MASTER

Additive manufacturing in the spare parts supply chain

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Additive manufacturing in the spare parts supply chain

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Abstract

Additive manufacturing is a new manufacturing method. Recently, the public interest in this technology has been increasing and companies are starting to explore its applications. Additive manufacturing has the potential to reduce inventories in the spare part supply chain. In this thesis, the application of additive manufacturing in the spare parts supply chain of Philips Healthcare is investigated.

A selection procedure is developed to identify which spare parts in the spare part portfolio of Philips Healthcare can be produced using additive manufacturing. Given the current status of the technology, only small, slow moving mechanical spare parts should be selected. This selection procedure is used to select a number of parts which are seen as the best candidates for additive manufacturing.

A model is developed in which the expected total costs of applying additive manufacturing in the last time buy process are calculated. In the last time buy process, currently a large order needs to be placed to be able to fulfill the demand for spare parts in the last phase of the lifecycle after the supplier has stopped the production of a part. The model has been applied to the selected parts of Philips Healthcare. The results show that additive manufacturing can be used to replace the safety stock. Additive manufacturing generates cost savings in the last time buy decision for all the selected parts, through a reduction of the inventory.
Management summary
Additive manufacturing, also known as 3D printing, is a new manufacturing method in which products are built up by adding material layer by layer. Recently, the public interest has been increasing and companies are now starting to explore the applications of this technology. Additive manufacturing can potentially change the configuration of the spare part supply chain. Philips Healthcare would like to gain a better understanding of the technology. They are especially interested in the applications of additive manufacturing in the spare parts supply chain. This is elaborated in this thesis. The main contributions of this thesis for Philips Healthcare are:

- An understanding of additive manufacturing and the developments of this technology
- A selection procedure to identify printable spare parts
- A list with the printable spare parts of Philips Healthcare
- Domains of the Philips Healthcare supply chain operations where additive manufacturing adds additional value and cost savings can be obtained, these domains are called niches in this thesis
- A model to calculate the required last time buy quantity when additive manufacturing is applied as resupply option in the last time buy decision

Selection procedure
Not every part can be produced using additive manufacturing, due to the technical limitations of the technology. A selection procedure is developed to select the 3D printable parts of the Philips Healthcare portfolio. In this selection procedure, both economic and technical selection criteria are used. Candidates to be 3D printed are small, slow moving mechanical spare parts, made from plastic or metal. Parts belonging to this category are for example grips, pins, covers and cooling vents. Using this selection procedure, six spare parts which are considered the best candidates for additive manufacturing are selected.

During the selection procedure the following observations are made. The majority of the supply chain costs in Philips Healthcare are related to electronic components. From the supply chain perspective, a solution for these high value parts is required. However, electronic parts cannot be produced with additive manufacturing. The printable mechanical spare parts have a low value compared to the electronic components. Printing these parts will not solve the supply chain issues Philips healthcare is experiencing. Therefore, a mismatch is observed between what you want to 3D print and what is possible to 3D print.

In addition to this observation, another problem with additive manufacturing is observed. Most of the suitable candidates for additive manufacturing are currently mass produced using technologies like injection molding. This technology can exploit economies of scale, which leads to low production costs per part. Additive manufacturing cannot compete with these product prices, even when the inventory reduction is taken into account. Therefore, additive manufacturing is not a suitable technology to be used in mass production.
These two observations reduce the scope of applications of additive manufacturing. However, this does not mean that additive manufacturing should not be applied in the spare parts supply chain. There are still several other areas in the supply chain where this additive manufacturing can add value.

From this it is concluded that additive manufacturing should not be used purely as a substitute of traditional manufacturing methods. Instead, companies should focus on applications in which additive manufacturing can provide added value. Additive manufacturing can then be applied in those special areas.

**Value of additive manufacturing**

We have seen above that additive manufacturing should not be used simply as a replacement of current manufacturing technologies. Instead, companies should focus on applications in which additive manufacturing can provide added value. These applications areas are called niches. Three niches are identified. These are the following:

- Last time buy (LTB) decision
- No molds available anymore
- Redesign

**Last time buy (LTB) decision**

The supplier of a part can decide at any point that it will no longer support a particular part. For these parts, a last time buy order needs to be placed to be able to fulfill the demand during the remainder of the service contract with the customer. Last time buy decisions are common for Philips healthcare due to the combination of fast technological developments in the industry and long service contracts. Additive manufacturing can be used to reduce inventories. This feature makes it an interesting technology to be used in the last time buy process.

**No molds available anymore**

When molds are no longer available, new molds have to be produced. This is an expensive and time consuming process. When only a few parts are made with this mold, the costs per part will be high. Additive manufacturing can print in batch sizes of one without an increase in the cost per part. This feature makes additive manufacturing a suitable manufacturing method when no molds are available anymore.

**Redesign**

Redesigning spare parts can be interesting with regard to the “Restriction of Hazardous Substances” (RoHS). Due to this restriction, Philips Healthcare needs to limit the use of hazardous materials, like lead, to a minimum. Additive manufacturing can be used to redesign parts which are currently manufactured with materials which are on the RoHS list.

**Network design**

If Philips Healthcare starts to use parts produced with additive manufacturing, it is best to outsource the production of these parts to 3D printing service providers. In-house production using additive manufacturing is not preferred at this moment. This is mainly because of the high investment cost, high
raw material costs, the current limitations of the technology and the rapid technology developments. Each two years the productivity of 3D printers is expected to double. Due to these rapid technology developments, 3D printers get obsolete very quickly.

**Last time buy model**

A model is developed which can be used to calculate the expected total costs of applying additive manufacturing in the last time buy process. In this model, additive manufacturing is considered as alternative production method, after the supplier of a part has stopped the production of that part. The decision variables in this model are the order up to level at the last time buy moment ($S_1$) and the basestock level for additive manufacturing ($S_2$). A detailed description of this model can be found in chapter 8.

The model shows that a combination of a last time buy order and additive manufacturing is preferred. This implies that a last time buy order still has to be placed at the supplier. However, this order is lower than when additive manufacturing would not have been available. Cost savings can be generated by applying additive manufacturing in the last time buy process for all the selected parts. These costs savings are generated through a reduction of the inventory. The results show that additive manufacturing is used as an alternative for the safety stock. If the costs of additive manufacturing decrease, inventories can be reduced further. This will result in larger costs savings.

**Recommendations**

At this moment, the technology is not advanced enough for a widespread implementation within Philips Healthcare. Although the technology is only feasible for a small percentage of the spare parts portfolio at this moment, Philips Healthcare should not neglect additive manufacturing. If the technology developments would be neglected, there will be a risk that Philips Healthcare will be surprised by its applications in the future.

It is recommended to apply additive manufacturing in the last time buy process. This will have two benefits. First of all, cost savings will be generated. Also, because Philips Healthcare will be using additive manufacturing, experience with this technology is built. Because the company will be more involved with the technology, new applications or possibilities will be discovered earlier. When new applications become feasible due to technological progress, the scope of additive manufacturing in Philips Healthcare should be extended gradually.
Preface

This thesis is the final work of my master “Operations Management and Logistics” at Eindhoven University of Technology. I have started the graduation project in March, after returning from my semester abroad at the University of Technology in Munich. During my stay in Munich, Philips Healthcare provided me the opportunity to be present at the ISLA innovation forum in Munich at 19 November 2013. The topic of this forum was additive manufacturing and 3D printing of spare parts. This event was a good preparation for my thesis. It provided me insights in the topic and brought me into contact with professionals on additive manufacturing which proved valuable during my graduation project.

I performed my graduation project in the SPS department of Philips Healthcare in Best, The Netherlands. The SPS department is responsible for the global supply of spare parts belonging to all the systems sold by Philips Healthcare. Philips Healthcare would like to acquire more insights in potential applications of additive manufacturing within the spare parts supply chain. This master thesis was set up as a first step for Philips Healthcare to learn more about additive manufacturing.

I would like to thank several people for their help and support during this project. First of all I would like to thank Henry van der Schoot, the principal of this project, for setting up this interesting project and giving me the freedom to define the scope within the broader scope of additive manufacturing. I would also like to thank Johanna Schindler-Chaloub, my direct supervisor in Philips Healthcare, for the feedback, critical questions and support. In addition, I would like to thank all people within Philips Healthcare who have somehow been involved in this project for taking the time to answer all my questions and for helping me with gathering the data I needed.

From the university I would like to thank Joachim Arts. First of all for bringing me into contact with Philips Healthcare and his help in defining the project. During this project, his feedback and suggestions were of great help. Especially during difficult times in the project, he always made time to answer my questions and provide me with useful comments. I would also like to thank Engin Topan, the second supervisor of this project, for his feedback and comments which helped me to improve my thesis.

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Bouke Wullms

Eindhoven, August 2014
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1. Introduction

In this master thesis the application of additive manufacturing to the spare parts supply chain of Philips Healthcare is investigated. Philips Healthcare sells medical equipment which is used in hospitals. A company description will be provided in chapter 2. The products sold by Philips Healthcare are capital goods. Capital goods are machine or products that are used by manufacturers to produce their end products or that are used by service organizations to deliver their services (Kranenburg & Van Houtum, 2014). These products are typically expensive and are used for a large number of years. The downtime of these machines is very costly. Therefore, in case of a failure, the failed part has to be replaced as quickly as possible. In recent years, customers are increasingly outsourcing the maintenance activities to the manufacturer of the system, the original equipment manufacturers (OEM), (Oliva & Kallenberg, 2003). To prevent downtime as much as possible, it is very common for the OEM to engage in a service contract with the customer. In this service contract a required service level is specified. Capital goods are intended to be used over a long period of time (about 10-40 years (Kranenburg & Van Houtum, 2014)). These service contracts can therefore be very long. To ensure a high service to the customers, high spare parts stocks are required. These spare parts stocks tie up a lot of capital (Basten & Van Houtum, 2013). A major challenge in the spare parts supply chain is to stock the right amount of spare parts. The aim is to provide the highest possible service at the lowest possible costs.

Additive manufacturing is a relatively new manufacturing method. With this technology, products are built up layer by layer. A detailed description of additive manufacturing will be provided in chapter 3. This technology has been developing over the last years. Recently, the public interest has been increasing and companies are now starting to explore the applications of this technology. Additive manufacturing can potentially change the configuration of the spare part supply chain (Berenschot, 2012). This potential will be described in more detail in chapter 3.5.

The goal of this thesis is to find out how additive manufacturing can be applied in the spare parts supply chain of Philips Healthcare. The outline of this thesis is as follows. In chapter 2, a description of Philips will be given. Also, the department in which this project took place will be introduced and some context on the problems faced in this department is provided. Before the applications of additive manufacturing in the supply chain can be considered, one should first have a general understanding of the technology and its capabilities. This information on additive manufacturing is provided in chapter 3. This chapter is concluded with some context on additive manufacturing inside the spare parts supply chain. In chapter 4, a selection procedure is presented. This selection procedure enables companies to identify which spare parts in their portfolio are suitable candidates to be 3D printed. The selection procedure is applied to Philips. Whether additive manufacturing is preferred over other manufacturing technologies is dependent on the situation. In chapter 5, the niches where additive manufacturing can add additional value for Philips Healthcare will be identified. In chapter 6, the network design issue will be discussed briefly. This issue concerns the deployment of additive manufacturing within the Philips Healthcare supply chain. Additive manufacturing has the biggest potential for cost savings in the last time buy decision. The last time buy process is considered in chapter 7. A literature review on the last time buy process will be provided.
Next, in chapter 8, a model is developed to include additive manufacturing within the last time buy decision. This model is implemented in a software tool and results will be described. Finally, a conclusion on additive manufacturing within the Philips Healthcare spare parts supply chain is provided in chapter 9.
2. Company description

In this chapter, information on Philips will be provided. First general information on the company is given. Afterwards, the department in which this thesis is performed, the SPS department, will be described. In addition, a small introduction on the spare parts in Philips Healthcare will be given.

2.1 Company background

Philips

Philips was founded in 1891 by father, Frederik and son, Gerard Philips. Four years later, Gerard’s brother Anton joined Philips as well. Philips originally produced light bulbs. Within a few years it was one of the largest light bulbs producers in the world. Today, Philips has developed into a large diversified technology multinational, selling a variety of technological products. Philips consists of three main sectors: Healthcare, Lighting and Consumer lifestyle. The sales, of Philips as a whole, were 23 billion euro in 2013. It has manufacturing sites and sales and services in over 100 countries. Their headquarters is located in Amsterdam. In January 2013, 115,000 employees were working for Philips worldwide. The mission of Philips is to improve people’s lives through meaningful innovation.

Philips Healthcare aims to develop innovative solutions to help clinicians diagnose, treat and manage today’s most prevalent diseases as effectively and efficiently as possible. It is a world leader in cardiology and has a strong presence in cardio-pulmonary, oncology and mammography.

Philips Lighting is dedicated to enhance people’s life by developing innovative lighting solutions for customer and industrial markets. Markets served by Philips lighting are homes, office and outdoor, industry, retail, hospitality, entertainment, healthcare and automotive.

Philips Consumer Lifestyle develops technologies such as consumer electronics and small appliances. Examples of products are shaving appliances and coffee machines.

Philips Healthcare

The headquarters of Philips Healthcare is located in Andover, Massachusetts. 37,000 employees are working for Philips Healthcare worldwide. Philips Healthcare sells over 450 products in over 100 countries. The sales over 2012 equaled 10 billion euros. Healthcare is divided in 5 business units:

- Imaging Systems (IS)
- Patient Care and Monitoring Solutions (PCMS)
- Home Healthcare Solutions (HHS)
- Informatics Solutions and Services (ISS)
- Global Customer Services (GCS)

Global customer service (GCS) department

The goal of the customer service department is to provide a good service to the customers. GCS is split up in the following departments

- Global Service Operations (GSO)
• Global Service Engineering (GSE)
• Spare Parts Supply Chain (SPS)
• Information Supply Chain (Academy)
• Service Business Excellence

**Spare parts supply chain (SPS) department**

SPS aims at reliable and cost effective delivery of high quality service parts worldwide. It provides the spare parts of all systems supported by Philips Healthcare. SPS needs to assure the right part at the right place at the right time at the right cost. To achieve this goal, a partnership with Accenture, UPS and Sanmina has been formed. This partnership is displayed in figure 1.

![Supply chain control tower used by SPS](image)

**Figure 1: Supply chain control tower used by SPS**

Accenture provides the transactional activities, which mainly involve adding and changing data in the SAP information system. UPS performs the warehousing function for Philips Healthcare. They provide global storage and distribution. Sanmina manages the reverse supply chain. SPS provides the global planning for the spare part supply chain and coordinates all activities.

SPS is divided in several teams:

• Business Analytics
• Customer Demand
• Global Logistics
• IS Service Parts Lifecycle Management
• Materials & Logistics Optimization
• Service Parts Quality
• Strategic Planning
• Supply Chain Services
• Supply Management
An overview of the different responsibilities of the business teams is provided in figure 2. Global logistics has the responsibility for transportation and warehousing of the parts. Each part needs to be at the correct time at the customer.

2.2 Spare parts of Philips Healthcare
To provide after sales service for Philips Healthcare products, an enormous amount of spare parts is required. SPS manages over 100,000 spare parts. All ranging in size, cost, material and demand pattern. The spare parts inventory represents a value of over 600 million euros. Combined, the demand for all spare parts is over 1 million customer order per year. These orders have a transaction value of 1.800 million euros a year.

Inventory control
For planning purposes, an aggregate fill rate is considered on a network level. In a network, parts with similar characteristics are bundled. Three criteria are used: the business unit to which the part belongs, the part nature and the location of storage. SPS requires a 98% aggregate fill rate for networks consisting of customer critical parts (CCP). The CCP spare parts cause machine downtime and have relatively high demand rates. For all other parts, an aggregate fill rate of 95% for each network is required. With this performance, SPS belongs to the top 20% of the high tech industry service providers.

Logistics
SPS owns several warehouses located all over the world. These warehouses are organized on a hierarchical level. There are three RDC’s, located in Roermond (The Netherlands), Louisville (US) and Singapore. These are the biggest warehouses, used for forward shipping of parts. Local distribution centers are located in Coventry (UK), Paris (France), Madrid (Spain) and Tokyo (Japan). In addition, SPS
owns 50 smaller forward stockings locations spread out over the world. SPS owns several bluerooms which are return warehouses for the returned goods flow. These are located in Tatabanya (Hungary), Fort Mill (US), Tokyo (Japan) and Singapore. Figure 3 shows the warehouse locations of SPS on the map.

Figure 3: SPS warehouses
3. Additive manufacturing

Additive manufacturing is a manufacturing technology in which products are built up layer by layer. It is an additive process, in contrast to most current manufacturing methods, which are subtractive processes. The input for an additive manufacturing process is a 3D computer aided design (CAD) model (Berman, 2012). A 3D printer transforms the 3D model to multiple 2D models of the object. These are used to print the desired shape layer by layer. Additive manufacturing is a relatively new technology of which the first applications in companies are arising. It has potential to change the configuration of current supply chains (Berenschot, 2012). However, the technology also has several technical limitations at this moment.

Additive manufacturing is known under several different names including: 3D printing, additive fabrication, rapid prototyping and rapid manufacturing. When referring to the consumer market, the term 3D printing is preferred. In the industrial market, additive manufacturing is the preferred term for this technology. However, in most literature, these terms are used interchangeably. In this thesis, I consider the technology only for the application in an industrial setting. Therefore, I will use the term additive manufacturing.

Additive manufacturing has several beneficial characteristics over traditional manufacturing. Based on these characteristics, three main application fields for additive manufacturing are recognized in literature.

1. Mass customization
2. Design of products with superior characteristics over normally manufactured parts
3. Change the supply chain configuration

In this master thesis, the focus will be on the third application only.

