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Implementing Additive Manufacturing for Spare Parts in the Automotive Industry

A case study of the use of additive manufacturing for spare parts

Master of Science Thesis
in the Management and Economics of Innovation Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2015
Report No E2015:108

MASTER'S THESIS E 2015:108

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Chalmers Reproservice
Göteborg, Sweden 2015

Abstract

Previous research investigates what causes problems in the supply chain. However, there is a gap in research for possible solutions to these problems. As logistic systems grow bigger they become more difficult to manage and therefore it's vital to find resources to minimize risk and increase efficiency. Research suggests that additive manufacturing could be a solution to some of the problems that the supply chain may face. The paper aims to investigate if inventory costs for low turnover spare parts can be lowered, but still offer the same availability by using additive manufacturing. Therefore, the nature of this research was to investigate the consequences of implementing additive manufacturing for manufacturing spare parts in the automotive industry.

A case study was done with the cooperation with a big truck manufacturer, which had done similar research and wanted to take necessary steps to increase the management capacity. In order to measure the effect that additive manufacturing would have on the supply chain, spare parts that could possibly be manufactured using additive manufacturing and be profitable were identified. Different methods that was suggested by literature was used in order to find a sample; the first method was a hierarch process and the second method used three factors Annual Usage, Standard Cost of Sales and Lead time. The framework for finding the best-suited spare parts for additive manufacturing could be applied again in different divisions of the supply chain.

The identified spare parts would only be theoretically beneficial to produce with additive manufacturing. To get real measurements, the identified spare parts were subjected to a cost analysis. Two different comparisons was done; the first was done by using a mathematical model from a previous case study and the second was done by cost estimations from third party additive manufacturers. The data from these sources was compared with the actual cost gathered from the truck manufacturers master system.

From the empiric findings showed that 6.7% - 20% of a sample of 30 products was profitable compared to the actual cost. Investigating transportation this increased to 6.7% - 23.3%. However, the main finding was the lowering of spare parts lead-time. Of the profitable spare parts 66.6% - 85.7% could lower the lead-time down to 1-2 weeks. If investigating the whole sample of 30 products the lead-time could be lowered for 19 products (63.3%). This could implicate that the main benefit of using additive manufacturing is a big increase in customer service. Arguably, if the technology for additive manufacturing develops in the same rate as in the past, it would be worthwhile to do further investigation in this area as cost could go down.

Keywords: Spare parts, Supply Chain Management, Additive Manufacturing, Automotive, ABC-Classification

Sammanfattning (Abstract in Swedish)

Tidigare forskning undersöker vad som skapar problem i leveranskedjan. Dock existerar det en lucka i forskningen kring möjliga lösningar till dessa problem. När logistiksystemen blir större blir det svårare att hantera och därmed är det avgörande att hitta resurser för att minimera risker samt öka effektiveten. Tidigare forskning anser även att additiv tillverkning kan vara en lösning till några av de problem som kan uppstå i en logistikkedja. Därför var naturen av denna forskning att undersöka konsekvenserna av att implementera additiv tillverkning för tillverkning av reservdelar inom fordonsindustrin.

En fallstudie gjordes tillsammans med en stor lastbilstillverkare. Företaget har gjort liknande undersökningar och ville ta nödvändiga steg för att öka kunskapen och hanteringskapaciteten. För att mäta effekten av additiv tillverkning i logistikkedjan, reservdelar som skulle vara möjliga samt lönsamma att produceras med tekniken identifierades. Olika metoder som har föreslagits av litteraturen har använts för att hitta ett stickprov; den första metoden innebar en hierarkisk process och den andra använde tre faktorer (årlig användning, standardkostnad för försäljning och ledtider) som användes för en ABC-klassifikation. Ramverket för att hitta de bäst lämpade reservdelarna för additiv tillverkning skulle kunna appliceras igen för olika divisioner i logistikkedjan.

De identifierade reservdelarna skulle endast teoretiskt sätt vara fördelaktiga att producera med additiv tillverkning. För att få riktig mätdata, användes de identifierade delarna i en kostnadsanalys. Två olika jämförelser gjordes i detta steg; det första gjordes via en matematisk metod från tidigare forskning kring en fallstudie och den andra utfördes genom en kostandsestimering via ett tredje företag som tillverkar produkter med hjälp av additiv tillverkning. Data från dessa källor jämfördes med aktuell kostnaden som insamlats ifrån företagets master-system.

De empiriska upptäckterna visade att 6.7% - 20% utav ett stickprov på 30 produkter var lönsamma att tillverka med additiv tillverkning. Genom att inkludera transportkostnaderna för den matematiska jämförelsen, kunde man få 6.7% - 23.3% produkter lönsamma. Dock var den största upptäckten att led-tider kunde sänkas. På de lönsamma produkterna kunde 66.6% - 85.7% sänka sina ledtider till 1-2 veckor. Om man undersökte hela stickprovet på 30 produkter kunde 19 produkter (63.3%) sänka ledtiderna, vilket motsvarar ungefär 63.3%. Detta kan innebära att de största fördelarna med additiv tillverkning är möjligheterna att öka företagets kundservice. Man kan argumentera för att om tekniken för additiv tillverkning utvecklas i samma takt, skulle det vara givande att forska djupare in på ämnet för att identifiera produkter.

Preface

This Master thesis has been written by two students at the M.Sc., Management and Economics of Innovation, at Chalmers University of Technology, Gothenburg, Sweden. This investigation is based on a single case, a big truck manufacturing company. The conclusions and discussions in the report are based on the authors' own opinions. Therefore, the conclusions and discussions aren't necessary supported by the truck manufacturer. The authors would like to use this opportunity to thank the truck manufacturer that dedicated resources and time during the investigation.

The authors would also like to express their gratitude toward their supervisor at Chalmers, Kenth Lumsden, to whom have given significant support during this study.

Robert Augustsson　　　　Denijel Becevic

Abbreviations

AM - Additive Manufacturing
ADU - Annual Dollar Usage
AU - Annual Usage
LT - Lead time
OEMs - Original Equipment Manufacturers
SKUs - Stock Units
AHP - Analytical Hierarchical Process

Definition of Central Concepts

Facilities are the physical location where product is stored, assembled or manufactured. Companies can gain benefit from scale economies by performing both at the same location, but at the cost of responsiveness. In the other way around, companies that have a lot of production sites can be closer to their customers. However, the cost for manufacturing would increase.

Inventory contains raw materials and finished products in the supply chain. Response time and the efficiency of the supply chain are affected by storage policies. Large stocks increases retailer costs and makes the supply chain less effective. However, maintaining a lower volume in stock will increase efficiency at the cost of response time.

Transportation is basically moving stock from one location to another. The choice of transportation is of importance in regard to response time and efficiency in the supply chain.

Information includes data and analysis regarding various parts of the supply chain, which can serve as guidelines to improve efficiency and response time. Information about the customers, facilities or inventory may give indications on how to coordinate the supply chain.

Location can be seen as one of the most important decisions in regard to strategy. Placement of production and inventory is highly affecting the trade off between responsiveness and costs. Companies can choose to be close to their customers for responding to demand more efficiently, or they can decide to produce and stock in low cost areas.

Price is the sum a firm requires in supplying goods along the supply chain. If a firm is demanded to provide goods in a shorter time, it will do so at a higher cost. Customer segments and their expectations affect the price. If customers expect a higher quality, they will get so at a higher price. Short-term price reductions can be used to eliminate old stock.

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1. Introduction

This section is meant to create a basis for the research questions and underlining supply chain problems and show the relevance of the study. The background is structured so that the starts with explaining spare parts management and the understanding of problems, strategies and the important of efficiency in spare part management. Moreover, the research paper investigates the outcome of implementing additive manufacturing in the supply chain and therefore a brief introduction of additive manufacturing is presented for the reader.

1.1 Background

Previous studies have touched upon problems and strategies for supply chain management. While previous literature has investigated efficient ways to minimize problems and cost wastes in supply chain. It does not sufficiently capture a possible solution to the underlying problems. The larger and complex a supply chain system becomes, performance measurements becomes crucial (Beamon, 1999). As the systems grow, choosing the appropriate indicators becomes difficult. A system can be seen as well developed if it's possible to identify critical components (Madu et al., 2011). Therefore, the supply chain has become one of the most important topics in regard to strategic operations to increase competitiveness (Albastroiu, 2012).

A case study with a big truck company was chosen to investigate the gap in research regarding additive manufacturing. The truck manufacturer operate and manage a big supply chain, which made it relevant for accessing relevant data and information needed for the case study. In the second part of the background and situation of the truck manufacturer is explained further.

1.1.1 Supply Chain management

The market for spare parts is worth hundreds of billions worldwide, and companies make tremendous investments to ensure high availability and customer satisfaction (Bacchetti, Plebani, Saccani, & Syntetos, 2010). Firms have become more aware of the impact after-sales and spare parts can have on profits and revenues (Wagner, Jönke, & Eisingerich, 2012). Strategies regarding spare parts management have therefore become increasingly important as companies aim to get competitive advantage in this area. However, the market for spare parts is considered to be a highly unpredictable, which creates difficulties for forecasting (Syntetos, Keyes, & Babai, Demand categorisation in a European spare parts logistics network, 2009), (Bacchetti & Saccani, 2012). Even though spare parts management has got an increasing attention in research, the connection between practice and research still needs more work (Cohen, Agrawal, & Agrawal, 2006) (Bacchetti & Saccani, 2012). Classification of spare parts stock keeping units is recommended in order to help companies make strategic decisions (Bacchetti, Plebani, Saccani, & Syntetos, 2010). Spare parts classification is connected to demand forecasting and inventory management in order to create performance assessments (Bacchetti & Saccani, 2012). Furthermore, classification may improve decision-making and create opportunities to increase spare parts availability and lower costs related to inventory (Syntetos, Keyes, & Babai, Demand categorisation in a European spare parts logistics network, 2009). To achieve cost effective spare parts management appropriate classifications has to be made. But in order to achieve this, more research has to put in when to use the different classifications (Bacchetti, Plebani, Saccani, & Syntetos, 2010) (Bacchetti & Saccani, 2012).

As customer satisfaction plays an important role, the ability to provide spare parts with high fulfilment at a low cost is a major challenge. Original equipment manufacturers (OEMs) have developed highly sophisticated supply chains in order to respond to the challenges (Khajavi, Partanen, & Holmström, 2014). In order to further improve the supply chain, new manufacturing concepts and supply chain designs have been developed. Getting closer to the customer has become more common for OEMs. However, there is usually a trade-off between having a cost effective supply chain or a responsive one (Gunasekaran & Cheng, 2008). Depending on a company's preferences, it can choose to either have lower costs or structure its supply chain closer to consumption for quicker response time.

Technology is starting to play a major role in strategic decisions regarding spare parts (Khajavi, Partanen, & Holmström, 2014). Firms can utilize technology in order to create strategic decisions regarding their after-sales market. Additive manufacturing is moving more towards manufacturing as it's prior been used for prototyping (Liu, Huang, Mokasdar, Zhou, & Hou, 2013). The technology may enable companies to make new strategic decisions in their spare parts supply chain as it becomes possible to produce on demand at various locations without the concern for large tooling costs (Khajavi, Partanen, & Holmström, 2014).

Similar research has been done in the aircraft industry. It's been concluded that the aircraft companies can lower the safety stock inventory for spare parts as well as draw the benefits of decentralized production and inventory (Khajavi, Partanen, & Holmström, 2014) (Liu, Huang, Mokasdar, Zhou, & Hou, 2013).

1.1.2 Additive manufacturing

It's important to understand the limitations of additive manufacturing in order to classify spare parts, which is described in the theory chapter. The additive manufacturing technology is continuously evolving and therefore it's important to keep up to date with limitations and new possibilities when investigating this technology. The initial cost for setting up additive manufacturing is cheaper than traditional production methods because of the use of expensive moulds, tooling, forms and punches (Berman, 2012) (Petrovic et al., 2010). Traditional production methods are usually cheaper for larger production series because it reaches a lower cost per unit after the larger the production becomes. Additive manufacturing is suited for small production series because of the low initial starting cost (Berman, 2012) (Reeves, 2009) (Ruffo, Tuck, & Hague, 2006). The elimination of tools will also bring down lead times, and cost in the first stages of the product development process and could help companies relieve problems with the money flow (Hopkins & Dickens, 2003).

Additive manufacturing means that designs are digitalized, which enables sharing and distributing on a global scale. The digitalized files share the same database and are often in (STL, DXF, IGES, STEP, etc.) format (Levy, Schindel, & Kruth, 2003). Digitalization also removes the error made by the human factor in production (Petrovic et al., 2010).

Additive manufacturing has evolved a lot since the first appearance and has showed signs of continuing to do so according to (Berman, 2012). According to Gideon et al. (2003) the scanning speed for SLS printers have increased productivity with a factor five from year 1996 to about year 2003 when the article was released, the scan speed can be seen in Figure 1. The speed of additive manufacturing compared to injection moulding is about 10-100 times faster (Berman, 2012). The accuracy still need to increase about 10 times before additive manufacturing can compete with current manufacturing methods e.g. injection moulding, extrusion moulding and resin casting (Berman, 2012). Berman (2012) suggests three evolutionary phases for additive manufacturing. In the first phase the additive manufacturing is used for prototypes and mock-ups, which also is supported by Bak (2003). In the second phase additive manufacturing is used to create finished products. In the third and final phase, consumers own their own additive manufacturing machines (3D printers).

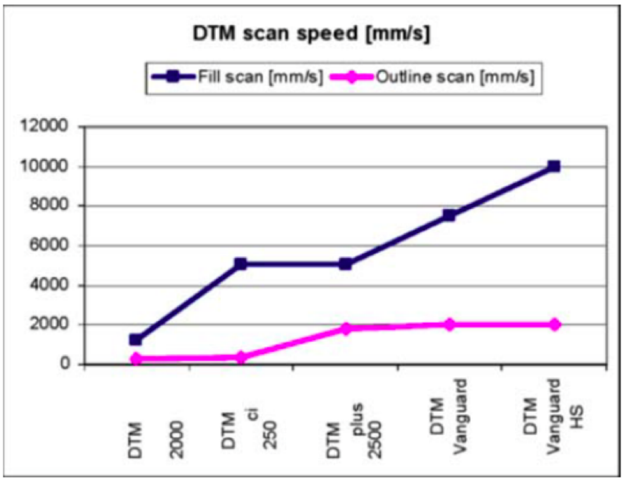

Figure 1. Scan speed of SLS printers (Gideon N. Levy, 2003)

Mass production in Europe is migrating to countries with cheaper and lower labour cost that has better material supply and tax-breaks (Petrovic et al. 2010). Nevertheless, the west countries are more advanced in technology and therefore have an advantage in developing new technology. European countries are therefore focusing on producing customized products and smaller series with additive manufacturing. This could also be cheaper and used on more niche markets (Berman, 2012). Eliminating tooling and using additive manufacturing instead makes it possible to create products at multiple locations simultaneously, which is called distributed manufacturing (Reeves, 2009).

