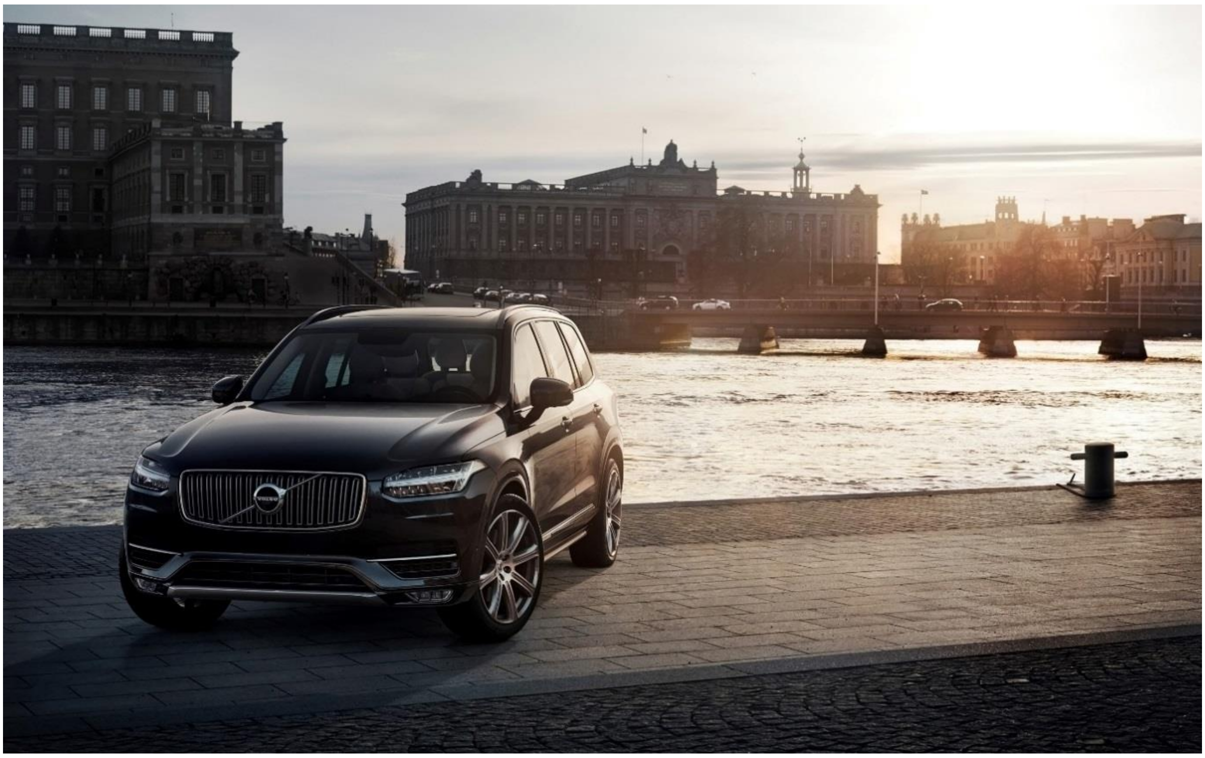

Additive Manufacturing in Low-volume Production

Business Case for Metal Components

Master of Science Thesis in Product Development

PETER EDLUND

Department of Industrial and Material Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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ABSTRACT

This master thesis describes the problems related to the understanding of when and how it is economically beneficial to implement additive manufacturing over conventional manufacturing in production for end-use metal components in low-volume production. For Volvo Cars it is important to understand and investigate new technologies that could change their way of developing premium products. This work includes a literature study, a competitor analysis and two different case studies. Feasible additive manufacturing (AM) techniques for the automotive industry was found during the literature study. Interviews were held with external machine suppliers and experts at Volvo Cars. These interviews were done to find the state of practice for the industry to compare with the situation of Volvo Cars. The competitor analysis showed that the German OEMs are at the forefront of the industry development regarding metal AM. The first a case study was done with a comparison of four non-redesigned components to find the break-even levels for AM and conventional manufacturing. Results showed that only one out of four components were beneficial to produce with AM for a volume of 1000 units or more. In the second study was one component redesigned to highlight the value of product optimization and possible value-adding parameters. The product optimization was done with topology optimization and the result was that the break-even level increased from 1446 units to 6854. If value-adding aspects is included, the break-even could be increased to 8371 units. As a conclusion, it shows that many competitors have implemented AM, not for metal production of end-use components but for plastic components and tooling in metal. The two case studies showed that metal AM can be beneficial without any redesign but if product optimization is taken into consideration, the break-even level can be increased to a level that shows great possibility for low-volume production.

Keywords: Additive Manufacturing, Powder Bed Fusion, Automotive, Business case, Cost-Value Modelling

Abbreviations

AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
B&T	Body & Trim
CAD	Computer Aided Design
CLIP	Continuous Liquid Interface Production
DMLS	Direct Metal Laser Sintering
DTM	Deutsche Tourenwagen Masters
EBM	Electron Beam Melting
FDM	Fused Deposition Modeling
LOM	Laminated Object Manufacturing
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
RM	Rapid Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	STereoLithography

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1. INTRODUCTION

Volvo Cars is a global automotive manufacturer competing in the premium car segment. In their continuous ambition to improve and develop as a leading car manufacturer they need to find new innovative ways to improve their productivity and efficiency and increase customer value of their products. AM is therefore a technology that can improve the product development process so Volvo Cars can remain in the top with competitive products.

Additive Manufacturing has emerged as a possible disruptive technology in many production industries under certain conditions. Additive Manufacturing (also known as 3D Printing) is a technology based on adding material layer by layer to create the desired shape of the product (Gibson, Rosen, & Stucker, 2015). This is the biggest difference compared to many conventional techniques, which are subtractive where material is removed systematically to get the desired shape. This gives the technology an advantage with higher flexibility, free form fabrication, and lower material waste.

To be able to adapt this new technology it must be economic beneficial compared to conventional manufacturing to remain profitable in an industry with generally low margins. Volvo Cars sees a great value in AM and need better guidelines and knowledge about economic analysis for end-use products fabricated with AM. This thesis project will give Volvo Cars valuable information and guidelines regarding the economic aspects of AM.

1.1. Background

In this chapter, a brief background of Volvo Car Corporation and the AM technology is presented. This is done to give the reader a better understanding of the project.

1.1.1. Volvo Cars

Volvo Car Corporation is an automotive manufacturer located in Torslanda, Göteborg. Volvo was founded 1927 by Assar Gabrielsson and Gustaf Larsson as a subsidiary to SKF (Svenska Kullagerfabriken). Volvo Cars was separated from Volvo Group 1999 when Ford acquired them. Ford sold Volvo to Zhejiang Geely Holding Group 2010 and this is the situation by today (Volvo Car Corporation, 2017). Volvo Cars is an automotive manufacturer for the premium segment and sold more than 500,000 cars 2016 (Volvo Car Corporation, 2017). Volvos strategy “designed around you” shows the importance of developing cars that are personal, safe and reliable (Volvo Car Corporation, 2017). Volvo entered the additive manufacturing area early and bought their first machine 1990. The interest for the technology has become more and more interesting especially during the last years and today is AM a focus area for their product development (Olsson, 2016).

1.1.2. Additive Manufacturing

Additive Manufacturing is an emerging technology that is being popular today among many people and companies. Different names are used for the technology such as 3D printing, Rapid Prototyping (RP), Freeform Fabrication (FFF), in this report it is written as Additive Manufacturing (AM). Charles Hull invented AM in 1980 when he created a stereolithography machine (SLA) (Bandyopadhyay, Bose, & Gualtieri, 2015). The basic concept of AM is that a part can be fabricated directly from CAD data without any tooling and less process planning compared to conventional manufacturing. A 3D-model is sliced in thin cross-sections so the machine can apply material layer-by-layer and finally achieve the desired geometry (Gibson, Rosen, & Stucker, 2015).

1.2. Purpose

The purpose of this master thesis is to understand under which conditions it is favourable to manufacture end-use products in low volumes with additive manufacturing technique compared to conventional manufacturing methods. This report will be a base for future guidelines that will help the company to understand which volumes that are suitable, what kind of components are suitable, what production capacity the technology have, what additional value AM can give and how the production might develop depending on the future improvement of machines and materials. This information will be available by answering following research questions:

When and how is it economic beneficial to implement Additive Manufacturing over Conventional Manufacturing in production for end-use components in low volume production?

RQ 1 What additional value is it to use AM?

RQ 2 What kind of components can be beneficial to produce with AM?

RQ 3 What factors are influencing the cost most in AM?

With these questions the cost aspects of AM can be analysed and together with the advantages of AM can the stakeholders evaluate the value of the advantages with AM. Four different parts are evaluated with the evaluation model that is developed to give the reader an understanding of how the model works and show examples of what kind of parts that have a good potential.

1.3. Problem definition

Automotive manufacturers are always eager to develop their product development. AM is a technology that can shorten the development time and fabricate more complex and optimized products. One problem with AM is that it is costly to implement and in this low-margin sector is manufacturing cost very important. The benefits of AM are not highlighted and the value of it is not easy to show.

1.4. Delimitations

This section describes the limitations for this thesis. The limitations are done to be able to go in deeper into a smaller research area. The limitations are set to make sure that the work can be executed within the period that is set to 20 weeks of work.

- **Rapid Manufacturing**: The work treat only production of end-use products, not manufacturing of prototypes.
- **Metal components**: The work addresses only production of metal parts, not plastic, ceramic or any other material.
    - **Body&Trim department**: The case studies are related to the Body&Trim department and includes components regarding interior, exterior and climate control. Components from different departments like powertrain are not investigated.

- **Production costs**: In the case studies are only tooling costs, direct part cost and production time investigated. Supply chain costs, overhead costs or any other non-direct costs are not discussed in the case studies.
- **Powder Bed Fusion**: Powder Bed Fusion is used as production technique in the case studies and no other technique is investigated.
    - **Direct Metal Laser Sintering**: Direct Metal Laser Sintering machines are used in the case studies. EBM is not investigated.

1.5. Actors and stakeholders

The main stakeholders for this master thesis will be Volvo Cars and Chalmers University of Technology. Since this is a thesis for the level of Master of Science, the university sets expectations on content and procedures via the MSc guidelines and examination criteria. This report is for partial fulfilment of a MSc degree in Product Development. Within Volvo Cars, main stakeholders are found among employees at Body&Trim, Concept Centre, Manufacturing and management at R&D department. This thesis will be published at Chalmers University of Technology and can be used by anyone. This work will help design engineers, cost estimators and directors to understand how and when AM could be used in a beneficial way. It will help Volvo Cars to educate their engineers to use AM in the entire organization and not only at Body&Trim. These guidelines can also help the Purchasing department, R&D, Manufacturing and management to understand each other from a technical and economical perspective.

2. RESEARCH METHODOLOGY

In this chapter, the research methodology is described. To execute this thesis several different methods are used. First, a literature study is conducted that includes information from databases, industry papers, and interviews with employees at Volvo Cars and external machine suppliers. To be able to investigate if AM can be economically beneficial, a case study has been chosen as a method to show the difference between manufacturing with AM and conventional manufacturing. Interviews with project leaders for a specific car project are held to find suitable components that can be studied. To be able to conduct the case study a software model will be developed that can calculate the production cost for parts produced with AM and also the potential value that can be gained by using AM. The model should also include a comparison between conventional manufacturing and AM to show the potential benefits that could be gained if the production method is changed. Diagrams will be created to state the break-even level for the components so the user can determine if it is suitable for the product volume.

The research was conducted by doing a literature study consisting of industry papers, recently published articles and interviews with external machine suppliers. To understand Volvos current knowledge were semi-structured interviews held with engineers, designers and managers at Volvo Cars. Semi-structured interviews were chosen to guide the interview in general and later on let the interviewee speak freely. This gave qualitative information that was used to understand the state of practice.

A competitor analysis was done as a benchmark both over Volvo Cars position and over the maturity of the industry. This competitor analysis gave except from an understanding also interesting examples and hints of which fields regarding components and materials that are suitable today and also which techniques that are used by whom. This gives a security to the research that this is in line with what others have done.

To evaluate when and how Additive Manufacturing can be economic beneficial, an evaluation tool is developed. This is to measure the cost and production time for AM to compare with actual costs and lead times for conventional manufacturing. The production time can both be calculated by hand or by software for virtual production simulation. Additional literature study was conducted at this time to understand how the production costs for AM differs between different technologies. Machine suppliers were interviewed to gain information about efficiency, costs and measurement methods. These interviews were compared with the literature to verify the information with different sources of primary and secondary data. The interviews were held in a semi-structured way to let the interviewees speak freely within a specific field set by the interviewer. The goal with the interviews were to gain qualitative information.

The production costs for AM are very depending on the production time. As an input to the evaluation tool can production time both be calculated by hand with formulas and by AM software's like Autodesk Netfabb (Autodesk , 2017) or Materialise Magics (Materialise, 2017). A software solution is selected because it can handle complex geometries in an easier way and is more user-friendly than manual calculations. To calculate it by hand will be to complex and can possibly avoid users from using the model. By using a software, the user can chose different machines to simulate production and different materials. It is also easier to do several calculations in a shorter time with different orientations and number of parts in the build chamber.

Different components from a new car project are used as verification for the evaluation model to check the reliability and to give the company examples of parts that could or could not be beneficial to manufacture with AM. Interviews were held with project leaders from B&T to get examples of possible parts for an investigation. After the interviews were all parts compared to a requirement specification list that can be seen in Appendix D. This requirement specification is done to ensure that a good sample of parts are chosen, that the analysis only consists of parts that could be manufactured with AM in reality and that the targets for the thesis are met. Requirements regarding geometry and materials are found during interviews with machine suppliers and information from their websites. These requirements works to make sure only components that could fit in current existing machines on the market are used.

For the business case will cost and value be mentioned. Both for the importance of reducing costs but also to discuss it in relation to what value that is created. To find the most preferred outcome of a design, the value must be maximized (Lee & Paredis, 2014).Value-adding aspects in the model are based on discussions with supervisor and colleagues to find cost cutting aspects that are available if AM is used instead of conventional manufacturing. The discussions are based on AM advantages found in literature (Klahn, Leutenecker, & Meboldt, 2014), (Baumers, Dickens, Tuck, & Hague, 2015) and (Wohlers Associates, Inc, 2017). These discussions were done to find aspects with reliable data on actual costs that could be reduced. Other aspects are inserted in the model with assumed costs so the users can change it themselves. This is done to highlight different possibilities and to give the user the chance to estimate the value themselves and see how much value-adding activities are needed to get a suitable business case for a component.

In the discussion chapter are potential drawbacks described and highlighted to show the reader that more work is needed to reduce risks and eliminate uncertainties.

3. THEORETICAL FRAMEWORK

This chapter will give the reader a good background and understanding of the technologies to be able to understand the entire report.

3.1. Additive Manufacturing

Gibson (2015) explains and categorize the work process for generic AM into eight different steps.

Figure 1 - Generic AM Proces (Gibson, Rosen, & Stucker, 2015).

First, a virtual component must be designed with correct shape and geometry and converted into STL format so the file can be transferred to an AM software. In the software, the STL-file is sliced up and converted to machine code to create the workflow for the machine to produce the part in the correct way. Machine setup is done afterwards regarding to the right configuration for the part with aspects like layer thickness. When the setup is done the building of the component can start which is the major part of the work timewise. After the building, the component must be removed from the build plate and unused metal powder must be removed before the post-processing can start. The post-processing is a section that can vary a lot. Most of the parts that are produced with AM cannot be used in an application without any post-processing. Post-processing can be many different treatments like polishing, milling or heat treatment for example.