3.1 Build processes

Additive manufacturing is a collective term under which many different technologies are combined. These technologies have in common that they all build up products layer by layer in an additive way. However, every technology uses a different underlying build processes. In an attempt to classify the available processes, the ASTM international committee on additive manufacturing has approved the following list of additive manufacturing processes (Wohlers Associates, 2013). This list is based on the “Standard Terminology for Additive Manufacturing Technologies”.

- Material extrusion
- Material jetting
- Binder jetting
- Sheet lamination
- Vat photopolymerization
- Powder bed fusion
- Directed energy deposition
An explanation of each of the build processes listed above will now be provided.

**Material extrusion**
In material extrusion, material is selectively dispensed through a nozzle. The desired form is created by depositing the material as a 2D wire of plastic. This idea is represented in figure 4. After each 2D layer, the build platform moves down and another 2D layer is added on top of the previous one. Material extrusion is a slow process. The strength of the parts is dependent on the build orientation but mostly the parts are rather weak. The surface finish of parts produced with material extrusion is very rough. An advantage of material extrusion is that the technology is widely available. Most consumer printers are based on this process. Raw materials for this process are also widely available. In an industrial setting, this process is mainly used for prototyping and for tooling. It is also used for low-volume manufacturing of parts (McKinsey global institute, 2013). The technology fused deposition modeling (FDM) makes use of this build process.

**Figure 4: Material extrusion process (3D printing industry, 2014)**

**Material jetting**
In material jetting, droplets of the raw material are deposited on the build platform. An illustration of this process is provided in figure 5. Raw material in this process, are liquid polymers. These are hardened by rays of UV light. Up to two materials can be used in the same run. This is mostly a combination of the photopolymer and wax, which is used as support material. An advantage of material jetting is that the raw material can be a combination of materials with different properties. It is for example possible to combine a very stiff material with a very flexible material to create a material with a medium stiffness. This method is very precise, resulting in accurate parts with smooth surface area (3D printing industry, 2014). However, since this process uses photopolymers, the durability of these parts is very low. Material jetting is mostly applied in prototyping and to produce mockups in the jewelry industry.

**Figure 5: Material Jetting process (THRE 3D, 2014)**
**Binder jetting**

In binder jetting, a liquid binder material is sprayed on a layer of powder. An illustration of this process is provided in figure 6. This powder can be a plastic, metal, glass, sand or ceramics. The layer of powder solidifies on the places where the drops of binder are sprayed on the powder. This build process is very similar to the traditional inkjet printing technology in which ink is sprayed on paper (here binder liquid is sprayed on a powder layer). As a result, binder jetting is also known as “3D printing”. A large range of materials can be used in this process. The binder jetting process can print objects in full color. This process is easy to use and relatively inexpensive. However, products produced using this process, are not very strong. Often post-processing is required to ensure durability. Binder jetting is mostly used for prototyping and for tooling.

![Figure 6: Binder jetting process](image)

**Sheet lamination**

In sheet lamination, objects are formed by bonding layers of sheet on top of each other. These sheets can be made of adhesive coated papers, metals or plastics. A laser is used to cut the sheet in the desired form. An illustration of this process is provided in figure 7. This process is used for form testing, rapid tooling patterns and producing less detailed parts. It main advantage is that several colors can be used (McKinsey global institute, 2013). For metals, this is a suitable process to fuse different materials with different melting points. Because the materials are not heated, it can also be used to embed wires or electronics between the layers of material. The disadvantage of sheet lamination is that it cannot produce complex shapes, so only simple parts can be made. The quality of these parts is relatively weak. The technology laminated object manufacturing was the first commercial technology based on this process.

![Figure 7: Sheet lamination process](image)
**Vat photopolymerization**
This process uses a vat, filled with liquid resin. A light source is used to react with the surface of the liquid photopolymer resin. The liquid is only solidified in places where the light source touches the liquid surface. The build platform moves down (into the liquid) after each layer, so a new layer can be added on top. An illustration of this process is provided in figure 8. The main advantage of this process is a high resolution. This enables the process to build parts with a smooth surface. Disadvantages of this process are that post processing is required to ensure the smooth surface and that support structures are needed in the build process. The main disadvantage is the weakness of the parts. Photopolymers are the weakest of all possible raw materials for additive manufacturing. Vat photopolymerization is mainly applied for prototyping. Technologies based on this process are stereolithography apparatus (SLA) and digital light processing (DLP).

![Figure 8: Vat photopolymerization process (3D printing industry, 2014)](image)

**Powder bed fusion**
In the powder bed fusion process, the build platform is completely filled with powder. An energy source is used to fuse the powder together. Since the powder only fuses on places where the energy source hits the powder, the desired shape can be obtained. An illustration of this process is provided in figure 9. Powder bed fusion can be used for both plastics and for metals. Advantages of this process are that it is possible to create fully dense and high quality, strong metal parts. It is also possible to create very intricate structures with this process. This process is relatively fast. Another advantage is that no support structures are needed. Disadvantages are the high cost of the process, the requirement of specialized personnel, the required post processing and a lack of surface quality. Applications of powder bed fusion are observed in the medical and aerospace industry. In medical it is used to create custom implants to be placed in the human body. The technologies based on this process are selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS) and electron beam welding (EBM). The figure below, illustrates the SLS technology. In the EBM technology an electron beam is used instead of the laser.
Figure 9: The powder bed fusion process (3D printing industry, 2014)

Directed energy deposition
Directed energy deposition is an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited (Wohlers associates, 2013). This is different from the powder bed fusion process, since in powder bed fusion, the powder was laying on the build platform. Here the powder (or metal wire) is sprayed from a nozzle on the platform and directly heated to create a solid object. An illustration of this process is provided in figure 10. The raw materials in this process are metals (metal wires or metal powder). The Optomec LENS systems are an example of systems using this process (Newman, 2012). With directed energy deposition it is possible to add material on existing parts. It is mostly used for the repair of parts or tools. It can also be used for the production of large objects. The advantages of this process are that up to two different metal raw materials can be used and that it is a fast process. Disadvantages are a lower accuracy, the use of support structures and the required post processing.

Figure 10: Directed energy deposition process (THRE 3D, 2014)

The processes described above are the basis for every additive manufacturing technology. For a detailed description of the available technologies, I refer to appendix A.

3.2 Materials
Several materials can be used as raw materials in additive manufacturing. The most used raw materials are plastics and metals (McKinsey global institute, 2013). In this chapter, only the most common materials will be discussed. Since there is a lot of research on this area, the number of materials available as raw material for additive manufacturing is increasing fast.
Plastics
Plastics can be subdivided into thermoplastic polymers and thermoset polymers. This distinction is based on the behavior of the polymers at high temperatures. Thermosets set into a given shape when they are heated, due to a chemical reaction called curing. This shape is permanent. So a thermoset cannot be melted and reshaped anymore after the curing process. A thermoplastic can be heated and cooled several times. Once the plastic is heated, it becomes moldable. After it is cooled the material will harden. A different shape can be given by re-heating the thermoplastic.

Types of plastics belonging to the thermoplastics group are:

- PA
- PLA
- ABS
- PC (polycarbonate)
- PPSF

These plastics are used in material extrusion processes like FDM.

Types of plastics belonging to the thermoset group are:

- Epoxy
- Acrylate
- Acrylic

These plastics are used as raw materials in vat photopolymerization technologies like the SLA and DLP, in the material jetting technology and in the powder fusion technology, SLS.

The prices for raw materials are relatively high. In general, the prices of plastics raw materials for additive manufacturing are between $175 and $250 per kilogram (Wohlers associates, 2013). Note that the exact price of a raw material is always dependent on the supplier, the type of plastic and the technology to be used. The prices for plastic raw materials for injection molding are about $2 to $3 per kilogram (Wohlers associates, 2013). This makes the raw materials for additive manufacturing about 100 times more expensive. The raw material prices for additive manufacturing are expected to drop in the near future, due to the increasing interest in the technology.

Metals
The following metals can be used as raw material in additive manufacturing. The choice for a particular metal is based on the desired properties of the end product. All materials have different properties.

- Steel
- Titanium
- Cobalt
- Several alloys (nickel based alloys, copper based alloys, cobalt-chromium alloys, titanium alloys and aluminium alloys
New metals are being developed by the 3D printer manufacturers with the aim to design products with superior quality over products manufactured using other manufacturing methods. Metals are used as raw materials in technologies based on the processes metal powder bed fusion, directed energy deposition or binder jetting. These include: SLS, SLM, DLMS, HSS, EBM and binder jetting. The prices for metal powders are high compared to the raw material prices used in other manufacturing technologies. These prices are expected to change when the number of suppliers increases. In the Wohlers report of 2013, the following raw material prices are estimated (Wohlers associates, 2013):

- Steel and aluminum alloys: $78 - $120 per kilogram
- Cobalt chrome alloy: $120 - $545 per kilogram
- Nickel based alloy: $210 - $275 per kilogram
- Titanium and titanium alloys $340 - $880 per kilogram

Other materials, besides metals and plastics, which can be used in additive manufacturing are for example ceramics, glass, paper, concrete and living cells.

Not all additive manufacturing technologies can make use of the same raw materials. If a company considers purchasing a 3D printer, it should first identify the intended application of that 3D printer and the materials which will be used (RedEye, 2014). An overview of the raw materials and the corresponding technologies is provided in the material matrix in table 1.
### Table 1: Material matrix

<table>
<thead>
<tr>
<th>Material group</th>
<th>Material</th>
<th>Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>SLA</td>
</tr>
<tr>
<td><strong>Photo polymers</strong></td>
<td>Epoxy</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Acrylate</td>
<td></td>
</tr>
<tr>
<td><strong>Thermo plastics</strong></td>
<td>PA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PLA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ABS</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PPSF</td>
<td></td>
</tr>
<tr>
<td><strong>Metal</strong></td>
<td>Steel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Titanium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cobalt</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alloys</td>
<td></td>
</tr>
<tr>
<td><strong>Ceramics</strong></td>
<td>Alumina</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Zirconia</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silicones</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.3 Printer capabilities

**Build size**
Currently available additive manufacturing technologies have a limited build size. For plastic parts, the maximum build size is 1500 x 750 x 550 mm. For metal parts, the maximum build size is around 500 x 500 x 500 mm at this moment.

**Lead time**
The average production speed to create full dense metal parts is about 10 cm³/h (Roland Berger, 2013), (Wohlers associates, 2013), (Fraunhofer Institute). Depending on the size of the desired object, the build time of the printer will range from under an hour until over a week. The average building time is between 20 and 50 hours. For plastic parts, the build speeds are faster. However, the products produced from plastic are on average larger than the products produced from metal. Therefore the lead time for plastic parts is in the same range. In conclusion, one could state that the typical production time with additive manufacturing is around 1 to 3 days. When a 3D printing service provider is used, the average lead time is about one week. This is based on information provided by a number of service providers.

#### 3.4 Technology developments
Additive manufacturing is developing rapidly. According to EOS, a manufacturer of 3D printers, the most important performance dimensions: production speed and build size are expected to double every two
years. Other performance dimensions like the quality of the products and the stability of the additive manufacturing process are expected to increase a little slower.

The cost of additive manufacturing is expected to decrease 50% over the next 5 years (Roland Berger, 2013). These costs consist for 74% out of indirect cost like machining, labour, energy and overhead. 26% of these costs are direct costs for materials (Roland Berger, 2013).

At this moment, additive manufacturing is mainly suitable for passive mechanical spare parts without active functionality. Parts in this category are for example: covers, grips and cooling vents.

Based on the information gathered during this thesis and the discussions with professionals on additive manufacturing, I expect that this same category will be the primary focus of additive manufacturing in the coming 5 years. At that time, these products will be produced faster, in better quality and at lower costs. In table 2, an overview of what can be produced now and what can be produced in 5 years using additive manufacturing is provided. This list is based my personal expectation on the technology developments, which is based on the information gathered during this thesis and the discussions with professionals on the field of additive manufacturing.

<table>
<thead>
<tr>
<th>Type of parts currently possible to produce using additive manufacturing</th>
<th>Type of parts which can be produced using additive manufacturing in 5 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Non-functional mechanical parts like covers and grips</td>
<td>✓ Non-functional mechanical parts like covers and grips</td>
</tr>
<tr>
<td>x Limited functionality: gears</td>
<td>✓ Limited functionality: gears</td>
</tr>
<tr>
<td>x Turning parts like torque, bearing etc.</td>
<td>x Turning parts like torque, bearing etc.</td>
</tr>
<tr>
<td>✓ Simple Assemblies</td>
<td>✓ Assemblies</td>
</tr>
<tr>
<td>x Parts with embedded electronic components</td>
<td>✓ Parts with embedded electronic components</td>
</tr>
<tr>
<td>x Electric components (PCB boards, electric circuits)</td>
<td>x Electric components (PCB boards, electric circuits)</td>
</tr>
</tbody>
</table>

Comparable expectations to the ones I have provided above are given in in a paper by the Deloite university press. Their insights on what can be produced now and what can be produced in the future using additive manufacturing in the automotive industry is illustrated in figure 11 (Deloitte University Press, 2014).
3.5 Potential of additive manufacturing in the spare parts supply chain

The current supply chains of large manufacturing companies are designed to make use of economies of scale. The supply chain configuration has the following characteristics:

- Mass production (due to economies of scale, large batch size)
- Global supply chains with centralized production
- Complex supply chains (lot of suppliers, many tiers, a lot of transport)

One of the main challenges in these supply chains is to obtain high service levels at the lowest possible costs.

The spare parts industry has the following characteristics:

- Low demand rates for most spare parts
- High inventory costs
- Response time often critical

The spare parts industry has a need to produce in small batches and locally, while current supply chains produce in large batch sizes, globally. This results in high inventories and inventory costs and high transportation costs. Therefore, a discrepancy is observed between the current supply chain
configuration and spare parts industry characteristics. Additive manufacturing provides potential to overcome this discrepancy.

A key characteristic of additive manufacturing is that economies of scale are not required. This enables batch sizes of one. Additive manufacturing introduces the concepts “producing (printing) on demand” and “printing on location”. These have several consequences for the supply chain of spare parts. Printing on demand has the potential to eliminate inventory levels, inventory obsolescence and the final order problem. In addition, printing on location will make transportation of physical spare parts redundant. Together, inventory cost and transport cost represent the majority of all costs in the supply chain.

The characteristics provided by additive manufacturing are:

- No economies of scale
- Small batch sizes feasible
- Local printing possible
- Small, simple, local supply chains

From this, one can conclude that additive manufacturing has the potential to provide significant opportunities for the spare parts supply chain.

Due to technical limitations, the full benefits of the additive manufacturing characteristics cannot be exploited any time soon. However, it is possible to use ideas of this future scenario to reduce cost in the supply chain by alternating the configuration of the supply chain step by step.
4. Selection of 3D printable spare parts
In this chapter, a selection procedure is developed which can be used to identify the spare parts of Philips Healthcare that can be produced using additive manufacturing. It will be used to create a list of the 3D printable spare parts in the Philips Healthcare portfolio. Chapter 4.1 provides the selection criteria which are used in the selection procedure and chapter 4.2 will describe the method which I have used to develop the selection procedure for Philips Healthcare. The selection procedure itself will be presented in chapter 4.3. In chapter 4.4, a short description of the selected parts of Philips Healthcare will be provided. The conclusions of this chapter are provided in chapter 4.5.

4.1 Selection criteria
The aim of the selection procedure is to identify the spare parts that can be produced using additive manufacturing. Whether a part is suitable to be 3D printed is dependent on its characteristics. First, it needs to be possible to produce the part using additive manufacturing. This is dependent on the capabilities of the technology. Second, the part needs to have a high potential for cost savings to make it an interesting candidate for additive manufacturing. So, to identify the 3D printable spare parts, technical and economic criteria need to be used.

Economic criteria
Using the economic criteria, the spare parts with the highest potential for costs savings are identified. Slow moving parts have the highest potential for cost savings. These parts are stored in stock for a long time. The potential for cost savings is even higher when these slow moving spare parts are expensive and have a large number of parts in inventory. Table 3 contains the economic criteria used in the selection.
Table 3: Economic criteria

<table>
<thead>
<tr>
<th>Economic Criteria</th>
<th>Description</th>
<th>Feasible range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>Purchase value of the part</td>
<td>High value</td>
</tr>
<tr>
<td>Inventory level</td>
<td>The amount of spare parts in inventory in the warehouse</td>
<td>High inventory level</td>
</tr>
<tr>
<td>Value times inventory level</td>
<td>The value of the part multiplied with the number of parts in inventory</td>
<td>High value*volume</td>
</tr>
<tr>
<td>Repairable *</td>
<td>Part can be repaired or not, normally repairable parts represent higher value</td>
<td>No repairable items</td>
</tr>
<tr>
<td>Customer critical parts (CCP) **</td>
<td>Customer critical part. CCPs are critical to the system and have high demands</td>
<td>No CCP’s</td>
</tr>
<tr>
<td>End of life (EOL) of a part</td>
<td>The date at which the service contract expires. After this date the spare parts do not have to be serviced by Philips anymore</td>
<td>No EOL dates in the past</td>
</tr>
<tr>
<td>Part nature</td>
<td>Description of a part: slow moving / new product introduction / last time buy item/ low cost fast moving item / high cost fast moving item etc.</td>
<td>Slow moving parts and parts which had a last time buy in the past</td>
</tr>
<tr>
<td>Demand rate</td>
<td>The number of times per year a part is requested by a customer</td>
<td>Low demand rates (slow moving parts)</td>
</tr>
<tr>
<td>Planned delivery time</td>
<td>The time required between the order of Philips at the supplier and the delivery of the part at Philips</td>
<td>Long lead time</td>
</tr>
<tr>
<td>Minimal order quantity (MOQ)</td>
<td>The minimal required quantity for each order</td>
<td>High MOQ</td>
</tr>
</tbody>
</table>

*With the current status of the technology, repairable items should not be selected. Many of the repairable items in Philips consist of electronic components. These cannot be produced using additive manufacturing. It might be possible to use the direct energy deposition process in additive manufacturing to repair mechanical spare parts without electronic components. However, this will be outside the scope of this thesis.

