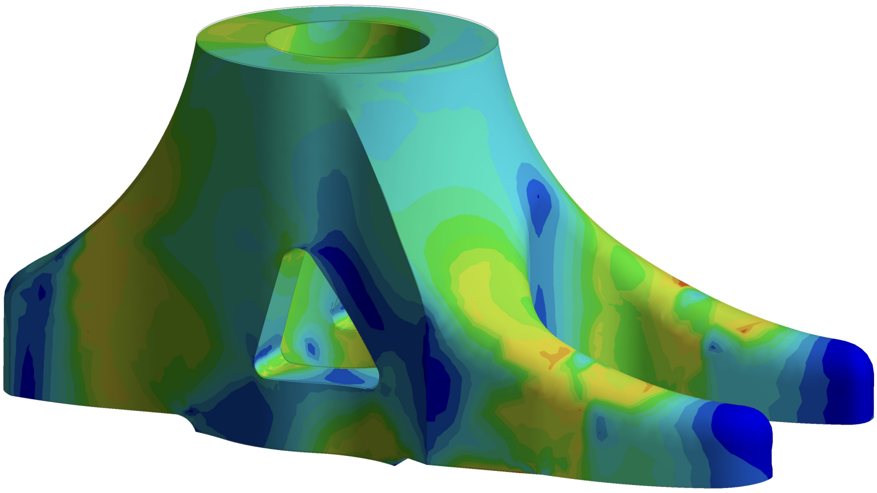

Application of Additive Manufacturing for Spare Parts in the Automotive Industry

A Case Study on the Heavy-Duty Vehicle Injector Yoke PN 469797

Bachelor's Thesis in Mechanical Engineering

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Department of Industrial and Materials Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg
Sweden 2018

Department of Mechanical and Nuclear Engineering
PENNSYLVANIA STATE UNIVERSITY
State College, Pennsylvania
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Cover: Finite element stress analysis performed in ANSYS R18.2 of an injector yoke optimized for additive manufacturing.

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Abstract

The injector yoke treated in this thesis, is one of the Volvo Group's many spare parts. The yokes have earlier been produced in large scale and kept in stock at a central warehouse. Although Additive Manufacturing (AM) has largely been focused on fields where high manufacturing costs have been acceptable, it is now also believed to be a possible solution to avoid unnecessary large scale production and storage of these yokes.

This thesis is a partnership between the Volvo Group, students from The Pennsylvania State University, and students from Chalmers University of Technology with the aim to investigate the possibilities of spare part manufacturing using AM. Provided with initial models, engineering drawings, and boundary conditions from the Volvo Group, initial research was conducted to optimize the current model for an additive manufacturing viewpoint. Different methods for additive manufacturing were examined and described in the report. Also, the economical aspects were analyzed.

The result of the project was a design for an injector yoke, capable of replacing the original part with a volume reduction of 28.4%, and a recommendation to use DMLS by EOS for this kind of products. The conclusion that AM would not be a profitable manufacturing option at this time was drawn.

Keywords: Metal Additive Manufacturing, Spare Parts, Injector Yoke, Design Optimization, Volvo

Sammandrag

Injektoroket som behandlas i detta projekt är en av Volvo Groups många reservdelar. Oken har tidigare producerats i stora kvantiteter och lagerhållts på centrallager. Trots att additiv tillverkning främst riktar sig mot områden där höga tillverkningskostnader tolererats, ses det som en möjlig metod för att undvika storskalig produktion och lagerhållning av lågfrekventa komponenter.

Denna avhandling är ett samarbete mellan Volvo Group, studenter från the Pennsylvania State University och studenter från Chalmers Tekniska Högskola med syfte att utreda möjligheterna med reservdelstillverkning via AM. Med befintliga modeller, ritningar och randvillkor från Volvo Group som utgångspunkt genomfördes grundläggande analyser för att optimera den ursprungliga komponenten, passande för additiv tillverkning. Olika AM-metoder undersöktes och beskrivs i rapporten. Dessutom analyserades de ekonomiska aspekterna av ett byte till AM.

Resultatet av projektet var ett designförslag till ett injektorok som förmår ersätta det ursprungliga oket, med en volymminskning av 28.4% samt en rekommendation att använda metoden DMLS från EOS för denna typ av komponent. Dessutom drogs slutsatsen att AM i dagsläget inte är en tillräckligt mogen teknik för att vara en lönsam tillverkningsmetod för delar av lika enkel karaktär som injektoroket.

Nyckelord: Additiv tillverkning i metall, Reservdelar, Injektorok, Designoptimering, Volvo

Acknowledgements

The group has had help from several external sources, and we would like to thank them for their contributions to this report. Our supervisors, Prof. Mikael Enelund, Prof. Magnus Ekh and Asst. Prof. Jessica Menold, worked closely with the team and helped guide us through the project. Many thanks to our industrial partner, Johan Svenningstorp, as well as his colleagues Henrik Karlsson, Bertil Prissberg, Cilla Zachau and Tomas Göransson for their help supplying vital information concerning the mechanics of the yoke and its supply chain. Also, many thanks to Chalmers Prof. Eduard Hryha for his valuable inputs and a big thanks to Zackary Snow from Cimp 3D and Jeremy Zuccarello from ExCCL lab for the educational tours of their facilities during the visit to State College.

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A. Blennow, P. Frick, M. Gardfjell, Gothenburg, May 2018
M. Harshey, I. Moyer, J. Zackarauskas, State College, May 2018

Abbreviations

AM Additive Manufacturing.
ASTM The American Society for Testing and Materials.

CDC Central Distribution Centers.
CNC Computer Numerical Control.

DED Directed Energy Deposition.
DMLS Direct Metal Laser Sintering.

EBAM Electron Beam Additive Manufacturing.
EBM Electron Beam Melting.
EDM Electrical Discharge Machining.

FEA Finite Element Analysis.

LENS Laser Engineering Net Shaping.

PBF Powder Bed Fusion.

RDC Regional Distribution Centers.

SDC Support Distribution Centers.
SDO Structural Design Optimization.
SLM Selective Laser Meting.
SO Shape Optimization.

TO Topology Optimization.

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1
Introduction

This project is carried out as a collaboration between Chalmers University of Technology, Pennsylvania State University and the Volvo Group. The purpose is to develop an additively manufacturable injector yoke, which holds the diesel injector in place on diesel engines. This chapter serves as a brief introduction to the problem statement (1.1), and continues with the objectives (1.2), of the project, addressing both customer needs (1.2.1) and delimitations (1.2.2). Finally, an ethics statement (1.3), as well as a statement of environmental aspects (1.4), are presented.

1.1 Background

The Volvo Group injector yoke with part number PN 469797 is no longer used in the production of new engines and is currently produced solely for the aftermarket. The current stock of parts is running out and new ones need to be produced. Originally, the yokes were mass produced via pressing and sintering in six-figure bulk volumes. However, due to the low annual consumption of less than 1 000 parts per year, the economical viability of this production route is questioned. The production route investigated in this report is on demand additive manufacturing (AM) and possibly on location to reduce shipping costs.

Furthermore, newly produced spare parts have been machined out of metal stock. These parts exhibit the same properties as the original ones, but to machine and distribute every spare part individually is costly. As a way to possibly decrease costs, metal AM has caught the attention of the Volvo Group as a method for producing spare parts, especially low frequency spare parts, in the future.

1.2 Objectives

The aim of this project is to redesign a spare part injector yoke, capable of replacing the PN 469797, suitable for AM techniques, while preserving the strength of the original yoke. To accomplish this, the aim is to identify an appropriate AM method and material, perform optimization techniques, and consider the cost efficiency. More details can be found in Section 1.2.1 and 1.2.2.

1.2.1 Customer Needs

As mentioned in the initial problem statement, the Volvo Group desires an additional option to produce the injector yokes in a more efficient and optimized process. To achieve this, the objective has been broken down into a list of the customer needs.

- **Reliability:** The AM method has to be reliable; when printing, the result has to follow the design specifications within the given tolerances. This means the part has to have similar or better strength and stiffness as compared to the original part.

- **Print time:** In high-end production, manufacturing cost is highly correlated to production time. Hence, for economical gain it is important to minimize printing time. This is mitigated by reducing part volume and use of support structures, as much as possible.

- **Post-processing:** By designing the component to reduce after treatments, such as surface finishing and heat curing, unnecessary lead time and waste can be minimized. To further increase the ease of post-processing the amount of support structures and their location should be carefully considered.

- **Cost:** A substantial consideration for the project is to increase the profitability. Hence, minimizing the inventory, production and distribution costs is essential.

1.2.2 Delimitations

The investigation of AM methods in this thesis is delimited to AM in metal, mainly Powder Bed Fusion (PBF) systems, because it is the markets leading method for this type of printed object. PBF is further developed and less expensive than other similar methods. Hence, other possible methods like Directed Energy Deposition (DED) are only briefly investigated and explained.

AM can be used for several different types of materials. This project is delimited to AM with commercially used steel, because of its low cost, high strength and international establishment. Costly materials, such as titanium based alloys, are therefore not within the scope of investigated materials.

The initial problem statement requests a redesign of the part to make it suitable for

AM. Such redesign and optimization can be very extensive and therefore the redesign is delimited to utilizing Topology Optimization (TO) and Shape Optimization (SO) with regards to reducing weight and volume, while maintaining the mechanical properties of the original component. It is possible to make an optimization of the design with the target to reduce the printing time. However, this is far more extensive than the scope of this project and requires more expertise as well as time.

To economically benefit the Volvo Group, a more efficient production route is desired. The project is therefore meant to investigate whether on demand AM will make production more efficient, by means of drastically reducing the inventory of spare parts and decreasing lead times. The focus is delimited to studying the economy and logistics of production, mainly using information gained from communication with contacts through the Volvo Group.

To summarize, the delimitations come down to:

- Focus on AM using PBF and not DED, since it seems more viable given the specifications especially considering cost.
- Investigating only commercially available steels to maintain low production cost.
- The main optimization criterion is to reduce the weight and volume, while maintaining mechanical properties, and not to minimize the printing time.

1.3 Ethics Statement

The Volvo Group is a global company known for its high quality, safety, and work ethics. Since this project is made in cooperation with the Volvo Group, the project must follow the code of conduct that is set up by the company. [6]

It is important to provide a safe and healthy workplace for all employees. This means that the use and handling of hazardous materials, dangerous parts as well as waste should be minimized. If necessary, all required precautions should be taken. Hence, the use of hazardous materials, such as chromium and nickel for top coating, should be avoided when designing the yoke, if possible.

The Volvo Group inventions, trade secrets and designs should be carefully protected. Therefore, it is important that the information shared between the team, the Volvo Group, and professors are handled with great care since it may be confidential.

While developing new methods it is utterly important to respect and to not use material protected by intellectual property that does not belong to the Volvo Group. When using material protected by intellectual property there should always be a consent from the Volvo Group and a permission from the third party, the owner of the intellectual property.

1.4 Environmental Aspects

AM is preferable in environmental aspects because it adds material instead of removing it. Therefore AM reduces material waste and lowers the environmental impact. Also, parts should be designed to minimize support structures, as to further decrease waste.

The use of AM enables decentralized manufacturing, meaning the component can be produced closer to the final customer. Hence, the environmental impact due to pollution from long distance transportation can be drastically decreased. Manufacturing on demand also eliminates the risk of overproduction, minimizing both material and energy use for production.

2

Theory

This chapter describes the different fields necessary for an assessment of design choice and manufacturing method. Section 2.1 introduces the concept of additive manufacturing and certain AM methods and materials. Section 2.2 examines the basics behind Structural Design Optimization (SDO), used to produce the different design concepts presented in Chapter 4. Lastly Section 2.3 and 2.4 takes a more industrial and economical approach to AM, summarizing the Volvo Group's supply chain and forecasting the future of AM.

2.1 Additive Manufacturing

AM is a relatively new branch of industrial production. As the field is still in its early years, a standardization has not yet been adopted and the market is full of up-and-coming companies developing various different methods[1]. This section will look at the advantages and disadvantages of current popular AM methods applicable in the automotive industry.

2.1.1 Methods of Additive Manufacturing

AM is a very broad term. It is more or less synonymous with 3D printing and they are often interchanged. There is no official difference, yet AM is the more professional term. Within the field of AM there are a vast amount of different methods and The American Society for Testing and Materials (ASTM), the organization setting the standards for AM, has divided all existing methods into the following seven categories [7]:

- **Binder Jetting**: AM process in which a liquid bonding agent is selectively deposited to join powder materials.

[1] Wohlers Annual Worldwide Progress Report provides up-to-date information about techniques, strategics, developments and trends within the field of additive manufacturing.

- **Direct Energy Deposition**: AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

- **Material Extrusion**: AM process in which material is selectively dispensed through a nozzle or orifice.

- **Material Jetting**: AM process in which droplets of build material are selectively deposited.

- **Powder Bed Fusion**: AM process in which thermal energy selectively fuses regions of a powder bed.

