Additive Manufacturing and Thales' After Sales Service

Logistical impact of additive manufacturing on the after-sales service supply chain at Thales Nederland B.V.

Antoine Katgert

Supervisors:
Jeroen van der Wel (Thales Nederland B.V.)
Dr. M.C. (Matthieu) van der Heijden (University of Twente)
N. (Nils) Knofius MSc (University of Twente)

28-10-2015

Preface

This report presents the results obtained from the research performed at Thales Nederland B.V. and is simultaneously my Thesis to conclude my Bachelor's degree in Industrial Engineering and Management (IEM) at the University of Twente. This period at Thales was a great way to apply the knowledge acquired during the study to a real life situation. The time at Thales taught me a lot and I am satisfied with the results of my research. I hope Thales can use these results in the future.

I would like to thank Thales and especially Jeroen van der Wel for offering the internship, the support and advice during my thesis and my time at Thales. I would also like to thank Dr. M.C. van der Heijden and Nils Knofius MSc for the excellent support and advice during the thesis.

Furthermore I would also like to thank all the other persons who have made this research possible, by providing information about Thales through interviews and through guided tours but also for backing me up with the data necessary for the research. This research would not have been possible without their collaboration.

Antoine Katgert

Executive Summary

Thales wants to exceed its customers' expectations by delivering high quality service. This high quality service translates into on time delivery, high quality products and a good anticipation of the demand. Though at this moment it remains challenging for Thales to achieve the goal of on time delivery. Thales' customers are often dealing with long lead times; these long lead times do not benefit the overall customer satisfaction. It is believed that shortening the overall delivery lead time of spare parts would greatly improve the customer satisfaction.

This is where additive manufacturing comes in; this production technology offers several benefits which could help improve the overall customer satisfaction. The benefits of this technology may be, among others, shorter lead times, lower initial investment, lower overall costs and more design freedom.

Though additive manufacturing offers a lot of benefits and possibilities some restrictions still exist which makes that it cannot be used to manufacture every kind of part and it is also not relevant to use it for all kind of parts, as will be explained further on in this report. To identify the most attractive (type of) parts for additive manufacturing within Thales' spare parts portfolio a selection framework was drawn up. This selection framework was based upon multiple criteria, among others, MTBF (Mean Time Between Failures), lead time, demand and design ownership. Furthermore, interviews, brainstorm sessions and discussions with product experts were held to identify parts most interesting for additive manufacturing.

The framework was applied upon a list containing 204 LRUs (Line Replaceable Units), these are spare parts of a radar system which can be replaced directly in the field (during a mission). The list contained spare parts of four different radar systems of Thales' current product portfolio. The application of the framework resulted in a list with spare parts ranked based upon their attractiveness for additive manufacturing. The top 10 of this list can be found in Appendix 9.4.

The above-mentioned spare parts though are mostly assemblies of a large number of sub components and therefore will in most cases not be printable in their entirety. For this reason further research will be required to find out which sub components may be most interesting for additive manufacturing. The result of a quick analysis of the list concluded that mostly casings of some smaller sub components may be interesting for additive manufacturing.

The interviews, brainstorm sessions and discussions resulted in a few potentially interesting types of parts for additive manufacturing. The types of parts identified as potentially interesting are the following:

- Currently injection moulded parts: theoretically almost every currently injection moulded part may be printable. Though further research is required to find out whether it could be beneficial to print a certain part or not.
- Parts with a high impact on the functioning of the radar system and which simultaneously have long lead times (due to complex manufacturing processes), such as waveguides, may be very interesting to consider for additive manufacturing.

Additionally, a few recommendations on how to implement additive manufacturing in Thales' business have been identified. The recommendations are the following:

- The introduction of additive manufacturing as a standard manufacturing will give more design freedom during the design of new radar systems. This may open up new opportunities, which were not possible before.
- A second recommendation is to impose the consideration of additive manufacturing a part that has become obsolete over time, whenever a customer requests it. This would mean the obsolescence management would have to change slightly to implement the possibility to print a part which has become obsolete instead of manufacturing it using conventional production methods.

Due to current limitations in additive manufacturing and limited data availability from Thales it was concluded that it is best for Thales to start a close collaboration with a few of its suppliers to identify how Thales could benefit most of the advantages offered by additive manufacturing. The main recommendation is to first start a close collaboration with Norma, which is one of the main suppliers of (mechanical) parts. Besides Norma was previously part of Thales and thus also has a lot of insights in the radar system technology. Mechanical parts will be interesting to look at for their attractiveness for additive manufacturing, Thales should therefore start close collaborations with suppliers of such parts. Thales could then use the expertise these suppliers have in their own field of work. Besides some of these suppliers may already have some expertise on the additive manufacturing front as well. Norma for example already has an own additive manufacturing department. The facts about Norma named in this paragraph makes that it is a logical step to start expanding the additive manufacturing implementation within Thales by starting a close collaboration with Norma.

Table of Contents

1 Introduction

Thales Nederland B.V.

Thales is the Dutch division of the Thales Group, with its headquarters situated in Hengelo (OV). At this location, present research took place. The Dutch division of the Thales group is specialized in designing and producing radar systems, communication systems and professional electronics for defence and security applications (Thales group, 2015). The assignment was mainly done within the Customer Service and Support (CSS) department of Thales Hengelo; this department is, among other things, responsible for the after-sales service.

Additive manufacturing technology

Additive manufacturing (which is also known as 3D printing) has been around for more than 25 years now, but it has been rapidly developing and gaining popularity in the past few years. The technology has become faster, more versatile and more reliable. This development has led to more and more companies looking into opportunities for additive manufacturing in their own production process (IDA - science and technology policy institute, 2012). According to predictions the development and gain in popularity is far from over, it is said the additive manufacturing market will be worth US$ 16.2 billion by 2018, a significant increase when compared to US$ 2.5 billion in 2013 (Canalys, 2014).

Additive manufacturing is suitable for a vast amount of products, for example rapid prototyping, parts of airplanes, jewellery, hearing aids, hips and many more. Also, 3D printers are getting more affordable and the printing possibilities are increasing. These developments make the technology more accessible for both companies and customers.

With additive manufacturing an item is created on a layer-by-layer basis. The CAD (computer aided design) file is sent to the 3D printer and the printer then starts printing layer after layer until the final three-dimensional object is obtained (IDA - science and technology policy institute, 2012).

Research motivation

As part of a bigger project called SINTAS (Sustainability Impact of New Technologies on the After sales service in Supply chains), to which Thales Hengelo is participating, Thales wants to know what impact additive manufacturing could have on their spare parts supply chain. At the moment Thales Hengelo has already done some tests with 3D printed parts and 3D printing is already being used to some extent during testing and prototyping, but this happens on a relatively small scale. The SITE department (the department responsible for the production of test equipment and specific tools within Thales) already uses additive manufacturing to manufacture testing equipment, with satisfying results. As additive manufacturing is becoming more important in today's manufacturing process and is expected to take up an even more significant place in the future, Thales wants to explore the opportunities for improving its service through the use of additive manufacturing.

1.1 Research goal

The goal of this research is to develop a framework to analyse what type of spare parts could be suited for additive manufacturing, while striving for an improvement of Thales' service. Additive manufacturing is a rapidly growing and evolving technology that could possibly influence the way Thales' products are designed and build. Besides that, it could greatly change how the logistics of after-sales work. For this reason it is important to take a look at what the current opportunities are for additive manufacturing within Thales but also to investigate what might be the future improvements/opportunities. The outcome of this research should be a quick scan which will result in a list of interesting components that, when 3D printed, might have a positive influence on a part of Thales' services portfolio. And thus how additive manufacturing might improve Thales' after-sales service in the near and distant future.

1.2 Main problem

Based on the assignment and the discussions with the supervisors at Thales and the University of Twente the following main problem was formulated:

From a logistical point of view, how can additive manufacturing positively influence Thales' Services? What part of the service portfolio should be regarded and what needs to be done to take advantage of additive manufacturing?

1.3 Sub questions

To be able to answer the main problem five sub questions were formulated.

1. What are the current and what might be the future possibilities of additive manufacturing?
2. What does Thales' current spare parts supply chain look like and in what way can additive manufacturing impact Thales' service?
3. What framework for selecting spare parts suitable for additive manufacturing within Thales' portfolio can be used?
4. Which spare part(s) are suitable for additive manufacturing according to the framework and what are the benefits and risks, both economical and logistical, for Thales?
5. For one of the most promising parts obtained in sub question 4, how should the spare part supply chain be redesigned if additive manufacturing turns out to be a promising option for some spare parts?

1.4 Relevance

This research is relevant as it is a critical point for identifying whether additive manufacturing can have a positive impact on Thales' after sales service.

From a scientific point of view the relevance of this research is that it will deliver a framework for selecting parts suitable for additive manufacturing, which, when 3D printed, will simultaneously improve services. Services can for example be improved by shorter lead times, more customer specific parts and manufacturing nearer to the customer. The framework will probably be suitable for researching possibilities for additive manufacturing within other companies.

1.5 Report layout

The report has been divided in several chapters; First the theoretical background will be given in Chapter 2. The current possibilities and the expected future possibilities of additive manufacturing will be discussed; this will be based on a literature study. In Chapter 3 there will be an analysis of the current spare parts supply chain at Thales, the information about this will be acquired through different interviews and an analysis of data available at Thales. Besides a part of this chapter will be dedicated to describing the impact additive manufacturing can have on Thales. In Chapter 4 a framework for selecting parts suitable for additive manufacturing within Thales will be drawn up, this will be done on basis of the data and information acquired from both the interviews and the literature research. In Chapter 5 the framework will be applied for the available spare part data of Thales and both the risks and benefits for Thales will be analysed. In Chapter 6 a short business case will be described. A description of what general changes should be made at Thales to take advantage of the additive manufacturing technology for some of the selected parts. Finally, Chapter 7 will be dedicated to the conclusion and discussion, so what could be the next step for Thales and what should they take into account.

2 Theoretical background: additive manufacturing

In this chapter the current and future possibilities of additive manufacturing will be described. After this, the possible impact of additive manufacturing for Thales will be discussed.

2.1 Current possibilities of additive manufacturing

Additive manufacturing (often called 3D printing) can be used for a wide range of applications, for example prototypes, spare parts, medical applications and many more. The technology started out as an easy and cheap way to print three-dimensional prototypes, called rapid prototyping. The advantages of rapid prototyping are that it allows to quickly print a design (overnight), which can be tested and changed if needed. This process is repeated until the designers have obtained the desired form/functionality. Rapid prototyping shortens and lowers the costs of the designing process. Rapid prototyping is still an important aspect of additive manufacturing, but another application of additive manufacturing, direct part manufacturing, is quickly gaining popularity. Direct part manufacturing means that the final product/part is directly produced using additive manufacturing technology. This has become possible thanks to improved additive manufacturing technology but also higher quality raw materials used for additive manufacturing (IDA - science and technology policy institute, 2012). According to Wohlers Associates, Inc. the direct part production grew from 3.9 % of the total additive manufacturing market in 2003 to 28.3 % in 2012 and this figure is only increasing (TCT magazine, 2015).

The high quality of printed parts has in some cases led to the redundancy of "normal" production method, for example EOIR Technology had to design new mounts for gun sights aboard armoured tanks, due to a tight budget and deadlines they decided to use additive manufacturing for rapid prototyping. Finally it turned out that the 3D printed mounts were strong enough for end-use and EOIR Technology thus decided to print all the parts, by this mean they saved money and time (when compared to conventional manufacturing methods) (Stratasys, 2015).

Illustration 1: The gun sight mount as printed by EOIR (Stratasys, 2015)

Another example is that of Airbus which is implementing additive manufacturing technology in the design of their planes but also for the production of obsolete parts. The parts are strong enough to be used in planes and have several benefits such as significant weight reduction of 30 to 55 % when compared to conventionally manufactured parts. At the same time the use of raw materials is reduced by 90 %. The combination of weight reduction and the decrease in raw material usage means an overall reduction of the environmental impact (Airbus, 2014). These are only a few examples of the many applications additive manufacturing can have for the manufacturing of end-parts.

Besides the two applications for additive manufacturing discussed here above additive manufacturing can be used for tooling and for maintenance and repair applications. By tooling the following is understood: it is possible to manufacture moulds by using additive manufacturing techniques; this makes it easier and less expensive to print and test certain moulds. These moulds can sometimes also be used for final production of items. Additive manufacturing can be used to repair broken parts; a small section of the part can then be repaired using additive manufacturing. This type of repair is especially interesting for parts with high prices and/or long lead times (IDA - science and technology policy institute, 2012).

At the moment it is still not possible to 3D print electronics. The nearest to 3D printing electronics researchers have come is a printer where you can add the electronic components during the printing so that they are ‘embedded’ into the printed part, but these are not real 3D printed electronics (voxel8, 2015).

At the moment several types of additive manufacturing techniques are available, an overview of the different techniques is given in Table 1. For each technique the materials that can be printed with it are given and the market for which it is (mostly) used is given.

Table 1 additive manufacturing techniques, materials and markets. (IDA - science and technology policy institute, 2012)

Technique	Material(s)	Market(s)
Vat photo polymerization	Photopolymers	Prototyping
Material jetting	Polymers	Prototyping, casting patterns
Binder jetting	Polymers, metals, foundry sand, ceramics	Casting moulds, direct part
Material extrusion	Polymers	Prototyping
Powder bed fusion	Polymers, metals	Prototyping, direct part
Sheet lamination	Paper, metals	Prototyping, direct part
Directed energy deposition	Metals	Repair, direct part

For the sake of comparability, a quick overview of the advantages and disadvantages of the different techniques is given in Table 2. A more in depth overview of the advantages and disadvantages of the different techniques can be found in Appendix 9.1.

The following scores have been used to rate the different aspects: -- = performs really badly; - =performs bad; +/- = average performance; + = performs good; ++ = performs really well.

Table 2 Advantages and disadvantages of the various additive manufacturing techniques. Based upon (VIL, 2015) and (Loughborough University, 2015)

Additive manufacturing technique	accuracy	speed	printing size	printing costs	support structures	material compatibility	post processing	colours	strength
Vat Photo Polymerization	++	+	++	-	--	--	--	-	+/-
Material Jetting	++	++	-	-	--	--	--	+	+/-
Binder Jetting	--	+	++	++	++	++	-	+	-
Material Extrusion	--	--	+	++	--	+	--	-	-
Powder Bed Fusion	++	--	-	-	+/-	++	-	-	+
Sheet Lamination	--	++	-	++	++	--	--	-	--
Directed Energy Deposition	++	--	++	--	+	--	-	-	+

2.2 Advantages of additive manufacturing

Additive manufacturing has several advantages when compared to conventional manufacturing methods; these advantages all contribute to the more flexible character of additive manufacturing. The advantages mentioned in the literature will be discussed in this section.