**Customer critical parts should not be selected. These parts are critical to the system. Since additive manufacturing is a new technology, it is better to start with exploring its possibilities with non-critical parts.

**Technical criteria**
The technical criteria are used to select those parts that are printable based on their technical specifications. These criteria are dependent on the technological limitations of the 3D printers. At this moment, additive manufacturing can only be used to print mechanical spare parts without active functionality, like grips, pins and covers. It is not possible to print spare parts which consist of electrical
components. All electronic parts need to be filtered out using this selection procedure. Table 4 contains the technical criteria considered in the selection.

Table 4: Technical criteria

<table>
<thead>
<tr>
<th>Technical Criteria</th>
<th>Description</th>
<th>Feasible range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazardous material number</td>
<td>Code for hazardous material</td>
<td>No hazardous material</td>
</tr>
<tr>
<td>Material Group</td>
<td>The material code of which the parts consist. Data not very reliable because of data entry issues</td>
<td>No electronic components should be selected</td>
</tr>
<tr>
<td>Material group description</td>
<td>Description of the type of material matching the material group code</td>
<td>No electrical components should be selected</td>
</tr>
<tr>
<td>Length</td>
<td>The length of a parts packing. It is assumed that if a part fits inside its packaging it would fit in the building space of the 3D printer</td>
<td>Plastics: 2100 mm, Metals: 550 mm</td>
</tr>
<tr>
<td>Height</td>
<td>The height of a parts packing. It is assumed that if a part fits inside its packaging it would fit in the building space of the 3D printer</td>
<td>Plastics: 700 mm, Metals: 550 mm</td>
</tr>
<tr>
<td>Width</td>
<td>The width of a parts packing. It is assumed that if a part fits inside its packaging it would fit in the building space of the 3D printer</td>
<td>Plastics: 800 mm, Metals: 750 mm</td>
</tr>
</tbody>
</table>

**Target group of the selection procedure**
The goal of this selection procedure is to identify the parts of Philips Healthcare which belong to the target group. Parts in this target group have characteristics which make them interesting candidates to be produced using additive manufacturing. The parts in the target group are small, slow moving mechanical spare parts made from plastic or metal. These are for example pins, covers and grips. Preferably, these parts should have complex geometries, high minimal order quantities and long lead times. In addition, only so called “under the hood parts” should be selected. These are parts which are not visible to the customer. This is due to a lack of surface quality of parts produced using additive manufacturing. From all parts which meet these requirements, the high value parts are preferred over the low value parts. The Philips Healthcare portfolio consists mainly of electronic components. These parts will not be printable any time soon. Only a small percentage of all the parts in the Philips Healthcare portfolio belong to the target group. This selection procedure is used to identify those.

### 4.2 Method
The following steps are undertaken in the development and application of the selection procedure:

- Development of selection criteria

To choose good selection criteria, the study by Barkawi and AGCO was used as starting point. Their selection approach is refined based on interviews with article specialist and planners in Philips Healthcare.
• Create database

For every spare part in the Philips Healthcare portfolio, data on the selection criteria was gathered. This data was found through interviews with employees from the master data department, article specialists of the IXR department and supply chain planners.

• Define suitable “cutoff values”

Cutoff values were chosen based on data analysis of the database and consultation with employees from the departments planning, production and master data.

• Improve the selection criteria and develop generic selection procedure

The selection criteria are improved in an iterative process. Several selections are performed. Based on the outcome of these selections, the criteria are adjusted. Afterwards, a new selection was made. Based on the results of the new selection, it is possible that more adjustments are required. This process was repeated until the selection procedure returned a pre-selection of around 100 parts. A generic selection procedure, developed using this iterative process, will be presented later in this chapter.

• Select best candidate spare parts for additive manufacturing

From this pre-selection, the six best parts were selected. This was done based on discussions with article specialist and a manual evaluation of the available CAD files of the parts from the pre-selection.

Assumptions

Several assumptions have been made in the selection process. These assumptions are required to decrease the scope of this selection and to make it feasible within the available time for a master thesis.

1. **Regulatory aspects are out of scope**: Spare parts of Philips Healthcare have strong regulatory requirements. Many of these spare parts have to be approved by the food and drug administration (FDA). At this moment, additive manufacturing is not yet approved as manufacturing technology for spare parts. However, several standardization initiatives are arising (US FDA Wants An Open Dialogue About 3D Printing Medical Devices, 2014). For the scope of this thesis, these regulatory aspects will not be considered.

2. **Product ownership is out of scope**: Philips can only print those products for which Philips is the product owner. Otherwise intellectual property (IP) infringement issues could arise. However, since IP issues are outside the scope of this thesis, it is assumed that Philips is the owner of all spare parts in the portfolio.

3. **IXR department only**: In this thesis, only parts from the interventional X-ray department (IXR) are selected. This is due to data availability. The IXR department is located on the same campus as the SPS department. As a result it is easier to access data and make appointments with article specialists.
### 4.3 Selection procedure

In this section, the selection procedure, which can be used by Philips Healthcare to identify their printable spare parts, will be presented. The description of the selection procedure will be as generic as possible. This enables the use of this procedure in several business units within Philips. This selection procedure could also be used as a starting point for other companies when they want to identify the suitable candidates for additive are manufacturing in their portfolios. Most cutoff values in the selection criteria are made generic. Note that the cutoff values for purchase value and stock level cannot be made generic. These will always be dependent on the dataset. Companies selling inexpensive products will have a lower cutoff value for the criteria: “purchase value” than producers of expensive complex technological systems. Evaluation and data analysis should prove what a good cutoff value for these criteria will be. As a general rule of thumb the following can be used: Choose the cut off value for purchase price (or value) such, that 20% of the parts in the dataset have a purchase value higher than this cutoff value. The generic selection procedure is presented in table 5.

**Table 5: Selection procedure**

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>In category: EOL, select only parts that do not have a EOL date in the past</td>
</tr>
<tr>
<td>2</td>
<td>In category Part nature: <strong>Select slow moving items</strong>, items with an LTB in the past and tooling</td>
</tr>
<tr>
<td>3</td>
<td>In category CCP: select no</td>
</tr>
<tr>
<td>4</td>
<td>In category repairable: select no</td>
</tr>
<tr>
<td>5</td>
<td>In category: planned delivery lead time, select parts with a delivery time of 14 days and larger</td>
</tr>
<tr>
<td>6</td>
<td>In category value: Choose a value such that only the 20% of the highest value items in the dataset remain.</td>
</tr>
<tr>
<td>7</td>
<td>Manually evaluate the list made using the first steps: Filter out all electronic components in category description (start with material description first)</td>
</tr>
<tr>
<td>8</td>
<td>Sort parts based on dimensions, from small to large</td>
</tr>
<tr>
<td>7</td>
<td>Identify whether the part falls within metal size range, plastic size range or outside range (metal: 550x750x550, Plastic: 2100x800x700)</td>
</tr>
<tr>
<td>8</td>
<td>In category dimensions: delete all parts outside the feasible dimensions</td>
</tr>
<tr>
<td>9</td>
<td>Sort list based on value times stock from high to low</td>
</tr>
<tr>
<td>10</td>
<td>In category: value times stock, 20% of highest value*stock parts</td>
</tr>
<tr>
<td>11</td>
<td>In category: stock, select parts with high stock levels. The cutoff value is database dependent and can only be found by a manual evaluation of the data or with a data analysis.</td>
</tr>
</tbody>
</table>

After this selection procedure, the CAD files of the parts in the remaining list should be evaluated manually. If the selection procedure described above does not provide enough printable parts, the cutoff values need to be improved based on an iterative process as described in chapter 4.2. One should start with less strict cutoff values for the selection criteria “value times stock” and “stock level”. If this does not provide the expected results, one could consider lowering the cutoff value of the category “value” in step 6. It could also be considered to change the order of the selection steps. Instead of starting with technical criteria, one could also start with the economic criteria.

Applying these selection criteria to the Philips Healthcare dataset resulted in a list containing 26 of the highest potential printable spare parts within the IXR department.
Alternative selection procedure
As alternative selection method, one could start with a particular end system which contains many mechanical spare parts. Strip this system down to evaluate of all the parts whether they would be printable based on technical criteria. One could consider: covers, grips, pins and other mechanical spare parts. For all those parts which are printable, select only the highest value items.

Selection procedure in the future
Since the technology is developing, it is expected that the list with potential candidates for additive manufacturing is increasing in size. This impacts the selection procedure. When a selection is redone in the future, the same selection procedure can be used. The economic criteria are not dependent on the technological progress, therefore these can be used without any change. The technical criteria need to be updated to take the technological status at that time into consideration. Also note that the parts database needs to be updated before a new selection is performed.

4.4 Selected parts
By applying the selection procedure to the spare parts of Philips Healthcare, and doing a manual evaluation of the CAD files afterwards, six candidate parts are selected. The selected parts are all mechanical spare parts. The value of these items range from €12,93 for the cheapest part to €465,73 for the most expensive part. In the thesis these spare parts will be named spare part 1, spare part 2 etc. due to confidentiality. More details on these parts can be found in Appendix B.

4.5 Conclusion
Additive manufacturing is a new technology. As with any new technology, there are still several technical limitations. Given the current status of the technology, companies should only consider small, slow moving mechanical spare parts which are made from plastic or metal as possible candidates for additive manufacturing.

The majority of the supply chain costs in Philips Healthcare are related to electronic components. From the supply chain perspective, a solution for these high value parts is required. However, electronic parts cannot be manufactured with additive manufacturing. The printable mechanical spare parts have a low value compared to the electronic components. Printing these parts will not solve the supply chain issues Philips healthcare is experiencing. Therefore, a mismatch is observed between what you want to print and what is possible to print.

In addition to this observation, another problem with additive manufacturing is observed. Most of the suitable candidates for additive manufacturing are currently mass manufactured using technologies like injection molding. This technology can exploit economies of scale which leads to low production costs per part. Additive manufacturing cannot compete with these product prices, even when the inventory reduction is taken into account. Using additive manufacturing as a replacement of current mass manufacturing methods, leads to negative business cases, as displayed in Appendix F. This effect is even larger when the required knowledge on additive manufacturing processes is not inside the organization.

So, even if parts can be made using additive manufacturing, additive manufacturing should not be used purely as a substitute of current manufacturing technologies. In many situations, traditional
manufacturing methods are still preferred over additive manufacturing. Instead, companies should focus on applications in which additive manufacturing can provide added value. These applications will be called niches in the remainder of this thesis. The niches in which additive manufacturing can add value to the supply chain of Philips Healthcare are discussed in the chapter 5.
5. Added value of additive manufacturing for Philips Healthcare

There are several situations in which additive manufacturing will not be the preferred production method. Simply using additive manufacturing to replace current manufacturing methods will be a mistake. Instead, the added value of additive manufacturing should be identified. This will be the aim of this chapter.

Additive manufacturing can add additional value to the supply chain of Philips Healthcare in the niches illustrated in figure 12. Note that the focus is still on slow moving spare parts in the following scenarios.

![Diagram](image)

Figure 12: Added value of additive manufacturing in the spare parts supply chain of Philips Healthcare

5.1 Last time buy (LTB) process

An important topic in inventory control is a last time buy (LTB) decision. The supplier of a part can decide at any point that it will no longer support a particular part. For these parts, a last time buy order needs to be placed to be able to fulfill the demand during the remainder of the service contract. Last time buy decisions are common for Philips healthcare due to the combination of fast technological developments in the industry and long service contracts.

As a result of a last time buy order, often large inventories are held for a long period of time. Additive manufacturing provides the possibility to print on demand. Therefore, additive manufacturing has the potential to reduce inventories and in this way reduce the costs related to the last time buy decision. Because of this potential it is interesting to evaluate the impact when additive manufacturing would be used in the last time buy process. This topic will receive more attention in this thesis. In chapter 7, more information on the last time buy process will be provided. In chapter 8, the impact of including additive manufacturing in the last time buy process is investigated.
5.2 No molds available
The spare parts under consideration are all slow moving. Therefore, these need to be ordered in low quantities. Many of the candidates for additive manufacturing are currently made using injection molding or die casting technologies. As long as the molds for these technologies are still available, these will be preferred over additive manufacturing. But when the molds are no longer available, new molds have to be produced. This is an expensive and time consuming process. When only a few parts are made with this mold, the costs per part will be high. Additive manufacturing can print in batch sizes of one without an increase in the cost per part. This feature makes additive manufacturing a suitable manufacturing method when no molds are available anymore. Further details on the applications of additive manufacturing in this niche are outside the scope of this thesis. This is an interesting topic for further research.

5.3 Redesign
Additive manufacturing provides the possibility to redesign products. Normally this will not be very relevant for spare parts, because the design of a part is determined at the start of its lifecycle, not at the end. However, redesigning of spare parts can be interesting with regard to the “Restriction of Hazardous Substances” (RoHS). Due to this restriction, Philips Healthcare needs to restrict the use of hazardous materials, like lead, to a minimum. Additive manufacturing can be used to redesign parts which are currently manufactured with materials on the RoHS list.

Recently, two new metals, Niobium and Molybdenum, have been developed as raw materials for additive manufacturing. These are super dense refractory metals. Therefore they can be used in X-ray machines to block the X-rays. Niobium and Molybdenum are potential substitutes for lead. They have the same property as lead, which is blocking the X-rays, but are less harmful for the health and environment (Eitel, 2014). So, additive manufacturing could be used to avoid (or reduce) the use of RoHS materials in spare parts. Parts currently consisting of lead for example could be redesigned to be able to produce them with Niobium or Molybdenum. Further details on the applications of additive manufacturing in this niche are outside the scope of this thesis. This is an interesting topic for further research.
6. Network design
When a new technology is introduced by a company, the way this technology is integrated within the supply chain should be considered. This is especially true for additive manufacturing, which has the potential to significantly change the supply chain configuration. The two most prevailing issues in the network design for additive manufacturing are

- Insourcing vs outsourcing
- Central vs decentralized deployment of additive manufacturing

The central vs decentralized tradeoff is only relevant when the company decides to insource additive manufacturing. As we will see in this chapter, the outsourcing strategy is preferred for Philips Healthcare. As a result, the central vs decentralized tradeoff will be outside the scope of this thesis. For a qualitative analysis of this tradeoff I refer to the article “Additive manufacturing in the spare parts supply chain” (Khajavi, Partanen, & Holmström, 2014). They conclude that at this moment, the centralized deployment of additive manufacturing is preferred. The decentralized scenario only becomes interesting when:

- Printers become more versatile
- A higher utilization can be achieved
- The costs related to additive manufacturing (purchase costs, labour costs, raw materials costs) will decrease
- The production time will be decreased
- A higher automation can be attained

6.1 Insourcing vs outsourcing of additive manufacturing
Insourcing of additive manufacturing implies that a company purchases 3D printers and performs all production of the parts using these 3D printers within the company boundaries. In the outsourcing scenario, the design file of a part is send to a 3D printing service provider. This service provider produces the parts and sends them back to the company.

Both options have pros and cons. In general, the insourcing option is characterized by high investment costs, low production cost per part and a larger degree of flexibility which enables a company to better exploit the potential benefits of additive manufacturing. When the outsourcing option is chosen, the initial investment will be low and the cost per part will be relatively high. It is common that a part which is outsourced is 3 to 5 times more expensive compared to when this part would have been produced in-house using additive manufacturing (Object, 2011). Also, some of the benefits of additive manufacturing are lost with outsourcing. For example, the lead time of additive manufacturing is higher with outsourcing due to the additional transportation. Based on a comparison between both options, it is concluded that Philips Healthcare should not insource additive manufacturing. The following reasons are given.
**High investment costs**

3D printers are expensive machines. The prices for industrial 3D printers vary between €500.000 and €1.500.000.

**Low versatility**

3D printers are dedicated to a limited number of raw materials. As a result, only a limited variety of parts can be manufactured with a particular printer.

**Low utilization**

The parts under consideration are slow movers. Therefore, the total yearly demand at a 3D printer is too low to justify the large investment required for the purchase of the 3D printers.

**Expensive raw materials**

The raw material prices can be up to 100 times more expensive compared to raw material prices of the materials used in other manufacturing technologies.

**Rapid technology developments**

The technology is developing rapidly. Important performance dimensions of additive manufacturing, speed and build size, will double in performance every two years. As a result, 3D printers will be obsolete very quickly. In addition, the costs of additive manufacturing are expected to decrease 50% over the next 5 years (Roland Berger, 2013).

**SPS becomes manufacturer (strategy)**

When SPS would purchase 3D printers, it will become its own supplier. This can lead to conflicts with current suppliers. In addition several issues like intellectual property and liability need to be considered.

**Need for specialized personnel**

One can only successfully use additive manufacturing when the knowledge on this technology is available inside the organization. This requires specialized personnel, which can be expensive.