- **Sheet Lamination**: AM process in which sheets of material are bonded to form an object.

- **Vat Photopolymerization**: AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

Material Extrusion, Material Jetting and Vat Photopolymerization use polymers and plastics, exclusively. In Sheet Lamination, sheets of various materials, e.g. plastic or metal, are welded together and cut into the desired geometry. The welding does, however, not fully melt the metal, thus making the bond between the sheets relatively weak. The process also produces a substantial amount of material waste. Binder Jetting fuses powder by dropping small drops of a liquid binding agent onto selective regions of the powder. The binding agent acts as an adhesive and solidifies the powder. The bond between the powder however, is too weak for structural components. The two remaining methods, Powder Bed Fusion (PBF) and Directed Energy Deposition (DED), both use digital 3D models to produce metal components.

2.1.1.1 Methods of Powder Bed Fusion

PBF creates an object by thermally fusing selective regions of metal powder one layer at a time. All PBF methods have a thermal source to fuse metal powder, a selective method to isolate regions for fusion and a powder container with a mechanism for adding additional layers of powder. A schematic view of the process can be seen in Figure 2.1. The build takes place inside an enclosed chamber, where the environment is chosen with regards to the thermal source and choice of metal powder. The powder inside the chamber is constantly maintained at a temperature just below the critical fusing temperature, often using infrared light. The build process is a cycle of three simple steps. Firstly, a thin layer of metal powder is spread out over the build platform, typically, about 0.1 mm thick. Selective regions of the powder are then thermally fused according to the digital model. Finally, the build area is lowered by one layer, making room for the next layer of metal powder. Repeating these steps, ultimately produces an object. During printing, the object is surrounded and supported by the bed of powder. Therefore, with few exceptions, support structure is only needed in order to keep the object in place. Lastly, the object must cool down inside the enclosed environment to avoid exposure to oxygen and curling caused by uneven thermal contraction. [2, 8]

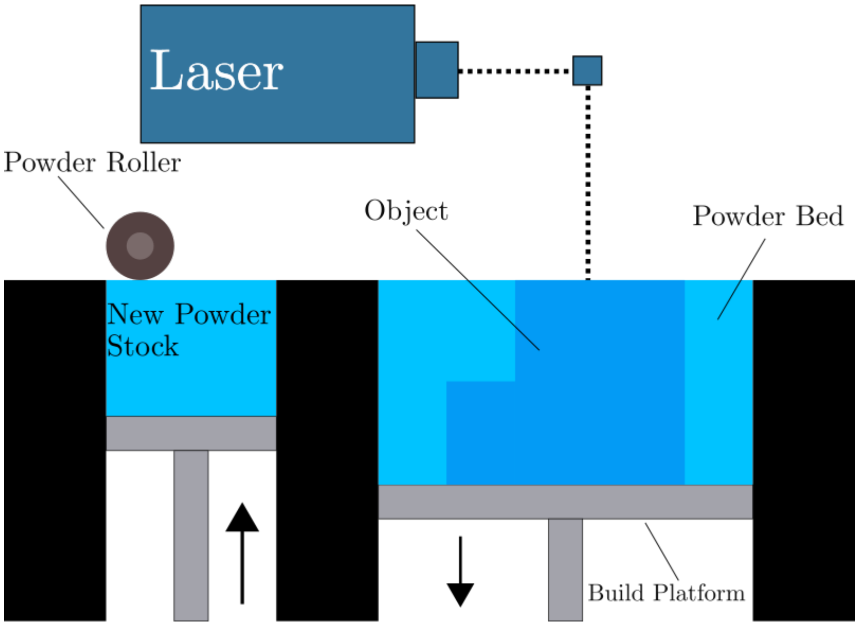

Figure 2.1: A schematic figure of the powder bed fusion process using a powder roller as powder spreading mechanism and a laser as thermal source.

PBF can be useful for manufacturing numerous parts at once by filling out the build volume on every print. The low amount of support structures needed also benefits printing complicated parts. Minimal support material is also preferred in order to minimize the time of post processing. [8]

The three main methods of PBF are Direct Metal Laser Sintering (DMLS), Selective Laser Meting (SLM), and Electron Beam Melting (EBM). The DMLS technology is supplied by EOS, SLM by SLM Solutions and EBM by Arcam AB. Specifications of these methods and certain similar medium-sized printers can be found in Table 2.1 and 2.2, respectively. Currently, the most popular method for metal AM is EOS DMLS. The other two methods are not as widely established, but all three, according to Wohlers Report 2016 [2], are among the top methods most companies wish to invest in. The differences between DMLS and SLM are not extensive. Both processes use similar thermal sources and mechanics as well as the environment in the enclosed chamber, namely nitrogen gas, to limit oxidation. The two companies behind the methods even cooperate and share certain patents with each other [2].

EBM is in concept very similar to SLM and DMLS, with the exception of the thermal source being an electron beam, instead of a laser. The most significant advantage of using an electron beam instead of laser is the energy efficiency. The reflective nature of metals, result in energy losses using laser melting. EBM however, can utilize most of the energy put into the beam. Arcam's MultiBeam technology supplies a 3500 W electron beam that can be split up into a 100 smaller beams [3]. Aside from faster build times, the splitting of the beam also inflicts smaller thermal gradients resulting in lower residual stresses. Decreasing the thermal stress has proven useful, since parts exhibit a lower tendency to bend. Hence, less support structure is required to hold the part in place. Therefore, EBM is both more energy and time efficient.

EBM is performed in a vacuum system, eliminating oxidation and other unwanted chemical processes. The largest disadvantage of EBM is its cost. Therefore, EBM is mostly used in high-end industries such as manufacturing of medical prosthetics or aerospace components. Because the method is costly, it is mainly used for costly materials such as titanium alloys and not for ordinary structural materials such as stainless steel. [2]

2.1.1.2 Methods of Directed Energy Deposition

Similarly to PBF, DED thermally fuses metal powder, or metal wire. Although, instead of using a powder bed as a build region, the metal powder or wire is deposited through a multi-axis nozzle and thereafter thermally fused to the surface of the object, using a thermal source, see Figure 2.2. The multi-axis nozzle often has three or five axes, the latter enabling it to deposit material at almost any angle. Some machines work the other way around, rotating the printed object and leaving the nozzle movable in only one dimension. Because of the many degrees of freedom in DED, enabling deposition of material at almost any point on the surface of an object, making it an excellent tool for repairing damaged components or adding material to existing ones.

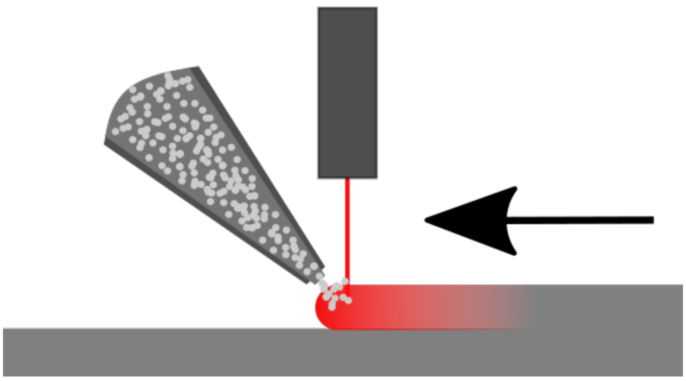

Figure 2.2: A schematic view of Direct Energy Deposition (DED) using powder feedstock and a laser as thermal agent. The laser melts the deposited powder creating a pool that gradually cools and hardens while the nozzle-head and the laser move forward. The arrow indicates printing direction.

One of the advantages of DED is the deposition rate – it can print up to 330 g/min

– which is about ten times faster than PBF [9]. Another advantage is the possibility of multiple powder-nozzles using different metal powders. By regulating the flow of the different powders the composition of the material can be customized. This enables for the printing alloy to be easily changed without interrupting the print. The drawbacks of DED are however the reduced capability of printing multiple parts simultaneously and its detailing capability. Thus, for upscale production and high accuracy components DED might not be preferable. [8]

Two of the most popular DED methods are: Laser Engineering Net Shaping (LENS) and Electron Beam Additive Manufacturing (EBAM). LENS uses powder feedstock and a laser as thermal source, while EBAM uses wire feedstock and an electron beam. LENS technology is supplied by Optomec and EBAM by Sciaky. The two types of thermal sources require different work environments. Advantages of using wire instead of powder are both the deposition rate and cost reduction. Metal powder is about twice as expensive as wire, but yields a higher accuracy, smoother surface finish and lower residual stress [2, 9].

Table 2.1: Specifications on the different technologies print capabilities. The data is for a single component, in this case a 125 mm cube. Table data taken from Wohlers Report 2016 [2].

	DMLS	**SLM**	**EBM**	**LENS**
Company	EOS	SLM Solutions	Arcam	Optomec
Key process time†	1-2 days	1-3 days	12 hours	<1 day
Materials‡	TS, SS, CC, TA, NA, Al	TA, TS, SS, Al, CC	TA, CC	TS, SS, TA
Density range	$\sim$ 100%	$>$ 99%	100%	$>$ 99%
Detailing Capability (mm)	0.3	<0.1	0.25	0.5
Accuracy (mm)	0.02-0.05	0.05	0.2	0.125
Surface Finish R_a (µm)	9	<10	10-20	12-25
Printers	EOS M 100, EOS M 290*, EOS M 400	SLM 125, SLM 280 2.0*, SLM 500	Q10plus*, Q20plus, A2x	LENS 450, LENS MR-7, LENS-R

† Time for producing a single 125 mm cube, material non-specific.
‡ Tool Steel (TS), Stainless Steel (SS), Cobalt Chrome alloy (CC), Titanium alloy (TA), Nickel alloy (NA), Aluminum (Al). Material properties of finished parts are for all methods comparable or equivalent to the base material.
* Further information about these printers is found in Table 2.2.

Table 2.2: Specifications of similar PBF Machines from EOS, SLM Solutions and Arcam. [3, 4, 5]

	EOS M 290	SLM 280 2.0	Q10plus
Build volume (mm^3)	$250 \times 250 \times 325$	$280 \times 280 \times 365$	$200 \times 200 \times 180$
Laser/Beam Power	400 W	1000 W †	3000 W
Min. beam diameter	100 µm	80 µm	140 µm
Cost‡	$594 000	$557 000	$700 000

† 1000 W is the maximum, but SLM Solutions also provides 400 W, 700 W as well as dual laser combinations of these combined.
‡ All costs are estimations from [2].

2.1.2 Post-processing for Metal AM

All treatments of the component that occur from the time that the build is complete until the time the part is ready for its intended use are called post-processes. Post-processing is a critical aspect of metal AM and often equally or more important than the actual print. Following is a summation of post-processing procedures and its consequences as described in [2].

Before printing it is necessary to identify the surface areas of the product that need extensive surface finish. To compensate for the material that will be removed during surface treatment extra material should be added to the CAD model in these areas. Keep in mind also that prints using PBF methods have a thin outer layer of half sintered powder due to the surrounding powder melting from the heat of the newly printed part. Before printing it is also necessary to determine the support structure. Support structure is needed in the first couple of layers to anchor the product to the base plate and under all unsupported layers that follow. Due to thermal stress the product can bend and cause it to pull away from the support material if the support structure is not correctly placed. This problem is especially frequent using laser-based systems.

After the build is completed, the excess metal powder surrounding the finished part must be removed. If not removed the powder will likely interfere with the post-processing. Furthermore, the powder is recyclable, so it is profitable both economically and environmentally to collect it. The process of removing the powder often involves brushes and other hand tools. If the powder does not brush off abrasive blasting can be used. In some cases compressed air or ultrasonic equipment is used to remove powder from complex internal structures. Because of the exposure of heat the powders average grain size is slightly increased after each print. After the powder is collected it may therefore need to undergo treatment before being used again.

Once all powder is removed the part undergoes post-thermal processes. The heat treatment is usually used to relieve residual stress and impart better mechanical properties. Heat treatment is especially needed for AM due to the layer-wise printing. Without heat treatment bonds between layers are much weaker. Which heat treatment is most suitable depends on the product. A common heat treatment might include the following three steps: Firstly, stress relief by heating the component below the lower critical temperature and thereafter cooling uniformly. Secondly, reduction of porosity by hot isostatic pressing (HIP). Lastly, hardening and increased yield strength is achieved through precipitation hardening.

The component is typically removed from the build plate after the first stress relieving heat treatment. A common method of removal is wire Electrical Discharge Machining (EDM). In wire EDM the part is cut of the build area by running high voltage trough a metal wire. The resistance in the wire combined with the high voltage heats the wire enough to melt and cut through the support structure. Before continuing the heat treatment additional support structures are removed with traditional machining techniques. This can be done by hand for rough removal or more precisely with an automated machine tooling device, also known as Computer Numerical Control (CNC).

