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Is additive manufacturing the solution for slow moving inventory?

a supply chain comparison between regular production and additive manufacturing, regarding economic and environmental costs

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A supply chain comparison between regular production and additive manufacturing, regarding economic and environmental costs

by

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Abstract

The after sales of spare parts with a low turnover rate is difficult to forecast, resulting in high downtime costs when a part is not on-hand, or in obsolete stock when there are too much parts in inventory. Additive manufacturing is suggested by literature as a solution for this problem, resulting in less financial costs due to reduction of downtime costs and no obsolete parts. Moreover, it is suggested that this will reduce the environmental footprint due to the local production on demand. This master quantifies both the financial- and environmental costs over the supply chain for the low demand spare parts. For one-by-one replenishments, regular production is preferred. However, in the case of Minimum Order Quantities being much larger than the expected demand; in a portfolio of items with demand smaller than 1; and when regular production needs investment in tooling, is additive manufacturing as well economically, as environmentally, the preferred production method. The major insight is that when additive manufacturing becomes economically more sustainable, it is also environmentally more sustainable.

Keywords and phrases: Additive manufacturing, 3D printing, spare parts, slow moving, obsolescence, environmental, sustainable, green supply chains, case study

Preface

This report is the result of my Master thesis project in completion of the Master of Science Program in Operations Management and Logistics at Eindhoven, University of Technology (TU/e). The research project was carried out during my internship at DiManEx BV, from May 2017 till November 2017. In this section, I would like to use the opportunity to express my gratitude to some people for their help and support.

First of all, I would like to thank my mentor and first supervisor, Dr. Maxi Udenio. Thank you for guiding and helping me through the Master thesis project, but also from guiding and supporting me throughout my whole Masters' education. I may have not always have been the easiest student, but you were always there for me, to push me back in the right direction. Thank you, without you my education would have been less fun!

Also, I want to thank my second supervisor, Dr. ir. Rob Basten, for giving me critical, but constructive, feedback and helping me out with loads of information about re-ordering; even from his holiday abroad. Not only his help in the project is appreciated, but also the opportunity to present at the SINTAS event, resulting in interesting questions and good discussions about additive manufacturing. Next to that, I would like to thank Bram Westerweel for pushing me in the right direction when I was stuck on the backordering.

I would also like to thank all my colleagues at DiManEx: Henk, Tibor, Pieter, Chris, Alexander, Alessio and Mohammad. You were always making time for me in your busy schedules; to answer one of my many questions, or just for latte macchiato and a laugh. You introduced me to many of your contacts, giving me a head-start in the data collection. As for that, I would like to thank Katy, Tom, Michel, Wouter and Lianne from the anonymous companies for having me over and having endless conversations about inventory, spare parts and additive manufacturing.

Finallly, I would like to thank my family, boyfriend and friends, for supporting me all years throughout my entire study. For this thesis in particular; I would like to thank my friends Marieke and Alex, for proof reading many pages.

This project was a big challenge without a Bachelor degree in Industrial Engineering or having followed a course about spare parts, but, I can proudly say, that I have learned more in this past half year, than in the 2 years before. And yes Maxi; *'One day I will wake up, and the thesis project will be done.'*

Elise Kok

Hooglanderveen, December 2017

Management summary

Additive manufacturing, which is also knows as 3D-printing, is a relatively new production process, evolving rapidly in the last decades. Using a digital model, a part can be printed at a print-hub without any set-up costs. This printing has a relatively low lead time and is not location depended. This together makes additive manufacturing interesting for the low demand spare part supply chains, which is characterized by low turnover rates, long lead times if there is no on-hand stock or, on the other hand, obsolete stock because forecasting is difficult in low-demand supply chains.

When additive manufacturing is used for the low demand spare parts, instead of regular production, is the production made to order (MTO) near the location of the customer, resulting in no obsolete stock (no scrapped inventory) and less kilometers transported. This suggests an environmental benefit. However, this benefit is not quantified by the literature. To be able to support this suggestion with quantitative data, have we built a model, and did we conduct a case study to answer the research problem: "What is the influence of additive manufacturing on the environmental and economic performance in the supply chain of low-demand spare parts?".

This study is split in three major parts: Creating the economic cost model, creating the environmental cost model and conducting the case study.

Economic cost model

For the model, we looked at a single-echelon model, with a scope from the raw materials to the customer. In this scope, we included the following costs factors:

- Downtime costs
- Holding costs
- Production costs
- Scrapping costs
- Transportation costs
- Investment costs
- Potential benefits

The model is based on backordering, meaning that if there is no on-hand stock, the demand is queued and as soon as a part arrives, it is assigned on "first in first" out basis.

Environmental cost model

For the environmental model, we look within the scope at the life cycle assessment (LCA) of the part. The environmental model is based on the Eco-Indicator system, calculating in Eco-Indicator milliPoints (mPts). The following factors are included in the model:

- Material
- Production process
- Transportation
- Extra energy (if relevant)

Case study

Based on an example supplied by Company A, a case study is conducted. In this case study we look at possible situations when additive manufacturing is more economically and/or environmentally cost efficient. In contrast to the expectations and suggestions by literature, is in a regular situation of one-by-one replenishment, additive manufacturing having a larger environmental footprint than regular production.

However, there are four situations in which the case study shows that MTO production by additive manufacturing is as well the most environmentally, as economically sustainable production method. These situations are:

- Minimum Order Quantity (MOQ)

In the situation that one-by-one replenishments are not possible and a MOQ is required when ordering, for instance in production methods like injection moulding, is the case study showing that when the MOQ is approximately factor ten larger than the total demand, additive manufacturing the preferred production method.

- Portfolio of uncertain demand

In this situation, there are a number of parts, of which is expected that only one item is demanded. This could be, for instance, different variants of a part. In the case of regular production, on-hand stock is preferred, to prevent high emergency downtime costs. At the end of the after sales period, all the on-hand stock becomes obsolete and is scrapped. As the portfolio of parts grows, are the number of scrapped parts also growing, resulting in higher costs. Economically, in this situation additive manufacturing is preferred, in the case study, from a portfolio of three items and up. Environmentally, in this situation additive manufacturing is always the production method resulting in a lower environmental footprint, due to the on-hand, scrapped, stock.

- Investment of mould/tooling

The final interesting situation is the situation where investment is required for regular production. This could be the case when the tooling or mould is lost or damaged, resulting in a fixed set-up cost. In the case of the simplest, smallest mould, the total demand must be lower than 22 parts for additive manufacturing to become financially favorable, and less than 3000 parts to become environmentally preferred. As the mould or tool becomes bigger and more complex, additive manufacturing is gaining more profit at low demand, as well financial as environmental.

Conclusion

Before the case study, based on the literature, we expected a tradeoff for the economic and environmental costs, since the literature suggested that additive manufacturing would be more expensive, but would also be reducing the environmental footprint.

The gained quantitative insights are not as expected beforehand. Looking back at the situations where additive manufacturing is impacting the supply chain, we see that in each of the situations exists environmental positive impact, if there is a positive economic impact. Instead of a tradeoff and behaving contrary, the environmental benefits move in the same direction as the economic benefits, where the environmental costs are impacting the supply chain faster. Assuming financial driven decisions, this is always resulting in environmental benefit for additive manufacturing, if there also is a financial benefit.

In this research has only been looked at the stage of after sales. Additive manufacturing is due to its high production costs, not suitable for large-scale production. However, looking at the product life cycle, additive manufacturing can be an interesting production method at the product development stage. This stage is characterized by the low demand and design adjustments; an ideal situation for additive manufacturing. A positive addition is that when the design is accepted and taken into production, the part is already available as a digital model. This makes the step to change production method to additive manufacturing later in the product life cycle smaller, and more accessible.

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1. Introduction

Additive manufacturing is called a disruptive technology: Over the last decades it has gained popularity and now is evolving from a technique mainly used for prototyping to a technique used for production of industrial produced products at a larger scale. The method is often claimed to be environmentally friendly because material is added instead of removed, less transport is necessary because production can happen close to the customer, and finally there are less items on stock becoming obsolete because production can happen at the moment a product is required.

All these claims sound very interesting and promising. However, the amount of quantitative research done about these claims is very limited. If there is some quantitative data, then this is only about a part of the supply chain; for instance, only the energy consumption of the machines (Baumers et al., 2011). Thus, to better understand the total impact of additive manufacturing further research, encompassing all stages of the supply chain, is needed.

This chapter starts by introducing DiManEx, and other companies with whom this study is conducted. This is followed by the research design in Section 1.2, including the research problem, research questions and scope. Later, in Section 1.3 is the methodology explained, followed by the contribution to science, in Section 1.4. The final section explains the structure of the rest of the thesis.

1.1. DiManEx and other companies involved

DiManEx is a Dutch company, founded in 2015 with the slogan: *'Supply any part anywhere - Reducing financial and material waste in your supply chain'*. It is a cloud based networking company committed to improving and optimizing the supply chain of its clients. With its platform and service combined with strong global partnerships, it promises to provide the best customer results and experience.

The product that DiManEx sells is a service in combination with a platform, also known as SaaS (Software as a Service), therefore DiManEx is seen as a service provider. Famous examples of companies in this area are AirBnB and Uber; the companies themselves don't offer the product the customers buys, but they connect the customer to people or companies who do offer the product, in a way which is convenient for all the parties. As DiManEx states themselves; they create value and reduce the Total Cost of Ownership by saving cost on material, logistics and the number of stock units. Moreover, the flexibility of the customer is increased, and the time constraints are reduced.

DiManEx also claims to be more sustainable by embedding additive manufacturing in the supply chain. With less materials being used, a reduction of unneeded logistics, and amount of scrap, they help customers by contributing to a more sustainable environment.

With the service of DiManEx, it will be possible to easily produce a small series production of just tens of pieces, printed at a location close to the customer. With traditional manufacturing this would be very expensive considering the moulds that have to be machined. Products would be delivered within 2 weeks, which makes it unnecessary for companies to keep a large (safety) stock.

This thesis is a collaboration of Eindhoven University of Technology and DiManEx, which means that DiManEx supplies many of the insights in the industry and as well available as data and connections to other companies to gain more data and insights.

Besides DiManEx, other companies are involved in this study. However, these companies are anonymized for confidentiality. The data supplied by the companies is also rounded for confidentiality. The following companies are included in the study:

- Company A: A Belgian based company, producing large industrial machines and offering these for sale and for rent. They ship to customers world-wide. For this study, this company was visited twice for semi-structured interviews.
- Company B: A Dutch company offering industrial cleaning machines, for sale and for rent. They ship to customers in Europe. This company was visited once, for an extensive semi-structured interview.
- Company C: A Danish company offering parts for agricultural machines, with a large warehouse located in the Netherlands. This company was visited to experience the process of selection for eligible parts for additive manufacturing.
- Company D: An English, third party logistics (3PL) company, which was once met in person, and several times by Skype.

1.2. Research design

In this section the design of the research is described, starting with the research problem and the research questions, but also mentioning the scope in which this research is placed.

1.2.1. Research problem

The major challenge is to see the influence of additive manufacturing in the low demand spare parts supply chain, because a large amount of the spare parts are not offered for after-sales due to the low projected demand combined with the high scrap costs. When producing to order with additive manufacturing, these scrapping costs of obsolete products are eliminated. Furthermore, it is expected that environmental costs will be reduced because there are fewer kilometers traveled in transportation. For low-demand spare parts, production with additive manufacturing appears to be a promising solution, both economically and environmentally. These statements define our research problem:

> *"What is the influence of additive manufacturing on the environmental and economic performance in the supply chain of low-demand spare parts?"*

1.2.2. Research questions

To be able to assess the research problem, this problem is split up into four research questions. The first question is based on the economic impact of additive manufacturing on the supply chain, as the financial aspects are an important decision variable when choosing for a production method. This research question is:

RQ1: "What is the impact on financial costs of adopting additive manufacturing in the low demand spare parts supply chain?"

These financial costs are calculated using an Excel sheet where the developed model is implemented. This model includes cost factors such as downtime costs, inventory holding costs, costs for transportation, production costs and scrapping costs. For this financial cost, an optimal (base) stock level is calculated, minimizing the total costs. Once the financial cost impact and the stock level is known, the second question can be answered, considering the environmental side of the research problem:

RQ2: "What is the impact on environmental costs of adopting additive manufacturing in the low demand spare parts supply chain?"

For the calculation of the environmental costs, we look at the Life Cycle Assessment of each of the production processes. Considering the stock levels and scrapped items based on the optimal strategy for minimal financial costs, the total supply chain environmental costs are calculated. This shows that additive manufacturing, in case of a one-to-one replenishment method for regular production, has significantly higher environmental costs than regular production. In some cases, however, additive manufacturing is the production method with the least environmental costs.

The next research question combines the two previous research questions:

RQ3: "How can we measure the tradeoffs between economic and environmental costs when adopting additive manufacturing in the low demand spare parts supply chain?"

Beforehand we expected, based on the literature, that additive manufacturing would be the more expensive method, but due to the reduction of transport, the method with the least environmental costs. We can conclude that the two costs generally move in the same direction and it can be concluded, for the current situation, that if additive manufacturing is financially the most interesting production method, it generally also has the lowest environmental footprint.

This results in the final research question, regarding a stimulation of environmentally conscious production:

RQ4: "What could the government do as an intervention to stimulate environmentally conscious production?"

The government of the Netherlands is pursuing an environmental policy towards cleaner rivers, reduction in carbon emissions, reduction in waste streams, and the cleanup of contaminated soil (Government of the Netherlands, 2017). It would be possible for the Dutch government to do an intervention to stimulate environmental production. Our case study shows that intervention by subsidizing the production price or reducing the energy consumption would not make a large impact on the decision of the production method. However, by sponsoring digitalization of the models of the parts offered, the government of the Netherlands could make it more attractive to switch to additive manufacturing because there are no investment costs and effort necessary, making it easier for the very low demand items ($\lambda<1$) to be produced with the more environmentally conscious additive manufacturing.

1.2.3. Scope

In this thesis we look at a single-echelon model (supplier – warehouse – customer), where there are after-sale items which were produced regularly (for instance with injection moulding) that need to be replaced and the company is required by contract to offer replacement parts. The question is what method the company will use, which is economically interesting, but preferably also having fewer environmental costs. We chose a single-echelon supply chain because this is the supply chain which is most optimal for regular production, since there are no parts travelling from warehouse to warehouse, and therefore the financial and environmental differences compared to additive manufacturing will be the smallest: When the supply chain becomes a multi-echelon supply chain, more stock on different locations and more transportation is involved, making additive manufacturing even more favorable if it was already favorable in a single-echelon supply chain.

The research is limited to a certain scope and assumptions. First, we only focus on parts that are eligible for printing. There are several other studies dedicated to study whether a part is suitable for additive manufacturing production, e.g. Jansman (2017) and Balisteri (2015). Therefore, we assume that only parts suitable for additive manufacturing are analyzed.

The intellectual properties have been taken out of scope as we expect the customer who orders the part also to have the rights to produce it. These parts can be unpatented parts, or the customer can be an Original Equipment Manufacturer (OEM) who is the owner of the rights.

For our model, we look at the supply chain from the raw materials to the customer. The whole supply chain is included due to, (as Section 2.3 explains), the reduction of travelled kilometers in additive manufacturing from local production versus the global supply chain in regular production. The after-life phase of recycling or landfill of the produced parts is not included, as we assume the parts to be comparable: Having the same dimensions and the same material but built using different production methods and at different locations. As we use the results only for comparison between the two methods, the values for parts of the Life Cycle which are the same can be neglected in the comparison. A diagram of the scope for regular production is found in Figure 1, and a diagram of the scope for additive manufacturing is found in Figure 2.

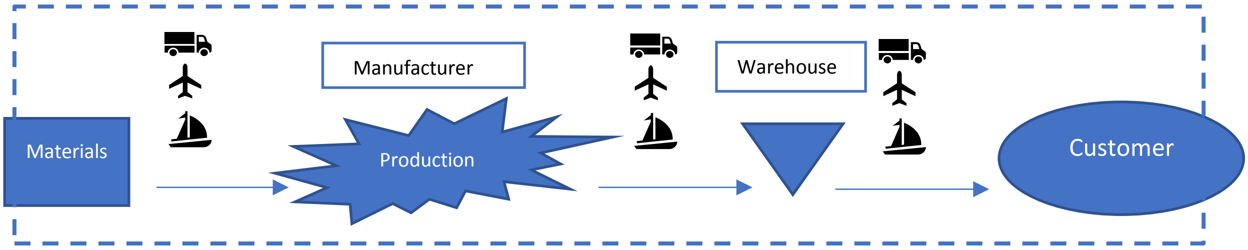

Figure 1: Scope of the cost model with regular production methods

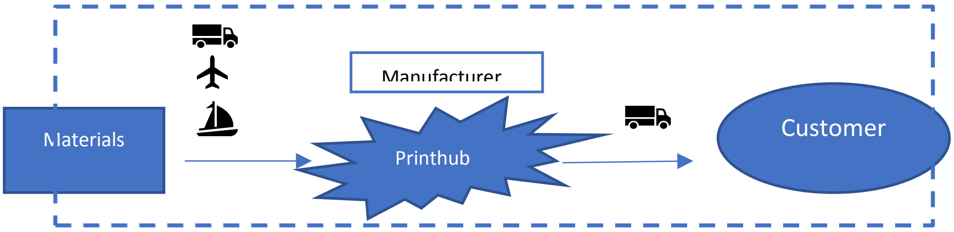

Figure 2: Scope of the cost model in case of production using additive manufacturing

1.3. Methodology

To be able to answer the research questions, we follow a research design methodology based on the research design of Moen (1998). An overview of this structure is given in Appendix A. The project was started by combining the reviewed literature, experience from the industry given by an operations and supply chain specialist at DiManEx, and preliminary semi-structured interviews at several companies. From that point, a preliminary model was created, and the companies were (re)visited for more semi-structured interviews and data collection.

With most of the data collected, the parameters of the model could be filled in and the missing general parameters like process and material data were found in the literature. From this model first findings and conclusions were made and by using feedback loops, the model was optimized, and final conclusions were drawn.

1.4. Contribution to science

Chapter 2 shows that there have been several studies undertaken about the financial costs of additive manufacturing and in which situations additive manufacturing is the preferred method. Those methods usually take into account the production costs, holding costs and downtime costs. The model in this thesis also adds the costs for scrapping parts on hand when the item becomes obsolete, and the costs of transportation, which are assumed to be higher in global production than local production.

The major contribution to science of this thesis is the environmental model, as limited research has been done about this subject in combination to additive manufacturing. As Barros et al. (2017) state; the reduction of transport in the supply chain is a benefit to additive manufacturing regarding the environmental costs, but that study does not quantify that statement. This thesis shows that the reduction of kilometers travelled, and the reduction of scrapped obsolete parts on-hand are a negligible factor compared to the higher energy consumption of additive manufacturing.

The results of the case study are of interest to science as well as practitioners. In the situation of one-to-one replenishment, regular production is both financially and environmentally more sustainable, but when large minimum order quantities occur, or the tooling for regular production needs to be (re-)manufactured, additive manufacturing becomes the most sustainable production method. Also interesting, is that the case study shows that when additive manufacturing is financially preferred above regular production, it is also having a smaller environmental footprint than regular production. Finally, this thesis gives valuable insights regarding the different supply chain situations.

1.5. Thesis structure

After a literature review in Chapter 2 the costs model is shown in Chapter 3, describing how the economic costs are build up and how the level of on-hand stock is determined. Later, in the numerical example is shown how these costs work out in a case study and when additive manufacturing would be an interesting option resulting in a reduction of total costs.

After the economic costs, the environmental cost model is given in Chapter 4. This chapter shows how the environmental cost model is built up. Later, in Chapter 5, a case study demonstrates several supply chain situations showing under which circumstances additive manufacturing could be a sustainable method for replacing regular production. In Chapter 6 the main conclusions are summarized and in Chapter 7 the recommendations are given.

2. Literature review

This chapter summarizes the existing literature used as a background for the thesis. First, the technique of additive manufacturing is introduced in Section 2.1, including a brief explanation of some of the most common techniques. In Section 2.2 the existing literature regarding the costs of additive manufacturing versus regular production is summarized. Section 2.3 shows the studies about the environmental concepts of additive manufacturing; finally, the trends and expected development of additive manufacturing as an industrial production method are discussed in Section 2.4.

2.1. Additive manufacturing

Additive manufacturing is the general name for a manufacturing process based on adding material instead of removing it, like in subtractive manufacturing in the traditional supply chain. It is the global term for processes such as 3D printing, which is developing rapidly in the last few years (Campbell et al., 2011).