For these reasons it is concluded that Philips Healthcare should outsource additive manufacturing.
7. Additive manufacturing and the last time buy decision

As discussed in the introduction, the systems sold by Philips Healthcare are capital goods. Capital goods are expensive, high complex goods which are intended to be used for a large amount of time, typically between 10 and 40 years (Kranenburg & Van Houtum, 2014). In the capital goods industry it is common for the manufacturer of the system to engage in a service contract with the customer. This contract states the number of years the manufacturer has to provide spare parts to the customer, which is called the service period. An illustration of the service period is provided in figure 13. Since the life time of the systems is long, the service period tends to be long as well. During the first part of the service period, the complete system is still in production. The production of spare parts is done in the same batch as the original parts. As long as the supplier produces the parts, it is relatively easy for Philips Healthcare to supply a spare part to its customers. However, at some point during the service period, the supplier might stop the production of the parts. After the supplier has stopped the production, it becomes much harder and more expensive to source the parts. Therefore it is common to place a large order, when the supplier announces it will stop the production. This order is called a last time buy order. The last time buy is required to be able to fulfill the demand during the remainder of the service period.

The last time buy option is a costly option due to the high level of inventory required. To reduce the costs of the last time buy order, recent literature focuses on alternative sources of supply in the period between the end of production and the end of the contract, also known as the remaining service period. When an alternative source of supply can be used, the last time order quantity can be reduced. The following alternatives are considered in literature (Behfard, Van der Heijden, Al Hanbali, & Zijm, 2013):

- Repair of failed parts that are returned from the field
- Strip phased-out systems for reusable spare parts
- Buy second-hand parts on the open market
- Substitute by a compatible part
- System redesign avoiding the need of the specific spare part

![Figure 13: Service period](image)
As been discussed in this thesis, additive manufacturing provides the possibility to reduce inventories by printing on demand. This feature makes it a very interesting remanufacturing alternative supply source in the remaining service period. Whether additive manufacturing can indeed be used as alternative supply source in the last time buy order is investigated in chapter 8. The aim of this chapter is to provide some context. In chapter 7.1 a literature review on state of the art literature on the last time buy process will be provided.

7.1 Literature review last time buy (LTB)

The last time buy decision is a stochastic inventory management problem. Several authors have done research on this topic. The first work on this topic was performed by Moore in 1971. During the 1980s, Fortuin described the last time buy decision in a more realistic industrial setting. These early authors solely focus on finding the LTB order quantity (Behfard, Van der Heijden, Al Hanbali, & Zijm, 2013). More recent works on LTB include alternative sources of supply (Behfard, Van der Heijden, Al Hanbali, & Zijm, 2013). An overview of the topics studied by several authors is provided by Behfard et al. Their results are displayed in figure 14 (Behfard, Van der Heijden, Al Hanbali, & Zijm, 2013).

<table>
<thead>
<tr>
<th>Literature</th>
<th>LTB</th>
<th>Repair of parts</th>
<th>parts from dismantling</th>
<th>extra production</th>
<th>external market</th>
</tr>
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<tr>
<td>Moore (1971)</td>
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<tr>
<td>Teunter, R.H. Fortuin, L (1998)</td>
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<tr>
<td>Teunter, R.H. Fortuin, L (1999)</td>
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<td>Kleber, R. Schulz, T. Voigt, G. (2012)</td>
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<tr>
<td>Behfard, Van der Heijden, Al Hanbali, Zijm (2013)</td>
<td>x</td>
<td>x</td>
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</tbody>
</table>

Figure 14: Overview of topics considered in the literature related to the LTB decision

In the work by Fortuin in 1981, a set of formulas was developed to determine the quantity which should be bought at the last time buy moment. Teunter calculates the last time buy quantity using:

\[ S = \mu_D + V \]

Where \( S \) is the LTB quantity, \( \mu_D \) is the expected demand during the remaining life cycle and \( V \) is the required safety stock. The safety stock is dependent on the required service level. In this paper Fortuin assumed the demand to follow a normal distribution and the demand rate to be decreasing in time. Fortuin developed a set of curves that indicate which size of the LTB quantity is required to attain a
certain service level. In a follow up paper, Fortuin showed that lower costs can be realized if the customer agrees with a lower service level at the end of the contract (Fortuin, 1981).

In the following years, the authors Teunter, Fortuin and Klein Haneveld have developed several extensions to the last time buy model (Teunter & Haneveld, The ‘final order’ problem, 1997), (Teunter & Fortuin, 1998), (Teunter & Fortuin, 1999), (Teunter & Klein Haneveld, 2002).

As been discussed, several alternative sources of supply are considered in recent literature. Most work is done on the alternative: strip phase out systems for reusable parts. This has been investigated by a number of authors including: Teunter & Fortuin (1998), Teunter & Fortuin, (1999), Pourakbar, Van der Laan, & Dekker (2011) and Kleber, Schulz, & Voigt (2012).

Tan and Van Kooten consider the last time buy decision with repair of failed parts as alternative sourcing option. It is assumed that when repair is not possible or not economically feasible, the parts are condemned. In the paper a methodology is developed to obtain a final order for repairable spare parts, taking condemnation specifically into account while considering a predefined service level (Van Kooten & Tan, 2009). The drawbacks of this approach are the relatively high amount of inventories required early in the service period and the risk of inventory obsolescence at the end of the service period (Behfard, Van der Heijden, Al Hanbali, & Zijm, 2013). In their paper, Behfard et al consider repair of failed parts as alternative sourcing option as well. They develop a heuristic method to find the near-optimal LTB quantity (Behfard, Van der Heijden, Al Hanbali, & Zijm, 2013). Their method differs from the work of Van Kooten and Tan in the sense that Behfard et al decide the LTB quantity based on an explicit cost trade-off.

**Summary and gap in literature**

All the models discussed in the literature review, aim to find the optimal LTB quantity. Early models focus solely on finding the last time buy order quantity. Recent literature focusses on finding the last time buy order quantity while alternative sources of supply are used during the remaining service period. These alternative sources of supply enable a reduction of the last time buy quantity. This can lead to a reduction of the holding costs.

The new technology, additive manufacturing has not yet been considered as alternative source of supply in the last time buy process. Additive manufacturing provides the possibility to reduce inventories by printing on demand. This feature makes it a very interesting alternative supply source in the remaining service period. It has the potential to significantly reduce the holding costs in the last time buy process.
8. Last time buy model
The last time buy (LTB) models described in the literature review in chapter 7.1 cannot be used to calculate the costs of additive manufacturing in the last time buy decision. Additive manufacturing has to my knowledge not yet been investigated as remanufacturing option in the last time buy decision. As been discussed in this thesis, additive manufacturing provides the possibility to reduce inventories by printing on demand. This feature makes it a very interesting remanufacturing option after the supplier of a part has stopped the production. The aim of this chapter is to identify the impact of additive manufacturing on the last time buy decision. A model will be developed which can be used to calculate the expected total costs of applying additive manufacturing in the last time buy decision. Since a last time buy decision is normally taken for only one item at a time, only a single item model is presented.

8.1 Description of the model
For producers like Philips Healthcare, who produce expensive, high complex, technological systems, it is common to engage in a service contract with the costumer. In this contract, an agreement is made on the number of years in which Philips Healthcare is obliged to provide spare parts to this customer. It is often observed that at some point before the end of the service contract (EOC), the supplier of a spare part stops the production of that part. This is called the end of production (EOP). The time between the EOP and the EOC is known as the remaining service period (RSP). To be able to fulfil the demand in the RSP, a last time buy order is required.

In the classic LTB models without remanufacturing options, parts could only be purchased at the last time buy moment. In this model, two opportunities are available to purchase parts. The first option is to purchase parts at the last time buy moment (the same option as in the classic LTB models). These parts are bought from the supplier which produces these parts with traditional manufacturing technologies. The second option available in this model is to buy parts from a 3D service provider. These parts are produced using additive manufacturing. The parts produced with additive manufacturing are more expensive than the parts made with traditional manufacturing technologies.

A conceptual presentation of the last time buy model including additive manufacturing is presented in figure 15. The model consists of two phases. In the first phase of the model, the demand is fulfilled using inventory depletion. This is similar to the classic last time buy models. In the second phase of the model, the demand is fulfilled using additive manufacturing.
At the EOP, the last time buy order has to be placed. At the moment of the order, the company might still have some stock in its warehouse. This stock is called the initial inventory level ($S_0$) and is an input parameter for this model. The size of the order ($Q$) is dependent on the required order up to level ($S_1$). $S_1$ is a decision variable of this model. The order size, $Q$, is equal to $S_1 - S_0$. It is assumed that demands arrive according to a stationary Poisson process with rate $\lambda$. In the inventory depletion phase, each time when a demand arrives, the inventory level decreases with one. This continues until the inventory level reaches the basestock level, $S_2$. From this moment onwards, the inventory is controlled using a basestock policy. In a basestock policy, the inventory position (IP), which is defined as sum of the physical inventory on stock (OH) and all outstanding orders (IO) minus the backorders (BO), is kept constant at a basestock level ($S_2$). Each time a demand arrives, an order is placed at the 3D service provider. This order will arrive after a stochastic lead time ($LT$). $LT$ is randomly distributed with mean $ELT$. $S_2$ is a decision variable of this model. During the basestock policy it is possible that the inventory level decreases to 0. All demand which cannot be delivered from stock immediately is backordered. The number of backorders is given by BO.

The behaviour of the model switches at some point during the RSP from inventory depletion to a basestock policy. The time from the EOP to the switch (the duration of the inventory depletion phase) is equal to $a$ in figure 15. The time from the switch to the EOC (the duration of the basestock policy) is equal to $RSP - a$ in figure 15. The time to the switch moment is a random variable denoted by $A$. $A$ is the realization of this random variable. The time to switch ($A$) is Erlang distributed with shape parameter($n$) $S_1 - S_2$ and scale parameter $\frac{1}{\lambda}$. This is due to the following general property of the Poisson distribution:
The time between \( n \) events of a Poisson distribution is Erlang distributed with shape parameter \( n \) and scale parameter \( \frac{1}{\lambda} \) (Nahmias, 2009).

Since the inventory depletion phase starts with an inventory level equal to \( S_1 \) and ends when the inventory level reaches \( S_2 \), in total \( S_1 - S_2 \) demands will occur in the interval \([0, A]\).

In this thesis, both a costs model and a service model have been developed. The expected total costs in the cost model consist of:

- Total purchase costs for parts produced using traditional manufacturing methods (\( C_{acq1} \))
- Expected total purchase costs of parts produced using additive manufacturing (\( C_{acq2} \))
- Expected total holding costs for parts produced using traditional manufacturing methods (\( C_{hold1} \))
- Expected total holding costs for parts produced using traditional manufacturing methods (\( C_{hold2} \))
- Expected total penalty costs for backorders (\( C_{penalty} \))

In the service model, the penalty costs are not taken into account. The decision variables in both the service- and the cost- model are:

- The order up to level at the last time buy moment (\( S_1 \))
- The base stock level using additive manufacturing (\( S_2 \))

The optimal values for the decision variables are found by minimization the expected total costs function. In the minimization problem of the cost model, the expected total costs are minimized without a service restriction, since the service restriction is translated into a penalty costs for backorders. In the minimization problem of the service model, the expected total costs are minimized, while a certain target service level (\( \beta_{target} \)) needs to be fulfilled. The service level is defined as the percentage of the demand which can be fulfilled from stock directly. The model consists of two phases. During the inventory depletion phase, the inventory level will never drop below \( S_2 \). The service level in this phase of the model is therefore 100%. The service level during the basestock policy (\( \beta(S_2) \)) is dependent on the basestock level. The service level during the entire RSP (\( \bar{\beta} \)) is a weighted average of these service levels.

The minimization problem of the service- and the cost- model are given in chapter 8.8. The required expressions for the minimization problem will be derived in chapter 8.7.

8.2 Duration of the inventory depletion phase (\( B \))

In the description of the model provided above, it is implicitly assumed that the switch moment will always occur before the end of the RSP. In the described scenario, the inventory depletion phase is used on the interval \([0, A]\) and the basestock policy is used on the interval \([A, RSP]\). This implies that \( A < RSP \). However, this does not necessarily have to be true.
Consider the situation in which the demand during the \( RSP \) is smaller than \( S_1 - S_2 \). In this scenario, the inventory level will never drop to the level of \( S_2 \). This implies that the switch will not occur. In this scenario, the duration of the inventory depletion phase \( (B) \) is \( RSP \).

So, the model can behave in two ways. Either, a switch will occur before the end of the \( RSP \), which means that the inventory depletion phase will be used on the interval \([0, A]\) and the basestock policy will be used on the interval \([A, RSP]\). Or, no switch will occur. In this scenario, the inventory depletion phase is used on the interval \([0, RSP]\). To be able to include this into the model, the following expression for the duration of the inventory depletion phase \( (B) \) is used.

\[
B = \min(A, RSP)
\]

8.3 Assumptions

Time is assumed to be a continues variable in the interval \(0 \leq t \leq RSP\)

No discounting is used. If discounting would be used, current costs would get a higher emphasis. This would bias the LTB decision by preventing a high investment in the last time buy quantity in favour of the lower discounted costs in the future.

Demand is assumed to follow a stationary Poisson process with rate \( \lambda \)

The parts produced using additive manufacturing have the same quality as the parts produced using traditional manufacturing methods

There are no repairs or returns

The \( RSP \) is known and deterministic, since at the EOP, the EOC is known

It is assumed that the holding costs \( ch_2 \) apply on the interval \([B, RSP]\). In reality, this is not completely true, because for the first \( S_2 \) parts sold after \( a \), a holding costs of \( ch_1 \) should be applied. These parts where bought at the LTB moment. This assumption does not significantly change the costs in the model.

This model calculates the expected total costs. Because expected values are used in the calculations, the model is an approximation of the total costs. As a result of this approximation, non-convex cost terms are observed if the demand during the \( RSP \) takes large values. This will be explained in more detail in chapter 8.9. It is assumed that the demand during the \( RSP \) is sufficiently low. This assumption is justified, since this model is intended for slow moving spare parts.

It is assumed that the model is immediately in steady state after the switch moment. Therefore, the steady state probabilities instead of the transient state probabilities can be used in the basestock policy to determine the values of the variables \( OH, IO \) and \( BO \). This assumption does not significantly impact the model as long as the lead time is small compared to \( RSP - a \) (the duration of the basestock policy phase).

This model only works in a feasible range, therefore we assume that
- \( c_c \leq c_{3D} \). If this assumption does not hold, the model should not be used. In this case, additive manufacturing is the cheapest option and all parts should be produced using additive manufacturing.
- \( S_2 \leq S_1 \). This is a result of the relatively high costs for additive manufacturing compared to the costs of traditional manufacturing.
- \( S_0 \leq S_1 \). Once \( S_0 \geq S_1 \), this model can still be used. However instead of buying a negative quantity at the LTB moment, no order should be placed. The cost function is now an underestimation of the costs since the holding costs of the abundant parts still on stock are not taken into account.

### 8.4 Parameters

Table 6: Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \beta_{\text{target}} )</td>
<td>The target service level: the percentage of demand that can be fulfilled from stock directly during the RSP</td>
</tr>
<tr>
<td>( c_{3d} )</td>
<td>Purchase costs for parts produced using additive manufacturing. Applied in the interval ([B, RSP])</td>
</tr>
<tr>
<td>( c_c )</td>
<td>Purchase cost for parts produced using traditional manufacturing methods. Applied in the interval ([0, B])</td>
</tr>
<tr>
<td>( ch_1 )</td>
<td>Holding cost per part per year applied on the interval ([0, B])</td>
</tr>
<tr>
<td>( ch_2 )</td>
<td>Holding cost per part per year applied on the interval ([B, RSP])</td>
</tr>
<tr>
<td>( cp )</td>
<td>Penalty cost for backorders in the interval ([B, RSP])</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>Demand rate per month</td>
</tr>
<tr>
<td>( Q )</td>
<td>The size of the last time buy order ((S_1 - S_0))</td>
</tr>
<tr>
<td>( RSP )</td>
<td>The remaining service period</td>
</tr>
<tr>
<td>( S_0 )</td>
<td>Initial inventory level at the moment of the last time buy decision</td>
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</table>

### 8.5 Decision variables

Table 7: Decision variables

<table>
<thead>
<tr>
<th>Decision variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_1 )</td>
<td>Order up to level at the last time buy moment</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>Base stock level in second phase of the model (on the interval ([B, RSP]))</td>
</tr>
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</table>

### 8.6 Random variables

Table 8: Random variables

<table>
<thead>
<tr>
<th>Random variable</th>
<th>Definition</th>
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<tbody>
<tr>
<td>( A )</td>
<td>The time until the switch moment. ( A \sim \text{Erlang}(S_1 - S_2, \frac{1}{2}) )</td>
</tr>
<tr>
<td>( B )</td>
<td>The duration of the inventory depletion phase. ( B = \min(A, RSP) )</td>
</tr>
<tr>
<td>( \beta(S_2) )</td>
<td>The percentage of demand which can be fulfilled from stock directly</td>
</tr>
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</table>
### 8.7 Expressions

In this paragraph, the mathematical expressions for the costs factors and the random variables will be provided.

