Increase in investment costs by emergency shipment costs.](image)
When minimizing mean waiting time, the cost aspect of emergency shipments is taken into account. This means that when emergency shipments are cheap, they will be preferred instead of increasing the safety stock level. On the other hand, when emergency shipments are relatively expensive, increasing the safety stock level will be more likely. This can be seen in figure 6.9. Clearly around an emergency shipment cost of €11,000 a tipping point is reached, where after the total costs spent on emergency shipments decreases (and thus base stock levels are increased). Figure 6.10 depicts how the investment costs are affected when the emergency shipment time is increased.

![Figure 6.10: Increase in investment costs by emergency shipment time.](image)

Most notable is the downward slope of the total emergency shipment costs, which makes sense. As emergency shipment lead times increase, it is less advantageous to make use of emergency shipments. Furthermore it can be observed that at higher emergency shipment lead-times the total investment costs even exceed investment costs of the standard aggregate model. This is because all out-of-stock situations will result in an emergency shipment. When emergency shipments are very expensive, the model will try to compensate the emergency shipments costs by increasing the safety stock level.

6.3.6 Change in preferred deliver quantity

Finally the influence of the preferred deliver quantity will be examined. Figure 6.11 shows how the total number of items on stock (sum of all minimal stock levels) reacts on the aggregate increase of the preferred deliver quantity.

![Figure 6.11: Increase in items by Q.](image)
As has been discussed before, increasing the deliver quantity will result in a lower minimal stock level needed to achieve the service level requirement, because on average the inventory position will increase. This is exactly what can be observed in figure 6.11 and figure 6.12. The total number of items on stock more or less decreases linearly by increasing the preferred deliver quantity, while the investment costs increase.

With regard to these increase in investment costs, a tradeoff exists between the higher average inventory position and the decrease in other parameters like acquisition costs, production costs, shipment costs (more pooled) and administration costs. If these cost changes are taken into account, one can determine an optimal deliver quantity.

![Figure 6.12: Increase in investment costs by Q.](image)

### 6.4 Results for the original situation

Now it is clear that the model behaves as expected when certain parameters are changed. The following tables (6.12 and 6.13) show how the model reacts when the original 58.84 fill rate service level is regarded with all other original parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Average</th>
<th>Incremental parameter increase</th>
<th>Percentage parameter decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average lead time</td>
<td>69.9 working days</td>
<td>1.9% increase in investment costs per extra day</td>
<td>8.8-9.0% decrease in investment costs per 10% decrease</td>
</tr>
<tr>
<td>Procurement lead time</td>
<td>86.7 working days</td>
<td>0.67% increase in investment costs per extra day</td>
<td>4.5-5.5% decrease in investment costs per 10% decrease</td>
</tr>
<tr>
<td>Repair lead time</td>
<td>36.6 working days</td>
<td>1.0% increase in investment per extra day</td>
<td>2.5-3.6% decrease in investment costs per 10% increase.</td>
</tr>
<tr>
<td>Demand Rate</td>
<td>8.3 items per year</td>
<td>1.7-4.6% increase in costs per extra item/year</td>
<td>8.8% decrease in investment costs per 10% decrease</td>
</tr>
</tbody>
</table>

Table 6.12: Lead-time and demand rate parameter changes with 58.84% fill rate service level as reference

The effect of other parameters can be seen in table 6.13. Note that the effect of emergency shipment costs and emergency shipment times heavily depends on the type of the item. Emergency shipments will generally be more beneficial for expensive items, outweighing the emergency costs.
Furthermore items with a relatively short lead-time will benefit less from emergency shipments. The effect of these costs should be assessed per item.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill rate service level</td>
<td>Costs increase exponentially</td>
</tr>
<tr>
<td>EBO service level</td>
<td>Costs increase exponentially</td>
</tr>
<tr>
<td>Emergency shipment costs</td>
<td>Depends on item and emergency shipment lead-time</td>
</tr>
<tr>
<td></td>
<td>&lt;€2000 beneficial for moderately expensive (10 days)</td>
</tr>
<tr>
<td></td>
<td>&lt;€5000 considerable for expensive items (10 days)</td>
</tr>
<tr>
<td>Emergency shipment time (days)</td>
<td>Depends on item and emergency shipment costs</td>
</tr>
<tr>
<td></td>
<td>&lt;14 days, for cheaper emergency shipment cost (€600)</td>
</tr>
<tr>
<td></td>
<td>&lt;10 days for expensive emergency shipment costs (€5000)</td>
</tr>
</tbody>
</table>

Table 6.13: Other parameter changes with 58.84% fill rate service level as reference
7. Conclusion and Recommendations

In this chapter, conclusions and recommendations towards the supplier based on this research are given. Thereafter recommendations for future research are given.