AM is categorized differently depending on the type of process. ASTM International Committee F42 on Additive Manufacturing Technologies approved 2012 a categorization system that included seven different AM process (Wohlers & Caffrey, 2014) . These seven am processes are:

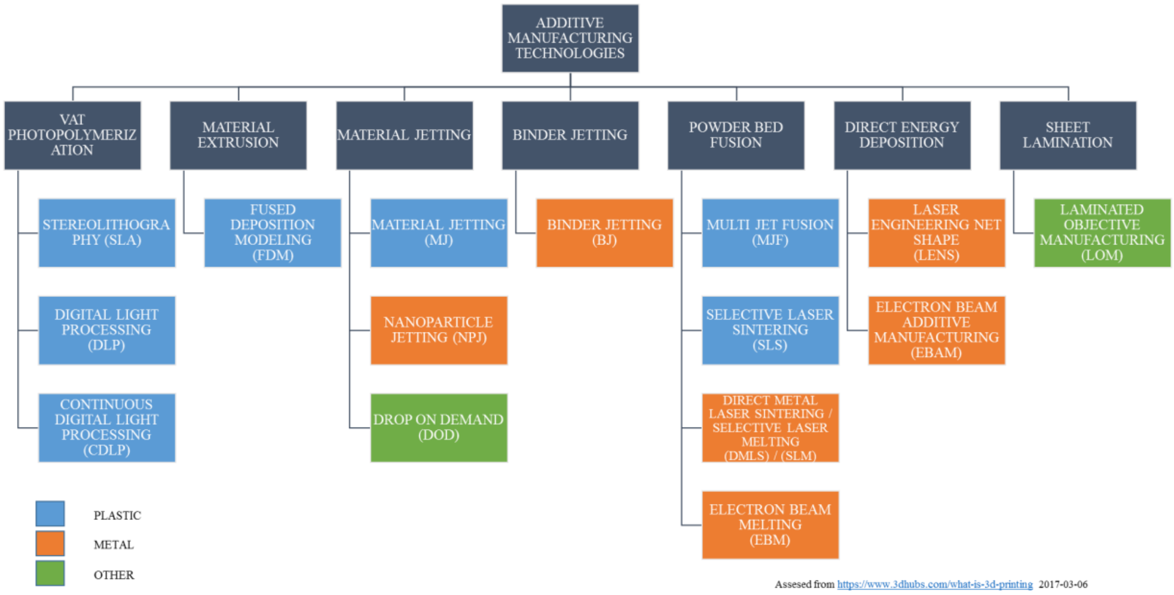
- VAT Photopolymerization
- Material Extrusion
- Material Jetting
- Binder Jetting
- Powder Bed Fusion
- Direct Energy Deposition
- Sheet Lamination

Powder Bed Fusion is the selected process for this study because it is the most suitable process based on the selection parameters in table 1.

Table 1 - Process Selection Parameters

Process selection parameters
Metal Material
Production of End-use Components
Build Size
Maturity

Direct Energy Deposition is not chosen because it is focuses more on re-build and adding material on existing geometries (Gibson, Rosen, & Stucker, 2015). Nanoparticle Jetting and Binder Jetting are not considered neither because it is not as mature as Powder Bed Fusion in terms of the amount of machine suppliers. The majority of metal AM systems are based on PBF (Wohlers Associates, Inc, 2017).



Assesed from https://www.3dhubs.com/what-is-3d-printing 2017-03-06

Figure 2 - Overview of different AM Technologies, derived from: (3D Hubs, 2017).

3.2. Advantages of Additive Manufacturing

In this chapter the advantages of AM are related to both process improvements and product improvements and are presented.

3.2.1. Process improvement

AM is often mentioned as a part of the fourth industrial revolution, also known as Industry 4.0 (The Boston Consulting Group, 2017). One of the great advantages with AM is the speed. Not the speed in minutes of part production but the general process from idea to fabricated part. AM provides a great flexibility for manufacturing of low volume parts without any overhead costs in form of tools (Baumers, Dickens, Tuck, & Hague, 2015). The setup time for production with AM is usually shorter than for conventional manufacturing due to it is mainly based on 3D CAD data of the product and does not need any data of the tools that is needed for conventional manufacturing. The AM production process has fewer steps from idea to fabricated part than conventional manufacturing since it does not require any specific production tools like molds for example. This gives organizations a greater freedom and a bigger part of the product development can be spent on the design phase. This is due to the time between design and manufacturing is shortened because no tools need to be fabricated (Weller, Kleer, & T.Piller, 2015).

This gives a multiple factor if the process need to be iterative and require many versions of the tool before the right component can be manufactured. All geometrical changes for a part will only affect the 3D CAD file and not the required tooling. It gives the user a better prediction of production time since fewer process steps gives less uncertainty. The number of processes and resources can also be significantly reduced when an additive technology is used instead of subtractive. Despite the high cost of an AM machine, the total capital allocation of equipment can be reduced by replacing several conventional machines with AM systems. To reach the right geometry can a conventional process require both drilling, milling and welding for example which increases the time in between the different processes and increasing the error possibility. AM can streamline many production processes (Gibson, Rosen, & Stucker, 2015). With AM can also inventories be smaller and warehousing costs be reduced because of the manufacturing flexibility that AM provides. Many different components can be fabricated simultaneously in a machine so parts that are sold out can be manufactured directly with a batch of other components (Weller, Kleer, & T.Piller, 2015).

3.2.2. Product improvement

AM gives designers many opportunities to improve their products and in this section, different ways of improvements are mentioned.

Product Integration

The design freedom is a significant advantage and gives the designer full flexibility to focus on functions and not Design for Manufacturing. This function focused design gives a greater value to the product since more functions can be integrated in fewer number of parts. With a fewer number of parts, fewer interfaces between parts are needed, less assembly steps, less administration costs in case of warehousing and article information for example. Most of these features are related to manufacturing constraints that are not applied to AM (Klahn, Leutenecker, & Meboldt, 2014).

Customization

To create a successful product is it important to meet the needs of the customers on the market. Product customization is important to reach out to as many customers as possible since it changes the products in a way that suits the customer. In conventional manufacturing with large overhead costs in form of production tools is it very costly to customize since it will increase the production cost per product. With AM will these costs be fixed and not depending on the customization level since it does not require any tools or fixtures (Klahn, Leutenecker, & Meboldt, 2014).

Lightweight Design and Efficient Design

Weight is an important parameter in products that are moving during their life cycle. In the automotive industry is weight directly correlated to fuel consumption and battery range, key factors for customers. An improvement of these factors can compensate for the usually more expensive manufacturing that AM is. AM´s free form fabrication advantages gives the designer more freedom during the design process to optimize the product so the functions and design can be in focus and be better developed without any manufacturing constraints. Part complexity can be increased and material and weight can be reduced which both gives a higher value to the customer in form of lower weight and also a benefit for the company in case of less material is melted which gives a shorter manufacturing time and less material cost. To get the benefit of lightweight design, the designer must have knowledge about how the load cases are applied on the specific product. As a comparison to conventional manufacturing is lightweight design favourable for manufacturing costs since both manufacturing time and material costs will be reduced in most cases depending on the amount of support material. For conventional manufacturing as milling can the manufacturing time be even longer with a lightweight design since more material must be removed and the material waste is increased which gives a higher buy-to-fly ratio and a bigger environmental footprint (Klahn, Leutenecker, & Meboldt, 2014).

3.3. Limitations of Additive Manufacturing

Here should drawbacks and limitations be discussed to show both sides of the technology. With AM comes drawbacks both technological and economical. With AM comes limitations in production speed and repeatability. Differences between batches can be problematic with quality issues that can cause economical drawbacks and damage the brand (Baumers, Dickens, Tuck, & Hague, 2015). There are limitations with AM in forms of build size and materials available on the market. This is something that is continuously developing but by today it is a drawback since many parts cannot be manufactured (Weller, Kleer, & T.Piller, 2015). AM also requires more skilled labour and better knowledge. The complexity of the technology forces the companies to employ people with more experience and provide more education activities to keep up with the technology development (Weller, Kleer, & T.Piller, 2015). Economies of scale for AM compared to conventional manufacturing is regarding to (Weller, Kleer, & T.Piller, 2015) not exploitable but regarding to (Schröder, Falk, & Schmitt, 2015) can it be exploited for small body components but not for larger sized.

3.4. Powder Bed Fusion

Powder bed fusion (PBF) was among the first commercialized AM processes with the SLS process developed at the University of Texas at Austin, USA (Gibson, Rosen, & Stucker, 2015). All PBF processes share the basic technology and requires one or more thermal sources for inducing between the powder particles, laser distribution system to control which areas of the powder layer that should be melted, mechanism for powder distribution from feed cartridge to build platform in a controlled manner.

The thermal source differs between the different methods. PBF can be divided up in four different categories:

- Multi-Jet Fusion (MJF)
- Selective Laser Sintering (SLS)
- Direct Metal Laser Sintering (DMLS) / Selective Laser Melting (SLM)
- Electron Beam Melting (EBM)

It is only DMLS and EBM that can be used for metal components so these two are studied more deeply. SLS and DMLS are often mentioned as similar with the difference in material where DMLS refers to metal and SLS to other materials like plastics and ceramics. SLM is similar to DMLS but it is not sintering the material but melting it instead.

For EBM is an electron beam used to fuse the particles into the desired shape and for DMLS is laser used as a thermal source. Laser machines can be equipped and mapped for many different materials such as plastics, metals, ceramics and composites. PBF is a widely-used process worldwide, it is used more and more for direct manufacturing of end-use products, as the development of material and processes are improving.

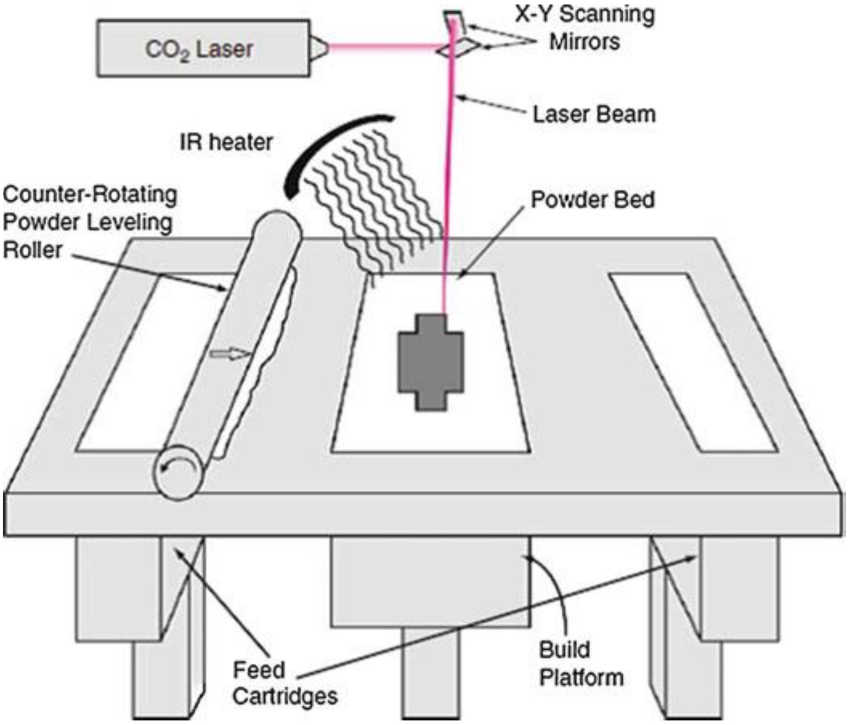


Figure 3 – Powder Bed Fusion Process (Gibson, Rosen, & Stucker, 2015).

The PBF process starts with spreading a thin layer across the powder bed in the machine with a counter-rotating roller. The layer is decided before process start and is a parameter that is adjusted by the operator. The thicker powder layer the shorter build time because less layers needs to be distributed but on the other hand will the part properties change so the layer thickness need to be determined so it meet the requirements set before fabrication. The building process takes place in a build chamber that is filled with nitrogen gas to minimize oxidation and of the powder. When the powder distribution is done and preheated to the desired temperature, the powder is fused together by the laser (for the DMLS, in EBM is it an electron beam). The laser is moved using galvanometer to form the cross section from the STL file. Not all powder is fused but the remaining powder works as support for the part. The powder bed is lowered with one layer thickness after the laser and then a new layer of powder is distributed. This processes repeats until the complete part is fabricated (Gibson, Rosen, & Stucker, 2015).

Direct Metal Laser Sintering is a technology similar to SLS but it can sinter metal powders. The first DMLS machine was launched 1995 by Electro Optical Systems (EOS) (Bandyopadhyay, Bose, & Gualtieri, 2015).

3.5. Cost-Value modeling

A Cost-Value model is created to highlight the value of AM as a production technique. By highlighting the value and not only investigating the cost of a method, decision-makers can easier select the solution that is most likely to meet the requirements in a project. As mentioned in (Lee, Binder, & Paredis, 2014), “the purpose of a value model is to enable designers to make consistent, rational evaluations of an alternative, even when faced with complex scenarios rife with uncertainty”. For AM with many potential benefits, values can be difficult to highlight and by using a cost-value model, a justified decision can be taken. By only going for the most cost-effective solution, designers should keep in mind that it is important to find a solution that maximize the value. AM should be used in cases where the costs can be reduced or when value is larger than for conventional manufacturing. The presented value model in this report is done to remind the reader of the need of consider the value-adding aspects. In the future, a more developed model could be developed.

In this section is first the cost model described and later the value drivers are described. How the value aspects are inserted in the cost model are also described.