This technique uses digital designs to create “build paths” that reproduce a digital model and this digital model can form a product when integrated with material and an energy source. The process of additive manufacturing typically uses a binder, a laser or an electron beam which makes the inserted material solid when it is directed along the build path. This method already works with polymers, metals, and ceramics (Petrick & Simpson, 2013). There are many different methods based on additive manufacturing technology, but the methods most commonly used for industrial production are SLA, SLS, SLM, FDM, (Binder) Jetting, and EBM (Baumers et al, 2011). These methods are explained in the following paragraphs.

2.1.1. Stereolithography (SLA)

This technique dates from 1986 and uses a UV laser and a photosensitive monomer resin to build the layers to the support structures on the build platform. The laser beam traces the cross-section of the product to make the resin solid. This solid piece is later wiped by a blade to make sure it has the exact thickness of one layer before it is lowered back in the resin and the next layer is built using the UV laser. SLA needs manual post-production because the support structures need to be removed and another disadvantage is that the size has a maximum of a 60 cm edge. On top of that, it is an expensive method since the photopolymer already costs between $300 and $500. An advantage of this method is that the surface looks smooth and it works fast, which makes it good for prototypes. (Anderson, 2007)

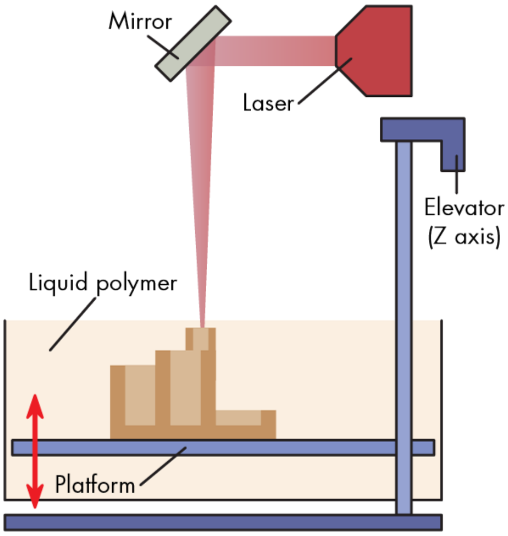

Figure 3: Schematic overview of the SLA technique. The SLA laser travels through the liquid photo-resin, building the part layer by layer (Kerns, 2015).

2.1.2. Selective Laser Sintering (SLS)

SLS was patented in 1989 and, as Kamrani and Nasr (2010) state, this technique uses a high-powered laser which is used to fuse small particles of the build material. By heating the material just below the melting temperature, the qualities of the materials are assured. Every time one layer is heated in the right shape to form a layer of the product. The non-heated material stays in place to support the formed product and can be removed and recycled afterwards. Any material that can be pulverized can be used; such as polymers, metals, ceramics or glass. The build time of SLS is fast and the final result is more durable and has better functionality than the other additive manufacturing techniques. The counterpart is that the process is complicated, that the material changeover is difficult and that the surface finish is not as good as with SLA.

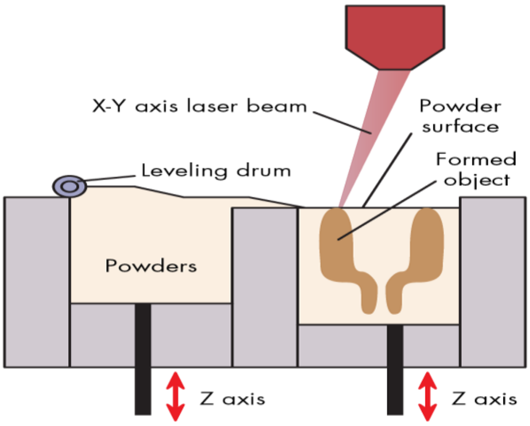

Figure 4: Schematic overview of the SLS process. After the part is formed in the powder-bed process, it is removed and cleaned for any post processing. The powder that is left un-sintered acts as a support material; after the process, it can be sifted and reused

2.1.3. Selective Laser Melting (SLM)

Over the last few years, SLM has developed to be the most effective powder based additive manufacturing method for metal parts. The process is similar to SLS. As Gebhardt et al., (2010) state, the powder is melted and each layer welded together using a laser beam. To control welding related problems as shrinkage, distortion, cracks and surface hardening, the process is run under shielding gas, fine grained powders are used and the product is scanned to check the exposure by the laser beam.

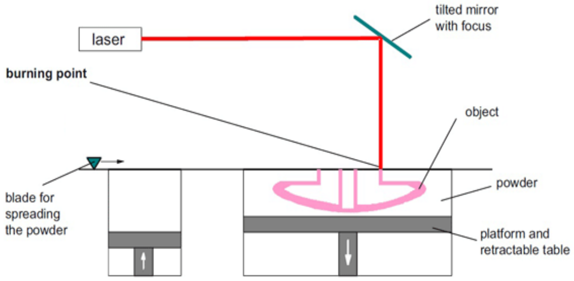

Figure 5: Schematic overview of the Selective Laser Melting (SLM) powder-bed process (Metal AM, 2017)

2.1.4. Fused Deposition Modeling (FDM)

In this technique, where the first machines were sold in 1991, the liquid thermoplastic material is extruded and layered by a movable head in very thin layers on top of each other. The temperature is one degree Celsius above the melting temperature, so it solidifies immediately. A lot of different materials can be used in FDD and the accuracy can be around 0.05 mm. The machine is compact and the maintenance is low. The disadvantages are the seam lines between the layers, the supports it requires during the process and the long time it takes to build a product. (Skelton, 2008)

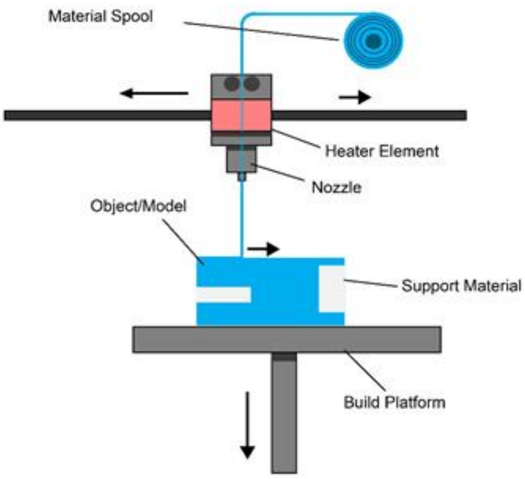

Figure 6: Schematic overview of the Fused Deposition Modeling (FDM) process (MKS Techgroup, 2017).

2.1.5. (Binder) Jetting

Binder jetting was founded in the 1990s at a research institute at MIT but it was commercialized in 2010. According to Xu et al. (2015), binder jetting technology can handle many materials like sand, polymer, glass, and metal. The process works as follows: First the printhead jets the binder on the loose power which makes one layer. With an electrical infrared heater, the excessive binder is removed. Then, the layer is lowered and the new powder is rolled over the existing layer. This process is repeated until the part is finished. This process is fast and low cost, but the products made with this technique have limited mechanical characteristics.

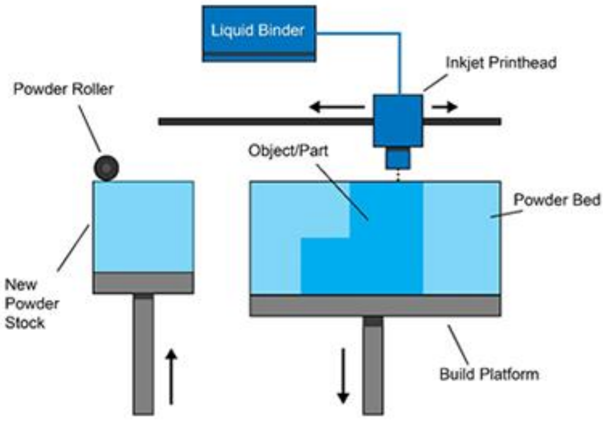

Figure 7: Schematic overview of the Binder Jetting process (Loughborough University, 2017).

2.1.6. Electron Beam Melting (EBM)

The Electron Beam Melting is similar to SLM. This process has been made commercial in 2005. As Murr, et al. (2012) describe, the EBM process works just like the SLM process, only here the powder is not melted by a laser, but by an electron beam under a high vacuum atmosphere. Just like the DLMS, after a layer is formed, the product is lowered and a new layer will be formed on top of it with fresh metal powder. The advantages and disadvantages are the same as for SLM, only less thermal stress is formed in EBM so also fewer support structures are required.

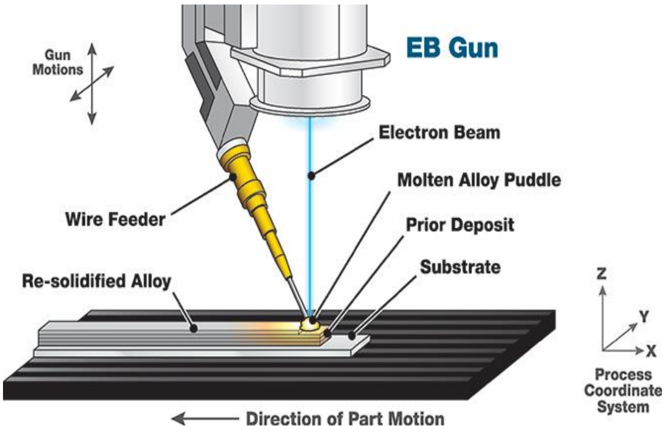

Figure 8: Schematic overview of the Electron Beam Melting process (Sciaky, 2017).

2.2. Economic costs in additive manufacturing

In traditional manufacturing, the costs are linked to the complexity of a product. In additive manufacturing this connection is not straight forward. Also, since there is no need of tooling for production of spare parts, it is unnecessary to hold legacy tooling in storage. The complexity of the production and the whole management decreases and therefore savings in the entire business can be achieved. Additive manufacturing also helps to shorten the time-to-market duration and increases the diversity of possible variants offered, while there is a lower turnover rate per variant (Lindemann et al., 2012).

Recently, the economic costs and cost optimization of additive manufacturing have been subject of a number of Master thesis projects. In the thesis of Jansman (2017) the options of last time buy and the second-hand market are considered besides additive manufacturing production for the aviation industry. The purchasing costs, holding costs and shortage costs due to supply shortages are included in the calculation. Jansman concludes that additive manufacturing will only be economically interesting if there is no second-hand supply and a low predicted demand. The high costs of certification of the digital model make the investment for additive manufacturing of the case study cost more than keeping the last time buy items in inventory. Next to that, Westerweel et al. (2016) developed a cost model to study when additive manufacturing is more economical than regular production. The factors of investment, production, possible benefits per product, holding costs and downtime costs (using a lost sales model) are included. This study also concludes that the researched case studies are economically better-off in regular production.

For now, the production costs per product are still high compared to the traditional manufacturing. Also, the rejection rate is high and quality issues occur often due to machine failures or a mistake by the operator. Companies require significant investments to improve the quality and assurance. But looking at the perspective and evaluating the expect improvements, this would lead to a cost reduction potential of around 60% in the next 5 years and another 30% within the next 10 years (European Commission, 2014).

2.3. Environmental costs in additive manufacturing

Not much research has been done about the environmental aspects of additive manufacturing. This technique is relatively new and still developing. Thus, calculating the environmental aspects is not the highest priority in the development and, with a lot of factors changing rapidly, calculations are rough estimates which change as the techniques become quicker, newer, and more developed.

Early research has been done about the environmental performances of three main additive manufacturing methods (Luo, Ji, Leu, & Caudill, 1999). At that time, additive manufacturing was called Solid Freeform Fabrication (SFF) and the study looks at three methods; stereolithography (SL), selective laser sintering (SLS) and fused deposition modeling (FDM), which are still used today. In this early analysis the environmental results per method differ when different machines are used. Between the different methods, SL and SLS have approximately the same values for energy consumption; a factor of ten lower than FDM.

In their comparative research about sustainability in additive manufacturing, Gebler, Schoot Uiterkamp & Visser (2014) estimate the projected changes when additive manufacturing will be implemented instead of the regular production method. They look at three different dimensions of sustainability; social, economic, and environmental. The environment dimension is split up in the following criteria: Resource demands, Process energy, Process emissions, Life cycle energy, Life cycle emissions, Recyclable waste and Non-recyclable waste. They state that when 3D printing is used in production processes with low volume, customization, and high-value products, there will be a significant reduction of process related waste amounts. Unfortunately, they did not quantify this lowering of the waste in their paper.

When looking at the materials and energy used in the production process, the case study of Barros, Zwolinski & Mansur (2017) shows that additive manufacturing uses less material (199 grams in traditional manufacturing versus 75 grams in additive manufacturing) but it costs more energy in the production process (1250 watt-hour in traditional manufacturing versus 13856 watt-hour in additive manufacturing). Barros et al. researched a case study of orthotic insoles which are custom made by the therapist. They mention the shorter transport the printed insoles have, since they were printed close to the customer, but they did not quantify it. This part is very important in the sustainability analysis to possibly compensate the energy consuming machines of additive manufacturing.

For the environmental costs of additive manufacturing a limited number of studies were conducted. Some of the studies looked at the quantitative energy consumption of additive manufacturing methods (Barros et al., 2017) and others from a Life Cycle Assessment (LCA) point of view (Gebler et al., 2014), but did not quantify the results. Barros et al. (2017) did look at quantitative data for the production process, but also suggested that the fewer kilometers transported could compensate for the higher energy consumption of additive manufacturing. Unfortunately, they did not quantify this part of the supply chain, therefore this suggestion is an interesting topic to study.

2.4. Trends

As Mohr and Khan (2015) state in their trend overview, the rationalization of inventory and logistics is a big opportunity for additive manufacturing. Keeping inventory will become easier because the production happens on demand and at the point of consumption. The digital inventory in the form of 3D model files could replace the physical inventory for technically complex products, reducing the number of Stock Keeping Units (SKUs) and the total number of stored parts. Anastassacos (2015) also notes that a key challenge can be found in the traditional aftermarket supply chains, for example, managing appropriate inventories of spare parts, particularly for older, legacy products. With 3D printing, relatively small facilities with on-site additive manufacturing capabilities could replace large regional warehouses. Spare parts than could be made using data supplied directly by the manufacturers or through reverse engineering. This happens already in the legacy automobiles and other vehicles, where numerous online markets and communities are offering 3D printed parts. Business models will erupt where revenue is generated through the sale of proprietary 3D designs and perhaps certification of 3D printing and fabrication facilities.

Additive manufacturing used to be mostly for making prototypes, but slowly the market is changing towards production. The printers and materials must improve before they can be good, fast, cheap and easy to use for making goods to be sold. It is not likely that this printing is going to happen at individuals' homes; it is more likely that there will be local hubs where the customers can go and print the design (Harvard Business Review, 2016).

These trends and challenges, combined with the little amount of research which has been done in this subject, makes us choose to research the area of the low-demand spare parts industry. This industry has low volume (Gebler et al., 2014), it can replace inventory (Mohr & Khan, 2015), and is a challenge in the traditional aftermarket supply chain (Anastassacos, 2015).

3. Economic costs

In this chapter, we develop a model used for comparing the supply chain costs of regular production versus additive manufacturing. In Section 3.1 the assumptions are stated. Section 3.2 is dedicated to the basic model, assuming one-by-one replenishments. After that, Section 3.3 shows special implications of the model, when batch ordering applies.

With varying demand and a lead time usually being long, it is common in regular production to have the parts made to stock (MTS). In an ideal world, a company would like to order a part every time it is demanded. However, with this strategy, the customer has long waiting times before delivery, which leads to customer dissatisfaction, lost sales and lower profits. On the other hand, keeping inventory has higher costs due to the warehouse expenses, insurance costs and lost interest (the money used to buy the inventory can't be used for investing purposes). (Kaminsky & Kaya, 2006). Slow-moving inventory parts can be a large percentage of the number of SKU's, which sums up in a large value of inventory (Snyder et al., 2012).

Theoretically the problem of having a large value of slow-moving inventory could be replaced by producing with additive manufacturing. As Mohr & Khan (2015) state: The rationalization of inventory and logistics also becomes easier because the production happens on demand and at the point of consumption. The digital inventory in the form of 3D model files could replace the physical inventory for technically complex products, reducing the number of SKU's and the total number of parts on-hand. Controversially; the costs to produce a printed part are higher than the production costs when producing with a traditional method like injection moulding. (Lindemann et al., 2012).

Research about the costs of production using additive manufacturing (e.g. Westerweel et al., 2016 & Lindemann et al., 2012 & Schröder et al., 2015) show that the cost price of production is calculated based on different factors in the production process. The study of Lindemann et al. (2012) states that in a sample part, the major cost driver is the machine costs (73%) followed by the material costs (12%) and the post processing and preparation process (both around 5%).

Neither of these studies calculates the costs over the whole supply chain or compares the costs to regular production. Comparing the costs of additive manufacturing to regular production is of high interest to practitioners who are considering this production method. As Mohr and Khan (2015) state; additive manufacturing can reduce or even replace the physical inventory as the production happens on demand near the location of the customer. This can significantly reduce overproduction and excess inventory as well as the costs for transportation.

3.1. Assumptions

To be able to quantify statements about reduction of costs, we use a model which calculates both the total costs over the whole supply chain for traditional produced parts and for parts produced by additive manufacturing. The foundation of this model is deducted from the model of Westerweel et al. (2016) where the costs of a critical component of a capital good from a OEM are calculated. Unlike the model of Westerweel, we assume that an item is backordered on demand when there is no on-hand stock. This assumption is based on the interviews at companies A & B, who both stated that this was the case for most of their offered parts. This model can also be interpreted also for our scope where we look at a single-echelon supply chain, consisting of one manufacturer, one warehouse and customers, as explained in Section 1.2.3.

To see when it is financially interesting to produce using additive manufacturing, we use the supply chain of the same part as described in Figure 1, but now the part is produced on demand in a 3D print hub located close to the customer, resulting in the supply chain depicted on page 8 in Figure 2. These printing hubs batch all the incoming orders economically, minimizing the start-up costs per product, resulting in linear costs per part printed.

In the model, we assume the company (for instance an OEM) sells products or machines which require service regarding the offering of spare parts. The company is deciding whether they are going to buy traditionally produced parts and keep them in inventory, or whether they are going to buy parts produced on demand, produced near the customer, by additive manufacturing. The part is purchasable at one-by-one replenishment from the regular production manufacturer.

3.2. The economic cost model with Q=1

The total supply chain costs are an addition of different cost factors. The common cost factors like downtime costs (*CD*), holding costs (*CH*), production costs (*CP*) and investment costs (*I*) (Westerweel, 2016 & Jansman, 2017) are used. Furthermore, additional cost factors are added for scrapping costs (*CR*) and transportation costs (*CTr*). Besides the costs factors, are also the potential benefits (*B*) per product sold. All these costs factors added together give the total economical supply chain costs (*TC*) and its dependence on the base stock level *S*, as shown in Equation 1.

$$TC(S) = CD(S) + CH(S) + CP + CR(S) + CTr(S) + I - B \tag{1}$$

3.2.1. Distributions

In forecasting low demand per average lead time, the Poisson distribution is tested to be the best fit to give a good forecast (Archibald et al, 1974). This low demand is a maximum demand of ten units per average lead time. From the turnover data given by company B, shown in Appendix B, we conclude that the parts with low turnover rate have less demand than ten units per average lead time. Therefore, we assume that the demand rate is following a Poisson process with the mean being the number demanded parts per year (λ).

A Poisson distribution gives the probability that a certain number of demand will occur when there is an average demand rate for that period. The average demand rate is given by λ and the probability of an exact number of demand per year is given by the Poisson probability function, shown in Equation 2:

$$P\{D = d\} = \frac{e^{-\lambda}\,\lambda^{d}}{d!} \tag{2}$$

Figure 9 shows the Poisson probability density function when λ = *2*. When calculating the probability that exactly four items are demanded in that period, this results in 0.090. This can also globally be interpreted from the graph. With a mean demand rate of two items per period, the probability that exactly two items are demanded in that period is 9.0%.