This could be equally disruptive as the PC and Internet (Campbell et al., 2011). Additive manufacturing means that manufacturing becomes digitalized and thus disrupting the original way of doing things, such as removing inventories of products. It can also bring manufacturing closer to the consumers, which means less waiting time and better on-demand service. Additive manufacturing is according to Campbell et al. (2011) a revolutionary technology that will have significant impact in social, economic, political, demographic, environmental, and security related issues over the coming two centuries. Using additive manufacturing for manufacturing allows for lower cost/part for smaller series and different designs (Berman, 2012). The material used in the printed parts varies are plastics, ceramics and metal alloys. Usually parts consist of different materials and it's therefore important to integrate an efficient flow in the supply chain (Berman, 2012).

Additive manufacturing is applicable in different industries and has shown positive result. An example of the how additive manufacturing could be used is within the Formula 1 race cars, were fully functional engine parts was printed (Campbell, Williams, Ivanova, & Garrett, 2011).

Before the late 1980's, the majority of manufacturing techniques were using a subtractive approach such as milling or a formative approach as moulding (Reeves, 2009). Additive manufacturing, also known as 3D printing, employs a manufacturing technique in where products are built on a layer-by-layer basis (Berman, 2012). They work in a similar fashion as inkjet printers, but they also build in a third dimension fusing material together. The technology uses 3D drawing from 3D CAD software's to determine how each layer is to be constructed. The machines can produce simpler designs in short time. There are different production techniques when it comes to additive manufacturing, however they all have the same operating principles. The 3D CAD drawing is to be translated into an STL-file, which can be properly processed by the machines.

Since this technology was first commercialized in the early 1980's it has grown at an exponential rate (Reeves, 2009). It was first introduced used for simpler prototypes and forms to move towards medical implants with various materials to choose from 25 year later.

The machines themselves have a build volume inside in which the objects for manufacturing can fit (Petrovic et al., 2010). Then material is added in the build volume and fused together in accordance to the 3D drawing. The material in the interior that is not fused is left untouched and may be recycled. However, the material that is left untouched cannot support fused structures. The machine knows where to fuse the material as the 3D file is sliced into many two-dimensional pieces, which are fused together to form a final three-dimensional object.

The process for additive manufacturing can be explained and illustrated in a number of stages starting with the modelling of a 3D CAD file of the object. When this is done, the CAD file is converted to an STL-file, which slices up the object into many small layers. The machine calculates which areas that need to be fused in each layer then processes these layers. Then it starts fusing one layer of material and fuses the calculated areas. This stage is repeated until the build volume is complete and the object is fused together (Reeves, 2009). Orientation of the product in the build volume is highly affecting quality and delivery because of the layer-by-layer manufacturing process (Reeves, 2009).

The process of Additive Manufacturing can enable product developers to work in a high degree of geometric freedom, as opposed to usual ways of manufacturing (Lindemann et al., 2013). More complex designs are possible to create product designs based on functionality and don't have to worry about the limitation of manufacturing restrictions.

Types of 3D printing methods
There are several different additive manufacturing methods available today and in this section they are described individually. Techniques for printing ceramics and metals are not presented due to the scope of this research.

Stereolithography (SLA)
SLA stands for Stereolithography and it's a method, which uses a laser beam. The laser beam achieves photopolymerisation of a material and turns the liquid state into a solid state (Petrovic et al., 2010) (Bak, 2003). SLA has the capability to work with different types of resins to imitate properties of thermoplastics materials (Bak, 2003). This is used to produce different raisins with different heat and temperature properties. This technique is good for developing products with high thermal resistance, smoother surface, elasticity and precision (Petrovic et al., 2010). Thus, SLA is usually used for functional prototypes. The benefits are complex structures, thin walls and high reliability. The primary disadvantage is the changing of resin, because it takes some time.

Fused deposition modelling (FDM)
This method uses heater to melt a plastic thread attached to a header head (Petrovic et al., 2010). The material is usually based on polycarbonate and ABS or both mixed together. These polycarbonate materials usually have the properties of thermoplastic materials (Bak, 2003) (Petrovic et al., 2010). The primary benefit of using the FDM method is the use of cheap material. This can be used to create cheap and functional prototypes. The cons are poor surfaces and bad quality with some issues with dimension accuracy (Petrovic et al., 2010).

Selective laser sintering (SLS)
SLS technology uses laser beams on different material in powder form. This melts and solidify the powder and creates a layer of the material, this is done several time and creates layer on layer to

create the finished product (Petrovic et al., 2010) (Bak, 2003). For this method polyamide powder is usually used alone or combined with glass fibres or aluminium material (Petrovic et al., 2010). SLS is used to create products with good mechanical properties. Prototypes, models and finished products are made from SLS and this technology can create parts without support material that also can withstand higher temperatures than parts made from SLA technology. However, the surface might have a porous surface and the possibility to disfigure in higher temperatures.

Digital light processing (DLP)
DLP uses UV-light to melt and create layer of solid material. This technology is highly accurate but works at a slow speed. Thus making DLP methods appropriable for small parts and products with complex geometries, thin details, and the need for flawless surface finish. However, making small parts makes it difficult to remove support material without damaging it after it's finished (Petrovic et al., 2010).

1.1.3 Case of Study

The automotive industry needs to rethink their supply chain to stay competitive when facing overcapacity and demand instability (Desmond, 2004). The truck manufacturer company where the case study took place was facing these problems and therefore suffering of high costs. In order for the truck company to stay competitive, they wanted to investigate new and efficient ways to supply spare parts to their customers. The company believes additive manufacturing could be a solution in order to lower cost and increase competitiveness. Based on these reasons the truck company was interested in investigating the possibilities and limitations of additive manufacturing that could possible solve problems with safety stocks cost and delivery time. Thus, an investigation into the spare parts inventory was done in order to identify these considerations.

1.2 Purpose

The paper aims to investigate if inventory costs for low turnover spare parts can be lowered for a large truck manufacturer, but still offer the same availability by using additive manufacturing. It does so by applying generic theories and principles regarding spare parts management and identifying which products can be applied within the boundaries of additive manufacturing in the spare parts supply chain.

Research Questions:

1. What types of low turnover spare parts would be best suited to produce with additive manufacturing?
2. Is it possible to increase the profitability of the truck manufacturer company by lower the costs of production and distribution of spare parts, but at the same time provide the same availability with additive manufacturing compared to regular manufacturing?

The two research questions together, examine if it's sustainable for the truck manufacturer company to implement additive manufacturing in their spare parts supply chain. The growing attention for additive manufacturing has led the case company to examine how they can benefit from using the technology in their business, more particularly for spare parts. The questions purpose is to see if it's possible for the truck manufacturer company to make their spare parts supply chain more profitable by using additive manufacturing. The first question intends to identify which types of spare parts that are best suited to manufacturer with additive manufacturing. The second question compares additive manufacturing and regular manufacturing, for the chosen spare parts in question one, in order to see if the truck manufacturer can draw benefits of lower inventory costs but provide the same deliverability.

1.3 Scope

The scope of this case study is to investigate if inventory costs for low turnover spare parts can be lowered in a big supply chain. Therefore, a large truck manufacturer was the focus of the case study. This means no data from other companies was used in the analysis of this study. The focus of this study is to highlight the pros and cons of using additive manufacturing for production of spare parts. There is a lack of theory of this subject and the use of additive manufacturing within the automotive industry, which limits the information available for the researchers. Therefore, the researcher might miss new or recent research concerning the thesis topic that might be relevant for the study.

Only additive manufacturing technology for producing plastic parts was included in this research. Plastic technology considered to be developed further than other technologies for printing other materials. Moreover, the timeframe of this project limited the researcher to investigate the metal parts at the truck manufacturer. In general the majority of parts in a truck is metal and with over 90'000 parts to investigate, plastic would narrow down the complexity and research time. Also, metal parts have a high chance of being critical to the functionality of the truck, thus having a high risk of needing further investigation before being produced with additive manufacturing. This is compared to plastic products that doesn't generally have a critical role for the functionality and therefore doesn't need as much further research.

In this case of the truck manufacturer, one big cost factor is the aftersales market and the warehousing cost attached to the low turnover spare parts, thus they wanted that this research should investigate low frequency spare parts. There are other areas within the truck manufacturer that are interesting to investigate, for example production and R&D. But since there is a lack of theory in these areas this case study is limited to the low volatile spare parts, which have high costs to keep in inventory.

1.4 Report Structure

The report is structured according to Chalmers Technological University (CTH) preferences. A structure of the report is shown in Figure 2.

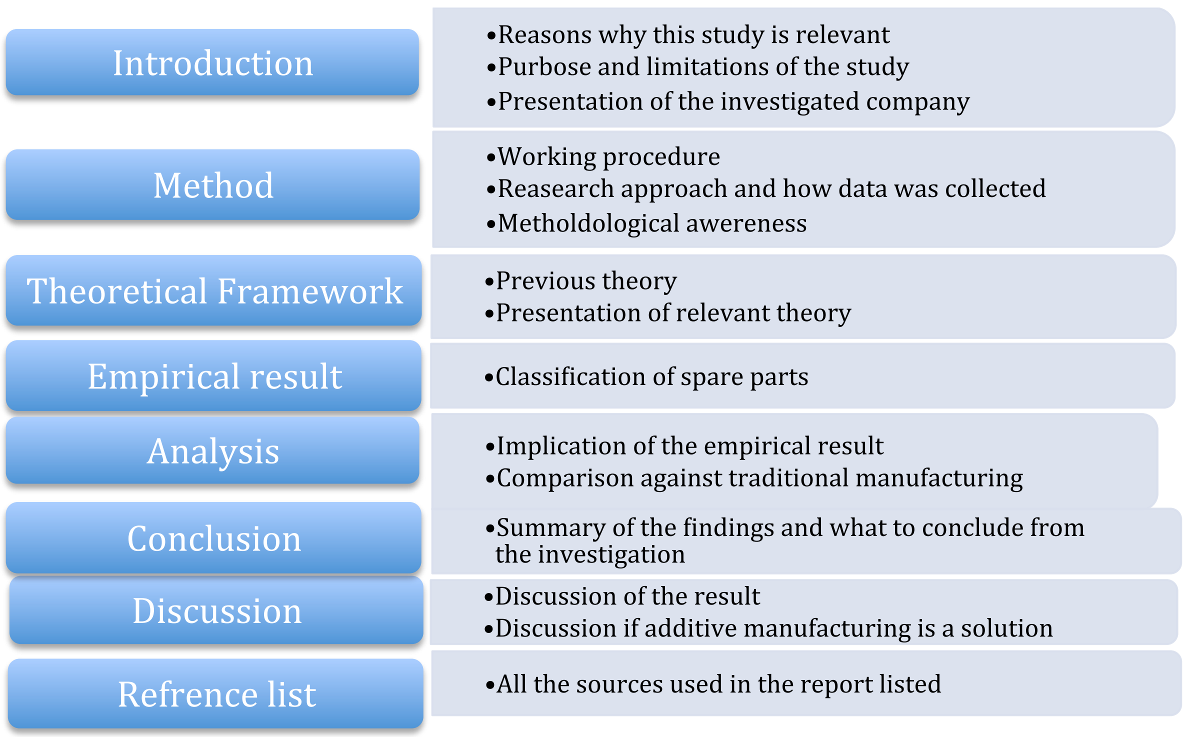

Figure 2. Structure of the report.

2. Method

In this chapter the method, which was used in the case study is presented. This section is divided into smaller categories, starting with the emerging of the problem. The chapter continues with a description of how the data was collected. In the ending of the method chapter brings awareness to how well the study was performed. Moreover, the methodology awareness gives the reader an understanding of influencing factors that could have disturbed the result.

2.1 Emerging of research problem

The research problem first occurred when the researchers contacted the truck manufacturer about a potential project. The ties between the researcher and truck manufacturer are linked through this previous engagement to discuss improvement and cost reduction within the spare-part division. The purpose of the project was to investigate the classification of spare parts and the ramifications of adopting additive manufacturing as a new production tool. The research problem was interesting because of the high maintenance and after-sales cost for spare parts. To get a better understanding of the problems and limitations within this industry a literature investigation was done. This gave the researcher a better understanding of the research area of where to focus their attention in order to solve the research problem.

2.2 Previous relationship with the case company

In the previous section it was mentioned that the researcher had contact with the truck manufacturer company before the project started. This is due to a previous work related project when the issue of investigating the profitability of using additive manufacturing for manufacturing spare-parts. The researchers worked together with the staff of the truck manufacturer company. This enabled the researchers with access to relevant data and expert insight within the industry.

2.3 Research Strategy

This is a single case study performed at a single truck manufacturer where the goal was to answer two research questions. The research was divided in two parts, the first part investigate the first question, which then made it possible to answer the second question. According to Bryman & Bell (2011), research methods can be of a quantitative or a qualitative nature, or a mix of both. The different types of methods refers to how data are collected, where quantitative data generally consist of interviews or other processes to generate abstract data consisting of non-numeric data, and quantitative data is generated for example by experiments, surveys, or official data and is described by numbers.

Part one

Part one includes the research on question 1) "What types of low turnover spare parts would be best suited to produce with additive manufacturing?" The first part comprised of a quantitative and qualitative research approach, which was used to classify spare parts used in the investigation. A mixed research approach was chosen, since the researcher lacked necessary skills to determine product specifications. According to Bryman & Bell (2011), this approach is useful when it's necessary to fill in the gaps of information. In this case study the researchers had limited access to essential information thus creating a knowledge gap. The information gap was filled by the truck manufacturer because of their access to the many in-house systems and with their keen knowledge within the spare part industry. The strategy for solve the research question was to gather theory and cross reference this with the employees knowledge in order to classify spare parts and sort them into a manageable size from where the sample size was decided, see Figure 3. The end goal was to evaluate and compare costs of traditional spare part management against implementing additive manufacturing and the implications that follows.

Part two

In order the investigate the second question 2) "Is it possible to increase the profitability of the truck manufacturer company by lower the costs of production and distribution of spare parts, but at the same time provide the same availability with additive manufacturing compared to regular manufacturing?" a quantitative approach was chosen. A comparison between the standard cost of sales (standard cost of sales = standard cost (purchase price + acquisition cost) + internal costs) from current spare parts management, and the same costs from additive manufactured spare parts was performed, in order to answer research question 2, see Figure 3. The cost estimation for additive manufactured spare parts where taken from three sources. The first source was from a mathematical model, based on previous research. The second and third sources were taken from two big third party suppliers called i.Materialise and Shapeways. These two were chosen because they are two established suppliers and they provided easy access to cost estimations based on CAD-models.