Additive manufacturing is well suited for small production runs; there is no need for moulds or other tools of which the costs have to be split by the number of units produced with it. For additive manufacturing the production costs per unit are relatively constant, especially when compared to conventional production methods, which have relatively high economies of scale effect. On the other hand, as will be discussed in Section 2.3, when a large number of parts is required the traditional production might become more interesting again. Then the total costs can be split up on a per unit basis; there is an economy of scale (IDA - science and technology policy institute, 2012).

The direct, and on location, printing of parts can reduce the transportation costs but also the holding costs, parts can be manufactured on demand and thus do not have to be kept on stock. The on location production of parts make rapid repair possible. The direct production allows for a 'responsive production' mainly thanks to shorter lead times, companies can react much faster to customer demand. On location manufacturing also implies a significant shortening of the supply chain, as the part is directly available at the customers location and thus has not to go through a whole supply chain (Royal Academy of Engineering, 2013).

The fact that moulds are not required means that those do not have to be kept in stock for several years but that only a digital file of the desired part has to be preserved, this reduces the holding costs to almost naught. Besides obsolescence may become less problematic as keeping a digital file is not expensive and thus the supply risk will also go down.

Additive manufacturing allows printing parts/products with high levels of complexity, which are not possible to produce using conventional production techniques. This sometimes allows for lighter but at the same time stronger parts/products (IDA - science and technology policy institute, 2012). Additive manufacturing opens up a vast amount of new design opportunities, as with the technology some shapes that were previously not achievable can be printed. Designers have to adapt the way they design parts to take advantage of the new possibilities offered by additive manufacturing (Royal Academy of Engineering, 2013).

The need for tooling is eliminated because 3D printers can directly print end use parts; this lowers the overall production costs (IDA - science and technology policy institute, 2012). Another advantage of additive manufacturing is that it is possible to print complete products, which eliminates the need for assembly, which saves time and money (Gao, et al., 2015).

Additive manufacturing allows for real customization as products can be printed as the customer desires. It also allows for a more open designing platform, where customers can share designs and edit/improve each other's designs. This could also be interesting for companies to involve customers more into the designing of new products and thus better satisfy customers' desires (Royal Academy of Engineering, 2013).

As it was already mentioned in several of the advantages, additive manufacturing could lead to an overall lowering of the production costs of parts. This is mainly due to eliminated costs for moulds, lower holding costs and easier production and less labour intensive production of some complex parts (Royal Academy of Engineering, 2013).

2.3 Disadvantages of additive manufacturing

Though additive manufacturing has several very interesting advantages it also has its downsides, which means that it still is not the "solution for everything". The disadvantages of additive manufacturing, mentioned in the literature, are listed hereunder. Some of the disadvantages can be solved and researchers and companies are working on solutions for these at the moment and will continue to work on it in the future.

The printing of large objects is still difficult and in most cases relatively expensive, this restricts the number of fields where additive manufacturing can be applied (CSC, 2012). However, Section 2.4 describes how companies and researchers are already working on bigger 3D printers making them more affordable and easier.

The number of printable materials is still an issue, this means that not every part can be 3D printed. Besides the combining of multiple materials into one product and in one print run is still quite restricted, printers capable of printing multiple materials are mostly only able to print materials of the same group, so for example only plastics (CSC, 2012). This is also one of the reasons why electronics cannot be printed.

The quality and durability of 3D printed parts/products is still an issue, though some parts/products are already strong and durable enough for end use the majority of the 3D printed products is still not suited for end use (CSC, 2012).

Though there are some exceptions, the finishing of 3D printed objects is mostly relatively rough which means that it mostly needs quite extensive post-processing, but also that it can not be used for purposes where objects need to be very precise (CSC, 2012).

Additive manufacturing is not well suited for mass production as it is still relatively slow and current manufacturing processes are optimized to be very efficient in mass production. Besides the costs of additive manufacturing are relatively linear. Whether you produce one unit or a thousand the price per unit will stay (about) the same, this is really interesting when producing small batches, but when producing big amounts conventional manufacturing methods are more interesting because the costs per unit diminish the more units you produce (IDA - science and technology policy institute, 2012).

Since there are only very limited standards for additive manufacturing at the moment, there is no agreement or standard to assure a comparable quality from producers all around the world. It is now up to organizations as the International Organization for Standardization (ISO) to develop standards for additive manufacturing. Once these standards are released companies can strive to obtain the ISO certificate and thus insure their customer a decent quality level (Royal Academy of Engineering, 2013).

2.4 Future possibilities of additive manufacturing

As already emphasized in Section 2.3, additive manufacturing still has several drawbacks but as the technology is quickly evolving, opportunities open up every year. It is thus important to look at the expected developments of the technology for the near future but also for the more distant future.

2.4.1 Near future

In the near future the technology will become cheaper especially when looking from the consumer's perspective (CSC, 2012). Nowadays consumer 3D printers are available starting from € 600 all the way up to a few thousand euros (tweakers.net, 2015). These prices are for consumer 3D printers, it is difficult to say something about the price development of the industrial 3D printers. But as businesses are more likely to always want to have the latest additive manufacturing technology in house it can be expected that the prices will vary less.

Besides the printing speed is expected to improve as well, major speed improvements are already underway, recently carbon 3D announced a 3D printer which promises to be 25 to 100 times faster than current additive manufacturing technologies. The 3D object is 'grown' out of UV curable resin, the resin is cured by a UV light projector which shines through an oxygen permeable window, the object is then continuously lifted out of the resin and thus is not build on a layer-by-layer basis (Carbon 3D , 2015).

Besides lower prices and faster printing speeds it is expected that the printable sizes will increase. The size of printable parts, especially metal parts are still quite restricted and every increase in printable size brings along high costs also due to the extra energy required (IDA - science and technology policy institute, 2012). But there are already significant steps being set on this front at the moment, in China a printer able to print metal parts up to 6 meters big has been developed and it successfully printed titanium parts for stealth fighters (3Ders, 2014). Though it is most likely that in the near future bigger parts will still be manufactured using conventional methods, especially as the additive manufacturing technology is not yet well adapted for these big parts which means it still is very expensive and time costly, the titanium part discussed previously for example took 55 days to be printed (3Ders, 2014).

At the moment machines combining the benefits of traditional subtractive processes with the capabilities of additive manufacturing (additive manufacturing) are in development. This could improve the additive manufacturing process because a lot of additive manufacturing methods still need quite extensive post processing. Machines could do this automatically and it would probably save time and money (CSC, 2012).

Additive manufacturing is expected to allow true mass customization in a cost-effective manner, this has already happened in the dental care area where every mouth is different and thus requires different dental crowns and so on (CSC, 2012). The development of the technology will allow more industries to use the mass customization benefits of additive manufacturing.

Another major improvement that needs to be done is to improve the quality and durability of 3D printed parts especially for when these will be destined to be end use products. In recent years improvements in quality and durability have been achieved, this has helped the additive manufacturing technology to gain popularity. Still quality issues remain a problem for the expansion of the additive manufacturing technology. But it is expected that the quality and durability of 3D printed parts will further improve in the near future thanks to improved additive manufacturing techniques and materials (CSC, 2012). Thanks to the design freedom, it is sometimes possible to make lighter but at the same time stronger parts. The development of better additive manufacturing techniques and materials will make it possible to make even stronger parts for more applications.

2.4.2 Distant future

In the distant future it is expected that the whole supply chain design will change dramatically, the production will be localized instead of centralized as it is now. This change already happened in industries as the dental care and is rapidly developing in other medical sectors (Stratasys, 2015). There will be a wide network of printers all over the world that will provide the consumers with a very flexible and small-scale manufacturing (D'Aveni, 2013). Several players in the supply chain are expected to disappear as the end consumer will be closer to the manufacturing process, for example some retailers will become unnecessary (CSC, 2012).

The possibility to print multiple materials together in one run is expected to further develop itself, at the moment there are some printer models which can print different materials together but this is mostly limited to materials of the same group, so for example only plastics. The vision for the distant future is to be able to print complete products (so with all kinds of materials combined, such as metals, plastics and glass) in one run, but that is not going to happen anywhere in the near future. The possibility to print multiple materials on a single printer is also expected to make it possible to 3D print electronic components. To be able to print this it will also be necessary to be able to print more materials (CSC, 2012).

A vision for the distant future is that it will be possible to print complete cars, phones or whatever end consumer product. Though it sounds like a very interesting development most people agree when saying that it is not going to happen any time soon and some are not even sure it is ever going to be that way. But it is almost certain that the time to market will be shortened thanks to the (partial) elimination of tooling and setup times and the more local production (CSC, 2012).

In the distant future there is also hope to be able to print most spare parts directly on location, may it be on the battlefield, on a boat, in the most remote areas, etc. This would make it possible to directly repair machines without having to wait for long periods of time to get spares. The first steps have already been set as the US army has equipped its mobile parts hospitals with 3D printers to be able to quickly print parts in the field, this is especially handy when it comes to part that normally have delivery lead times of weeks if not months (Defense Industry Daily, 2013). The US Navy recently equipped one of its vessels with a 3D printer, at this moment it is still in the test phase but the goal is to be able to print their own spare parts in the middle of the ocean in the future (Sevenson, 2014). Though the on location printing of spare parts will remain difficult in the near future, especially when looking at the printing of parts on vessels. One of the main problems is the fact that the vessel is continuously moving and vibrating due to the engines and waves. This adds a big extra challenge when 3D printing parts as to obtain a good quality part the printer needs to be still. For this reason the printing of end use spare parts on location is expected to be possible in the distant future.

Thanks to the more open platform of additive manufacturing and the ability to share own designs online it is expected this will have a significant impact on the way products are designed. The end consumer will have more participation in the designing and improving of products. Besides the customer will be able to customize his/her own product to match his/her own taste. The more open platform will also express itself in the fact that additive manufacturing offers design possibilities previously impossible with normal manufacturing techniques (CSC, 2012).

3 Current spare parts supply chain at Thales

To get a better understanding of what influence additive manufacturing may have on Thales' services it is relevant to understand the working of the current spare part supply and repair chain. Therefore an overview of both the internal and the external spare part supply chain will be given in this chapter. The information for this chapter was gathered by interviewing several of Thales' employees involved in the spare part supply chain management and by consulting the master thesis of another student working at Thales.

3.1 Spare part supply chain

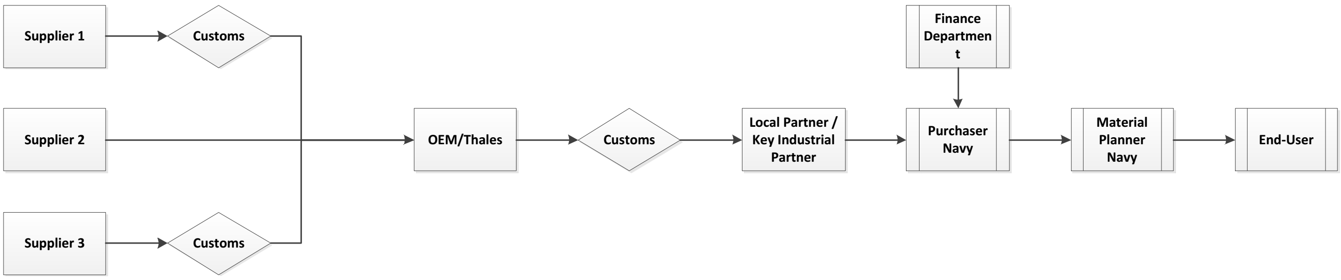

Figure 1 A simplified view of the (forward) spare part supply chain (Veldhuis, 2015)

Thales' current spare part supply chain at Thales is depicted in Figure 1; this figure will be further clarified in this section.

As Thales is growing more towards a service company than a production company more and more of the production is being outsourced to external suppliers. Thales' suppliers are thus the first step in the spare part supply chain. These suppliers are both located within the Netherlands and outside of the Netherlands. This means that parts sometimes have to go through customs before being delivered to Thales. Once Thales has received a part it mostly has to be tested in order to check whether the part fits the quality requirements imposed by Thales. If the part passes these tests it can be sent to the customer, it then has to go through customs once more. When the part has cleared customs it arrives at the local partner. The navy then directly buys the parts from this partner. The required parts are specified and ordered by the material planner at the Navy. The material planner bases the order on the requests from the end user, thus what parts are needed for the upcoming missions but also what parts are required for repairs and so forth.

Thales has an unknown total amount of spare parts, though for this research a total of 204 spare parts were analysed. This set should give a good overview of Thales' total spare part portfolio, as will be discussed in Section 4. For several reasons it is not possible to determine the total number of spare parts available in Thales' portfolio. The first reason being that spare parts can be defined differently (so for example a Shop Replaceable Unit (SRU) or a Line Replaceable Unit (LRU)), this makes that there are multiple levels of spare parts and this makes it not possible to combine all of these parts into one list. A second reason is that there are spare parts that are currently not even inserted into the databases; this renders it not possible to export a complete spare parts list. The third reason is that the most complete item list (thus consisting of the parts with all the smallest nuts and bolts included) does not have any information about which parts are spare parts and which are not.

3.2 External processes in the spare part supply chain

In the previous section the 'forward' supply chain has been discussed, in this section the 'backward' supply chain will be discussed. This 'backward' supply chain is for example used when the navy sends a part for repair to Thales.

To explain the working of the external spare part supply chain the example of the Dutch Navy will be discussed. There are several different situations in the Dutch Navy: when the ship is on a mission, when the ship is in the harbour and when the ship is docked for maintenance. Every situation will be addressed in this section.