7.1 Conclusions

This project focuses on both the performance evaluation of the spare parts supply chain of a capital good’s module and on how a supplier of this module can develop a model to optimize the supply chain performance. As a result of a transfer initiative, where several responsibilities within this supply chain are transferred from the manufacturer of the capital good to the supplier of the module, the supplier should be able to assess forthcoming risks, have understanding of the supply chain and determine effects of future improvement efforts.

A decision-support tool, developed to suit the after-transfer scenario, can be used by planners, purchasers and other employees at VDL ETG to determine optimal stock levels and the costs of the supply chain under various circumstances.

The research question given in chapter 2 will now be discussed.

Main Research Question

*What internal changes should VDL ETG implement with regard to the spare parts supply chain in order to achieve economic benefits by taking over spare parts management responsibilities and ownership?*

Economic benefits can be accomplished by VDL ETG by reducing the costs of the spare parts supply chain and subsequently be rewarded by the manufacturer for these improvements. VDL ETG has several options for improving the supply chain performance. First of all the system’s responsiveness can be improved by shortening supplier lead-times for SKU’s. A system that can respond faster upon replenishment requests, needs a smaller investment to achieve the desired service level. Second, design (or reliability) improvements can reduce failure rates in the field. Less demand from the field simply means less investment needed to react on failures. Third, emergency shipments (or fast-lane spares) from suppliers of spare parts towards the GDC can be introduced to improve performance. Especially for expensive SKU’s, it is inconvenient to keep much stock. Although emergency shipments could be costly, an optimal mix of demand fulfilled from on-hand stock and from emergency shipments could lead to cost improvements, depending on the cost and lead-time parameters of emergency shipments.

Research Question 1

*What exact changes could take place with regard to parameters that affect the supply chain performance in order to achieve economic benefits?*

Since VDL ETG is still in an early phase of the transfer project, a lot of aspects important for the future supply chain are still subject to debate. On the other hand, it is certain that VDL ETG and the manufacturer will implement a ‘three-phase’ transfer project and VDL ETG will be engaged in service activities in the future. As discussed before, during phase one all second-tier supplier parts will be rerouted via VDL ETG, resulting in more work, risk and costs for VDL ETG. VDL ETG will be compensated with a margin of the part acquisition price, which translates in an equal increase of the
total investment costs over the long-term. Concluding from the case study, a 1.9% increase in investment costs is the result of adding one extra day to the aggregate average lead-time (assuming a base stock replenishment strategy is applied as in the current situation and the current service level is realized). Table 8.1 shows how several important parameter changes affect the investment costs of the supply chain. The percentage effects of changing lead-times and demand rate parameters can be used to determine what exact changes need to be made in order to achieve the desired improvement.

<table>
<thead>
<tr>
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</tr>
</tbody>
</table>

Table 8.1: Lead-time and demand rate parameter changes with 58.84% fill rate service level as reference

**Research Question 2**
If VDL ETG accepts the responsibility of maintaining spare parts inventory in the GDC, how can VDL ETG optimize their internal production by determining order moments and production quantities for spare parts and smoothening production facility utilization?

Through the use of a mathematical model, described and tested in this research, a cost-wise inventory stocking solution for a global distribution center (or the first echelon) can be formulated. It is demonstrated that the model is able to perform similar, or even better that the original situation. Using this model, VDL ETG can make better supported decisions on behalf of the order moments for spare parts, because for example the effect of replenishment batches can be tested. Batching can lead to savings in production and shipment costs. Furthermore, implementing emergency shipments can make sure to smoothen production facility utilization. For example when factory utilization is relatively low, one would prefer to produce more spare parts and rely less on emergency shipments. On the other hand, when utilization is low, priority should be given to parts used for new machine, while spare part demand could be covered by emergency shipments.

**Research Question 3**
What terms should be included in a service contract between the manufacturer and VDL ETG and, depending on the risk of these terms, how should the costs of the improved situation be shared in order to at least realize a break-even situation?