#### Duration of the inventory depletion phase (B)

As described above, the duration of the inventory depletion phase is given by:

\[
B = \min(A, RSP)
\]

In this expression, \(A\) is Erlang distributed with shape parameter \(n\) and scale parameter \(\theta\). Here, \(n = (S_1 - S_2)\) and \(\theta = \frac{1}{\lambda}\). The Erlang distribution is a special case of the Gamma distribution for positive integer values of \(n\). The Erlang distributed random variable \(A\), with shape parameter \((S_1 - S_2)\) and scale parameter \(\frac{1}{\lambda}\) has the following probability density function (Jansen, 2012), where the subscript of \(f\) gives the shape parameter and the scale parameter:

\[
f_{(S_1-S_2)}(x) = \frac{\lambda e^{-\lambda x} \lambda^{(S_1-S_2)-1}}{\Gamma(S_1-S_2)}
\]

Here, \(\Gamma(n)\) is the gamma function evaluated at \(n\). The cumulative distribution function of \(A\) is given by (Jansen, 2012):

\[
F_{(S_1-S_2)}(y) = \int_{x=0}^{y} \frac{\lambda e^{-\lambda x} \lambda^{(S_1-S_2)-1}}{\Gamma(S_1-S_2)} dx
\]

The expression for the duration of the inventory depletion phase, \(B = \min(A, RSP)\), can be simplified using formula 5.54 on page 163 by Jansen (Jansen, 2012)

\[
B = E[A] - E[(A - RSP)^+]\]

With

\[
E[A] = \frac{(S_1 - S_2)}{\lambda}
\]
And, by applying formula 5.52 on page 162 by Jansen (Jansen, 2012):

\[ E[(A - RSP)^+] = \frac{(S_1 - S_2)}{\lambda} \cdot \left[ 1 - F_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(RSP) \right] - RSP \cdot \left[ 1 - F_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(RSP) \right] \]

This leads to:

\[ B = \frac{(S_1 - S_2)}{\lambda} \cdot \left[ 1 - F_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(RSP) \right] - RSP \cdot \left[ 1 - F_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(RSP) \right] \]

\[ B = \frac{(S_1 - S_2)}{\lambda} \cdot F_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(RSP) + RSP \cdot \left[ 1 - F_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(RSP) \right] \]

The duration of the inventory depletion phase can also be written as:

\[ B = \min(A, RSP) \]

\[ B = \int_{x=0}^{RSP} x \cdot f_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(x) \, dx + RSP \cdot P(A \geq RSP) \]

With

\[ P(A \geq RSP) = 1 - P(A \leq RSP) \]

and

\[ P(A \leq RSP) = \sum_{x=0}^{(S_1-S_2)} \frac{(\lambda \cdot RSP)^x \cdot e^{-\lambda \cdot RSP}}{x!} \]

For the readability of the thesis, the notation \( f(x) \) will be used instead of \( f_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(x) \) from this point onwards. Therefore, each time when \( f(x) \) is mentioned in the following calculations, one should refer to \( f_{(S_1-S_2) + 1}^{\frac{1}{\lambda}}(x) \) as defined above.

**Acquisition costs 1**

The acquisition costs 1 are the costs for purchasing parts at the last time buy moment. These parts are manufactured using traditional manufacturing methods. The costs per part are \( cc \).

The total acquisition costs are:

\[ Cacq1 = cc \cdot (S_1 - S_0) \]

**Acquisition costs 2**

The acquisition costs 2 are the expected costs for the parts which need to be bought in the second phase of the model. These parts are produced with additive manufacturing. There are two possible
scenarios. If $A \geq RSP$, no switch occurs and no parts are bought. In this scenario the acquisition costs are 0. If $A < RSP$, a switch occurs. The expected acquisition costs in this scenario are equal to:

$$\text{Cacq2} = \int_{x=0}^{RSP} c3d \star \lambda \star (RSP - x) \star f(x) \, dx$$

$$= \int_{x=0}^{RSP} c3d \star \lambda \star RSP \star f(x) \, dx - \int_{x=0}^{RSP} c3d \star \lambda \star x \star f(x) \, dx$$

$$= c3d \star \lambda \star RSP \star \mathcal{F}_{\mathcal{N},\lambda}(RSP) - c3d \star \lambda \star \int_{x=0}^{RSP} x \star f(x) \, dx$$

**Holding costs 1**

The holding costs are the expected holding costs for parts manufactured using the traditional manufacturing methods. These holding costs are applied during the inventory depletion phase. Since $B = \min(A,RSP)$, there are two scenarios for the costs. If $A \geq RSP$, no switch occurs. This happens when the demand during the RSP is less than $S_1 - S_2$. The demand during the RSP ($D_{RSP}$) is Poisson distributed with mean $\lambda \star RSP$. Figure 16 illustrates the inventory behavior in this scenario. During the inventory depletion phase, the inventory level decreases from $S_1$ to a level between $S_1$ and $S_2$. Lets call the total demand in this scenario $x$. In this case, $S_1 - x$ products will not be used and will stay in inventory during the entire RSP. This is indicated in the blue rectangle (h). Since, the demand during the RSP is equal to $x$, the average inventory level in the red triangle in figure 16 is equal to $\frac{x}{2}$. The total expected holding costs is equal to $ch_1$ times the expected surface under the line (the expected surface of the blue and the red part).

**Inventory level**

![Inventory level diagram](image)

Figure 16: Representation of the inventory level when no switch occurs

$$\text{expected surface of } g = \sum_{x=0}^{S_1 - S_2} \frac{1}{2} \star x \star P(D_{RSP} = x) \star RSP$$

The expected surface of h (the blue square) is equal to:
The total expected surface in the figure is \( g + h \). Therefore, the expected holding costs in this scenario are equal to:

\[
\sum_{x=0}^{s_1-s_2} c_h (S_1-x) \frac{1}{2} x RSP \cdot P(D_{RSP} = x)
\]

In the second scenario, a switch occurs since \( A < RSP \). In this scenario, \( S_1 - S_2 \) demands are fulfilled during the inventory depletion phase. An example of this scenario is displayed in figure 17.

**Inventory level**

![Diagram showing inventory level with two parts, S1 and S2, and a switch occurring at S1 - S2.](image)

**Figure 17:** Representation of the inventory level when a switch occurs

During the inventory depletion phase, \( S_2 \) parts stay in inventory without being used. This is illustrated in the blue rectangle (j).

The surface of j is equal to:

\[ \text{surface of } j = S_2 * a \]

Since, \( S_1 - S_2 \) parts are sold in this interval, the surface of the red triangle is equal to:

\[ \text{Surface of } i = \frac{(S_1 - S_2)}{2} * a \]

The total surface \((i + j)\) is equal to

\[ i + j = \left( \frac{(S_1 - S_2)}{2} + S_2 \right) * a \]
Remember that $a$ is the realization of the random variable $A$. The expected holding costs for this scenario are:

$$\int_{x=0}^{RSP} c h_1 \left( \frac{S_1 - S_2}{2} + S_2 \right) \ast x \ast f(x) dx$$

The total expected holding costs in phase 1 are therefore:

$$Chold1 = \sum_{x=0}^{S_1-S_2} ch_1 \left( (S_1 - x) + \frac{1}{2} \ast x \right) \ast RSP \ast P(D_{RSP} = x) + \int_{x=0}^{RSP} ch_1 \left( \frac{(S_1 - S_2)}{2} + S_2 \right) \ast x \ast f(x) dx$$

**Holding costs 2**

In the second phase of the model, the inventory is controlled using a base stock policy. It is assumed that the model is in steady state immediately after the switch. Because of this assumptions, the steady state distribution can be used in the calculations of the expected on hand inventory ($E[OH]$) and the expected number of backorders ($E[BO]$). Again there are two scenarios, either no switch occurs and the holding costs are 0 or a switch will occur. If a switch occurs the expected holding costs in interval $[B, RSP]$ are:

$$Chold2 = \int_{x=0}^{RSP} ch_2 \ast E[OH] \ast (RSP - x) \ast f(x) dx$$

$$= ch_2 \ast E[OH] \ast RSP \ast F_{\frac{1}{\lambda}}(RSP) - ch_2 \ast E[OH] \ast \int_{x=0}^{RSP} x \ast f(x) dx$$

With

$$E[OH] = \sum_{x=1}^{S_2} (S_2 - x) \ast \left( \frac{(\lambda ELT)^x \ast e^{-\lambda ELT}}{x!} \right)$$

For a detailed derivation of $E[OH]$ I refer to appendix A.

**Backorder costs**

For the backorder costs, the same two scenarios apply, either no switch occurs and these costs are 0 or a switch will occur. If a switch occurs the expected costs for backorders in this policy are equal to:
\[
C_{\text{penalty}} = \int_{x=0}^{\text{RSP}} cp \cdot E[BO] \cdot (\text{RSP} - x) \cdot f(x) dx
\]

\[
= cp \cdot E[BO] \cdot \text{RSP} \cdot F_{\frac{1}{\lambda}}(\text{RSP}) - cp \cdot E[BO] \cdot \int_{x}^{\text{RSP}} x \cdot f(x) dx.
\]

With

\[
E[BO] = \lambda \cdot ELT - S_2 + E[OH]
\]

For a detailed derivation of \(E[BO]\) I refer to appendix A.

**Constraint**

The service level should be a weighted average of the service level in the first phase of the model and the service level in the second phase of the model. The service level is defined as:

*The percentage of demand which can be fulfilled from stock immediately.*

In the first phase of the model, the service level is 100%, since all demand can be fulfilled from stock immediately. In the second phase of the model, during the base stock policy, the service level is equal to:

\[
\beta(S_2) = P(OH(t) \geq 1) = P(IO(t) \leq S_i - 1) = \sum_{x=0}^{S_2 - 1} P(IO = x) =
\]

\[
\sum_{x=0}^{S_2 - 1} \left( \frac{(\lambda \cdot ELT)^x \cdot e^{-\lambda \cdot ELT}}{x!} \right)
\]

The probability of a switch is taken account in the calculations. The following expression is used to calculate the weighted average service level:

\[
\bar{\beta} = \int_{x=0}^{\text{RSP}} \left( \frac{x}{\text{RSP}} \ast 1 + \frac{\text{RSP} - x}{\text{RSP}} \ast \beta(S_2) \right) \ast f(x) dx + \left( 1 - F_{\frac{1}{\lambda}}(\text{RSP}) \right)
\]

\[
\bar{\beta} = \frac{1}{\text{RSP}} \left[ \int_{x=0}^{\text{RSP}} \left( x + (\text{RSP} - x) \ast \beta(S_2) \right) \ast f(x) dx \right] + \left( 1 - F_{\frac{1}{\lambda}}(\text{RSP}) \right)
\]

\[
\bar{\beta} = \frac{1}{\text{RSP}} \left[ \int_{x=0}^{\text{RSP}} \left( x + \beta(S_2) \ast \text{RSP} - \beta(S_2) \ast x \right) \ast f(x) dx \right] + \left( 1 - F_{\frac{1}{\lambda}}(\text{RSP}) \right)
\]
Minimization problem

Both a cost model and a service model have been developed. In the cost model a penalty cost for backorders is calculated. Since these costs are mostly unknown, the service model is preferred. The service model minimizes the costs while fulfilling a service level constraint.

Cost model

Minimize

\[ E[TC(S_1, S_2)] = Cacq1 + Cacq2 + Chold1 + Chold2 + Cpenalty \]

Service model

Minimize

\[ E[TC(S_1, S_2)] = Cacq1 + Cacq2 + Chold1 + Chold2 \]

S.t.

\[ S_1 \geq S_0 \]
\[ S_2 \leq S_1 \]
\[ \bar{\beta} \geq \beta_{target} \]

Analysis

The mathematical formulas derived above are implemented in MATLAB.

Solution procedure

As solution procedure, the complete enumeration method is used. In complete enumeration, all possible solutions are calculated. This method guarantees that the optimum solution is chosen. But, since it calculates all possibilities, complete enumeration is not preferred for large problems. This last time buy model is a relatively small problem. The minimization problem consists of only two decision variables, \( S_1 \) and \( S_2 \). Since the model is designed for slow moving spare parts, these decision variables
will not take too high values. In addition, the variables can take only integer values in this problem. This enables the use of the complete enumeration method. Many other solution procedures require a convex objective function. As we will see later, the total expected cost function is not convex for all input parameters. To guarantee an optimal solution anyway, complete enumeration is used.

**Domain of the decision variables**
Decision variable $S_2$ can take values between 0 and infinity in theory. However, since the model concerns slow moving spare parts, a small value for $S_2$ is expected. As upper bound ($S_{2\text{ max}}$), a value is chosen which is low enough to limit the required calculation time and high enough to not become restrictive to the optimal solution. $S_{2\text{ max}}$ is equal to the expected demand during the lead time plus a safety factor. The following upper bound is used for $S_2$.

$$S_{2\text{ max}} = \lambda \cdot \text{ELT} + 10 \cdot \sqrt{\lambda \cdot \text{ELT}}$$

$S_1$, can take all values between $S_2$ and the upper bound for $S_1$ ($S_{1\text{ max}}$). Since in complete enumeration all values for $S_2$ are calculated starting from $S_2 = 0$, the range for $S_1$ will be between 0 and $S_{1\text{ max}}$. The following upper bound is used for $S_1$.

$$S_{1\text{ max}} = \lambda \cdot \text{RSP} + 4 \cdot \sqrt{\lambda \cdot \text{RSP}}$$

The number of calculations required with complete enumeration is equal to $S_{1\text{ max}} \cdot S_{2\text{ max}}$.

**Convexity issues**
To test for convexity, 3D plots have been made in which the variables expected total costs (z axis), $S_1$ (x axis) and $S_2$ (y axis) have been plotted. In figure 18, the 3D plot belonging to part 1 is displayed. This plot is obtained using the input parameters belonging to this part. These input parameters can be found in appendix D.

![3D plot: Total costs, S1, S2](image)

Figure 18: 3D plot with input parameters belonging to part 1
This plot shows that the objective function is convex for the used input parameters. However, it is no prove that the cost function is convex in every situation. Only one scenario of non-convexity has to be found to conclude that the model is not convex.

3D plots have been made for all the selected parts. For the selected parts, the objective function is convex. However, when less realistic input variables are used, like for example an extremely long lead time at the 3D service provider, the objective function is not convex. This is only observed in the cost model. In the service model, the non-convex costs are not obtained, since these values are excluded from the calculations through the service level constraint. Figure 19 displays the 3D plot of the cost model for part 1, when the lead time at the service provider would be 2 years (instead of 2 weeks).

![3D plot: Total costs, S1, S2](image)

*Figure 19: 3D plot for part 1 with lead time is 2 years, all other input parameters can be found in appendix D*
Plots of all the costs terms against $S_2$ were evaluated to discover which cost terms cause the non-convexity of the objective function. It is concluded that the non-convexity is caused by the holding costs 1 and the penalty costs as displayed in figures 20, 21 and 22.

![Figure 20: Plot of expected total costs 1 vs $S_2$ level](image)

![Figure 21: Plot of expected holding costs 1 vs $S_2$ level](image)

![Figure 22: Plot of expected backorder costs 1 vs $S_2$ level](image)

The non-convexity issues can be explained by the behavior of the model. It is caused by the approximation for the switch moment.

First, let’s explain the behavior of the penalty costs. Consider the situation in which the $S_2$ level is 0. With a high lead time and a $S_2$ level of 0, the backorder costs are high. If the $S_2$ level is increased by 1, the number of backorders will not significantly decrease. However, the switch moment will be slightly earlier because, as a result of a higher $S_2$, a lower $S_1$ is chosen which results in a lower value for $A$. Therefore, the number of backorders will stay the same but the time these backorders are experienced is increased. This combination leads to higher backorder costs. Apparently this effect happens for $S_2$. 
values between 0 and 4 for these input variables. Starting from $S_2 = 4$, the reduction in backorders costs behaves normally.

For the holding costs 1, the cost function is concave when the difference between $S_1$ and $S_2$ is large or when the $RSP$ is small. This happens because the presented model is an approximation for the total costs. The concave shape of the holding cost 1 function is caused by the following integral:

$$\int_{x=0}^{RSP} x * f(x)dx$$

This integral is used to calculate the expected time to the switch moment ($A$), if a switch occurs on the interval $[0, RSP]$. Here $A$ has an Erlang distribution with shape parameter $S_1 - S_2$ and scale parameter $\frac{1}{\lambda}$. The Erlang distribution can take different shapes depending on the parameters. To see the effect of the parameters on the shape of the distribution, the following three plots have been made. In figure 23, the values of the integral are plotted against $S_2$, for the input parameters: $S_1 = 50$, $RSP = 5$, $\lambda = 15$, $ch_1 = 0.2 * cc$ of part 1. In figure 24, the same parameters are used, only the $RSP$ is increased to 10, and in figure 25, the $RSP$ is increased to 15.
From these plots, we can observe that the $RSP$, $\lambda$ and the difference between $S_1$ and $S_2$ influence the shape of the Erlang distribution. Due to this influence of the Erlang distribution, a concave shape can be obtained for the expected holding cost $1$. From this, one can conclude the holding costs $1$ function is only convex when the $RSP$ is sufficiently large compared to $\lambda$. If the demand during the $RSP$ is too high, concave expected cost functions are observed.

8.10 Numerical results

In this paragraph, the model will be applied to the selected parts. This numerical analysis will identify the cost of using additive manufacturing in the last time buy decision for the selected parts. To identify whether this model leads to cost benefits, the results of this model will be compared to the results of a benchmark model. The benchmark model is developed to represent the situation without additive manufacturing. The order placed at the last time buy moment is the only opportunity to get the parts. This benchmark model therefore consists of the inventory depletion phase only. The costs consist of purchasing costs and holding costs. The decision variable is $S_1$, which again represents the order up to level at the last time buy moment. As constraint, a service level of 95% is used.

Assumptions

In performing the numerical analysis, several assumptions for the input variables are required. The costs at the 3D service provider are between 5 and 10 times more expensive. For this numerical analysis a value of 5 times the regular purchase value is chosen. A sensitivity analysis will identify the impact of a change in the variable $c3d$. The demand rate per year is based on data of the past 4 years. An average is taken over these years. The remaining service period is assumed to be 15 years. The holding costs are assumed to be 20% of the purchase value.

The costs of the model with additive manufacturing and the costs in the benchmark model will be provided part by part. Spare part 2 of the selected parts is excluded from the results. This part is not a slow moving spare part. Due to its high demand rate, the calculations would take too long.