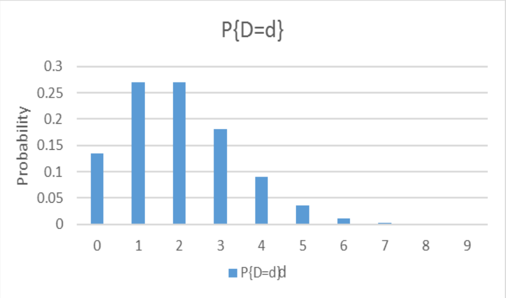

Figure 9: The discrete Poisson PDF graph of λ =2 with on the x-axis the number of demand and on the

In our model this translates to the number of items demanded per year when the rate is λ, with *n* being the total number of parts sold over the service time. Continuing, the total number of parts demanded in full service time *T* is given in Equation 3.

$$n = \lambda T \tag{3}$$

Assuming Poisson distributed demand, this also means that the available inventory is comparable to the number of free servers at an M/M/c queue (Erlang-C model). In this queue the first M stands for Markovian arrivals (Poisson process with mean λ), the second M for the Markovian lead times, with exponential distributed mean μ, and *c* being the number of parallel servers. In our model, the number of parallel servers stands for the inventory position base stock level (*S*). The lead time is the production lead time *(L)* per year. This model assumes backordering, meaning that if there is no on-hand stock available, the demand is backordered and queued. When replenishment arrives, the queue is cleared first in, first out (FIFO).

This Erlang-C equation is based on a call center with a specific number of servers. Calls arrive with an average arrival rate λ and the servers handle the calls with exponential service time *L*. We calculate the server occupancy (*ρ*) with the following equation, where *u* is the traffic intensity with $u = \lambda L$:

$$\rho = \frac{u}{S} \tag{4}$$

3.2.2. Backorders

We assume that when parts are not available in on-hand inventory, the customer will still demand this part and the order will be backordered. Using the traffic intensity ρ, the Erlang-C equation, shown in Equation 5, gives the probability of a backorder. In this equation is $E_c(S, u)$ the probability that an item is not available from on-hand inventory.

$$Probability(Backorder) = E_c(S,u) = \frac{\frac{u^S}{S!}}{\frac{u^S}{S!} + (1-\rho)\sum_{k=0}^{S-1}\frac{u^k}{k!}} \tag{5}$$

The Erlang-C equation for Average Speed of Answer (ASA) translates to the average time an order is backordered. This average back order time T_w is the average time all the customers have to wait, including the directly served demand and is given in Equation 6.

$$ASA = T_w = \frac{E_c(S,u) * L}{S * (1 - \rho)} \tag{6}$$

3.2.3. Downtime costs

In the costs of downtime there are two types of costs: Downtime and repair costs when a part is available on-hand, and “emergency” downtime (penalty) costs when the part is not available on-hand. The regular downtime and repair costs account for all the costs during the period of repair when the item is available from on-hand inventory. According to the maintenance contract this is a fixed amount of money for a period of the first few days. These costs are calculated by multiplying the downtime and repair costs per part (c_d) by the total number of parts demanded in full service time *(n).* We assume that the time to retrieve an item from the inventory in the warehouse and ship it to the customer takes as long as printing the item at a printing hub near the customer. Therefore, producing with additive manufacturing near the customer results in only the regular downtime costs factor c_d.

On the other hand, the emergency costs of repair are variable and linked to the lead time of the part when it is not in on-hand inventory. These costs are added to the fixed downtime costs of repair. According to the maintenance contract the emergency costs can consist of penalty costs, loss of income or costs for renting a replacement machine. The emergency downtime cost is calculated by multiplying the average period of backordering in years *(T_w)* by the total number of parts demanded in full service time *(n)*. This is multiplied by the cost per day of emergency down time (c_e) and gives the total downtime costs over period *T* for when there are no on-hand stock parts available. Adding up the costs for regular downtime and repair and the downtime costs when there is no on-hand inventory, results in costs for C*D*:

$$CD = 365T_w nc_e + nc_d \tag{7}$$

3.2.4. Holding costs

One of the cost factors is the cost for keeping inventory. Inventory costs are an important cost factor for parts with a low turnover rate. In Appendix B, data is shown supplied by company B. This table shows that the items with a low turnover rate account for 75% of the stock value, while the sales turnover is only 4%. From economic perspective, it is not desirable to have the low rotating SKU's in stock, but by law or contracts the manufacturer is obligated to have spare parts available for several years after production ceases (UK whitegoods, 2016).

The inventory holding costs are calculated in several ways. From experiences of the senior logistics manager at DiManEx and by consulting a business analyst at 3PL Company D, we found out that holding costs as a percentage of the production costs is the most common way to calculate the costs of inventory. According to the 3PL business analyst, this number can vary from 7 to 25 percent, depending on the company and the type of products. The other method is by the volume of space reserved, which is approximately €180/year/m³ according to the 3PL business analyst. For the calculations in this study, the holding costs are most suitable. Appendix C shows the different methods for holding costs in the case study, concluding that the volume based calculation has the best fit.

Using the holding costs per m³ and the dimensions of the part, the total holding costs (*CH)* are calculated when reserving storage space for the base stock level of the parts. In this equation h_{vol} are the holding costs per m^3 and the dimensions are the dimensions of the packaging of the part. In the case of shipping printed parts directly to the customer from the printing hub there are no inventory costs.

$$h_{item} = h_{vol} * length * width * depth \tag{8}$$

$$CH = h_{item}ST \tag{9}$$

3.2.5. Production costs

The costs for all the produced items are calculated using the production price supplied by the manufacturer, c_p, and the total number of items sold. This is given in Equation 10.

$$CP = nc_p \tag{10}$$

3.2.6. Scrapping costs

Another costs factor is the scrapping of on-hand stock when the part becomes obsolete. To my best knowledge, there is limited research done about the scrapping of inventory in low demand supply chains. From the experience of the LMS Analyst of Company D, vary the cost of disposing an obsolete item between 3% and 5% of the total production costs. Because these costs are not clearly determined, we assume that the scrapping costs are formed by the production cost price which is multiplied by the optimal number of stock. This means that the company keeps the optimal amount of on-hand stock until he suddenly decides to stop offering the part and must scrap all his on-hand inventory for which he has made useless production costs. The equation for this is given by *CR* in Equation 11:

$$CR = c_p S \tag{11}$$

3.2.7. Transportation costs

The next costs factor in the supply chain are the costs for transportation. These costs are split in inbound logistics costs and outbound logistics costs. In the industry those costs are accounted for as a percentage over the total production costs, but as well as a fixed cost per item. We assume that in our low demand spare parts supply chain all the transport to the customer consists of one or just a small number of parts. This transport is usually parcel transport for which a fixed price for transportation is calculated, depending on the distance and speed. However, we assume that the incoming goods come with multiple items and SKUs from the same manufacturer, therefore the costs can be split among all the items with an average transportation cost percentage over the production price. This results in the total cost of transportation (*CTr)*:

$$CTr = \left((CP + CR) * Tr_{in}\right) + (n * Tr_{out}) \tag{12}$$

3.2.8. Investment

With either method, it is possible that there are one-time investment costs which need to be made especially for the aftersales of spare parts. For additive manufacturing, this can for example be costs for digitalizing the existing drawings to a digital model. In regular production, this can be costs for instance when a mould for injection moulding needs to be (re-)manufactured. In the model these costs are modelled by respectively I_{AM} and I_R; generally annotated by *I*.

3.2.9. Potential benefit

Besides costs there is also a potential benefit for replacing parts by printed spare parts. For instance, in the aerospace and aircraft industry, the weight of all the parts is very important as a reduction in weight also means a reduction in fuel needed (Allen, 2006). If the weight of a part is reduced because less or a lighter material is used, this gives a yearly performance benefit per printed part installed (b_p). In our assumption, all the installed products are made in regular production. To approach the total performance benefit over the whole period by all installed printed parts, we multiply the total number of sold printed parts by the total years of the sales period and divide this by two. This approximates the average number of printed parts installed at a certain time.

$$B = b_p n \frac{T}{2} \tag{13}$$

3.2.10. Optimization

For companies using regular production methods, most cost factors are fixed. One variable which they can adapt relatively easy is the base-stock level *S*. We assume that the companies base their strategy driven by economic perspectives, consequentially, our goal is to find the base stock level which results in the minimum supply chain costs. To do this, the base stock level *S* variates, resulting in minimum Total supply chain costs (*TC).* This is summarized in Equation 14:

$$\min TC(S) \tag{14}$$

$$\text{subject to } S \geq 0$$

Using Equation 14, we know the optimal base stock level under which the company will operate. Now the differences can be calculated between regular production with the optimal *S* and additive manufacturing production with *S*=0. A numerical case study is projected in Chapter 5.

3.3. Minimum Order Quantity (*(s,Q)* model)

In the M/M/c model discussed in Section 3.2, the orders can be placed per single part, immediately when the inventory position becomes *S-1*, where *S* is the optimal stock level. Unfortunately, it is not always possible to order parts per single piece in regular production; then producers start production only when a larger batch is ordered. The company has the choice not to order, or order the minimum quantity: The Minimum Order Quantity (MOQ). When suppliers handle a MOQ, they usually do not charge fixed costs, as this is accounted by the MOQ. The ordering costs per item are linear with the ordering quantity (Zhao & Katehakis, 2006).

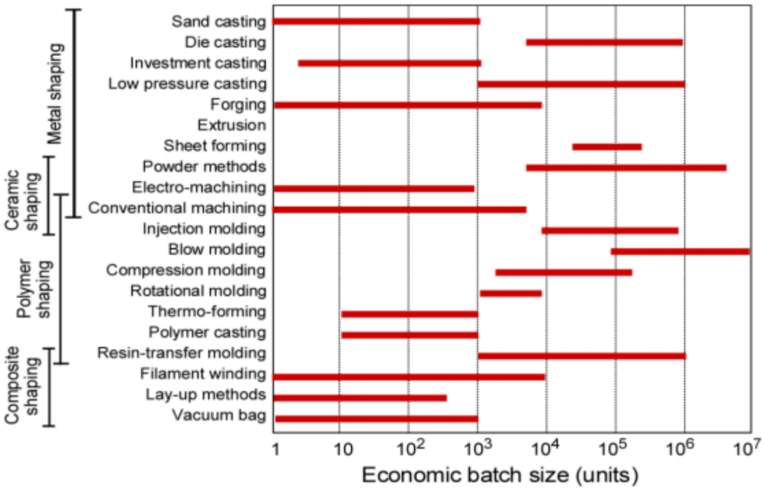

Figure 10: Economic batch size in units per traditional production method (Granta, 2010)

In the M/M/c model presented in Section 3.2, we assumed a Poisson demand with a yearly arrival rate of λ. In that model, the order quantity Q = 1, which means that any number of items can be ordered. The ordering takes place as soon as the base stock level S becomes S-1. In the case of a MOQ, the customer is required to order a quantity larger than 1 at the same time (Q > MOQ). In this study additive manufacturing is considered as a replacement of products produced with traditional methods like injection moulding and sheet forming. Figure 10 shows that these production methods, in combination with the low turnover rate of the spare parts, are likely to have a minimum order quantity a lot larger than 1 (MOQ >> 1).

In the costs model defined in Section 3.2, an Erlang process is used to determine the backorders. This is a Markov process which means that only changes of states in steps of 1 at the same time are possible (Takacs, 1969). A Minimum Order Quantity >1 means that after the lead time, multiple parts arrive. This is not possible in a Markovian process, which makes the M/M/c model with the Erlang equations used in the previous chapter unusable.

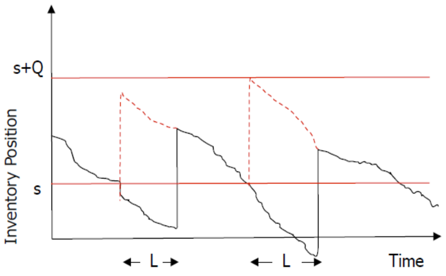

Figure 11: A graphical representation of a (s,Q) model which orders a quantity of Q, every time the Inventory Position drops below reorder point s (Singhkum, 2016)

When there is a MOQ, the inventory levels behave differently from the M/M/c situation described in Section 3.2. For this MOQ model, we assume that the demand is still Poisson distributed but the lead time is deterministic. This translates in a *(s,Q)* model where *s* is the re-order point and *Q* is the quantity which is ordered. As the mean demand is low and a probable MOQ >> 1, is the optimal *Q* is expected to be lower than the MOQ, resulting in *Q = max{Q, MOQ}*.

3.3.1. Total costs

To give the expected costs of the (s,Q) model with minimum order quantity, the *TC* function of Equation 1 is used. The cost build-up is similar to the M/M/c model, but all the cost factors depending on *S* are calculated differently, based on the inventory on hand and the backorders.

The costs for downtime are calculated based Equation 7, where the regular downtime costs remain nc_d, but the emergency downtime costs are based on the expected backorders ($E[BO]$) and the daily emergency costs c_e. These expected back orders are the expected value of every day, therefore it needs to be multiplied by 365 and by *T* for the full period costs.

$$CD = 365(E[BO])c_e\mathrm{T} + nc_d \tag{15}$$

For the total holding costs *CH,* the expected on-hand inventory ($E[OH]$) is multiplied by the holding costs per item from Equation 8, h_{item}. This gives the steady state holding costs per day. Multiplying this number by 365 days and the total time *T* approximates the holding costs, shown in Equation 16. The steady state assumes unlimited *T* and therefore immediately orders when *s* is reached. In reality, it is usually known when a part is soon to be phased out. If this is about to happen, the company will probably not choose to order another batch and will accept the downtime costs or look for another solution.

$$CH \approx E[OH]h_{item}T \tag{16}$$

To calculate the production costs, the ordered number of batches of Q must be known. Therefore, the expected total demand is divided by *Q* and rounded upwards. This gives the number of batches produced *(q)*, including the items which need to be scrapped when the product become obsolete. This is multiplied by the costs of production c_p to give the total costs of producing *P*.

$$q = \left\lceil \frac{n}{Q} \right\rceil \tag{17}$$

$$CP = qQc_p \tag{18}$$

The scrapping costs when the part is obsolete, are dependent on the number of parts which are currently on-hand at that point. We assume that physically throwing away or recycling the left inventory is not adding costs, only the already accounted unnecessary production costs. In this model the production costs of the scrapped parts are included in Equation 18, therefore these are not mentioned in the *CR* and result in scrapping costs equal to zero. In the case that there are additional costs per recycled item (*j*), then the total scrapping costs for minimum order quantities is described in

Equation 19, where *E[End OH]* is the expected on-hand inventory at the end of period *T,* when the MOQ is much larger than the demand.

$$CR = \begin{cases} E[OH]\, j & else \\ E[End\ OH]\, j & if\ Q \gg n \end{cases} \tag{19}$$

Assuming the same type of rates for transport apply with minimum order quantities, the base of Equation 12 is used, but adjusted for the number of items produced (*qQ*), which can be more than the number of items sold (*n)*.

$$CTr = \left(qQc_pTr_{in}\right) + \left(nTr_{out}\right) \tag{20}$$

The initial costs of investment for each of the methods, I_{AM} and I_R are similar to the first M/M/c model, where the fixed costs are added to the *TC* function. The additional benefit *B* is handled in the same way, using Equation 13.

3.3.2. [E]BO and [E]OH when *Q* < *n*

In the situation that the MOQ is smaller than the total demand, the batch size is ordered at least twice. When elongating time period *T* to infinity, batch *Q* is reordered at a constant rate and the systems is considered a steady state. For this (*s,Q*) model, the batching model by van Houtum and Kranenburg (2015) is used. The batching model assumes steady state and uses pipeline stock. This is the stock which currently is on order at the supplier but is not on-hand inventory yet. This stock is denoted by variable *X* and it is also Poisson distributed with mean *λL* where *λ* is the demand rate per year and *L* is the lead time to the warehouse in years. This results in the probability of a pipeline stock given by the following distribution in Equation 21.

$$P\{X = x\} = \frac{(\lambda L)^{\mathrm{x}}}{x!} e^{-\lambda L} \tag{21}$$

Besides the pipeline stock, the variable *U* is introduced, which accounts for the available stock before re-order point *s* is reached. This is a uniformly distributed random variable with values from 1 to *Q.* As this variable is uniform distributed, is the probability given in Equation 22.

$$P\{U = u\} = \frac{1}{Q} \tag{22}$$

Given the two distributed variables and the decision variable *s,* the steady state on-hand inventory (*OH*) and the backorders (*BO*) are formulated by Equations 23 and 24, where $(x\text{-}y)^+$ means *max(0,(x-y))*:

$$OH = (s + U - X)^+ \tag{23}$$

$$BO = \left(X - (s + U)\right)^+ \tag{24}$$

To determine the expected on-hand inventory and the expected backorders, the probabilities given by the distributions of the variables are used. This is executed in Excel by formulating a matrix with on one axis the different values for pipeline stock *X* and on the other axis the different values for available on-hand stock *U*. The values for the steady state *OH* and *BO* are multiplied by the probability that the both variables occur. Concluding, these results are added up and result in the expected on-hand inventory and the expected number of backorders in steady state. This process is summarized in Equations 25 and 26.

$$E[OH] = \sum_{U=1}^{Q} \sum_{X=0}^{\infty} ((s + U - X)^{+}) \, (P\{X = x\} \, P\{U = u\}) \tag{25}$$

$$E[BO] = \sum_{U=1}^{Q} \sum_{X=0}^{\infty} \left((X - (s + U))^{+}\right) (P\{X = x\} \, P\{U = u\}) \tag{26}$$

3.3.3. [E]BO and [E]OH when *Q >> n*

In some situations, the MOQ of regular production methods can be significantly higher than the expected demand, as shown in Figure 10. In these cases, only one single order will take place in time *T*, and not the whole ordered batch is sold. In the case that *Q >> n*, this steady state does not apply. In this case the following equations are used for the expected ending inventory on-hand (Equation 27), the average expected number of inventory on-hand (Equation 28) and the expected average number of backorders, which are expected to be zero, due to Q being much higher than the demand.

$$E[End\ OH] = \sum_{x=0}^{Q} \left(P\{D = x\}(Q - x)\right) \approx (Q - n) \tag{27}$$

$$E[OH] \approx \frac{Q + (Q - n)}{2} = Q - \frac{n}{2} \tag{28}$$

$$E[BO] \approx 0 \tag{29}$$

Accepted Q

At production processes, the MOQ will be >1000 pieces, even for relatively low demand cases like the numerical case study discussed above. In those situations, a company can outweigh the benefits of having enough inventory on-hand for a stochastic future demand. However, unused on-hand inventory costs first of all transportation costs to physically receive the inventory at the DC, but also yearly holing costs apply. With an expected demand of 60 items over the coming 30 years, it does not seem necessary to have all the 1000 parts come over to the DC and have an enormous number of parts stored there for 30 years. To avoid this, the company has only a chosen number of parts come over to the warehouse, for instance 100 parts. The other 900 parts are recycled at the supplier, but the production costs of the full batch of 1000 parts is billed to the company. In the model this problem can be modelled by entering a new production cost price, as shown in Equation 30. In further calculations in the model value of the *acceptedQ* must be used for parameter Q.

$$c_{p.partofbatch} = \frac{MOQ}{acceptedQ} c_p \tag{30}$$

To decide how many parts the company must accept when placing an order with a very large MOQ, he can use the cumulative value of the Poisson distribution, shown in equation 31. This distribution gives the probability that with mean demand λ and duration T there will be enough parts accepted without having to re-order.

$$P\{D \leq d\} = e^{-\lambda T} \sum_{i=0}^{k} \frac{\lambda T^{i}}{i!} \tag{31}$$

Figure 12 shows the cumulative Poisson demand with $\lambda = 2$ and $T = 30$. From this graph it can be concluded that if the company wants at least 99.9% confidence that his accepted quantity of the batch will be sufficient for the demand over period T, the company should accept at least 85 parts. When this situation occurs with a very large MOQ (and therefore an *acceptedQ)*, the expected number of backorders is 0.

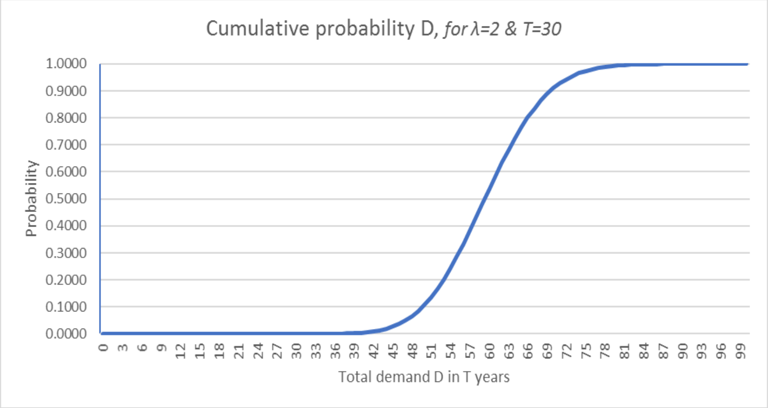

Figure 12: Cumulative Poisson function for the demand , when λ =2 and T=30

4. Environmental model

Chapter 4 is dedicated to defining the environmental model. Section 4.1 explains what the Eco-Indicator is, and why this is the chosen method. Section 4.2 defines the model and have the costs are added.