3.5.1. Cost modeling

To answer the research questions in this project must knowledge related to different cost models for AM be gained. Piili et al. (Piili et al., 2015), proposed in their paper a detailed model for cost calculation that is split in indirect cost and direct cost. The direct cost is divided in raw material and electricity. Indirect cost is the machine and it is multiplied with the build time of the part to split this overhead cost on all samples. In this model is the gas consumption included in the indirect cost and the labour cost is not taken into account and the same goes for the post processing costs.

$$C_{build} = C_{indirect} * T_{build} + w * Price_{material} + E_{build} * Price_{energy} \qquad (1)$$

The build time is a major influencer for the total part cost and it can be calculated with the formulas (2), (3) and (4) (Piili et al., 2015).

$$T_{build} = N * \left(T_p + d_p * \left(\frac{A_p}{A_{phr}} + \frac{A_p}{A_{psr}}\right)\right) + d_s * \frac{A_s}{A_{sr}} \qquad (2)$$

$$A_s = \frac{S_A * l_d}{N * l_t} \qquad (3)$$

$$A_p = \frac{V_p}{N * l_t} \qquad (4)$$

Table 2 - Nomenclature for Cost Modelling

Nomenclature	
A_p	Average cross section area of part [mm2]
A_{psr}	Area rate scanning the interior of the part [mm2/s]
A_{phr}	Area rate hatching the interior of the part [mm2/s]
A_s	Average cross section area of support [mm2]
A_{sr}	Area rate scanning the support [mm2/s]
C_{build}	Cost of build [€]
$C_{indirect}$	Machine costs [€ / h]
$C_{material}$	Cost of material [€ / kg]
d_p	Density of part [kg/m3]
d_s	Density of support structure [kg/m3]
E_{build}	Energy consumed during build [J]
l_d	Laser beam Spot Diameter [mm]
l_t	Layer thickness [mm]
$m_{material}$	Mass of material [kg]
N	Number of layers
$Price_{energy}$	Price of the energy [€ / J]
$Price_{material}$	Price of material [€ / kg]
S_A	Surface area of part [m2]
T_{build}	Total build time [h]
T_p	Idle time between layers[s]
V_p	Process velocity [mm3/s]
w	Mass of the piece [kg]

3.5.2. Value modeling

To understand if AM can be economic beneficial over conventional manufacturing, benefits related to AM is added to the total equation. In this thesis is advantages regarding tooling, part costs mentioned and production time. In equation (5) is the total value added described with its contributors. In table 3 is the nomenclature for the value modeling described.

$$V_{Build} = W_{Weight\ Reduction} * V_{Weight\ Reduction} * N_{Volume} + T_{Production\ Difference} * V_{Lead\ Time} * F_{Time} + V_{Warehousing} * T_{Warehousing} + C_{Tooling} * F_{Tooling} * V_{Tooling} + V_{Article\ Reduction} * F_{Article\ Reduction} \qquad (5)$$

Table 3 - Nomenclature for Value modelling

Nomenclature	
V_{Build}	Added value for the fabrication of the complete volume [SEK]
$W_{Weight\ Reduction}$	Weight reduced per part [kg]
$V_{Weight\ Reduction}$	Value-adding factor weight reduction [SEK/kg]
N_{Volume}	Number of parts for the entire volume
$T_{Production\ Difference}$	Difference in production time between AM and conventional manufacturing [h]
$V_{Lead\ Time}$	Value-adding factor lead time [SEK/h]
F_{Time}	Time importance factor
$V_{Warehousing}$	Value-adding factor warehousing [SEK/year]
$T_{Warehousing}$	Years of storing tools [year]
$C_{Tooling}$	Cost of tooling [SEK]
$F_{Tooling}$	How many times the tooling needs to be redone
$V_{Tooling}$	Value-adding factor tooling [%]
$V_{Article\ Reduction}$	Value-adding factor article reduction [SEK]
$F_{Article\ Reduction}$	How many parts that is integrated due to product optimization

3.6. Low-Volume Production

Low-volume production is a generic term used for production of niche models, special vehicles and high-performance versions for example. Low-volume production differs depending on industry. With low-volume production are all the overhead costs such as tooling split on a fewer number of parts which increases the part cost. For more high-volume products like the Volvo XC 60 that sold more than 150’000 cars 2016 (Volvo Car Corporation, 2017), tooling has not as big impact on the revenue as for a special edition car like Volvo XC 90 First Edition that was produced in 1927 units only (Volvo Car Corporation, 2017). Low-volume production is usually slower in production per part compared to greater volumes.

4. COMPETITOR ANALYSIS

A benchmark of automotive OEMs is performed during this project to give an understanding of how mature the technology is and to find suitable applications. The focus is on metal fabrication, polymer fabrication is mentioned when no information regarding metal could be found. The benchmark focuses on competitors to Volvo Cars with similar volumes and price category. Other OEMs were also investigated to find more automotive applications.

4.1. Audi (VW Group)

Audi is using AM in their production and have several different machines with various technology. Research mainly on internet shows that they have SLA, FDM, SLM and SLS. Audi uses it for prototyping, tooling and production (Koslow, 2015). One example is the Auto Union Type C that is showed in figure 4. The car is printed in metal in a scale 1:12 (Feigl, 2015). Audi is using metal printers from SLM Solutions Group AG and purchased in May 2016 a SLM280HL printer, a selective laser melting machine with a build envelope of 280 x 280 x 365 mm (3ders.org, 2016).

Figure 4 - Audi Toolmaking prints "Auto Union Type C" (Feigl, 2015).

Regarding to (Krassenstein, 2016) Torsten Ronneberger, Strategy Technical Development Head at Audi said in an interview that in five years (interview was held in august 2015) will they process components in several different metals and increase the utilization of plastic components produced with AM. Ronneberger also said that there is potential in a more distant future that 4D printing will become important when parts can be produced with shape memory alloys. (Krassenstein, 2016).

4.2. BMW Group

BMW are pioneers in 3D printing and have used the technology for 27 years since they produced their first polymer prototype in a SLA machine. In the beginning AM was mainly used for concept cars but today is the purpose different and BMW uses AM now for small batches or very complex components for pre-development, validation and testing. BMW have implemented AM also for their toolmaking division and for series production. For the labour at the assembly lines BMW are producing custom-made ergonomic tools to protect them from thumb joint strains. An interesting area where AM is widely used is the classic cars sector. BMW uses 3D scanning to scan existing components of a vehicle, generate 3D data sets, and later print the spare parts to collectors. BMW is also equipping the DTM Cars with water pump wheels printed in metal. The pump wheel is a perfect example of application with a small complex component (Schillmoeller, 2015).

More than 10,000 parts are integrated into series production of the Rolls-Royce Phantom (BMW subsidiary). Example of components are holders for hazard-warning lights, centre lock button and different sockets and brackets (Wibbe, 2016). BMW is collaborating with Hewlett Packard to develop the new AM system HP Jet Fusion 3D series. CLIP technology is investigated at BMW Group Technology Office in Silicon Valley (Schillmoeller, 2015) and Stratasys have delivered FDM machines to BMW AG plant in Regensburg to manufacture Jigs and Fixtures for their production units for example (Stratasys, 2015).

BMW is delivering more than 100,000 components annually to customers from the Additive Manufacturing Centre (Schillmoeller, 2015).

4.3. Mercedes (Daimler)

Mercedes is investigating how 3D printing could be implemented for production of metal, plastic, ceramic and glass spare parts. It could redefine the supply chain, reduce lead times, transportation costs, and warehousing costs for markets far away from the production facilities and logistics centres. This strategy is mostly focusing on plastic parts with SLS technology for special parts and old parts that are taken out of production. The strategy is only for the truck division right now because of lower production volumes (Taylor & Cremer, 2013).

The chief designer of Mercedes told AutoExpress that the next-generation Mercedes-Benz S class coming 2018 could have for example air vents and speaker grilles produced with 3D printing (Bunkley, 2014).

Daimler is collaborating with Concept Laser to develop a metal AM machine that could replace the costly die- and sand-casting components for the product development in the early phases (3ders.org, 2012).

4.4. Ford Motor Corporation

Ford is one of the biggest automotive OEMs when discussing AM. Ford bought their first 3D printing SLA machine 1988 and has produced over 500,000 parts (3ders.org, 2015). In 2016 Ford produced 225,000 parts in their facilities using several different plastic AM technologies such as SLS, FDM, LOM and CLIP. Ford has five global research centres mainly focusing on AM. Ford use AM for functional prototypes, jigs & fixtures, end-use parts, visualization and assembly models. Example of components they have produced with AM are door seals, ducts, intake manifolds and oil pans. All of these are not for end-use but could be for prototyping to visualize or do a functional test (Forsmark, 2016).

Ford is collaborating with Carbon3D to test the CLIP technology as a prototyping tool. This is a technology for plastic production and is a process that continuously grow objects from a pool of resin. This makes the technology much faster than common AM technologies and it could be as much as 25 to 100 times faster. Different applications have already been produced with CLIP such as oil connector and bumper parts (3ders.org, 2015).

4.5. General Motors

GM have adopted AM in their organization and is using it for rapid prototyping to shorten the product development cycle. This is done by reducing the lead-time for prototype production. GM uses SLA and SLS machines from 3D Systems to visualize, build mock-ups, manufacture small batches of parts and fixtures for production for example (3D Systems, 2017). GM produce more than 20,000 plastic parts at their Rapid Prototype Development Centre. GM is a selected beta user for 3D Systems that means new machines will be available for GM before it reaches the market (3D Systems, 2017).

4.6. Honda

Honda is using AM for producing accessories for their cars and motorcycles. Their development centre is located in Japan and it is the hub for the entire group and serves the entire group with 3D printed accessories. Honda uses a Stratasys Objet Eden500V 3D printer to design up to 300 accessories for each model each year for Hondas car program (3ders.org, 2015). Honda used AM when the Honda Pilot model was developed. It was used for visualization and prototyping to verify the packing of dashboards. Test versions of parts and tools are produced with 3D printing at Honda Cars (Halterman, 2015).

4.7. Hyundai

Hyundai uses AM since 2007 at least when flooring components were produced with PBF technology for their QarmaQ concept car (Gibson, Rosen, & Stucker, 2015).

Figure 5 - FDM Dashboard Prototype Holds Tight Tolerances; Improves Design (Stratasys, 2017).

Stratasys supplying Hyundai with AM systems like Fortus FDM system that Hyundai use for design verifications and prototyping for assembly and functional testing of instrument panel for example. In figure 5 is a dashboard prototype showed. The Fortus system is well used and

Hyundai are planning to increase the production by acquiring another Fortus system. Hyundai said the payback time for the first machine was less than 30 months (Stratasys, 2017).

4.8. Toyota

Figure 6 - Slicing technology from Materialise shaves kilograms off Toyota's 3D-printed car seat (3ders.org, 2015).

Toyota together with Materialise created a lightweight car seat with AM to reduce the weight. The concept had a weight reduction from 25 to 7 kg and a volume reduction of 72% by using topology optimization and 3D printing (3ders.org, 2015). The new seat prototype can be seen in figure 6.

For Toyotas innovation project, the uBox which is a study of the future of car ownership. The uBox project owners will be able to customize parts like door trim, air vents and dashboard display fixtures with 3D printing and then share it on an online hub with other users (Conditt, 2016). The fully owned subsidiary Daihatsu is collaborating with Stratasys to create customized skins. The skins had several different patterns and were placed on the front and rear bumpers on the Daihatsu Copen. This is the first step into the customization and the skins are available in 15 different patterns and 10 different colours. One version of the skin is viewed in figure 7. The customers can adjust the patterns themselves by changing design parameters.

Figure 7 - Stratasys collaborates with Daihatsu to create customizable effect skins (Stratasys, 2017).

4.9. Summary of Competitor Analysis

The competitor analysis gives insights into the automotive sector and showed the status of the competitors. The main competitors, in this case the German brands, have already started to use AM. The use of metal AM for end-use parts is not as developed as plastic AM.

Overall it seems that AM is developing and more and more automotive OEMs are adopting technology. The premium companies are leading the development and it is not surprising given that it is more expensive products than the Japanese manufacturers.

Audi use metal AM with equipment from SLM Solutions and see that a wide range of components can be processed in metal material in a few years. BMW also have metal AM systems but none of them use it for production of end-use parts.

Mercedes, BMW and Ford uses plastic AM in production today. Mercedes has focus on spare parts and old parts that are taken out of production. The focus is on plastic parts with SLS. BMW is producing more than 10,000 parts for series production for their subsidiary Rolls-Royce. Ford is a pioneer in the automotive sector when it comes to AM. Ford produced more than 225,000 plastic components 2016 and have a partnership with Stratasys. The Japanese manufacturers use AM mainly for prototyping.

5. ANALYSIS

The work regarding the evaluation of the component sample is presented in this chapter. The components are analysed with the developed evaluation model regarding production cost and production time.

5.1. Case study

Four different components are selected to generate a simulation and a study of how AM could replace conventional manufacturing focusing on economic aspects. The break-even level is assumed to 1000 units since this is the level for special vehicles at the company. Battery holder, geoconsole, Hood hinge, and spoiler module are selected after a screening process together with supervisor and concept leaders at the B&T department.

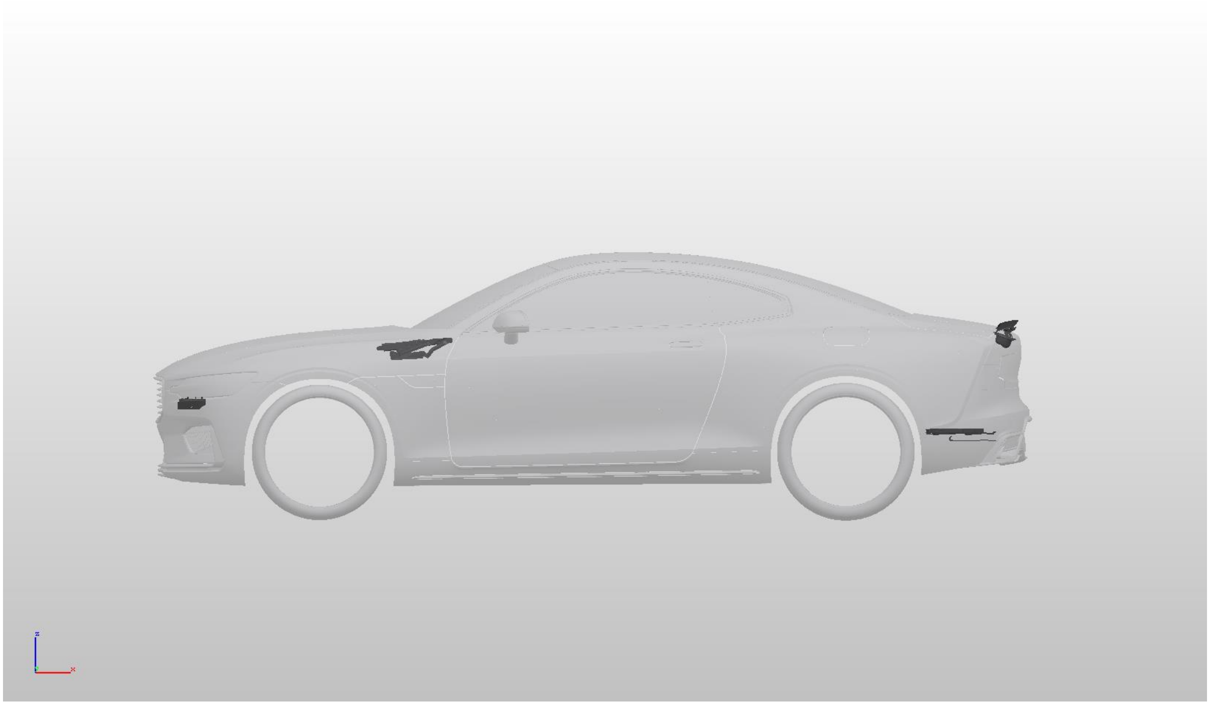


Figure 8 – The selected components and their position on the car.

A virtual production simulation process is chosen instead of doing it manual by hand. This decision is based on an analysis based on interviews with machine suppliers, research articles and market information to understand what options are available. Three interviews were held. The companies EOS Solutions, Arcam AB and Swerea IVF were interviewed to understand what kind of technology that would be most suitable. Arcam and EOS were chosen because Arcam is using EBM and EOS is using DMLS and there is a difference between these technologies. After a discussion with supervisors and a technology comparison, DMLS was chosen.

Table 4 - DMLS vs EBM Comparison

DMLS (Direct Metal Laser Sintering)	EBM (Electron Beam Melting)
Advantages	**Advantages**
Better finish and structures	Higher speed
Bigger size of build envelope	Focus on conductive materials
Already established in the automotive industry	Established in aerospace and medical industries
Many machine suppliers	
Can handle many different material	
Disadvantages	**Disadvantages**
Slower build process	Less materials available
	Smaller build envelope
	Only one manufacturer

With this as a background, a benchmark of many of the most well-known DMLS system suppliers was done to find the most suitable machine for the simulation. The important parameters for the machine is build envelope, deposition rate, laser power and brand reputation. Brand reputation is used as parameter to filter reliable and mature suppliers. Build envelope, deposition rate and laser power are important for the production efficiency and the build speed. As mentioned by (Baumers, Dickens, Tuck, & Hague, 2015) deposition rate and build volume are the factors with greatest potential for cost reduction for AM.