First of all, if VDL ETG is going to be responsible for any spare parts stock, the desired level of the service KPI should be agreed with the manufacturer. In the current situation a fill rate service measure of 58.84% is realized. Another option would be to define a maximum number of backorders during one year, or the average waiting time for a spare part demand to be fulfilled. The expected
backorders KPI does a better job at realizing an optimal solution under a certain service level, it is therefore recommended to use this KPI.

Another important aspect of a service contract would be how VDL ETG is compensated for taking the additional risk and costs which arise from the stock keeping. As already mentioned, the extra lead-time should be no more than 2 to 3 days in order prevent the investment costs to exceed the marginal increase, unless other performance increases are realized. This percentage reimbursement seems therefore marginal. A better option would be to penalize VDL ETG for every out-of-stock situation or too long waiting time and reimburse a share of the realized cost reduction every fiscal year. That way VDL ETG is motivated to realize a cost-down over time and also to minimize the spare parts inventory.

To determine what should change in order to realize a break-even situation is quite difficult to say. If the as-is situation is considered and VDL ETG would be responsible for the GDC parts inventory, the model realized an investment cost reduction of 6.3%. Taking in mind the small percentage reimbursement, some extra lead-time and extra work should be included, one could argue that taking over the situation as-is would more or less realize a break even situation, if the extra risk for VDL ETG is disregarded.

7.2 Recommendations

Recommendations for VDL ETG

**Implementation of the decision-support tool:** As has been discussed before, VDL ETG should be able to search for optimal spare parts stock values in order to understand the supply chain better. In this research, a multi-item, single location optimization model has been developed to determine the optimal stock levels such that investment costs can be determined. Furthermore this model can be used to validate proposed parameter changes. It is recommended to VDL ETG to use this decision-support tool that can support multiple departments in their decision-making with regard to the spare parts supply chain.

**Investigate internal cost parameters:** This research mainly concentrated on how input parameters should change in order to realize a certain cost-down in investment costs. On the other hand it is very important to determine what costs are incurred when changing these parameters. For example, in order to realize a decrease in demand rate, an investment has to be made for improving the design or upgrading installed base parts. These costs are the other side of the coin with regard to the improving the supply chain’s performance.

**Investigate supply chain redesign possibilities with the proposed model:** When more is known about costs for internal parameter changes, it is recommended to search for improvement opportunities with the decision support tool.

**Re-evaluate economic order quantities with new spare parts usage insights:** Because VDL ETG now has insight in expected spare parts demand for a sufficiently long time horizon, the economic order quantities should be re-examined. Since the order quantities are now only dependent on internal production variables, the inclusion of external spare parts data could be used for improvements.
Research optimization of end-of-life products: As has been discussed before, VDL ETG will be responsible for the production of spare parts for 10 years after a certain product goes end-of-life. When a product is end-of-life, this has a significant impact on the production price of spare parts, mainly because there is no regular flow of new-build parts anymore. Since it can still be beneficial to maintain a stock of spare parts for end-of-life product, it is recommended to investigate how VDL ETG should make the transition from regular spare parts inventory to end-of-life spare part inventory and how the production of end-of-life spare parts during this 10 year period should be produced.

Discuss the customer service approach with the manufacturer: In the case study section it was observed that a different approach towards the service measure resulted in different obtained inventory solutions. Knowing that the mean waiting time for parts is a more appropriate KPI for spare parts, where time is a very important factor, VDL ETG should discuss on which type of KPI is wants to be reviewed by the manufacturer.

Recommendations for future research

Research a way to include batching with emergency shipments and stochastic lead-times: One major drawback of the proposed model is that it is not possible to apply the batching strategy when lead-times are stochastic. Batching can lead to significant performance improvements and the nature of some parts, which are subject to partial condemnation, prevents the use of them. It is therefore recommended to investigate how batching can be applied when lead-times are considered not deterministic.