Besides the economical costs, as proposed in Chapter 3, there are also environmental costs which are gaining more importance in the last few decades. Where in 1999 the first research was conducted about additive manufacturing and its environmental impact by Luo et al., limited research has taken place about the sustainable impact of this technology later. Nevertheless, environmental production and “green” industries is a current topic on which businesses, as well as institutions, have constant debates on regulations for stimulation of sustainable development. For instance, the European Union has the Environmental Action Programme (European Union, 2013) which is a guiding European environment policy until 2020 and has a long-term vision where the Union should be in 2050.

> *"In **2050**, we live well, within the planet’s ecological limits. Our prosperity and healthy environment stem from an innovative, circular economy where nothing is wasted and where natural resources are managed sustainably, and biodiversity is protected, valued and restored in ways that enhance our society’s resilience. Our low-carbon growth has long been decoupled from resource use, setting the pace for a safe and sustainable global society."* (European Union, 2013)

To encounter this vision and follow the guidelines, institutes and businesses need to focus not solely on earning money, but also on reducing waste and carbon emissions and improving the circular economy.

In the literature (e.g. Reeves, 2008; Sarkis, 2003) but also by many production companies, is it often claimed that additive manufacturing would reduce waste because material is added layer by layer in the production process and not removed by milling or drilling, like in traditional production processes. Moreover, by producing on demand, the scrapping of obsolete stock is not relevant anymore. It is also claimed that additive manufacturing would have a smaller environmental footprint than regular production due to less transport demanded between the different echelons and production closer to the customer.

Unfortunately, there has only been a limited number of studies which focused on quantitative research, on the different environmental footprints of production by additive manufacturing or regular production. The first research was done in 1999, by Luo et al.; they compared the environmental impact of different additive manufacturing machines by using Eco factors (see Section 4.1). Later, Gebler, Schoot Uiterkamp & Visser (2014) also published their research on sustainability and additive manufacturing but unfortunately, they did not include a model which assesses all the supply chain stages. To the best of our knowledge, there is no quantitative research done on the impact of additive manufacturing on the whole supply chain. This brings us to our research question of what the impact is of additive manufacturing on the low demand spare parts supply chain.

4.1. Eco Indicator

Every product or process made, influences the environment in some way. This can be either by its material, the energy it consumes or the landfill. A common way to assess products is by a Life Cycle

Assessment (LCA). In this LCA all the life cycle phases are assessed environmentally to be compared to other products or processes. Besides that, collecting all the environmental data for the LCA of a product is very complex and time-consuming, and the results are also hard to interpret: As the LCA consists of the products' contribution to the greenhouse effect, acidification and other environmental problems with each a different quantity and unit, these different environmental effects are hard to add together by weighting factors (Goedkoop & Spriensma, 1999).

Goedkoop and Spriensma found a solution for this problem and made a tool for designers, in a way that they could effectively compare the LCA's of different products. This tool is called the Eco-Indicator and includes the effects of a product on the human health, the ecosystem quality and the use of resources. These effects are accounted for in a very broad aspect, including number of diseases and life years lost due to premature death from environmental causes, respiratory effects, the effect on species diversity coming from ecotoxicity, acidification and land-use. For used resources are the energy to extract minerals and fossil resources included.

These effects are calculated using the Eco-indicator point. This is a dimensionless unit which is based on the yearly environmental load of one average European inhabitant, who on average use 1000 Eco points. In calculations the unit of measure is often milli-point (mPt) where 1000 mPt = 1.0 Pt. These (milli) Eco-indicator points are by itself not a single score but they are generally used for comparison between products.

Since there are many ecological factors included in the Eco-indicator model, the methodology to create the normalized and weighted mPts is also very complex. This model, including all the tables with the impact of different materials and methods on all the eco factors, is described in the methodology report of Goedkoop and Spriensma (2000). Appendix D summarizes the methodology with all the factors which are included before the indicator point is formed.

Besides the Eco-Indicator method, different methods are available, like the EVR model (Vogtländer et al., 2001). The EVR model considers less factors than the Eco-Indicator model which influence the ecological footprint. Moreover, the Eco-Indicator method is used most often in literature, making it a convenient method to use and compare with other studies.

4.2. The mPts model

With the help of the Eco-Indicator and the parameters used in the cost model in Chapter 2, the environmental model is executed. The Eco-Indicator uses three phases *("Production, Use and Disposal").* We will assume that the Use, Packaging and Disposal of the regular and additive manufacturing produced part are similar. The use and disposal after the customer is out of scope and the scrapped inventory which depends on being landfilled (positive mPts) or being incinerated (negative mPts), neglectable (≈1 mPts/kg, Goedkoop & Spriensma, 1999) to the production and material costs of the obsolete part, and is therefore not included in the calculation. Because these phases are similar, we neglect them in the comparison between the two production methods.

This leaves the following steps to be considered in the model: Materials, processing, transport and extra energy. With these steps the previous knowledge of number of scrapped items and (base) stock levels, the mPts model is built.

In additive manufacturing we assume the same situation as the additive manufacturing supply chain in the cost model. This implies together with the current assumptions:

- This supply chain consists out of a 3D printing hub facility located close to the customer and the customer itself.
- The parts are Made to Order (MTO), which means they are produced on demand and not stored somewhere in a warehouse.
- Raw materials which are transported to the print hub by ship and by truck, because the print hub can forecast the demand well due to a large turnover rate of material.
- The print hub uses (Selective) Laser Sintering as a production method. This is the most common used method in industrial additive manufacturing.
- The print hub builds the part by optimally combining the single part with other orders in a crate, creating a full build.
- Because the print hub is chosen close to the customer, the last-mile transportation is by van.

4.2.1. Total environmental costs

The total environmental costs are calculated by adding the environmental cost factors of material (*EM),* process (*EP)*, transport (*ET)* and extra energy (*EE)* together. This addition of the total environmental costs (*ETC)* is given in Equation 30. Each of the cost factors is described in the coming sections.

$$ETC = EM + EP + ET + EE \tag{32}$$

As stated before, the result of this calculation is a number given in Eco Indicator milliPoints. These points do not have a unit of measure, but they are solitary meant for comparison with each other and other products, as the Eco-Indicator system is a widely used method for environmental costs.

4.2.2. Materials

Additive manufacturing is claimed to be more material friendly because material is added to form the product instead of being removed like in milling or drilling (Wong & Hernandez, 2012). Also making to order is claimed to be more environmental friendly because there is no stock and consequentially there are no items scrapped and unnecessarily produced.

A lot of materials have their own value of mPts per kilogram, these are shown in Table 1. As the Eco-indicator model is already almost 20 years old, not all modern materials have their weighted mPts calculated yet. In these cases, the value of a comparable material can be used. In our model, the mPts of the material used is accounted by parameter *m.*

To perform the backwards deduction as we start with a finished product from which we want to deduct how much material is used in the process, we also need to know generally how much material is wasted in production process *u.* This approximation of the utilization rate of the material is given by parameter u_{eff}, where a u_{eff} of 0.6 means that 60% of the material input is part of the final product. Parameter *weight* is the weight of the final product. Equation 33 is the equation for the total amount of material used to produce one product (u_p).

$$u_p = weight * \frac{1}{u_{eff}} \tag{33}$$

As stated before, we assume that the material for packaging and transport is equal between two comparing products, and will not make a difference to the comparison. Therefore, we only focus on the material used to produce the product. When there are multiple materials or production processes involved in a product, these calculations can naturally be added-up. The total mPts for the material of all the products (*EM)* of the full supply chain in timeframe *T* is calculated by Equation 34 for regular production and by Equation 35 for additive manufacturing.

$$EM_R = \begin{cases} mnu_p + mSu_p & for\ Q = 1 \\ qQmu_p & for\ 1 < Q \leq n \\ Qmu_p & for\ Q > n \end{cases} \tag{34}$$

$$EM_{AM} = mnu_p \tag{35}$$

Material **(plastics in granulate)**	**mPts per kg**
PA (Nylon)	630**
PP	330**
HDPE	330**
PS	360**
ABS	400**
Stainless Steel	900* (Kerbat et al., 2016)
Steel	86**
Aluminum	60* (100% Recycled) 780* (0% Recycled)**
Titanium	80-100 (Kutzs, 2007)

*Table 1: Eco-Indicator millipoints per material used for additive manufacturing. *in block material **(Goedkoop & Spriensma, 1999)*

4.2.3. Process

In the processing of the material, the electric energy by which the machines are powered, have the most impact on the environment. In the Eco-Indicator system are the processes calculated in mPts/kWh, where in practice machines often have their energy use often notated in MJ/kg. To transfer energy in MJ (e_{MJ}) to kWh (e_{kWh}), Equation 33 is used. The electric energy in the Netherlands is 37 mPts per kWh (Goedkoop & Spriensma, 1999). This is an average of different methods of gaining energy and comparable to the other European countries, so we assume the electricity to be coming from the Netherlands.

$$e_{kWh} = 0.278\ e_{MJ} \tag{36}$$

For the energy consumption of additive manufacturing machines, we assume full build energy consumption. This means that the production capacity of the machines per build is maximized and that the machine is not running for one single part (Baumers et al., 2011). This is the most efficient way (economically but also environmentally) to use the machine and is common for print hubs to do, as they can cluster together different orders to improve their

Method	**Machine**	**Energy consumption full build**
SLS	EOSINT P 390	107 MJ/kg
SLS	EOSINT M270	241 MJ/kg
FDM	FDM 300 mc	519 MJ/kg
Jetting	M3 Linear	423 MJ/kg
SLM	SLM 250	83 MJ/kg
EBM	A1	61 MJ/kg

Table 2: Energy consumption of a number of additive manufacturing machines, considering full build (Baumers et al, 2011).

Processing of metals	Eco Indicator points
Aluminium extrusion	72 mPts per kg
Milling, turning, drilling	800 mPts per dm³ removed material, without production of lost material
Pressing	23 mPts per kg deformed metal
Spot welding aluminum	2.7 mPts per 7mm weld
Shearing/stamping aluminum	0.000036 mPts per mm² cutting surface
Shearing/stamping steel	0.00006 mPts per mm² cutting surface
Processing of plastics	**Eco Indicator points**
Injection moulding (PE, PP, PS, ABS)	21 mPts per kg
Injection moulding (PVC, PC)	44 mPts per kg
Milling, turning, drilling	6.4 mPts per dm³ machined material, without production of lost material
Pressure forming	6.4 mPts per kg
Vacuum-forming	9.1 mPts per kg

Table 3: Eco Indicator points of a number of regular production methods (Goedkoop & Spriensma, 1999).

efficiency. In this way the warm-up and cool down time can be spread amongst the most products as possible. Table 2 shows the energy consumption in mega Joules per kilogram of final product, based on a full build (Baumers et al., 2011). Possibly different types of machines are used, or machines are renewed, but when there is no specific information on the energy consumption known, the indication from Table 2 can be used as a general approximation.

Regular manufacturing is very broad and varies from manually made products to fully automated production lines. Per type of products the calculation for the sustainability costs needs to be tailor made. The regular production process must be analyzed and translated to mPts to be able to compare to additive manufacturing. Each manufacturing step and type of production has its own average normalized indicator points (u_e), usually per kilogram of final product, given in Table 3.

With these mPts, an estimation is made for the production process (*EP)* of regular production, as well for additive manufacturing production. The calculation of the additive production process is given in Equation 37, where e_e is the number of mPts for electric energy used (37 mPts per kWh in the Netherlands), and the calculation of regular production process is given in Equation 38. The *weight* is the regular weight in kilograms, but in the case of milling, turning and drilling, it is the volume in dm³ (*v)* which is removed from the original material. When this volume is unknown, it can be calculated using Equation 39.

$$EP_{AM} = n * weigth * e_{kWh} * e_e \tag{37}$$

$$EP_R = \begin{cases} n * weight * u_e + S * weight * u_e & for\ Q = 1 \\ qQ * weight * u_e & for\ 1 < Q \leq n \\ Q * weight * u_e & for\ Q > n \end{cases} \tag{38}$$

$$v = \frac{u_p - weight}{density\ material} \tag{39}$$

4.2.4. Transport

In the literature, the reduction of transport is a large sustainability driver (Huang et al., 2012) for additive manufacturing. In our single-echelon model is the necessary transport less than when there are multiple warehouses or retailers and the product travels more (unnecessary) routes. We assume that additive manufacturing has optimized logistics and is printed near the location of demand. Sea transport is generally done for long distances, trucks for national and intercontinental transport and by airplane for fast international delivery. Depending on the urgency of the demand, the choice is made between sea- and truck transport and a combination of air- and road transport.

Transport method	mPts/kg/km	Description
Delivery van <3.5t	0.14	Road transport, with 30% load including fuel and return
Truck 16t	0.034	Road transport, with 40% load including fuel and return
Truck 28t	0.022	Road transport, with 40% load including fuel and return
Truck 40t	0.015	Road transport, with 50% load including fuel and return
Freighter ship oceanic	0.0011	Water transport, with 70% loadd
Average air transport	0.078	Air transport with 78% load (Average of all flights)

Table 4: Eco Indicator points per kilogram per kilometer transported of several transportation methods (Goedkoop & Spriensma, 1999).

For the calculation of transport (*ET)*, all the travelled kilometers of each transport method need to be added together and multiplied by the weight and the Eco Indicator points. This is shown in Equation 40 and 41, where km_i are the travelled kilometers per transportation method *i* and t_{ii} are the Eco Points per production method *i*. Since not all produced parts reach the warehouse in the case that Q > n and not all parts are sent from the warehouse to the customer, the kilometers travelled are separated; *man* means all the kilometers travelled until the materials reach the manufacturer, *war* means all the kilometers traveled from the manufacturer until the last warehouse is reached. Lastly, *cus* means all the kilometers travelled from the last warehouse until the final customer is reached.

$$ET_R = \begin{cases} (n+S)\sum_i km_{i,man}t_i * u_p + (n+S)\sum_i km_{i,war}t_i * weigth + n\sum_i km_{i,cus}t_i * weigth & for\ Q = 1 \\ qQ\sum_i km_{i,man}t_i * u_p + qQ\sum_i km_{i,war}t_i * weigth + n\sum_i km_{i,cus}t_i * weigth & for\ 1 < Q \leq n \\ Q\sum_i km_{i,man}t_i * u_p + acceptedQ\sum_i km_{i,war}t_i * weigth + n\sum_i km_{i,cus}t_i * weigth & for\ Q > n \end{cases} \quad (40)$$

$$ET_{AM} = n\sum_i km_{i,man}t_i * u_p + n\sum_i km_{i,cus}t_i * weigth \quad (41)$$

4.2.5. Extra energy

The factors described in the previous subchapters are each basic and common, necessary, supply chain factors. Occasionally, extra steps are needed. The basic steps described above are the basis and these extra steps are bundled under the name of “extra energy” (*EE*). Examples of this are for instance the energy required for post-production processes like polishing or washing. In the case of post-production coloring like painting, the material used for the coloring must also be considered, besides the energy used by the coloring machine. This extra energy is calculated by repeating the equations for material, processes or transportation given in the sections above.

5. Case study

In this chapter are the models defined in Chapter 3 and Chapter 4 quantified to a case study, based on parameters given by the industry. Section 5.1 is devoted to the quantification of the economical model and Section 5.2 quantifies the environmental model.

To experience what the influence of the choice of production method is on the total economical- and environmental costs in the supply chain of slow rotating spare parts, we set up a case study. For these examples, numbers provided by DiManex, Company A and Company D, are used. According to insights given by Company A, Company B and the operations expert at DiManEx, four interesting situations are simulated, and their results analyzed. These situations are:

- The value of the parameter of a **major cost driver changes**, for instance due to competition, technological development or changed contracts.
- The manufacturer demands a **Minimum Order Quantity** for purchasing
- The case of **uncertain low demand** ($\lambda < 1$). This can be the case when there is a portfolio of products, but it is uncertain which of the products are demanded in the coming years, and which products are not demanded at all.
- The **mould** or tooling, used for regular production is lost or damaged; resulting in extra start-up costs when choosing for regular production.

The following case study is based on a part used as the back cover of an LCD display of a machine, made traditionally from the plastic PA (Nylon). This part is non-critical, meaning that the machine can be used safely, with a cracked back cover and an unprotected LCD display. Nevertheless, replacement is essential to prevent damage to the LCD screen. When the spare part is not available in a short amount of time, extra daily emergency costs of €100/day are charged for not being able to rent out the machine. We also assume that in both production methods, there are no investment costs, which means that there is a digital file with the modelled part available and that there are also moulds available for injection moulding. In this case we assume that the printed part is a near replica of the traditionally produced part, so the dimensions, weight, mean time between failures (mean demand) and other functional parameters are the same.

Model parameters	**Description**	**Regular production**	**AM production**	**Accounts for both**
I_{AM}, I_R	One-off investment costs in €	0	0	x
b_p	Performance benefit per AM produced part	x	x	0
T	Estimated time in years until the products are phased out	x	x	30
$c_{p\text{-}AM}$, $c_{p\text{-}R}$,	Part production costs in €	15	175	x
$L_{Pday\text{-}AM}$, $L_{Pday\text{-}R}$	Mean part production lead time in days	82	7 (within c_d)	x
c_d	Regular costs for downtime and repair in €	x	x	€50
c_e	Emergency downtime costs per day in €	x	x	€100
Tr_{in}, Tr_{in}	Inbound transportation costs as a percentage	8%	x	x
Tr_{out}, Tr_{out}	Outbound transportation costs in € per part	€10	€5	x
Length	Length of part in meters	x	x	0.2 m
Width	Width of part in meters	X	x	0.1 m
Depth	Depth of part in meters	x	x	0.1 m
h_{vol}	Costs of inventory space in € per cubic meter	x	x	€180
n	Total number of after sale items demanded	x	x	60
λ	Mean yearly demand	2	2	x

Table 5: Model parameters case study based on data of an industrial machine manufacturer.

The parameters in Table 5 are used, based on data from Company A, Company D and experiences of the operations and supply chain specialist at DiManEx.

5.1. Economical costs

The optimal stock level S is calculated, based on the lowest total supply chain costs. Besides the regular production MTS to the warehouse and the additive manufacturing printed MTO near the customer. Besides, a method is analyzed which balances the two methods; here the parts are MTS and are stored at the warehouse, but they are manufactured using the more expensive printing method, having a shorter lead time. A method like this was preferred for the implementation phase by Company A, to have an extra quality check at the warehouse before the part is sent to the customer. This results in additional shipping- (compared to MTO), scrapping- and inventory costs, as well as longer lead times, resulting in higher downtime costs when the part is not on-hand, because the part is printed near the warehouse, and after inspection shipped to the customer. These parameters result in Figure 13 and Table 6.

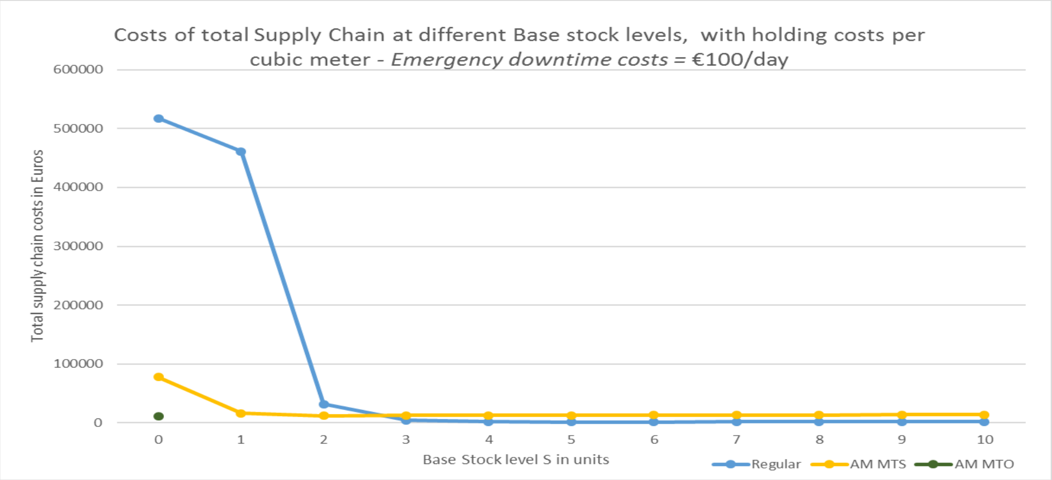

Figure 13: Costs of total Supply chain when including emergency downtime costs of 100 euros a day

Minimum costs for total supply chain with holding costs per cubic meter (c_e =100, c_d = 0)			
	Regular (S=5)	**AM MTS (S=2)**	**AM MTO (No S)**
Total supply chain costs	€ 1,735.71	€ 12,405	€ 10,800

Table 6: The optimal base stock level S for each of the production methods and its corresponding total supply chain costs with emergency downtime costs c_d=€100

As the out-of-stock penalty costs are higher than the costs for keeping inventory, on-hand stock becomes valuable to have as prevention for the expensive emergency downtime costs. This is shown by Figure 13: Although additive manufacturing MTS has a relatively short lead time and therefore relatively low downtime costs, keeping inventory and having the accompanied costs, is cheaper than keeping no inventory on-hand, resulting in an optimal base stock level of *S=2*. Additive manufacturing MTS will always be more expensive than additive manufacturing MTO, therefore the case study uses in further calculations solely regular production and additive manufacturing MTO.