Now that the product has the right shape and mechanical properties, all that is left is the surface treatment. Without surface treatment, the surface finish of metal AM components is very rough. The demand of good surface finish depends on the application. Not all products need good surface finish. If needed, there are a large variety of both mechanical and chemical alternatives. Except for general machining, the method of shot-peening is probably of most relevance. Shot-peening smooths out the rough surface of the product by shooting round metal pebbles at it with sufficient force to produce plastic deformation. The technique is similar to sandblasting, with the difference of achieving surface finish through plastic deformation and not through abrasion. Besides surface smoothing the plastic deformation from shot-peening also creates a compressive stress in the surface preventing cracks from propagating in the material.

2.1.3 Materials

As recently stated, the injector yoke requires a hard, stiff and inexpensive material. The stainless steel 316 and the tool steel H13 were suggested by the industrial partner. Other materials used in AM are, but are not excluded to, cobalt chrome alloys, titanium alloys, nickel alloys and aluminum. As a reference, the current injector yoke is made of sintered steel. It has a density of about $7200\,\mathrm{kg\,m^{-3}}$ and a hardness of more than 400 HV. The following materials are stainless or tool steels manufactured by EOS. Material properties of the powders were measured after printing in a EOS M 290. Because of the layer-wise build that material has different properties vertically and horizontally.

2.1.3.1 EOS Maraging Steel MS1

A martensite-hardenable tool steel with excellent strength combined with high toughness. At 8000 kg m^{-3} it is slightly heavier than the original yoke. The parts are easily machinable and can be post-hardened to more then 50 HRC. Suggested heat treatment consists of solution treatment at 940 °C for 2 hours, followed by aging at 490 °C for 6 hours. After treatment the material has an ultimate tensile strength of 2080 MPa, both horizontally and vertically, and a horizontal as well as a vertical yield strength of 2010 MPa and 2000 MPa respectively, meaning it is an exceptionally brittle material. The fracture elongation is 4% in both directions. After shot-peening surface roughness is typically Ra 4-6.5 µm [10].

2.1.3.2 EOS Stainless Steel 316L

The 316L Stainless Steel is an iron-based alloy that is characterized by a high ductility and corrosion resistance, which is also heavier than the original, with a density of 7900 kg/m^3. The finished product has a horizontal and vertical ultimate tensile strength of 640 MPa and 540 MPa, respectively, as well as a horizontal and vertical yield strength of 530 MPa and 470 MPa, respectively. Fracture elongation is 40% horizontally and 50% vertically, i.e. a much more elastic material than the Maraging Steel MS1. The material's hardness is pretty low at 89 HRB. The material does, however, not need extensive heat treatment, simple stress relief is enough, according to [11].

2.1.3.3 EOS Stainless Steel PH1

A stainless steel with excellent mechanical properties, such as good corrosion resistance as well as high hardness and strength. PH1 has a density of 7700 kg m^{-3} and can be hardened up to 45 HRC. Post hardening, the finished product has a horizontal and vertical tensile strength of 1450 MPa and 1440 MPa respectively, as well as a horizontal and vertical yield strength of 1350 MPa and 1300 MPa, respectively. Elongation to break typically occurs at 15% horizontally and 13% vertically. [12]

2.2 Structural Design Optimization

SDO is a tool used to optimize the design of mechanical structures. The definition of optimal may well be subjective but often refers to minimizing the weight or maximizing stiffness of the structure. In the process of optimization, the boundary conditions must be taken into consideration. Such conditions can be the geometry

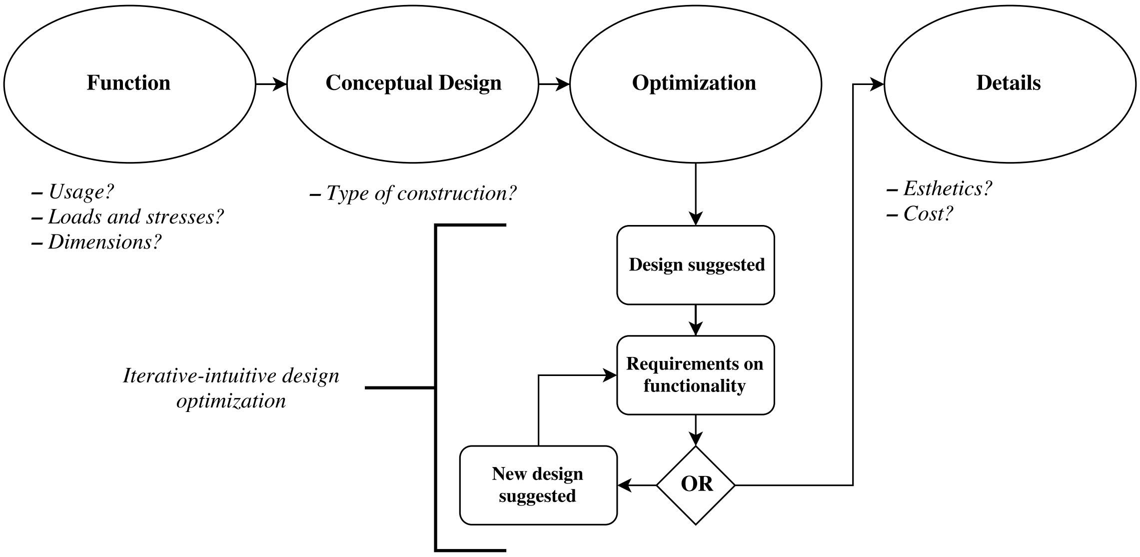

Figure 2.3: A flowchart illustrating the steps in the structural design process.

of the structure or the stress and load on the structure. A problem without these conditions has no well defined solutions. Further details can be found in [13, 14].

The optimization is usually quantitative and mathematically defined, resulting in *optimal* being the minimum or maximum of a function, referred to as the objective function. However, parameters such as cost, aesthetics, and functionality also often play a role in the design process, see Figure 2.3, which according to Kirsch, Christensen and Klarbring [13, 14] can be divided into four steps:

- Functionality
- Conceptual design
- Optimization
- Detailed design

The functionality serves to answer the purpose of the construction and the basic specifications it must fulfill. The conceptual design focuses on what type of construction that would be suitable to achieve the predefined specifications. The optimization is often performed using an iterative-intuitive method. Meaning that a new design is suggested iteratively until the design meets the functional requirements. Thereafter, details of the design are assessed. For a visual representation of the iteration see the optimization step of the design process in Figure 2.3.

To formulate a problem mathematically, the optimization criterion must be expressed as an objective function $f(\mathbf{x})$, where $\mathbf{x}$ is a design vector, a set of design parameters, which can be changed. Also, the response of the structure, $\mathbf{p}(\mathbf{x})$, which for a mechanical structure could be stress or displacement, and constraints must be introduced. There are two types of constraints – inequality and equality constraints – with the aforementioned dealing with the design requirements, for example the total mass of structure and the latter equilibrium constraints. Thus a general structural optimization problem, as stated by Christensen et al. [13], can be expressed as:

$$\mathbb{SDO}:\begin{cases}\text{Minimize:} & f(\mathbf{x},\mathbf{p}) \qquad\qquad \text{Objective function}\\ \text{Subject to:} & \begin{cases}\mathbf{g}(\mathbf{x},\mathbf{p})\le 0 & \text{Inequality constraints}\\ \mathbf{h}(\mathbf{x},\mathbf{p})=0 & \text{Equality constraints.}\end{cases}\end{cases}$$

One mainly deals with three categories of structural design optimization methods. *Size optimization*, *shape optimization* and *topology optimization*, respectively.

- **Size optimization:** The most primitive form of optimization. The overall structure remains the same but changes the size variables such as thickness or dimensions of cross sections in order to find the optimal design of the structure.

- **Shape optimization:** more general than size optimization, yet the topology is unchanged, thus no new holes can be introduced in the design. Typically used to minimize stress concentrations and achieve stress homogenization over a surface.

- **Topology optimization:** is the most general form of optimization and serves to find the optimal layout given a certain design domain Ω and specific boundary conditions. Both the locations and geometry of holes as well as the boundaries of the structure are computed.

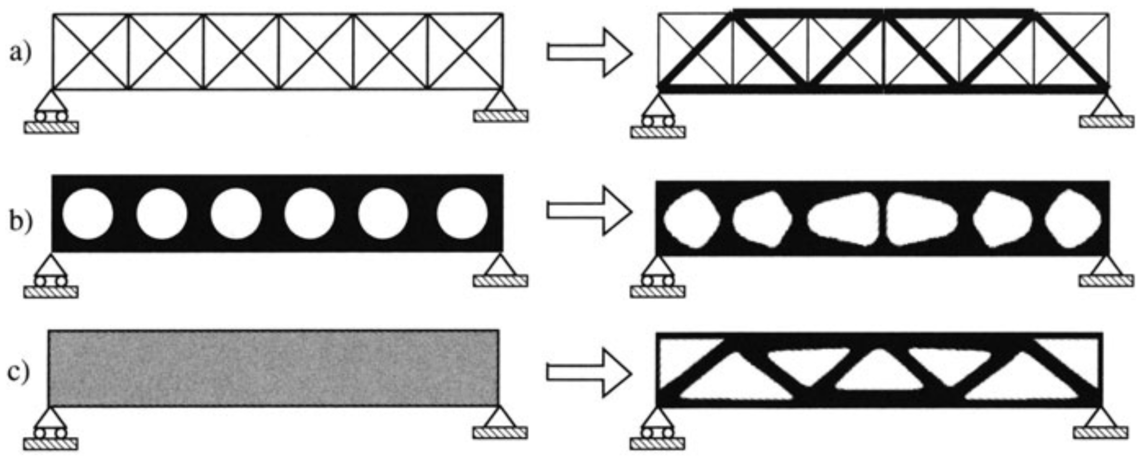

Figure 2.4: Illustration of the three structural optimization methods. a) Size optimization, b) shape optimization and c) topology optimization. Figure taken from Bendsøe & Sigmund [1].

While topology optimization (TO) might be the most challenging method, it is often the most rewarding. This type of optimization has the greatest ability to decrease the mass needed in the part [13]. This can lead to significant improvements in cost and print time. For a schematic representation of the methods see Figure 2.4.

2.3 The Volvo Group's Supply Chain

The Volvo Group has just over 5 000 suppliers and over 300 dealers worldwide [15]. For each of Volvo Group's 600 000 products there is a contract with a supplier which states various agreements concerning an order. Among other things, this agreement states the price, the manufacturing time and the minimum order quantity. For low frequency products minimum order quantity has a high impact on logistical costs. After the products are manufactured they enter the storage and distribution system. The storage can be broken down into four different types of units. The Central Distribution Centers (CDC), the Regional Distribution Centers (RDC), the Support Distribution Centers (SDC) and lastly the dealers [15], see Figure 2.5.

The deliveries of parts, or the distribution chain, are categorized into *day orders* and *stock orders*. Day orders are parts that the dealers can supply to their customers within 24 hours from the moment the order is placed. The stock orders take up to eight weeks or longer to deliver. About 94% of all deliveries are day orders [15]. The supply chain is well adapted to the day orders, since these are fairly frequent and possible to foresee. The products are stored systematically between the six CDC, 30 RDC, 10 SDC as well as at the dealers [15]. If the dealer does not have the product in stock they order it from their local RDC or SDC. If the stock in the RDC or the SDC is running low they place an order to the CDC. If the CDC do not have them in stock they contact the supplier.

The lead time between ordering a shipping from the suppliers, until it arrives in a CDC, is usually eight weeks [15]. Because stock orders are not frequent, they are not foreseeable and therefore it is not possible to systematically stock up on products in the distribution centers beforehand. There are articles with order frequencies as low as once every other year. If a low frequency product is order while out of stock, the whole chain, from supplier to dealer, has to been gone through. The lead time of around 8 weeks can be a big loss for the customer. Also, as mentioned before, the supplier has a minimum order quantity. Meaning the Volvo Group has no choice but to order the minimum order quantity even if they only need a single unit. Minimum quantity orders may be 100 units, meaning the rest of the 99 units will be placed on a shelf in a CDC until the next order arrives. This means a loss of resources for handling and storing. On top of that, it is required for companies to pay taxes for inventoried resources. For articles with such low frequencies, these unsold units can cost a lot of money just lying on a shelf. Ultimately these unsold units usually end up being sold for scrap metal, which is a huge loss, both economically and environmentally [15].