Extending the model to a two or three-echelon model: Although this is not the case yet, a multi-echelon model would be able to incorporate the effect of local warehouses. This could result in a more accurate model for finding an optimal spare parts inventory solution.
8. References


### Appendix A: Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BO</td>
<td>Backorder</td>
</tr>
<tr>
<td>CFD</td>
<td>Customer forced demand</td>
</tr>
<tr>
<td>CS</td>
<td>Customer support</td>
</tr>
<tr>
<td>DOA</td>
<td>Dead on arrival</td>
</tr>
<tr>
<td>EBO</td>
<td>Expected backorders</td>
</tr>
<tr>
<td>EC</td>
<td>Engineering change</td>
</tr>
<tr>
<td>EOL</td>
<td>End-of-life</td>
</tr>
<tr>
<td>EOQ</td>
<td>Economic order quantity</td>
</tr>
<tr>
<td>ERP</td>
<td>Enterprise resource planning</td>
</tr>
<tr>
<td>FC</td>
<td>Field change</td>
</tr>
<tr>
<td>FSD</td>
<td>Field service defect</td>
</tr>
<tr>
<td>GDC</td>
<td>Global distribution center</td>
</tr>
<tr>
<td>KPI</td>
<td>Key performance indicator</td>
</tr>
<tr>
<td>MDT</td>
<td>Mean downtime</td>
</tr>
<tr>
<td>METRIC</td>
<td>Multi-echelon technique for recoverable item control</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean time between failures</td>
</tr>
<tr>
<td>MTTD</td>
<td>Mean time to diagnose</td>
</tr>
<tr>
<td>MTTR</td>
<td>Mean time to repair</td>
</tr>
<tr>
<td>MTWfP</td>
<td>Mean time waiting for parts</td>
</tr>
<tr>
<td>NOK</td>
<td>Not OK</td>
</tr>
<tr>
<td>OEM</td>
<td>Original equipment manufacturer</td>
</tr>
<tr>
<td>OH</td>
<td>On hand</td>
</tr>
<tr>
<td>OPEX</td>
<td>Operational expenses</td>
</tr>
<tr>
<td>RS&amp;S</td>
<td>Repair, Spares and Service</td>
</tr>
<tr>
<td>SKU</td>
<td>Stock keeping unit</td>
</tr>
<tr>
<td>SL</td>
<td>Spares logistics</td>
</tr>
<tr>
<td>TCO</td>
<td>Total cost of ownership</td>
</tr>
<tr>
<td>VDL ETG</td>
<td>Van der Leegte Enabling Technologies Group</td>
</tr>
<tr>
<td>WIP</td>
<td>Work in process</td>
</tr>
</tbody>
</table>
### Appendix B: Inventory Model parameters

The inventory model's parameters are defined as follows:

#### Decision variables

- $S_i$: Sum of stock levels for SKU $i$. (items)
- $Q_i$: Optimal deliver quantity for SKU $i$. (items)
- $EBO_{obj}$: Aggregate expected backorders service level (items)
- $EBO_i^{obj}$: Average mean backorders per SKU $i$ service level (items)
- $W_i^{obj}$: Aggregate mean waiting time service level (time units)
- $\beta_{obj}$: Aggregate fill rate service level (%)
- $\beta_i^{obj}$: Fill rate per SKU $i$ service level (%)
- $I$: Total set of SKU’s (items)

#### Dependent variables

- $X_i$: Net stock of SKU $i$. (items)
- $EBO_i$: Expected amount of backorders of SKU $i$. (items)
- $\beta_i$: Expected fill rate of SKU $i$. (%)
- $W_i$: Mean waiting time for backorders of SKU $i$. (weekdays)
- $OH_i$: Amount of on hand items of SKU $i$. (items)
- $BO_i$: Amount of backordered items of SKU $i$. (items)
- $IP_i$: Inventory position of SKU $i$. (items)
- $s_i$: Reorder level for SKU $i$. (items)

#### Production, consumption and transport parameters

- $m_i$: Poisson demand rate for SKU $i$. (items/year)
- $t_i^{rep}$: Mean repair lead-time for SKU $i$. (time units)
- $t_i^{proc}$: Mean procurement lead-time for SKU $i$. (time units)
- $t_i^{em}$: Mean emergency shipment lead-time for SKU $i$. (time units)
- $r_i$: Average scrap rate for SKU $i$. (%)

#### Cost parameters

- $c_i^a$: Standard new price of SKU $i$. (€/unit)
- $c_i^Q$: Price of SKU $i$ when $Q$ is ordered. (€/unit)
- $c_i^{rep}$: Price of SKU $i$ when $Q$ is repaired. (€/unit)
- $c_i$: Expected price for SKU $i$. (€/unit)
- $c_i^{hs}$: Supplier holding costs for SKU $i$ per time unit. (€/unit)
- $c_i^{hm}$: Manufacturer holding costs for SKU $i$ per time unit. (€/unit)
- $c_i^{em}$: Emergency shipment costs for SKU $i$. (€/unit/shipment)
- $C(S, Q)$: Total costs with respect to S and Q. (€)
- $C_i(S, Q)$: Total costs with respect to S and Q, for SKU $i$. (€)
Other parameters