Spare part 1

The results of this numerical analysis are displayed in tables 12, 13 and 14 of appendix D. In the model with additive manufacturing, the order up to level at the last time buy moment is 69 and the basestock model for additive manufacturing is 1. The expected duration of the inventory depletion phase is 13,4 years. This is long, considering a $RSP$ of 15 years. The main cause for this behavior is the expensive costs of additive manufacturing. It can be observed that the model uses additive manufacturing as a replacement of a safety stock. A little less than the expected demand during the $RSP,(\lambda \ast RSP)$, is bought at the last time buy moment. If the demand is higher than this original quantity, additive manufacturing is used as remanufacturing option. In the benchmark model, the value for $S_1$, the order up to level, is 90, which is much higher. Since, additive manufacturing is excluded from this model, there is no remanufacturing option during the $RSP$. Therefore, a safety stock (equal to 15) is required. The total cost savings of using additive manufacturing in the last time buy decision is €3.199,00. From this numerical analysis, it is concluded that additive manufacturing leads to savings in the last time buy decision for this part, mainly by preventing a safety stock.
Spare part 3
The results of this numerical analysis are displayed in tables 15, 16 and 17 of appendix D. For spare part 3, an order up to level of 14 and a basestock level of 1 is optimal. The same behavior of the model as with spare part 1 can be observed. The expected duration of the inventory depletion phase is large with 12.29 years. Additive manufacturing is again used as alternative for a safety stock. Since the demand rate for spare part 3 is low, the value for $S_1$ is low as well. The total cost with additive manufacturing are €1,470,00 lower than in the benchmark model. So, additive manufacturing is the preferred option for spare part 3.

Spare part 4
The results of this numerical analysis are displayed in tables 18, 19 and 20 of appendix D. Interesting from the results of this part, is that the same values for the decision variables, $S_1$ and $S_2$ are obtained as for spare part 3. This is caused by the demand rate, which is equal for both parts. Both parts differ in costs, from which can be concluded that the costs of a part have no direct influence on the decision variables as long as the difference between additive manufacturing costs and regular costs is fixed. Again, the same model behavior is observed. Additive manufacturing is only used in the last part of the RSP. Because of the combination of a low demand rate and a relatively low purchase price, the saving of including additive manufacturing is relatively low for this part. Including additive manufacturing in the last time buy decision of spare part 4, results in a saving of €444,10.

Spare part 5
The results of this numerical analysis are displayed in tables 21, 22 and 23 of appendix D. The optimal values of the decision variables are $S_1 = 103$ and $S_2 = 0$. The reason for a basestock level of 0 is explained in the sensitivity analysis of parameter $\lambda$ in chapter 8.13. In this scenario, inventory depletion is used for the far majority of the RSP. The savings of using additive manufacturing in the last time buy decision for spare part 5 are €1,7750.

Spare part 6
The results of this numerical analysis are displayed in tables 24, 25 and 26 of appendix D. The decision variables, $S_1$ and $S_2$, are 62 and 1, respectively. Again, it can be observed that the expected duration of the inventory depletion phase is long. So the same model behavior as described above is observed. This part has a low purchase value. Therefore, the cost saving of additive manufacturing is relatively small. By using additive manufacturing, a saving of €183,20 compared to the benchmark model can be generated.

Conclusion of the numerical analysis
For all parts, the same model behavior is observed. The inventory depletion phase is used for the majority of the RSP. The order up to level at the last time buy moment is always only a little smaller than the expected demand during the RSP: $\lambda \times RSP$. For all the input parameters used in this analysis, the model uses additive manufacturing as an alternative for the safety stock. Additive manufacturing leads to cost benefits in the last time buy decision for all the selected parts. The largest saving obtained in this numerical analysis, is €3,199,00. The lowest saving obtained in this numerical analysis is €183,20.
In total, Philips Healthcare can generate a costs saving of € 7,051,30 when additive manufacturing is applied to the last time buy decision of these five spare parts.

### 8.11 Sensitivity analysis

Several assumptions have been made in order to select appropriate values for the input parameters in the numerical analysis. To identify the impact of these input parameters on the behavior of the model, a sensitivity analysis is performed. Since the model shows similar behavior for all the selected parts, the analysis is performed on one part only. For this sensitivity analysis, spare part 1 is used. In the sensitivity analysis, the following parameters will be varied one by one.

- Purchase costs of additive manufacturing ($c_3d$)
- Demand rate ($\lambda$)
- The remaining service period ($RSP$)
- Holding costs ($ch_1$ and $ch_2$)

#### Change of the purchase costs of additive manufacturing

In the numerical analysis, it is assumed that the costs of additive manufacturing are 5 times more expensive than the costs of regular production. In this sensitivity analysis the impact of the costs of additive manufacturing relative to the regular purchase costs is identified. The results of this sensitivity analysis are displayed in table 27 of appendix E. The cost of additive manufacturing has a significant impact on the expected total costs. If additive manufacturing is 10 times more expensive, additive manufacturing will not lead to savings. In this case it would be cheaper to use a safety stock. If the cost of additive manufacturing would decrease to 1.5 times the costs of regular production, the cost savings of using additive manufacturing in the last time buy decision will be €21,573. When additive manufacturing becomes cheaper, more demand during the $RSP$ will be fulfilled with additive manufacturing. This causes the expected duration of the inventory depletion phase to decrease. This lowers the required inventory, which leads to a decrease of $S_1$. As a result, the expected total holding costs are decreased as well. This is reflected in the expected total costs.

#### Change in the demand rate

To see the effect of a change in the demand rate on the decision variables and the expected total costs, a sensitivity analysis on $\lambda$ is performed. The results are shown in table 28 of appendix E. An increase in the demand rate causes an increase in the expected total costs. Also, an increase in $S_1$ is observed. This is due to an increase in the term $\lambda \times RSP$. The optimal value for $S_2$ is 0 when $\lambda$ is 9 or higher. This might seem strange at first, but is caused by the service level constraint. It can be explained as follows. First, consider the basestock policy only. A higher $\lambda$ causes the service level to go down. Let’s consider that for $S_2 = 1$, the service level is below the target. The only option to increase the service level, is to increase the basestock level to $S_2 = 2$. Since the costs of additive manufacturing are relatively expensive, this would significantly increase the holding costs. Now consider the model consisting of inventory depletion and additive manufacturing. This model has an additional option to increase the service level. The inventory depletion phase can be extended. In this scenario, a higher $S_1$ is required. The increase in $S_1$, turns out to be cheaper than an increase in $S_2$ for these input parameters. So, for high values of lambda, it is more beneficial to increase $S_1$ and set $S_2 = 0$, than to increase $S_2$ to 2. It can
be concluded that the value of additive manufacturing in the last time buy decision is larger for higher values of $\lambda$, because the increase in the expected total costs of the additive manufacturing model is lower than the increase in the expected total costs of the benchmark model.

**Change in the remaining service period**
In the numerical analysis, the remaining service period is set to 15 years. The results of the sensitivity analysis are displayed in table 29 of appendix E. From this table it is concluded that additive manufacturing provides more value to the last time buy decision when the remaining service period is long.

**Change in holding costs**
In the numerical analysis, the holding costs are assumed to be 20% of the purchase value. Some might argue that this estimate is too low. To identify the effect of the holding costs to the last time buy model, the holding costs are varied in this sensitivity analysis. The results are displayed in table 30 of Appendix E. The expected total costs increase when the holding costs increase. To compensate for an increase in the holding costs, a lower $S_1$ value is used. In the benchmark model, this is not possible. The expected total costs in the benchmark model, therefore increase faster than the expected total costs in the proposed model, for an increase of the holding costs. So, the higher the holding cost, the higher the benefit of additive manufacturing. This is due to the same property as we have seen before, the possibility to prevent the safety stock.

**Conclusion of the sensitivity analysis**
The value of additive manufacturing in the last time buy decision is higher for:

- Lower costs of additive manufacturing
- Higher demand rates
- Longer remaining service periods
- Higher holding costs

**8.12 Conclusion**
In this chapter, a model has been developed which can be used to calculate the expected total costs of applying additive manufacturing in the last time buy process. The decision variables in this model are the order up to level at the last time buy moment ($S_1$) and the basestock level for additive manufacturing ($S_2$). The optimal values for these decision variables are found by minimizing the expected total cost function, while fulfilling a desired service level. The minimal expected total costs are found using complete enumeration.

To identify whether additive manufacturing leads to cost advantages in the last time buy decision, the model has been applied to the selected parts of Philips Healthcare. The results of the model have been compared to the results of a benchmark model. In this benchmark model, the situation without additive manufacturing is represented. An advantage of additive manufacturing in the last time buy decision is that safety stocks are not required. This leads to a reduction of the holding costs. In the numerical analysis it is assumed that the costs of additive manufacturing are 5 times more expensive than the costs of regular production. With this assumption, the total costs with additive manufacturing are lower
than the total costs of the benchmark model for every part. It is therefore concluded that additive manufacturing leads to cost advantages in the last time buy decision. However, when the costs of additive manufacturing would be as high as 10 times the cost of regular production, additive manufacturing would not be beneficial. In this case, the technology is simply too expensive and the reduction in the inventory costs is not enough to overcome the increase in acquisition costs.
9. Conclusion and recommendations

This chapter will provide the conclusions of this thesis and the recommendations for Philips Healthcare. Also, some areas for further research will be identified. The conclusions drawn from this thesis are provided in chapter 9.1. Chapter 9.2 contains the recommendations. The areas for further research are provided in chapter 9.3.

9.1 Conclusion

In this thesis, the application of additive manufacturing to the spare part supply chain of Philips Healthcare is investigated. First the technology additive manufacturing is described and the current status of the technology was given.

To identify the printable spare parts of Philips Healthcare, a selection procedure was developed. Using this procedure, six of the highest potential candidate parts were selected. During the selection, a mismatch is observed between what parts Philips would like to print from a supply chain perspective and the parts which are possible to print given the current status of the technology.

From the selection it is concluded that only small, slow moving mechanical spare parts should be selected. Even for this category, additive manufacturing is not always the preferred technology. The following niches, where additive manufacturing adds additional value, are identified:

- The last time buy decision
- No more molds available
- Redesign of spare parts

Because of the technical limitations and the rapid developments of the technology, it is not preferred to invest in 3D printers at this moment. Instead, 3D service providers should be used to manufacture the spare parts.

A mathematical model is made to quantify the effect of including additive manufacturing to the spare parts supply chain in the last time buy process. This model considers a combination of the classic last time buy decision and a base stock policy using additive manufacturing in the last phase of the remaining service period. The model calculates the optimal order up to level at the last time buy moment ($S_1$) and the optimal base stock level using additive manufacturing ($S_2$). The main advantage of using additive manufacturing in the last time buy decision is that safety stocks can be prevented. Given the used input parameters, costs savings are obtained for all selected parts when additive manufacturing is included in the last time buy process.

From this thesis, it is concluded that the applications of additive manufacturing are limited to small, slow moving mechanical spare parts. These parts represent only a small portion of the Philips Healthcare spare parts portfolio. Therefore, additive manufacturing will not lead to a revolution in the supply chain of Philips Healthcare in the coming years. However, additive manufacturing is a feasible technology to reduce the costs in several niches, as identified in chapter 5. At this moment, additive manufacturing can add value in the last time buy process. Applying additive manufacturing in the last time buy process resulted in costs savings for all the selected parts, through a reduction of the inventory.
9.2 Recommendations

At this moment, the technology is not advanced enough for a widespread implementation within Philips Healthcare. Although the technology is only feasible for a small percentage of the spare parts portfolio at this moment, Philips should not neglect additive manufacturing. If the technology developments would be neglected, there will be a risk that Philips Healthcare will be surprised by its applications in the future.

It is recommended to apply additive manufacturing in the last time buy process. This will have two benefits. First of all, cost savings will be generated. Also, because Philips Healthcare will be using additive manufacturing, experience with this technology is built. Because the company will be more involved with the technology, new applications or possibilities will be discovered earlier. When new applications become feasible due to technological progress, the scope of additive manufacturing in Philips should be extended gradually.

In addition, quantitative analysis should be done to evaluate whether applying additive manufacturing in the other two identified niches indeed lead to cost savings. If this leads to cost savings, it is recommended to apply additive manufacturing in these niches as well. This will increase the experience with the technology.

9.3 Further research

This thesis was a first step to identify applications of additive manufacturing in the spare part supply chain. Since, this technology is relatively new, there are many directions for future research. A few of these directions will be provided below.

For the application within a company, the quality of products produced with additive manufacturing needs to fulfill the quality standards. Especially in the Healthcare industry, since spare parts in this industry often have to be approved by the Food and drug administration (FDA). In this thesis it is assumed that the quality of additively manufactured parts is equal to the quality of other products, since the aim of this thesis was to identify the impact on the spare parts supply chain. Further research on the quality of additively manufactured parts is required.

Redesign capabilities of additive manufacturing are only briefly mentioned in this thesis. In this thesis, it is indicated that redesign capabilities of additive manufacturing could help to eliminate the use of materials which are on the Restriction of hazardous substances (RoHS) list. This could be investigated in more detail. To exploit full benefits of additive manufacturing, the scope should be broadened from spare parts only to the complete lifecycle of a part. Here it is interesting to see how the design of a part can be optimized for additive manufacturing. This might lead to several advantages, such as weight, material and cost reductions.

Also briefly mentioned in this thesis, is the added value of additive manufacturing when no more molds are available. There are two options to use additive manufacturing in this scenario. It is possible to produce the parts directly using additive manufacturing, instead of producing the molds first. However, it is also possible to produce the mold using additive manufacturing and afterwards produce the parts
with injection molding or die casting technologies using this mold. These tooling applications could be investigated in more detail.

In the network design provided in chapter 5, I referred to the article by Kahjavi et al. for a quantitative analysis of the centralizing/decentralizing tradeoff. This analysis was performed for spare parts of the F18 Super Hornet Fighter of the United States Navy. It would be interesting when something similar would be performed for the spare parts of a system of Philips Healthcare. In relation to this, it would be interesting to see how a decentralized supply chain would impact the transportation operations.

Another issue in the network design was the insourcing or outsourcing decision. In this thesis it was concluded based on qualitative reasons that the outsourcing option is preferred. It would lead to more insights when a quantitative analysis on the insourcing option would be performed. In such an analysis the total cost of ownership of owning an additive manufacturing machine should be investigated. This gives a company in-depth knowledge on all the costs related to buying a 3D printer. These in-house production costs can then be compared to the outsourcing costs of additive manufacturing.

Open source information sharing is getting more important with additive manufacturing. This can lead to intellectual properties right issues and liability issues. At this moment, the questions and unknowns around intellectual property rights and liability issues are hurdles for the technology development. Further research in this area is required.
Bibliography


# Appendix A Additive manufacturing technologies

## Appendix A.1 Overview of the technologies

Table 9: Overview of the technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Description</th>
<th>Material</th>
<th>Max build size (mm³)</th>
<th>Tolerance (mm)</th>
<th>Minimal layer thickness (mm)</th>
<th>OEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereolithography (SLA)</td>
<td>Laser solidifies liquid polymer</td>
<td>Photopolymers, wax</td>
<td>2100 x 700 x 800</td>
<td>0,15</td>
<td>0,016</td>
<td>3D systems, Stratasys, Envision tech EOS</td>
</tr>
<tr>
<td>Digital light processing (DLP)</td>
<td>Light beam solidifies liquid polymer</td>
<td>Photopolymers, wax</td>
<td>280 x 210 x 200</td>
<td>0,04</td>
<td>0,1</td>
<td>Envisiontec Solidator</td>
</tr>
<tr>
<td>Fused deposition modelling (FDM)</td>
<td>Thermoplastics heated and deposited in required form</td>
<td>Thermoplastics, wax</td>
<td>914 x 610 x 914</td>
<td>0,178</td>
<td>0,178</td>
<td>3D systems Stratasys Makerbot</td>
</tr>
<tr>
<td>Selective laser sintering (SLS)</td>
<td>Laser sinters powder into solid</td>
<td>Metals, glass, sand, ceramics</td>
<td>550 x 550 x 750</td>
<td>0,25</td>
<td>0,1</td>
<td>3D systems, EOS, Optomec, Concept laser</td>
</tr>
<tr>
<td>SLM</td>
<td>Laser melts powder into solid</td>
<td>Metals (steel, cobalt, titanium, aluminium)</td>
<td>250 x 250 x 350</td>
<td>0,25</td>
<td>0,02</td>
<td>SLM solutions, Concept laser</td>
</tr>
<tr>
<td>DMLS</td>
<td>Laser sinters powder into solid</td>
<td>Metals</td>
<td>250 x 250 x 250</td>
<td>0,25</td>
<td>0,02</td>
<td>EOS</td>
</tr>
<tr>
<td>HSS</td>
<td>Laser sinters powder into solid</td>
<td>Metals</td>
<td>300 x 250 x 300</td>
<td>0,25</td>
<td>0,02</td>
<td>No OEM, research by Loughborough university</td>
</tr>
<tr>
<td>Electron beam melting (EBM)</td>
<td>Electron beam transforms powder into solid (vacuum environment)</td>
<td>Metals</td>
<td>350 x 350 x 380</td>
<td>0,2</td>
<td>0,05</td>
<td>Arcam</td>
</tr>
<tr>
<td>binder jetting (belongs to polyjet printing category)</td>
<td>Sprays binder on powder to solidify the powder</td>
<td>Anything in powder form (Metals, glass, sand, ceramics, plastic, wax)</td>
<td>4000 x 2000 x 1000</td>
<td>0,13</td>
<td>0,09</td>
<td>The ExOne company, Voxeljet, 3D systems</td>
</tr>
<tr>
<td>material jetting</td>
<td>Sprays liquid</td>
<td>Heavy metals,</td>
<td>1000 x</td>
<td>0,025</td>
<td>0,016</td>
<td>Stratasys, 3D</td>
</tr>
</tbody>
</table>
### Appendix A.2 Strengths and drawbacks of technologies