The current sintered yoke is purchased from Eliasson & Lund AB for 166.25 SEK

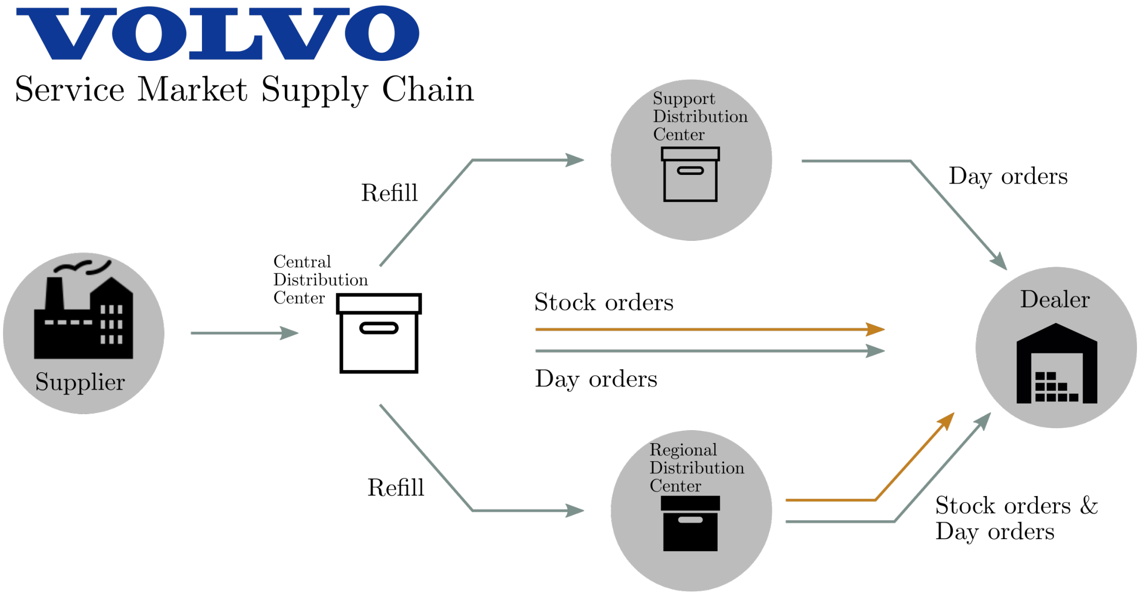

Figure 2.5: A flowchart of the supply chain within the Volvo Group. The chart is a description of how most products are distributed. The figure illustrates the distribution the day and stock orders, originating from the suppliers, and the distribution through the central distribution centers (CDC), the regional distribution centers (RDC) and the support distribution centers (SDC), before finally making it to the dealers.

($\sim$ 19.5 USD) per unit [16]. The minimum order quantity is 100 units per order and the Volvo Group acquires between 500 and 600 units a year [17]. In Table 2.3 a cost division for the yoke is presented, as of year 2017. If AM is implemented the costs in bold could be reduced to zero. These cost reductions summarize to 10.5 SEK ($\sim$ 1.2 USD) per unit. In time, demand will become lower, raising purchase price and individual shipping costs.

2.4 The Future of AM

A brief summation of the AM industry's growth rate is here presented as a hint on how the industry can be expected to be in the future. In Table 2.4 annual machine sales and overall industrial revenue can be found in the years 2009-2015. The numbers show a clear trend of increasing sales and revenue. Several years revenue increases by 50% or more, implying a large exponential growth.

The AM industry is today quite mature for rapid prototyping and is moving fast towards production and manufacturing. Already we see a wide spread of desktop 3D-printers for plastic prototyping. The explosion of cheap desktop printers came in 2009 after the patent for Fused Deposition Modeling expired [18]. Without the restrictions of the patent, competition in the market created a so called "race to the

Table 2.3: An estimation of the division of cost for 573 units of the current injector yoke PN 469797. All prices are in SEK and are calculated for the CDC in Gent for the year 2017. Costs in bold text will be reduced to zero if the yoke is produced using AM. They summarize to a total of 6 536 SEK ($\sim$ 771 USD), which is about 10.5 SEK ($\sim$ 1.2 USD) per unit. The data was provided by Cilla Zachau and Tomas Göransson from the Volvo Group's logistics department FOIP on March 16, 2018.

ID	VTB-VO-469797
Part No	PN469797
Qty out	573 units
Cost per year	19467
Capital Cost per year	**880**
DIM/Refill cost per year	1436
Goods In cost per year	1941
Goods Out cost per year	4259
Inbound transport cost per year	**3128**
Overhead Warehouse cost per year	**527**
Order Office cost per year	294
Packaging cost per year	2176
Procurement cost per year	**1428**
Scrap and Obsolescence Cost per year	737
Warehouse Building Cost per year	**573**
Development and other OH Cost per year	2090
Gent Surcharge cost	19830
Brand Specific Gent Surcharge cost	19114
Value Out per year	104819

bottom". Companies like MakerBot paved the way and prices fell to less than a tenth of what they previously cost. Because of this, almost all educational institutions, as well as several home enthusiasts, own desktop 3D-printers today. History often repeats itself, and when the patents for current Metal AM methods and materials expire, one could expect a burst of new competitive technology, hopefully lowering costs substantially. Also, as AM becomes cheaper a snowball effect can be expected. The cheaper it is to buy printing systems and material, the more products can be expected to be produced, lowering cost per product.

Metal AM faces a number of challenges not directly correlated to technology, the main challenge being cost. Not only must AM become cheaper, but also cost estimation must become justifiable. When estimating cost and building a business case for switching manufacturing process to AM, the cost of producing in AM is often only compared to the traditional manufacturing cost. Cases like these almost always show favor towards traditional manufacturing. In order to find cases where AM truly is favorable one must look at the entire picture. Correct cost justification involves regard to reduced tooling, quick design changes, decentralized manufacturing, reduction of inventory, part consolidation etc.

Even professional AM companies estimate cost with large differences. The Volvo Group recently reached out to over a dozen companies and asked for quotes on a couple of their products. The estimated production cost varied a lot depending on the manufacturer. For example, a simple elbow nipple in 316L stainless steel, got seven quotes ranging from 470 SEK to 5900 SEK [19].

Another big challenge Metal AM faces is quality assurance. Products with high performance required rigorous and consistent quality control. From high regulations it follows that certifying new designs risk being both time consuming and expensive. Especially because Metal AM suffers from lack of consistent data [2]. The problem at hand is a consequence of the fact that two identical prints do not necessarily have the exact same properties. For a complete quality assurance a very thorough control is required, thereby making it expensive. A simple way to solve this problem, for products without sensitive weight restrictions, is to add enough mass in crucial areas to assure guaranteed performance. With the future development of AM regulations might change and new standards for quality control could be adapted, making quality assurance less problematic.

The global manufacturing economy is said to be about 12.8 trillion USD [2]. The day that AM becomes economically profitable it will completely change the industry and the companies at its forefront will reap the benefits. Hopefully, the replacement of subtractive manufacturing with additive manufacturing will also reduce resource consumption and make global industrial manufacturing more environmentally friendly.

Table 2.4: Total revenue for Metal AM between the years 2009-2015, as well as Metal AM material sales and Metal AM machines sold. Lastly Metal AM machines sold for companies of interest are stated. The machines sold for EOS include all there products, i.e. including machines for plastic. Revenue and sales are stated in million USD. [2]

	2009	2010	2011	2012	2013	2014	2015
Total Metal AM Revenue:	12	13.5	18	24.9	32.6	48.7	88.1
Metal AM Material Sales†:	25.0	30.6	37.6	48.0	56.8	73.6	88.4
Metal AM Machines Sold:	125	135	177	202	353	550	808
by Arcam:	11	14	14	24	27	42	60
by EOS‡:	72	89	137	145	201	284	370
by SLM:	-	-	10	21	30	62	102

† In 2015 Metal AM stood for 11.5% of all material sales. The sales stated are estimated as 11.5% of the total material sales. [2].
‡ Total machines sold for EOS, including plastic.

3

Method

This chapter describes the evaluation process (3.1), and the structural design optimization (3.2), of the original component. Subsequently, the design process of generating new concepts (3.3) and the evaluation processes finite element analysis (3.4), concept selection (3.5) and shape optimization (SO) (3.6) are described.

3.1 Analysis of Existing Component

Primarily, a thorough analysis of the existing component PN 469797, and previous break load tests performed by the Volvo Group, was made to identify the constraints and boundary conditions. The main focus was on identifying how the yoke is mounted in order to clarify where the load is applied and distributed, how the component is supported and which surfaces that have to remain unchanged to ensure the mountability of the redesigned part.

The purpose of the yoke is to apply a load on the injector to ensure that it has a proper seal. It is mounted on the motor with a bolt, resting on the bottom of the forks and the back of the yoke, this is illustrated in Figure 3.1. The bolt and the injector also contributes with support, preventing the yoke to move in horizontal direction, this is illustrated in Figure 3.2. All of the reaction forces are simulated as frictionless supports.

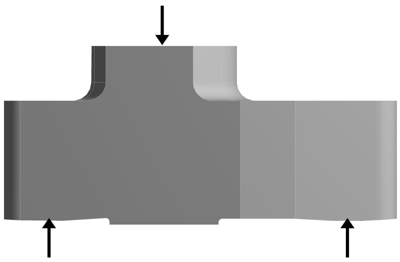

Figure 3.1: The downwards facing arrow represents the load from the bolt and the upwards facing arrows represent the reaction forces from the contact surfaces.

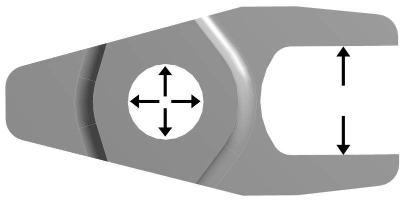

Figure 3.2: Reaction forces from the bolt and the injector, preventing horizontal movement.

3.2 Topology Optimization of Existing Component

To obtain a new, optimized design of the component the first step was a topology optimization. Boundary conditions were established, a target volume set and an exclusion region decided. Then, a mesh with an element size of 1 mm was generated and stresses were calculated for each element, respectively. The elements with the lowest strain energy, in respect to each other, were removed. This process was made for three different target volumes, 25%, 50% and 75% of the initial design. Since the software removes entire elements the resulting model from the TO could not be extracted and used directly for redesign. Instead, the result was used as a guidance and inspiration for the new conceptual designs.

3.3 Concept Generation

The process of modeling a conceptual design for the optimized yoke was based on the result from the TO described in Section 3.2. The result was used as an inspiration and several suggestions of concepts were generated and quickly sketched. The concepts were roughly evaluated and the concepts that was expected to not reach the criteria were dismissed. The remaining concepts were drawn in CATIA V5.8[1] and evaluated in ANSYS R18.2[2] in an iterative process. The first suggestion of each concept were analyzed in ANSYS whereafter minor changes in design, such as radii, thickness of arches and angles, were made to achieve a strong structure and

[1]Software from Dassault Systèmes, more information found on `www.3ds.com`.
[2]Software from ANSYS, Inc., more information found on `www.ansys.com`.

therefore, better meet the specifications.

3.4 Finite Element Analysis of Concepts

With Finite Element Analysis (FEA) several calculations were conducted in ANSYS, using the constraints identified in the analysis of the existing component, see Section 3.1. The bottom of the forks and rear of the yoke, as well as the inside of the bolt hole and the inner sides of the forks, were simulated using frictionless supports. The load was set as an evenly distributed force on the top of the yoke, on the area that is in contact with the bolt.

A nonlinear analysis, allowing yielding, was made using properties for stainless steel, yield strength of 360 MPa and ultimate tensile strength of 650 MPa. To simulate the real environment as closely as possible temperature was set to 120 °C and the applied load was ramped, from 0 MPa to 50 kN and then unloaded to 40 kN, simulating the actual mounting procedure of the yoke. The element size of the mesh was set to 10^{-3}m and a refinement was applied in areas expected to reach a high stress. In the FEA, the total deformation, equivalent von Mises stress and the size and level of the plastic zones were studied.

3.5 Concept Selection

To choose the best design for the optimized yoke all of the different concepts were evaluated in performance; if the stress levels were beneath yield strength, if the deformation was negligible, less than 0.80 mm, and if the plastic zones could be considered as small, in other words, concentrated to the areas close to the stress concentrations. The data, used for the evaluation, was made from simulations in ANSYS using the method described in Section 3.4. The concepts that did not reach the criterion for stress response were neglected.

The designs that performed well in the first simulation were compared to each other in aspects of more specific customer needs, as mentioned in Section 1.2.1. The comparison was made using the Pugh Concept Selection method. In the method a Pugh matrix is made using one of the concepts as a reference, while the others are compared to it and graded as better (+1), equal (0) or worse (-1). The concept with the highest total score is chosen as the new reference in a second iteration of Pugh matrices. This process is then repeated until it converges and the best concept is found [20].

3.6 Shape Optimization

To improve the chosen design further, shape optimization was made in ANSYS. The maximal stress and the body volume were set as parameters, as well as four different radii, the three radii in the triangular hole and the radii on the bottom of the forks. A span was set for each parameter and the program tried combinations of the different values within the spans, calculating the maximal stress for each combination of values. The result was analyzed and the combination of parameters that gave the lowest maximal stress were chosen, whereafter a new, full analysis was made with the new dimensions. The final validation was made with the new dimensions, chosen from the TO. The same boundary conditions and loads as in previous calculations were used.

4
Results

This chapter presents the outcome of the method from the previous chapter. Firstly, the results of the topology optimization are presented (4.1) and then the concept designs are shown (4.2), which originated from the results of the TO. Thereafter, the design concepts are evaluated using finite element analysis (4.3) and a final concept is chosen (4.4). Lastly, the results regarding printing and manufacturing are presented (4.6).