\( U_i \) Uniformly distributed random variable on \( \{1, \ldots, Q\} \). (items)

\( \Gamma_i \) Service level increase versus cost increase ratio (number)

\( M \) Aggregate demand for all SKU’s (items/year)

\( \Delta_i EBO \) Difference in expected number of backorders when increasing the re-order level by one for SKU \( i \). (items)

\( \Delta_i \beta \) Difference in expected fill rate when increasing the re-order level by one for SKU \( i \). (%)

\( \Delta W_i \) Difference in mean waiting time when increasing the re-order level by one for SKU \( i \). (days)
Appendix C: Comparison of the model with the current situation

<table>
<thead>
<tr>
<th></th>
<th>Total initial investment (millions)</th>
<th>Total Holding Costs (millions)</th>
<th>Actual Fill Rate (%)</th>
<th>Actual EBO ($/year)</th>
<th>Mean Waiting time (days)</th>
<th>Total Items</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Situation</strong></td>
<td>€ 3.00</td>
<td>€ 0.450</td>
<td>58.84%</td>
<td>25.42</td>
<td>6.71</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Item Fill Rate Model</strong></td>
<td>€ 4.75</td>
<td>€ 0.712</td>
<td>96.4%</td>
<td>1.69</td>
<td>0.45</td>
<td>908</td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td>+58.2%</td>
<td>+58.2%</td>
<td>+63.8%</td>
<td>-93.4%</td>
<td>-93.4%</td>
<td>-9.2%</td>
</tr>
</tbody>
</table>

Table C.1: Comparison between original situation and model output with an item fill rate target of 95%.

The item fill rate service measure over performs with respect to the service level of 95% (table C.1). An item fill rate service measure can therefore be considered suboptimal.

<table>
<thead>
<tr>
<th></th>
<th>Total initial investment (millions)</th>
<th>Total Holding Costs (millions)</th>
<th>Actual Fill Rate (%)</th>
<th>Actual EBO ($/year)</th>
<th>Mean Waiting time (days)</th>
<th>Total Items</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Situation</strong></td>
<td>€ 3.00</td>
<td>€ 0.450</td>
<td>58.84%</td>
<td>25.42</td>
<td>6.71</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Item Fill Rate Model</strong></td>
<td>€ 3.34</td>
<td>€ 0.501</td>
<td>66.1%</td>
<td>26,97</td>
<td>7.11</td>
<td>677</td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td>+11.3%</td>
<td>+11.3%</td>
<td>+12.3%</td>
<td>+6.1%</td>
<td>+6.0%</td>
<td>-32.3%</td>
</tr>
</tbody>
</table>

Table C.2: Comparison between original situation and model output with an item fill rate target of 58.84%.

The same accounts when the target is set at the original level of 58.84% as can be seen in table C.2. The model realizes a service level of 66.1%, which is unnecessarily higher than the target level.

<table>
<thead>
<tr>
<th></th>
<th>Total initial investment (millions)</th>
<th>Total Holding Costs (millions)</th>
<th>Actual Fill Rate (%)</th>
<th>Actual EBO ($/year)</th>
<th>Mean Waiting time (days)</th>
<th>Total Items</th>
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<tr>
<td><strong>Current Situation</strong></td>
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<td>6.71</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Item EBO Model</strong></td>
<td>€ 3.39</td>
<td>€ 0.508</td>
<td>66.7%</td>
<td>19.23</td>
<td>5.07</td>
<td>820</td>
</tr>
<tr>
<td><strong>% Difference</strong></td>
<td>+12.9%</td>
<td>+12.9%</td>
<td>+13.4%</td>
<td>-24.4%</td>
<td>-24.4%</td>
<td>-18.0%</td>
</tr>
</tbody>
</table>

Table C.3: Comparison between original situation and model output with an item EBO target of 25.42.