Table 10: Strengths and drawbacks of the technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Advantages</th>
<th>Drawbacks</th>
<th>Applications</th>
<th>Relevant for spare parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereolithography (SLA)</td>
<td>High surface quality, high accuracy, large build volume</td>
<td>Slow process, only suitable for polymers, not durable</td>
<td>Prototypes, tooling</td>
<td>No</td>
</tr>
<tr>
<td>digital light processing (DLP)</td>
<td>High accuracy, large objects possible</td>
<td>Not strong, expensive</td>
<td>Prototypes, tooling</td>
<td>Yes</td>
</tr>
<tr>
<td>Fused deposition modelling (FDM)</td>
<td>Good mechanical properties, durable, accurate, reliable</td>
<td>Slow, old process, bad surface quality (step structure)</td>
<td>Prototypes, support parts(like jigs, fixtures), small series parts</td>
<td>No</td>
</tr>
<tr>
<td>Selective laser sintering (SLS)</td>
<td>Strong materials, no support structures required, price competitive for small lot sizes (SLM is more expensive)</td>
<td>Slow (long cooling times), Low surface quality</td>
<td>Prototypes, Support parts (jigs, fixtures), small series parts</td>
<td>Yes</td>
</tr>
<tr>
<td>DMLS</td>
<td>Faster as SLS, almost as strong and dense as EBM</td>
<td>More expensive only one provider</td>
<td>Small series metal parts</td>
<td>Yes</td>
</tr>
<tr>
<td>HSS</td>
<td>Faster than SLS, high volume production</td>
<td>Still in research phase</td>
<td>Small series metal parts</td>
<td>Yes</td>
</tr>
<tr>
<td>Electron beam melting (EBM)</td>
<td>Very strong metals, Full dense</td>
<td>High temperature, long cooling, slow (but faster than SLS), expensive materials, post processing, worse surface quality than SLS</td>
<td>Small series spare parts, Prototypes, Support parts</td>
<td>Yes</td>
</tr>
<tr>
<td>Binder jetting</td>
<td>Full color, smooth surface quality</td>
<td>Weak (fragile), post processing</td>
<td>Prototype, molds, tooling</td>
<td>No</td>
</tr>
</tbody>
</table>
### Material Jetting

| Material Jetting | Different materials in one print job, accurate, smooth surface quality | Not strong | No (only for prototyping) |

---

### Appendix A.3 Detailed description of the technologies

The following technologies will be discussed:

- SLA: Stereolithography apparatus
- DLP: digital light processing
- FDM: fused deposition modeling
- SLS: Selective laser sintering
- SLM: selective laser melting
- DMLS: direct metal laser sintering
- HSS: high speed sintering
- EBM: electron beam melting
- LOM: Laminated object modeling
- MJ: material jetting
- BJ: binder jetting

**Stereolithography (SLA)**

SLA uses a laser to react with a liquid photopolymer resin. The liquid is only solidified in places where the laser touches the liquid. The build platform moves down (into the liquid) after each layer, so a new layer can be added. The SLA process is very accurate, which results in a high surface quality. However, it is slow compared to other technologies. Post processing is often required to clean and cure (fully hardening the resin in an oven) the parts and to remove support structures. This technology is mainly used for rapid prototyping and to create intricate shapes with high quality finishes, like for example jewelry (McKinsey global institute, 2013).
DLP: digital light processing
This technology is similar to the SLA technology. Instead of a laser, DLP uses a light source. A vat of liquid polymer is exposed to light from a DLP projector under safelight conditions. The exposed liquid polymer hardens. When the product is finished, the liquid polymer is drained from the vat, leaving the only the model. DLP produces high accurate parts like SLA. However, DLP is faster than SLA, has lower running costs and results in less waste, since less liquid resin can be used.

Fused deposition modelling (FDM)
The FDM technology uses a heated extruder that deposits plastic or wax in a desired form. It creates the desired form by depositing the material as a 2D wire of plastic. The input for the extruder is a plastic filament which is melted before it can be extruded. After each 2D layer, the build platform moves down and another 2D layer is added on top of the previous one. The most commonly used materials are ABS and PLA, which are plastics. This process is relatively slow and often requires post processing. It is quite accurate and reliable. This technology is mainly used for prototyping. It is also used for low-volume manufacturing parts (McKinsey global institute, 2013).
Selective laser sintering (SLS)

The SLS technology uses a laser to solidify a layer of powder in the desired shape. Because of the heat of the laser, the powder is transformed to solid material. The technology is also known as laser melting. When one layer is finished, the build platform moves down and a new layer of powder is added on top. SLS can be used to create strong metals. Other materials which can be used in this technology are plastics, glass, sand and ceramics. Parts produced using SLS are very strong. Another advantage is that no support structures are required. A drawback is that cooling times are considered since high temperatures are required to solidify the powder. Also, the surface quality is lower compared to other technologies. This technology is used to create prototypes and to manufacture finished products. General electric uses this technology to build parts for their jet engine (McKinsey global institute, 2013).

Selective laser melting (SLM)

SLM fuses the powder at higher temperatures than SLS. In SLS the powder is sintered below the melting point while SLM melts the material. The SLM produced parts are stronger and denser than SLS produced parts.
Direct metal laser sintering
DMLS is developed by EOS. It uses melted metal powder instead of normal powder as input. (McKinsey global institute, 2013). This technology is also comparable to SLS but has some advantages, as it produces denser products and it has a better surface quality due to thinner layers.

High speed sintering
High speed sintering (HSS) is different from the SLS technology. Instead of lasers, this technology uses print heads. These print heads heat the powder using an infra-red lamp. This process enables faster build rates which makes it suitable for higher volume production. (Loughborough university, 2014)

Electron beam melting
Electron beam melting (EBM) is a type of additive manufacturing for metal parts. It is similar to Selective Laser Sintering (SLS), the main difference being that EBM uses an electron beam as its power source. The technology manufactures parts by melting metal powder layer by layer with an electron beam in a high vacuum. Unlike some metal sintering technologies, the parts are fully dense, void-free, and extremely strong.

![Figure 30: Electron beam melting process (THRE 3D, 2014)](image)

Laminated object manufacturing
In the Laminated object manufacturing (LOM) a sheet of material is put on the build platform and added to the layer below. Then a laser cuts out the desired form the material. This technology is used for form testing, rapid tooling patterns and producing less detailed parts. It main advantage is that it can use with several colors (McKinsey global institute, 2013).

Binder jetting
In binder jetting, a liquid binder material is sprayed on a layer of powder. This powder can be a metal, glass, sand or ceramics. The layer of powder solidifies on the places where the drops of binder are sprayed on the powder. This 3D printing technology is very similar to the traditional inkjet printing technology in which ink is sprayed on paper (here binder liquid is sprayed on a powder layer). Therefore, polyjet printing is also known as “3D printing”. This technology does not need support structures. A large range of materials can be used. This is the best technology to print in full color. However, the products produced using polyjet printing are not as strong as using the SLS technology and often post-processing is required to ensure durability.
Material jetting

In material jetting, the material is sprayed on the build platform. As material, mostly liquid polymers are used. These are hardened by rays of UV light. An advantage of this technology is that a combination of materials (with different properties) can be used within a print job. This method is very precise, resulting in accurate parts with smooth surface area (3D printing industry, 2014).
Appendix B Selection results
This appendix is excluded due to confidentiality.
Appendix C Base stock policy expressions

Inventory
The inventory in the second phase of the model is controlled using a basestock policy. To evaluate this policy, the inventory position, inventory on hand ($OH$), inventory on order ($IO$) and the backorders ($BO$) need to be known. For this evaluation, the stock balance equation is used.

$$S_2 = OH + IO - BO$$

Where $OH - BO$ is also known as the inventory level ($IL$). $IL = OH - BO$, so $S_2 = IL + IO$

This balance stock equation will be explained in more detail using the following figure which represents the inventory behaviour in the base stock policy.

![Figure 33: Base stock policy](image)

Demand for the spare parts arrive with rate $\lambda$. When a demand is received by OEM, a part is send from the on hand stock to the customer immediately, if a part is available. At the same time, an order is placed at the 3D printing service provider. Therefore, after an order is received, the $OH$ will drop by 1 and the $IO$ will increase with 1. It will take an ordered part a certain lead time to arrive at the OEM. The lead time may follow any distribution and has mean $ELT$. When the ordered part arrives, the $IO$ will decrease with 1 and the $OH$ increases with 1. In case there are no $OH$ inventory left at the moment a demand arrives, a backordered is placed. In this scenario, the $IO$ the $BO$ increase with 1 when a demand arrives. Backordered demands are always handled using the First Come First Serve policy. In this base stock policy, either the $OH$ or the $BO$ queue will be empty.
The variables $IO(t)$, $OH(t)$, $BO(t)$ are used to describe the inventory on order, the on hand inventory and the number of backorders respectively at any time $t$. Using the figure above, it holds that

$$OH(t) = (S_2 - IO(t))^+$$
$$BO(t) = (IO(t) - S_2)^+$$

This leads to the balance equation

$$S_2 = OH(t) + IO(t) - BO(t)$$

With $IO$, $OH$ and $BO$ are the steady state variables corresponding to $IO(t)$, $OH(t)$, $BO(t)$. So the steady state balance stock equation is

$$S_2 = OH + IO - BO$$

With

$$OH = (S_2 - IO)^+$$
$$BO = (IO - S_2)^+$$

Based on this logic, it is possible to derive expressions for

- The inventory on order, $IO$
- The on hand inventory, $OH$
- The amount of backorders, $BO$
  - Inventory position ($IP$)

The inventory position, which is defined as sum of the physical inventory on stock ($OH$) and all outstanding orders ($IO$) minus the backorders ($BO$), is always equal to the base stock level, since as soon as a demand is placed, an order is placed at the supplier

$$IP = S_2$$

- The inventory on order, $IO$

When an order is placed at the service provider, it will be delivered after a lead time $LT$. The lead time is randomly distributed with a mean lead time, $ELT$. This ordering process can be seen as a queueing system with infinitely many servers and a service times $LT$. Therefore, Palms theory can be applied:

**Palm’s Theorem:**

*If jobs arrive according to a Poisson process with rate $\lambda$ at a service system and if the times that the jobs remain in the service system are independent and identically distributed according to a given general*
distribution with mean $EW$, then the steady state distribution for the total number of jobs in the service system is Poisson distributed with mean $\lambda$ $EW$.

As a result of Palm’s theorem, the number of parts on order is Poisson distributed with mean $\lambda$ $ELT$

$$E[IO] = \lambda$ $ELT$$

and

$$P[IO(t) = x] = \left(\frac{(\lambda ELT)^x}{x!} e^{-\lambda ELT}\right)$$

- **$OH$**: The on hand inventory is the physical stock on the shelf, which values range from 0 until $S$.

$$OH = (S_2 - x)^+$$

The distribution of $OH$ is given by

$$P(OH = x) = \sum_{y=S_2}^{\infty} P(IO = y) \quad \text{if } x = 0$$

$$P(OH = x) = P(IO(t) = S_2 - x) \quad \text{if } 1 \leq x \leq S$$

And

$$E[OH] = \sum_{x=0}^{S_2} (S_2 - x) \cdot P(IO = x)$$

With

$$P(IO = x) = \left(\frac{(\lambda ELT)^x}{x!} e^{-\lambda ELT}\right)$$

- **$IL$**: Inventory level. $IL = OH - BO$

From the balance stock equation we know:

$$IL = S_2 - IO$$

$$E[IL] = S_2 - E[IO]$$

$$E[IL] = S_2 - \lambda$ ELT$$

**Backorders**

The probability on backorders is:
\[ P(BO = x) = \sum_{y=0}^{S_2} P(IO = y) \quad \text{if } x = 0 \]

\[ P(BO = x) = P(IO = x + S_2) \quad \text{if } x \geq 1 \]

\[ P(BO > 0) = P(IO > S_2) = \sum_{x=S_2}^{\infty} P(IO = x) \]

\[ E[BO] = \sum_{x=S_2}^{\infty} (x - S_2) \cdot P(IO = x) \]

\[ E[BO] = \sum_{x=0}^{\infty} (x - S_2) \cdot P(IO = x) - \sum_{x=0}^{S_2} (x - S_2) \cdot P(IO = x) \]

\[ E[BO] = E[x] - E[S_2] - \sum_{x=0}^{S_2} (x - S_2) \cdot P(IO = x) \]

\[ E[BO] = E[x] - E[S_2] - \sum_{x=0}^{S_2} (x - S_2) \cdot P(IO = x) \]

\[ E[BO] = \lambda \cdot ELT - S_2 + \sum_{x=0}^{S_2} (S_2 - x) \cdot P(IO = x) \]

\[ E[BO] = \lambda \cdot ELT - S_2 + E[OH] \]
Or the equation can be found using the balance stock equation:

\[
S_2 = E[OH] + E[IO] - E[BO]
\]

\[
\]

\[
E[BO] = E[OH] + \lambda * ELT - S_2
\]

\[
E[BO] = \sum_{x=1}^{S_2} (S_2 - x) * P[IO = x] + \lambda * ELT - S_2
\]

With

\[
P[IO(t) = x] = \left(\frac{(\lambda ELT)^x * e^{-\lambda ELT}}{x!}\right)
\]
Appendix D Numerical analysis of the last time buy model

Spare part 1

Table 11: Numerical results of the model for spare part 1

<table>
<thead>
<tr>
<th>Model with additive manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inputs</strong></td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>cc</td>
</tr>
<tr>
<td>C3d</td>
</tr>
<tr>
<td>lambda</td>
</tr>
<tr>
<td>RSP</td>
</tr>
<tr>
<td>Ch1</td>
</tr>
<tr>
<td>Ch2</td>
</tr>
<tr>
<td>S0</td>
</tr>
<tr>
<td>LT</td>
</tr>
<tr>
<td>Beta target</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
</tr>
<tr>
<td>Decision variables</td>
</tr>
<tr>
<td>S1</td>
</tr>
<tr>
<td>S2</td>
</tr>
<tr>
<td><strong>Output variables</strong></td>
</tr>
<tr>
<td>Acquisition costs 1</td>
</tr>
<tr>
<td>Acquisition costs 2</td>
</tr>
<tr>
<td>Holding costs 1</td>
</tr>
<tr>
<td>Holding costs 2</td>
</tr>
<tr>
<td>Total costs</td>
</tr>
<tr>
<td>Buy</td>
</tr>
<tr>
<td>Expected time to switch</td>
</tr>
<tr>
<td>Service level total</td>
</tr>
<tr>
<td>Service level basestock</td>
</tr>
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</table>

Table 12: Numerical results of the benchmark model for spare part 1

<table>
<thead>
<tr>
<th>Benchmark model</th>
</tr>
</thead>
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<tr>
<td><strong>Inputs</strong></td>
</tr>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>cc</td>
</tr>
<tr>
<td>lambda</td>
</tr>
<tr>
<td>RSP</td>
</tr>
<tr>
<td>Ch1</td>
</tr>
<tr>
<td>S0</td>
</tr>
<tr>
<td>Beta target</td>
</tr>
<tr>
<td><strong>Outputs</strong></td>
</tr>
<tr>
<td>Decision variables</td>
</tr>
<tr>
<td>S1</td>
</tr>
<tr>
<td><strong>Output variables</strong></td>
</tr>
<tr>
<td>Acquisition costs 1</td>
</tr>
<tr>
<td>Holding costs 1</td>
</tr>
<tr>
<td>Total costs</td>
</tr>
<tr>
<td>Buy</td>
</tr>
<tr>
<td>Service level total</td>
</tr>
</tbody>
</table>
### Table 13: Cost savings for spare part 1

<table>
<thead>
<tr>
<th>Cost savings as a result of additive manufacturing</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings</td>
<td>€ 3,199,00</td>
</tr>
<tr>
<td>Total costs</td>
<td>€ 3,199,00</td>
</tr>
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</table>
## Table 14: Numerical results of the model for spare part 3

### Model with additive manufacturing

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
<td><strong>value</strong></td>
</tr>
<tr>
<td>cc</td>
<td>€ 465,73</td>
</tr>
<tr>
<td>C3d</td>
<td>€ 2.328,65</td>
</tr>
<tr>
<td>lambda</td>
<td>1</td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 93,15</td>
</tr>
<tr>
<td>Ch2</td>
<td>€ 465,73</td>
</tr>
<tr>
<td>S0</td>
<td>2</td>
</tr>
<tr>
<td>LT</td>
<td>2</td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
</tr>
</tbody>
</table>

### Output variables

- Acquisition costs 1: € 5,588,80
- Acquisition costs 2: € 6,305,20
- Holding costs 1: € 1,008,40
- Holding costs 2: € 1,236,10
- Total costs: € 23,214,00
- Buy: 12,00
- Expected time to switch: 12,29
- Service level total: 0,9964
- Service level basestock: 0,9802

## Table 15: Numerical results of the benchmark model for spare part 3

### Benchmark model

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
<td><strong>value</strong></td>
</tr>
<tr>
<td>cc</td>
<td>€ 465,73</td>
</tr>
<tr>
<td>lambda</td>
<td>1</td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 93,15</td>
</tr>
<tr>
<td>S0</td>
<td>2</td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
</tr>
</tbody>
</table>

### Output variables

- Acquisition costs 1: € 9,314,60
- Holding costs 1: € 15,369,00
- Total costs: € 24,684,00
- Buy: 20,00
- Service level total: 0,9673
Table 16: Costs savings for spare part 3

Cost savings of additive manufacturing

<table>
<thead>
<tr>
<th></th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total costs</td>
<td>€ 1,470,00</td>
</tr>
</tbody>
</table>