Table 5 - AM System suppliers

AM System Suppliers					
Supplier	**Model**	**Technology**	**Build Size (X x Y x Z) MM**	**Deposition (cm^3/h)**	**Laser Power**
3D Systems	ProX DMP 320	DMLS	275x275x420	Not available	500W
EOS	M400-Quattro	DMLS	400x400x400	100	4x400W
SLM Solutions	SLM 500 HL	DMLS	500x280x365	105	4x700W
Phenix Systems	PXL System	DMLS	250x250x300	Not available	500W
Renishaw	RenAM 500M	DMLS	250x250x350	Not available	500W
Concept Laser	X LINE 2000R	DMLS	800x400x500	120	2x1000W
Realizer	SLM 300i	DMLS	300x300x300	37	1000W
Arcam	Arcam A2X	EBM	200x200x380	Not available	8000W

These suppliers are the most well-known and established companies in the industry. From this benchmark Concept Laser, EOS and SLM Solutions was the three best alternatives for the study based on the parameters above. These three machines are checked in the software Autodesk Netfabb 2017 which is a software for build simulations. Concept Lasers machine was not available for software simulations so it was only two solutions left. These two machines are compared with the same component to check which performed best in fact of volume and build speed. The SLM Solutions SLM 500 HL had better performance so it is selected for all the simulations. In figure 9 and 10, the SLM 500 HL and the EOS M400 machines are filled with geoconsoles.

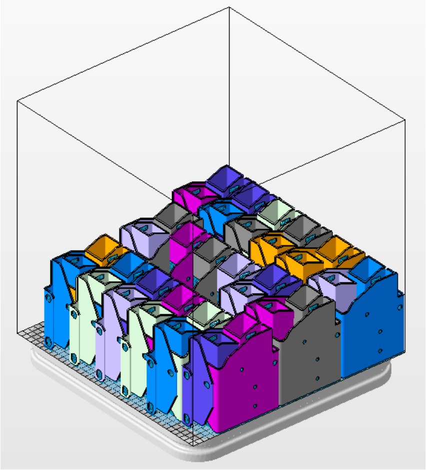


Figure 9 - 34 geoconsoles packed in an EOS M400

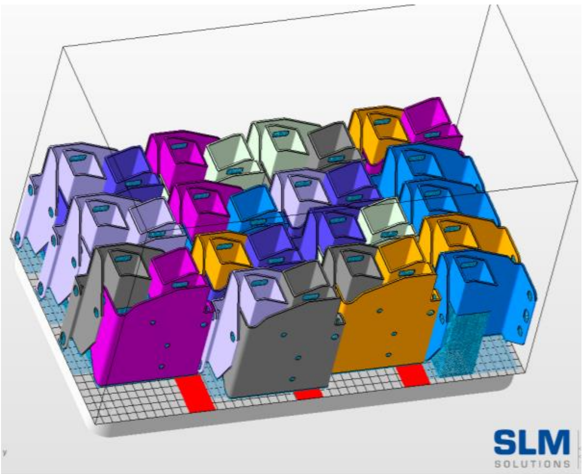


Figure 10 - 28 geoconsoles packed in a SLM 500 HL

The EOS machine could build 34 components in 468 hours and the SLM 500 HL could print 28 components in 86 hours. It gives the EOS machine a build rate of 14 hours per part and the SLM 500 HL a build rate of 3 hours per part which is 11 hours less.

5.2. Components for evaluation

Below, all components are described and costs are presented. Pictures of the parts are showed to give the reader a better understanding. In chapter 5.3 are original components compared and in 5.4 a redesigned case is presented.

5.2.1. Original Design

In this chapter, an analysis of non-redesigned components is presented. These four components are compared without any AM advantages taken into consideration. These components differs in size, complexity and cost of part and tooling which make this a suitable sample. The sample size could have been larger but due to the product requirements presented in Appendix D, the sample size is set to these four components.

5.2.1.1. Battery Holder

The battery holder is a metal reinforcement for a plastic holder in the trunk holding the battery for the hybrid cars. In figure 11, the battery holder is showed and in figure 12 a machine is filled with components. Current production technique is stamped and bent sheet metal. The tooling costs are 399’000 SEK and the part price is 7.5 SEK (Junback, 2017).

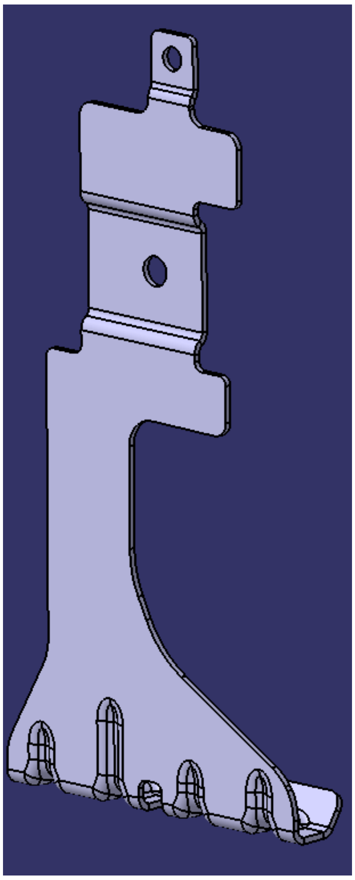


Figure 11 – Battery holder

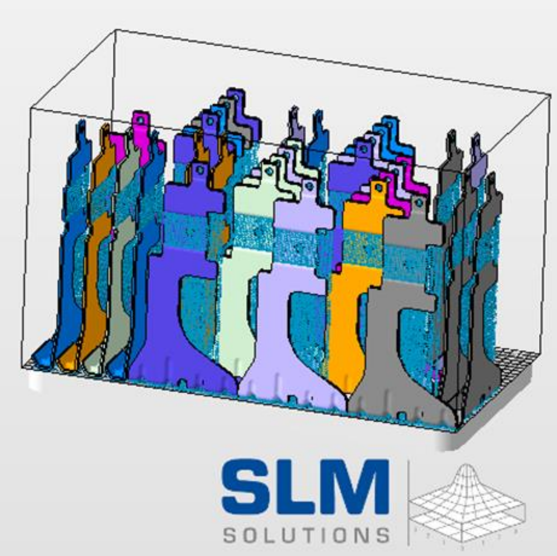


Figure 12 - Battery holder placed standing to fit as many as possible

5.2.1.2. Geoconsole

The geoconsole is a mount in the engine compartment holding the front bumper and the front carrier. It is a metal component made with extrusion technique and the design can be seen in figure 13. The production costs for the geoconsole consists of tooling costs of 150’000 SEK and a part price of 28.94 SEK (Junback, 2017). In figure 14, an AM machine with geoconsoles is filled.

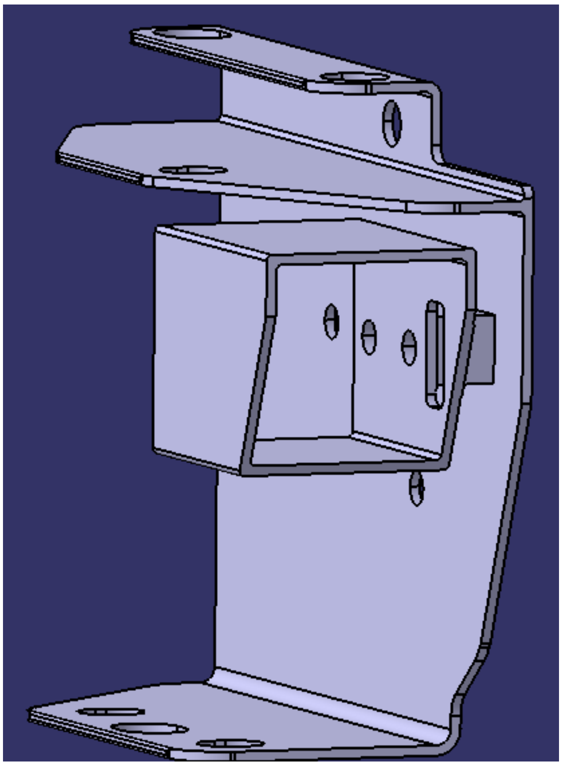


Figure 13 - Geoconsole

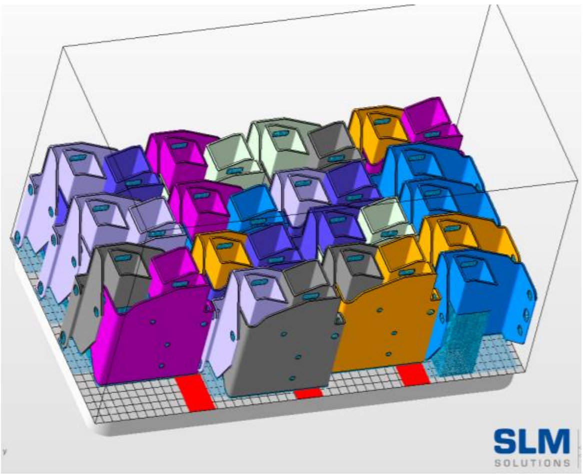


Figure 14 - 28 geoconsoles placed in a SLM 500 HL

5.2.1.3. Hood Hinge

The hood hinge consists of six pieces of stamped and bent sheet metal. The cost for the hood hinge is split on tooling costs of 206’029 £ and part price of 30.20 £ (Junback, 2017). With an exchange rate of 1 £ equals to 11.02 SEK the costs is 2’270’521.99 SEK for tooling and 332.82 SEK for the part (EUROINVESTOR, 2017). Figure 15 shows the hood hinge and figure 16 shows a machine filled with components.

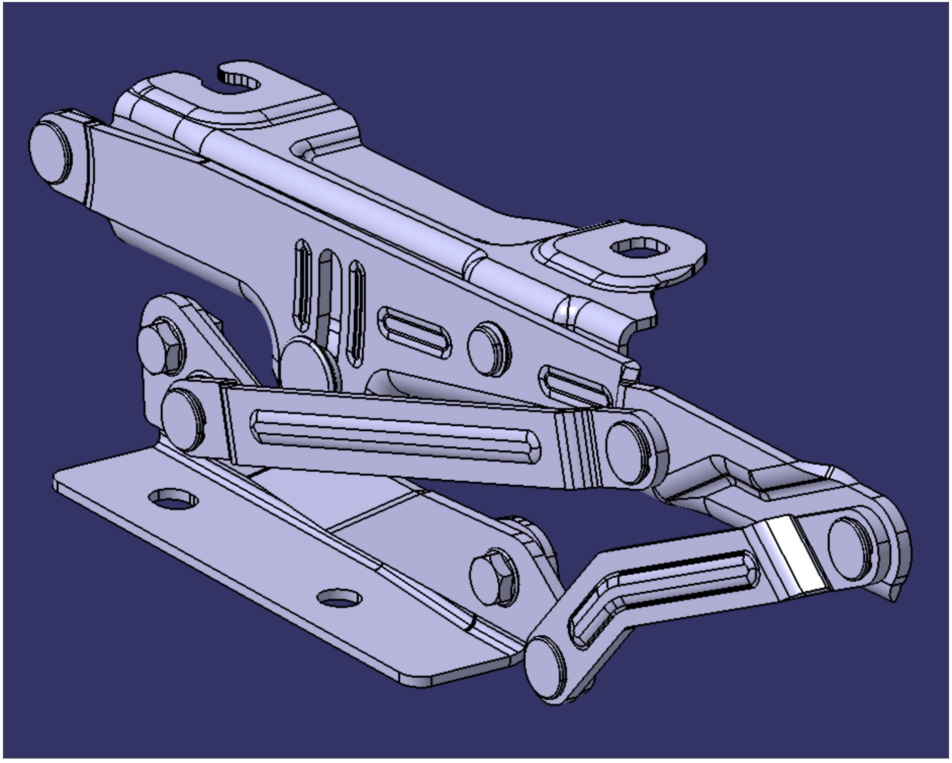


Figure 15 - Hood hinge

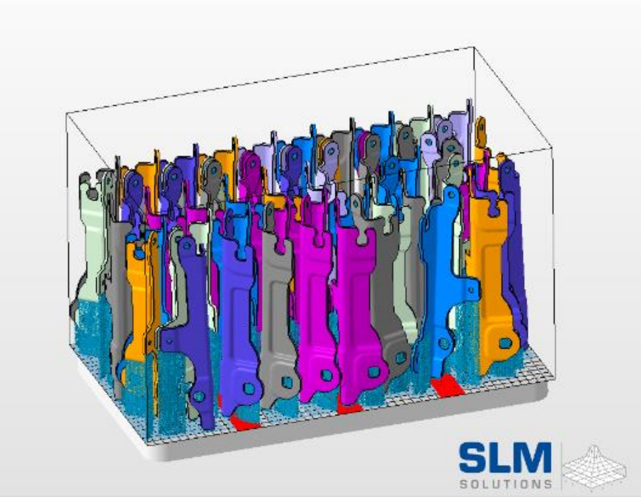


Figure 16 - 81 details loaded in a SLM 500 HL

5.2.1.4. Spoiler Module

The spoiler linkage moves the rear spoiler up and down depending on the velocity of the car. The spoiler module is showed in figure 17 and in figure 18, a machine with several levers is filled. The lever is one out of the six components in the spoiler module. For the conventional production the tooling costs are 154 800 £ and the part price is 51.99 € (Junback, 2017). It is 1 476 792 SEK for the tools and 495.98 SEK per part with an exchange rate of 1 € equals to 9.54 SEK (EUROINVESTOR, 2017).

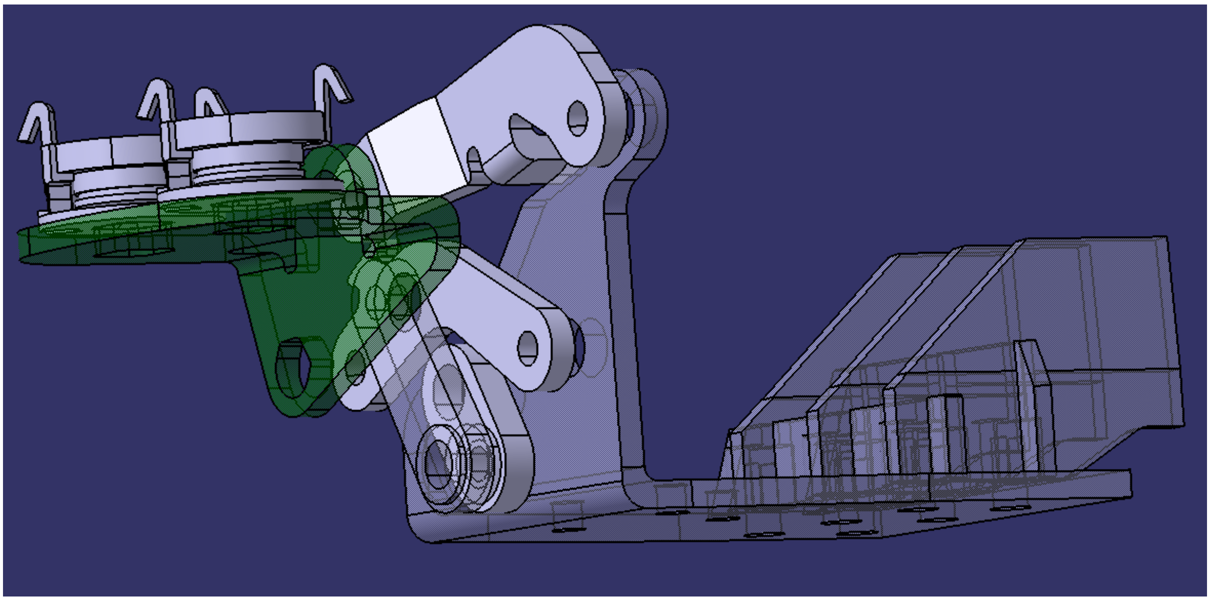


Figure 17 – Spoiler module

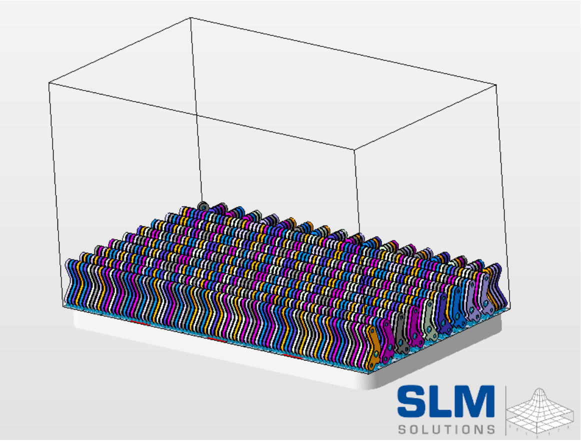


Figure 18 - Fully loaded machine with levers

5.3. Redesigned Component

In this chapter, the analysis for the redesigned component is presented. Specialists at Volvo Cars are consulted to do the redesign. One component is redesigned by topology optimization to save weight and volume. The spoiler module consists of six parts and the two biggest parts are optimized. The component has the same load cases in both variants and using the same design space.