When applying the item EBO service measure, the model performs almost equal to the item fill rate service measure. Yet there are a lot of more items on stock. Again this is because the lead-time effect is taken into account, resulting in a more skewed distribution.
Appendix D: Inventory Model parameters

![Increase in Items by Lead-Time](image1.png)

**Figure D.1:** Increase in items by Lead-time.

![Increase in Items by Procurement Lead-Time](image2.png)

**Figure D.1:** Increase in items by Procurement Lead-time.
Figure D.1: Increase in items by Repair Lead-time.

Figure D.1: Increase in Items by Fill Rate service level.
Figure D.1: Increase in items by EBO service level.

Figure D.1: Increase in items by Emergency shipment costs.
Figure D.1: Increase in items by Lead-time.
Appendix E: Implementation of the model

The implementation of the model discussed in chapter 5 together with the optimization heuristics discussed in chapter 6 results in a decision support tool, which is discussed in this chapter.

The decision support tool created in this assignment will enable supply chain engineers, purchasers, logistics planners or service support engineers to plan service part stock levels for a central warehouse. Furthermore it can be used as an analysis tool for decisions to be made about KPI’s like service level targets and supplier lead-time modifications. The impact of the supply chain modifications determined by the tool can be used to make an assessment of the proposed decision. This way one could obtain a more in-depth and robust understanding of the inventory tradeoffs of the supply chain under scope.

Basically the tool functions as a gateway between an Excel input file and several Matlab models that actually perform the optimization heuristic based upon the input preferences. It is possible to use the tool as an easy way to either determine stock levels for a particular set of SKU’s or compare different settings of decision variables by running the model multiple times and determine the impact of these settings. Whenever the desired results are obtained, it is possible to export the results into an output Excel file.

Figure E.1 shows how the tool’s input parameters, model calculations and model output relate towards each other. These three steps will be discussed in more detail in this appendix.

---

**Figure E.1: Model input, model calculations and model output parameters of the decision support tool**

- **Model Input**
  - Model Focus
    - Aggregate
    - Item
    - Emergency
  - Service Focus
    - EBO
    - Fill Rate
  - Product Parameters
    - Demand rate
    - Mean procurement lead-time
    - Mean repair lead-time
    - Emergency shipment lead-time
    - Mean scrap rate
    - Item cluster
  - Cost Parameters
    - Acquisition costs
    - Holding costs
    - Emergency Shipment costs

- **Model Calculations**
  - Greedy heuristics for model preferences
  - Determine initial output values
  - Determine relative contributions per SKU
  - Increase stock level
  - Repeat until service requirement is met
  - Determine costs
  - Determine actual performance

- **Model Output**
  - Optimal S levels
  - Total investment costs
  - Total holding costs per period
  - Total emergency shipment costs
  - Investment costs per cluster
  - Actual EBO
  - Actual fill rate
  - Mean waiting time for parts
  - Total number of items on stock
The model’s input

The excel file ‘Input.xlsx’ should be used to import pre-formatted data of the set of SKU’s. It consists of two sheets. In the first sheet one can paste the specific input parameters needed per SKU. In the second sheet, one can divide the total group of SKU’s into different clusters and subsequently define service preferences for each of these clusters.

Sheet ‘Data’

- **Material description**: This is the code of the service part as it is recognized by the service supplier.
- **Acquisition price**: This is the price of a service part for which the transaction is made between VDL ETG and the manufacturer (in euros).
- **Scrap rate**: This is the average percentage of returned parts of a service part that will be scrapped (fraction).
- **Procurement lead-time**: This is the average procurement lead-time of a service part from the moment an order is placed up to the moment of delivery to the warehouse (in days).
- **Repair lead-time**: This is the average repair lead-time of a service part from the moment a repair order is placed up to the moment of delivery to the warehouse (in days).
- **Demand rate**: This is the expected demand for a service part per year (in items/year).
- **Emergency shipment costs**: This is the cost of performing an emergency shipment for a service part (in euros).
- **Emergency shipment time**: This is the average time for a service part to be delivered by an emergency shipment (in days).
- **Holding costs**: This is the cost of keeping a service part unused on stock, expressed in a percentage of the acquisition price (fraction).
- **Optimal deliver quantity**: this is the ideal number of items shipped when an order is processed. Note that this is not always equal to a part’s Economic Ordering Quantity, as regular parts can also be used for the production of new products. Furthermore it is not possible to increase this parameter when emergency shipment are applied for an SKU or when there is not a 0% or 100% scrap rate.
- **Cluster number**: This is the cluster where a service part is assigned.