Spare part 4

Table 17: Numerical results of the model for spare part 4

**Proposed model**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>value</td>
</tr>
<tr>
<td>cc</td>
<td>€140,70</td>
</tr>
<tr>
<td>S3</td>
<td>€703,50</td>
</tr>
<tr>
<td>lambda</td>
<td>1</td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
</tr>
<tr>
<td>Ch1</td>
<td>€28,14</td>
</tr>
<tr>
<td>Ch2</td>
<td>€140,70</td>
</tr>
<tr>
<td>S0</td>
<td>4</td>
</tr>
<tr>
<td>LT</td>
<td>2</td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output variables</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition costs 1</td>
<td>€1,407,00</td>
</tr>
<tr>
<td>Acquisition costs 2</td>
<td>€1,904,80</td>
</tr>
<tr>
<td>Holding costs 1</td>
<td>€3,046,30</td>
</tr>
<tr>
<td>Holding costs 2</td>
<td>€373,43</td>
</tr>
<tr>
<td>Total costs</td>
<td>€6,731,60</td>
</tr>
<tr>
<td>Buy</td>
<td>10,00</td>
</tr>
<tr>
<td>Expected time to switch</td>
<td>12,29</td>
</tr>
<tr>
<td>Service level total</td>
<td>0,9964</td>
</tr>
<tr>
<td>Service level basestock</td>
<td>0,9802</td>
</tr>
</tbody>
</table>
### Table 18: Numerical results of the benchmark model for spare part 4

**Benchmark model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc</td>
<td>€ 140,70</td>
</tr>
<tr>
<td>lambda</td>
<td>1</td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 28,14</td>
</tr>
<tr>
<td>SO</td>
<td>4</td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition costs 1</td>
<td>€ 2.532,60</td>
</tr>
<tr>
<td>Holding costs 1</td>
<td>€ 4.643,10</td>
</tr>
<tr>
<td>Total costs</td>
<td>€ 7.175,70</td>
</tr>
<tr>
<td>Buy</td>
<td>18,00</td>
</tr>
<tr>
<td>Service level total</td>
<td>0,9673</td>
</tr>
</tbody>
</table>

### Table 19: Cost savings for spare part 4

**Cost savings by using model**

| Total costs | Savings | € 444,10 |
Spare part 5  
Table 20: Numerical results of the model for spare part 5

### Proposed model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc</td>
<td>€ 94,05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C3d</td>
<td>€ 470,25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lambda</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 18,81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch2</td>
<td>€ 94,05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S0</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LT</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Benchmark model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc</td>
<td>€ 94,05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lambda</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 18,81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S0</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**Proposed model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Decision variables</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc</td>
<td>€ 94,05</td>
<td>S1</td>
<td>103</td>
</tr>
<tr>
<td>C3d</td>
<td>€ 470,25</td>
<td>S2</td>
<td>0</td>
</tr>
<tr>
<td>lambda</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 18,81</td>
<td>Acquisition costs 1</td>
<td>€ 8.558,50</td>
</tr>
<tr>
<td>Ch2</td>
<td>€ 94,05</td>
<td>Acquisition costs 2</td>
<td>€ 2.421,60</td>
</tr>
<tr>
<td>S0</td>
<td>12</td>
<td>Holding costs 1</td>
<td>€ 14.822,00</td>
</tr>
<tr>
<td>LT</td>
<td>2</td>
<td>Holding costs 2</td>
<td>€ -</td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
<td>Total costs</td>
<td>€ 25.802,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buy</td>
<td>91,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Expected time to switch</td>
<td>14,26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Service level total</td>
<td>0,9510</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Service level basestock</td>
<td>0,0000</td>
</tr>
</tbody>
</table>

**Benchmark model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Decision variables</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc</td>
<td>€ 94,05</td>
<td>S1</td>
<td>122</td>
</tr>
<tr>
<td>lambda</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 18,81</td>
<td>Acquisition costs 1</td>
<td>€ 10.346,00</td>
</tr>
<tr>
<td>S0</td>
<td>12</td>
<td>Holding costs 1</td>
<td>€ 17.211,00</td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
<td>Total costs</td>
<td>€ 27.557,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buy</td>
<td>110,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Service level total</td>
<td>0,9534</td>
</tr>
</tbody>
</table>
Table 22: Cost savings for spare part 5

<table>
<thead>
<tr>
<th>Cost savings by using model</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Savings</td>
<td></td>
</tr>
<tr>
<td>Total costs</td>
<td>€ 1,755.00</td>
</tr>
</tbody>
</table>

Spare part 6

Table 23: Numerical results of the model for spare part 6

| Proposed model |

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>value</td>
</tr>
<tr>
<td>cc</td>
<td>€ 14,43</td>
</tr>
<tr>
<td>C3d</td>
<td>€ 72,15</td>
</tr>
<tr>
<td>lambda</td>
<td>4,5</td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
</tr>
<tr>
<td>Ch2</td>
<td>€ 14,43</td>
</tr>
<tr>
<td>S0</td>
<td>21</td>
</tr>
<tr>
<td>LT</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output variables</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition costs 1</td>
<td>€ 591,63</td>
</tr>
<tr>
<td>Acquisition costs 2</td>
<td>€ 538,30</td>
</tr>
<tr>
<td>Holding costs 1</td>
<td>€ 1,284,00</td>
</tr>
<tr>
<td>Holding costs 2</td>
<td>€ 21,87</td>
</tr>
<tr>
<td>Total costs</td>
<td>€ 2,435,80</td>
</tr>
<tr>
<td>Buy</td>
<td>41.00</td>
</tr>
<tr>
<td>Expected time to switch</td>
<td>13.34</td>
</tr>
<tr>
<td>Service level total</td>
<td>0.9905</td>
</tr>
<tr>
<td>Service level basestock</td>
<td>0.9139</td>
</tr>
</tbody>
</table>
Table 24: Numerical results of the benchmark model for spare part 6

**Benchmark model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cc</td>
<td>€ 14,43</td>
</tr>
<tr>
<td>lambda</td>
<td>4,5</td>
</tr>
<tr>
<td>RSP</td>
<td>15</td>
</tr>
<tr>
<td>Ch1</td>
<td>€ 2,89</td>
</tr>
<tr>
<td>S0</td>
<td>21</td>
</tr>
<tr>
<td>Beta target</td>
<td>95%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>81</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output variables</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition costs 1</td>
<td>€ 865,80</td>
</tr>
<tr>
<td>Holding costs 1</td>
<td>€ 1,753,20</td>
</tr>
<tr>
<td>Total costs</td>
<td>€ 2,619,00</td>
</tr>
<tr>
<td>Buy</td>
<td>60,00</td>
</tr>
<tr>
<td>Service level total</td>
<td>0,9525</td>
</tr>
</tbody>
</table>

Table 25: Cost savings for spare part 6

**Cost savings by using model**

<table>
<thead>
<tr>
<th></th>
<th>Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total costs</td>
<td>€ 183,20</td>
</tr>
</tbody>
</table>

Appendix E Sensitivity analysis

Purchase costs of additive manufacturing

Table 26: Sensitivity analysis for the purchase costs of additive manufacturing

<table>
<thead>
<tr>
<th>Sensitivity analysis</th>
<th>Expected time to switch</th>
<th>Service level</th>
<th>Total costs</th>
<th>S1 benchmark</th>
<th>Total cost benchmark</th>
<th>Cost savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>c3d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10*cc</td>
<td>77</td>
<td>0</td>
<td>14,49</td>
<td>0,9659</td>
<td>€43.774,00</td>
<td>€43.553,00</td>
</tr>
<tr>
<td>5*cc</td>
<td>69</td>
<td>1</td>
<td>13,40</td>
<td>0,9899</td>
<td>€40.354,00</td>
<td>€43.553,00</td>
</tr>
<tr>
<td>2*cc</td>
<td>37</td>
<td>1</td>
<td>7,20</td>
<td>0,9505</td>
<td>€27.309,00</td>
<td>€43.553,00</td>
</tr>
<tr>
<td>1,5*cc</td>
<td>15</td>
<td>2</td>
<td>2,60</td>
<td>0,9961</td>
<td>€22.080,00</td>
<td>€43.553,00</td>
</tr>
</tbody>
</table>

Demand rate

Table 27: Sensitivity analysis for the demand rate

<table>
<thead>
<tr>
<th>Sensitivity analysis</th>
<th>Expected time to switch</th>
<th>Service level</th>
<th>Total costs</th>
<th>S1 benchmark</th>
<th>Total cost benchmark</th>
<th>Cost savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>lambda</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>55</td>
<td>1</td>
<td>13,27</td>
<td>0,9911</td>
<td>€32.418,00</td>
<td>€34.904,00</td>
</tr>
<tr>
<td>5</td>
<td>69</td>
<td>1</td>
<td>13,40</td>
<td>0,9899</td>
<td>€40.354,00</td>
<td>€43.553,00</td>
</tr>
<tr>
<td>6</td>
<td>83</td>
<td>1</td>
<td>13,50</td>
<td>0,9887</td>
<td>€48.264,00</td>
<td>€51.694,00</td>
</tr>
<tr>
<td>7</td>
<td>103</td>
<td>0</td>
<td>14,26</td>
<td>0,9510</td>
<td>€56.039,00</td>
<td>€59.835,00</td>
</tr>
<tr>
<td>8</td>
<td>111</td>
<td>1</td>
<td>13,62</td>
<td>0,9864</td>
<td>€64.027,00</td>
<td>€67.976,00</td>
</tr>
<tr>
<td>9</td>
<td>132</td>
<td>0</td>
<td>14,30</td>
<td>0,9536</td>
<td>€71.782,00</td>
<td>€76.116,00</td>
</tr>
</tbody>
</table>

Remaining service period

Table 28: Sensitivity analysis for remaining service period

<table>
<thead>
<tr>
<th>Sensitivity analysis</th>
<th>Expected time to switch</th>
<th>Service level</th>
<th>Total costs</th>
<th>S1 benchmark</th>
<th>Total costs benchmark</th>
<th>Cost savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>51</td>
<td>0</td>
<td>9,53</td>
<td>0,9529</td>
<td>€21.683,00</td>
<td>€22.998,00</td>
</tr>
<tr>
<td>15</td>
<td>69</td>
<td>1</td>
<td>13,40</td>
<td>0,9899</td>
<td>€40.354,00</td>
<td>€43.553,00</td>
</tr>
<tr>
<td>20</td>
<td>86</td>
<td>1</td>
<td>16,95</td>
<td>0,9855</td>
<td>€61.936,00</td>
<td>€69.197,00</td>
</tr>
</tbody>
</table>
### Sensitivity analysis

<table>
<thead>
<tr>
<th>Holding costs</th>
<th>Expected time to switch</th>
<th>Service level</th>
<th>Total costs S1 benchmark</th>
<th>Total costs benchmark</th>
<th>Cost savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>69</td>
<td>1</td>
<td>13,40</td>
<td>0,9899</td>
<td>€ 40.354,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>€ 43.553,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 40.354,00</td>
<td>€ 3.199,00</td>
</tr>
<tr>
<td>25%</td>
<td>65</td>
<td>1</td>
<td>12,72</td>
<td>0,9856</td>
<td>€ 45.140,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>€ 50.422,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 45.140,00</td>
<td>€ 5.282,00</td>
</tr>
<tr>
<td>30%</td>
<td>61</td>
<td>1</td>
<td>11,98</td>
<td>0,9808</td>
<td>€ 49.411,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>€ 57.291,00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>€ 49.411,00</td>
<td>€ 7.880,00</td>
</tr>
</tbody>
</table>
Appendix F Business case: additive manufacturing as a replacement of traditional manufacturing technologies

In this business two scenarios are considered: In the first scenario, the current situation is considered. The production is done with traditional manufacturing technologies. In the second scenario, additive manufacturing is used to produce all parts during the lifetime of a part. Additive manufacturing is used as a replacement of current manufacturing technologies.

Please note that this is not an in depth analysis. In this business case, only an insight in the situation is provided. The only costs considered in this business case are the holding costs and the production costs.

It is assumed that the average stock level is equal to the target stock level (TSL).

Three possibilities for the cost of additive manufacturing are considered:

1. Cost of additive manufacturing is 10 times the cost of traditional manufacturing
2. Cost of additive manufacturing is 5 times the cost of traditional manufacturing
3. Cost of additive manufacturing is 2 times the cost of traditional manufacturing

Results

When the same TSL is used in the additive manufacturing scenario, the costs total costs will logically be 10, 5 or 2 times higher than with traditional manufacturing. The only way for additive manufacturing to have an advantage over traditional manufacturing is when a holding cost saving can be generated by decreasing the TSL.

For all parts, the TSL is decreased to 0 to see what the reduction in the holding costs would be and if this reduction would compensate for the extra production costs. For all parts negative saving were observed. Therefore, the reduction in inventory is not enough to compensate for the extra production costs when the complete lifetime of a part is considered. Additive manufacturing turned out to be more expensive than traditional manufacturing in every situation. It is concluded additive manufacturing should not be used to replace traditional manufacturing technologies.

The results for each part will be displayed in the following tables.
### Table 30: Business case for spare part 1, additive manufacturing as replacement

<table>
<thead>
<tr>
<th>Spare part 1</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>current situation</td>
<td>additive manufacturing</td>
<td>additive manufacturing</td>
</tr>
<tr>
<td>AM 10x more expensive</td>
<td>TSL = 6</td>
<td>TSL = 6</td>
<td>TSL = 0</td>
</tr>
<tr>
<td></td>
<td>€25.234,00</td>
<td>€252.340,00</td>
<td>€203.500,00</td>
</tr>
<tr>
<td>AM 5x more expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM 2x more expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 31: Business case for spare part 2, additive manufacturing as replacement

<table>
<thead>
<tr>
<th>Spare part 2</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>current situation</td>
<td>additive manufacturing</td>
<td>additive manufacturing</td>
</tr>
<tr>
<td>AM 10x more expensive</td>
<td>TSL = 4</td>
<td>TSL = 4</td>
<td>TSL = 0</td>
</tr>
<tr>
<td></td>
<td>€26.971,98</td>
<td>€269.719,80</td>
<td>€267.651,00</td>
</tr>
<tr>
<td>AM 5x more expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AM 2x more expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 32: Business case for spare part 3, additive manufacturing as replacement

<table>
<thead>
<tr>
<th></th>
<th>current situation</th>
<th>additive manufacturing TSL = 2</th>
<th>additive manufacturing TSL = 0</th>
<th>Current costs</th>
<th>best scenario AM</th>
<th>cost saving of AM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AM 10x more expensive</strong></td>
<td>€13.040,44</td>
<td>€130.404,40</td>
<td>€93.146,00</td>
<td>€13.040</td>
<td>€18.629</td>
<td>€-5.589</td>
</tr>
<tr>
<td><strong>AM 5x more expensive</strong></td>
<td>€13.040,44</td>
<td>€65.202,20</td>
<td>€46.573,00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AM 2x more expensive</strong></td>
<td>€13.040,44</td>
<td>€26.080,88</td>
<td>€18.629,20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*This part already has a TSL of 0*

### Table 33: Business case for spare part 4, additive manufacturing as replacement

<table>
<thead>
<tr>
<th></th>
<th>current situation</th>
<th>additive manufacturing TSL = 0</th>
<th>Current costs</th>
<th>best scenario AM</th>
<th>cost saving of AM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AM 10x more expensive</strong></td>
<td>€2.814,00</td>
<td>€28.140,00</td>
<td>€2.814,00</td>
<td>€5.628,00</td>
<td>€-2.814,00</td>
</tr>
<tr>
<td><strong>AM 5x more expensive</strong></td>
<td>€2.814,00</td>
<td>€14.070,00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>AM 2x more expensive</strong></td>
<td>€2.814,00</td>
<td>€5.628,00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*This part already has a TSL of 0*
### Table 34: Business case for spare part 5, additive manufacturing as replacement

<table>
<thead>
<tr>
<th>Spare part 5</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>current situation</td>
<td>additive manufacturing</td>
<td></td>
</tr>
<tr>
<td>TSL = 0</td>
<td>TSL = 0*</td>
<td></td>
</tr>
<tr>
<td>AM 10x more expensive</td>
<td>€13.167,00</td>
<td>€131.670,00</td>
</tr>
<tr>
<td>AM 5x more expensive</td>
<td>€13.167,00</td>
<td>€65.835,00</td>
</tr>
<tr>
<td>AM 2x more expensive</td>
<td>€13.167,00</td>
<td>€26.334,00</td>
</tr>
</tbody>
</table>

* This part already has a TSL of 0

<table>
<thead>
<tr>
<th></th>
<th>best scenario</th>
<th>cost saving of AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current costs</td>
<td>AM</td>
<td></td>
</tr>
<tr>
<td>€13.167,00</td>
<td>€26.334,00</td>
<td>€-13.167,00</td>
</tr>
</tbody>
</table>

### Table 35: Business case for spare part 6, additive manufacturing as replacement

<table>
<thead>
<tr>
<th>Spare part 6</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>current situation</td>
<td>additive manufacturing</td>
<td>additive manufacturing</td>
</tr>
<tr>
<td>TSL = 7</td>
<td>TSL = 7</td>
<td>TSL = 0</td>
</tr>
<tr>
<td>AM 10x more expensive</td>
<td>€1.702,74</td>
<td>€17.027,40</td>
</tr>
<tr>
<td>AM 5x more expensive</td>
<td>€1.702,74</td>
<td>€8.513,70</td>
</tr>
<tr>
<td>AM 2x more expensive</td>
<td>€1.702,74</td>
<td>€3.405,48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>best scenario</th>
<th>cost saving of AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current costs</td>
<td>AM</td>
<td></td>
</tr>
<tr>
<td>€1.702,74</td>
<td>€2.597,40</td>
<td>€-894,66</td>
</tr>
</tbody>
</table>