4.1 Topology Optimization

The preliminary analysis through finite element analysis made on the original component PN 469797 resulted in a datum for the topology optimization. The FEA result of the stress analysis is shown in Figure 4.1. As mentioned in Section 3.2, the TO was set for retaining three different target mass reduction, 25%, 50% and 75%, respectively. The results of the TO are shown in Figure 4.2, 4.3 and 4.4.

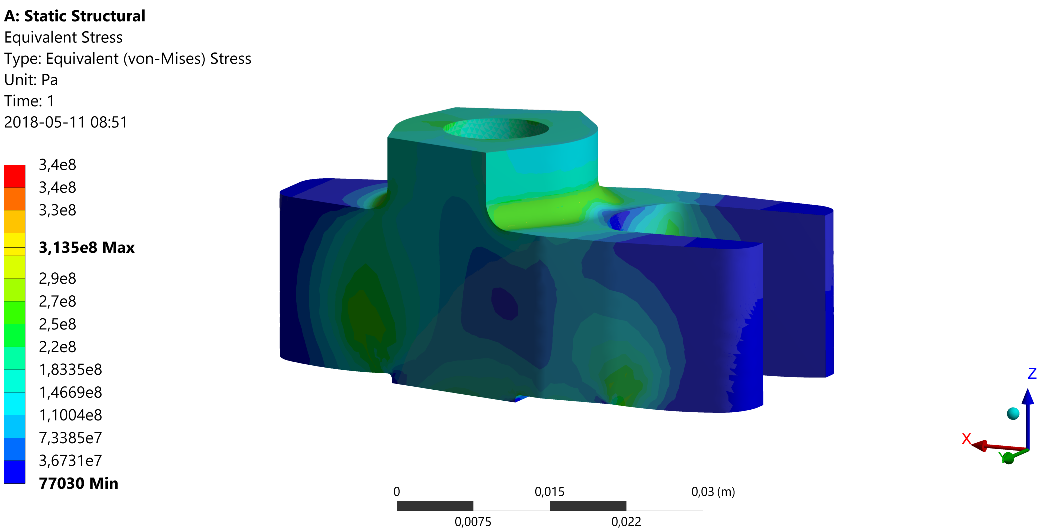

Figure 4.1: Result of the finite element analysis (FEA) using of the original yoke PN 469797 and the aforementioned loading conditions, see Section 3.1.

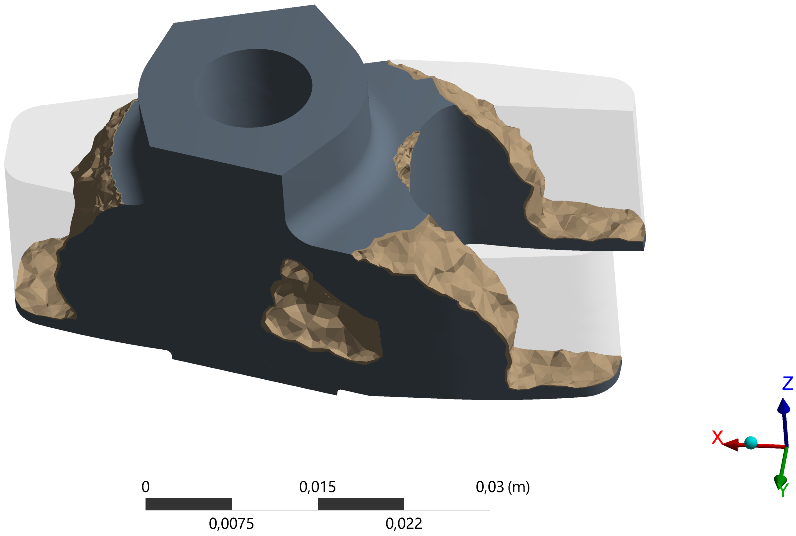

Figure 4.2: Result of the topology optimization (TO) with a mass reduction of 25%. Notice that the TO firstly removes almost all material from the forks and the back.

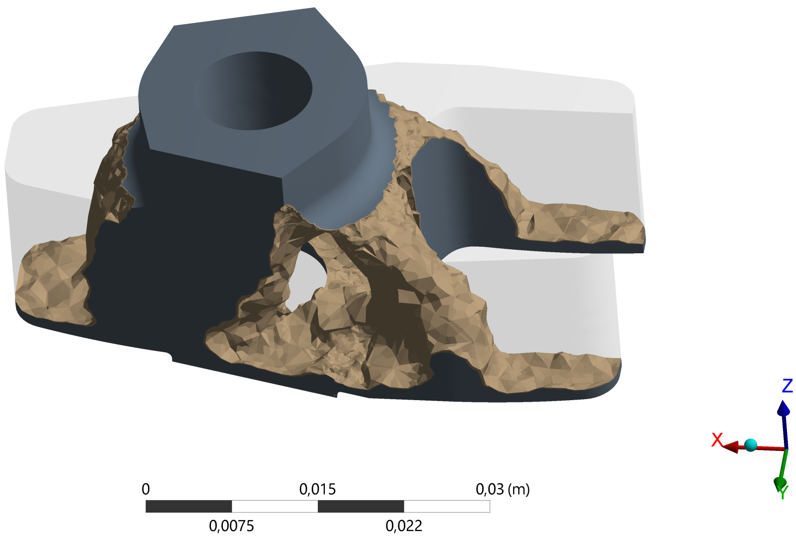

Figure 4.3: Result of the topology optimization (TO) with a mass reduction of 50%. At this point the TO mostly removes material from the sides, creating a hole through the yoke crossing the bolt hole.

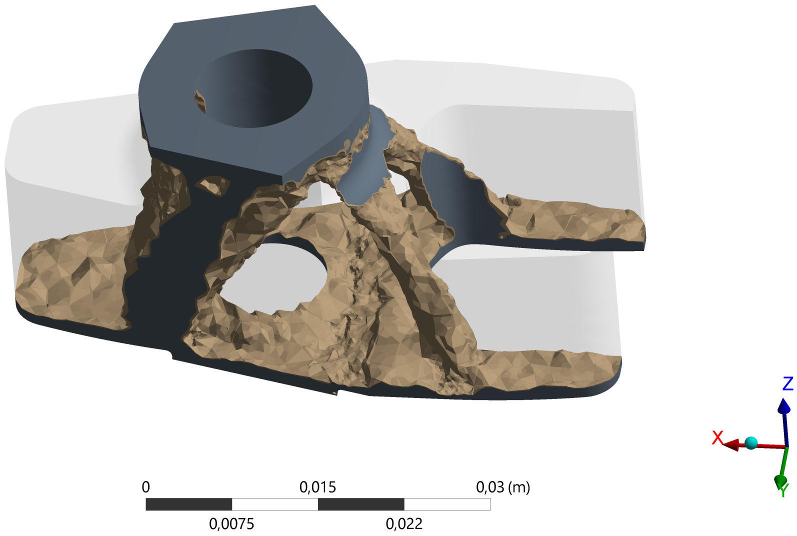

Figure 4.4: Result of the topology optimization (TO) with a mass reduction of 75%. With this much mass removed it becomes clear that the core support is located behind the bolt hole

4.2 Concept Design

Six different conceptual designs were modeled in CATIA and evaluated in ANSYS. The first concept (C1), shown in Figure 4.5, reduced the body volume with 20%. C1 was influenced by the large removal of mass from the forks in the TO by hollowing out two holes and creating two arches. The TO's removal of mass from the back inspired the round off of the yoke. Also, the hole through the yoke created in the TO is mimicked. Evaluation in ANSYS showed large stress concentrations in the upper radii of the arches of the forks due to the small radii. In the back of the yoke the stress levels remained relatively low and it was concluded that more material could be removed. This led to the second concept (C2), shown in Figure 4.6. The front arches were made thicker and the radii were increased. The volume was reduced by 24%, compared to the original yoke. A nonlinear analysis was made, resulting in lower, more reasonable stress levels than for C1. The nonlinear analysis also showed plastic deformation in the bottom surface of the yoke. This plastic deformation was relatively small, compared to the fracture elongation for stainless steel, see Section 2.1.3, therefore considered to have very little impact on the performance of the yoke. The evaluation of C2 showed that the the maximal stresses occurred in the bottom plate.

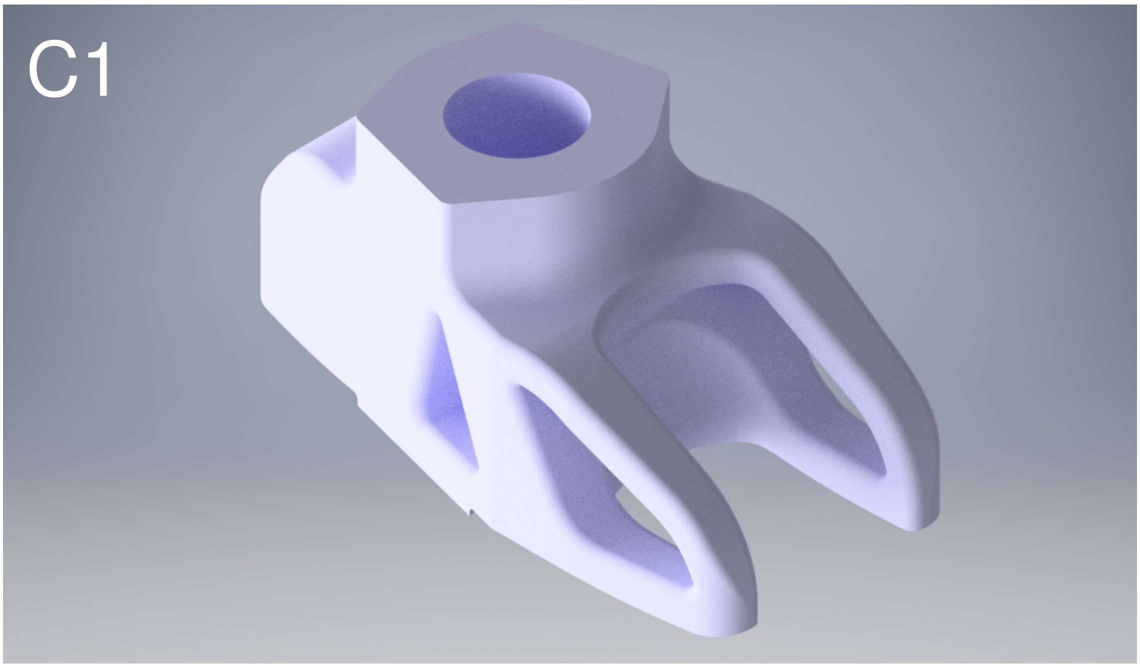

Figure 4.5: Three-dimensional view of concept one (C1). Notice that the forks has been hollowed out, creating arches. With inspiration from the topology optimization, a hole through the yoke has been made and the back of the yoke has been slimmed down.

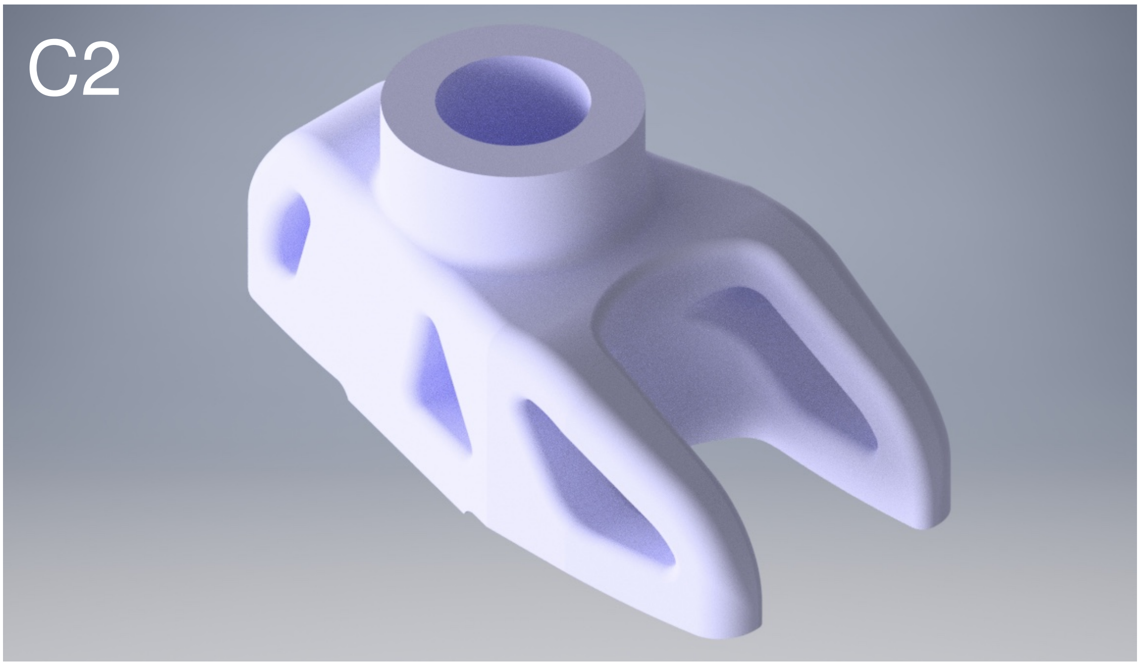

Figure 4.6: Three-dimensional view of concept two (C2). Inspired by C1, but the arches are made thicker and a hole has been made in the back of the yoke. The top of the yoke has been optimized to the size of the bolt head.