Table 6 - Volume comparison spoiler module original and redesigned

	Volume - Original	Volume - Optimized	Volume Saving
Part 1	29,34 cm³	11,23 cm³	61,2%
Part 2	13,82 cm³	6,78 cm³	50,1%

Table 6 shows the results of the topology optimization. The volume is reduced with 61.2% and 50.1% respectively. In figure 19, 20 and 21, the original and redesigned versions are showed.

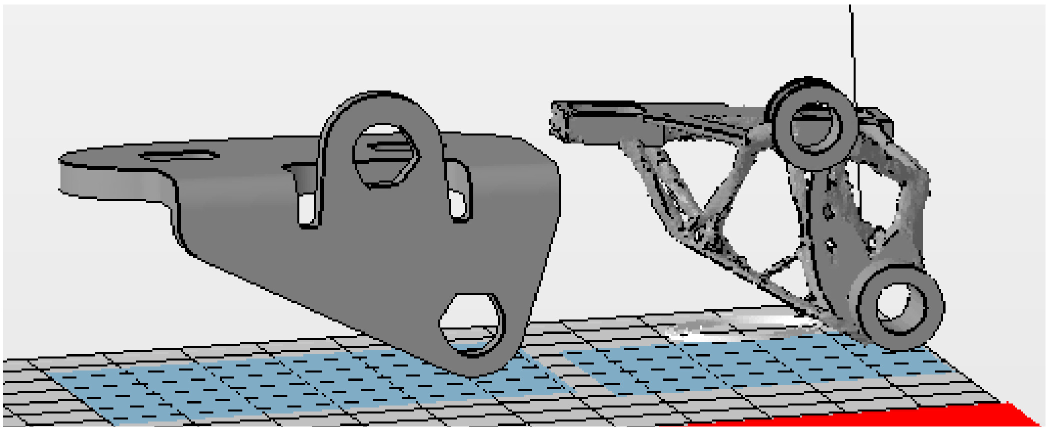


Figure 19 - Upper mounting of spoiler module original and redesigned

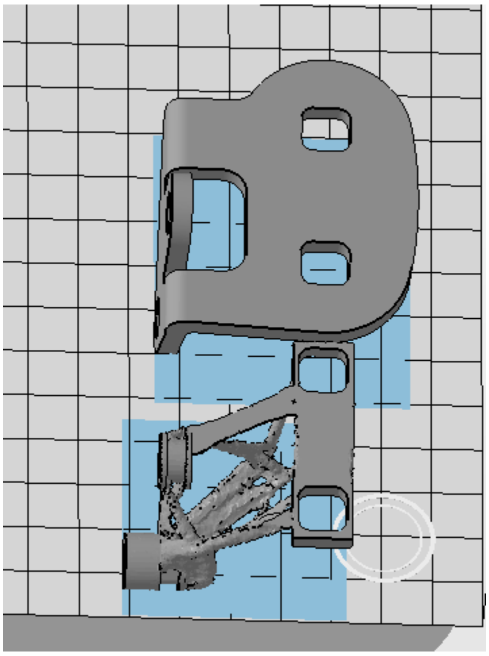


Figure 21 - Upper mounting of spoiler module original and redesigned

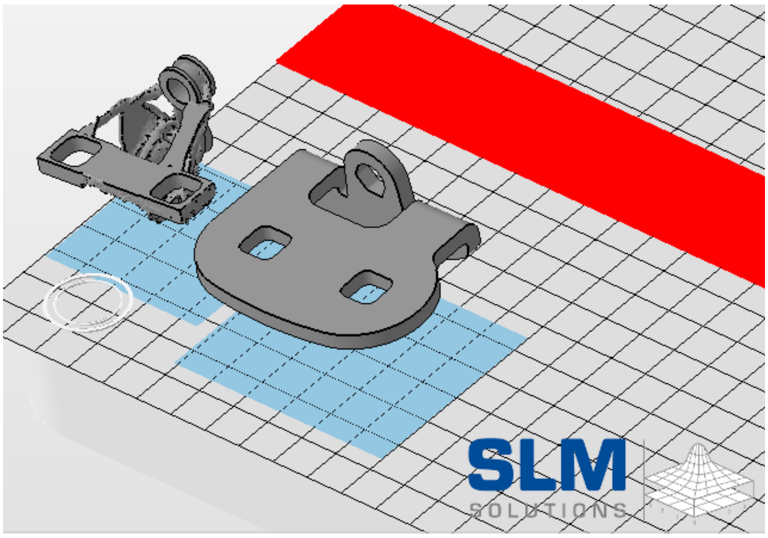


Figure 20 Upper mounting of spoiler module original and redesigned

5.4. Cost-Benefit Evaluation Model

This model is based on research papers and interviews with representative from machine suppliers. Equation (1) in section 3.6 is the original equation that is redesigned to consider benefits. Equation (2), (3) and (4) are not used in the model and is replaced with software calculation performed in Autodesk Netfabb 2017 Ultimate. This software can automatically generate necessary support structures and orient parts inside the build chamber. This is used in the calculations since support structures and orientations are not investigated in this project so therefor the automatic generation feature is used. All calculations are performed with the same settings for support structure and orientation. In the presented cost model in Appendix A Labour is also inserted and mentioned as a direct cost. This is done since there is work that has to be done to run the batch like preparing of the machine with loading CAD-files, fill in powder and remove parts from the building tray. The calculation is based on a purchase of a new SLM 500 HL for list price, depreciation costs over 5 years and a warranty extension package for 5 years (D'Intino, 2017). The cost calculation can be found in Appendix A. With a running time of 6720 hours the indirect machine cost are calculated to 58.99 euro per hour. 6720 hours, this time is derived from the existing utilization rate of the existing machines at the company. Energy and electricity consumption are assumed from number of other similar machines and are not given from the supplier. The price of raw material and building tray are given from SLM solutions (Rieder, 2017) (Schonefeld, 2017).The nitrogen price is 2.24 euro per m^3 (D'Intino, 2017) and the electricity price is 0.08 € with a currency rate of 9.54 SEK per EUR (Compricer AB, 2017). Labour cost is given from the customer recipient at the prototype centre at Volvo Cars (Liljendahl, 2017). The different cost factors are shown in the model separately so the user can see the cost divided between direct or indirect costs and what kind of direct cost.

The benefits in the evaluation model are factors regarding the product and tools. Many other factors can be beneficial but regarding to the delimitations in this project it is not added in the evaluation model. Five value drivers are integrated in the model:

- Weight Reduction
- Article Reduction
- Lead Time Shortening
- Tooling changes
- Tooling warehousing

The model can be found in Appendix B. These factors are directly related to production costs and product performance. Weight reduction and article reduction are factors with given numbers of 47 SEK per KG and 40'000 SEK per article and year (Olsson, 2016) . Tooling changes are a percentage number that are used in budgeting for new car project (Junback, 2017). Lead-time shortening and tooling warehousing are inserted as assumptions since no clear numbers were found. This gives the users the possibility to assume it themselves. Tooling changes and article reduction also have a factor included in the formula to decide how many tooling changes and how many articles that can be integrated.

The total value-adding is split on the total number of parts fabricated and this value is subtracted from the production cost per part.

In this model, a comparison function that compare the production cost of AM with Conventional manufacturing is implemented and presents it both with the cost difference, time difference and a diagram to visualize it.

6. RESULTS

In this chapter all results are presented. In the first section, results are presented of a study where four components are fabricated with conventional manufacturing and AM without any redesign or value-adding aspects taken into consideration. In the second section, a case study is presented with one part that is fabricated with AM and one that is redesign and value-adding factors.

6.1. Original Design

All four components are presented in this section. Cost split and break-even diagrams are showed for each component and in the end a summary is provided.

6.1.1. Battery Holder

For the battery holder a break-even at 290 parts was reached. With break-even means how many parts that can be manufactured with AM until conventional manufacturing is more profitable. The total cost is 1384 SEK per part and the machine cost is 90.2% of it. The production time is 2 hours and 13 minutes and the batch size is 32 pieces for this component.

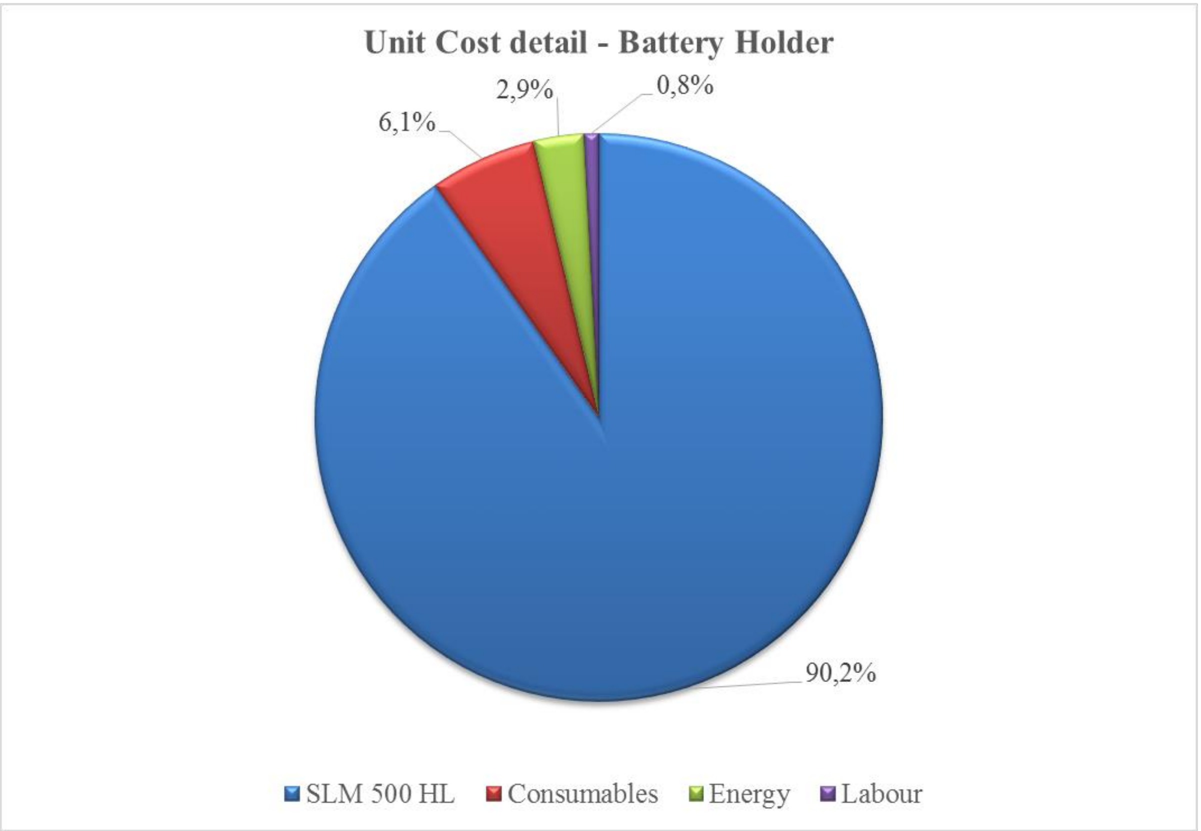


Figure 22 - Unit Cost Detail - Battery Holder

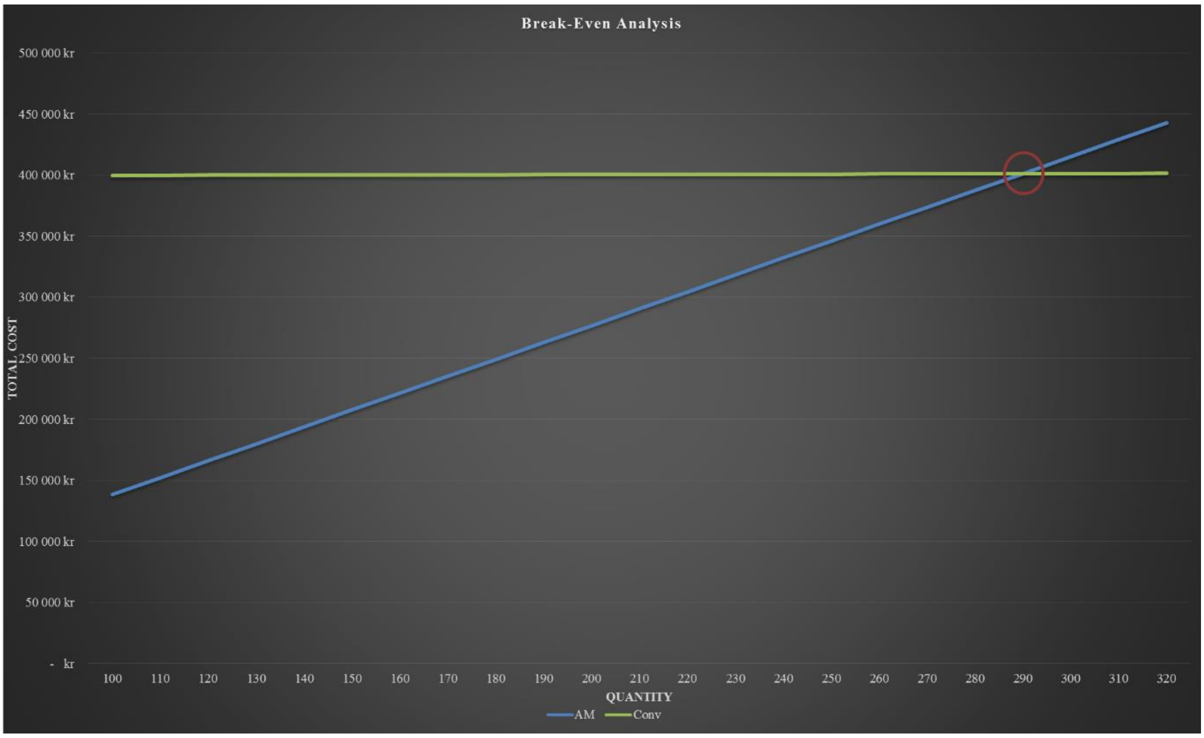


Figure 23 - Break-Even Analysis for Battery Holder. Y-axis is total cost and X-axis is Quantity.

6.1.2. Geoconsole

The geoconsole is profitable to manufacture with AM up to 80 piece and for volumes greater than that conventional manufacturing is more profitable. The total cost is 1911 SEK per part and the machine cost is 89.4% of it. The production time is 3 hours and 2 minutes and the batch size is 28 pieces.