Sheet ‘Clusters’

- **Fill rate service level**: This is the desired initial percentage of orders that need to be delivered from on-hand stock, i.e. without a backorder (fraction).
- **EBO service level**: This is the desired initial absolute number of orders that are allowed to be backordered (number of items)
- **Service measure**: This is the desired initial service measure to be applied to the group of service items (Fill Rate, EBO)
- **Service focus**: This is the desired initial service focus to be applied to the group of service items (Aggregate, Item, Emergency)
Using the tool

When opening the tool, by clicking the .exe file, one will see the following window (figure E.2). Initially, the only available option is to open the input file.

The Excel ‘Input’ file can be loaded by clicking the ‘Open’ button when the tool is started and then locate the file directory. Importing the file can take several seconds. After the tool has imported the input file’s data, one will see a window similar to figure E.3.

The input data table shows values of the discussed input file for all individual SKU’s. Note that all values can be changed, with exception of the material descriptions and cluster numbers. Another way to modify the input parameters is to make use of the ‘Parameter Modifications’ panel. By making use of this panel, one can change a parameter in its entirety. For example one could increase the procurement lead-time by 10% for each SKU by typing +10% in the white box and subsequently click ‘set’. Absolute changes are also possible by not including the percentage symbol, e.g. ‘-10’. Finally one can reset the data to its original state by clicking the ‘reset’ button.

The ‘clusters’ table shows preformatted service measure preferences for all different clusters. These preferences can be modified by simply changing the values in the table, or by making use of the ‘Service per cluster’ panel. Making use of the panel is not necessary, though can be preferable when dealing with a lot of clusters. Furthermore note that the fill rate service measure needs to be noted as a fraction (between 0 and 1) and the EBO service measure can be any positive number.
Whenever the user is finished modifying the data, clicking the ‘Run’ button initiates the optimization calculations. Depending on the preferences, the tool is able to run different optimization algorithms, resulting in the best suitable solution for the scenario.

Figure E.4 shows a screenshot of how the output data is shown by the tool. Besides the optimal values per SKU, like optimal safety stock levels, aggregate results, like the total investment costs, are also shown. This makes it very easy to compare multiple input settings.

Note that the ‘Output/Input’ button right next to the ‘Run’ button can be used to switch views between the output data and the input data.
In order to re-run the algorithm using different parameters, one can simply change the input settings and click the ‘Run’ button once more. When the user is satisfied with the output, the ‘Save’ button can be used to export the optimal parameters per SKU into an Excel output file. From this file it is possible to use the data in conventional Excel spreadsheets.

Finally, if something went wrong, clicking the ‘Restart’ button will restart the tool, returning to the situation of figure E.2.

The output
As discussed before, the model generates both output data per SKU, useful for operational purposes, as well as aggregate output data, useful for comparing different parameter settings.

Output data per SKU:
- **Material description**: This is the code of the service part as it is recognized by the service supplier.
- **Acquisition price**: This is the price of a service part for which the transaction is made between VDL ETG and the manufacturer (in euros).
- **SSL**: This is the optimized safety stock level per service item determined by the optimization model in order to meet the service requirements (in items).
- **Investment costs**: This is the investment cost per service item depending on the safety stock level and acquisition price (in euros).
- **Holding costs**: This is the holding cost per year per service item depending on the safety stock level and the holding costs percentage (in euros).
- **Emergency costs**: This is the cost for emergency shipments per service item (in euros).
- **Fill rate**: This is the expected percentage per service item to be delivered from on-hand stock (fraction).
- **EBO**: This is the expected number of backorders per service item (number of items)
- **Mean waiting time**: This is the mean waiting time per service item before demand will be fulfilled (in days).

Aggregate output data
- **Total investment**: This is the sum of investment costs, holding costs and any emergency shipment costs (in euros).
- **Total holding costs**: This is the total expense to be spent on holding costs (in euros).
- **Total items**: This is the sum of all safety stock levels, i.e. the total number of items preferably on stock in order to meet the service measure preferences (in items).
- **Total emergency costs**: This is the expected total expense to be spent on emergency shipment costs (in euros).
- **Actual EBO**: This is the total number of expected backorders (in items).
- **Actual fill rate**: This is the expected fill rate realized by the output data (fraction).
- **Mean waiting time**: This is the expected mean waiting time per SKU (only when emergency shipments are included) (in days).

Another option to export the output data is to simply copy the data from the tool and paste it into a word processor or spreadsheet programs.