The third concept (C3) was generated by removing material from the sides of the yoke. C3 is shown in Figure 4.7 and has a volume reduction of 30%, compared to the original. The nonlinear analysis resulted in stress concentrations in the same areas as for C2, although considerably larger, above yield strength.

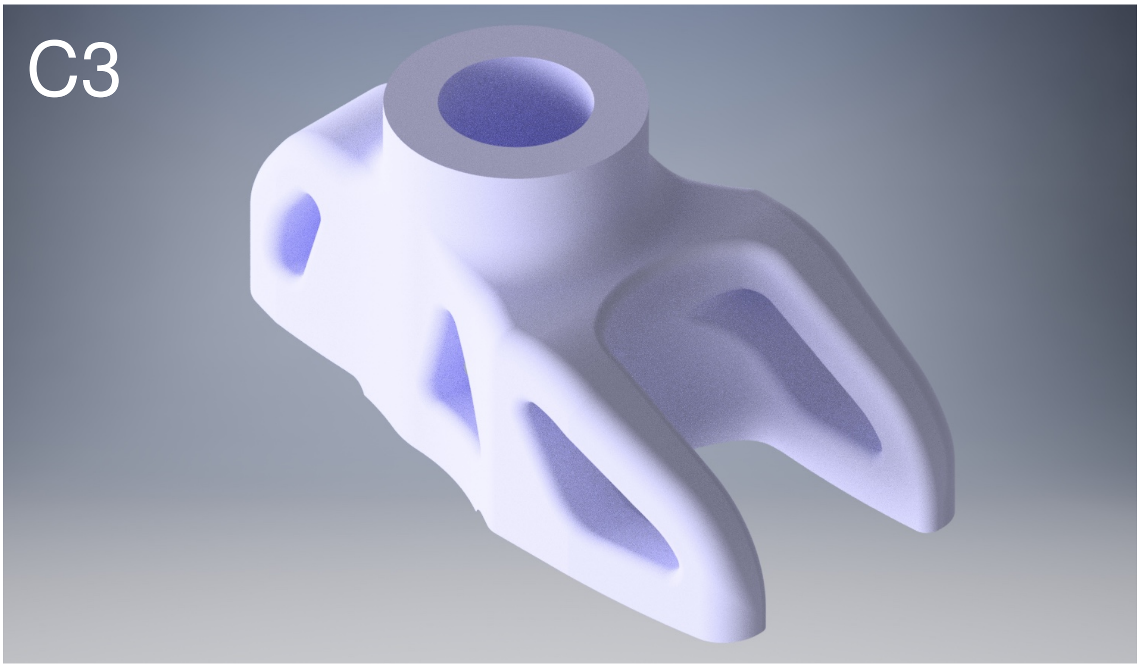

Figure 4.7: Three-dimensional view of concept three (C3). Material has been removed from the sides of the yoke, resulting in a slimmer version of C2.

In the fourth concept (C4) the base plate was allowed to be modified. The TO used as inspiration is presented in Apendix A. The constraints of the base plate were chosen with regards to the applied loads in the specification of the test rig, used in the break load tests. In other words, all free surfaces, meaning surfaces not affected by vertical reaction forces, were allowed to be removed. The topology optimization, see Appendix A, removed material in the bottom of the yoke around the bolt hole. This TO inspired the design of concept four (C4), shown in Figure 4.8. From analysis in ANSYS, high stress concentrations where found in the bottom inner radii where material was removed. The nonlinear analysis also showed plasticity in the same region. The largest deformation appeared in the forks which are supposed to keep the injector in place and the deformation can therefore be problematic if it results in inferior grip.

Concept five (C5), shown in Figure 4.9, is very similar to the result from the TO 4.3. The height of the part as well as the bottom plate were retained. The design is very simple and the idea behind it is to minimize stress concentrations by eliminating as many small radii as possible. The ANSYS simulation had the same constraints as for C1 was used and the results both showed reasonable stress levels and deformations.

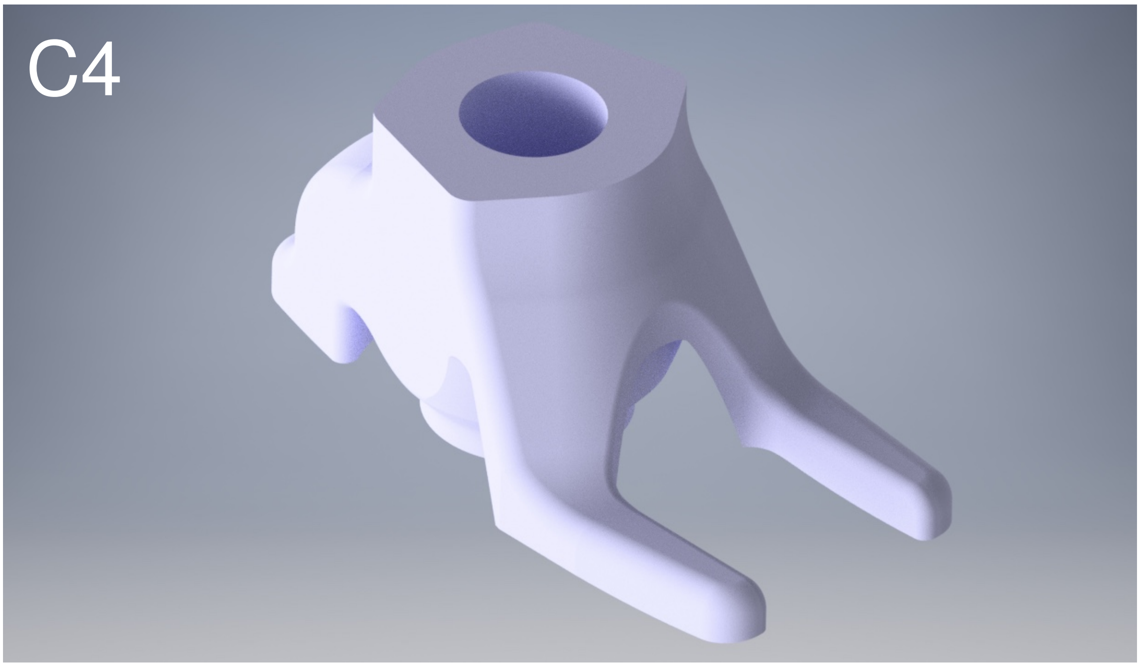

Figure 4.8: Three-dimensional view of concept four (C4). Material has been removed from the bottom of the yoke, still the contact surfaces are maintained. This design was inspired by the TO found in appendix A.

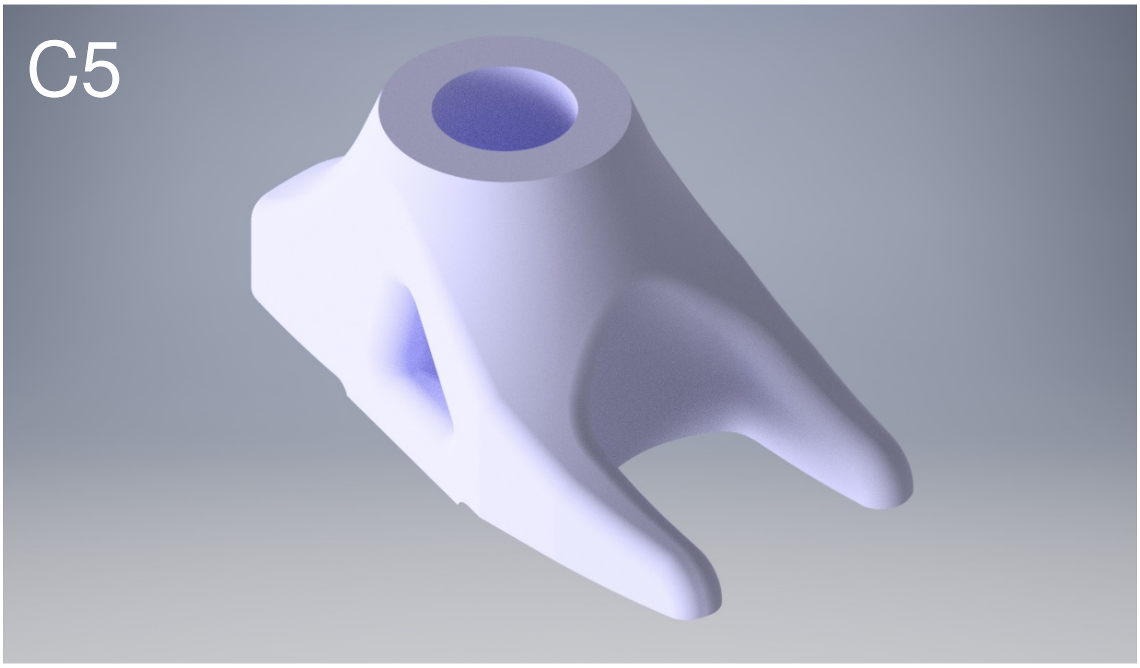

Figure 4.9: Three-dimensional view of concept five (C5). With inspiration from the topology optimizations, the back as well as the forks has been slimmed down and a hole has been made through the yoke. The streamlined geometry of the yoke minimizes the amount of small radii, and therefore minimizes stress concentrations.

The sixth concept (C6) is a tapered version of C5, identically to the way C3 is a tapered version of C2 by removing material on the sides of the yoke, where the stresses are low. The design of C6 is shown in Figure 4.10 and the volume was reduced by approximately 31%. The simulation in ANSYS, using the same loads and constraints as in previous simulations, resulted in stress levels below yield strength everywhere except in small areas in the radii in the bottom of the yoke. However, the plastic area is, however, too small to negatively affect the performance of the yoke substantially.

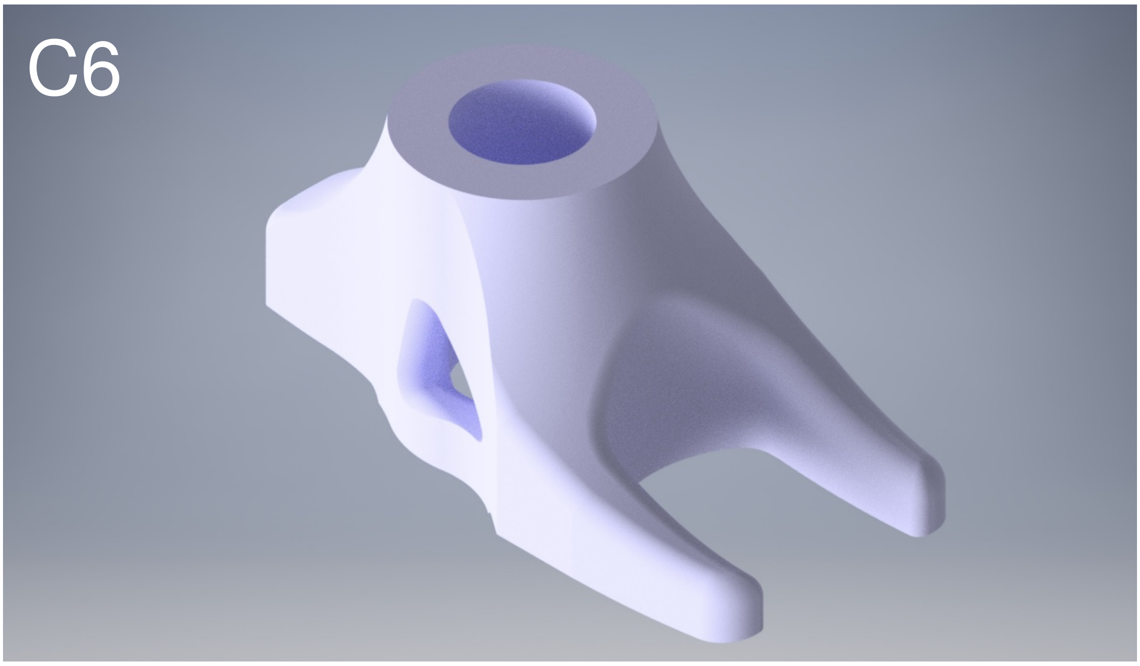

Figure 4.10: Three-dimensional view of concept six (C6). Material has been removed from the sides of the yoke, resulting in a slimmer version of C5

4.3 Evaluation and Selection of Concepts

In this section the results from the finite element analyses and the concept decisions are presented with the purpose to ensure that the chosen concept inherits the most suitable design for the purpose.