- *When the ship is on a mission:* these missions have different lengths, for example 21 days or 90 days. Depending on the length of the mission and on the size of the ship the amount of spare parts taken along is different. Logically the longer the mission and the bigger the boat, the more spare parts are taken along on the mission. This is due to the fact that the ship has to be self-sufficient for the duration of the mission. When a relatively small ship goes on a mission only the most critical parts are taken along. This set of spare parts is required to keep all the systems and the ship itself up and running during the entire mission. But if the ship is bigger it also caries less critical parts, this to be able to solve most problems that can happen when sailing. The parts taken along on such a mission are mostly LRU's.
- *When the ship is in the harbour* the parts that have broken down during the mission are sent back to the stocking facility and new parts are loaded on board for the next mission. In the stocking facility the parts are analysed to conclude whether they can be fixed or not. If the part cannot be fixed it is "thrown away" but in case it can be fixed it is sent to DMI (Marine Bedrijf), this the repair shop of the Dutch Navy. If DMI cannot fix the problem the part (of the radar system) is sent back to Thales and the engineers at Thales try to repair it. It sometimes happens that the costs to repair a certain part are too high. In that case the part is discarded and a new one is ordered (this of course with the customer's approval). With each step described here above the skill level of the engineers and the level of maintenance increases. At Thales or at the OEM (in case the part was not manufactured by Thales) the highest possible maintenance and skill level is reached.
- *When the ship is docked:* this happens once every few years for a major maintenance round, the radar systems are removed from the ship and sent to DMI. At DMI the radar systems are overhauled, this means that they are completely disassembled, then the more vulnerable and worn parts are replaced and the radar system is reassembled. Again if some parts cannot be fixed at DMI they are sent to Thales.

3.3 Internal completion of a customer's order

In this section the internal completion of a customer's order will be discussed. Also the way obsolescence is dealt with will be discussed.

It all starts with a RFQ (Request For Quotation), this means that the customer wants to order a certain spare part from Thales and thus wants to know the price and the lead time.

Thales then determines what the delivery lead time and the price of the part are. For most parts of recent systems the customer gets the price and the lead time almost immediately, this is the case for about 70 % of the requests. The remaining 30% of the requests are mostly for parts of older systems. It is then often more difficult to determine lead times and prices because those parts mostly are not on stock anymore and are quite difficult to acquire, this means that it can take quite some time until this information becomes available for Thales and thus the customer.

Obsolescence has to be dealt with relatively often, sometimes the whole spare part is not available anymore but it can also be that only a small piece of the spare part is not available anymore. In both cases a solution has to be found. This is done by the obsolescence managers. Though sometimes they are not able to find a suitable solution, then the customer has to be notified about this. Obsolescence can both happen beforehand (when the whole part is not available), then the customer is notified directly, but it can also happen during the manufacturing of the desired spare part, in this case Thales first tries to solve it but if that is not possible the customer is notified that it will not be possible to supply the spare part anymore.

After the customer has accepted the price and lead time Thales has to define what tests the part will have to go through before being delivered to the customer. Thales has strong quality requirements that also have to be taken care of when supplying spare parts. Most spare parts are tested at Thales before being sent to the customer. So even when the part is completely manufactured by a third party it has first to go through Thales' testing facility before being delivered to the customer.

Parts like microelectronics and bigger, more complex units are assembled at Thales, the parts are then tested and after this are sent to the customer. The assembly jobs mostly consist of the assembling of sub components that are often manufactured by third parties.

For most spare parts Thales uses a 'make to order' strategy, this means that the production of the spare part is only started when a customer places an order. The same holds for the ordering of a part requested by a customer. Thales though has a rule of thumb that parts with a value of up to € 5000 are kept in stock and parts above this amount are not kept in stock and thus are ordered/manufactured when the customer requests it.

3.4 Why additive manufacturing for Thales?

Based upon the advantages and disadvantages mentioned in Chapter 2, the current situation at Thales and the expected future developments of the additive manufacturing technology the following can be concluded about why additive manufacturing could be very interesting for Thales.

- First, Thales produces radar systems in relatively small batches or even one item at a time for some models. Although Thales is trying to go more towards common parts (and building blocks) that can be used across multiple systems a lot of parts remain unique for specific systems. This implies small production batches for most of these parts, but even the parts that are being used across multiple systems are mostly produced in small batches, as no big amounts are required at once. Additive manufacturing is especially well suited for small production quantities as was mentioned earlier. This is one of the reasons why additive manufacturing might be very interesting for Thales.
- Second, Thales has a vast amount of complex and really specific parts, which are produced exclusively for Thales. Additive manufacturing is very well suited for the production of complex and specific parts, also when regarding complex internal structures; this is also an interesting point for Thales as some parts have complex internal specifications due to for example cooling channels.
- Third, due to the field of work Thales is active in, the demand rates can sometimes vary strongly. For example it can sometimes be that there is no demand for a radar system for a few years and that then suddenly a system is ordered again. This though means that all the

moulds and some specific parts have to be kept on stock for the long period of time in between, this implies very high holding costs. Additive manufacturing could be interesting as the need for moulds is removed and the number of parts that have to be kept on stock can probably be lowered thanks to the (on average) shorter lead times of additive manufacturing. This all could lead to lower total holding costs and production costs.

- A lot of parts which Thales uses have long lead times due to their complexity, among others. Additive manufacturing may make a difference by shortening the total lead times.
- In the near future additive manufacturing could be an interesting way to make parts which have become obsolete over time. As when a part is printed no moulds are needed. This lowers the total production costs, especially when parts have to be produced in low volumes.
- Most of Thales' systems are used on very remote locations; this means an extra challenge when spare parts need to be delivered. In the distant future it may be interesting to be able to print spare parts on location (thus directly aboard the ship) or at least nearer to the customer. Additive manufacturing makes it possible to produce on remote locations or with improving technology even aboard of ships (as was discussed earlier).

3.5 Additive manufacturing's impact on Thales

During the interviews with various employees of Thales it became clear that Thales has already been experimenting with additive manufacturing technology and even already uses it on a regular basis within certain departments. Especially the SITE department (the department responsible for the production of test equipment and specific tools within Thales) already uses the technology to some extent to produce test equipment and specific tools. For this department it has proven itself to be a good and reliable technology especially as they mostly only require a small amount of parts of the same sort, most of them are actually only one unit. Additive manufacturing is very well suited for these purposes because it doesn't require any moulds or expensive tooling. Multiple times the costs to 3D print the required parts were lower than to manufacture it using conventional methods, according to the interviewee some 3D printed parts were as low as 1/4th of the price of the same part manufactured using conventional methods. An external party prints all the 3D parts for Thales; Thales does not own a 3D printer. At the moment Thales' only supplier for 3D printed parts is *VDM kunststoftechnieken*.

Though additive manufacturing still had some drawbacks for example the fact that 3D printed polymers/plastics do not conduct electricity this could cause the part to become static and could by this mean damage the electronics in the system it was installed into. Applying a conducting layer on the 3D printed part solved this problem. The current 3D printed parts are mostly not ESD (electrostatic discharge) safe, this is a requirement for parts used in radar systems, especially when these contain electronics, as an electrostatic discharge could severely damage the electronics. The printing of ESD safe materials is thus still quite a challenge, but it can at this moment be solved by applying a conducting layer as was mentioned before.

At the moment additive manufacturing has not had a significant impact on Thales but as the technology is ever developing and gaining popularity in especially the defence industry it is imaginable that it could have a significant impact in the near to distant future. Additive manufacturing will probably allow to shorten the lead times for spare parts delivered by Thales, this will help improve the customer satisfaction as it has come up during the interviews that one of the main complains from customers is the long service lead times. In the distant future it could maybe even be possible to print spare parts on location or at least nearer to the customer and by this mean even further shortening the lead time.

When Thales delivers a radar system they warrant at least 20 years of support, which means that for at least 20 years Thales has to be able to provide the necessary spare parts. This also means that Thales has to either have enough stock of the specific spare part to cover 20 years' demand or has to be able to build the requested spare part for at least 20 years. The latter one means that the mould to produce the part also has to be kept in the storage for 20 years, this brings along significant costs. The same holds for the parts that have to be kept in stock for at least 20 years, this means very high costs. By using additive manufacturing for some spare parts the costs could possibly be brought down significantly because there would not be costs for keeping the parts or moulds in stock. The only thing that would need to be done then is to keep the file of the 3D design and when needed this file could be sent to the printer which would print the part quite rapidly.

The introduction of additive manufacturing in the production process could bring down the total production costs of radar systems. At the moment each part which has to be injection moulded needs its own mould, this brings along high costs, first because the mould needs to be manufactured which often costs more than 10K€ and after this the mould has to be kept in stock as long as the part needs to be produced. If Thales were to print those parts instead of using injection moulding this would mean that it would not be necessary to make moulds and keep them in stock for several years, this may bring down the costs significantly. The costs of moulds are mostly not amortized on a lot of units; this is because Thales is not a company that mass produces products.

The part of the supply chain described in Section 3.2 is the customer side of the spare part supply chain of Thales. This is where additive manufacturing may imply the biggest benefits when compared to the current situation. For example during the overhaul of radar systems at DMI some parts could be 3D printed. This may diminish the spare parts inventory that has to be kept both at the Dutch Navy and at Thales. When looking at the ship it may be possible, in the future, to install a 3D printer aboard the ship, this would make it possible to print spare parts right away, even during a mission. Parts that may be interesting to print on the ship are things like protection caps, but also mounting and fixing materials; those tend to break down regularly. As mentioned before the U.S. Navy is already experimenting with a printer aboard of a ship (Sevenson, 2014).

4 Selection framework

The selection framework used for the spare part analysis at Thales is based upon that provided by Knofius (2015)*, the selection framework has though been adapted to fit the situation at Thales. The selection framework drawn up for this specific situation will be explained in this chapter.*

4.1 Scoping

According to Knofius (2015) *it is first important to look at the data availability in the organisation where the research is being held. Based upon the available data the spare part population for further analysis will be selected. This was done for the situation at Thales and yielded the following results.*

Illustration 2: Smart-S Mk2 radar system (Marine schepen, 2015)

There were multiple spare parts and items lists available but most of these lists were incomplete and in some cases highly polluted with redundant and/or out-dated data. Besides not all parts/items were available in the digital systems, there are some parts that have not yet been entered into the databases. Thus after evaluating multiple lists and through discussions with multiple employees it was decided to take one of the most promising lists for further analysis. The selected list is a list with data about 204 critical spare parts of a total of four different radar systems (the variant, the Mirador, the Smart-S Mk2 and the Stir 1.2 EO) by combining the data of those four systems it was possible to get a good view of the possibilities for other systems. This is made possible through the fact that several parts are used across multiple systems (other than the four selected here above). Besides the four systems belong to four different radar categories Thales sells, this makes that the obtained set is a good representation of Thales' total product portfolio. The Variant is a two-dimensional short to medium-range surveillance radar system. The Mirador is an electro-optical multi-sensor radar system, which can be used for surveillance, tracking and fire control. The Smart-S Mk2 is a three-dimensional medium to long-range surveillance radar system. The Stir 1.2 EO is a track radar for gun and missile fire control (Thales group, 2015).

The provided list contains LRUs (Line Replaceable Units); these are spare parts that can be replaced directly in the field without the need for extensive tooling. LRUs are mostly assembled parts consisting of both mechanical and electronic parts. Most parts that will come out as potentially interesting will thus not be printable in their entirety but further analysis to identify what subcomponents could be printed will be required. The LRU list has been used because no SRU (Shop Replaceable Unit) list was available. The LRU list was selected because it is up to date, besides it contains data about the spare parts most important according to Thales and this list has no data pollution.

The selected list discussed here above is recent and has been drawn up as part of the Performance Based Logistics (PBL) contracts, which are being offered to Thales' customer. A PBL contract is a contract where the customer pays for a certain pre-fixed availability rate, the customer pays a fixed amount for the reparations and maintenance of the radar system. For this reason Thales has to make sure the pre-fixed availability rates are met. Thus Thales has to have a clear overview of the critical spare parts of the systems but also the associated delivery time and costs of the spare part. To identify these parts an internal analysis was performed, the critical spare parts list that will be used for the present research is the result of this internal analysis.

4.2 Scoring model

As described in the framework proposed by Knofius (2015) *the following step is to analyse the data using a scoring model. For this a few selection criteria have been acquired and each part in the above-mentioned list will be attributed a score for each of these selection criteria. For the scoring several threshold values have to be found, this will be done by analysing the available data but also by discussing the results with experts within Thales. Now the selection criteria will be further defined. To be able to correctly compare the parts on their suitability for additive manufacturing each criteria will be attributed a certain weight, the weights will be determined using the AHP* (Analytical Hierarchical Process) *method, as will be discussed in section 4.2.3.*

During the research multiple criteria were considered, of these criteria the MTBF, lead time, price, demand, manufacturer and supply risk remained. The choice for these criteria was based on the availability of data at Thales but also on the results of discussions with both the supervisors and several of Thales' employees. The criteria that were considered, but finally left out can be found in Appendix 9.2.

Each of the criterion was attributed a different scoring scale. The criteria *MTBF, lead time, price and demand* are scored based on a 1 to 5 scoring system. The criteria of *manufacturer and supply risk* are scored based on 1, 3, 5 scale. When data for one of the criteria was not available the part was attributed a "neutral" score for that specific criterion, the "neutral" score being 3 for both scales. In this fashion all the 204 spare parts could be included in the selection. First the criteria scored using a 1 to 5 scale will be explained and the different scoring categories will be motivated. After this the remaining criteria scored using the 1, 3, 5 scale will be explained and motivated.

4.2.1 MTBF, lead time, price and demand

The scoring categories for the different selection criteria were drawn up by consulting multiple product experts within Thales. This resulted in the following scoring categories for the different criteria:

Table 3 Scoring of the criteria (scale 1 to 5)

Score \ Criteria	MTBF (years)	Lead time (days)	Price (euros)	Demand (units)
1	0 <…=< 5	0 – 50	0 <…=< 1000	>12
2	5 <…=< 10	51 – 100	1000 <…=< 5000	9 < … =<12
3	10 <…=< 15	101 – 200	5000 <…=< 7500	6 < … =< 9
4	15 <…=< 25	201 – 400	7500 <…=<10000	3 < ... =< 6
5	> 25	> 400	> 10000	0 < … =< 3
Neutral (3)	No data available	No data available	No data available	Not applicable

MTBF (Mean Time Between Failures)

The scores have been based on Thales' assumption that a radar system has an average life span of 25 years. Thus all parts that are not that likely to break down within those 25 years, meaning parts with an MTBF of more than 25 years, will be given a score of 5. This means that an MTBF of more than 25 years makes the part strongly more interesting for additive manufacturing. The reason for this being that a breakdown is not expected during the life span of the radar, thus Thales most likely did not anticipate demand, but if the part eventually breaks down it could imply serious problems. The problem could be that the broken part is a critical part with a long lead time; this could mean that the radar system would have to stand still for a long period of time. On the other hand the lowest score (1) was attributed to spare parts with an MTBF of at most five years, when parts have an MTBF of less than five years it is assumed that the demand rate will be relatively high and constant, for this reason it is less interesting to look at parts with a short MTBF for additive manufacturing. As can be seen in Table 3. The remaining scores have been attributed accounting a constant step size. The range of MTBF values getting a score of 4 is slightly bigger than the previous ones, this has been done because all parts with an MTBF of more than 15 years are considered relatively interesting for additive manufacturing. This is because the parts are still likely to break down at least once during the life span of the radar system but due to the long MTBF the demand pattern is more variable and thus less predictable.