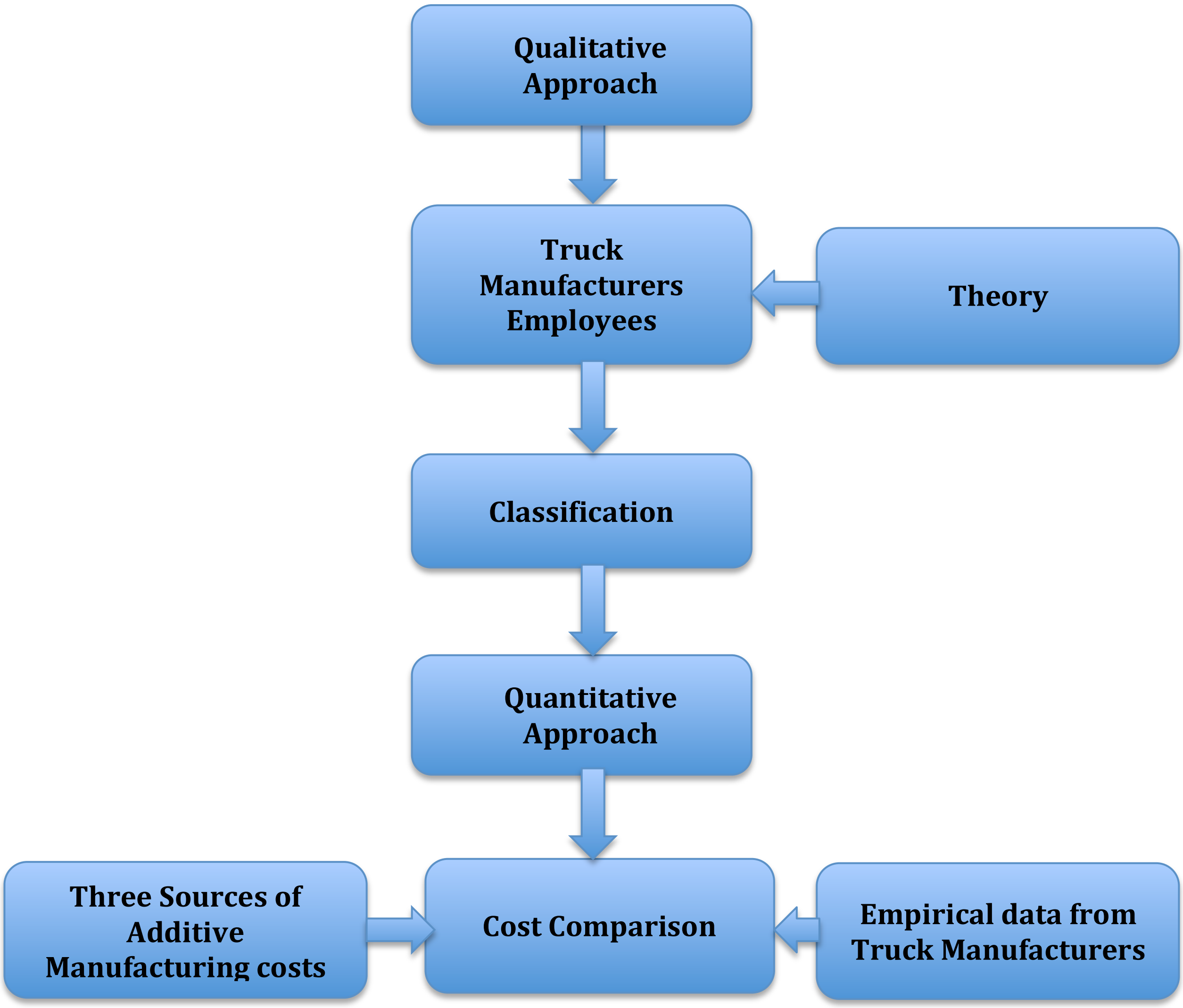

Figure 3. Strategy for solving research question 1 and 2.

2.4 Research Process

As the research strategy is consisting of both qualitative and quantitative research to an extent, the process described by Saunders et al. (2009) considered as a good fit, see Figure 4. However, in this case, the sampling process can be visualized as a process in two steps combining qualitative and quantitative sampling in each step (tech qualitative -> tech quantitative -> economical qualitative -> economical quantitative). Therefore, the research process is an iterative process.

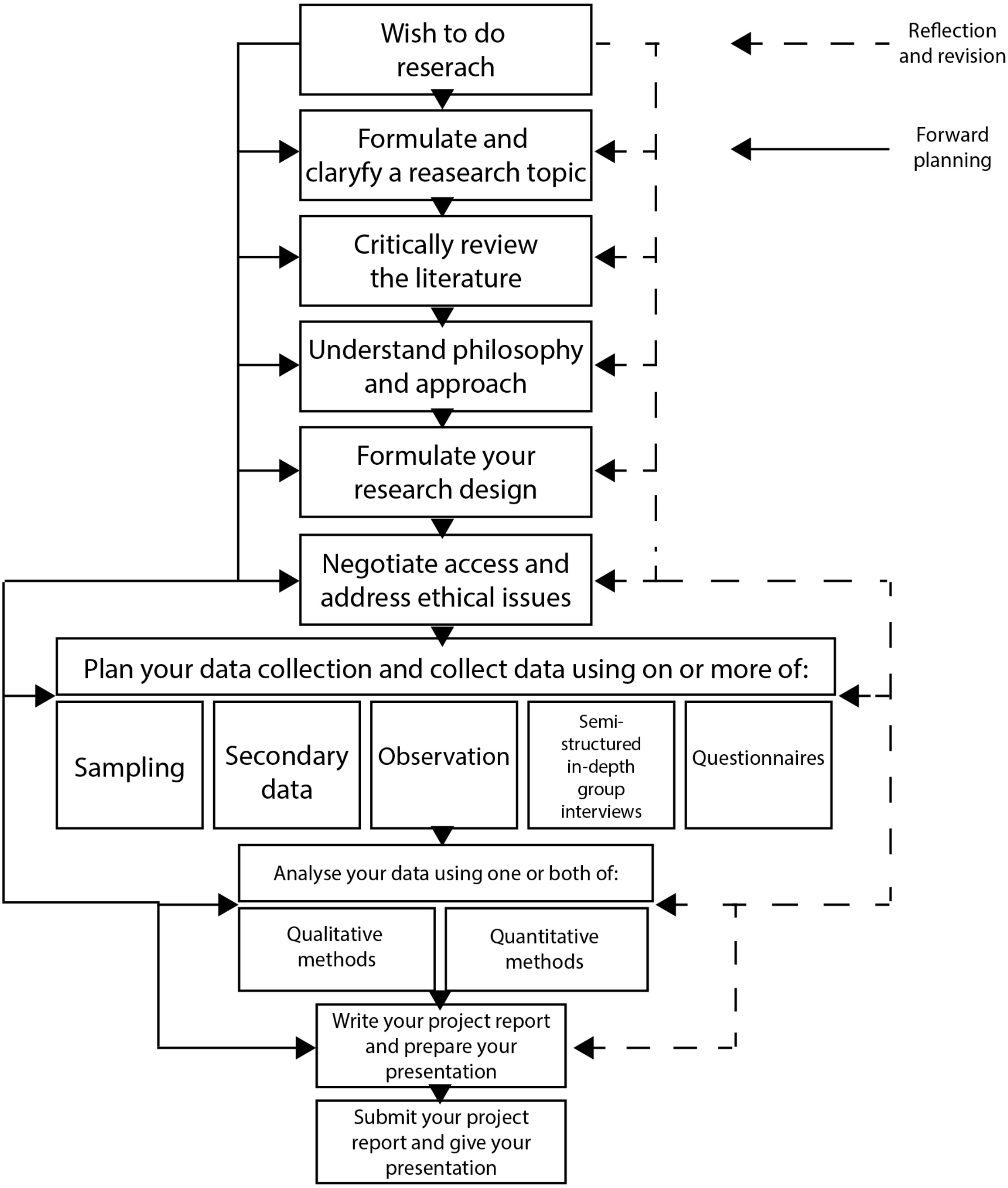

Figure 4. "The research process" (Saunders, Philip, & Thornhill, 2009) page 11.

The formulating and clarifying of the research topic can be seen as the starting point that helped choosing an appropriate research strategy, data collection and analysis techniques (Saunders, Philip, & Thornhill, 2009). In this case, the research topic was generated in line with rational thinking. This approach of generating ideas lies in the research own strengths and interests, as well in researching literature. However, the research purpose has been revised and set with regards to the need of the truck manufacturer company and the research supervisors at Chalmers. Thus, the research questions and objectives have been formed through influence from the two sources. By formulating the research purpose and strategy, the next step 5 regarded structuring a research design in order to answer the research questions. As the research has a deductive approach, which analyses collected data with gathered theory, step 3 is conducting literature studies (Saunders, Philip, & Thornhill, 2009). This phase consisted of gathering previous research for spare parts and additive manufacturing, to compile how the latter topic can solve issues in the former topic. Furthermore, the literature study regarding spare parts also consists of classification, which is a major part in order to organize different spare parts. With the compiled literature, step 8 was consisted of qualitative interviews and meetings with experts at the company in order to get an appropriate sample size for spare parts classification. The sampling was first done with a qualitative approach to identify technical factors that have to be considered for producing with additive manufacturing. When the factors were identified with the help of employees at the truck manufacturing company, the spare parts database got sampled quantitatively and creating a population size. To further decrease the sample size, a classification analysis (ABC-analysis) was done. These factors were also quantitatively applied to get the final sample size of spare parts. When the sampling was set, analyses were made in order to answer the first research question. The aim of the first analysis was to compare additive manufacturing with spare parts properties in order to identify, which spare parts that are possible to produce with additive manufacturing, based on economical and technical factors.

The second phase of the research regards the second research question. Based on the collected and analysed data for the first phase, studies was conducted to find out if additive manufacturing could lower costs but offer the same availability as the local company's current logistic system. Phase two was structured in a way to find a breaking point where additive manufacturing can offer the same availability of spare parts as regular manufacturing.

2.5 Research Design

The research design can be considered as a general plan of how to approach the research questions (Saunders, Philip, & Thornhill, 2009). Furthermore, the research design can be considered as a framework for collecting and analysing data (Bryman & Bell, 2011). The framework is supposed to help in different steps in gathering and analysing data. The research conducted can be regarded as a case study at a single organization. According to Bryman and Bell (2011), the conducted case study falls in line with *a critical case* as the combined literature study created a hypothesis that was tested.

As the theme of the research topic was relative new to the authors, the early phase of the literature study was of exploratory nature in order to gather knowledge and understanding. This step led to deeper understanding in where the problem lies and how it can be solved according to theory. This approach led further develop a clear purpose and hypothesis to be tested in the case and comparative study conducted at the truck manufacturing company. An exploratory study has the benefit of being flexible, which is fit for this research. The second part of the literature study was to analyse the gathered data from previous research and compile it in order to be able to state a clear hypothesis, thus creating a critical case study, see Figure 5.

As the research was conducted as two phases for the empirical investigation, two quite different research designs were undertaken with the same base data gathering. The first phase consisted mainly of identification of data, which was compared between two different manufacturing techniques. The second phase on the other hand was comparing different forms and logistic systems to identify if the local company could benefit from implementing a new technology within their logistic operations, see Figure 5. Therefore, a comparative study can be regarded as a part within the case study as it compares two different manufacturing methods of the same products.

Conducting a case study is limited because of its external validity (Bryman & Bell, 2011). However, a case study is mainly not purposed to generalize a case or population beyond the research case.

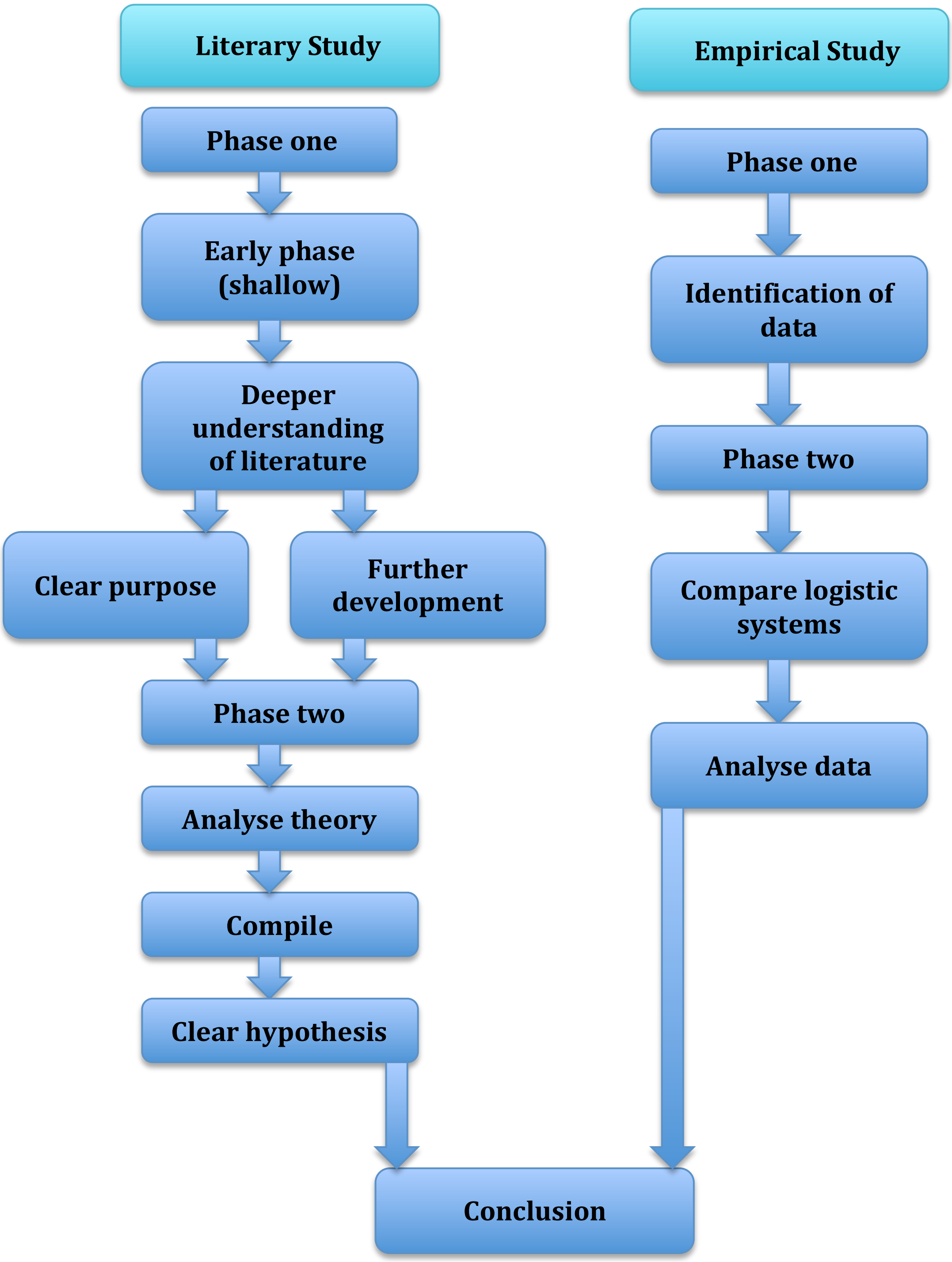

Figure 5. Literature and empiric research approach.