The emergency downtime costs of €100 per day, is a rough estimation, but the exact value of the downtime emergency costs is relatively unimportant; this is shown in Figure 14. The biggest difference in cost is seen when the downtime emergency costs change from €0 to €5 a day. When the emergency costs change from €5 to €5000 a day, the total supply chain costs rise only by €81, which is assumed to be neglectable over 30 years.

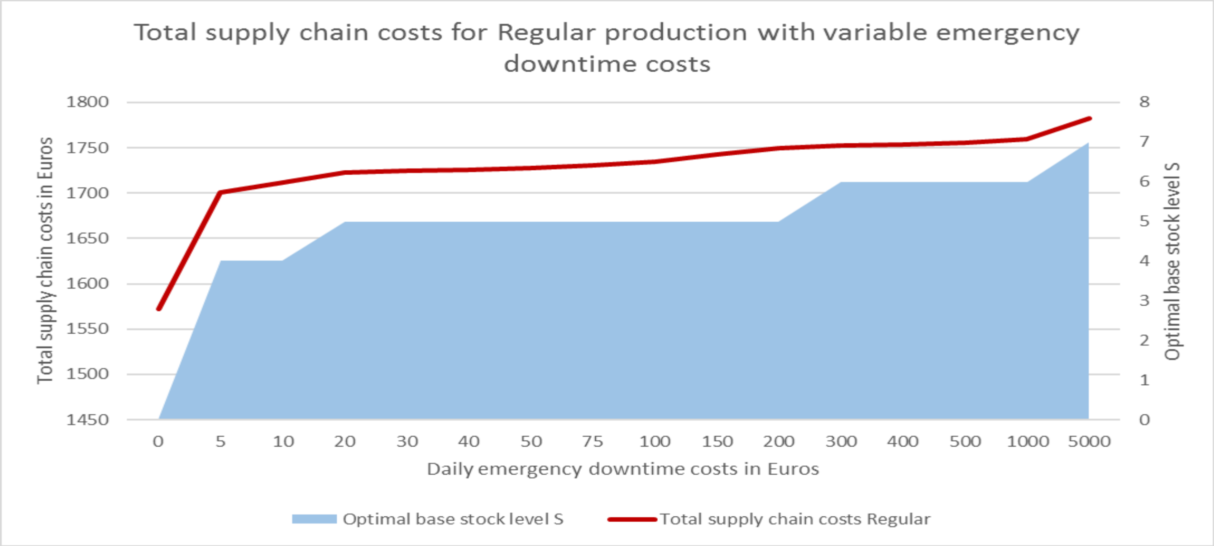

Figure 14: The total supply chain costs when varying the daily emergency downtime costs. Note: the total supply chain cost for additive manufacturing stay at a constant value of €10800

As the downtime emergency costs rise, the base stock level *S* rises as well, because keeping inventory and scrapping the base stock at the end of *T* is cheaper than paying the downtime emergency costs. Figure 15 shows how the total costs are built up in this case study when the emergency downtime costs are €100. In both the regular and the additive manufacturing production, the most important costs driver is the costs of production. These cost drivers are studied in Section 5.1.1. Changes in holding costs or downtime emergency costs minimally influence the total costs and therefore these costs are concluded not to be an important factor in this comparison.

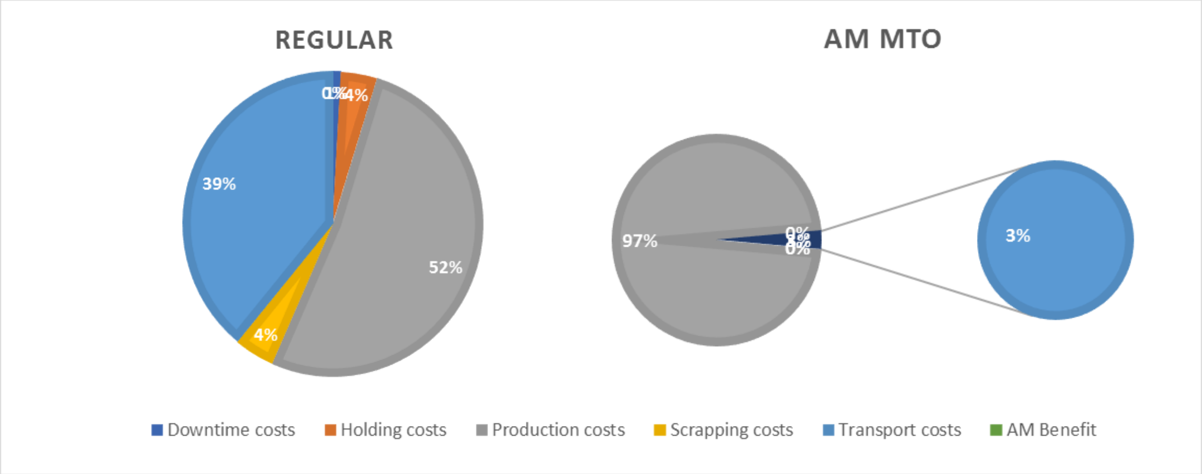

Figure 15: Build-up of the total supply chain costs in regular production and additive manufacturing made to order with emergency downtime costs = 100/day. The downtime costs and the holding costs account in regular production only for a very small part of the total costs. The total costs for Regular are €1,735 and the total costs for AM MTO are €10,800

5.1.1. Changing major cost driver

As the machines for additive manufacturing are used more often and are improved, the production costs expect to lower (European Commission, 2014). With lower production prices, the total supply chain costs will also lower. Figure 16 shows the total supply chain costs when the production price for additive manufacturing is varied. The point of intersection is around €24, which implies that if the additive manufacturing production price drops below €24 per part, the MTO additive manufacturing solution is cheaper than regular production.

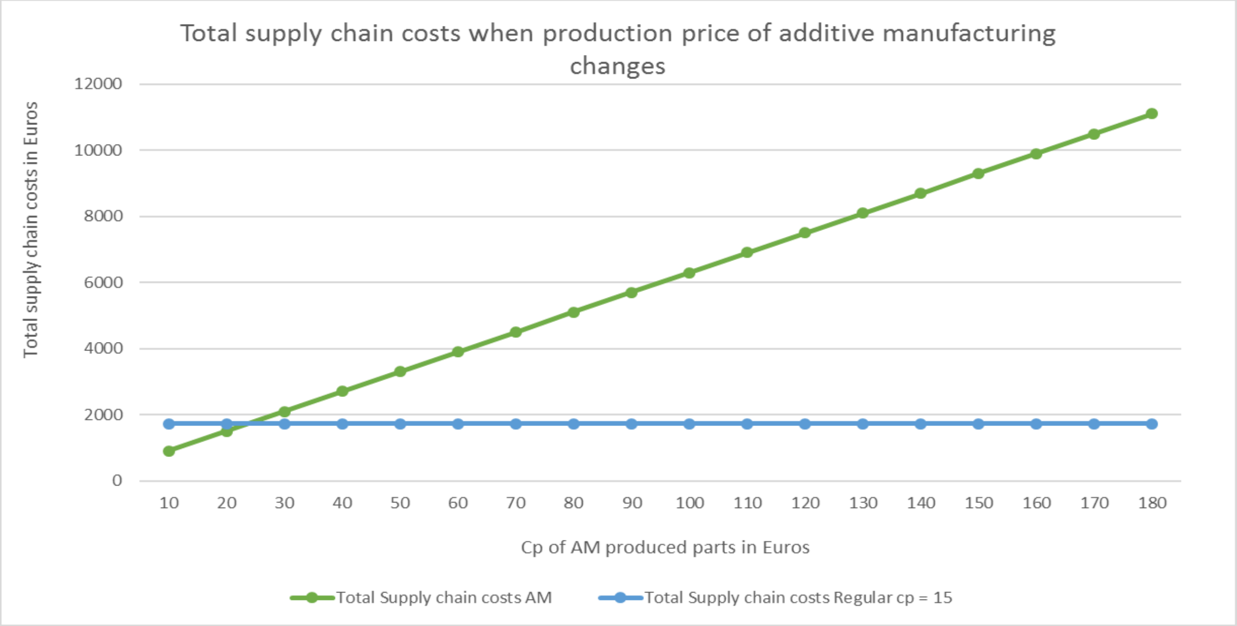

Figure 16: The total supply chain costs when the production price of additive manufacturing is varied. With a production price of €24 and up, additive manufacturing is significantly more expensive than regular production.

Price changes can also occur for regular production. This can happen when contracts with manufacturers end, and the new negotiations result in having a higher price. Or, when there are less suppliers available which cause the prices to go up as well. In Figure 17 is shown how this effects the total supply chain costs and that the point of intersection is at €144. Therefore, the prices for regular production must rise to €144 before additive manufacturing costs less than regular production.

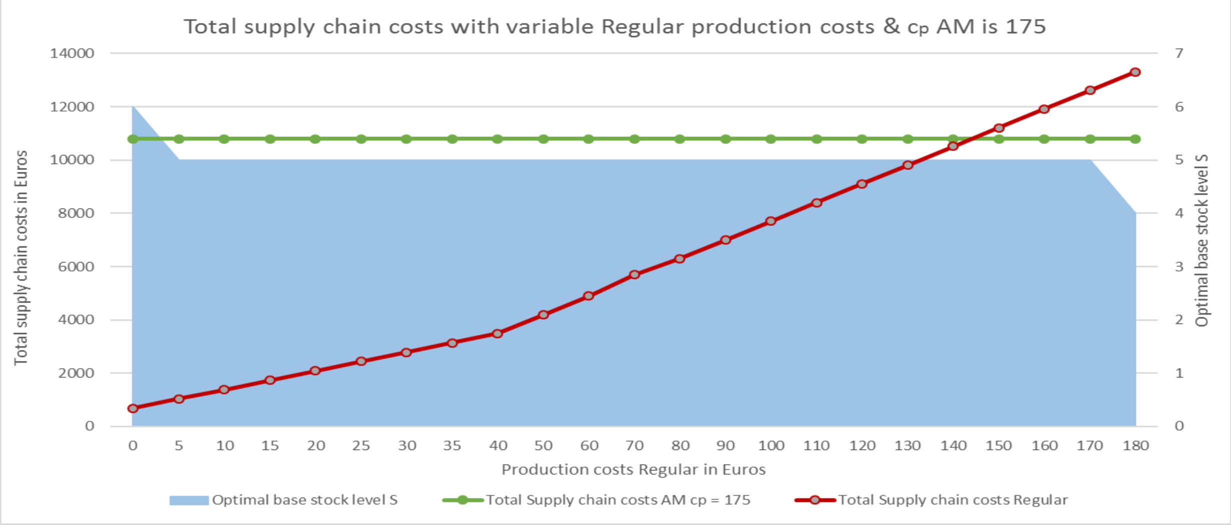

Figure 17: The total supply chain costs when the production price of regular manufacturing is varied. With a production price of 144 Euros and up, regular production is more expensive than additive manufacturing.

Conclusion

As Figure 15 shows, are the production costs the major impact in the total supply chain costs of regular production as well as additive manufacturing. A variation in these costs will also change the total supply chain costs linear. Currently, the production price of additive manufacturing is 10 to 15 times the price of regular production. As Figure 16 shows, if the production price of additive manufacturing drops, the total supply chain costs will drop as well in a linear ratio. Nevertheless, the production price must drop to less than twice the price of regular production before additive manufacturing becomes the cheaper method. It is expected that the prices of additive manufacturing will drop, but dropping from ten to fifteen times the regular production price to less than twice the production price is not assumed to be expected in short term.

Another option is that the costs of regular production are raised, for instance due to expired contracts or less manufacturers available which can result in less competitive prices. Figure 17 shows that the production price of regular production must to rise almost to the production price level of additive manufacturing (€144 versus €175) before additive manufacturing becomes the economical solution.

Although a change in production costs is very possible to happen in a certain point in time and these costs are sensitive to the total supply chain costs, is it not very probable that in the near future these costs will rise or drop that drastically that additive manufacturing will become the economical production process in this case. In this case an additive manufacturing production price drop from €175 to €24 or a price rise in regular production costs from €15 to €144 must happen before additive manufacturing is the economical option. Therefore, we conclude that a change in production price is not the main driver for additive manufacturing to become economically interesting.

5.1.2. Minimum Order Quantity

In industrial production, parts are regularly produced in large, economically interesting batches as shown in Figure 10. This results from the used production method, where often a lot of material is wasted before correct parts can be manufactured. Another possibility is that the required mould is only available with a large number of cavities for parts and re-engineering the mould to limit the

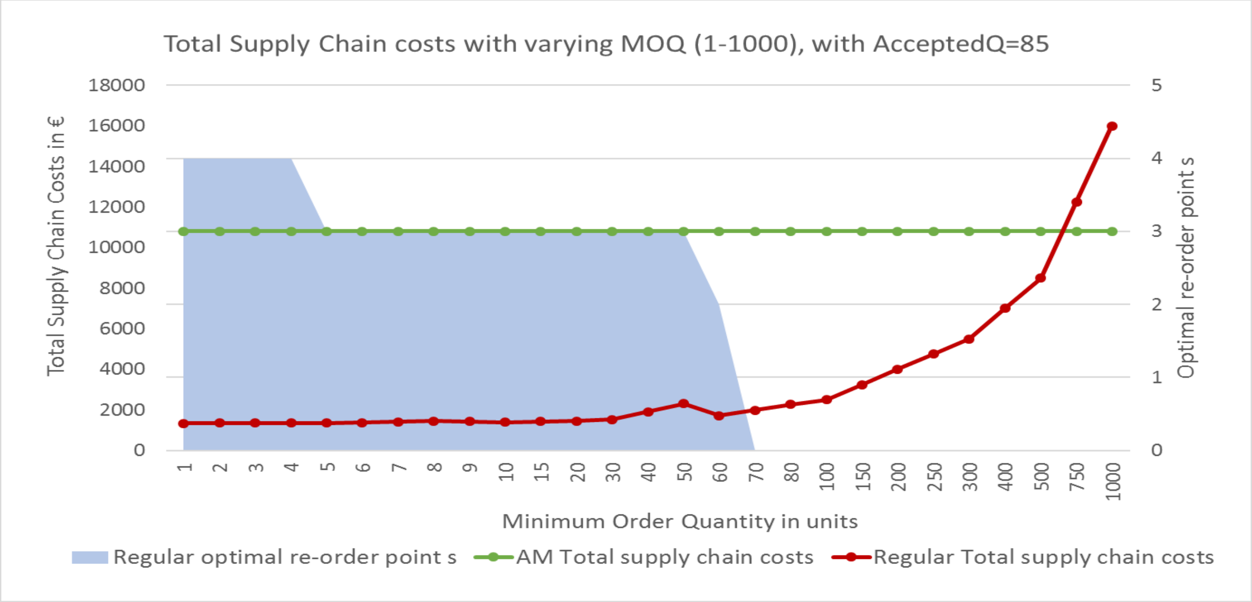

Figure 18: The total supply chain costs for different MOQ. The light blue color shows the optimal re-order point s for MOQ = 1 up to MOQ = 1000

number of cavities, is a time consuming and consequentially costly job. This results in a large minimum order quantity, where it is only possible to order at least the minimum order amount.

When the *acceptedQ* is set on 85 units, a MOQ larger than 85 will only affect the *CP* (costs of production) because the holding costs and transportation costs are based on actual number of items shipped to the warehouse (*acceptedQ)*. In figure 16 is shown how the optimal re-order level *s* and the total supply chain costs change when the MOQ is varied. As expected, the costs will start to rise drastically when MOQ > *acceptedQ.*

In Figure 18, the interesting point is the intersection between the total supply chain costs of additive manufacturing production and regular production. In this specific case study, this point is reached at MOQ = 654 units. This concludes that with the current parameters and a MOQ larger than 654 units, it is more economic to choose for additive manufacturing.

Figure 19 focusses on the part where MOQ < *acceptedQ*, showing that generally the costs increase slowly when the (MO)Q increases, but with a MOQ of the size *0.5n < MOQ < n,* it is economically interesting to order a larger quantity to fulfill the demand. For instance, in this case, with an expected demand of 60, and a MOQ of 40 or 50 units, are total supply chain costs lower when 60 units are ordered than when ordering 40 or 50 units twice.

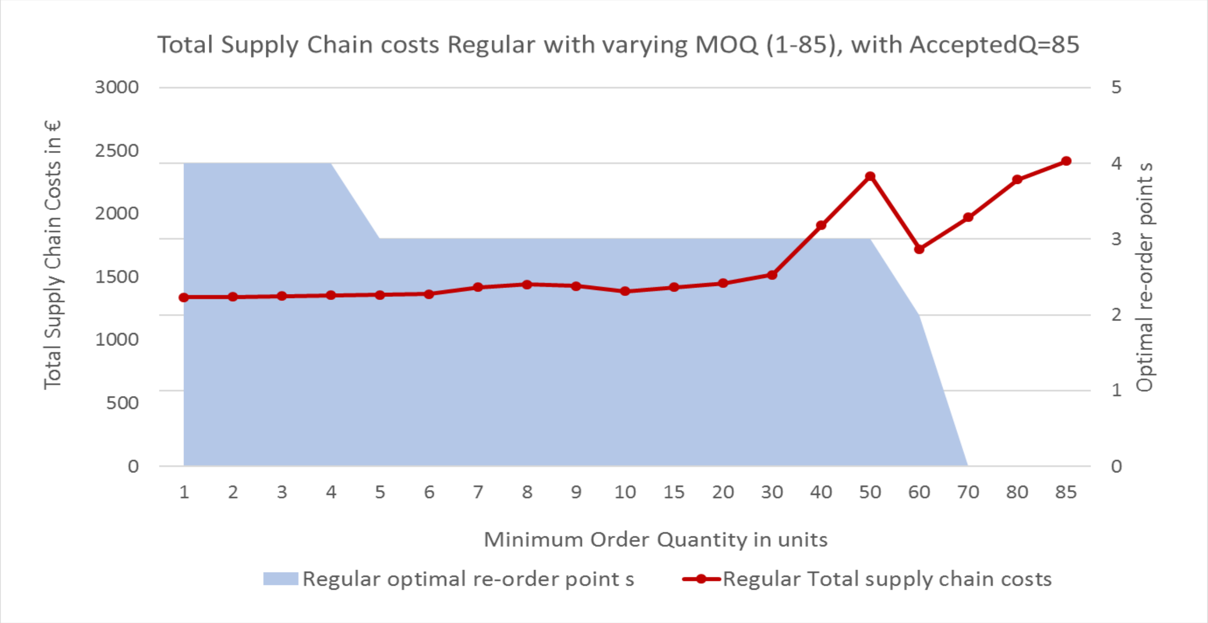

Figure 19: The total supply chain costs for MOQ = 1 to MOQ = 75 (acceptedQ), where the total supply chain costs for additive manufacturing are still €10,800

Conclusion

For looking at batching and minimum order quantities, the model is changed to a (s,Q) model where at re-order point *s* an order of size *Q* is placed. When the *acceptedQ* is smaller than the MOQ, the surplus items will not be transported to the warehouse, but production costs are accounted. Therefore, the costs will rise linearly for every extra item added to the MOQ after the value of *acceptedQ*. In the case that the MOQ is significantly larger than *acceptedQ*, additive manufacturing is a cost-efficient option to consider.