The MTBF is a suited criterion to get a quick overview of what parts may be interesting for additive manufacturing, but one of the drawbacks is that the MTBF is a theoretical approach of the life expectancy of a certain part. The time between failures has namely been measured in strongly controlled environments, which are not always comparable to the real working environment. For this reason it can sometimes happen that the real MTBF comes out a lot shorter or higher than the theoretical MTBF. MTBF can therefore not be used to predict the demand. For this reason it was decided to use the demand criterion in the framework, the demand criteria is based on data acquired from field usage of the radar systems and their components and therefore gives a better overview of the real time between failure. This criterion will be discussed later on in this section. Due to the fact that Thales does not use the demand data to improve/change their MTBF calculations it is not possible to combine both the MTBF and the demand criteria into one criterion and it was thus decided to account them both separately to acquire the best possible results from the selection framework.

For the MTBF criterion 15,7% of the data points were missing, for these data points a neutral score of 3 was given. In this fashion the parts with lacking data were not completely excluded from the research.

Lead time

When regarding lead times, parts with shorter lead times are less interesting to look at than parts with (extremely) long lead times. In general the biggest improvements with using additive manufacturing can be obtained for parts with a currently very long lead time. For this reason parts with a lead time shorter than 50 days have been attributed a score of 1, those parts are less interesting to look at when considering 3D printing as the lead time is already relatively short. The threshold of 50 days has been selected because it is relatively short when compared to the average delivery lead time of 5 months at Thales. On the other hand parts with an extremely long lead time (400 days) have been attributed a score of 5 as it is expected that there might be room for improvement thanks to additive manufacturing. The threshold value of 400 days was chosen as it equals about one year, this is considered a relatively long-time which is not desirable, so every part with an even longer lead time is interesting to look at for additive manufacturing. To which values the scores in between have been attributed can be found in Table 3.

For the lead time criterion only 1% of the data points were missing, for these data points a neutral score of 3 was given.

Price

The different scores for the price criterion were based upon information provided by Thales and in collaboration with product experts from Thales. As a rule of thumb Thales says that parts under € 5000 are kept on the shelf to insure a fast(er) delivery to the customer. Based on this the following ranges were attributed to the scores. Parts with a price lower than € 1000 are considered parts which can be procured relatively easily and are parts that are kept on the shelf, for these reasons these parts were attributed a score of 1. The threshold value of € 1000 was taken as parts with a lower value are considered routine parts for Thales, due to the relatively low value. This makes them less interesting for additive manufacturing. Parts with a price of € 1000-5000 were attributed a score of 2 as these parts might be slightly more interesting for 3D printing but they still are parts which Thales most likely keeps in stock. Parts with a price of € 5001-7500 got a score of 3 as those are parts that are not standard on the shelf and thus probably have longer lead times, this is where 3D printing might be relevant. Parts with prices of € 7501-10,000 have a score of 4, the chance of these parts being kept in stock is even lower, so this possibly brings along long lead times and the higher price may indicate that it is a complex part, this also makes it interesting for 3D printing. Parts with a price higher than € 10,000 got a score of 5, for the same reasons as the parts that got a score of 4.

These scoring categories were based on the assumption that the parts are still available for the same price, but it may be that some relatively cheap parts become obsolete. If Thales would then want to order that part one more time it would become a lot more expensive. This is where additive manufacturing may come in handy as it eliminates the need for moulds and the production set up costs are relatively low as well. It is thus important to keep in mind that if parts happen to be obsolete that the scoring categories may look totally different, for example a part that now gets a score of 1 or 2 could end up with a score of 4 or 5. One example of this at Thales is that of a light pen for which the moulds need to be manufactured every time one is needed, this makes that the light pen has extremely high production costs, the original pen cost a fraction of the current price when it was manufactured in bigger batches. In such a case as the one described in this section the total costs should be regarded (including moulds, handling costs, stocking costs, etc.) and not only the per unit production costs. These costs would have to be calculated per part though and it was thus not possible to calculate these costs for this research but it may be an interesting starting point for a follow up research.

For the price criterion 9,8% of the data points were missing, for these data points a neutral score of 3 was given.

Demand

The demand rates of the spare parts were acquired and combined with the current list. The demand data has been derived from the spare part order overview for the period of March 2012 through April 2015. So the demand rate used is the sum of all the orders per part for the past three years. It was relevant to include the demand criterion as this gives an overview of the real life demand for certain parts and thus not a theoretical approach such as the MTBF. As was mentioned earlier there can be big differences between the theoretical demand (according to MTBF) and the practical demand. Because the only available demand data was from the past three years it was considered to take also take the MTBF into account as this would help draw better conclusions about the attractiveness of a certain part for additive manufacturing.

The demand rates were scored, in collaboration with product experts, according to the following linear scale. The best score, 5, is attributed to parts with a demand rate of 0 through 3 in the past 3 years. Thus the maximum average demand rate for this score is one unit per year. As the scoring is done on a linear scale the parts with a demand from 4 through 6 were attributed a score of 4. This means that the maximum average demand for this part amounts to two parts per year. In the same fashion parts with a demand rate of 7 through 9 in the past three years have been attributed a score of 3 and parts with a demand rate of 10 through 12 have been attributed a score of 2. Parts with a demand of more than 12 in the past three years have been attributed a score of 1 as these parts have an average demand rate of at least four parts a year, and are thus considered relatively high demand parts, this makes them less interesting for additive manufacturing.

For the demand criterion no data points were missing.

4.2.2 Manufacturer and supply risk

The two remaining criteria were scored using a different scale due to the different nature of the data. These criteria were also scored in collaboration with product experts within Thales. As stated before when no data was available the criteria was attributed a neutral score of 3.

Table 4 Scoring of the criteria (scale 1, 3, 5)

Score \ Criteria	Manufacturer	Supply risk
1	Other than Thales (non H0203)	Low
5	Thales (H0203)	High
Neutral (3)	No data available	No data available

Manufacturer

The manufacturer is important, as when Thales is not the manufacturer they in most cases do not possess the designs of the specific part. This would mean that when Thales would want to print the part or a subcomponent of it they would either have to acquire the designs from the current manufacturer or redesign the part to be able to produce it. For both of the cases the costs will be high. It is therefore far more interesting to look at parts for which Thales actually possesses the designs when assessing what parts would be interesting for additive manufacturing. Based on this parts of which Thales owns the designs (manufacturer code H0203) will be attributed a score of 5 and parts of which Thales does not own the designs (so manufacturer codes other than H0203) will get a score of 1. Parts of which the manufacturer is not known will be given a neutral score of 3.

For the manufacturer criterion 17,6% of the data points were missing, these data points were attributed a neutral score of 3.

Supply risk

The supply risk is relevant as parts with a low supply risk will most likely be less interesting for additive manufacturing than parts with a high supply risk. Parts with a low supply risk will in most cases be available from a large number of suppliers so in case one of the suppliers stops delivering the specific part Thales can go to another supplier and obtain the part via this supplier. Parts with a high supply risk on the other hand are far more interesting for additive manufacturing as when one of the suppliers stops delivering it becomes impossible or nearly impossible to acquire that specific part. This is where additive manufacturing may come in handy. For these reasons parts with a low supply risk are attributed a score of 1 and parts with a high supply risk are attributed a score of 5. Parts where the supply risk data was lacking were attributed a neutral score of 3.

For the supply risk criterion 32,8% of the data points were missing, these data points were attributed a neutral score of 3 was attributed.

4.2.3 Determining the weights

Each of the criteria will be given a certain weight. On basis of this the total weighted score for each of the parts will be obtained. The best scoring parts will be a starting point for further research.

Using the AHP (Analytical Hierarchical Process) the weights displayed in Table 5 were obtained. The total calculation of the weights and the description of the steps taken can be found in Appendix 9.2. In this section the different weights will be shortly described and motivated.

Table 5 Weights of the different criteria, determined using the AHP method

Criteria	Weights
MTBF	7%
Lead time	28%
Price	16%
Demand	15%
Manufacturer (IP/design owner)	29%
Supply risk	6%

The criteria have been drawn up to identify what parts may be most interesting for additive manufacturing within Thales. Not every criterion has the same importance in the decision whether additive manufacturing is interesting. For this reason weights were attributed to the different criteria, this has been done through the use of the AHP method. For this method each criteria was compared on a pairwise basis. This pairwise comparison was done for all of the criteria and after applying the AHP method the weights mentioned in Table 5 were obtained. It can be noticed that the criteria of manufacturer and lead time were considered strongly more important than the other criteria, in accordance with the opinion of the product expert. These weights also correspond with the company goals most important for Thales, which are to secure supply and to increase the customer satisfaction.

4.3 In depth analysis

The following step in the framework proposed by Knofius (2015) is an in depth analysis of the best scoring part in the previous step (discussed in section 4.2). As most of the parts selected in the previous step are LRU's which consists of a lot of subcomponents it will be necessary to look at the subcomponents piece by piece and analyse whether these subcomponents would be potentially interesting for additive manufacturing. Besides this break down it is relevant to look at the lead time impact of each of the sub components, it is for example not interesting to print a part with an extremely small impact on the production lead time. But on the other hand when a specific part has a big impact on the total production lead time it may be very interesting to further analyse that part for additive manufacturing. Such an in depth analysis is a time costly process and will therefore not be realised during this research, but it could be a good starting point for some follow-up research based upon the list of potentially interesting parts that will be obtained after the scoring in Chapter 5.

4.4 Business case

The fourth and final step of the framework proposed by Knofius (2015) is that of making a business case of the selected part. In this business case the most promising parts selected in the previous step (discussed in section 4.3) will be further analysed and a complete report on the feasibility, the total costs, advantages and disadvantages of printing this part compared to manufacturing it using conventional methods will be written. This step will not be realised in this report as it does not fit within the scope of the quick scan but the results of this research can be a good basis for a follow-up research.

4.5 Overview of the steps

In this chapter the framework, which will be used to analyze the spare parts list in Chapter 5, was discussed. This section gives a quick summary of the different steps of the framework.

First is the scoping step, in this step the availability of data is checked, on basis of this the data set which will be used for the continuation of the research is selected. In the second step the selection and scoring criteria are drawn up. This is done on basis of the available data from Thales and in collaboration with product experts within the company. In this step the weightings of the different criteria are also determined by applying the AHP method. In the third step a more in depth analysis of the list obtained after the scoring is performed. In this step the high scoring parts will be analyzed to identify whether these (or subcomponents) are indeed printable and whether this yields any benefits compared to conventional production methods. The fourth step consists of writing a business case for a selected part which came out as promising throughout the rest of the framework. In this step a full comparison between additive manufacturing and producing the part using conventional methods is done, on basis of this business case a decision can be taken of whether to print the part or not.

5 Selected spare part(s)

In this chapter the framework proposed in chapter 4 will be applied for Thales' situation. After this the benefits and the drawbacks of 3D printing the chosen parts will be explained. The frameworks defined above will be applied on both of the spare parts lists mentioned in chapter 4.

5.1 Applying the framework

The framework presented in Chapter 4 was applied on the selected list of spare parts. This finally yielded a list containing the 204 spare parts ranked on basis of their weighted score for the criteria mentioned in Section 4.2. The top 10 of the total list can be found in Appendix 9.4. In this list the spare parts were sorted on basis of high to low score on the weighted score. The first part is the most promising part for additive manufacturing according to the framework. But as the total list contained a lot of different spare parts with each different characteristics an additional (manual) step was required to analyse whether this part or maybe some subcomponents were really printable or not. This step was realised by analysing the list together with a product expert who had insight in the subcomponents of the specific part. He then could tell whether the part may be interesting or not for additive manufacturing. This analysis resulted in a few possibilities; the parts which are highlighted in green are, at first sight, very interesting to print. The parts which are highlighted in orange most likely contain subcomponents which may be interesting for additive manufacturing, but to make sure this is indeed the case some further and more in depth analysis is required. Finally the parts highlighted in red are considered not interesting for additive manufacturing, this is mainly due to two reasons. The first being that those parts are mainly electronics and the second being that those parts are bought as end products from the supplier. The latter one refers to the 'manufacturer' criterion, for most of these parts Thales is not the owner of the designs/IP and thus it is a lot more difficult to start producing the part as the part would have to be either redesigned or Thales would have to buy the designs from the current supplier. In Appendix 9.4 remarks have been added to each of the product to specify what sub components may be printable or for what reason a part may not be printable.

5.1.1 High scoring parts

Four out of the ten best scoring parts are have been identified as being potentially interesting parts for additive manufacturing by the product expert. Of these parts only one, the 'TIU', is expected to be printable in its entirety. This part is a casing for a camera, this type of part is expected to be well suited for additive manufacturing. Though one challenge remains, it being that the casing has to be EMC safe. EMC safe means that the casing needs to be shielded so that electro magnetic waves from external sources do not distort the internal components. It is also important that the internals do not disturb other parts outside the casing. It is though still challenging to print an EMC safe casing and thus some future research may be required before being able to print this part.

For the three remaining potentially interesting parts some sub components may be printable, for example the casing. The other six parts are less interesting for additive manufacturing as these are parts that are bought directly from the manufacturer, Thales thus does not own the designs of these parts.

5.2 Results obtained from interviews and brainstorm

Besides analysing the data using the selected framework it was also considered relevant to gather information during interviews and brainstorm sessions. The purpose of these interviews and brainstorm sessions was to identify what parts might be relevant to look at for additive manufacturing according to several people in the organization. This approach allowed looking at the problem from another point of view that, in the end, may also lead to interesting results that would otherwise not be found by just analysing the available data.

The different ideas that came up during the interviews as well as the brainstorm session will be discussed one-by-one in this section.