2.6 Data collection methods

The data used in this research was theoretical and empirical, which was separated in two different categories. The theoretical data was collected through literature studies and gathered through recommendations and expert help. The empirical data was gathered from the truck manufacturing company.

2.6.1 Literature Study

As the research conducted follows a deductive approach of testing a hypothesis, a literature study was performed for both topics in this report. First the study regarded spare parts, in where literature was analysed in order to identify the main concerns companies might have within this area. Next, previous research regarding additive manufacturing was examined in order to map out the limitations and possibilities with the technology. Hence it gave an understanding of how additive manufacturing might solve or minimize issues regarding spare parts management. The literature study regarding the two topics helped shape the developed theoretical framework, creating two hypotheses. In addition, two frameworks were included from previous research as they assist in classifying spare parts, which is crucial for spare parts management.

2.6.2 Business Performance Monitoring

As the study was mainly done through observation and evaluation of data from the truck manufacturer, most of the data was collected through documentations within their databases, which is described by Phillips and Stawarski (2008) as business performance monitoring. Furthermore, the data was based on current measures in where the proposed measurement factors were regarded necessary by both the company and previous research. To classify the spare parts, the factors were chosen and ranked with the assistance of relevant staff ranging from the most relevant factors to the least relevant. Employees that were involved in the study were part of management for spare parts and logistics at the truck manufacturer. Thus, having access to relevant information for this research.

2.6.3 Sampling

According to (Saunders, Philip, & Thornhill, 2009), a large population can be represented through a sample if to minimize resource consumption. As the local company posses a large amount of products, a sampling method was performed due to resource restrictions. The sampling process was structurally conducted, which can be regarded as a probability sampling. A probability sampling contains a list, called a sampling frame, from which the sample will be drawn based on set preferences. However, when choosing a sample, it’s important to be aware of possible issues using existing databases (Saunders, Philip, & Thornhill, 2009). One of the issues in researching an organization’s databases is that information might be out of date. Therefore, the researcher needs to make sure that the sampling frame is up to date and accurate. In order to determine the sampling size, at least a 95% confidence level is appropriate to achieve (Saunders, Philip, & Thornhill, 2009). This means that at least 95% are certain to represent a population.

Saunders et al. (2009) describe the probability sampling in four stages as shown in Figure 6. In the first step, the sampling frame was decided based on the literature study and from meetings with experts from the truck company. It was decided that the sampling frame was to first be conducted based on technical data and limitations of additive manufacturing. Hence a second sampling round was made based on economical factors i.e. frequency and costs. An appropriate sampling size was decided upon that was manageable. In step three; consolidating with relevant people from the company set a multi-stage sampling technique to some extent. This sampling technique refers to deciding upon sampling frames of relevance to create sub-areas. However, since the sample was created through technical secondary data found in databases, the random selection was conducted after classification of the chosen products was done. Choosing to conduct a random sampling for each class of products was done in order for the sample to only represent the populations of a specific class. Furthermore, as the products in the sampling size have similar characteristics as the population, the sampling can be regarded as representative of the population to some extent (Bryman & Bell, 2011). The final sampling size was narrowed down to 30 products from the original amount 90 000, see figure 6. The description of the sample size will be presented in the empirical findings chapter.

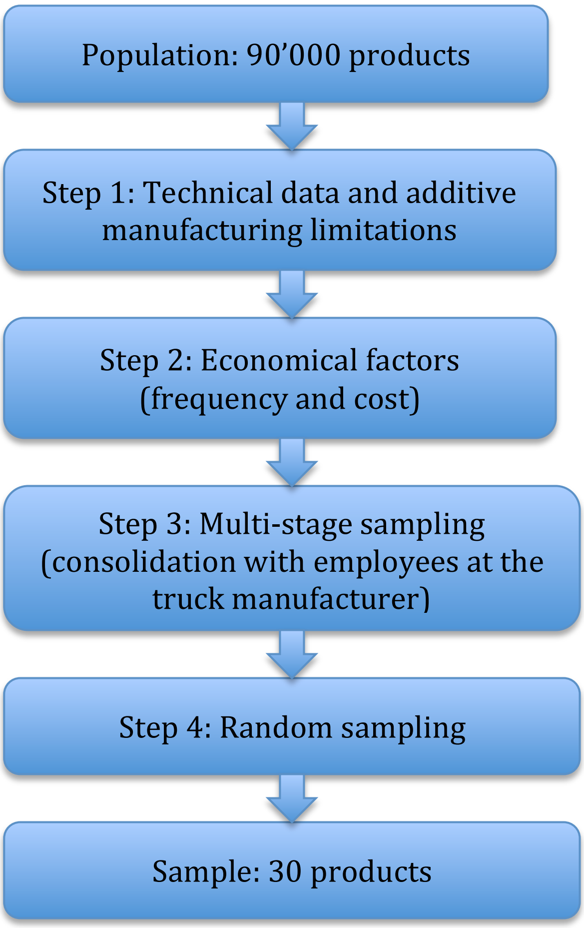

Figure 6. Sampling process.

2.7 Data Analysis

Collected data was analysed in in two steps. Each research question had it’s own analysis based on the same product data as illustrated in Figure 5. For the first research question, a numerical analysis was conducted in order to rank products according to their frequency, lead times and costs and put into a data matrix. The next step involved relevant staff from the company in order to rank the three factors in terms of importance. This was needed in order to create a non-subjective classification using the weighted linear optimization model. The classification model divided the chosen products into A, B or C classes, based on their weighted importance. The class for each product was then put into the matrix, ranking them in accordance to which class they belonged. After the classification, a sample from each class was randomly taken for a cost analysis of additive manufacturing. The cost difference was later generalized within an interval of how much more additive manufacturing is in terms of production costs. When the production costs were written down, a comparison was made between the different production methods to identify, which products that were best suited to produce with additive manufacturing.

The second analysis regards research question two. Here the data and identification from the first research question was applied, but the logistic demands and the total costs for supplying a product were also considered. A weighting was conducted by comparing two scenarios. The first (1) scenario was the ordinary supply chain and their total costs, and availability demands. The second (2) scenario considered additive manufacturing as a production method for the identified parts, making production costs higher, but lowering inventory and transportation costs. In the comparison, the total costs were first calculated with the help from staff at the company. If it the case showed that total costs could be lowered using additive manufacturing, the research would move into the next step of comparing availability. The different forms of availability were analysed based on the pace of production and transport, trying to find a breaking point in where a slower production method can offer the same delivery time. In addressing research question two; the hypotheses created in the theoretical framework were tested.

2.8 Methodology awareness

The validation of the gathered data was investigated in order to determine the quality of the research. This part is important in order to highlight the credibility of the research and also gives the truck manufacturer an opportunity to assess the reliability of the case study. The data collection was done in two parts, the first part was collected through a mixed method and the second part was collected through a quantitative method. Hence, this section is divided in two parts in order to analyse each method. The findings from the research and the method used will be discussed. The researcher's bias throughout the study should be pointed out since one of the researchers is a stakeholder in company within the additive manufacturer industry. But as this research could possible verify the potential business opportunity for his company and act as guidelines for future research thus the risk for bias is considered medium. If the researcher have interpret data or transcribed wrong information or data this could be a possible risk and contribute to an unsuccessful study. But with the help of two supervisors and two opponents that reviewing the research this risk is considered low.

This research was based on a single case, which makes it highly unlikely to generalize the findings for other cases. The data analysed was specific for the truck manufacturer and therefore the findings are hard to compare with other companies in the automotive industry. Depending on other companies system and product data their analysis would look different and might cause other findings.

Part 1

The quantitative approach was done in order to fill the gap of knowledge of the researcher. The experts helped with sorting and finding parts that was later classified through certain steps. Using the expert's knowledge and sorting through thousands of articles and finding a population size of a couple of hundred to analyse. Using their knowledge in order to narrow down the sample size might cause the researcher to miss certain aspects that could have occurred if they did the sorting of the sample size themself. The risk of getting biased information is considered high because of the experts have worked their for a long time.

From the population the researchers using a quantitative method chose size the sample size. The quantitative method was used create the sample size from population size. This was done with a mathematical method. The parameters used in the mathematical method were produced from theory and a hierarchic method. Using a hierarchic method was done with the help of employees on the truck manufacturer company. Hence, having a high risk for biased information.

Part 2

In part two the data was in the form of archival data obtained from the truck manufacturer, thus making it highly reliable. The data is however restricted and highly dependable by the nature of the industry. This means the data is hard to replicate for other case studies, as other companies would have different arrangements with retailers, suppliers and logistic services etc. In order for the data to be replicable or transferable to other cases then it would have to be under the same conditions as the investigated truck manufacturer.

3. Literature Review

This chapter presents previous research that will be analysing with the empiric finding. The theory has been chosen based on the relevancy to create an understanding of issues in spare parts management and the benefits of additive manufacturing. To do so, it first regards issues in supply chain and spare parts management then generally presents theory on additive manufacturing.

3.1 Previous research

This section contains previous research of supply chain, supply chain management and additive manufacturing.

3.1.1 Supply chain

A supply chain can be defined as integrations between key business processes from supplier to end-user (Perumal, 2006). By dividing a supply chain into primary and secondary components it's possible to understand how companies can improve in terms of responsiveness and efficiency (Vierasu & Balasescu, 2011). Furthermore, the components within a supply chain do not operate independently; instead they interact with each other and determine the performance of the supply chain in terms of responsiveness and efficiency. The parts of the supply chain range from the actual facilities that store materials and products, through the process of inventory holdings and transportation. Furthermore, it includes the information gathering through this process and the costs of supplying resources through the chain. Management's strategic goals usually lay the ground for the structure of the supply chain. Traditionally, supply chain management has been seen as a process for moving and distributing goods. This has led to that supply chains has mainly been regarded as major costs that do not drive revenues (Albastroiu, 2012). As product life cycles are becoming shorter and the competitive landscape increases, it's crucial to explore more dynamic practices within their supply chain.

3.1.2 Supply Chain Management

Supply chain management has gained tremendous attention since the 1980's, as the term was introduced (Lambert & Cooper, 2000). Supply chain management was viewed as logistics outside the firm to include customers and suppliers. Thus, logistics management was to be seen as a part of supply chain management. Objectives of supply chain management are to create the most value throughout the whole supply chain, ranging from suppliers to end customers. As the research from Lambert and Cooper (2000) suggests, the structure of activities within and between companies is vital for creating superior competitiveness and profitability. For a supply chain to function properly, synopsis of basic practices can be regarded as necessary. However, an excellent supply chain contributes to enhance a business strategy (Perumal, 2006). Organizations that manage to fulfil the criteria of a supply chain excellence usually have a clear strategic direction.

Companies should focus on minimizing costs, increasing profits and maximizing market share. However, lowering costs in the supply chain comes at the expenses of increased risk. Therefore risks and uncertainty needs to be minimized and dealt with effectively (Albastroiu, 2012). Moreover, in an optimal state, the supply chain strategy should enhance the company's overall business strategy. Hence the design of a strategy should regard both internal and external elements.

However, companies need to rethink their supply chain strategies as technology keeps evolving, as the effectiveness of a supply chain lies in the ability to react to new demand situations and customer needs (Perumal, 2006). The ability to react uncertainties demand lies in the supply chain flexibility (Vickery, Calantone, & Droge, 1999). Flexibility can be put down into four main areas, namely *Volume, Product, Launch, Access* and *Responsiveness.* Volume, launch and target market flexibility has the highest ranging impact on financial and market performance, in where volume flexibility is highly related to overall firm performance. As illustrated by (Vickery, Calantone, & Droge, 1999), uncertainty does not result in higher emphasis on one certain flexibility. However, top performers in terms of flexibility assigned a higher value to product flexibility in manufacturing.

3.1.3 The long tail – Low frequent flows

The automotive industry has since the 1950s been mostly evolving by incremental innovation (Fujimoto, 2013). Innovations occurring have not radically changed the products or disrupted the industry. Parts that have been developed have mainly enhanced performance and increased the companies' competitiveness. Demand is distributed in accordance to the new innovations (Syntetos, Babai, & Altay, On the demand distributions of spare parts, 2012). There is a higher volume of slow moving spare parts with an intermittent demand than fast moving parts. This could be explained by Poission distribution, thus creating a "long tail" (Topan & Bayindir, 2012). The term "long tail" was first mentioned by Chris Anderson in order to explain the pattern of Poission distribution (Wu, Luesukprasert, & Lee).

From being able to sell merchants in physical form it's possible to sell over the Internet in digital form. The sale sum of the low frequency items added up is starting to compete with the top selling product (Wu, Luesukprasert, & Lee) (Bentley & Madsen, 2009). The Pareto principle describes distributors sales, 20% of the sold products sums up to 80% of the overall income (Wu, Luesukprasert, & Lee) (Brynjolfsson, Hu, & Smith, 2006).

With the emerging of e-commerce and a market for digital files, the 80/20-rule is not applicable. For example the Amazon.com case were half of their income come from low frequency products. Selling digitalized products means that the tail can continue to grow since there is no noticeable cost in having a bigger range of digitalized product. Bentley & Madsen (2009) suggest that there is a limit of the tail. If the long tail grows over the millions then the administrated cost gets too high and the long tail stops being profitable. With the Internet the reachable customers have increased exponentially and therefore the niche markets that used to be unprofitable has found a way to become profitable (Brynjolfsson, Hu, & Smith, 2006). This has been beneficial for niche books that sell in small quantities. Print-on-demand systems have shown profitable for volumes under 1'000 because larger prints have a large initial printing cost, which means there is a great risk involved (Brynjolfsson, Hu, & Smith, 2006). Using a print-on-demand service is also great for small publisher since there is no cost upfront, making it ideal for uncertain market demands (Brynjolfsson, Hu, & Smith, 2006).

3.1.4 Spare parts in the supply chain

Spare parts are an important part of an organization's business as they can account for up to 45% of gross profits and about 24% of revenues (Cohen, Agrawal, & Agrawal, 2006). However, even though they can account for a large part of a business, organizations' usually squander its potential. Even though companies hold a large amount of items in stock they are usually poor at handling their service (Bacchetti et al., 2010) (Cohen, Agrawal, & Agrawal, 2006) Service networks usually have to handle 20 times the stock units (SKUs) as the manufacturing function. Moreover, after-sales are an unpredictable and inconsistent marketplace. They can be highly varied in terms of costs, service requirements and demand patterns (Bacchetti et al., 2010).

Spare parts management can be defined as the technique of maintaining stocks of resources with the minimum investment. Quick inventories result in larger profits. Besides the importance of keeping a smooth production, it's important to provide safety against price-rise and scarcity. Inventory hold ups for spare parts usually occur when quantities received are larger than consumption. The availability for spare parts in terms of time is crucial for production. In applying the latest innovative techniques for spare parts management, a more accurate forecast of spare parts can be achieved (Kumawat, 2014).