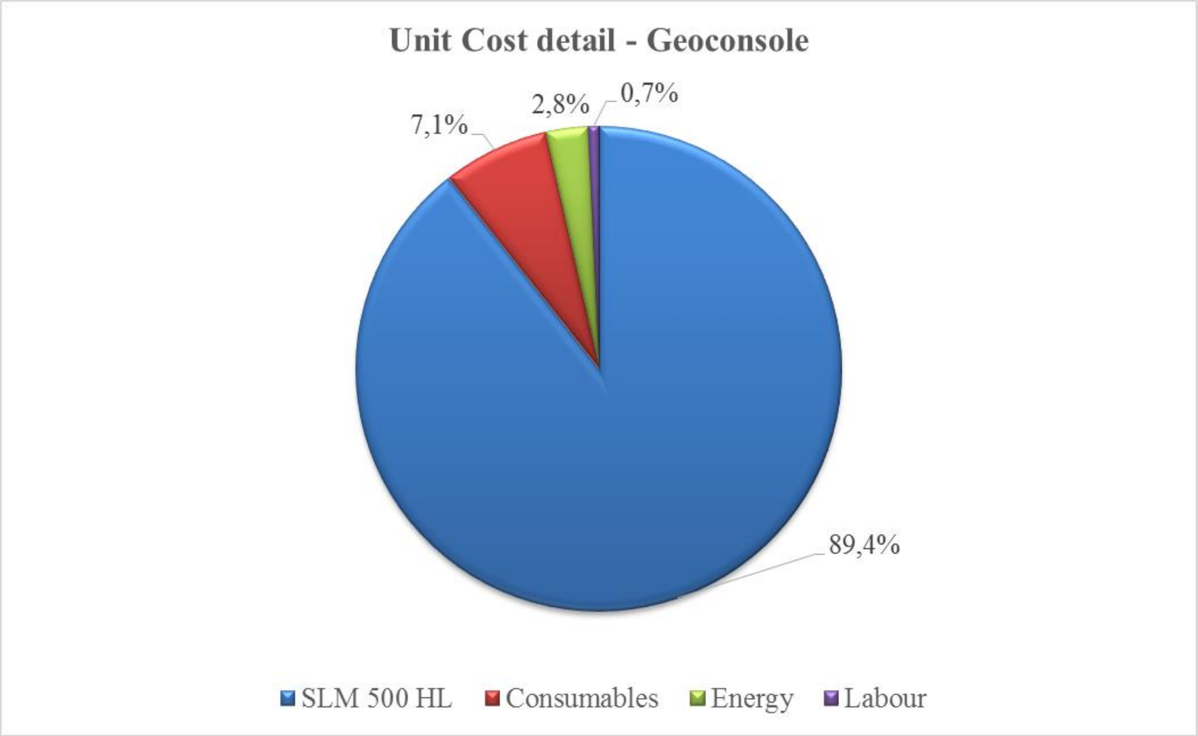


Figure 24 - Unit Cost Detail – Geoconsole

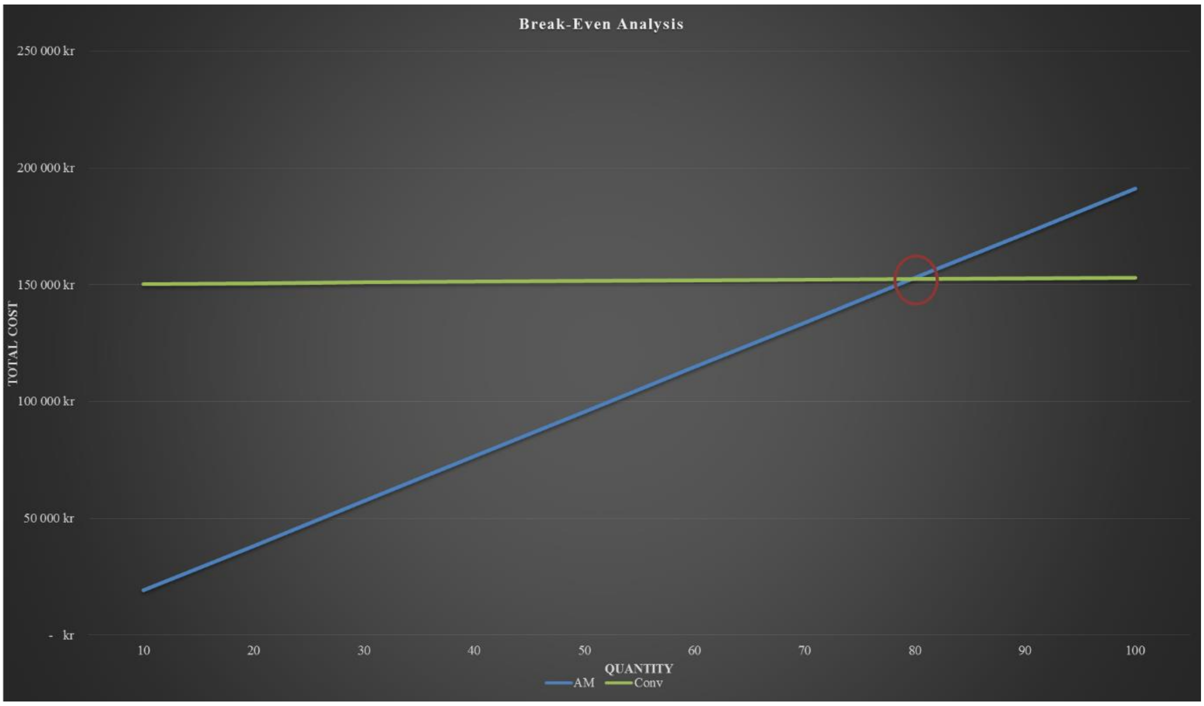


Figure 25 - Break-Even Analysis for Geoconsole. Y-axis is total cost and X-axis is Quantity.

6.1.3. Hood Hinge

Break-even for AM fabrication of Hood Hinge is 445 piece until conventional manufacturing is more profitable. The total cost is 5439 SEK per part and the machine cost is 89.3% of it. The production time is 8 hours and 37 minutes for one complete product. The batch size varies between 12 and 482 depending on which part is in the machine.

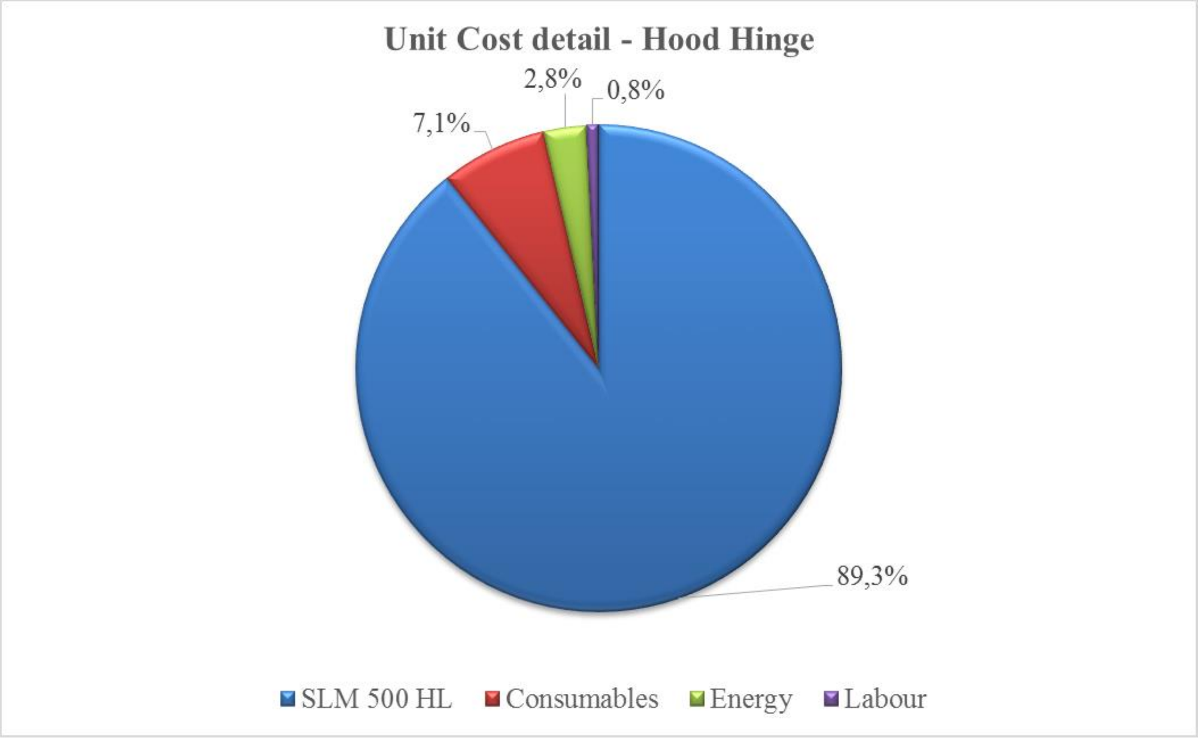


Figure 26 - Unit Cost detail - Hood Hinge

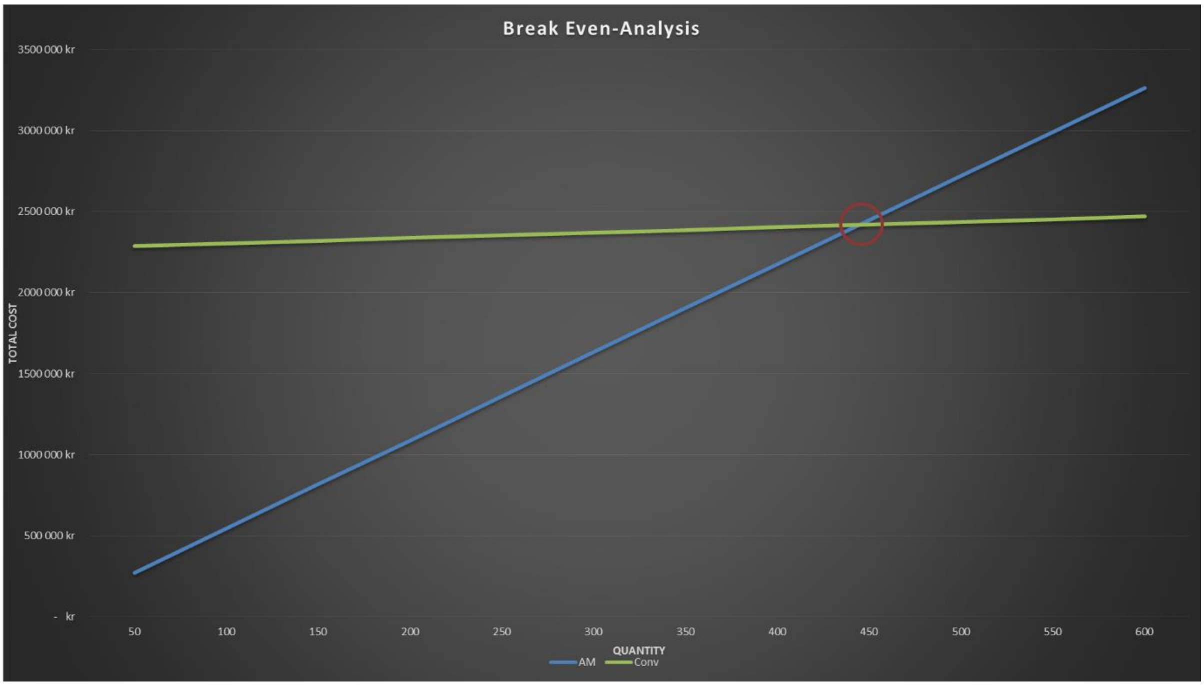


Figure 27 - Break-Even Analysis for Hood Hinge. Y-axis is total cost and X-axis is Quantity.

6.1.4. Spoiler Module

The spoiler module is the component with highest break-even point. Break-even point is 1446 pieces. The total cost is 1517 SEK per product and the machine cost is 88.6% of it. The production time is 2 hours and 23 minutes and the batch size is between 45 and 1245 pieces depending on which part is manufactured.

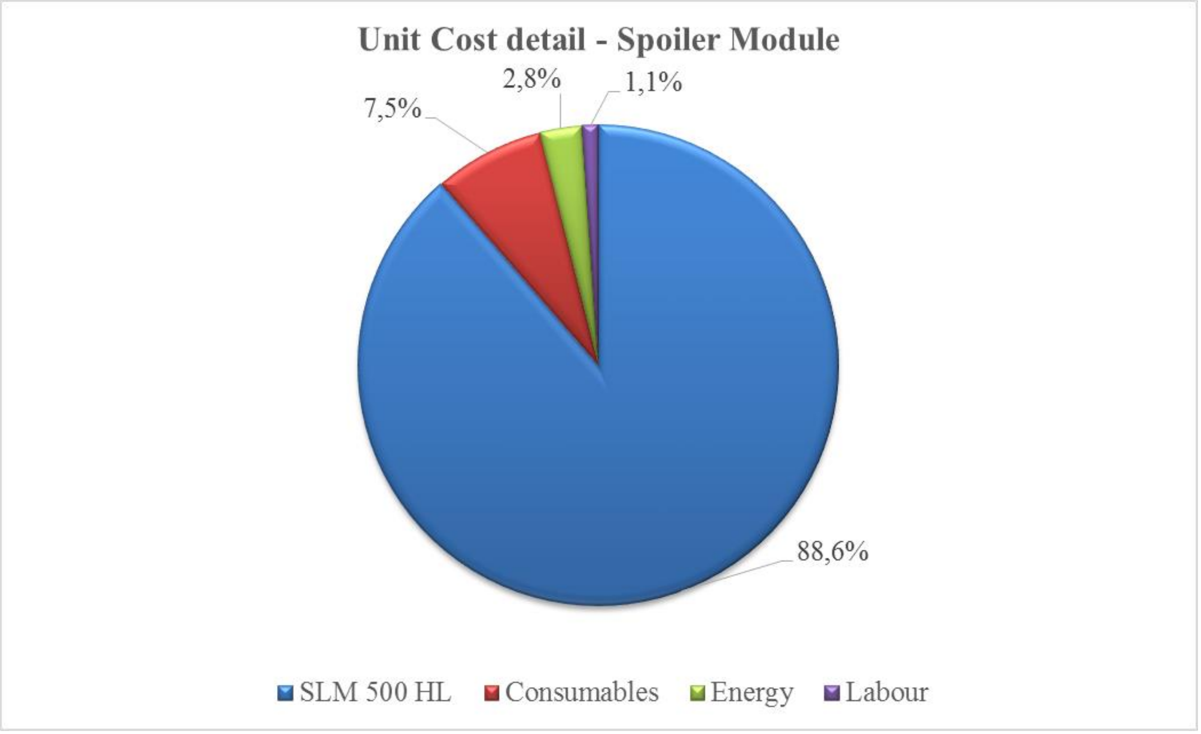


Figure 28 – Unit Cost detail - Spoiler Module

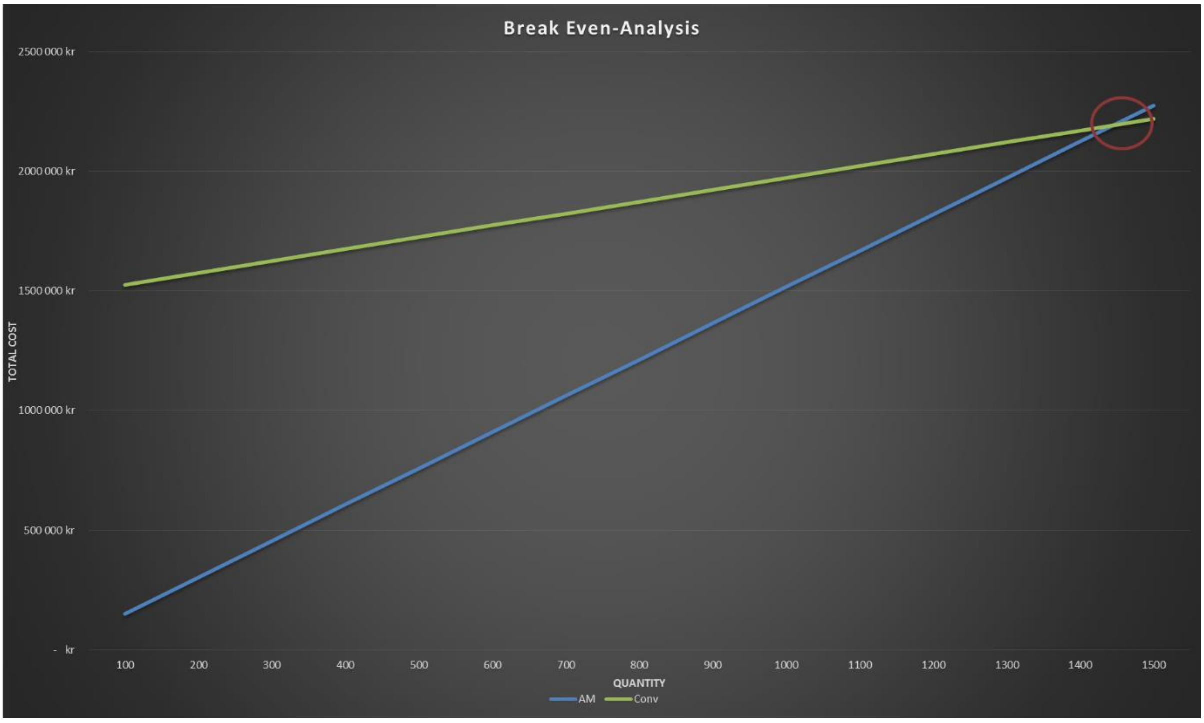


Figure 29 - Break-Even Analysis for Spoiler Module. Y-axis is total cost and X-axis is Quantity.