5.2.1.1 Waveguides

In several of the interviews and brainstorm sessions held throughout Thales the waveguides came out as potentially interesting parts for additive manufacturing. These parts are very important parts as they conduct electromagnetic waves throughout the whole radar system. Waveguides were used quite extensively in older radar systems, in most recent radar systems waveguides have been replaced by electronics. In the selected spare parts list the waveguides do not appear, this is because waveguides commonly are not considered spare parts. But still there is some demand for waveguides and because they are not standard spare parts the lead times are mostly relatively long. Both persons from the after-sales service department and the development departments were enthusiast about the possibility to print waveguides. There were several reasons for which waveguides were considered as interesting parts for additive manufacturing, these will be discussed here under.

First, the current (average) lead time on waveguides is about 40 weeks and as the waveguide(s) is a critical part for the functioning of a radar system it is a big problem when the customer has to wait for such a long period to get a spare waveguide. Another reason that made the printing of waveguides attractive is that these are mostly parts with high prices mainly due to the high complexity and precision required during the manufacturing process.

Additive manufacturing may lead to a significant reduction in the production and thus the delivery lead time, the lead time could for example be brought down to a few weeks compared the current lead time of 40 weeks. After some discussions with the persons from the development department (TURF) it became clear that the printed waveguides will probably not have the same performance as a normal one, but it could still allow the radar system to be operable but then with a slightly shorter range for example. A printed waveguide could thus be used as a temporary solution in the awaiting of an original waveguide.

Following the second reason for which additive manufacturing could be interesting. Additive manufacturing is especially well suited for the manufacture of parts with complex internal and external shapes, it would thus (on paper) be a very interesting production technique for waveguides. Besides waveguides currently require quite extensive processing, this makes the price higher. On average the required processing time with additive manufacturing is lower than with conventional production methods and it thus may be very interesting for the manufacture of waveguides.

Though additive manufacturing sounds very promising to manufacture waveguides there are still some challenges, like the precision and the number of available materials. The precision problem is one that has to be further researched to exactly know what the influence would be on the final performance of the radar system. On the other hand the additive manufacturing technology is ever evolving. This also means that the manufacturing precision is also increasing. When doing research about the possibilities of printing a waveguide this fact should not be left out. The number of available materials for additive manufacturing is quite restricted at this moment, current test with printing waveguides have mainly been done by first printing the waveguide using polymers and after this plating it with copper (Geterud, Bergmark, & Yang, 2013). This kind of waveguides could work to a certain extent for radar systems. According to the developers at Thales this could mainly work for the lowest range of the high frequency signal used in the radar systems. As when the frequencies increase the heat production also increases, this could mean that waveguides made of polymer could start to distort. However with the evolving technique it may at some point also become possible to print waveguides out of metal, these could thus resist higher temperatures and be suited for more applications. It is for this reason necessary to take this into account when doing research on the possibilities to print waveguides.

It should be noted that the statements about precision and performance made in this section are only expectations of the designers/developers. To get a better understanding of what the impact of a printed waveguide would be on the overall performance of radar system it is required to do some further research and for example print a sample part to do extensive field tests. This could be a good starting point for a follow up research. As stated in the previous paragraph this follow up research should also take into account the expected future developments of the additive manufacturing technology.

5.2.1.2 Radar systems with irregular demand

For this section the APAR radar system was taken as an example, this is a system with a strongly irregular demand. The spare parts of this radar system did not appear in the list, as it was not one of the systems for which the list was drawn up. But as it came up as an interesting application multiple times it was decided to take it along as one of the applications.

Some radar systems have a very irregular and non predictable demand pattern, this makes that moulds and parts required for this radar have to be kept on stock for a long time or that the moulds are thrown away because they have been on the shelf for too much time. In that case the moulds have to be remanufactured, which implies high costs. Besides due to the low demand the parts cannot really be manufactured in high quantities, this means that no economy of scale applies.

Illustration 3: APAR on top of a Danish Navy frigate (The Shephard News Team, 2015)

The earlier mentioned APAR is a radar system which has already been around for more than 15 years but has been sold only 10 times. The first official order was issued in 1997 for 7 systems in total and the next order was issued in 2006, so almost 10 years later. This is an example of such a situation where the demand pattern makes that moulds and part have to be kept on stock for a long time without being sure they will ever be used again. Unlike other parties in the SINTAS Project (The Dutch Army), keeping moulds and parts on stock for such a long time imply very high holding costs for Thales. This is where additive manufacturing could come in handy as with this method it is only necessary to keep the digital files of the specific part saved on a server and when the specific part is needed solely the digital has to be sent to the 3D printer.

The potential application discussed in this section is mainly aimed towards the production of new radar systems, but it can also be interesting to look at this problem from an after-sales point of view. In the after-sales, especially with the radar systems with a relatively low demand (thus low amount of active systems) the demand for certain spare parts can be very irregular. This will cause the same problem as the one described in the previous paragraph, expensive moulds have to be kept on stock for a long time or moulds have to remanufacture when they are required. In this case keeping a digital (printing) file of the parts and printing it when needed may be significantly less expensive.

5.2.1.3 Injection moulded parts

In general every currently injection moulded part can be considered as a candidate for additive manufacturing. For all injection moulded parts there is a strong economy of scale effect, this means that relatively larger batches of a certain part have to be ordered to get an interesting per piece price. This is among others due to the fact that the mould has to be amortized on the number of manufactured parts, thus the more parts produced the lower the per unit costs will be. With additive manufacturing however only a restricted economy of scale effect applies, this means that it can be very interesting to consider this manufacturing method for such small batches of parts.

One way to identify what parts are injection moulded within Thales' spare parts assortment would be to take a look at which suppliers deliver exclusively (injection) moulded parts and then filter on these suppliers to see what parts they do supply. The information about what suppliers exclusively deliver (injection) moulded parts could for example be acquired by interviewing people responsible for the purchase of parts but also persons responsible for the development and the design of parts. By interviewing a few people at Thales it came up though that Thales does not use moulding that extensively and nearly never uses injection-moulded parts. Most injection-moulded parts are namely already implemented into parts that Thales buys from its different suppliers. The moulded parts are mainly ordered by *Norma* (one of the most important supplier of mechanical parts of Thales Hengelo and previously part of Thales) and thus Thales has less say in the production of these parts. Still a few supplier names came up and these could still be used to identify parts that may be interesting for additive manufacturing. The suppliers in question are the following: *Aluminium Gieterij Oldenzaal, Zollern Aluminium-Feinguss* and *Buderus Feinguss*. In the list, which was used for this research, there were no spare parts coming from these suppliers, mainly because the MTBF is extremely high to almost infinite for this kind of moulded parts. The list contained parts with an MTBF lower than 500,000 hours.

5.2.1.4 High impact, long lead time parts

Another set of interesting spare parts are spare parts with a long lead time and a high impact, for example parts that are required for the radar system to work. The fact that these parts have long lead times is strongly undesirable as it mostly means that the radar system cannot be used during the whole lead time. An example of a high impact and long lead time part is a waveguide, as discussed in section 5.2.1.1. It may be very relevant to further look into these kind of spare parts and see where additive manufacturing can possibly make a difference. The critical spare parts list used for this research contains several parts that fit the high impact and long lead time criteria.

As it has been said before it will in most cases not be possible to print the whole spare part as it mostly consist of electronic parts as well as mechanical parts. So it will be required to do a full breakdown of the part and analyse what sub-parts may be interesting for additive manufacturing, in this breakdown it will also be important to look at things like the supply lead time of each sub-part, but also to look at things like supply risk (so is there only one supplier who can supply the desired part or is the part available from a large number of suppliers?). By analysing what sub-parts cause the long total lead time and looking if there are possibilities to shorten the lead time by printing some of these sub-parts (assuming they are printable). A similar breakdown has already been done for the 'TWT-ASSY', in this breakdown namely the lead times of the critical spare parts were analysed. The biggest impact on the lead time was caused by the production of the PCB that had a lead time of about 503 days of the total of 813 days. This a PCB though, so additive manufacturing will not offer any possibilities to improve that lead time, but there are still 310 days where there may be sub-parts that may be interesting for additive manufacturing and that will at the same time shorten the lead time.

5.2.1.5 Changing the obsolescence solution procedure

During the presentation that was held internally it came up that it might be interesting to change the way obsolescence is dealt with. The proposal is to, when an obsolete part (mostly belonging to an older system) is requested to then first look at whether this obsolescence problem can be solved by using additive manufacturing. For most mechanical parts it will indeed be possible to print these the parts, this may in a lot of cases be cheaper than remanufacturing the original part using conventional techniques. As the obsolescence problems mostly apply to older systems, it generally opens up more possibilities for additive manufacturing, this for several reasons. First the older systems have much more mechanic parts inside them than the newer models which more and more consist of electronics. Besides the older systems were still mostly manufactured at Thales, this means that Thales possesses the designs of a majority of parts. Possessing the designs makes a lot easier and a lot less expensive to produce a specific part.

5.2.1.6 3D scanning of (broken) parts to remanufacture

During one of the interview interest for 3D scanning of parts was also shown. This is a technology where a part is scanned by multiple cameras to finally create a digital 3D image of the part, this file can then for example be used to 3D print a replica of the scanned part. This technology could be especially interesting to reproduce a part that has become obsolete overtime. There are though a few drawbacks of this technology, first at least one original part has to be available, second the internal shape of a certain part cannot be scanned and third the scanning technology is not detailed enough to reproduce high precision parts.

5.2.1.7 Strategic parts according to the Kraljic matrix

The four categories identified in the Kraljic matrix are the following (Patagonia , 2015):

Table 6 Kraljic Matrix

Financial risk		
High	Leverage Products	Strategic Products
Low	Routine Products	Bottleneck Products
	Low	High
	Supply risk	

- Leverage products: these are parts with a relatively high financial impact on the total product but where the supply risk is relatively low, it is thus quite easy to find another supplier when the current supplier is not able to supply the desired part.
- Strategic products: these are parts with a high financial impact on the total product and which also have a high supply risk, only one or a small number of suppliers is able to supply that specific part. So if that specific supplier goes out of business for example, Thales will have a big problem.

- Routine products: these are products with both a low financial impact and a low supply risk, this means that the parts can be acquired relatively easily and that the total added value is small. These parts can easily be replaced by other parts from other suppliers.
- Bottleneck products: these are products with a low financial impact but a high supply risk, thus only a small amount of suppliers are able to supply that part and if this supplier goes out of business or stops manufacturing the specific part Thales will have a serious problem even though the added financial value of the part is relatively low.

In the list Thales has attributed a category to each spare part. Parts identified as strategic in the list may be interesting to look at as Thales is striving for a shorter lead time of at most 16 weeks for these parts. This is to insure an on time delivery of spare parts. Of the total of 204 analysed parts 72 are labelled strategic parts for Thales. To realise this Thales is going to go into discussions with the suppliers to see how the lead times can be shortened, additive manufacturing could be very interesting as a way to shorten the lead time. Thus close collaboration with suppliers will be required to see where additive manufacturing could come in handy to shorten the lead time and thus reach the desired maximum lead time of 16 weeks.

5.3 Interesting (type of) parts

To conclude this chapter an overview of the interesting parts and types of parts discussed in this chapter will be summarized.

First the outcome of the framework mostly pointed towards the printing of casings and maybe some other smaller sub components of spare parts. Some parts came out as interesting parta from both the framework and the interviews and discussions with product experts.

Second the results obtained during the interviews, brainstorm sessions and discussions were discussed. Types of parts which were labeled as potentially interesting for additive manufacturing were the following: waveguides, parts of radar systems with irregular demand, injection moulded parts, high impact and long lead time parts and parts labeled as strategic parts according to the Kraljic matrix.

Third a change in the way obsolescence is solved came up as potentially interesting to implement additive manufacturing and 3D scanning broken parts to repair them using additive manufacturing came up as potentially interesting applications.

6 Redesigning the supply chain for additive manufacturing

If Thales was to come to the conclusion that it wants to start using additive manufacturing in the after-sales service, Thales could do two things; either invest in an own 3D printer or it could outsource the printing of the parts. Both solutions have advantages and disadvantages; these will be discussed in this chapter. After this Thales' opinion and decision on this matter will be discussed. To conclude the possible impact additive manufacturing could have on the after sale supply chain will be discussed. The changes discussed in this chapter are relatively universal changes in the supply chain which will occur when introducing additive manufacturing for some part. To know the exact impact of introducing additive manufacturing for one part it is would be necessary to do a more in depth analysis for that specific part, this is out of the scope of this research but could be an interesting point for some follow up research.

6.1 Investing in an own 3D printer

If Thales was to invest in an own 3D printer it would bring along several benefits but also some drawbacks, these will be discussed in this section.

Benefits

- The printer is always there whenever you need it, if a certain part is required it can be directly sent to the printer without the need to call in another company.
- When the printer is not in use printing for example spare parts, other departments could use it. You could for example think of the mechanical design departments who sometimes wants specific parts for the prototyping process of a new system.
- No waiting times or at least shorter waiting times than when Thales would outsource it to an external party. In case that the printing would be outsourced the waiting times would become longer as the printing company also has other jobs than yours, the same can be seen in the current production industry in most cases (long) waiting times apply as the order of another customer has to be finished first. At this moment, as the 3D printing technology is still not widely used, it can be debated that the waiting lines are not that long, but that will most certainly change in the future as the technology is increasing in popularity.

Drawbacks

- If Thales would want to buy a professional grade printer (which can for example also print metal parts) this would imply high initial costs, these costs would have to be amortized on the printed parts. This will mean higher overall costs per part when the usage rate of the printer is low.
- The 3D printing technology changes very rapidly, this means that a machine bought today can already be out-dated tomorrow. But Thales will not buy a machine every other day, this can be a limiting factor as Thales will then not be able to always use the latest 3D printing technology and capabilities.
- If Thales would only buy one printer (which would probably be the case) they would only be able to print a restricted amount of materials as different materials need different printing techniques. Though it is possible to buy multiple printers but this also implies higher initial costs.

6.2 Outsourcing the 3D printing

On the other hand Thales could decide to outsource the printing of spare parts, this again benefits as well as drawbacks, these will be discussed in this section.

Benefits

- All machines and materials are available, maybe it will be necessary to use several printing companies. But it is possible to get parts printed out in all the materials compatible with 3D printing techniques, this makes a wider array of applications possible.
- Compared to when Thales would have to buy its own 3D printer(s), the initial costs are very small to none when outsourcing the printing. This of course means less financial risks, as the machine does not have to be paid for, at least not by Thales.
- By outsourcing it will be easier to use the newest 3D printing techniques, as companies specialized in 3D printing will be more likely to invest in new technologies to make it available for their customer. This again offers more possibilities without necessarily increasing the costs (Thales does not need to buy a new printer).
- When outsourcing the printing jobs Thales could take advantage of the expertise of the additive manufacturing company. This could lead to higher quality parts and possibly even shorter throughput times.