Spare parts inventory management may face the challenge of responding to high customer expectations, even though there is an intermittent demand (Rego & Mesquita, 2011). Furthermore, life cycles of spare parts is facing reduction, creating higher chance of obsolescence. The demand structure for spare part differs from other stocking units. Similar to the overall supply chain; spare part inventory face the trade-off between customer service and lower cost (Wahba, Galal, & El-Kilany, 2012).

3.1.5 Classification of spare parts

Inventories with large numbers of spare parts are difficult to manage (Wahba, Galal, & El-Kilany, 2012). Spare parts can be classified in order to serve different purposes (Bacchetti & Saccani, 2012) Since companies usually stock large amounts of spare parts, Bacchetti et al. (2010) suggest that the SKU's should be categorized. Classification of spare parts can be used in order to help decision-making within organization and may be able to be done on a mono- or multi criterion basis (Wahba, Galal, & El-Kilany, 2012) (Bacchetti & Saccani, 2012). Spare parts might fall into more than one criterion, which increases the complexity of the classification. Recent research has mainly used multi criterion for spare parts to lower conflicts for stock control methods. However, multi criterion classification also has issues depending on how data is interpreted (Duchessi, Tayi, & Levy, 1988). Standard ways of classifying spare parts happen from a bottom-up approach. In this case, engineers, managers and other experts evaluate the importance of spare parts based on what is most likely to fail in operations. By applying a top-down approach for classification requires all spare parts to be analysed within a sample. Simple models/tools have been traditionally been used in order to classify spare parts, namely the ABC-model and VED-model (Roda et al., 2014). The ABC-model has been based on inventory items and often the annual usage per dollar, as the VED model has a more qualitative approach. As the VED-model is a qualitative approach, the results from a conducted analysis might be interpreted differently due to subjective judgments of users (Bucchetti et al., 2010).

Previous research that classifies spare parts in accordance to their *sales life cycle* usually divides the life cycle in parts of introduction, majority and decline. Furthermore, the sales cycle is relevant to consider in forecasting demand and purchasing/inventory management. Demand patterns and forecasting becomes difficult for spare parts of recently introduced products. An item is considered to be in the introduction phase when the interval between evaluation and first customer order is shorter than 6 months. When the time between evaluation and last customer order is larger than 18 months, the spare part is classified as dismissed. All other parts are regarded to be in the in-use phase.

Another classification of spare parts can be done in terms of *supply characteristics/uncertainty* and *lead times.* Lead time is regarded when deciding if a spare part should be held in stock or not. When response lead time is larger than or equal to replenishment lead time, it is not necessary to keep inventories (Bacchetti et al., 2010). Dekker et al. (1998) determine that service level is an important factor in inventory operations. The service level can be connected to demand volume/value as it counts for how large proportion of the demand that can be satisfied directly from the inventory level. Factors such as lead times criticality and obsolescence can in some cases be regarded as higher priority than financial factors (Flores, Olson, & Dorai, Management of multicriteria inventory classification, 1992).

Demand volume and *demand value* is important as customers very sporadically need some items, which leads to that some parts are only demanded once or twice over a period of several years. In these cases, forecasting becomes difficult and a reactive approach is more suitable (Bacchetti, Plebani, Saccani, & Syntetos, 2010). The service level can be connected to demand volume/value as it counts for how large proportion of the demand that can be satisfied directly from the inventory level.

A large proportion of spare parts usually have a slow moving demand pattern, creating a *variability of demand, f*orecasting for the ordering and stock holding of spare parts, (Eaves & Kingsman, 2004). The frequency of spare parts is related to the number of customers and demand. Varying demand creates issues in lead times, as it's not being normally distributed (Boylan, Syntetos, & Karakostas, 2008). In order to classify spare parts, it's important to know the rate of which a part is consumed (Wahba, Galal, & El-Kilany, 2012).

The market demand for spare parts can be divided in terms of *part criticality*, which determines if a part is critical or not (Dekker, Kleijn, & de Rooij, 1998). The penalty for not being able to provide a critical part is much higher than not providing a non-critical part. Part criticality is related to the effect a particular part has on a system in the cause of a failure (Huiskonen, 2001). A parts criticality is set by its functionality. This in turn affects the service level offered to customers (Bacchetti, Plebani, Saccani, & Syntetos, 2010). Companies create a distinction between functionality and aesthetic of a part and ask for different safety stocks and service levels for the two categories. According to (Wahba, Galal, & El-Kilany, 2012), a part can be considered as a critical one if it serves a critical purpose in a certain operation, and will cause shutdown if not working. The level of criticality can be divided into sub-levels depending of how essential a part is (Gajpal, Ganesh, & Rajendran, 1994). Higher critical spare parts result in higher losses at breakdown. Furthermore, critical parts can be considered to be expensive and have a varying demand. Thus a certain level of stock need to be ensured to be able to provide the part to customers (Wahba, Galal, & El-Kilany, 2012). Depending on the focus, Criticality can be interpreted differently (Roda, Macchi, Fumagalli, & Viveros, 2014). If focused on holding costs and financials, the unavailability of critical spare part would result in a mismatch in stocking policies.

Part value is a common characteristic in inventory management. Parts with a high value are not attractive to stock in the logistic chain (Huiskonen, 2001). Parties in the supply chain are forced to look for other solutions instead of stocking high valued parts. However, stocks have to be held if the part is not produced on demand, which created complications between the different parties. Furthermore, for low cost items it's important to achieve a certain level of efficiency so that the price is not increasing proportionally to the value of the part. Overall inventory-holding costs are influenced by the cost of an SKU (Bacchetti et al., 2010).

However, the majority of research classify spare parts in two main areas, namely part cost (unit or inventory cost) and part criticality (Bacchetti & Saccani, 2012). Other popular areas for classifications are part demand volume or value. Furthermore, replenishment lead times, supplier availability and risk of non-supply are also recurring as well as demand variability. Reliability, specificity and spare part life cycle phase have also been mentioned in research. However, little has been published on which criterion is preferable to others. Companies might experience an intermittent demand where many customer requests vary by possessing few large customers and many small customers. Due to the high variation in demand, forecasting for spare parts become difficult, resulting in that slow moving spare parts become held in stock as insurance against immerse costs that would occur if an item was required and not immediately available.

Classification of spare parts can be seen as crucial in forecasting (Bacchetti & Saccani, 2012). Eaves & Kingsman (2004) conclude that the best forecasting method for spare parts inventory is the approximations model. Furthermore, previous research has found that it's not sufficient to distinguish smooth from varied demand patterns on the basis of transactional variability. However, as stated by (Rau, Chein, & Wu), Even a well-designed spare parts methodology for forecasting does not guarantee expected results. It can be noted that research regarding spare parts has increased, but still lacks the practical adoption (Bacchetti, Plebani, Saccani, & Syntetos, 2010).

Also, classification of inventory may vary depending of characteristics of the firm and industry (Flores, Olson, & Dorai, Management of multicriteria inventory classification, 1992). Industries that deal with a fast paced obsolescence rate might consider factors related to that particular issue a higher priority.

3.1.6 Centralized and Decentralized warehousing

One of the main goals in supply chain management is to lower the cost of products tied up in inventory and to create a better service toward the customers (Andersson & Marklund, 2000). The warehousing issue is a big cost for companies and therefore has a central role for management (Graungaard Pedersen, Zachariassen, & Arlbjørn, 2012). The major inventory-cost are from bound capital in warehousing, storage space, service, risk-related, administrative and opportunity costs (Graungaard Pedersen, Zachariassen, & Arlbjørn, 2012). Often smaller companies use centralized inventory to get a quick response time and high coordination (Andersson & Marklund, 2000). Also, a centralized inventory may reduce the cost of local distributing centres (Graungaard Pedersen, Zachariassen, & Arlbjørn, 2012). Warehousing can be seen as risk-buffer to minimize the cost of unpredictable events and at the same time increase the customer service. In Figure 7, the benefits for centralized and de-centralized warehousing are listed.

A de-centralized warehouse will bring service and support closer to the customers and thus decrease the delivery time (Graungaard Pedersen, Zachariassen, & Arlbjørn, 2012) (Reeves, 2009). This structure is a way for companies to close the gap between them and customers and that is why companies have a hard time to change from de-centralized to centralized structure (Abrahamsson, 1993). This structure is beneficial for reducing transportation, carbon emissions, and increase stock usefulness (Reeves, 2009) (Hopkins & Dickens, 2003). According to Anderssons & Marklund (2000) findings when investigating the expected lead time at retailers performed well but the service level low. Thus, the optimal safety stock should be located at the retailers for best result. Having a centralized structure has shown to lower inventory costs because of the increased control over the warehousing (Abrahamsson, 1993). Less staff and training is needed due to a higher degree of control (Graungaard Pedersen, Zachariassen, & Arlbjørn, 2012). According to Graundaard Pedersen et al. (2012), several mathematicians have shown with the square root law, that the inventory in a centralized warehouse is lower than a de-centralized warehouse.

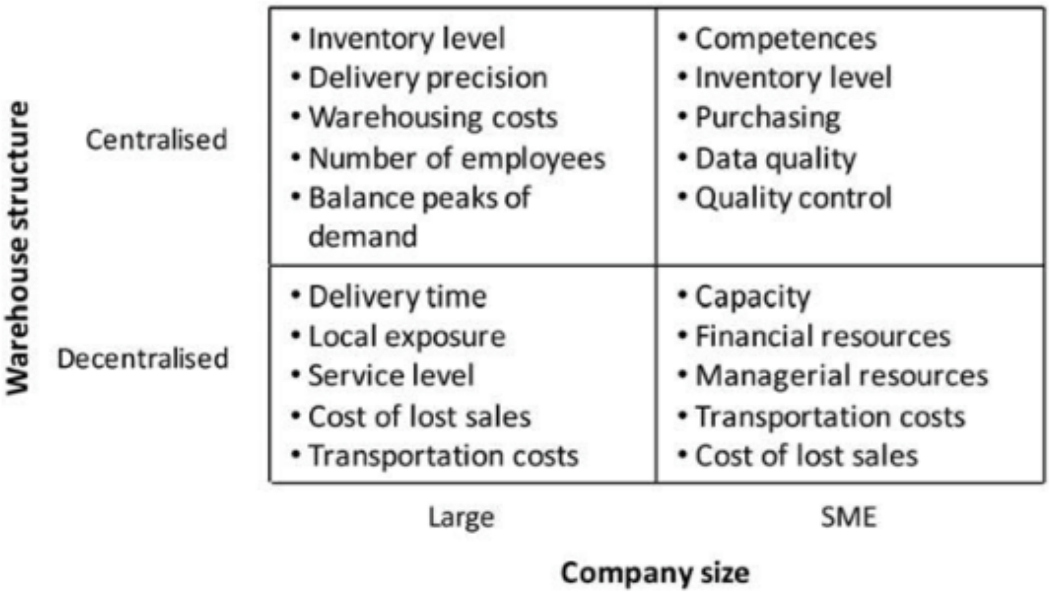

Figure 7. Centralized vs. De-centralized warehousing (Graungaard Pedersen, Zachariassen, & Arlbjørn, 2012).

3.1.7 Pro's and cons of Additive Manufacturing

The additive manufacturing technology is evolving in a fast pace and therefore there are several limitations and possibilities when using this technology. In traditional methods there are usually expensive moulds, tooling, forms, and punches, which isn't suited for small production series (Berman, 2012) (Reeves, 2009) (Ruffo, Tuck, & Hague, 2006). The elimination of tools will also bring down lead times, and cost in the first stages of the product development process and could help companies relieve problems with the money flow (Hopkins & Dickens, 2003). Mass production in Europe is migrating to countries with cheaper and lower labour costs that have better material supply and tax-breaks (Petrovic, Gonzales, Ferrando, Gordillo, Puchades, & Grinan, 2010). Nevertheless, the west countries are more advanced in technology and therefore have an advantage in developing new technology. European countries are therefore focusing on producing customized products and smaller series with additive manufacturing. This could also be cheaper and used on more niche markets (Berman, 2012). Eliminating tooling and using additive manufacturing instead makes it possible to create products at multiple locations simultaneously, which is called distributed manufacturing (Reeves, 2009).

According to both Berman (2012) and Bak (2003) the waste material can be reduced with additive manufacturing. Compared with traditional methods the waste material can be recycled up to 40%, and 95 – 98% of the waste material can be reused in a additive manufacturing (Petrovic et al., 2010). Materials available for additive manufacturing is limited to around 50 types compared to a traditional manufacturing were it's about 20'000 (Berman 2012). In the aerospace industry it's common with a 20:1 material ratio, meaning that for every 20 kg material used for production only 1 kg is used in the finished product (Reeves, 2009). This becomes a problem for higher value metals because the lead time it takes for the waste material to be recycled. One issue could be with the strength of products produced by additive manufacturing, which need more research according to (Berman, 2012) (Petrovic et al., 2010). The bonds between layers are often weak and can therefore lead to damage under stresses. Contrasting with traditional manufacturing, parts made with additive manufacturing behave differently. Products made with layers will be stronger in the direction of the layers and weak in the build up direction (Petrovic et al., 2010). It's important for products manufactured by additive manufacturing need to have the same life-cycle as old-fashioned made products (Levy, Schindel, & Kruth, 2003). According to (Petrovic et al., 2010) the full-density parts will be without remaining porosity and could be preferable to products made from traditional methods. Additive manufacturing enables free forming of products, which makes it possible to shape and design products more flexible (Ruffo, Tuck, & Hague, 2006). This removes former obstacles and hindrance from traditional manufacturing methods (Petrovic et al., 2010). Since the products are in digitalized form it's also simpler to correct mistakes and eliminate human error (Bak, 2003).

3.2 Theoretical Framework (conclusion)

In this section a framework is presented which aims to explain how the research is connected, see Table 1. The first part will explain similarities in the supply chain and spare-parts that is mentioned in the literature review and highlights the issues explained by scholars. Issues that are identified are then compared with the benefits additive manufacturing provides in order to showcase how the new technology might solve each issue. The second part explains the ABC-classification model using a hierarchical process for classifying spare parts.

3.2.1 Classification models

Issue 1: Shorter life cycles, demand and customer expectations

Research regards the supply chain as one of the most important operations in companies' strategies. However, the competitive environment and shorter lifecycles result in the need for dynamic practices and flexibility to respond to customer expectations. A company should strive for an effective supply chain that increases competitiveness but at the same time minimize costs.

Furthermore, increased awareness about the importance of spare parts has resulted in more effort in utilizing strategies regarding those operations. Similar to the overall supply chain, observations can be made regarding spare parts in where shorter lifecycles are occurring, creating a higher degree of obsolescence. In addition, firms are expected to offer a high customer service for spare parts even though the market has a high degree of intermittent demand and unpredictability. The ability to respond to uncertainty lies in the supply chain effectiveness and flexibility. As spare parts are considered slow moving, the demand is considered to follow a Poisson distribution. Furthermore, profits from spare parts usually follow a Pareto rule, where a small proportion of the spare parts stand for a large chunk of earnings. However, even for the slow moving parts with a high criticality, companies are forced to keep a safety stock.