5.1.3. Large portfolio with uncertain low demand

In the case study discussed, the mean yearly demand was λ = 2, this is a mean demand where the probability of an actual order is relatively large. In discussions with category managers of Company B and Company C, the problem was mentioned that it is expensive to have inventory on hand when the probability of actual demand over the coming years is nearly nothing. When it does occur that an item is ordered but is not on-hand, the managers face long lead times and downtime costs. The other possibility is to have a small base stock level, but with the possibility that this SKU will never be ordered. This results in unnecessary costs, which can become significantly large if the company runs a large portfolio with many uncertain SKUs. This kind of case study is modelled by adapting the mean demand and by changing the production costs in the maximum between $n*c_p$ and $S*c_p$.

For instance, if a company has 100 SKUs which are offered for $T = 10$ years, and they expect to sell only one single part of these 100 SKUs in the whole period. Than the mean demand becomes $\lambda = 1/(100*10) = 0.001$. The expected number of products sold over period T per SKU is $\lambda T = 0.01$. The other parameters remain the same. The total supply chain costs for each of the production methods and the corresponding base stock levels are given in Table 7.

Minimum costs for total supply chain with holding costs per cubic meter (c_e & $c_d = 0$)			
	Regular (S=1)	AM MTS (S=0)	**AM MTO (No S)**
Total supply chain costs on average per SKU	€ 37,0203	€ 12.99	€ 1.80
Total supply chain costs over all SKUs	€3702.03	€1299.00	€180.00

Table 7: Minimum supply chain costs on average per SKU at uncertain production and the total supply chain costs for all SKUs together

In this case, the numbers show the average costs per SKU when the probability on demand is 0.01. Table 7 shows clearly that in this case additive manufacturing MTO has the least costs. The cost that are still occurring are the average costs for production (€1.75) and the average costs for outbound transport (€0.05). These given costs are the average costs per SKU. In this case study there are 100 SKUs with each a mean demand of 0.01. To calculate the total costs, the supply chain costs per SKU must be multiplied by 100. This result is also given in Table 7. The results conclude that in this case it saves the manager almost €2000 when he is implementing additive manufacturing as a production

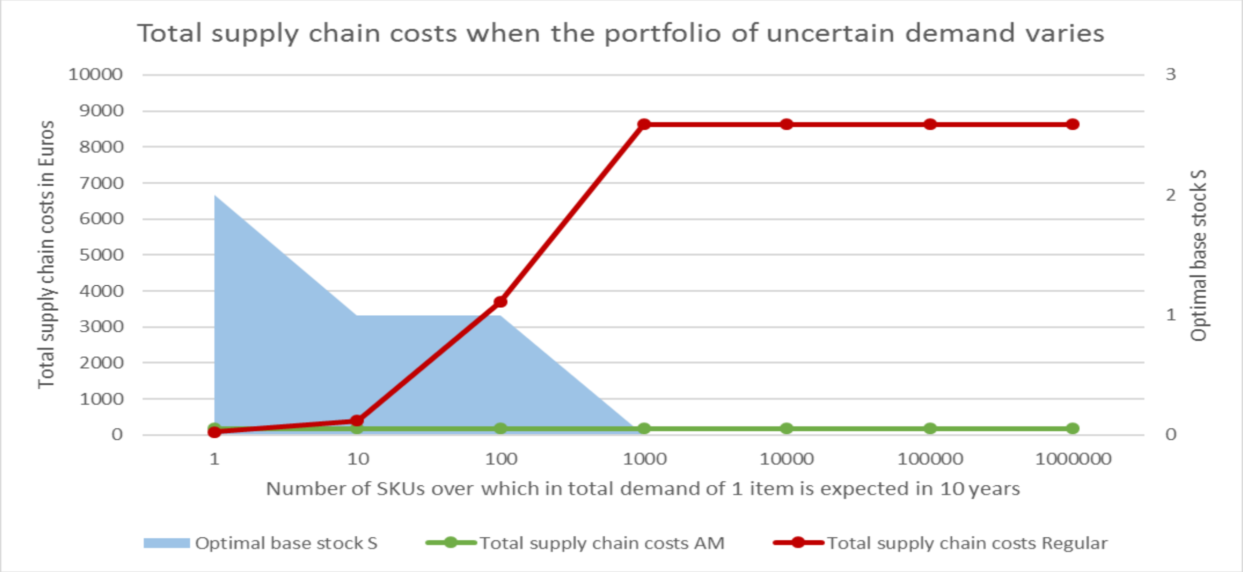

Figure 20: The total supply chain costs when there is an uncertain demand. The x-axis shows the size of the portfolio for which 1 item is demanded in the coming 10 years, but it is unsure for which SKU.

method and in practice there are even a larger number of SKUs with uncertain demand which shall result in even higher savings. This effect is demonstrated in Figure 21, where the total supply chain costs are shown when the portfolio size is varied between 1 and 1 million SKUs with in total 1 expected demand in 10 years. From a portfolio size of 1000 and up, the total costs remain steady because the optimal base stock becomes 0, and therefore no extra costs occur when the portfolio size grows.

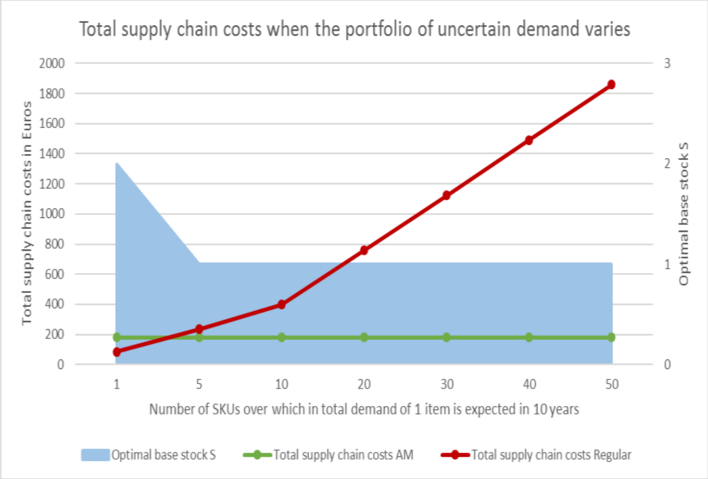

Figure 21: The total supply chain costs with T=10, when there is an uncertain demand. The x-axis shows the portfolio sizes of 1 to 50 SKUs

The graph in Figure 21 shows that already with a relatively small portfolio of different SKUs with uncertain demand, the total costs of regular production become higher than the total costs of additive manufacturing production and these differences become bigger until a steady level is reached when the optimal base stock level is 0.

A more precise view on the different portfolio sizes for smaller portfolios of groups of SKUs, is given in Figure 22. In here we see that from a relatively small portfolio on the additive manufacturing starts to be economically interesting. The point of intersection between 2 SKUs and 3 SKUs, meaning that with a portfolio of at least 3 products in this case study, production with additive manufacturing has the lowest supply chain costs and is economically most attractive.

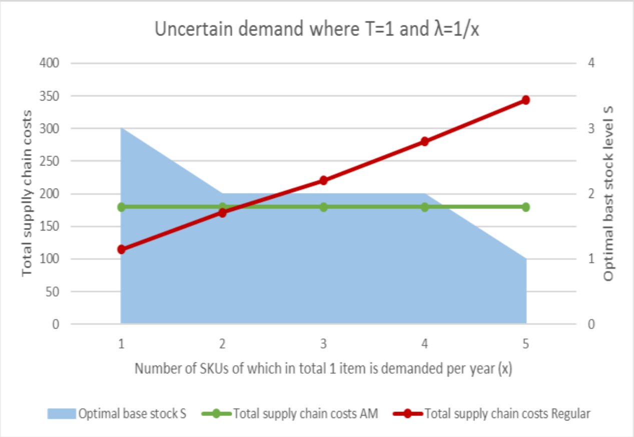

Figure 22: The total supply chain costs when T=1 and the portfolio size is 1 to 5, giving lower costs for additive manufacturing from >3 SKUs

Conclusion

The last situation is the situation where the demand of a SKU is not sure, but it is expected that 1 item will be ordered among a portfolio of SKUs. This is translated in the model as $0 < \lambda < 1$. Even if the demand is very low, it will still be more economical to have a base stock level $S > 0$ than to pay the downtime emergency costs. When at the end of T, no demand arrived for that particular SKU, all the invested costs for transport, production and holding were a useless investment.

Figure 22 shows that additive manufacturing is becoming the economical production method at already a small portfolio of uncertain SKUs. In this case study, from a portfolio with size > 2.2 is regular production having more supply chain costs than additive manufacturing. This is with yearly demand, meaning that the $\lambda < \left(\frac{1}{2{,}2}\right) = \lambda < 0{,}45$.

Looking at data from Company B, regarding the number of SKUs and the current levels of stock; from the 4700 items which are on order for the customer, 1000 items had 0 orders last year and 650 items had 1 order last year. This shows that if the 0 order items and the 1 order items have the same probability for an order coming year, on average their yearly demand will be $\frac{650}{1000+650} = 0.39$. Therefore, if indeed the probability of an order is the same, shall it be very likely that additive manufacturing has lower supply chain costs than regular production, assumer the parameters used in the case study.

From this we can conclude that uncertain demand could be an important driver for production with additive manufacturing. The bigger the uncertainty, the bigger the profit will be when producing with additive manufacturing, compared to regular production.

5.1.4. Mould production

Until now, we assumed that the mould or tooling for regular production was available at the manufacturer. Situations can occur when the mould or tooling is damaged or lost. In that situation, start-up costs are added to the total supply chain costs of regular production, while additive manufacturing still has linear supply chain costs regarding the demand.

The costs for manufacturing a mould depend on the size, number of cavities and complexity. The price can range from €3,000 to €80,000 (RexPlastics, 2017), which makes an impact on the total supply chain costs. Figure 23 shows that in the situation of manufacturing a simple, single-cavity mould, in combination with demand > 22, regular production is the option with the least costs. If the parts demand a complicated mould at higher costs, than additive manufacturing with limited demand the cheaper option (demand>136 parts for €20k mould and demand > 534 parts for €80k mould)

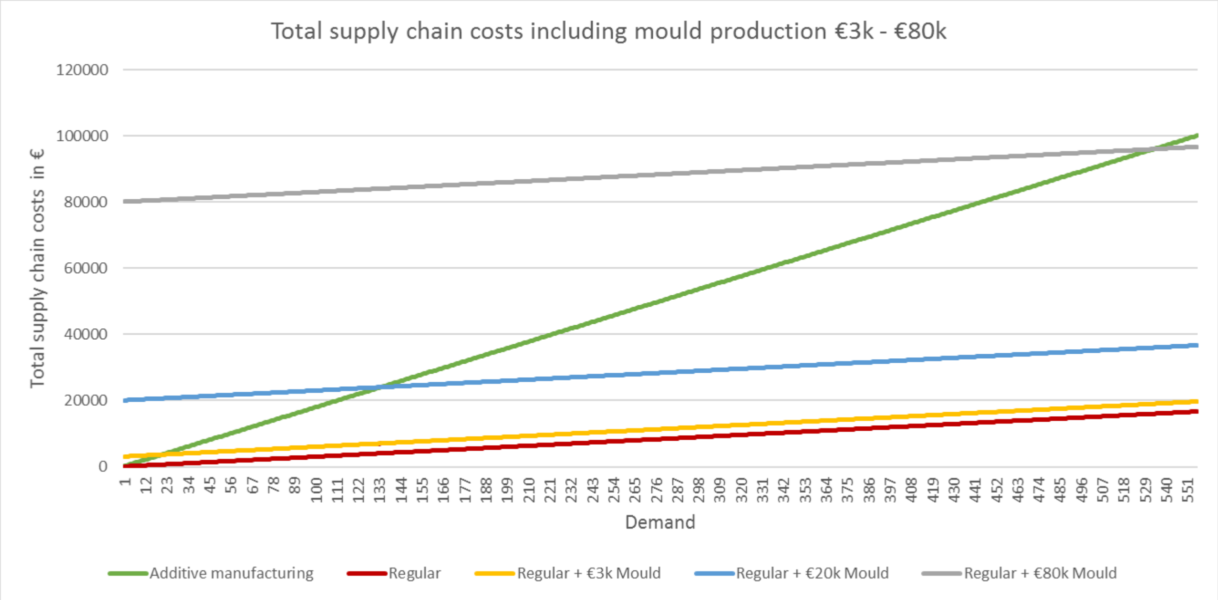

Figure 23: The total supply chain costs when investment costs for a tool or mould are included.

Conclusion

From Figure 23 we conclude that when a small, inexpensive, mould or tooling must be manufactured, the turnover point to regular production is at relatively low demand (22 parts). The more complex and at higher costs the mould or tooling becomes, the higher the turnover point will be. This method of weighing the investment costs of regular production versus the more expensive additive manufacturing could also be used for regular, new introduced products, instead of solely spare parts.

5.1.5. Conclusions

In this numerical case study, we studied the effect of additive manufacturing instead of regular production on the total supply chain costs. For this case study, parameters coming from an existing example from the industry are used. By iterating the model, we investigate what parameters are appearing to be interesting in the economic decision to produce with additive manufacturing. The values will change when different parameters are used, but the case study is expected to give a suggestion in which situations additive manufacturing is interesting.

Based on the previous mentioned findings, we can conclude that in regular, one-to-one replenishment situations, additive manufacturing is an expensive production method compared to regular production. The holding costs and emergency costs are relatively insensitive to this. A drastic change in production costs can influence the preferred method, but this is not expected to happen in the near future.

The most interesting situations are when there are minimum order costs (*MOQ >> n*), or when there is uncertain demand $\approx \lambda < 0{,}45$. These situations are common to be found in current examples from the industry and therefore, already are interesting for practitioners in present time. In the situation that investment costs for tooling or (re-)manufacturing of a mould, used in regular production, are required, is this depending on the expected demand *n* and the complexity and costs of the mould or tooling. There certainly are situations where additive manufacturing becomes the economic sustainable production process. These impacts are summarized in Table 8.

Changing Parameter or Situation	**Level of impact on economic decision for change of production method**
Emergency downtime costs	-/-
Production costs	+/-
Minimum Order Quantity	+
Uncertain very low demand	+/+
Mould production	+

Table 8: The result of a changing parameter on the economic advantage of production with additive manufacturing.

5.2. Environmental costs

In the Section 5.2 is shown how the economic supply chain costs are influenced when several parameters change and what happens consequentially to the costs-driven decision on what production method to use. In this section the environmental costs are studied and are looked upon on how they can change and what production method is preferred at a certain point. The assumptions regarding the part, given in the numerical example in Section 5.1 still apply, and that the company has an economic cost driven stock policy. In addition to that, the parameters of Table 9 are added, based on data from 3PL Company D and Goedkoop & Spriensma (1999).

Model parameters	**Description**	**Regular production**	**AM production**	**Accounts for both**
m	mPts per kg of used material (Nylon)	630	630	x
u_{eff}	Material efficiency of the chosen production method	0.8	0.6	x
e_e	mPts per kWh electric energy in the Netherlands	x	x	37
e_{kWh}	Amount of kWh used per kg of produced product	x	29.746	X
u_e	mPts in the production process per kg	44	X	X
t_i-van	mPts/kg/km for the last-mile transport by van			0.14
t_i-truck	mPts/kg/km for the longer road distances	x	x	0.022
t_i-ship	mPts/kg/km for transportation by freighter	x	x	0.0011
t_i-plane	mPts/kg/km for fast transportation by plane	x	x	0.078
km_{man}	Number of kilometers travelled before material reaches the manufacturer	5000	5000	X
Km_{war}	Number of kilometers travelled between the manufacturer and the warehouse(s)	0	5000	X
Km_{cus1}	Number of kilometers travelled between the warehouse and the customer, last mile transport, by van	100	100	x
Km_{cus2}	Number of kilometers travelled between the warehouse and the customer, (inter)national transport, by plane or big truck	1000	0	x

Table 9:Numerical assumptions used in the environmental costs calculation. These values are based on data from the industry

In this case study, the material used is PA, also known as Nylon. Nylon is common to be used in as well injection moulding and in additive manufacturing (SLS). It has a high melting temperature (220 degrees Celcius) and can therefore also be used as a substitute for metals. (Creativemechanisms, 2017). The production processes used are injection moulding for regular production, and SLS for additive manufacturing. These are common industrial methods used for the chosen material.

For calculation of the amount material needed, the u_{eff} of the production process must be known. Dotchev and Yusoff (2009) state in their paper that the use of nylon in SLS gives of the 100% input material 12% output material, 80% powder which can be reused in an other laser sintering process and 8% which is waste. This results in a material efficiency rate of 0.6. In injection moulding the batches are a lot bigger and therefore the waste produced in the startup process is less. We assume this efficiency to be 0.8., based on information given by the operations expert of DiManEx.

One of the most mentioned arguments for environmental benefits for additive manufacturing is that there is no need to keep on hand stock in inventory, which would mean reduction in transportation kilometers and less obsolete stock to be scrapped. Figure 23 shows the results when the base stock of regular production varies, resulting in a linear line which is only a fourth of additive manufacturing production, assuring that with these parameters and assumptions regular production is the sustainable choice.

In Section 5.1.2 is showed that with these assumptions, a base stock level of *S = 5* is optimal. Assuming this economically optimal base stock level, the sustainability costs for regular production are lower. Figure 25 shows that in comparison, the material costs are comparable. However, the production costs are the factor that influence the sustainability costs the most. Looking at the parameters, is this a reasonable result; since the mPts per kg for injection moulding are 44 versus 1100 for SLS.

Figure 24: The total supply chain sustainability costs, with varying base stock level S, n=60 and Q=1, showing that regular production is even with a very high base stock less sustainable.

From Figure 24 we can conclude that a varying base stock level is not a big influence on switching to additive manufacturing for sustainability reasons. Even when the base stock level would go up to30 items (half of the total demand), regular production is still more sustainable. Therefore, we conclude that this factor is not having a big impact on sustainability costs.

5.2.1. Changing major cost driver

As Figure 25 shows, the energy used in the production process of additive manufacturing, is the main costs driver in the total sustainability costs. The value for energy consumption of the machine is deducted from the research of Baumers et al. (2011) and it could have changed in recent years, or is going to change as additive manufacturing machines are rapidly developing.

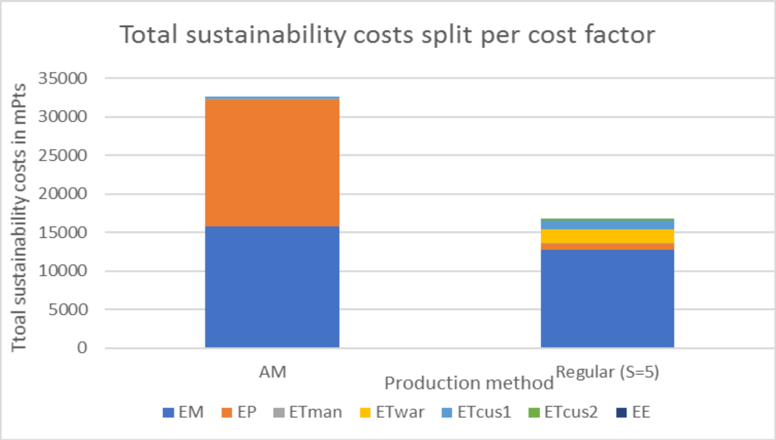

Figure 25: Total sustainability costs split per costs factor, for additive manufacturing and regular production with base stock level S=5.

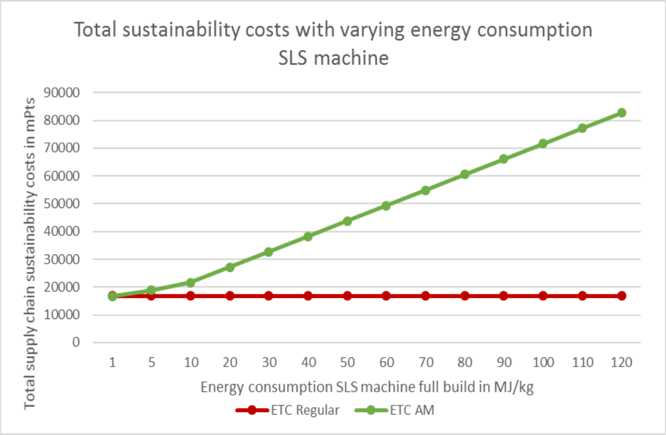

Figure 26: The total supply chain sustainability costs, when varying the energy consumption of the SLS machine, which is currently known as being 107 MJ/kg.

Figure 26 shows the total sustainability costs, when the energy consumption of the SLS machine changes. In the assumed situation (by Baumers et al., 2011) is this 107 Mega Joules per kilogram of product produced. The graph shows that reduction of energy consumption must lower to nearly 1 MJ/kg (1% of the current number), before additive manufacturing becomes the more sustainable choice. This concludes that an energy consumption reduction of the SLS machine in not the most plausible situation for additive manufacturing to become sustainable.