Drawbacks

- Though in theory there is almost no economy of scale effect when using additive manufacturing by Thales. On the contrary, when outsourcing the printing jobs the economy scale can apply. For example, when ordering 100 parts the price per part will be lower compared to the unit price when ordering a single part. The printing company is more interested in a job of 100 units than a job of 1 unit as one of its main concerns is to have the printers running 24/7.
- At this moment it is not really problematic for the printing company to start printing your part right away, as the technology is not that widespread but with the increasing popularity of the technology the demand for printing jobs will increase and this will most likely lead to waiting queues. So it will not go without saying that the printing company will be able to start printing the part for Thales right away. But there are solutions for this, an availability contract could be negotiated, which states that the printing company has to start the production within a certain amount of time after Thales ordered it.
- The outsourcing adds an extra step in the supply chain and an extra step mostly means extra time, this hinders one of the purposes of 3D printing, which is to shorten the lead time of a certain part. Though this argument is debatable as the 3D printed parts may still have a shorter lead time than the original parts. In this case there is still a shortening of the total lead time. It can also be that Thales has already outsourced the production of that specific part, then this argument doesn't go up as no extra step is added to the supply chain.

6.3 Evaluating the possibilities

After discussing the possible options with several of Thales' employees it came up that, despite the benefits of investing in an own 3D printer, it may be best for Thales to outsource the printing jobs, as is being done at the moment. This advice has been based upon the following considerations.

Thales strives towards being a knowledge and service company, for this reason more and more of the production is being outsourced to third parties. For this reason it would not fit within the current vision to invest in a 3D printer and thus start producing/printing at Thales.

The investment in a 3D printer not only consists of buying the printer itself but also consists of all the additional matters like employing people who are qualified to control or educating people to be qualified to control a 3D printer, the stocking of raw materials, etc. This all implies significant costs and not only initial costs but also throughout the lifetime of the printer.

Besides this the additive manufacturing technology is ever evolving, this makes that the machine you buy today is almost outdated by tomorrow. Thus to be able to keep up with the newest technology Thales would have to invest in new 3D printers regularly, this again increases the total costs.

The final recommendation is thus for Thales to outsource the additive manufacturing of parts, as is done at the moment. While outsourcing the printing of parts Thales will have to take several points into account to assure the desired results and benefits are reached when printing parts. These points will be discussed in Section 6.4.

6.4 Making the right decision

Based upon the opinion named in the previous Section it can be concluded that Thales would most likely outsource the 3D printing jobs, as is actually already being done at the moment (see Section 3.5). When outsourcing the 3D printing jobs Thales has some requirements the supplier will have to comply to, these requirements will be summarized and clarified in this section.

When outsourcing the production Thales will have several requirements the additive manufacturing company will need to meet. For example the production will have to be done relatively near to Thales, so within Europe (e.g. The Netherlands, Germany, Belgium), this will allow Thales to monitor the quality of the produced parts more precisely than when the printing jobs would be outsourced to countries in for example the far east (e.g. China, India). Also western European countries generally have stricter quality requirements and more consistent production processes. This is very important for Thales, as the delivered parts have to be very precisely built and have to comply with strict quality regulations. After the printing parts can be sent all over the world in a relatively short time, most places are reachable within 24 hours. The logistical channels in Europe are quite good, especially when compared to some countries in the Far East where it can sometimes take a much longer time before the part arrives to the customer. When looking at the Logistic Performance Index fixed by the World Bank, the Netherlands and Germany respectively score 4.23 and 4.32 on a scale from 1 to 5 for the quality of trade and transport-related infrastructure. In comparison China and India respectively score 3.67 and 2.88 on the same scale; these are significantly lower scores (The World Bank, 2014). Keeping the printing in Europe thus yields multiple benefits like an easier monitoring of the produced quality, a better overall quality and a better logistic performance (at least on the sending side, the receiving side can still be a country with a lower logistic performance). The printing of the parts will (at first at least) remain centralized, as is the case with the current production methods.

Besides sending the digital file to a country like China will also require an export license, when exporting a part this export license is also required. There is no difference on this front, thus it is as convenient to manufacture nearer to Thales as manufacturing in the Far East. The convenience is related to the arguments named in the previous paragraph.

6.5 Changes in the supply chain

By implementing the option described in Section 6.4**Error! Reference source not found.** the supply chain of Thales will not change drastically, the production/printing will mainly still happen in the same region as it does now. The production will, at least in the beginning, still be centralized. What may change though is the delivery lead time to the customer, as described earlier the production lead time of some parts may be positively influenced by printing these parts or some of the sub components. Thales could though try to produce nearer to the customer and directly implement the quality check at the printing location, in this fashion they could delete the step where the part has to go through Thales and may in this manner drastically shorten the overall lead time. The way products are designed could change though as Thales would have to collaborate more closely with its suppliers to take most benefit of the advantages of additive manufacturing.

An ideal (distant) future scenario would be to be able to print directly at the local partner or even at the Navy, thus printing on location. This could strongly change the supply chain; Thales could then become the highest key in the supply chain, for certain spare parts at least (as for non printable spare parts Thales would still have to rely on external suppliers). For the printable spare parts would then most likely become the suppliers of technical drawings and 3D digital designs of the spare parts. The local partner or the navy would be able to buy the designs from Thales and then print the parts themselves. The designs though probably still would have to go through customs as most of the parts have military specifications (even digital files), so that step in the supply chain would most likely remain unchanged. When looking at the quality check which currently takes place at Thales for most parts, that could be changed by for example setting up a testing facility at the customer's production facility.

7 Conclusion & discussion

7.1 Conclusion

The main question asked at the beginning of this research was: "*From a logistical point of view, how can additive manufacturing positively influence Thales' Services? What part of the service portfolio should be regarded and what needs to be done to take advantage of additive manufacturing?*"

The main question will now be answered based upon the research discussed in the report. First, additive manufacturing may be able to positively influence Thales' after sales services and with that improve the customer satisfaction.

From this research it can be concluded that the most promising parts for additive manufacturing within Thales are parts like casings, thus parts which are at this moment (injection) moulded or even milled.

Other parts that may be interesting for additive manufacturing are complex parts, especially parts with complex internal forms due to for example cooling channels, these parts are mostly expensive to manufacture, using additive manufacturing may lower production costs.

Waveguides also came out as promising parts; these are parts with a high impact on the functioning of the radar system and a complex production process, which makes for long lead times. The additive manufacturing technology is currently not precise enough for the manufacture of end-use waveguides, but there have already been positive tests with 3D printed waveguides and the technology is ever evolving. Waveguides are only one example of parts with a high impact on the functioning of the radar system and long lead times, other parts with the same characteristics may be very interesting for additive manufacturing as well.

Next to these applications a list of spare parts scored on basis of their attractiveness for additive manufacturing was obtained through the use of a selection framework. The 10 most attractive parts can be found listed in Appendix 9.4 and the complete list will stay inside Thales. It should though be noted that almost all of the parts on this list are assembled parts and thus will not be printable in their entirety. Therefore, further research will be required to analyse which sub components may be printable and whether the printing of these parts could indeed improves Thales' service.

As was already mentioned before, Thales strives towards being a service company and not a production company. For this reason most of the production is being outsourced. Hence, Thales has less influence on the production methods used by the suppliers, this is also due to the fact that a lot of parts for Thales are built to specifications. Meaning that as long as the part complies with the required specifications and functions it does not matter how it is manufactured. To be able to take most advantage of the possibilities of additive manufacturing the recommendation for Thales is to start a close collaboration with suppliers of critical parts. By doing this, Thales could, together with its supplier(s), analyse what parts could be best suited for additive manufacturing. This could possibly lead to the highest satisfaction for both parties. Thales is already envisaging such a collaboration with some of its suppliers to insure lead times of at most 16 weeks for their strategic parts, here additive manufacturing could come out as a very interesting manufacturing option to insure this short lead time. It may be most interesting to first start a close collaboration with Norma which is one of Thales' main suppliers and was previously part of Thales. Norma thus has a lot of knowledge about the field of work Thales is in and therefore may be the best supplier to start with to analyse where additive manufacturing could be best applied. Norma already has an own additive manufacturing department.

Beside the close collaboration with the suppliers some other actions could be taken to take most advantage of additive manufacturing technology.

One of those actions is to change the way obsolescence is dealt with. The obsolescence manager first would have to look at whether the part or some components of it could be manufactured using additive manufacturing. Subsequently, he would have to analyse whether the use of additive manufacturing is more profitable than the use of the normal production methods. If this were the case they would have to manufacture it using additive manufacturing.

Another application area is to start considering additive manufacturing as an extra manufacturing method, which can also be used for producing parts of new radar systems. The use of additive manufactured parts can have multiple advantages of which diminishing the total holding costs due to the absent need for moulds and possible weight reduction of the radar systems. The greatest improvements would then be for radar systems with an irregular demand, which often have moulds that are not being used for long periods of time.

To conclude, additive manufacturing has to be seen as an extra manufacturing technique which will not completely replace other techniques but can open up a lot of opportunities and possibilities for both the after sales service, development and production department. But to take most advantage of the technology Thales will have to collaborate closely with its suppliers.

7.2 Discussion

During this research a great amount of discussion points came up, some of the most important points are summarized in this section.

- Additive manufacturing has a lot of opportunities within the prototyping processes at Thales. The lead time for some non-complex parts is sometimes very long which only slows down the prototyping process. If the engineers could make a 3D CAD model of the desired part and then print right away this would probably improve the speed of prototyping.
- In the normal production of radar systems sometimes some special parts are needed which are not really available on the market. So the problems are mostly solved using alternatives or by taking parts out of other systems. If engineers at Thales would have access to additive manufacturing technology they would probably be able to print most of the desired parts this would make it easier to make a part which better suits the desired purpose.
- Almost every part used in Thales' systems has to comply with several ISO certifications and military standards. This brings along some extra challenges to get parts certified, but there are already several reputable additive manufacturing companies who already own several industry related ISO certificates. (Stratasys, 2011)
- It might be that by using additive manufacturing the production costs are not reduced but even increased. On the other hand, it might reduce the lead time for the customer quite significantly, which can improve the customer satisfaction. The quicker delivery can be adjusted in a higher customer price, thus compensating the higher production costs.
- The mechanical design team at Thales sees opportunities in additive manufacturing, but they emphasize that they would have to consider it as an additional manufacturing technique. Considering it as an additional manufacturing technique, it would open up a lot of new (design) opportunities.

- From a cost point of view, it may be a logical move to directly design parts for additive manufacturing and to use these parts in the radar systems. And thus not first design for normal production methods and then after several years design it to be able to change the production technique. When the part would be redesigned it would have to be certified all over again even if it is exactly the same, but as the manufacturing method has changed it is necessary to certify it again. This certifying costs money and time, which is not desirable for a production company. Therefore, it might be better to directly design the parts for additive manufacturing, as this will only make it easier and less costly in the after-sale life of the radar system. Also, redesigning the parts after several years is expensive.
- When implementing additive manufacturing as a normal production method, the way parts are designed may be changed drastically, for example parts composing of multiple small sub parts could be printed as one big part. This can of course reduce the total costs but also lower the total processing time. After a discussion with people from the mechanical design department at Thales it came up that there are some parts that may be interesting to print, as at this moment they mostly consists of all small sub parts soldered to each other. One such example is tube network in the Smart L radar system. There have already been positive tests in the field of combining multiple parts into one printed part, for example GE has now introduced fuel nozzles which are printed in one piece which is a great improvement compared to the previous parts where 20 sub components had to be welded together. This was a time consuming job and therefore highly expensive (Royal Academy of Engineering, 2013).
- Additive manufacturing may be interesting during the prototyping phase of the radar systems. It sometimes happens that specific parts are required to test a design, these parts do not need to be of a high quality but have to be shaped the right size to see whether it all fits together. At the moment most specific parts are ordered separately and it then takes up to a few weeks before the part is delivered. This of course slows down the prototyping process drastically. Here additive manufacturing could make a difference by allowing shorter lead times and still having a sufficient quality.

7.3 Limitations

As mentioned before, the acquired list is not a complete list of all the available spare parts from Thales. This limited the research in some way as it was not possible to analyse the complete spare parts assortment. Nevertheless, the list, which was used for this research, offers a representative overview of the total spare parts portfolio of Thales. The list contains a vast amount of different spare parts, which are being used across multiple systems. So also in other systems next to the four for which the parts were listed. Even though the list used for this research is suitable to get an overview of what type of parts may be interesting for additive manufacturing, it is still necessary to point the reasons why no complete list of all spare parts could be generated:

- Thales recently introduced a new database system in which all the parts and radar systems have to be registered, a lot of parts have already been entered in the system but not all of them. The old system on the other hand is not well organized, as there is no true hierarchy. It is therefore not possible to get an adequate data set out of this system. Additionally there are parts which are not even registered in any database and of which only non-digital information is available.

- Some parts can be exactly the same but still have different identification codes (12nc numbers), this is due to the fact that part numbers are often associated to the project number they belong to. The fact that the same part can be identified with different identification codes only makes it more difficult to draw good conclusions from the data.
- Some parts also lacked data for one or more of the selection criteria. As was stated in section 4.2.1 & 4.2.2 the parts with lacking data were attributed a neutral score for the missing criterion. In this way, the parts with missing data about some criteria were not left out, and will most likely end up somewhere in the middle of the list. To identify whether the part is interesting for additive manufacturing or not the part will have to be analysed more in depth, by analysing drawings or the physical part itself. Of all the analysed parts 85 were missing a data point for one of the criteria, 22 were missing data points for two criteria, 8 were missing data points for three criteria and one was missing data points for four criteria. All these missing data points were thus attributed a neutral score of 3.
- It was in most cases also not possible to draw any conclusions from the name of the spare part itself. Some names consisted of more than 10 characters, which resulted in the use of (unidentifiable) abbreviations. Some abbreviations could not be recognized nor lead back to specific parts.