6.2. Redesigned Component

For the redesigned component, the machine cost is less dominating and the material is carrying higher costs. The energy and labour costs are comparable with the original component. The break-even for the topology-optimized component is increased to 6854 from 1446.

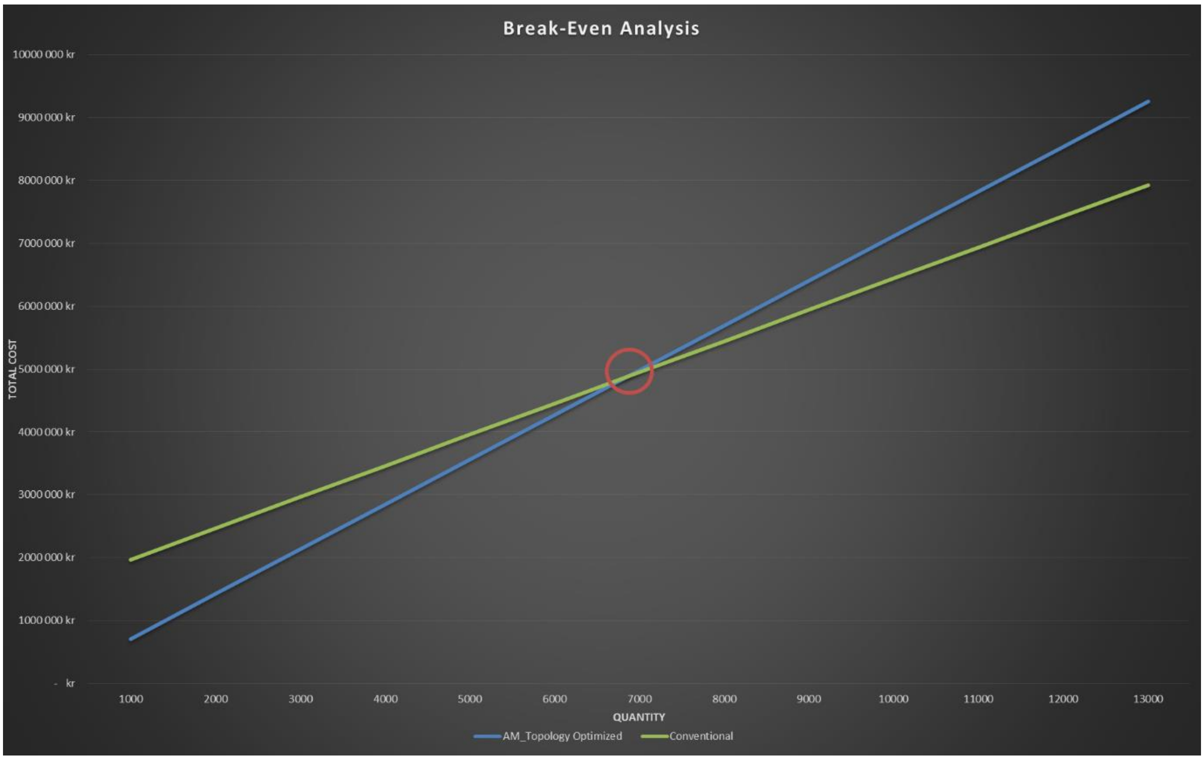


Figure 30 - Break-Even Analysis for Spoiler Module Topology Optimized. Y-axis is total cost and X-axis is Quantity.

The production time per part sunk from 2 hours and 23 minutes to 1 hour and 4 minutes. The production cost per part decreased from 1517 SEK to 711 SEK. With a machine rate of 58.99 EUR per hour can it be seen that the major cost reduction is because of the reduced production time. The part volume of the two redesigned parts of the component are 50.1% and 61.2% of original volume. Part 1 is the lower bracket and part 2 is the upper mounting of the spoiler module.

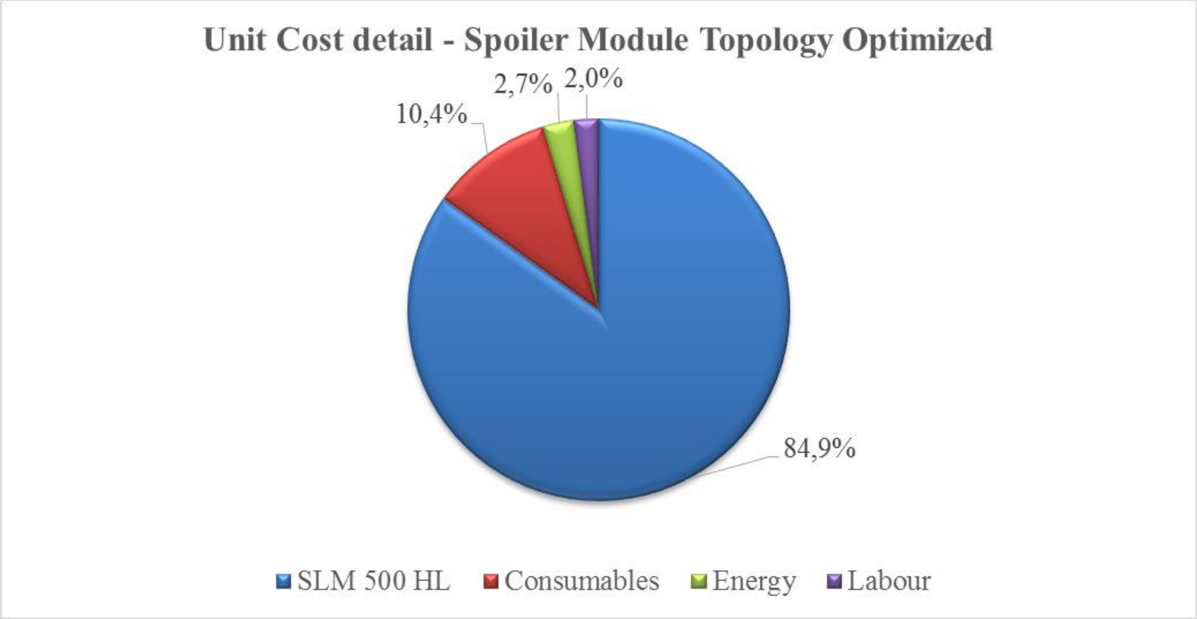


Figure 31 - Unit Cost detail - Spoiler Module Topology Optimized

With benefits from section 5.3 included in the cost-benefit calculation can it be seen that the break-even is increased to 8371 pieces. This is based on assumptions for value of tooling warehousing and lead-time shortening. The value-adding factors are found in Appendix B.

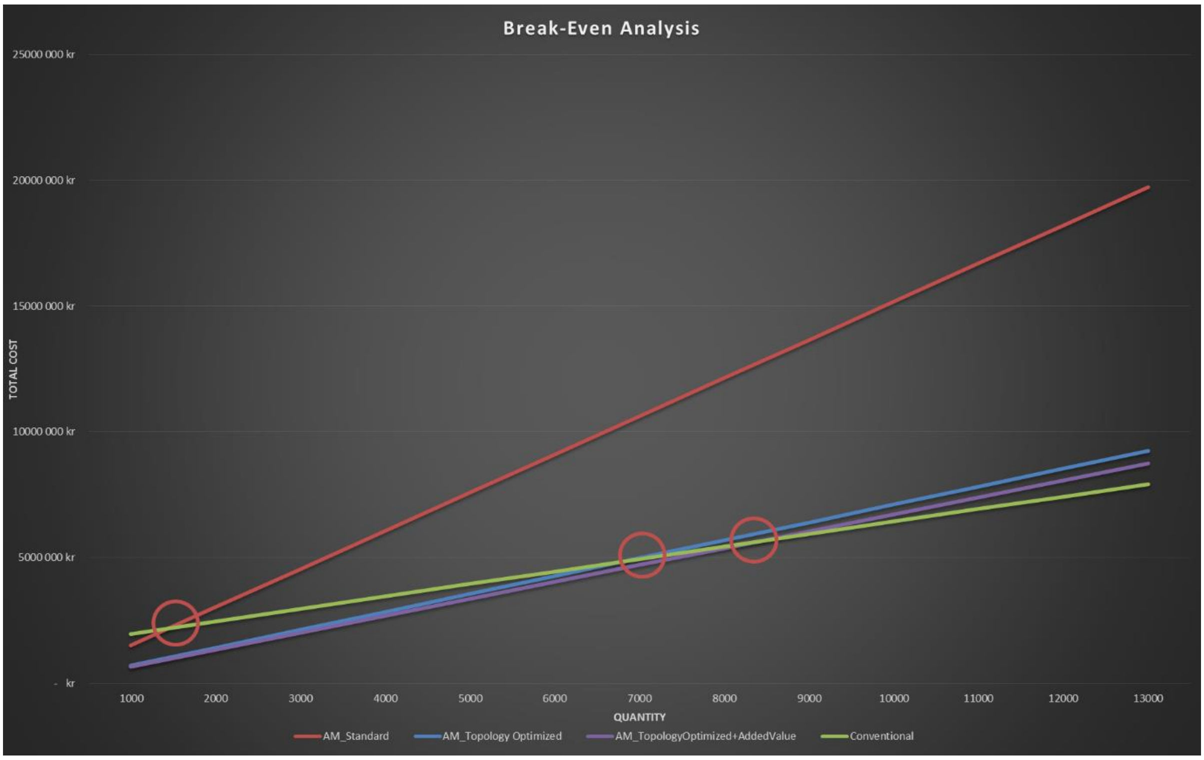


Figure 32 - Break-Even Topology Optimization and Value Added aspects. Y-axis is total cost and X-axis is Quantity.

6.3. Summary of results

In general the cost split is similar for all components. The machine cost is a significant cost element with 88.6%-90.2% of the part cost. The other three categories are in average around 10% whereof consumables are around 6%-7%. (Baumers, Dickens, Tuck, & Hague, 2015) Showed in a study that the raw-material cost for parts produced with PBF machines were around 10%.

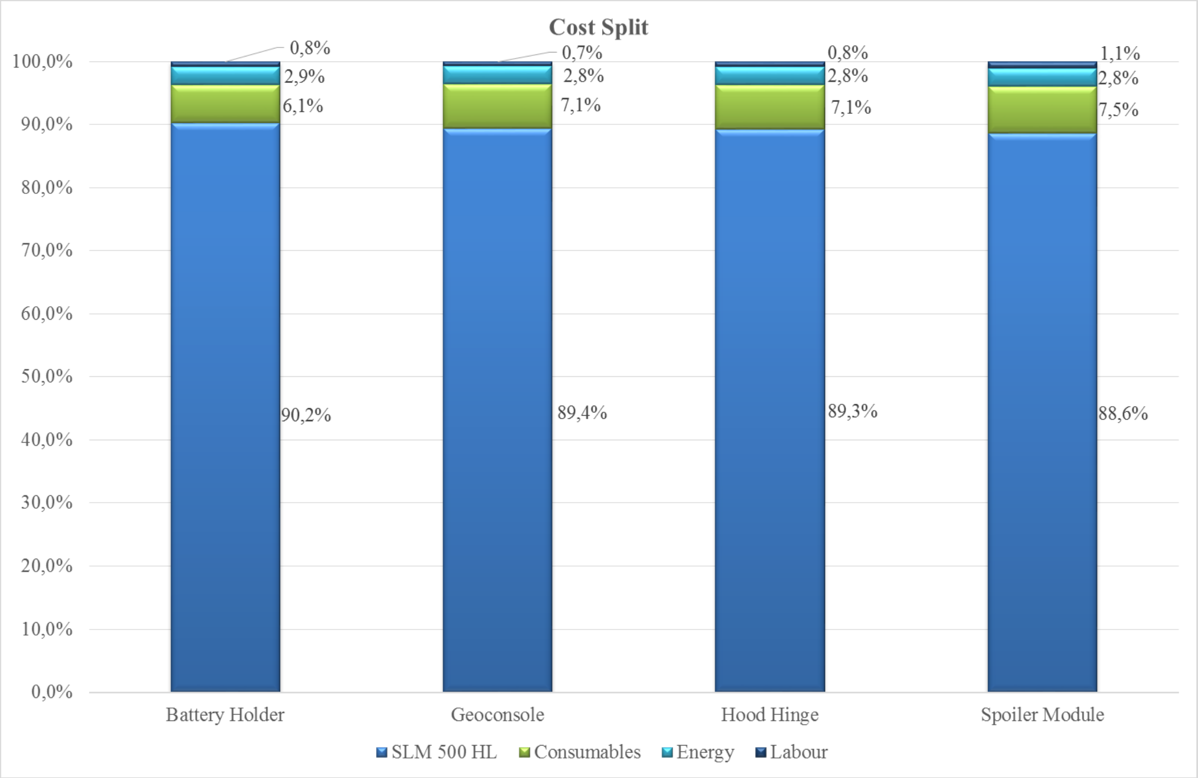


Figure 33 - Cost Split for all components

Table 7 - Cost Split Details

Unit Cost Details				
	SLM 500 HL	**Consumables**	**Energy**	**Labour**
Battery Holder	90,2%	6,1%	2,9%	0,8%
Geoconsole	89,4%	7,1%	2,8%	0,7%
Hood Hinge	89,3%	7,1%	2,8%	0,8%
Spoiler Module	88,6%	7,5%	2,8%	1,1%
Average	**89,4%**	**6,9%**	**2,8%**	**0,9%**

Table 8 - Overview over results

Article	Part Volume	Part cost	Tooling cost	Part cost AM	Break-even
Battery Holder	41,75 cm³	7,5 SEK	399’000 SEK	1’384 SEK	290
Geoconsole	75,79 cm³	28,94 SEK	150’000 SEK	1’910 SEK	80
Hood Hinge	208,08 cm³	332,80 SEK	2’270’440 SEK	5’439 SEK	445
Spoiler Module	54,84 cm³	495,98 SEK	1’476’792 SEK	1’517 SEK	1446

For the spoiler module there is a significant difference in break-even between the original and redesigned variant. The number increased with more than 6000 units for the topology-optimized variant and if value-adding aspects are included it reached a break-even almost 7000 units higher than original.