4.3.1 Finite Element Analysis of Concepts

Finite element analyses were made in ANSYS for all of the generated designs. The analysis of C1, shown in Figure 4.11, shows high von-Mises stresses, over the yield strength, in the arches of the forks, stresses above yield strength. Stress concentrations also appeared in the bottom surface of the yoke and the plastic zones were too large to be disregarded.

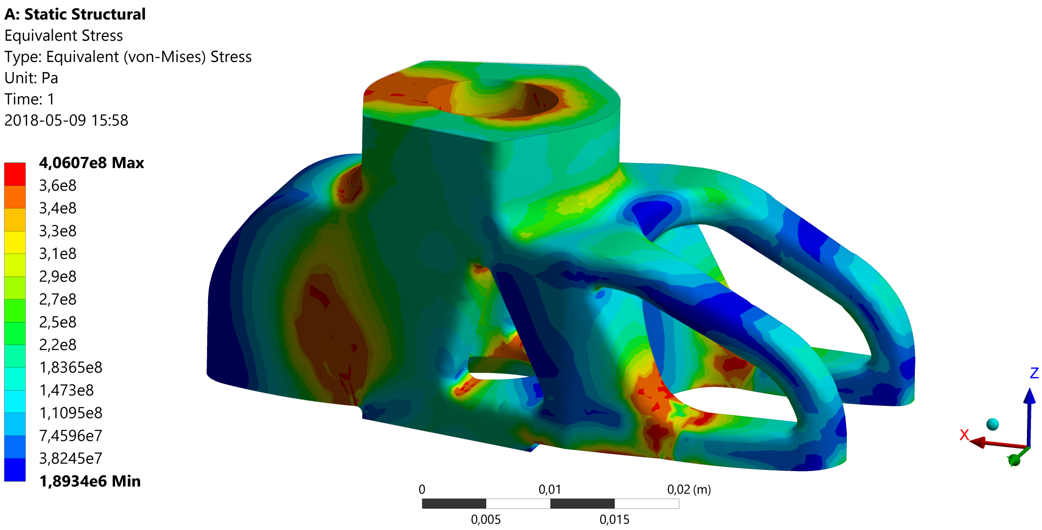

Figure 4.11: The von Mises stress field in C1. High stress levels occur in the forks and the back due to the slim arches

For C2 the arches experienced lower stress levels due to the increased thickness, see Figure 4.12. The main part of the structure experienced stress below the yield strength and small plastic zones appeared solely in the bottom surface.

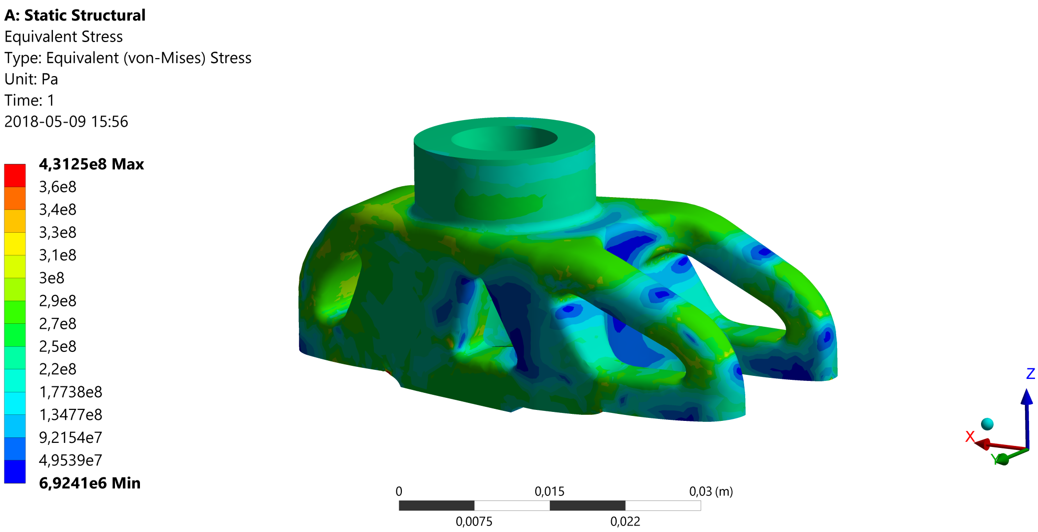

Figure 4.12: The von Mises stress field in C2. Thicker arches distribute the stresses more evenly.

The outcome of the analysis of C3 was very similar to the outcome of C2. Only in small areas in the radii in the bottom of the yoke, the stress exceeded the yield strength, resulting in small, negligible plastic zones.

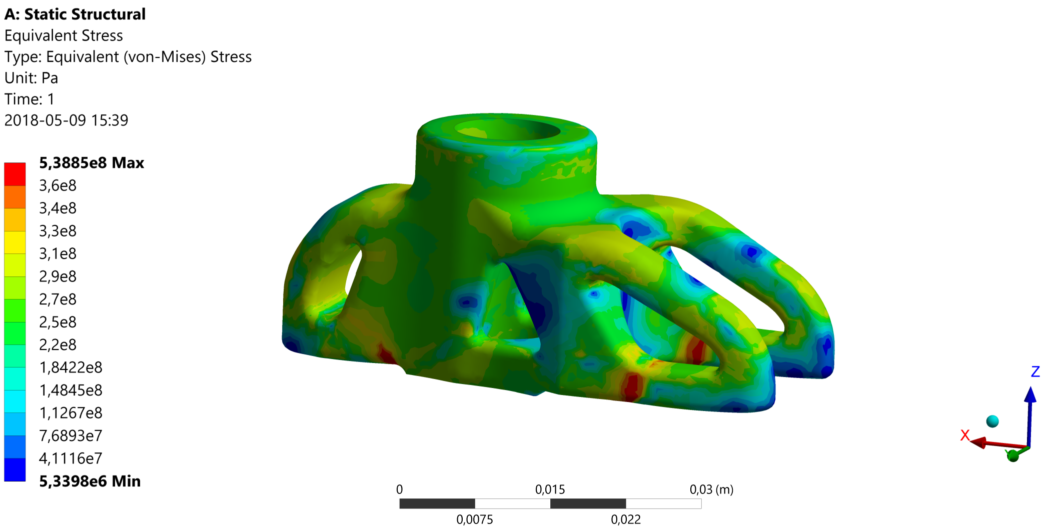

Figure 4.13: The von Mises stress field in C3. The reduction of material on the sides of the yoke creates higher stress levels in the yoke, mainly in the radii in the forks and in the back of the yoke.

C4 did not withstand the load and large deformations appeared in the forks that bent outwards, which could result in the yoke losing grip of the injector. Large stress concentrations appeared, mainly in the inner radii where material had been removed from the bottom surface, resulting in large plastic zones.

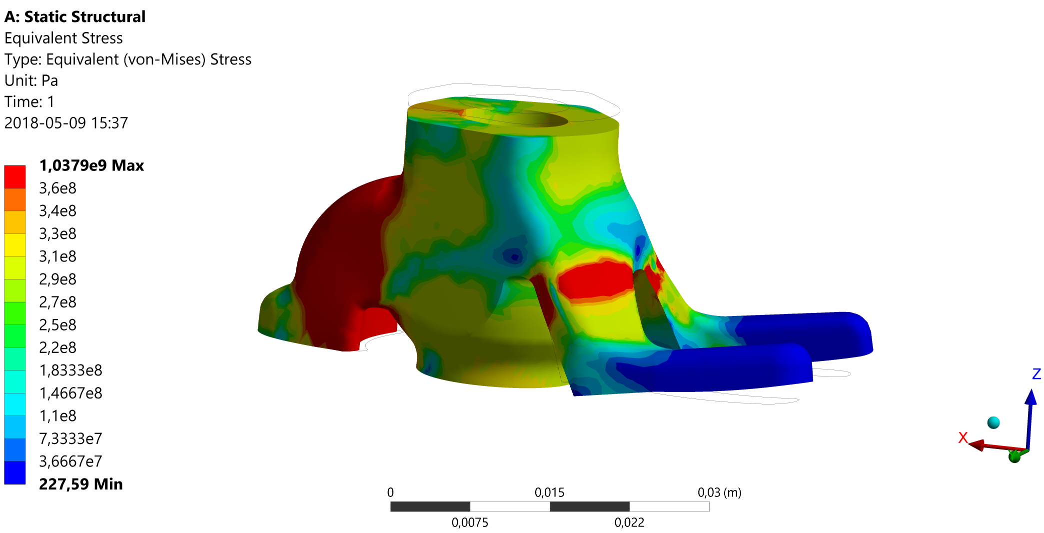

Figure 4.14: The von Mises stress field in C4. The inner radii due to the material removed from the bottom experiences high stress levels, far above yield strength.

C5 performed better, the stress levels were below the yield strength in the entire part with the exception of small areas in the bottom of the part, yielding small plastic zones.

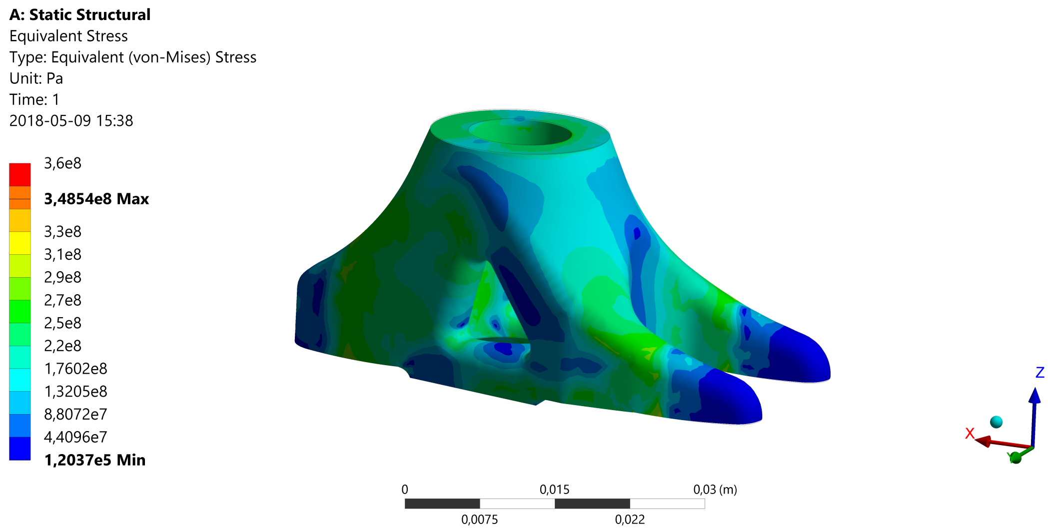

Figure 4.15: The von Mises stress field in C5. No stress concentrations with stress levels above yield strength appear.

The stress concentrations for C6 occurred in the same places as C5, with no major differences observed. The stress levels were slightly higher and the maximum von Mises stress reached above yield strength. However, this stress concentration was small enough to be disregarded. Apart from this small stress concentration, the equivalent stress was below the yield strength. Furthermore, the deformations were very similar, and also the size and location of the plastic zones.

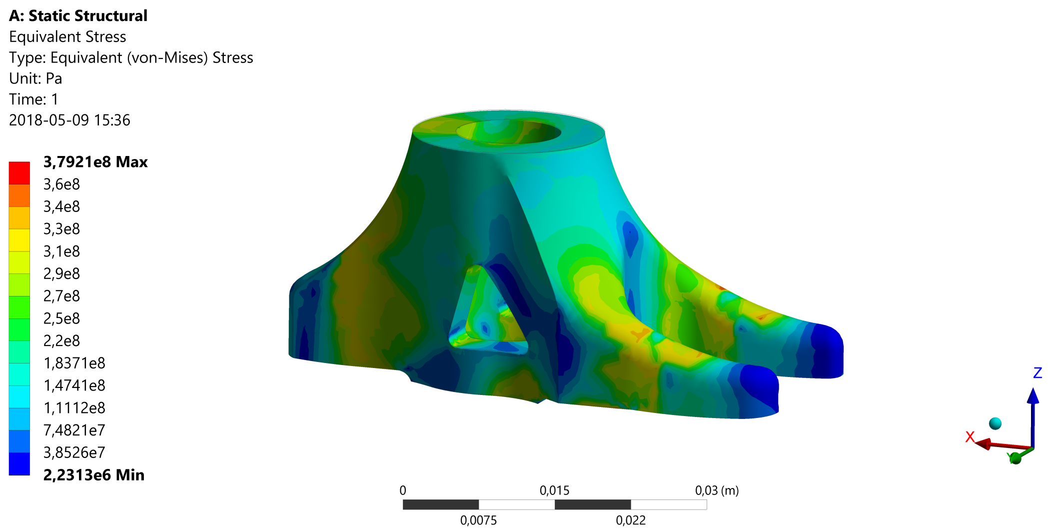

Figure 4.16: The von Mises stress field in C6, the reduction of material results in higher stress levels, still with a distribution similar to the stress distribution for C5.