Additive manufacturing regarding issue 1:
In order to cope with the high uncertainty in demand variations, on-demand manufacturing or a so-called *Make to order* approach is well suited (Cohen & Roussel, 2013). However, this approach can be seen as more costly than regular manufacturing, as companies cannot reap the benefits of economies of scale. With additive manufacturing lower production volumes are possible with a lower total cost (Khajavi, Partanen, & Holmström, 2014). The technology enables a print-on-demand possibility, which is ideal for markets with high uncertainty (Cohen & Roussel, 2013). Furthermore, the print on demand may let companies store a lower safety stock, as lead times might be shortened (Khajavi, Partanen, & Holmström, 2014).

Issue 2: Costs vs. Risk trade-off and distribution structure:
According to the reviewed literature, different supply chain structures serve different strategic goals. The main decision in deciding the layout of a supply chain mainly lies in a trade-off. The trade-off occurring lies having a responsive or efficient structure (lower costs) (Cohen & Roussel, 2013). This can further be translated into a trade-off between risk and costs. Similar phenomenon can be identified for spare parts. In terms of manufacturing and warehousing, the trade-off is determined via the choice of a *make to stock* or a *make to order* approach. Low cost inventory might result in higher risks in not meeting customer expectations as larger inventory improves response time and risks at a higher cost. Another part of the supply chain structure that deals with this trade-off is distribution layout. Companies can choose to either focus on having a central warehouse in order to increase control and lower costs, or it's possible to provide a decentralized distribution closer to the customer.

Additive manufacturing regarding issue 2:
According to Khajavi et al. (2014), additive manufacturing can enable companies to reap the benefits of decentralized manufacturing closer to the customers, thus lowering costs for transportation. In addition, total investment for adding on a manufacturing site at any location becomes less costly in comparison to traditional manufacturing (Khajavi, Partanen, & Holmström, 2014). As additive manufacturing uses digital files, switching costs does not exist. Furthermore, the possibilities to get closer to the customer and offer on-demand manufacturing can improve lead times and create better customer service.

Table 1. Theoretical framework.

	Supply chain/Spare parts regarding issue	*Additive manufacturing regarding issue*
Issue 1: Shorter life cycles, demand and customer expectations	• Shorter life cycles lead to higher degree of obsolescence • Customers expect high service even though demand is intermittent • A high degree of flexibility is needed • Slow moving part with criticality need higher safety stocks	• Offers on-demand manufacturing • Lower safety stocks due to manufacturing closer to customer
Issue 2: Costs vs. Risk trade-off and distribution structure	• Trade off between risk and cost • Lower cost inventory may not meet customer expectations • Larger inventory reduces risk at higher cost • Distribution structure trade-off between cost and customer service	• Possible to produce low volumes at lower total cost • Manufacturing closer to customers – lower transportation costs • Shorter lead times • Increased customer service

3.2.2 ABC-Classification model

Flores and Whybark (1986) explained how the cost-volume distribution for inventory items looks like, see Figure 8. Considering this curve, It's possible to see that a small portion of the inventory account for a large portion of the dollar usage. There is a need to manage the different inventory items. Inventories in organization may consist of thousands of different products (Chen, 2012). In order to facilitate decision-making and planning for a large amount of products, ABC classification is a common technique. The classification method is one of the most common and has mainly been used to classify inventory goods on a single criterion, namely annual dollar usage (Flores, Olson, & Dorai, Management of multicriteria inventory classification, 1992). But when classifying inventory items, criteria such as obsolescence, lead times, criticality may be regarded as more important than financial factors. When applying the classification method in practice multi-criteria need to be considered (Chen, 2012). The method is based on the Pareto principle and categorizes items in three levels, namely very important (A), moderately important (B) and relatively important (C). When applying multi criteria classification using ABC techniques, complex computing systems are needed (Ramanathan, 2006). Flores (1985) developed a matrix for using ABC analysis for classifying items over two criteria. However, it becomes difficult when more than two criteria need to be considered (Ramanathan, 2006). Research has moved to combining the ABC-model with other methods in order to provide a multi-criterion classification (Bacchetti & Saccani, 2012). Flores and Whybark (1986) presented a way to use ABC models for classifying items over multiple criterions. However, this approach may cause issues when more than two criteria need to be taken into consideration (Ramanathan, 2006).

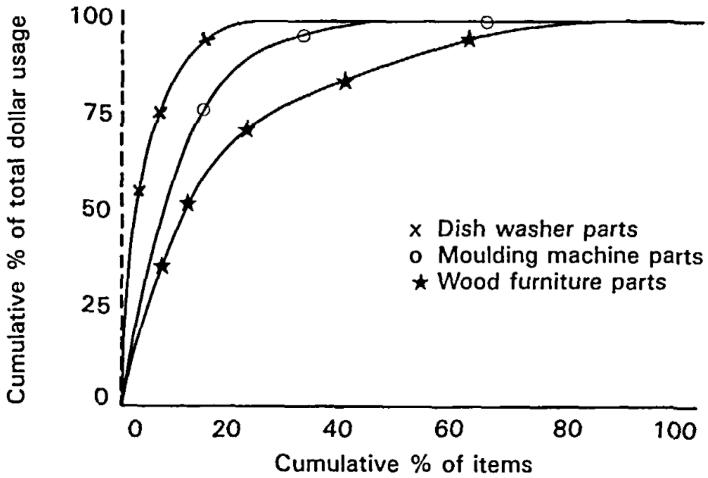

Figure 8. Example of Dollar Usage Curves for Inventory Items (Flores & Whybark, Implementing multiple criteria ABC analysis, 1987).

3.2.3 Hierarchical approach and weighted linear optimization classification

In order to help decision makers, the analytical hierarchical process (AHP) was developed (Saaty, 1990). The AHP has been deployed widely in multi criteria classification studies (Ramanathan, 2006). In order to make important decisions, the AHP process break down goals into criteria, sub-criteria and alternatives in different levels (Saaty, 1990). First the decision makers identify the important criteria that need to be considered (Flores, Olson, & Dorai, Management of multicriteria inventory classification, 1992). Identified criteria are then ranked in different hierarchical levels and then compared, giving then a weighted score of importance.

But the most important issue with AHP is the subjectivity involved in the study (Ramanathan, 2006). Therefore Ramanathan (2006) introduced a linear optimization model for classification without the issue of subjectivity. This approach regards each individual criterion and creates a score that is based on the sum of the weighted measurements (Ng, 2007). The different items are then grouped based on the score that is generated. However, this approach needs to do a linear optimization for each individual item, which causes a long processing time. Ng (2007) has further developed the weighted linear optimization model to offer a more flexible way of calculating scores for classification. This approach can obtain scores without a linear optimizer (Hadi-Vencheh, 2010). Despite the advantages of the Ng-model, the score of each item is independent and the weights do not determine the score of each item. This may lead to that some items may be falsely classified. To minimize this problem, Hadi-Venchen (2010) extended the model in order for it to consider weights in the score calculation.

If an inventory with *i* items are to be classified based on performance in terms of *j* criteria in A, B or C classes (Ng, 2007). Performance of the *i*th item of the *j*th criteria is denoted with *yij*. Criteria can be seen as positively related to the importance levels of the item. The purpose is to aggregate multiple scores in performance of a particular item considering different criteria into one score for the ABC classification (Hadi-Vencheh, 2010). First step is to transform all measurements into comparable base using transformation seen in equation [1].

$$\frac{y_{ij} - min_{i=1,2,\dots,j}\{y_{ij}\}}{max_{i=1,2,\dots,j}\{y_{ij}\} - min_{i=1,2,\dots,j}\{y_{ij}\}} \qquad [1]$$

By doing so, all item measurements are put in a 0-1 scale (Ng, 2007). The next step involves some level of subjectivity, as the decision maker needs to rank the importance of the different criteria.

However, this level of subjectivity is much weaker than the one occurred through AHP. This approach only requires rankings.

Furthermore, (Ng, 2007) defines a non-negative weight Wij. This is the weight of contribution of the performance of the *i*th item under the *j*th criteria to the score of the item. The assumptions are that the criteria are ranked in a descending weight order for all items. Then multiple performance scores for each item is aggregated to create a single score, denoted *Si*. This model by Ng's was extended by Hadi-Vencheh (2010), in which Wj was set to be the relative importance weights attached to the *j*th criteria (j = 1,2,..., J). This is calculated with equations [2] and [3] together with the limitations in equation [4].

$$\max \quad S_i = \sum_{i=1}^{j} y_{ij} w_{ij}, \quad [2]$$

$$s.t \quad \sum_{i=1}^{j} w_j^2 = 1, \quad [3]$$

$$\begin{aligned} & w_j \geq w_{j+1} \geq 0, \;\; j = 1,2,\ldots\ldots,J-1, \\ & w_j \geq 0, \qquad j = 1,2,\ldots.,J. \end{aligned} \quad [4]$$

According to Hadi-Venchen (2010), the model determines the most favourable weights within the feasible region in equation [5].

$$\Upsilon = \left\{ \boldsymbol{w} | \boldsymbol{w} = \left(w_1, \ldots, w_j\right), w_1 \geq w_2 \geq \cdots \geq w_J \geq 0, \sum_{j=1}^{J} w_j^2 = 1 \right\} \quad [5]$$

However, due to the ordering taken for granted in weight ranking above, the model for calculating scores is best solved using Microsoft Excel Solver or the LINGO (LINDO, 2015) software and usually cannot be solved analytically (Hadi-Vencheh, 2010).

4. Empirical findings from case study

This section will present the empirical findings from the case study. The findings will be presented in regards to the research questions, starting with the first one. The chapter aims to create a basis from observing the company, which will be used in contrast to the theoretical framework in the upcoming analysis. Hence, this part aims to present data that will be used in order to answer the research questions.

4.1 Product data

In order to find the appropriate type of spare parts within the scope of the project, consolidation was done with staff from the company. It was agreed upon that the products was to first be identified by technical specifications, e.g. material, then by economical factors, e.g. frequency and costs. After identifying an appropriate population consisting of 281 spare parts, each item's data was to be examined to prepare for the classification. The data represents three factors that were important for spare parts stock control. These factors were decided by discussing with staff at the truck manufacturer. The truck manufacturer employees help to generate factors to be considered during the classification. Among these, some of the more important factors to consider were identified as Annual Usage, Unit Cost and Lead time.

The data was gathered manually through a master data system company that the company possess. Furthermore, some products didn't have any registered data, or was missing in the master system. These 62 products were removed from the starting population, making the population consisting of 219 relevant products in total. In addition, as additive manufacturing has a limited volume for production, parts that would not fit in a machine were also removed, leaving 209 products left in the population. Lastly, any item without volume data was removed from the population because the volume data was necessary in order to get a cost estimation for additive manufacturing. 65 products were removed and the final population consisted of 144 products, see Figure 8. As the system itself did not have annual dollar usage, necessary data components were collected in order to calculate the factor in question. For this factor, the quantity of components used in the previous year (2014) was gathered as well as unit cost. The annual usage was calculated after all the data was collected, using the quantity sold previous year and using the standard cost of sales, see equation [1]. The data was classified, therefore it was left out on purpose.

[Annual usage = number of products used in a year * unit cost] [6]

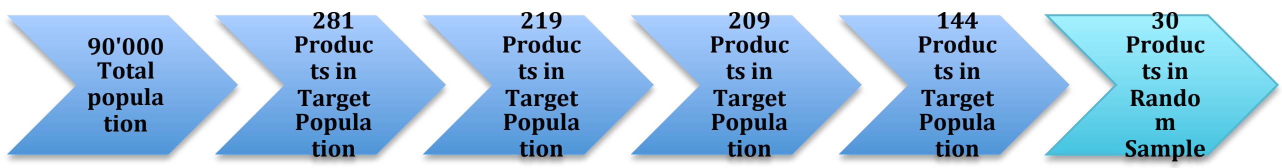

Figure 9. Screening process to obtain the target population.

4.2 Classification and sampling

The 144 spare parts were listed with the values showing for each criteria. The mathematical approach weighted each spare parts criteria against each other and listed them**.** In order to create the ABC-classification the value of every spare parts attribute was transformed into a combined score using the mathematical approach mentioned in the method chapter. The transformation of the scores was done in a program called MATLAB (MathWorks, 2014). The transformed score identifies which factor that has the largest influence, meaning that the highest transformed score will be assigned the highest weight variable. After the scoring in MATLAB (MathWorks, 2014)**,** spare parts were sorted in a list accordance to the score they received.

Furthermore, a linear optimization software LINGO (LINDO, 2015) was used in order to calculate an overall score, which was used to classify the spare parts according to an ABC-classification. Starting with the highest scored spare parts, the first 10% was put in the A-class, the following 20% was put in the B-class and lastly 70% was put in the C-class.

4.3 Cost estimation and comparison

This section contains the empiric data that was used to answer research question 1). In order to make a cost analysis of the spare parts, a sample size was created from the ABC-classification. The sample size was created by taking 10 items from each class, thus creating a sample size consisted of 30 items, see Table 2 and Table 3. Table 2 displays the data collected for the different products and their transformed scores. Table 3 displays the total score of the products and their respective classes.

Table 2. This table consists of the sample size with their transformed score done in MATLAB.

No.	LT (weeks)	AU (SEK)	STndCOS (SEK)	LT (trans)	AU (trans)	STndCOS (trans)
1	2	25733	695	0.03	1	0.12
2	1	22271	474	0	0.87	0.08
3	2	20864	695	0.03	0.81	0.12
4	2	10392	799	0.03	0.4	0.14
5	3	10683	150	0.05	0.42	0.03
6	3	10112	722	0.05	0.39	0.12
7	3	6672	1668	0.05	0.26	0.28
8	3	3581	1790	0.05	0.14	0.3
9	2	7292	810	0.03	0.28	0.14
10	4	0	1627	0.08	0	0.28
11	10	1896	948	0.23	0.07	0.16
12	12	0	16	0.28	0	0
13	1	0	1564	0	0	0.27
14	10	0	42	0.23	0	0.01
15	5	1473	736	0.1	0.06	0.012
16	2	2942	735	0.03	0.11	0.12
17	6	0	507	0.13	0	0.09
18	5	1276	638	0.1	0.05	0.11
19	3	1436	718	0.05	0.06	0.12
20	2	2023	674	0.03	0.08	0.11
21	4	261	261	0.08	0.01	0.04
22	4	126	126	0.08	0	0.02
23	4	0	21	0.08	0	0
24	4	56	14	0.08	0	0
25	3	0	114	0.05	0	0.02
26	3	0	19	0.05	0	0
27	3	0	20	0.05	0	0
28	2	35	35	0.03	0	0.01
29	1	0	112	0	0	0.02
30	1	0	94	0	0	0.02

Table 3. In this table the sample is sorted into their correct class, based on the scoring each spare part received in LINGO.