Conclusion

When the energy consumption of the additive manufacturing is lowered, it is expected that the total sustainability costs will drastically lower as the process is a large factor in the total costs. Figure 26 shows us that the Mega Joules consumed per kilogram product must be lowered to only 1% of the original 107 MJ/kg before additive manufacturing is the more sustainable option. Although the additive manufacturing machines are developing rapidly, an energy reduction this large is not likely to happen in short notice.

5.2.2. Minimum Order Quantity

The situation described in chapter 5.2.1, based on a one-to-one order replenishment, is uncommon in the case of injection moulding. In that process works the machine with moulds where multiple products are made in one batch. In the case of a company ordering an OEM item, a minimum order is common. In some cases, this minimum order quantity is smaller than the total number of expected demand *n*. In that situation, sometimes more items are produced than are demanded. This is the case when *qQ* > *n*. Figure 28 shows how this influences the sustainability costs when the demand *n* = 60 and

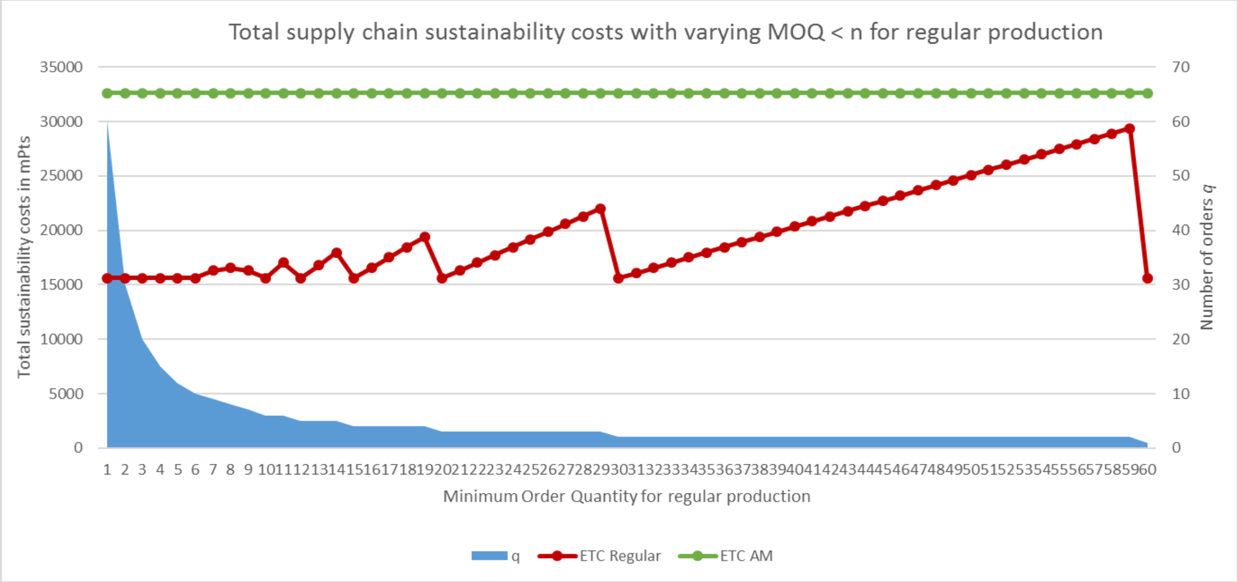

Figure 27: The total supply chain sustainability costs when there is a Minimum Order Quantity smaller than the total demand n.

the *Q* varies from 1 to 60. For the minimum order quantities where *n/Q* is not an integer, the sustainability costs are rising but not as high that they will intersect the costs for additive manufacturing. In addition to that, similar to Section 5.1.3, it sometimes is cheaper to order a larger quantity at once than ordering a smaller quantity twice, for instance when the MOQ is between 31 and 59.

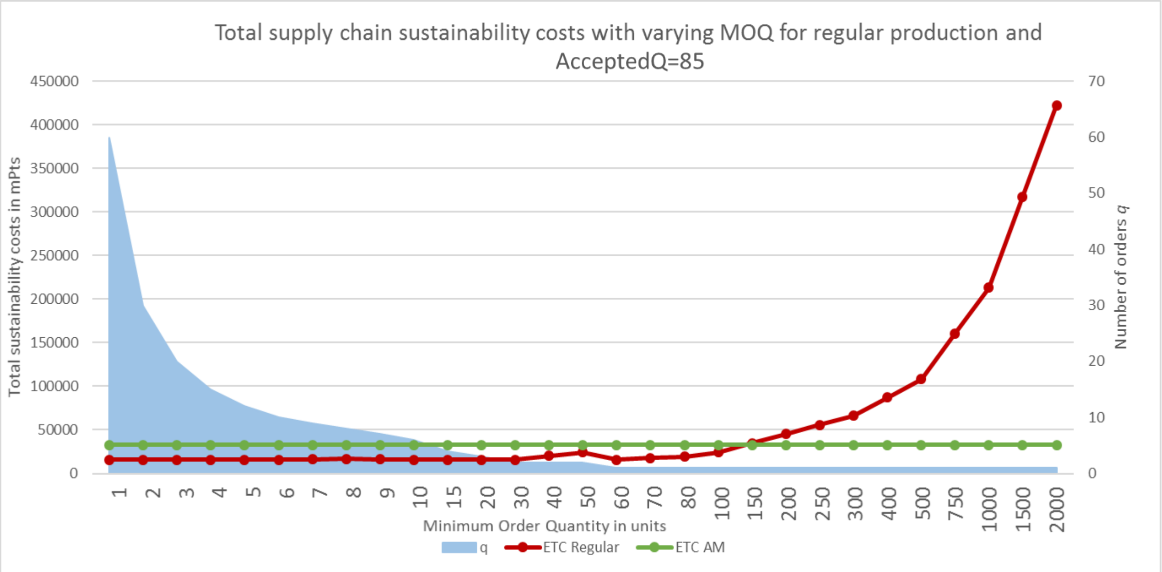

Figure 28: The total supply chain sustainability costs when varying the minimum order quantity and having an acceptedQ = 85 and n=60.

When the minimum order quantity is much larger than the expected demand, these situations can be found when processes like injection moulding have to be set-up for only one customer, additive manufacturing is rapidly starting to have less environmental costs than regular production. This is shown in Figure 28. This graph looks similar to Figure 18, but in this sustainability costs figure the point of intersection is at 140 items, which is lower than the point of intersection for economic costs (654 items). This means that there exists a region (*140 < MOQ < 654*) where additive manufacturing is more environmentally sustainable but less economically sustainable. As soon as additive manufacturing becomes the production process with the least supply chain costs, is it also having benefits on the sustainability side.

Conclusion

If the minimum order quantity is less than the expected demand, regular production stays the most sustainable choice. But, similar to the economic costs, when the *MOQ >> n*, there is a point where additive manufacturing is the option with the least costs. In this case is that the point when *MOQ > 140*, which for many production processes is a reasonable minimum order quantity.

5.2.3. Large portfolio with uncertain low demand

In Section 5.1.4 we discovered that there is an important opportunity for additive manufacturing when there is an uncertain demand ($\lambda < 1$). This can be the case when there is a large portfolio of many varieties but only one type is ordered a year or when the expected demand happens only once every *x* years, which results in a yearly demand of $\lambda = 1/x$.

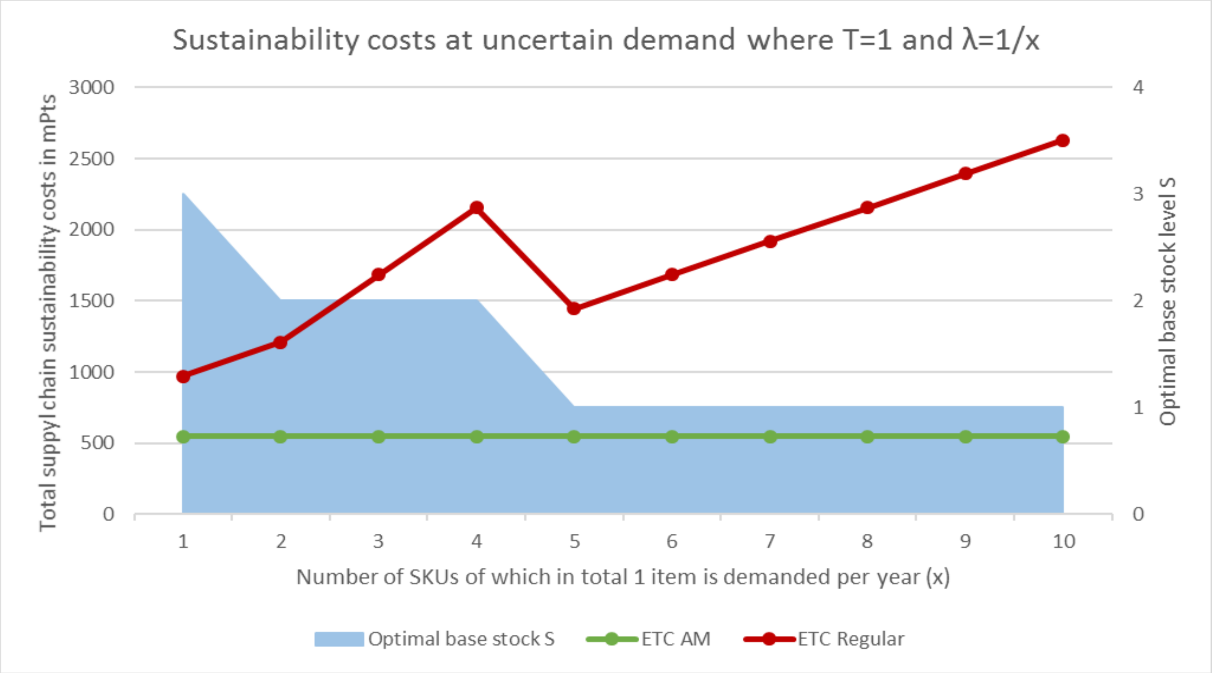

Figure 29: The total supply chain sustainability costs when λ = 1/x (uncertain demand over a number of SKUs), taking into account the optimal base stock level as calculated in figure 20.

In is situation, we found out that due to the emergency downtime costs, it is cheaper for the company to have a higher base stock level than to have a high risk of a stock out. Figure 22 showed that with a demand $\lambda < 1/2.2$, it becomes economically attractive to choose for additive manufacturing. This figure also showed for which base stock level the expected economic costs would be minimized. $\lambda = 1$ gives an optimal base stock level of 3 items, $1/2 \leq \lambda < 1/5$ gives an optimal base stock level of 4 items, and $\lambda \geq 1/5$ has an optimal base stock level of 1. In the case of a portfolio, from which 1 item is demanded a year, all the SKUs are required to have their amount of optimal base-stock level. This results in unnecessary produced parts when period T has ended, and the products become obsolete. The economic costs for production and inventory are relatively low compared to the penalty costs when there is no on-hand stock. However, every obsolete item on hand has comparable environmental costs as an item demanded, and with a larger portfolio can this number grow rapidly as shown in Figure 29.

From this figure, we conclude that due to the relatively low economic costs of keeping stock for SKUs with a very low (uncertain) demand, regular production costs at least twice the sustainability costs of additive manufacturing and therefore additive manufacturing is the sustainable production process.

Conclusion

In the case of a portfolio of uncertain demand (λ < 1) combined with the assumption that the company has a stock policy driven by economic costs, is additive manufacturing always the most sustainable choice. This occurs because due to the optimal stock policy, there are always at least a number of regular products produced, compared to the single part produced on demand in additive manufacturing.

5.2.4. Mould production

Up until now, we assumed that the mould would be still available at the manufacturer, used in the mass production when the regular parts were created. Occasionally, situations occur when the mould is damaged or lost and has to be (re-)manufactured. Besides the expensive economic costs, is the creation of the steel moulds also having very high environmental costs. Ribero (2016) calculates how many Eco mPts the creation of different sizes moulds would cost, and the results are between 0.9 million and 7.3 million mPts.

If we assume Ribero's smalles mould of 0.9 million mPts, which are consumed when the mould is made, irrespective how many products it produces, then these 4 million mPts need to be added to the total supply chain costs for each number of items produced. Additive manufacturing sustainability costs are linear to the number of items made since they do not have start-up costs. This situation in shown in Figure 31, showing that it takes around 3,000 produced parts (for the smallest mould) before additive manufacturing production has more sustainability costs in this situation.

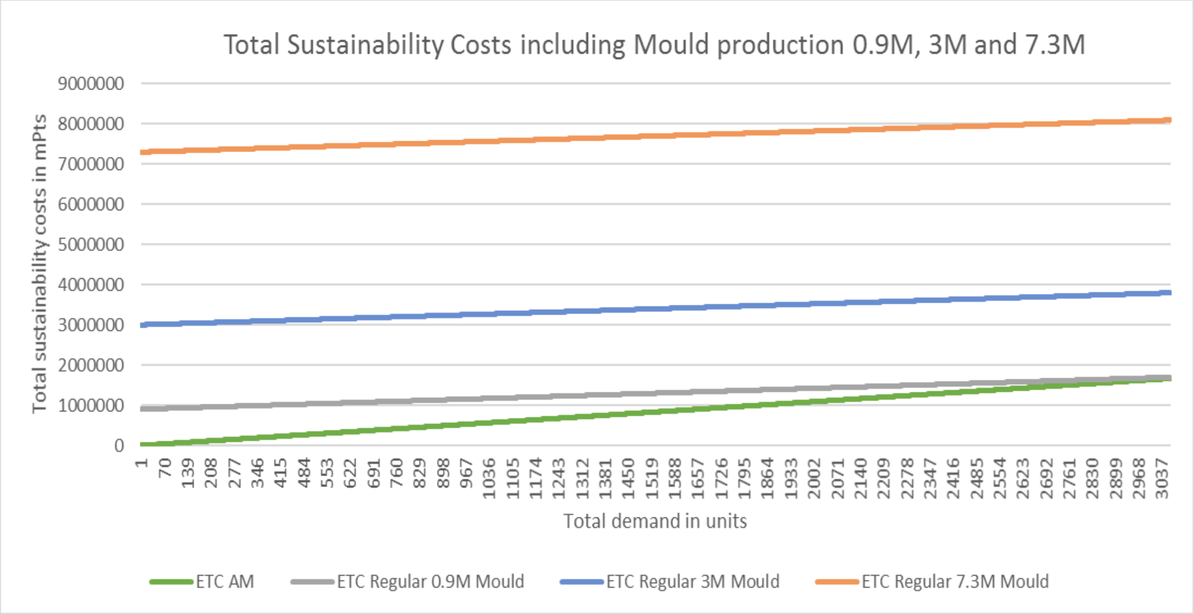

Figure 30: The total supply chain sustainability costs when a new injection moulding mould needs to be manufactured, including a small mould of 900,000mPts, a medium mould of 4,000,000mPts and a large mould of 7,300,000mPts. There are many produced items needed for regular manufacturing to become the sustainable attractive production method when this big investment occurs.

Conclusion

The loss or damaging of a mould is something which happens often in practicem due to change of manufacturer, or just over time. Figure 31 shows that even with the smallest injection moulding mould, the sustainability costs are lower for additive manufacturing if there are 3,000 items or less produced. In the low demand spare parts supply chain, a demand lower than 3,000 parts is very common and therefore we conclude that this situation is probable and has a major influence.

5.2.5. Conclusions

When comparing the numerical examples of economic and sustainable costs, it can generally be said that when additive manufacturing is the most economic production process, it is also the most sustainable choice. In the literature was often referred that additive manufacturing is the sustainable method for production, this is mostly not the case due to the little material efficiency of the machine used in this case study, compared to the regular mass production. There are situations where in this case study additive manufacturing is turning out to be more sustainable.

The sustainability supply chain costs are, with the current known parameters, higher for additive manufacturing in a one by one replenishment situation. A minimum order quantity much larger than the expected demand would change the situation and due to the obsolete regular produced items has become additive manufacturing the more sustainable manufacturing method. Also in the case of uncertain demand is additive manufacturing the more sustainable choice due to obsolete produced regular produced parts, to maintain the optimal base stock level for minimizing the downtime costs. Finally, the easiest decision is when a new injection moulding mould or tooling must be (re-)manufactured; in that case over 3,000 items are required to justify these invested sustainability costs, which is not often the case in the low demand spare parts. These conclusions are summarized in Table 10.

Changing parameter or situation	**Level of impact on economic decision for change of production method**
Varying base stock level *S*	-/-
Energy consumption AM machine	-/-
Minimum Order Quantity	+
Uncertain very low demand	+/+
Mould production	++/++

Table 10: The result of a changing parameter on the sustainability advantage of production with additive manufacturing

6. Conclusions

In this chapter the conclusions of the study are drawn, by answering the four research questions.

The aim for this research was to find out what the influence is of additive manufacturing on the supply chain, as stated in Chapter 1, in the research problem:

> *"What is the influence of additive manufacturing on the environmental and economic performance in the supply chain of low-demand spare parts?"*

To address this problem, we formulated four research questions, stated in Section 1.2.2. The first research question was:

> *RQ1: "What is the impact on financial costs of adopting additive manufacturing in the low demand spare parts supply chain?"*

This question is answered by the economic cost model, explained in Chapter 3. With the data and information retrieved from the literature as well as the industry, a case study was conducted, giving insights, shown in Section 5.1.

From this case study we conclude that the costs for transportation, inventory and downtime are neglectable compared to the higher production costs for additive manufacturing. In the case study, where 60 parts are demanded in 30 years, are the costs for regular production €1,735, versus €10,800 for additive manufacturing. This is a significant difference in costs, not favorable for additive manufacturing. The major cost driver of additive manufacturing, as well as of regular production, is the cost for production. However, the study shows that this cost factor must change drastically before additive manufacturing becomes the most economic production process. We expect in a regular situation of one-by-one replenishment, that additive manufacturing is not making a large impact on the financial costs, as the regular production method shall be preferred.

However, the we did find three interesting situations, suggested by the industry, which are making a significant impact on the financial costs. The first situation is when the there is a Minimum Order Quantity, being much larger than the total expected demand. All the extra, non-demanded, ordered parts will become obsolete and are useless costs. The case study shows that if the MOQ is approximately factor ten larger than the demand, additive manufacturing is becoming the economically sustainable production method, and is therefore impacting the low demand spare parts supply chain.

The second interesting situation is when there exists a portfolio of SKUs with an uncertain demand. For instance, when there are multiple variants, but of all the variants, only 1 part is expected to be demanded. Due to the high emergency (penalty) downtime costs, is the most economic solution for regular production to have at least one part for each variant on stock. As the number of variants (SKUs) grows, is the number of obsolete stock also growing, since the total demand over all the SKUs still is assumed to be $\lambda = 1$. In the case study discussed in Chapter 5, is additive manufacturing impacting the financial costs of the supply chain, when the number of variants (SKUs) is at least three. This is a common situation in the industry, and therefore accounted as a significant impact, since the profit grows rapidly, when the number of variants grow.

The final interesting discussed situation, is the situation when the required mould or tooling for regular production is damaged, or not available. This situation is often experienced by customers of DiManEx; being a reason to consider additive manufacturing as a production method. The costs for tooling or mould production have a large price range, and are difficult to determine, given the current parameters. In the case study, the costs of three different moulds are modelled; a simple, small-, medium- and a complex, large mould. For additive manufacturing, to make a financial impact, the total demand must be less than 22 parts, in the case of the small mould. For the medium mould, the total demand must be less than 136 parts, and for the large mould it must be less than 534 parts. Considering the scope of low demand spare parts, this situation could definitely make an impact, if the required mould is a little more complex than the simplest mould available.

The second research question was based on the environmental impact of additive manufacturing:

RQ2: "What is the impact on environmental costs of adopting additive manufacturing in the low demand spare parts supply chain?"

Chapter 4 is dedicated to the environmental model, which contributed to the environmental case study described in Section 5.2.

As we assume that companies financially optimize their decisions, interesting situations of RQ1 are assessed environmentally. The basic one-by-one replenishment situation shows that replacing regular production by additive manufacturing, is not reducing the environmental footprint, as the literature suggests. This is because of the high energy consumption of the SLS machine, which is 1100 mPts/kg versus 44 mPts/kg for an injection moulding machine. The extra environmental costs of transportation and scrapping in regular production, are neglectable to these high process costs. Future development, resulting in a reduction of energy consumption of the SLS machine, is barely affecting the impact, since the energy consumption must be reduced to 1% of the current consumption.