8 Bibliography

(n.d.). Retrieved from http://www.symbitron.eu/wp-content/uploads/2013/10/UT_Logo_2400_Black_EN1.png

(n.d.). Retrieved from http://www.alacartecruises.nl/wp-content/uploads/2013/11/F805-Zr.-Ms.-Evertsen-e1384254455282.jpg

(2015). Retrieved from http://www.ict-lola.eu/partners/Logo_Thales.PNG/image_view_fullscreen

3Ders. (2014, 02 07). *China developing world's largest 3D printer, prints 6m metal parts in one piece*. Retrieved 05 06, 2015, from 3ders.org: http://www.3ders.org/articles/20140207-china-developing-world-largest-3d-printer--prints-6m-metal-parts-in-one-piece.html

Airbus. (2014, 03 03). *Printing the future: Airbus expands its applications of the revolutionary additive layer manufacturing process*. Retrieved 05 05, 2015, from Airbus presscenter: http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/printing-the-future-airbus-expands-its-applications-of-the-revolutionary-additive-layer-manufacturi/

Bunruanmkaew, K. (2012, 03 01). How to do AHP analysis in Excel. University of Tsukuba.

Canalys. (2014). *3D printing market to grow to US$ 16.2 billion in 2018.*

Carbon 3D . (2015). *CLIP technology*. Retrieved 05 06, 2015, from carbon 3D: http://carbon3d.com/

CSC. (2012). *3D printing and the future of manufacturing.*

D'Aveni, R. A. (2013, 03). *3-D Printing Will Change the World*. Retrieved 05 06, 2015, from Harvard business review: https://hbr.org/2013/03/3-d-printing-will-change-the-world

Defense Industry Daily. (2013, 10 23). *Makers On the Front Lines: The Army REF's Ex Labs*. Retrieved 05 22, 2015, from Defense Industry Daily: http://www.defenseindustrydaily.com/makers-on-the-front-lines-the-army-refs-ex-labs-018510/

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., et al. (2015). The status, challenges, and future of additive manufacturing in. *Computer-Aided Design* .

Geterud, E., Bergmark, P., & Yang, J. (2013). Lightweight Waveguide and Antenna. *7th European Conference on Antennas and* .

IDA - science and technology policy institute. (2012). *Addtive manufacturing: Status and Opportunities.*

Kaso. (2015). *SLA or FDM? Choosing the Right 3D Printing Rapid Prototyping Technologies*. Retrieved 06 09, 2015, from Kaso plastics: http://www.kaso.com/news/2013/july/sla-or-fdm-choosing-right-3d-printing-your-prototyping-needs

Knofius, N. (2015). *Identifying technological and economical printable spare parts .*

Loughborough University. (2015). *About additive manufacturing - Binder jetting*. Retrieved 05 04, 2015, from Additive manufacturing research group - Loughborough University: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/

Loughborough University. (2015). *About additive manufacturing - Directed energy deposition*. Retrieved 05 05, 2015, from Additive manufacturing research group - Loughborough University: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/

Loughborough University. (2015). *About additive manufacturing - Material extrusion*. Retrieved 05 04, 2015, from Additive manufacturing research group - Loughborough University: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/

Loughborough University. (2015). *About additive manufacturing - Material jetting*. Retrieved 05 04, 2015, from Additive manufacturing research group - Loughborough University: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/

Loughborough University. (2015). *About additive manufacturing - powder bed fusion*. Retrieved 05 05, 2015, from Additive manufacturing research group - Loughborough University: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/

Loughborough University. (2015). *About additive manufacturing - Sheet lamination*. Retrieved 05 05, 2015, from Additive manufacturing research group - Loughborough University: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/

Loughborough University. (2015). *About additive manufacturing - VAT Photopolymerisation*. Retrieved 05 04, 2015, from Additive Manufacturing Research Group - Loughborough University: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/vatphotopolymerisation/

Marine schepen. (2015). Retrieved from http://marineschepen.nl/schepen/images/smart-s.jpg

Materialise. (2015). *Laser Sintering: Materials & datasheets*. Retrieved 06 09, 2015, from Materialise: http://manufacturing.materialise.com/laser-sintering-materials-datasheets-0

Materialise. (2015). *The factory for 3D printing*. Retrieved 06 09, 2015, from Materialise: http://manufacturing.materialise.com/

Patagonia . (2015). *Kraljic*. Retrieved 06 18, 2015, from Patagonia Adviesbureau voor rendementsverbetering: http://www.patagonia-bv.com/kraljic/

Royal Academy of Engineering. (2013, 11). Additive manufacturing: opportunities and constraints. London.

Sevenson, B. (2014, 04 23). *U.S. Navy Installs 3D Printer On Their First Ship, The USS Essex*. Retrieved 06 03, 2015, from 3D print: http://3dprint.com/2554/uss-essex-3d-printer-navy/

SLM solutions. (2015). *SLM® 500 HL*. Retrieved 06 09, 2015, from SLM solutions: http://www.stage.slm-solutions.com/index.php?slm-500_en

Stratasys. (2015). *Digital Dentistry*. Retrieved 06 03, 2015, from Stratasys: http://www.stratasys.com/industries/dental

Stratasys. (2011, 02 01). *Stratasys Implements Total Quality Management System; Receives ISO 9001: 2008 Certification*. Retrieved 05 22, 2015, from Stratasys: http://investors.stratasys.com/releasedetail.cfm?releaseid=599587

Stratasys. (2015). *Tough enough for armored tanks.* Retrieved 05 04, 2015, from Stratasys: http://www.stratasys.com/resources/case-studies/defense/eoir-technology?returnUrl=http://www.stratasys.com/resources/case-studies?search=eoir

TCT magazine. (2015). *Trends in AM direct part production*. Retrieved 05 05, 2015, from TCT: http://www.tctmagazine.com/blogs/industry-snapshot/trends-in-am-direct-part-production/

Thales group. (2015). *About us - Thales Netherlands*. Retrieved 1 05, 2015, from Thales Group: https://www.thalesgroup.com/en/netherlands/about-us

The Shephard News Team. (2015). *Thales' APAR completes first Sea Acceptance Test*. Retrieved from Shephard: http://www.shephardmedia.com/news/imps-news/thales-apar-completes-first-sea-acceptance-test/

The World Bank. (2014). *Logistics performance index: Quality of trade and transport-related infrastructure (1=low to 5=high)* . Retrieved 06 23, 2015, from The World Bank: http://data.worldbank.org/indicator/LP.LPI.INFR.XQ

tweakers.net. (2015, 05 06). *Pricewatch - 3D printers*. Retrieved 05 06, 2015, from Tweakers: http://tweakers.net/categorie/945/3d-printers/producten/

Veldhuis, S. (2015). *Supply Chain Promis of Spare Parts.*

VIL. (2015). *Opportuniteiten van 3D printing voor de wisselstukkenlogistiek.*

voxel8. (2015). *Developer's Kit: 3D Electronics Printer*. Retrieved 05 05, 2015, from Voxel8: http://www.voxel8.co/printer/

9 Appendix

9.1 Different additive manufacturing technologies

Each of the techniques has its own advantages and disadvantages, in the following sub-paragraphs each of the techniques will be discussed together with its advantages and disadvantages.

9.1.1 VAT Photo Polymerization (Figure 2)[1]

With this technique a vat filled with liquid photopolymer resin is polymerised on the spots assigned by the CAD model (this using UV light). This is done layer-by-layer, by lowering the platform each time a layer is done. Going through the whole process finally yields a 3D printed object (Loughborough University, 2015).

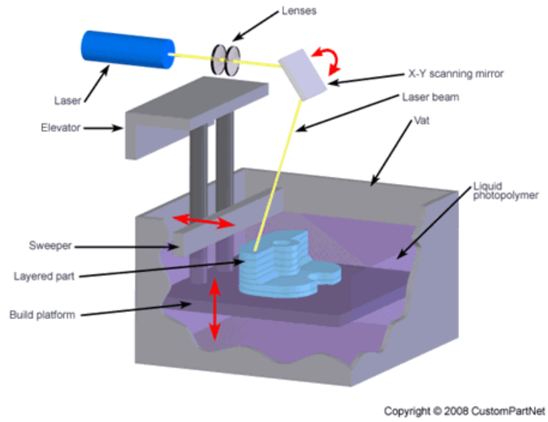

Figure 2 VAT Photo Polymerization

Advantages (Loughborough University, 2015)

- This technique has a high accuracy, so it is well suited to make complex objects.
- The speed is quite high compared to other additive manufacturing techniques.
- The printing size is big compared to other additive manufacturing techniques.

Disadvantages (Loughborough University, 2015)

- It is more expensive than some other techniques.
- Most models need support structures as the liquid resin does not offer support, after the printing these support structures have to be removed which increases the post processing time and costs.
- There is a limited choice of materials, as only photopolymers are suited for this technique.

9.1.2 Material Jetting (Figure 3)[2]

With material jetting the material is deposited through a nozzle on a build platform in a similar way as a normal inkjet printer. The material jet can be either continuous or a Drop On Demand (DOD) system. Once added the material is hardened using UV light. When one layer is finished the whole platform is lowered and the next layer is added, this continues until the final object is obtained. This method is quite restricted in terms of material choices; only polymers and waxes can be used. With the DOD system it is possible to add material only where needed, but there is only a small amount of materials that is suitable to form droplets, which again restricts the use of this technique on a wide scale (Loughborough University, 2015).

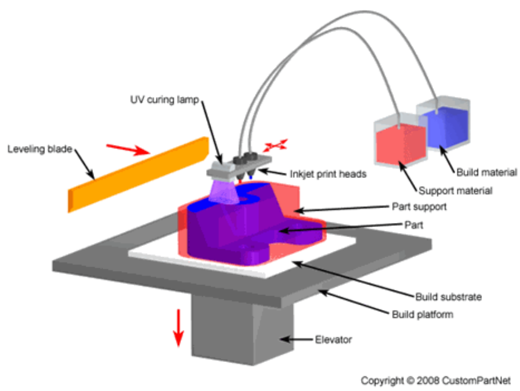

Figure 3 Material Jetting

[1] Image source: http://www.custompartnet.com/wu/stereolithography accessed 05/05/2015
[2] Image source: http://www.custompartnet.com/wu/jetted-photopolymer accessed 05/05/2015

Advantages (Loughborough University, 2015)

- Material jetting has a high accuracy thanks to the DOD system.
- It is possible to print multiple colours in one run, so you can get an object with multiple colours.

Disadvantages (Loughborough University, 2015)

- With this method support structures are mostly required because there is no other material around to support the printed object.
- As said before due to the required characteristics for the DOD system the number of material which are printable with this method is quite limited.

9.1.3 Binder Jetting (Figure 4)[3]

With the binder jetting method it is not the material itself that is jetted onto the platform but it is the binder fluid. To start with a layer of powder material is spread on the build platform using a levelling/powder roller, after this the print head jets the binder material on top of the powder material where necessary, the build platform is then lowered and the powder supply platform is elevated and another layer of powder material is rolled onto the build platform by the levelling roller. The new powder layer only binds to the previous layer where binder material was added. This process is repeated until the final object is obtained. After this the remaining powder material needs to be removed, this is mostly done with high-pressure air. This method is compatible with metals, polymers and ceramics (Loughborough University, 2015).

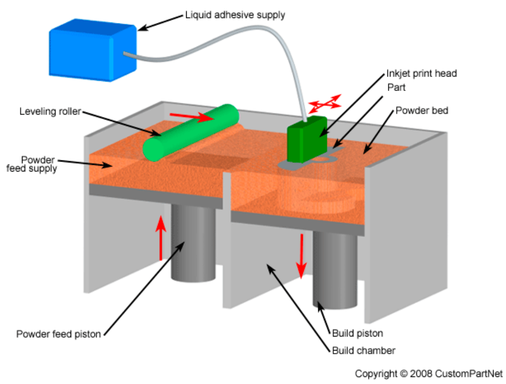

Figure 4 Binder Jetting

Advantages (Loughborough University, 2015)

- With this method it is also possible to make objects with multiple colours.
- Binder jetting is compatible with a wide array of materials of which metals, polymers and ceramics.
- In most cases binder jetting is faster than other additive manufacturing methods.
- The two materials method (binder and powder) makes a lot of different binder-powder combination with various mechanical properties possible.
- No need for supporting structures thanks to the remaining powder that acts as a support structure.

Disadvantages (Loughborough University, 2015)

- Due to the use of binder materials the objects are not always very sturdy and thus are not always suitable for structural use.
- The post processing is quite extensive with this technique, all the remaining powder has to be removed and sometimes the surfaces have to be smoothened up.

[3]Image source: http://www.custompartnet.com/wu/3d-printing accessed 04/05/2015

9.1.4 Material Extrusion (Figure 5)[4]

With material extrusion the material (coming from a spool) is drawn through a nozzle under constant pressure and heat to have a continuous flow of material that is then deposited on the build platform layer by layer. The layers are bounded to each other by temperature control or by using chemical agents. The build platform is moved down each time a new layer has been added (Loughborough University, 2015).

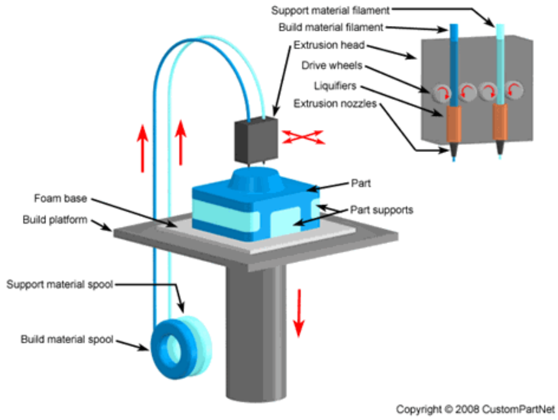

Figure 5 Material Extrusion

Advantages (Loughborough University, 2015)

- This is the most widespread additive manufacturing techniques; almost every 3D printer destined for consumer use uses this technique, mainly because it is the most affordable technique.
- This technique is compatible with ABS plastic; this plastic has good structural properties and is easy to procure.

Disadvantages (Loughborough University, 2015)

- The diameter of the nozzle is quite big, which means that the printer is not very accurate and the final results are not very smooth.
- Constant pressure in the nozzle is required to attain a reasonable finishing quality.
- With this technique support structures are also required.

9.1.5 Powder Bed Fusion (Figure 6)[5]

With the powder bed fusion process powder material is melted together by either a laser beam or an electron beam. This process is again done layer-by-layer, the system for adding powder layers is quite similar to that of the binder jetting technique. First one layer is applied on the build platform, then the laser or electron beam melts the powder material together on the required place, when this is done the build platform goes down and a next layer of powder material is added using a powder roller or blade. After this the laser or electron beam again melts the required shape, this process continues until the final object is obtained. There are multiple printing techniques which fall under the powder bed fusion process, those are: direct metal laser sintering (DMLS), electron beam melting (EBM), selective heat sintering (SHS), selective laser melting (SLM) and selective laser sintering (SLS). This additive manufacturing process is compatible with a wide range of materials, for example nylon and various metal(s) (alloys) (Loughborough University, 2015).