No.	LT (trans)	AU (trans)	STndCos (trans)	Total Score	Class
1	0.03	1	0.12	1.01	A
2	0	0.87	0.08	0.873	A
3	0.03	0.81	0.12	0.819	A
4	0.03	0.4	0.14	0.425	A
5	0.05	0.42	0.03	0.424	A
6	0.05	0.39	0.12	0.411	A
7	0.05	0.26	0.28	0.385	A
8	0.05	0.14	0.3	0.335	A
9	0.03	0.28	0.14	0.314	A
10	0.08	0	0.28	0.291	A
11	0.23	0.07	0.16	0.289	B
12	0.28	0	0	0.28	B
13	0	0	0.27	0.27	B
14	0.23	0	0.01	0.23	B
15	0.1	0.06	0.12	0.167	B
16	0.03	0.11	0.12	0.166	B
17	0.13	0	0.09	0.158	B
18	0.1	0.05	0.11	0.157	B
19	0.05	0.06	0.12	0.143	B
20	0.03	0.08	0.11	0.139	B
21	0.08	0.01	0.04	0.09	C
22	0.08	0	0.02	0.082	C
23	0.08	0	0	0.08	C
24	0.08	0	0	0.08	C
25	0.05	0	0.02	0.0529	C
26	0.05	0	0	0.05	C
27	0.05	0	0	0.05	C
28	0.03	0	0.01	0.032	C
29	0	0	0.02	0.02	C
30	0	0	0.02	0.02	C

4.4 Weighting, availability and scenario comparison

In order to investigate the cost for additive manufacturing two different methods were used. The first approach was conducted using equations from previous research in order to calculate manufacturing costs for additive manufacturing. The second approach, involved building 3D models with the same volume as the products in the sample size to get manufacturing estimates. It was not allowed to share actual CAD-drawings of the products with a third part. Therefore, the researchers created cubes where the volume specifications were met, but surface area and actual form was not met. Table 4 and Table 5 illustrate the cost calculations for the respective methods as well as the difference compared with regular manufacturing costs.

Table 4. The cost of using additive manufacturing to manufacture the spare parts in the sample is compared using a mathematical approach and two third party manufacturers.

No.	Cost LS (Based on previous research) (SEK)	Cost Shapeways (SEK)	Cost I.Material (SEK)
1	1119	11894	2268
2	6784	22996	3880
3	2936	11451	2207
4	1120	10917	2123
5	779	9778	1955
6	349	1028	266
7	814	20254	3490
8	605	13186	2459
9	1196	6315	1421
10	5241	95756	14061
11	7635	78650	11686
12	2	52	119
13	39	146	119
14	56	2172	733
15	6727	23135	3593
16	845	946	1909
17	902	3356	939
18	4264	106268	15505
19	5816	32721	5270
20	6465	23947	4017
21	337	128	119
22	79	1998	695
23	6095	26309	4354
24	8	194	119
25	48	990	251
26	55	2133	733
27	18	295	119
28	761	6892	1512
29	9776	40714	6393
30	854	10315	2032

Table 5. The difference between the actual production (traditionally made spare parts) costs with additive manufactured cost.

No.	Comparison Laser Sintering (SEK)	Comparison Shapeways (SEK)	Comparison I.Materialise (SEK)
1	-665	-11198	-1573
2	-6474	-22522	-3406
3	-2482	-10756	-1512
4	-598	-10118	-1324
5	-681	-9627	-1805
6	**113**	-306	**456**
7	**1173**	-18586	-1822
8	**556**	-11396	-669
9	-178	-5504	-610
10	-4212	-94129	-12435
11	-7022	-77702	-10738
12	**9**	-36	-103
13	**100**	**1418**	**1445**
14	-28	-2130	-691
15	-6256	-22399	-2857
16	-364	-8732	-1174
17	-593	-2850	-433
18	-3851	-105630	-14866
19	-5361	-32003	-4552
20	-6028	-23272	-3343
21	-321	**133**	**142**
22	-4	-1872	-570
23	-6081	-26288	-4332
24	-4	-180	-105
25	**23**	-875	-138
26	-48	-2114	-714
27	-5	-275	-100
28	-736	-6857	-1477
29	-9706	-40603	-6281
30	-798	-10221	-1937

As Table 5 illustrates, the second method of using third party manufacturers gives clearly higher costs in terms of manufacturing. In the first two columns, transportation is not considered, but it is considered in the second two columns. The first column illustrates cost using the mathematical model, see (Hopkins & Dickens, 2003). The second and third column shows the cost difference between regular manufacturing and ordering a product with the same volume from a third party manufacturers. Column two and three both represent separate actors that offer the same service. (2: Shapeways, 3: I.Materialise). As the first column does not include transportation cost in the calculation, the price was compared to the purchasing order price, which does not account for transportation. The other two columns have been compared with total cost of sales, which include transportation costs.

According to the calculated cost, there are 6 products from the sample that are cheaper to produce using additive manufacturing. However, by using the third parties for cost estimations, Shapeways had 3 profitable products and i.Materialise had 4 products that were cheaper to produce. These estimations were done with a quantitative estimation of a single product even though both of the manufacturing companies offer discounts based on the amount of product that are produced. In conducting this comparison, only the production and transportation costs we're taken into consideration. Therefore, the cost of purchasing a moulding form was not taken into consideration.

4.5 Transportation measurement

For the calculated price in column 2 in Table 5, the difference was only measured for production cost. According to the truck companies own cost model, transportation and handling costs add on average about 25.2% to the purchasing order cost and account for about 17.5% of the total cost of sales. In order to see if lowering transportation cost can impact the profitability using additive manufacturing, the cost of sales was added without transportation costs. This led to an increase of profitable products from 6 to 7 products. However, these measurements are in a scenario in where no transportation costs occur. Table 6 below represents the data of total cost of sales with original manufacturing and additive manufacturing, the latter without transportation costs. As cost of sales was calculated as proportional to the product price, transportation was also considered as proportional to the product price.

Table 6. Transportation cost is included in the comparison between actual cost and additive manufacturing cost.

No.	Total COS original (SEK)	Total COS AM (SEK)	Diff total COS (SEK)
1	695	1549	-853
2	474	9386	-8912
3	695	4063	-3367
4	799	1550	-751
5	150	1078	-928
6	722	491	**231**
7	1668	719	**949**
8	1790	842	**948**
9	810	1020	-209
10	1627	7439	-5813
11	948	10650	-9702
12	16	3	**14**
13	1564	328	**1236**
14	42	75	-34
15	736	6727	-8717
16	735	1169	-433
17	507	1320	-814
18	638	5933	-5295
19	718	8252	-7534
20	674	8993	-8319
21	261	4149	-3887
22	126	118	**8**
23	21	8575	-8554
24	14	25	-10
25	114	69	**46**
26	19	124	-104
27	20	25	-5
28	35	976	-941
29	112	13971	-13860
30	94	1277	-1182

In Table 6 there are 7 products that are profitable to produce with additive manufacturing. What can be seen is that products that products that are close to be profitable with additive manufacturing when comparing product price, can become profitable as total cost of sales has a lower transportation cost.

4.6 Empiric Results

In this section the empiric findings are summarized and simplified for the reader and in Figure 9 the tables relationship is shown. In the section product data, the process for creating the final population size is shown, as there were many steps to the elimination process. The values of the products in the final population size were transformed into separate scores in MATLAB, (MathWorks, 2014). The separate scores produced from the LT, AU and STndCOS values were combined into a single score in the software LINGO (LINDO, 2015), in order to compare the importance of each product. The 144 products in the population was then sorted in a ABC-classification where 10% of the highest score was classified as A-products, the next 20% was classified as B-products and the last 70% was classified as C-products, see Table 3. In the next section the sample was determined by random selection with 10 products from each class and creating a sample of 30 products, which was examined closer. In Table 2 all the 30 products are shown with the scored values from LT, AU and STndCOS together with the combined score. In the next section the weighting, availability and scenario comparison was done. In Table 4 the cost for producing the products in the sample with additive manufacturing is shown. The prices were received from three sources, the first were from a previous research (mathematical model), the second from a third party manufacturer called Shapeways, and the third from a third party manufacturer called i.Materialise. In Table 5 the prices received from the three sources were compared with actual cost (the cost for manufacturing the products with the traditional method). In the last section, the transportation cost was taking into consideration. From the first source the transportation cost wasn't included. Therefore, the assumption of using the same transportation cost model that the truck manufacturers using to estimate all the other products were used. This transportation cost was added to the first sources production price and then compared to the actual price again and shown in Table 6. Moreover, in the tables some values are in **bold** markings. This means that the additive manufacturing price is lower than using traditional manufacturing. If the values are in *cursive* text then a full comparison wasn't done or some values are missing for that row.

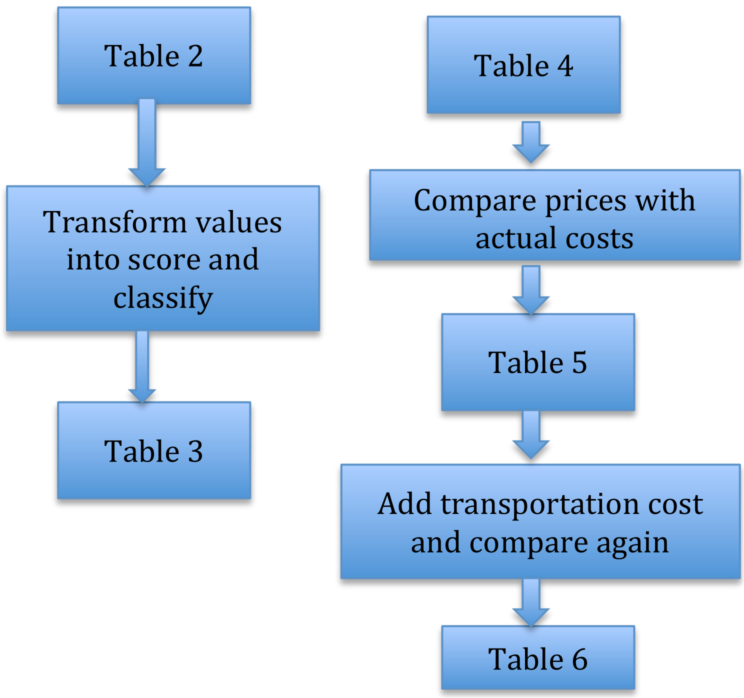

Figure 10. An explanation of how the tables are connected.

5. Analysis

In this chapter, the empirical data collected is compared to the developed theoretical framework. First the factors used in the identified products were analysed in order to see which factors had the most influence over profitability, if additive manufacturing was used for production. Furthermore, the issues and suggested solutions developed in the theoretical framework will be compared with the empiric findings in order to evaluate the real and theoretical costs of additive manufacturing, see Table 7. This approach is done in order to investigate the gaps between the theory and real data from third party manufacturers. Table 7 displays the hypothesis framework developed from the conducted literature study. In order to see which issues that can be solved or minimized with additive manufacturing, the data from the empirical chapter will be applied.

Table 7. Theoretical framework (see Table 1).

	Supply chain/Spare parts regarding issue	*Additive manufacturing regarding issue*
Issue 1: Shorter life cycles, demand and customer expectations	• Shorter life cycles lead to higher degree of obsolescence • Customers expect high service even though demand is intermittent • A high degree of flexibility is needed • Slow moving part with criticality need higher safety stocks	• Offers on-demand manufacturing • Lower safety stocks due to manufacturing closer to customer
Issue 2: Costs vs. Risk trade-off and distribution structure	• Trade off between risk and cost • Lower cost inventory may not meet customer expectations • Larger inventory reduces risk at higher cost • Distribution structure trade-off between cost and customer service	• Possible to produce low volumes at lower total cost • Manufacturing closer to customers – lower transportation costs • Shorter lead times • Increased customer service

The first part of the analysis includes the identification of factors that are needed in order to identify profitable products that could be replaced with additive manufacturing. As the theory suggested, there were different factors that was crucial for maintaining the same service and costs expected by customers. According to theory, companies use supply chain management in order to minimize uncertainties and risk to maintain the expected customer service. This was clear when the truck manufacturer company helped to validate the most crucial factors for identifying products that would benefit from an increased certainty and a lower risk and increase the service effectiveness and lower cost. The literature brought up that more products become obsolete because of shorter life cycles and slow moving part with a high criticality need to have a high safety stock. This was something also collaborated by the staff at the manufacturer through the hierarchy process. The list provided by the staff of the population showing items made of plastics and had a low or a non existing frequency (not stored) much like the "tail" from a Poisson's distribution curve. The staff had sorted all plastic products and filtered spare parts based on their frequency. Hence the hierarchy process help to identify AU (annual usage) and lead time as factors to use in the search for possible spare parts that fit the right criteria for profitable spare parts produced with additive manufacturing. For low frequency items and non-stored items the sold quantity was low or zero, which results in a small ADU. The ADU is good factor to use when searching for possible profitable additive manufactured items because it indicates the cost of the products in stock. The lead time was interesting because if non-stocked items were to be ordered then a short lead time is needed to maintain a high service level. The theory mentions that customer expects a high service even when the demand is low, thus making lead time a good factor to consider when checking for additive manufacturing items. Furthermore, the prices of the products were important in the sense of cost of storing a product. A high price for a low frequency item is costly because this item might be stored for long periods of time without being sold, which causes a high inventory cost. However, some factors that the theory brought up but the data available was insufficient and made it impossible to confirm if they were relevant.

5.1 The framework

This section is used to go through the framework created in the theory chapter, see Table 7. The framework will be used as a guide and the issues are reviewed alongside with the empiric data. Combining the two aspects are relevant in order to determine the benefits and drawbacks with additive manufacturing.

5.1.1 Issue 1: Shorter life cycles, demand and customer expectations

According the theoretical framework that was developed, by listing issues with the supply chain and how they can be solved using additive manufacturing, theory suggests that additive manufacturing can offer on-demand manufacturing, lower total costs for low volume series, lower safety stock and manufacturing closer to the customers. The main object under the investigation was technical and cost aspects. When looking at the benefits and drawbacks of additive manufacturing the cost factors are interesting from the stakeholder's point of view. According to theory there are limitations with additive manufacturing and therefore staff from the truck manufacturer company provided list of spare parts. These spare parts would have a low impact on the functionality of the truck if they break, thus only including spare parts that could be produced with additive manufacturing in the research. The costs that were identified and used were purchasing order price and total cost of sales. The first accounts for material costs and stocking costs, as the second one includes all costs from order to sale.

Offering On-demand Manufacturing

According to theory, companies face problems in obsolescence and high customer demand, even though products go "out of date" in production. As theory regards, the digitalization of books led to little or no cost in handling books with low frequency. Additive manufacturing enables the possibility to store products as digital files and produce when an order is laid, which enables low-frequent products only to be paid for when they are actually manufactured. On-demand manufacturing is possible using additive manufacturing and can offer lead times of about one week. So in this case, products with long lead times can offer higher flexibility in the supply chain.