However, comparable to the financial costs, we did look at the three situations where additive manufacturing is making a financial impact and we concluded that in each of these situations, additive manufacturing is making a significant environmental impact as well. The first situation is when there is a MOQ. In our case study, to make an impact on the environmental costs, the MOQ must be at least 140 parts; a situation likely to occur.

In the second situation, with the portfolio of uncertain demand, additive manufacturing is always impacting the environmental costs. The environmental costs for regular production are in the case study at least twice as high as the environmental costs for additive manufacturing. This is due to the assumption that the stock levels are financially driven, resulting in relative high stock levels, to prevent downtime emergency costs. These stock levels become obsolete and must be scrapped. All these unnecessary produced, scrapped items, result in the high environmental costs.

Finally, the production of a mould or tooling is environmentally assessed. Like in the financial assessment, determining the exact environmental costs of the mould or tooling is difficult, thus three different costs are used, ranging from a very simple single-cavity mould to a complex 64-cavities mould. In this situation is additive manufacturing also having a significant environmental impact, as there are at least 3000 demanded parts required, before regular production including manufacturing the simple single-cavity mould is environmentally preferred. A total demand of over 3000 parts (and even more for the more complex moulds) is not within the scope of the low demand spare parts supply chain and therefore, additive manufacturing is having a significant impact in this situation.

The third research question is combining the insights from the first and second research question:

> *RQ3: "How can we measure the tradeoffs between economic and environmental costs when adopting additive manufacturing in the low demand spare parts supply chain?"*

Before starting the quantitative study, based on the literature, we expected a tradeoff for the economic and environmental costs, since the literature suggested that additive manufacturing would be more expensive, but would also be reducing the environmental footprint.

The gained quantitative insights on this research question, might be the most interesting because it is not as expected beforehand. Looking back at the situations where additive manufacturing is positively impacting the supply chain, we see that in each of the situations exists a positive environmental impact, if there is a positive economical impact. Instead of a tradeoff and behaving contrary, the environmental benefits move in the same direction as the economic benefits, where the environmental costs are impacting the supply chain faster. Assuming financial driven decisions, this is always resulting in environmental benefit for additive manufacturing, if there also is a financial benefit.

The final research question stated was based on the environmental policy of the Dutch government:

> *RQ4: "What could the government do as an intervention to stimulate environmentally conscious production?"*

This research question was also based on the insights of the literature review that additive manufacturing would reduce the environmental footprint, but is more expensive. As stated above, answering RQ3, this is quantitively proved not to be true: When following financial driven decisions, regarding additive manufacturing, this automatically will become the most environmentally conscious decision.

Subsidizing additive manufactured produced parts is not reducing the environmental footprint, because in one-by-one replenishment situations, regular production is environmentally preferred. Since the economic costs follow the environmental costs, is this process self-regulated and stimulated by financial profit.

However, the government could stimulate the use of additive manufacturing in the situation of the portfolio with uncertain demand. The case study proves that additive manufacturing can have a financial, as well as environmental impact in this situation, but before this can be achieved, the whole portfolio must be digitalized to 3D models. Not all companies might be willing to invest time and money in this digitalization. This is where the government can intervene: By offering a service or financial aid for digitalizing the SKUs, the step to additive manufacturing and environmental conscious supply of spare parts is minimalized.

7. Recommendations

Although the outcomes of this study are different than expected beforehand, based on the literature, we are aware that the case study is very limited. We chose to narrow down the case study to a single machine and a single material, but to look at different situations which can occur in the industry. For further research we would recommend considering different machines and materials in the numerical example. Now only Nylon is taken as an example, but other materials and production methods have other parameters, possibly relating regular and additive manufacturing differently.

Next to that we expect also a big impact when material of regular manufacturing is replaced, for instance when a regular item is made from metal but when it is replaced by an additive manufactured plastic part. Besides the costs for the supply chain is it also important to consider the strength and technical aspects of the new part; a different material could result in different mechanical abilities, but also in extra costs for testing and certification.

One of the applications of additive manufacturing, is constructing shapes which are not possible to be constructed in that way by regular production. A new design can result in less material used or a combination of multiple parts, suggesting financial and/or environmental benefit.

The environmental model of this study, is not considering the environmental costs to produce the production process machines; like in the case study, the injection moulding machine and the SLS machine. In a more extensive environmental model, this will be an addition, encapsulating more of the supply chain.

In this research has only been looked at the stage of after sales. Additive manufacturing is due to its high production costs, not suitable for large-scale production. However, looking at the product life cycle, additive manufacturing can be an interesting production method at the product development stage. This stage is characterized by the low demand and design adjustments; an ideal situation for additive manufacturing. A positive addition is that when the design is accepted and taken into production, the part is already available as a digital model. This makes the step to change production method to additive manufacturing later in the product life cycle smaller, and more accessible

The current case study has a lot of assumptions and some of these assumptions can be questioned and re-considered. In the case of investment costs, has the case study no investment costs for as well regular production as additive manufacturing. In practice, this is usually different but depends per situation. For additive manufacturing, it is depending on whether there is already a digital model available, or only a technical drawing. In some situations, only the current part is available. When the digital model is to be made by an engineering firm, this can result in investment costs between €50 and €5000. Sometimes, making a digital model also involves rules and regulations like patents and certifications. If this is the case for a part, the investment costs can become even more. In regular production, these investment costs can involve the mould manufacturing, buying a special machine or buying the rights to a part.

The values from the Eco-Indicator model are outdated as they originate from 1999. Not all the materials are mentioned and especially, additive manufacturing is not stated. Because of this, we have taken only the consumed energy of the production process into account, while might, in reality, result in higher costs. Besides, the material values used, are given as granulates, not as powders, which is how they are prepared for additive manufacturing.

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Appendix A

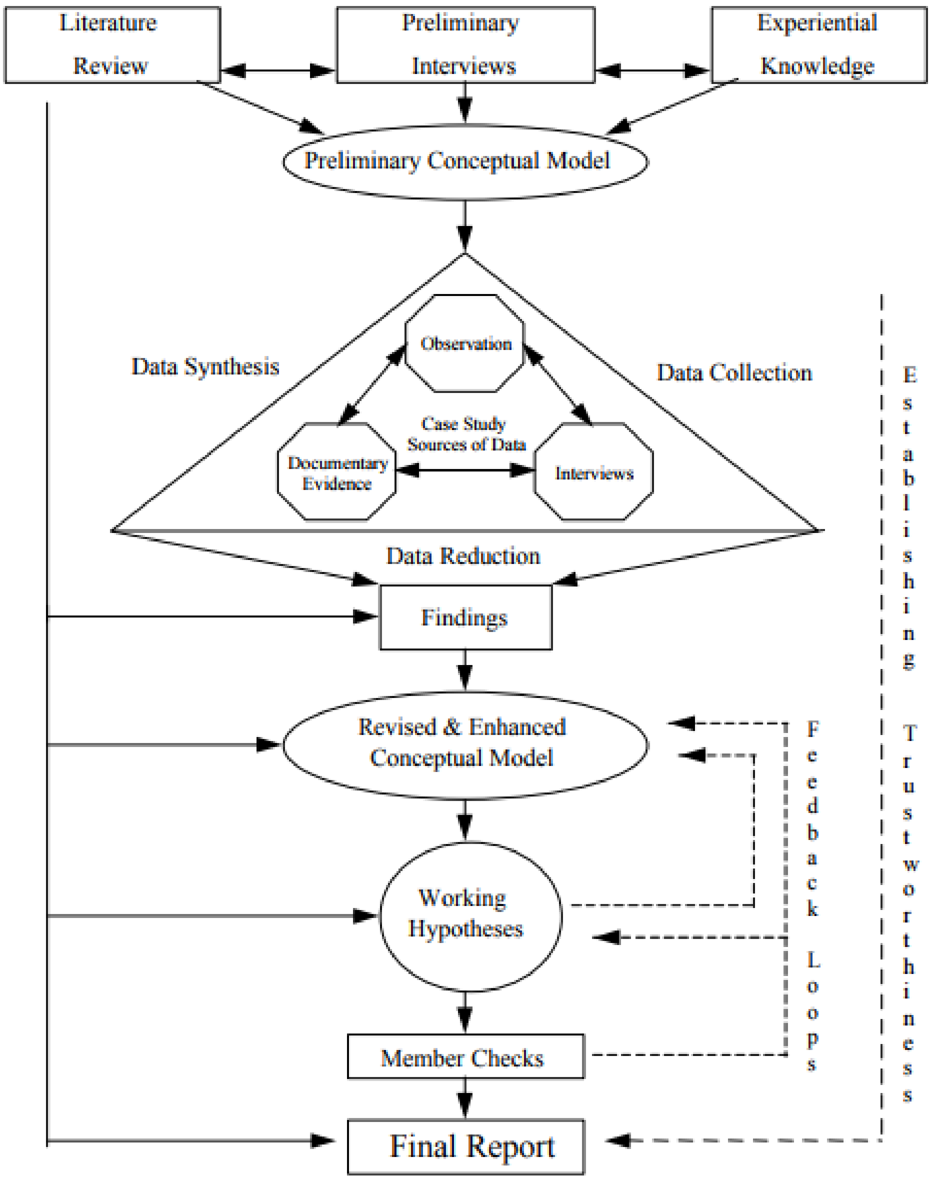

Figure 31: A schematic overview of the methodology used.

Appendix B

Rotations	**Turnover rate (items/year)**	**Nr. of sales per year**		**Nr. of unique SKU's**		**Value of stock**		**Nr. of items on hand**		**Average years on stock**	**Sales turnover per year**	
Low	<5	2.0 million	36%	29,000	83%	€15,500,000	77%	1,300,000	77%	0.66 year	€5.5 million	4%
Medium	5-10	2.1 million	38%	3,500	10%	€2,700,000	13%	300,000	18%	0.15 year	€5.5 million	4%
High	>10	1.4 million	26%	2,500	7%	€1,900,000	10%	84,000	5%	0.06 year	€129 million	92%
Total		**5.5 million**	**100%**	**35,000**	**100%**	**€20,100,000**	**100%**	**1,684,000**	**100%**		**€140 million**	**100%**

Table 11: Sales and stock numbers from Company B, split by the turnover rate:

Appendix C

Section 3.2.4. explains that there are two common methods for calculating the holding costs: Using a percentage of the production costs and by calculating the costs to reserve the demanded storage space.

When analysing the data of the industrial machine company, given in Appendix B, the costs of inventory per euro purchase price of the low rotating parts, are four times as high as the costs per euro purchase price of the high rotating parts, but on average this is 8% (supplied by Company B). This difference can be accounted to the average years on stock: The costs of a piece of shelf space can be divided among more sold items when an item has a higher rotation speed.

To calculate the holding costs using the percentage method, Equation 42 is used with CH_{perc} being the total holding costs calculated by the percentage, over the full time that the part is available for the customer, *h* the holding costs per €/€/year, *n* the total number of parts demanded in time *T* and c_p the production price.

$$CH_{perc} = hnc_p \tag{42}$$

This way of calculating inventory costs is discussable because the parts often have a low production costs which will result in costs of inventory due to the average inventory costs percentage, even if they keep the shelf space occupied for the whole year. Therefore, we will analyze the inventory costs when they are allocated in a different way: By dividing the company's total costs for inventory space by the volume of inventory space available. This results in the holding costs per m^3 (h_{vol}). With Equation 43 and the dimensions of the part, we can calculate the costs of reserving storage space for the base stock level of the parts. In the case of shipping printed parts directly to the customer from the printing hub are there no inventory costs.

$$h_{item} = h_{vol} * length * width * depth \tag{43}$$

$$CH_{item} = h_{item}ST \tag{44}$$

In most of the literature (e.g. Heizer & Render, 1999) and current business models, the holding costs are calculated by a percentage multiplied with the total production costs (*CP*). This is a fast and easy way to calculate an estimate of the holding costs for a certain SKU or product. Although, as shown in table 1, are the SKU's in the category C parts a lot longer in inventory than the category A parts. This means that the costs for inventory of the slow moving parts are higher than the average percentage used.

Instead of using a percentage of the production costs, are we now using the costs of inventory per cubic meter (m^3). This is a measurement regularly used by third party logistics companies (3PL) to calculate the rate for their customers. Depending on the contract, these costs can be around €180 based on interviews with 3PL managers.

Replacing Equation 42 by Equation 44 in the CH parameter, results in the new holding costs based on the yearly reservation of space. An item with dimensions 0.2x0.1x0.1 and yearly costs of €180 per m^3, results in costs of €0.45 per year to store. These low costs are nothing compared to the difference in production costs with additive manufacturing already mentioned before. The result of this is shown in Figure 32 and Table 12.

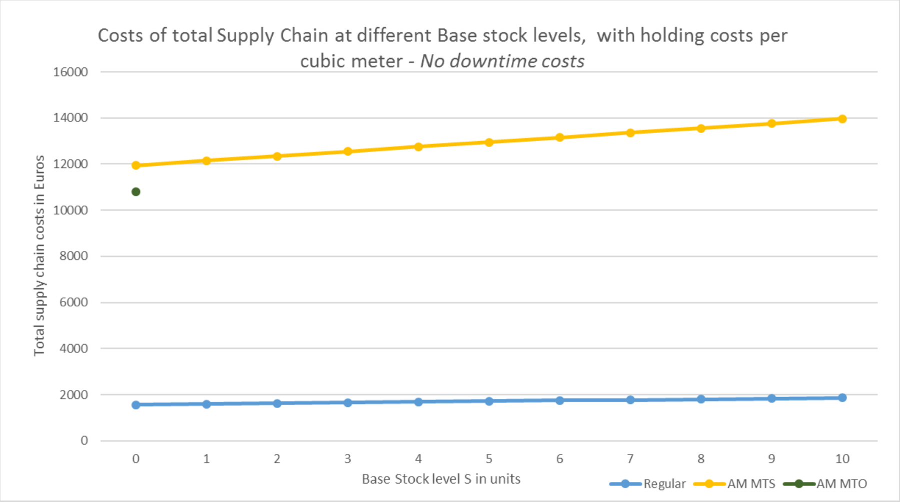

Figure 32: The total supply chain costs at different base stock levels with inventory costs per cubic meter, at no costs for downtime

Minimum costs for total supply chain with holding costs per cubic meter (c_e & c_d = 0)			
	Regular (S=0)	**AM MTS(S=0)**	**AM MTO (No S)**
Total supply chain costs	€ 1,572	€ 11,940	€ 10,800

Table 12: The optimal base stock level S for each of the production methods and its corresponding total supply chain costs with holding costs based on the base stock level per cubic meter.

In this example, the base stock level remains 0, which logically results in no holding costs for all the production methods. In Figure 33 is shown how the holding costs for the two production methods for each of the holding costs equations.

The constant line for additive manufacturing on stock, calculated by a percentage of *CP*, is clearly significantly higher than the other two lines while the products are nearly identical. Altough more valueble products have higher storage insurance costs, we think that this difference in costs is too high and therefore we chose the other method. In this method the costs for holding become higher as the base stock level rises. This seems a reasonable choice when working with 3PL companies. Hence, in further calculations, the holding costs are calculated per m³ of storage space reserved for the base stock, as explained by Equation 10.

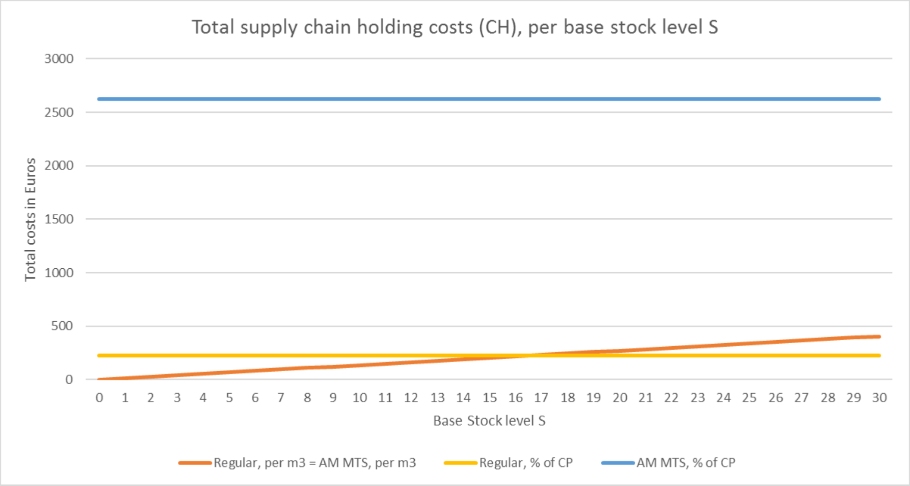

Figure 33: The difference between holding costs calculated as a percentage of the production costs (formula 7) and per cubic meter reserved for base stock (formula 10) for each of the production methods, per base stock level.

Appendix D

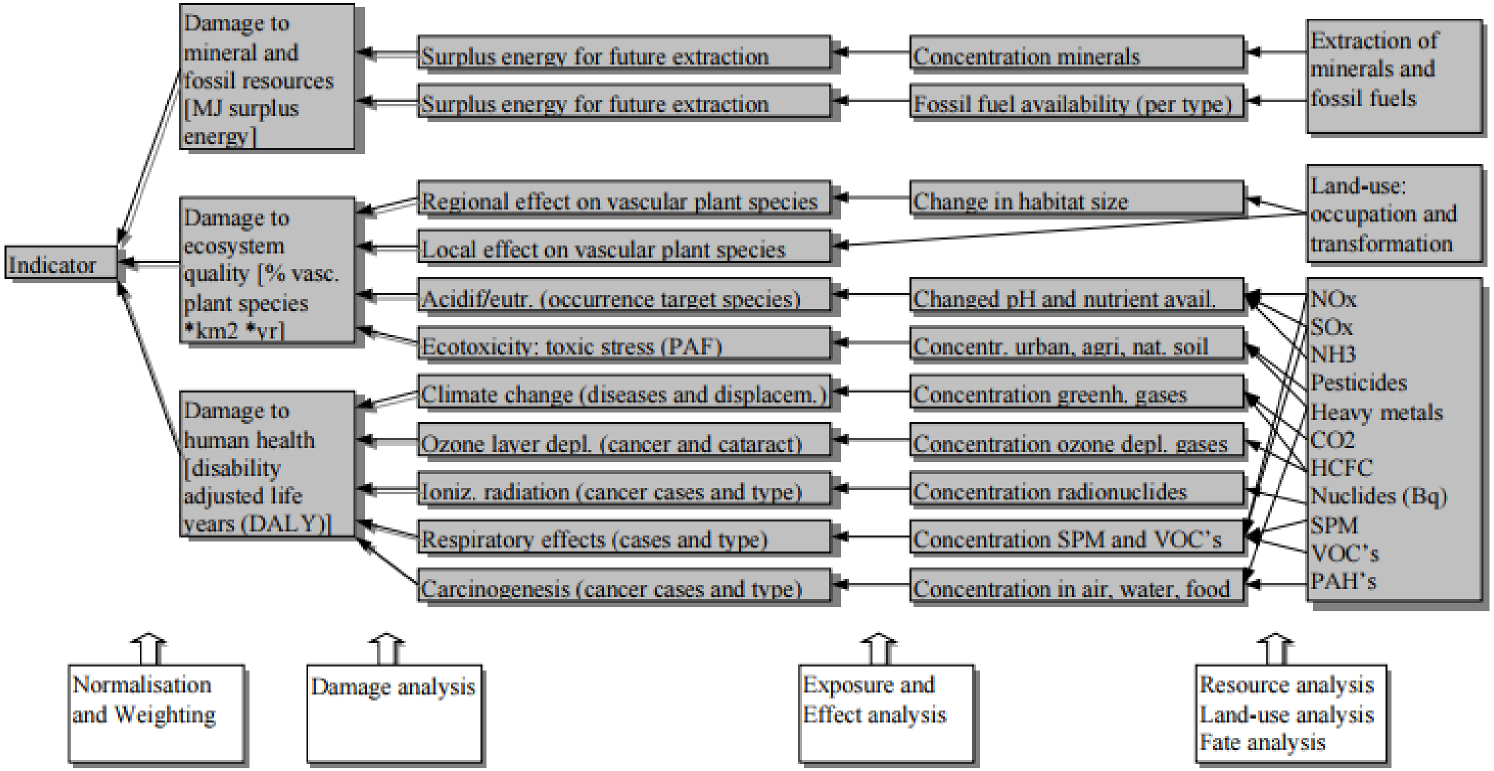

Figure 34: General representation of the methodology of the Eco-indicator 99. The white boxes refer to procedures, the gray boxes refer to (intermediate) results (Goedkoop & Spriensma, 2000).