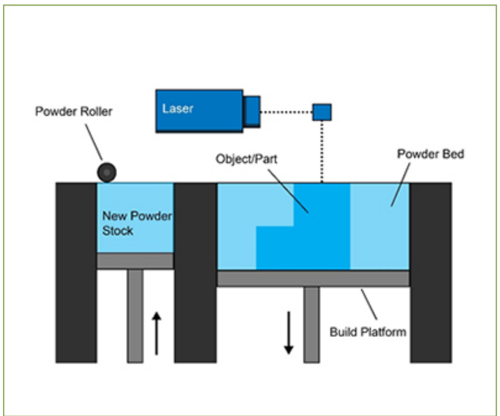

Figure 6 Powder Bed Fusion

Advantages (Loughborough University, 2015)

[4] Image source: http://www.custompartnet.com/wu/fused-deposition-modeling accessed 04/05/2015
[5] Image source: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/ accessed 05/05/2015

- When compared to other additive manufacturing techniques it is relatively inexpensive.
- It is possible to integrate the technique into office-sized machines, especially when looking at the SHS technique.
- With SLS there is no need for support structures as there is powder around the printed item, which can support it.
- A large amount of different materials are compatible with this technique.

Disadvantages (Loughborough University, 2015)

- The printing speed is relatively slow, especially when looking at the SHS technique.
- The structure is not always strong enough for use in end products.
- The maximum printable size is quite restricted and the machines for printing bigger items are relatively expensive.
- Due to the laser or electron beam the power usage is quite high.
- The finish quality strongly depends on the size of the powder grain.
- With SLM there is a need for support structures, otherwise the printed part will sink in the powder material that will have influence on the shape of the printed part.

9.1.6 Sheet Lamination (Figure 7)[6]

With ultrasonic additive manufacturing (UAM) multiple layers of metal are welded on top of each other using ultrasonic welding. Another method is the laminated object manufacturing (LOM) with this technique multiple layers of paper or plastic are fixed to each other using adhesive. Both processes need additional CNC machining to remove the excessive metal or paper and thus attain the desired shape, the cutting is either done by a laser beam or a knife. When one layer is done the material that is mostly fixed on a spool is pulled further so a new layer can be added/cut out. This process is repeated until the final object is obtained. Multiple metal sorts (aluminium, copper, stainless steel and titanium), plastics and paper are compatible with this method (Loughborough University, 2015).

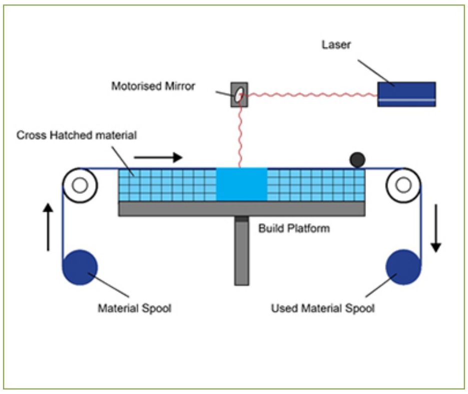

Figure 7 Sheet Lamination

Advantages (Loughborough University, 2015)

- The printing speed and the low costs are advantages of sheet lamination.
- The technique requires a low amount of energy as the metal does not need to be melted and the whole process takes place at low temperatures.

Disadvantages (Loughborough University, 2015)

- The finishing is not always very smooth and thus the 3D printed object may require a lot of post processing.
- The number of materials compatible is quite limited.
- The fusion still requires some research before being able to apply it widely.
- The objects created using this technique can only be used for aesthetic and visual models, they are not suited for structural use.

[6] Image source: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/ accessed 05/05/2015

9.1.7 Directed Energy Deposition (Figure 8)[7]

Directed energy deposition (DED) is mostly used to repair or to add additional material to an existing object. A DED machine consists of a nozzle mounted on a multi-axis arm, which makes it possible to move in every direction around the object. The material is deposited through the nozzle on the object, here it is melted using either a laser beam, an electron beam or plasma arc after this it solidifies and adheres to the object. This technique is compatible with polymers, ceramics and metals; with the latter one being the most used material (Loughborough University, 2015).

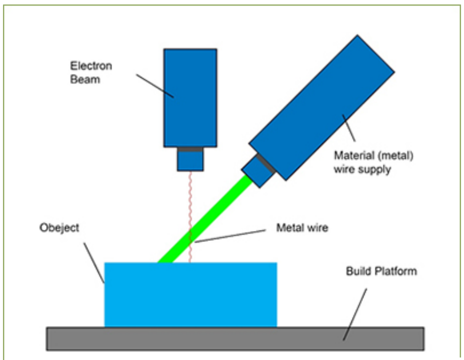

Figure 8 Directed Energy Deposition

Advantages (Loughborough University, 2015)

- It is possible to get very small grains and thus have a high degree of precision, which makes this technique well suited for repairing high quality, functional parts.

Disadvantages (Loughborough University, 2015)

- Post processing is sometimes required.
- The amount of compatible materials is quite limited.

[7] Image source: http://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/ accessed 05/05/2015

9.2 Left out criteria

For the framework multiple criteria were considered but some of these were finally left out, in this section the criteria that were left out and the reason for this decision will be discussed. The criteria discussed here under have been proposed by (Knofius, 2015).

- A *materials* criterion was considered, but this criterion was left out for two reasons. The first being that there was no data available in the databases about the materials used for the specific part. The second reason is that the spares parts list which was used for this research consisted of mostly assembled parts, this means that multiple materials were used in the same part, using a materials criterion would thus be impossible.
- The *dimension* criterion was considered as well, but it was left out due to a lack of data about dimensions of spare parts. Besides as for the materials criterion the spare parts analyzed for this research are mostly assembled parts which will not be printable in their entirety thus using a dimension criteria for the whole part is not relevant.
- The *production tolerance* criteria was considered but finally left out because of a lack of data about the production tolerances for specific spare parts. Though during further, more in depth, analysis it may be relevant to look at production tolerances as some parts may be not printable due to very narrow tolerances.
- The *installed base accessibility criterion* was considered but left out because of a lack of data about this criterion. Though it can be said that this criterion is not that relevant for the situation of Thales as the ships with the radar systems sail all around the world and this means that the installed base accessibility can change over time.
- The *life cycle phase* criterion was partly used, as the radar systems which were chosen for the research are radar systems which are still in use and in production. This makes analyzing the additive manufacturing opportunities for the spare parts of these systems more attractive for Thales.
- The *average days in inventory* criterion was considered but left out as there was too little data available about this criterion.
- The *end of life* criterion was also considered but finally left out as there was too little data available to include it in the research.

9.3 Weightings calculation

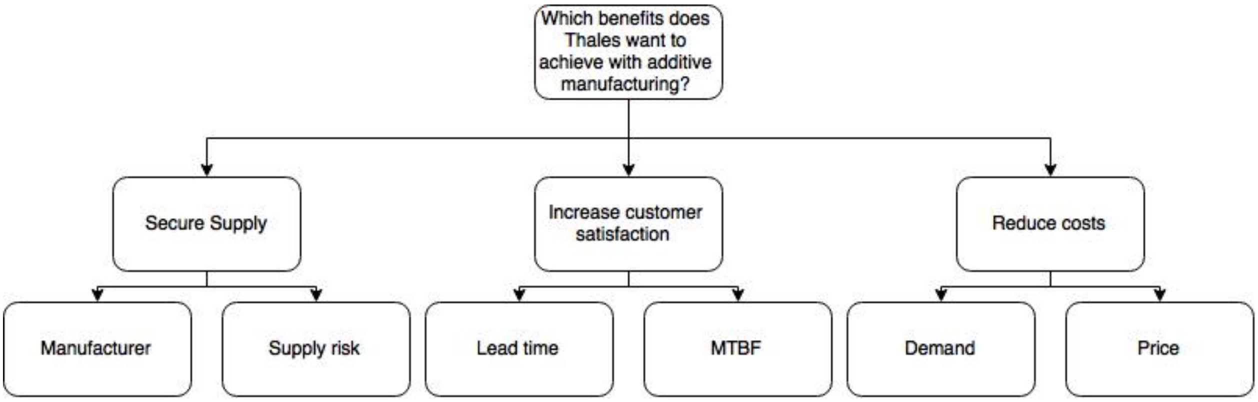

Illustration 4: Goals and associated criteria

In Illustration 4 it can be seen how the criteria selected for the selection framework fit into the business goals of Thales.

Table 7 Pair wise comparison matrix

	MTBF	Lead time	Price	Demand	Manufacturer	Supply risk
MTBF	1.00	0.20	0.20	0.17	0.20	3.00
Lead time	5.00	1.00	3.00	2.00	1.00	3.00
Price	5.00	0.33	1.00	1.00	0.50	3.00
Demand	4.00	0.50	1.00	1.00	0.33	3.00
Manufacturer	6.00	1.00	2.00	3.00	1.00	3.00
Supply risk	0.33	0.33	0.33	0.33	0.33	1.00
Total	**21.33**	**3.36**	**7.53**	**7.50**	**3.37**	**16.00**

Table 8 Normalization of the matrix and weightings calculation

	MTBF	Lead time	Price	Demand	Manufactur er (h0203)	Supply risk	Total	Weighting	Consistency measure
MTBF	0.05	0.06	0.03	0.02	0.06	0.19	0.40	0.07	6.25
Lead time	0.23	0.30	0.40	0.27	0.30	0.19	1.68	0.28	6.60
Price	0.23	0.10	0.13	0.13	0.15	0.19	0.93	0.16	6.79
Demand	0.19	0.15	0.13	0.13	0.10	0.19	0.89	0.15	6.69
Manufactur er (IP/design owner)	0.28	0.30	0.27	0.40	0.30	0.19	1.73	0.29	6.63
Supply risk	0.02	0.10	0.04	0.04	0.10	0.06	0.36	0.06	6.15
Total	1	1	1	1	1	1	6.00	CI	0.10
								RI	1.24
								CR	0.08

The AHP method was used to calculate the weights of the different criteria. This resulted in the above-mentioned weights; the weights have already been explained in more details in Section 4.2.3. In this section the calculations that had to be made and the decisions that had to be taken will be explained to give a good overview of the way the weights were obtained.

First pair wise comparisons were executed to identify which criteria were considered more important in the decision whether the part would be well suited for additive manufacturing or not. The total results of all the pair wise comparisons can be found in Table 7. The scores are attributed on a scale from 1 to 9 and the reciprocal values belonging to these scores, thus 1, 1/2, 1/3…1/8, 1/9. A score of 1 means that both criteria are considered equally important. A score of for example 3 means that the criterion (C1) attributed this score is considered slightly more important than the other criterion (C2) in the pair wise comparison. As a result of this decision the pair wise comparison of C2 versus C1 will be attributed the reciprocal value of 3, which is 1/3. As mentioned before the scores go all the way up to 9, 9 is the highest attributable score and it means that the criterion (C1) with this score is strongly more important than the other criterion (C2) in the pair wise comparison. In this fashion the whole matrix is filled in, the values above the diagonal are filled in and the values below the diagonal are the reciprocals of the values above the diagonal.

After the pair wise comparison matrix has been filled in completely the matrix is normalized. This means that all the columns should add up to 1, to obtain this the scores attributed in Table 7 are summed up on a column basis. Each entry in the column is divided by the column total (Bunruanmkaew, 2012), so for example to calculate the normalized score of MTBF versus Lead time 0.20 is divided by 3.36, yielding a normalized score of 0.06. Continuing in this fashion results in the normalized matrix displayed in Table 8. As can be seen in Table 8 all columns now add up to one. The following step is to take the sum of each of the rows; this is displayed in the 'Total' column. The sum of this column is then logically equal to 6. To now calculate the normalized weights of each of the criteria the row sum needs to be divided by 6. So for example for MTBF the normalized weight is equal to 0.40/6=0.07. In this way the 'weight' column is obtained.

After the weights were obtained it was necessary to analyse whether the decisions taken by Thales were consistent. To do this the consistency measure and the consistency ratio were used. To calculate the consistency measure the first row of Table 7 (MTBF row) was matrix multiplied by the weighting column in Table 8 and then divided by the weighting of that specific row (so in this case the MTBF). The consistency measure was required to calculate the consistency index. The consistency index (CI) is equal to: $CI = \frac{average\ consistency\ measure - \#criteria\ (6)}{\#criteria\ (6) - 1}$, performing this calculation yielded CI=0.10. The random index (RI) is the consistency index of a randomly generated pair wise comparison matrix; in this case for the matrix containing 6 criteria it is equal to 1.24 (Bunruanmkaew, 2012). The consistency ratio (CR) is determined by dividing CI by RI, in this case the consistency ratio is equal to 0.08. This score is under 0.10, this means that Thales was consistent in the scores they attributed to the pair wise comparisons and that the weights are correct and can be used for the weighting of the different criteria.

As was mentioned before the weights were determined in collaboration with Thales. Thales does agree with these weights and thinks it correctly reflects its current importance levels of the different business goals. The most important business goals being securing the supply of parts and the improvement of the overall customer satisfaction.

9.4 Top 10 of best scoring parts

Table 9 Top 10 best scoring parts for AM, according to framework

Item name	12nc	Weighted score	Links	Remarks
TIU	9556 521 105XX	4.88	Thales NL search	Casing
IR.CAMERA	9556 002 073XX	4.45	Thales NL search	Bought part, maybe on a higher level printable parts (for example the casing of this camera)
TR-BOOK	9556 001 871XX	4.45	Thales NL search	Casing, including fixation points and complex cooling channels
IF-GEN	8971 723 179XX	4.43	Thales NL search	Bought part
WG-LIMITER	9556 002 089XX	4.43	Thales NL search	Bought part
CONTR-UNIT	9556 514 932XX	4.42	Thales NL search	Bought part
PS-HV-ASSY	9556 519 855XX	4.38	Thales NL search	Casing
DRIVE ASSY	3522 441 131XX	4.36	Thales NL search	Bought part
DRIVE ASSY	3522 441 126XX	4.36	Thales NL search	Bought part
FCS_SEL	9556 723 131XX	4.30	Thales NL search	Bought part

Legend

Interesting for AM
Some subcomponents may be interesting for AM
Not interesting for AM