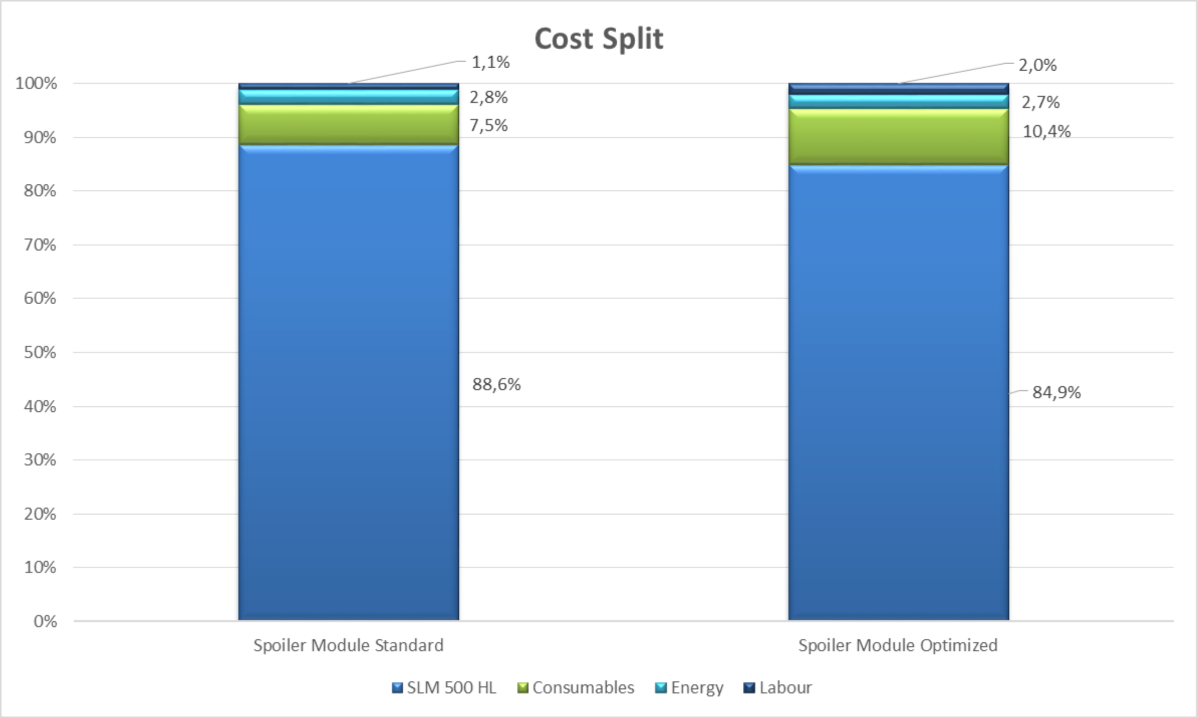


Figure 34 - Cost Split for original and redesigned spoiler module

7. DISCUSSION

In this chapter, the results of the research project are discussed. Personal reflections regarding the work are mentioned. This exploratory study shows the potential of additive manufacturing for metal components with an economical perspective. The results from chapter 6 shows good potential for the technology but a critical aspect here is that if the manufacturing quality decreases or the risk uncertainty increases it can easily be more costly to change production technique. How the product quality changes between different batches is not investigated. For an industry with high quality requirements can issues related to product quality cause great economic problems.

In chapter 2, build time is mentioned as a great influencer of the manufacturing costs and in this thesis is non-verified software's used. It is very important for future work to verify the software with a real machine to check the trustworthiness of AM software's. During the work has it been seen small bugs in simulations where build times have been longer even when components have been removed from the virtual build chamber. Another potential cost carrier for AM production is the post-processing part of the manufacturing process. When comparing, the AM components are not post-processed and the conventional manufactured components 100% finished so it is a difference.

In this research the target is to show when and how AM can be beneficial for low-volume production. With low volume my assumption is 1000 units of a specific component. For the automotive industry can low volume differ from 10 to 10 000 depending on if it is a special vehicle or if it is a standard car developed for high volumes.

This research is done with a focus on components from B&T and a finding is that most of the parts from this department is made with extrusion or stamped and folded metal sheet. Probably could the findings and results from this project be different if the work was not delimited to this department and parts from other divisions were chosen. Possibly could more parts made out of casting be selected to find components with higher tooling costs and geometries with higher complexity.

In this thesis, automatic placement and auto generated support structures is used. This is probably not the most optimal configuration so if this is done in reality build times can differ. This must be highlighted since it will change the cost of the component radically. In this thesis, only one material and one layer thickness is used. All simulations are done with same settings to make it easier to compare the results but it can also be that other settings give better or worse results regarding build time. It is also notable that for the products consisting of several parts, the build chamber are always filled with the same part and never filled with complete assemblies. If the build chambers would have been filled with different components in every batch the results could have been different.

All these simulated costs are compared with quotations from suppliers that are prepared to manufacture the components that are required. An aspect that is not mentioned is the situation of the supplier. If the supplier has a full or empty order book could influence the offer it gives to the OEM and if the supplier already is established as a supplier for Volvo Cars or for the industry overall. These aspects can change the results of when and how it can be economically beneficial.

8. CONCLUSION

Additive Manufacturing is a manufacturing technology with potential. Out of the four parts that are compared, one of them are beneficial over 1000 units without any redesign or other benefits taken into considerations. The three other parts reached a break-even between 80 and 445 units. The most significant finding is that redesign by topology optimization made it possible to increase the break-even level from 1446 to 6854 units. It clearly shows that the value and benefits of AM should be considered since it makes a great impact of the break-even.

When and how is it economic beneficial to implement Additive Manufacturing over Conventional Manufacturing for end-use components in low-volume production?

It is economic beneficial to use AM in small series and the results shows that without any redesign is it more beneficial the smaller the part is and the higher the total cost is for part and tools. The part volume is influencing both the build time since it is more material that needs to be deposited and the fact that more material is needed. Machine cost and material cost is the two biggest factors for the production cost with AM.

- **What additional value is it to use AM?**

AM can increase the value both for the customer and for the company. The customer value can be increased by the design freedom that AM provides. Structures that are more complex can be manufactured and customization can be generated in a greater extent without any bigger impacts for the cost. With part integration more functions can be integrated in a fewer amount of components. This can also be better for the customer in case of lower weight that is beneficial in many cases.

- **What kind of components can be beneficial to produce with AM?**

Small complex parts are more beneficial than larger parts with simple geometries. Results from chapter 6.2 shows that a redesigned spoiler module can lower the part cost from 1517 SEK to 711 SEK and increase break-even from 1446 to 6854 units. If other value added benefits also are taken into consideration, the break-even level is even higher. For components with high tooling costs, tooling changes can be avoided and money bound in tools can be reduced which can have a significant influence on the total cost.

- **What factors are influencing the cost most in AM?**

Machine costs counts for 89.4% of the total part cost in average in this study. It is without any doubt the most important cost carrier. Material cost is the second biggest factor with 6.9% in average, a lot less than the machine cost but much more than energy and labour which counts for 2.8% respectively 0,9%. Even for the redesigned part where the build time sunk from 2 hours and 23 minutes to 1 hour and 4 minutes, the machine cost is still high with 84.9% of the total cost. With a machine cost of almost 90% the importance of utilization is very high. Focus must be on part orientation and packaging in the machines to make sure it can run as close to 100% utilization as possible.

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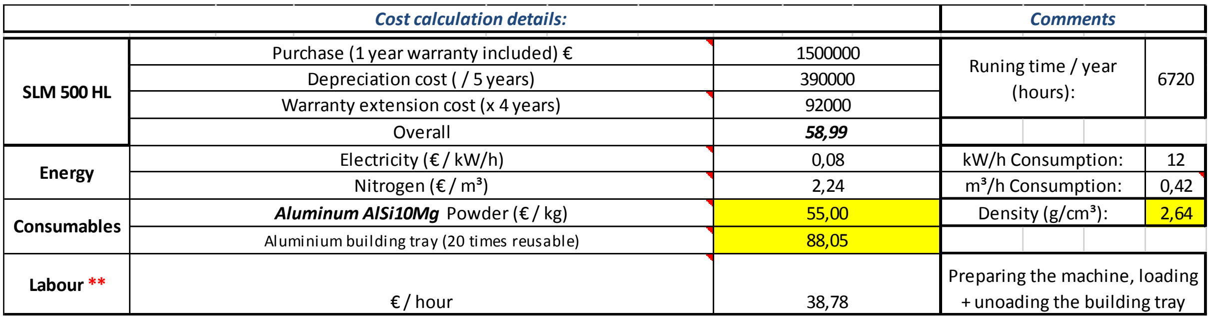
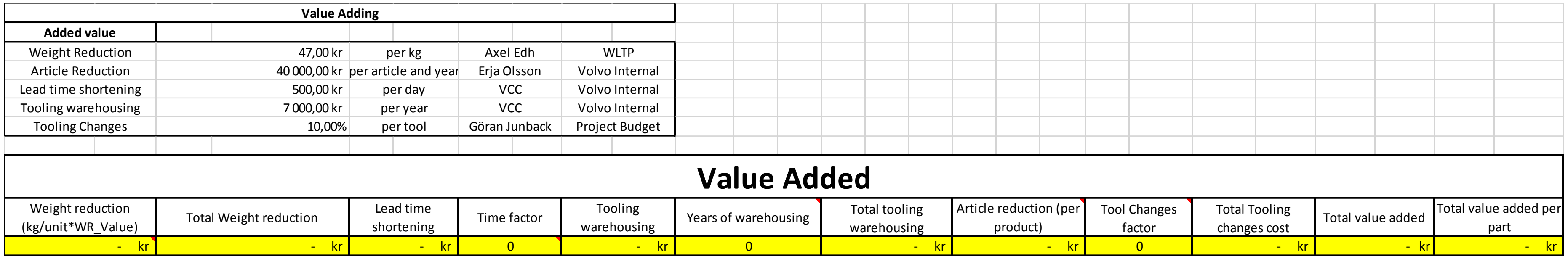
Appendix

Appendix A



	Cost calculation details:		Comments	
SLM 500 HL	Purchase (1 year warranty included) €	1500000	Runing time / year (hours):	6720
	Depreciation cost (/ 5 years)	390000		
	Warranty extension cost (x 4 years)	92000		
	Overall	***58,99***		
Energy	Electricity (€ / kW/h)	0,08	kW/h Consumption:	12
	Nitrogen (€ / m^3)	2,24	m^3/h Consumption:	0,42
Consumables	***Aluminum AlSi10Mg*** Powder (€ / kg)	55,00	Density (g/cm^3):	2,64
	Aluminium building tray (20 times reusable)	88,05		
Labour **	€ / hour	38,78	Preparing the machine, loading + unoading the building tray	

Appendix B



Value Adding				
Added value				
Weight Reduction	47,00 kr	per kg	Axel Edh	WLTP
Article Reduction	40 000,00 kr	per article and year	Erja Olsson	Volvo Internal
Lead time shortening	500,00 kr	per day	VCC	Volvo Internal
Tooling warehousing	7 000,00 kr	per year	VCC	Volvo Internal
Tooling Changes	10,00%	per tool	Göran Junback	Project Budget

Value Added

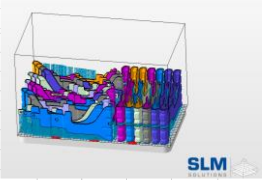
Weight reduction (kg/unit*WR_Value)	Total Weight reduction	Lead time shortening	Time factor	Tooling warehousing	Years of warehousing	Total tooling warehousing	Article reduction (per product)	Tool Changes factor	Total Tooling changes cost	Total value added	Total value added per part
- kr	- kr	- kr	0	- kr	0	- kr	- kr	0	- kr	- kr	- kr

Appendix C

Additive Manufacturing

		Manufacturing Data*						Unit Cost detail				Unit Cost			
Item	**Production Volume**	**Buildable units / Tray**	**Unit volume supports included (cm³)**	**Unit weight supports included (kg)***	**Full tray manufacturing time (h)***	**Labour time (h)**	**Production time per part**	**SLM 500 HL**	**Consumables**	**Energy**	**Labour**	**Overall unit manufacturing cost (€)**	**Overall unit manufacturing cost (SEK)**	**Total production cost (SEK)**	***Total Production Time***
Battery Holder	1000	32	41,75	0,11	71:00:00	1	02:13:08	130,88	8,81	4,16	1,21	***145,07 €***	***1 383,96 kr***	***1 383 963,76 kr***	2218:45:00

Cost calculation details:			***Comments***	
SLM 500 HL	Purchase (1 year warranty included) €	1500000	Runing time / year (hours):	6720
	Depreciation cost (/ 5 years)	390000		
	Warranty extension cost (x 4 years)	92000		
	Overall	***58,99***		
Energy	Electricity (€ / kW/h)	0,08	kW/h Consumption:	12
	Nitrogen (€ / m³)	2,24	m³/h Consumption:	0,42
Consumables	***Aluminum AlSi10Mg*** Powder (€ / kg)	55,00	Density (g/cm³):	2,64
	Aluminium building tray (20 times reusable)	88,05		
Labour **	€ / hour	38,78	Preparing the machine, loading + unoading the building tray	



**: Estimated on the parts already benchmarked*

***: Not include All post processing jobs: EDM/Milling cutting, Parts removing, heat treatment, surface finishing…*

****:Currency exchange rate: 1 € = 9,54 kr*

Conventional Manufacturing

Item	**Production Volume**	**Unit Weight (kg)**	**Number of Articles**	**Part Cost**	**Tooling Cost**	**Production Time Part (h)**	**Production Time Tool (h)**	**Overall unit manufacturing cost**	**Total Production Cost (SEK)**	**Total Production Time**
Battery Holder	1000	0,11	1	7,50 kr	399 000,00 kr	00:20	2520:00:00	406,50 kr	406 500,00 kr	2858:53:20

Comparison

Additive Manufacturing					Conventional Manufacturing				Difference	
Volume	**Unit cost AM**	**Unit production time**	**Total production cost AM**	**Total production time AM**	**Unit cost Conventional**	**Unit production time**	**Total production cost Conventional**	**Total production time Conventional**	**Total Cost**	**Total Time (h)**
1000	1 383,96 kr	02:13:08	**1 383 963,76 kr**	2218:45:00	406,50 kr	00:20	**406 500,00 kr**	2858:53:20	- 977 463,76 kr	640:08:20

Value Adding				
Added value				
Weight Reduction	47,00 kr	per kg	Axel Edh	WLTP
Article Reduction	40 000,00 kr	per article and year	Erja Olsson	Volvo Internal
Lead time shortening	500,00 kr	per day	VCC	Volvo Internal
Tooling warehousing	7 000,00 kr	per year	VCC	Volvo Internal
Tooling Changes	10,00%	per tool	Göran Junback	Project Budget

Value Added

Weight reduction (kg/unit*WR_Value)	Total Weight reduction	Lead time shortening	Time factor	Tooling warehousing	Years of warehousing	Total tooling warehousing	Article reduction (per product)	Tool Changes factor	Total Tooling changes cost	Total value added	Total value added per part
- kr	- kr	13 336,23 kr	1	7 000,00 kr	15	105 000,00 kr	- kr	0	- kr	118 336,23 kr	118,34 kr

Appendix D
Product Requirements

- Not included in crash structures
- Not visible for customers and users
- Feasible to build in AM machines available today