Lower safety stock as manufacturing closer to customers

Researched theory explains that additive manufacturing can lower safety stock as it enables both on-demand manufacturing and shorter lead times. According to the truck companies own cost models, transportation and handling costs add on average about 25.2% to the purchasing order cost and account for about 17.5% of the total cost of sales. However, in order to know if transportation costs can be lowered, a network map and additive manufacturing has to be done in order to see how much lower the transportation costs would account for. The same model for the transportation cover charge was used for the additive manufactured cases. This means that the transportation cost is dynamic and is proportional to the production cost. Consequently the transportation cost will be lower for the spare part with the lowest production cost. In some cases the production cost varies a lot between traditional manufacturing and additive manufacturing which means the transportation cost varies as well. When adding the cost for transportation for additive manufactured spare parts the profitability increased and went from 20% to 23.3%. The gap in transportation cost between the traditional manufacturing and additive manufacturing is the production price, and if the gap is big then the transportation price difference will become big.

5.1.2 Issue 2: How many are solvable?

As for the second group of issues stated by theory, there is a risk vs. cost trade-off in where also the distribution structure plays a major role. Maintaining a high volume inventory will make your supply chain more flexible in responding to demand. However, this will come at a higher total cost for maintenance and bound capital. The distribution structure also plays an important role, where keeping stock closer to your customers will enable a higher flexibility but come at lower control and higher cost. The company where the case was conducted had a structure in where a central warehouse maintained products with low frequency.

Producing lower quantities at lower total cost

The cost for using additive for production of small series was investigated in three different ways in order to determine the benefits and drawbacks compared to traditional manufacturing. In only calculating production costs using our first method, 20% of the products were able to reach a lower price per product. This comparison was made between the manufacturing cost for additive manufacturing and purchasing order price, which includes costs for production and stocking. According to theory, costs for stocking with additive manufacturing can be considered as close to nothing as products can be stored as digital files. The calculative approach did not account for the cost of moulding forms or the price for purchasing a machine for additive manufacturing, but mainly the actual production cost, which would illustrate if it's beneficial to move from moulding into additive manufacturing. In comparing costs with third parties, fewer products were considered cheaper. In comparing with Company A and Company B had 3 respectively 4 products with lower costs for manufacturing and shipping. In regard to theory, which states that additive manufacturing can lower total costs for low volume series. This is true to some extent, however by looking at existing products from only a cost perspective would lead to that only a few products are profitable to produce using additive manufacturing. In this investigation 6.7% - 23.3% of the products would have a lower cost.

Closer to customers and therefore lower transportation costs

The theory suggest that it would be possible to lower transportation cost by moving manufacturing sites closer to customers. This is something called distributed manufacturing. As the distribution network of the truck company is highly complicated and thus were complex to compute precisely. The data of a general model over all the cover charges of a product was gathered from the staff of the truck manufacturer. This model contains the cover charges of a product that is produced with traditional manufacturing. The cover charge for transportation was used in the cases where the spare parts are produced with additive manufacturing. The transportation cover charge is dynamic and is proportional to the production cost. In line with the above, the transportation cost for spare parts produced with additive manufacturing would therefore simulate a cost that is close to that it would be in a real scenario where the manufacturing sites are close to the customers. When comparing the additive manufactured products in the sample with the traditionally manufactured parts it showed that only one more product was cheaper to produce with additive manufacturing. This means that the profitability could increase from 20% to 23.3% an increase of 3.3%.

Shorter lead time

As additive manufacturing can produce different products simultaneously, it's possible to produce products on demand. Also, additive manufacturing may lower lead times for products with lead times over 2 weeks. In using the third parties for cost estimations, delivery time was also gained for the chosen products. This varied from 1 to 2 weeks, which means that 63% - 87% of the products in the sample could lower their lead times.

Increased customer service

Customer service is a high priority for the truck manufacturer company and was a critical aspect under the hierarchy process. The spare part should be available 1 day after the order was placed. This put some pressure on customer service and availability, thus forces the truck company to store products that are still in use. In contrast to this the data showed some products that were out of stock and had a lead time of several weeks. This contradicts the policy in some ways and could lead to customers having to wait for their spare parts for weeks. As indicated in the empirical section additive manufacturing the lead times could be lowered to about 1 week lead time. Also according to the theory, with the distributed manufacturing it would be possible to lower the lead times if the manufacturing was done at the same place as the part was needed, by removing transportation all to gather. This could result in a higher degree of customer service.

6. Conclusion

This chapter aims to highlight the main points of this research and to summarize the result of this case study. The content of this chapter is interpret by the researchers been based on the analysis in chapter 5.

This was a study about the consequences of using additive manufacturing in the automotive industry. The focus of the study was on spare parts in the aftermarket, where theory and previous research had identified a chance of increasing value for stakeholders. Spare parts that was investigated were made out of plastic and didn't have a high impact on the product they were part of, they had no real effect on the functionality but still had a high criticality where if the break they need to be replaced with the same speed as every other spare part. This case study was done with a big truck manufacturer in order to get a closer look in the industry and easy access to relevant and real data. With a hierarchy approach the keen experience of the employees combined with previous literature helped to answer research question 1 and revealing the best suited factors for identifying spare parts that could in theory be profitable. The initial population size consisted of 144 spare parts that was through constraints of additive manufacturing reduced to a sample size of 30 spare parts.

The empirical data was gathered with research, data gathering through the truck companies master system and from third party services. Data containing additive manufacturing was used in order to find out the speed of the production and the limitations of the production volume. The data gathered from the master system contained sale frequency, production cost, cost of sale and products in storage. All the different data types were used in order to filter the population, make cost analysis and to make a comparison with theory. The cost for producing the spare parts in the sample with additive manufacturing was done in three ways. The first cost analysis was based on previous research and was purely mathematically. A second and third analysis was done using third party manufacturer, Shapeways and iMaterialize. In order to get a cost estimation for each spare part a CAD file was sent to their database, CAD files created by the researchers.

In order to answer research question 2 the result was interpret. The mathematical comparison showed that 20% (without transportation) and 23.3% (with transportation) of the sample was profitable if additive manufacturing was used. In the case of no transportation the lead time could be lowered for 5/6 products (87.3%) and with transportation the lead time could be lowered for 6/7 products (85.7%). When comparing the third party supplier the result showed that 6.7% - 13% of the sample was profitable with additive manufacturing. The lead time could be lowered for 2/3 to 3/4 (66.6% - 75%) of these products. If the whole sample is examined it shows that 19/30 of the sample has a lead time over 1-2 weeks. This means that the lead time could be lowered for 63.3% products. The analysis suggests that only a small portion of low frequency items in the after sales market are profitable (in cost) to produce with additive manufacturing, from having them in storage or manufacture them on demand with a long lead time and instead use additive manufacturing to produce them with 1-2 weeks lead time. In 6.7% - 23.3% the company can save money and if decide to use additive manufacturing for all the products then the customer service would increase.

This study has given a deep understanding of which products that are profitable and a method to identify these. The result showed a small amount of promising spare parts that would cost less to produce with additive manufacturing. From the hierarchy process customer service was identified as a priority and the empiric findings found that 66.3% – 85.7% of the parts could decrease the lead time and thus increasing customer service. The research suggest as the theory have been suggesting, that companies have to weight service against cost in order to find the balance between costs and the level of customer service that is ideal for the company.

From the theoretical framework several issues from supply chain management and additive manufacturing has with the empirical evidence been analyses and in Table 8 a conclusion of the topics mentioned in analytic topics are summarized.

Table 8. This table displays the identified issues with supply chain management and solutions with additive manufacturing identified by theory as well as data from the empirics.

Area	Supply Chain Issues	AM solution in theory (hypothesis)	Data suggestion summary
Obsolescence	Shorter life-cycles lead to a higher degree of obsolescence	Enables print on demand. Obsolescence is no aspect that needs to take into consideration	**True for mainly B and C products**- Lead times can be lowered to 1-2 weeks. AM uses digital files.
Production cost vs. Customer service	High customer expectation even though demand is intermittent	Possible to produce on demand and low volumes at a lower total cost	6.7% - 23.3% of the spare parts receive a lower total cost. The lead time could be lowered to 1 - 2 week for about 60% of these spare parts.
xibility	High degree of flexibility is needed	Flexibility is achieved through manufacturing on demand.	This is possible with a 1-2 weeks lead time.
ailability	Trade-off between risk and cost	Lower lead times and on-demand manufacturing can prevent this trade-off	This is applicable for the products that are cheaper to produce using AM.
ucture	Distribution structure trade off between customer service and cost	Distributed manufacturing leads to increased customer service without inventory risks	Theory and empiric data suggest that lead times could be lowered and increase customer service. Data propose that outsourcing manufacturing and distribution (distributed manufacturing) of beneficial products would lower the total cost.

7. Discussion

In this chapter, the findings and the outcome of the study are discussed. Here the positive and negative aspects of this research will be pointed out. The structure of this chapter will include discussion parts on theory, method, empiric findings, and a general overlook of the result of the study.

Theory

In the theory and early research phase the researcher found a big gap in theory revolving additive manufacturing in the automotive industry. Since there was little research in this area there might be overlooked theory that could be interesting for this research. There was some similar research in the airplane industry. However, this research had only looked on customized parts that were optimized for additive manufacturing and therefore only partial information was relevant for this research. If a similar research was conducted then it might have yielded a more mechanical oriented research with more relevant research to back it up. There is also the interesting area of metal products. There is a bigger amount of part made of metal than plastic in the automotive industry. But in this study the focus was on plastic parts since the technology for plastic printers are further ahead than metal printers. There are both positives and negatives to this decision. The positive are that there are more data and information on additive manufacturing for plastic then metall. In the research we found a gap in theory revolving additive manufacturing and therefore it stands to reason to pick the plastic to get the most data from an already poor research area. When investigating automotive parts there is the question of quality and strength of the parts. There were a lot of safety issues when it comes automotive parts. The starting population was picked with quality aspect in mind. Investigating parts that could actually be printed and used in today's trucks would give a bigger value for the truck manufacturer company than investigating spare parts that would need further durability research.

Method

This was a case study with a hierarchy approach that meant we got a lot of information from the employees of the truck manufacturer. This information could be based on secondary information and could have been misinterpret. The researcher was acting under the beliefs that all the verbal data was correct and since the employees are experts in their own field and was therefore presumed correct. To increase the accuracy of this study, a bigger case study should be performed with similar industries.

The cost analysis was based on the limitation of the industrial printers that are actually used today. This was used in order to eliminate too big products from the population size. The volume was known but the parameters of height, length and width was unknown. The researched did a general estimation of the form of the spare parts and in order to calculate the cost cubes with all sides equally long was done in CAD. This means that some parts that might not actually fit in the industrial printer could still be in the sample. Higher quality of data would be obtained if each spare part that was investigated had actual measurements. This alternative wasn't available as this data was missing from the master system provided by the truck company.

Three different cost analysis was performed, one based on previous research and the other two from additive manufacturing companies. When calculating the cost based on previous research (Hopkins & Dickens, 2003), the equation used for the calculation was based on that specific case and therefore the factors in this equation might not be relevant in our case. This is not something that has been reflected upon and was assumed to be correct, but in for further research this could be interesting to investigate. In the two analyses CAD files was send to the two companies and then the researchers would receive a price specifications. The prices didn't include any additional information (e.g. how much the transportation cost was) this means a lot of information was missing. In order to estimate the transportation cost, the same pricing model that the truck company used for their current spare parts. The cover charge for transportation is dynamic and is thought to be accurate to some extent and was therefore a good option for calculating the transportation costs with the lack of information. To get a higher validity of this research the transportation cost from third party companies should be investigated thoroughly.

Empirical findings
The empiric chapter contains a lot of data that is relevant for this research. Because of the amount of data there might be some human errors contributing to wrongfully displayed data. This is something the researchers actively tried to avoid by constantly checking up with each other. The result also showed spare parts that wasn't profitable but was close to being profitable. For some spare parts the difference was very small, for some spare parts it was negative 100 SEK and less compared to traditional manufacturing. But they should still be reflected upon as the trade-off between manufacturing costs and customer service could be considered worth for the truck manufacturer. This is particularly interesting for spare parts number 22 and 26, because the cost would increased by about 5-10% and lead time lowered by 50%.

Analysis
The general view in this research was cost related to additive manufacturing and therefore the empirical finding could be found misleading. The cost saving of the 10% - 23.3% spare products might feel like a small amount. But the result also showed that 60% - 87% of sample could lower the lead time down to 1 or 2 week. Arguably this means that customer service could increase, but then the cost would increase as a factor. In line with the above, the truck company has an option to increase the customer service but for a higher cost, this might be a good strategy since top priority was to be able to send the product within a day of ordering.

Rapid evolution of Additive manufacturing
The fast technological evolution of additive manufacturing might cause a shift in today's industries. As additive manufacturing and material is getting cheaper it enables to make low frequency products for low cost, which it hasn't been before. The Pareto rule (80/20-rule) describes that in general, 80% of the product sold usually generate 20% of the profit. But with additive manufacturing this could be distorted and by lowering the cost of manufacturing the margins would increase for these products. Additionally, the 80% that are considered to be slow moving parts would not be mainly regarded as a cost factor as they can be stored as digital files and manufactured on demand. The research indicates that additive manufacturing is beneficial and continues to increase. However, it might be a bad investment to buy additive manufacturing machines if they will be out-dated within 5-10 years. Arguably it would make more sense to invest with a third party supplier that take the risk of updating the technology until the technology and materials matures and it becomes cheaper to buy in-house instead. In order to test these hypothesizes; further studies of the technological evolution and economical aspects are recommended.

Implication/Further research
This was a single case study, which makes it hard to generalize the result. In order to generalize the result, more case studies and further research of additive manufacturing need to be done. There was also a small risk of human error in this research. If the researchers made a clerical error then the result would be jeopardized. In order to ensure that the result was correct a repetitive study with the same focus could increase the validity of the research.

The difficulties in this research were finding the right data because it was so dispersed in the master system. The implication of this could be the overlooking of important data. Also an interesting perspective is to investigate the actual CAD drawings in order to determine the effect on the result. Because of the missing measurements of the spare parts the result be misinterpreted and adding the inspection of CAD drawing to the method might give other outcomes. As it was stated in the previous section the model for calculating the cover charge for transportation was missing so the same model for the current product was used. This data would be interesting to do further research on, to get a more accurate result on the cost. Moreover, it would be recommended to have these considerations in mind if doing further research or doing a replicated study.

While previous literature has mainly focused on cost and customer service it doesn't capture other important areas that could be improved with additive manufacturing. This could be on sustainability and reusing material for additive manufacturing. Thus, using additive as a complement to traditional manufacturing could improve the company brand and could possibly reduce waste and creating other benefits in form of tax breaks and ISO-certificates. Furthermore the available material for additive manufacturing is in the range of 50 materials compared with the material for traditional manufacturing, which lies in the range of 20'000. Further research into material could increase the range of available materials but also increase the scope of further research.

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