Table 4.1: Mass, volume, maximum von Mises stress and maximal deformation of the different concepts .

Concept	Mass[1] [g]	Volume [m^3]	Max von Mises stress [MPa]	Max deformation [m]
Original	109.34	1.42×10^{-5}	323	3.63×10^{-5}
1	87.78	1.14×10^{-5}	406	7.50×10^{-5}
2	83.16	1.08×10^{-5}	431	7.58×10^{-4}
3	76.69	9.96×10^{-6}	538	7.80×10^{-4}
4	69.53	9.03×10^{-6}	1038	3.13×10^{-3}
5	81.62	1.06×10^{-5}	349	1.21×10^{-4}
6	73.70	9.75×10^{-6}	379	8.75×10^{-5}

[1] The mass was calculated for the density of stainless steel PH1, 7700 $kg\,m^{-3}$. The original yoke had a weight of 102.24 g.

4.3.2 Selection of Concept

According to the finite element analyses in Section 4.3.1 C1, C3 and C4 do not fulfill the strength requirements. Therefore, the concepts were neglected. The rest of the concepts, namely C2, C5 and C6, all met the demand on strength and hence, were evaluated with Pugh concept selection.

For the first iteration C2 was chosen as reference. The decrease in volume for C2 is less than for the other remaining concepts and therefore, C5 and C6 score +1. The ease of post processing for C2 is considered to be rather complex due to the number of small holes in the topology. C5 and C6 only have one non-circular hole each and hence, they are considered as simpler in regards of post-processing, scoring +1 on both. The use of support structures increases material waste as well as the need of post-processing. Due to its rather complex geometry, C2 is estimated to use more support structures than C5 and C6. Accordingly, both C5 and C6 are considered better and score +1. The scoring is presented in Table 4.2 and concludes that both C5 and C6 are better than C2 in all aspects.

For the second iteration C5 was chosen as the reference. The volume of C6 is about 92% of the volume of C5, scoring +1 for C6. The post-processing was considered to be less complicated than for C2 due to the rather complex design. The post-processing for C6 was estimated to be equally difficult and time consuming compared to C5, scoring 0 for C6. The same arguments applies to the need of support structures; equally complex geometry results in the same amount of support structures required. Therefore, C6 needs the same amount of support as C5, resulting in score 0. In Table 4.3 the result is summarized and C6 is considered to be the best option.

To ensure that C6 is the best of the three a final iteration of Pugh matrices was made, choosing C6 as the reference, see Table 4.4. Consequently, C6 was chosen to

Table 4.2: First iteration of Pugh matrix, C2 is chosen as reference.

C2 as Reference	C5	C6
Volume	+1	+1
Ease of post-processing	+1	+1
Need of support structures	+1	+1
Total	+3	+3

Table 4.3: Second iteration of Pugh matrix, C5 is chosen as reference.

C5 as Reference	C2	C6
Volume	-1	+1
Ease of post-processing	-1	0
Need of support structures	-1	0
Total	-3	+1

be developed further.

Table 4.4: Third iteration of Pugh matrix, with C6 chosen as reference. The table concludes that C6 is the best concept.

C6 as Reference	C2	C5
Volume	-1	-1
Ease of post-processing	-1	0
Need of support structures	-1	0
Total	-3	-1

4.4 Chosen Concept

As mentioned, C6 was chosen as the best design for the optimized injector yoke. In Figure 4.17, 4.18 and 4.19 multiple views of C6 are shown. The bottom area of the yoke was made more narrow than the bottom surface of the original yoke. The length of the yoke, as well as the dimensions of the forks and the bolt hole were maintained, as to not prevent mountability on the engine. The top surface, which is in contact with the bolt head of an M10 bolt, was reduced to the size of the bolt head. The reason being to reduce volume, while not affecting the stress in the bolt given from the torque. The hole in the side of the bolt was designed to use as little support structure as possible with angles larger than 45°. For the exact dimensions of the geometry, see the part drawing in Appendix B. Here, dimensions affecting the mountability, can be found.

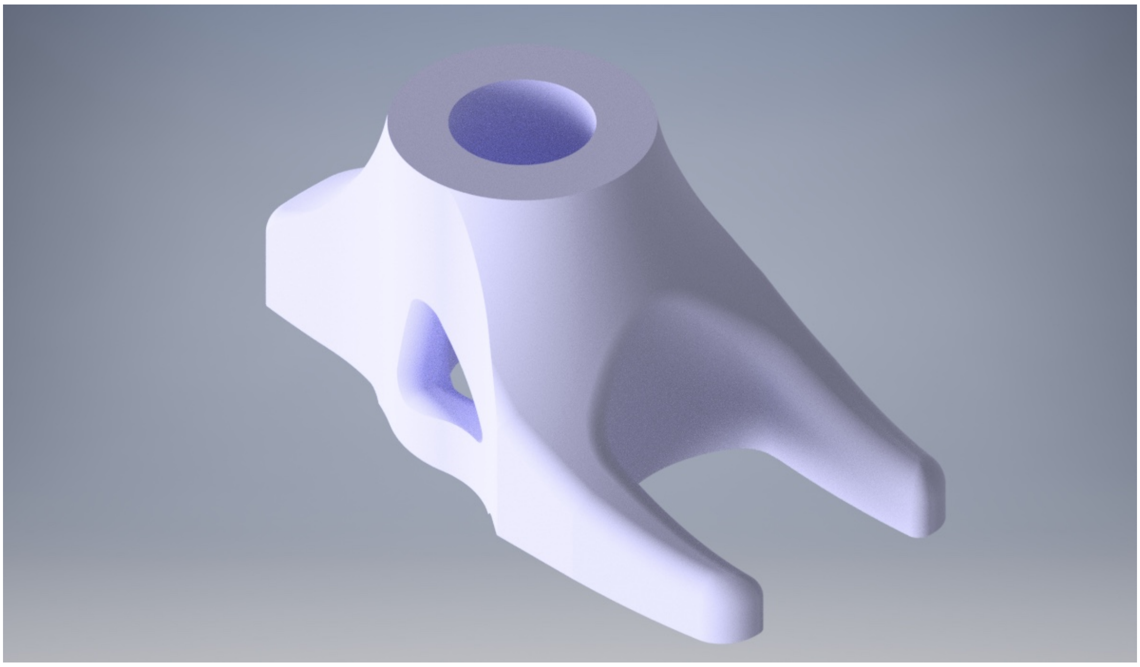

Figure 4.17: Three-dimensional view of the chosen concept, C6.

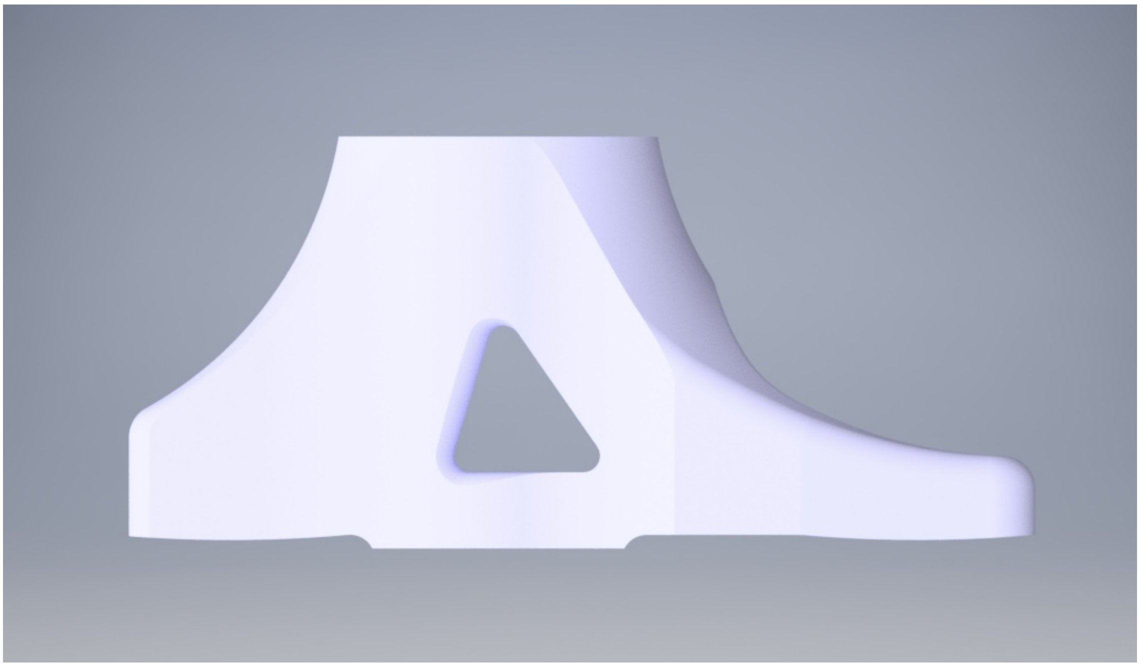

Figure 4.18: Side view of C6.

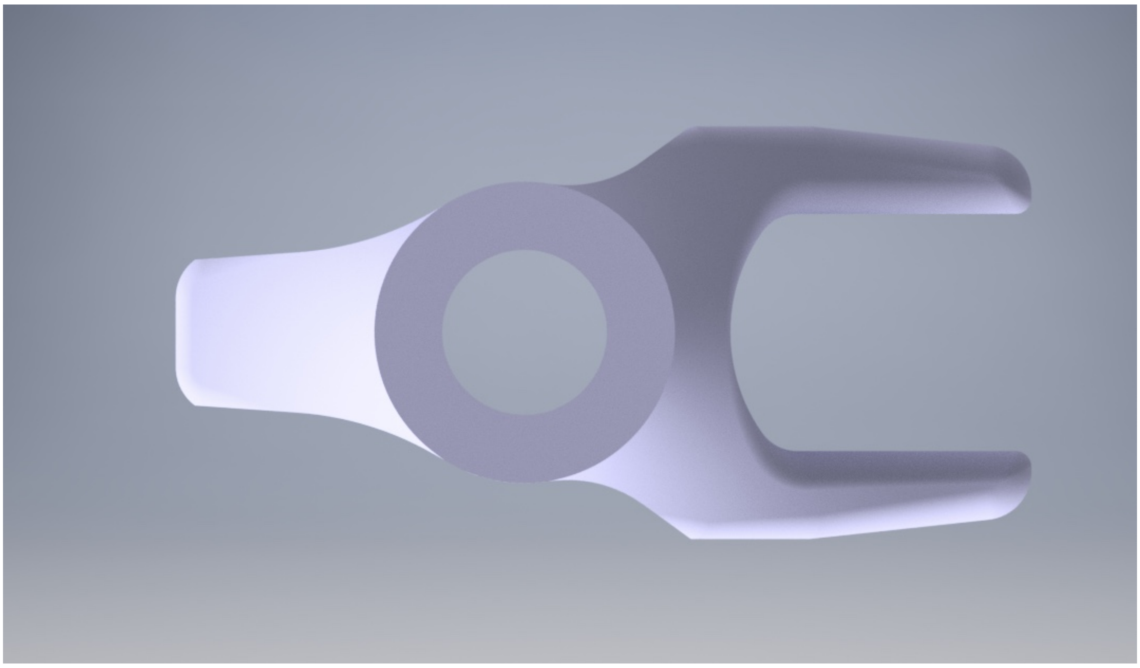

Figure 4.19: Top view of C6.

The shape optimization resulted in minor changes of the radii in the triangular hole and underneath the forks. This resulted in body mass of 65.57 g, compared to the previous 65.29 g, a difference to small to take notice of. The maximal stress was reduced from 391.2 MPa to 390.9 MPa, a difference more or less negligible.

As seen in Figure 4.10 the maximum von Mises stress reaches 391 MPa and appears in the fork bends and in the bottom surface around the small radii. This stress exceeds yield strength only in very small volumes and hence, assumed to not affect the performance of the yoke.

The plastic zones appeared in the radii in the bottom surface and they were all considered to be too small to negatively affect the performance of the yoke. The deformation was largest at the end of the forks where it reached 0.059 mm. The deformation would only result in a lower pressure on the last millimeter of the injector grip and should not affect the performance substantially.

The optimized design inherited a weight of 65.29 g and compared to the original design this corresponds to a mass reduction of 36.14%. Using Sculpteo the price can be estimated to 2 375 SEK (277 USD), which is precisely 70% of the cost of producing the original yoke.

4.5 Cost of Production and Storage

The price of the yoke per unit from the current supplier is 166.25 SEK. The maximum savings of replacing the supplier of the yoke, including warehouse storage, with in-house AM of the component at a CDC, would be 6 536 SEK per 587 units, equivalent to 10.5 SEK per unit, as seen in Table 2.3. Thus, the AM production route is not economically beneficial during the present market conditions. Instead, AM is a lot more expensive than the traditional production, even though taking lower costs of logistics into consideration.

Furthermore, estimation of production cost using AM, was attempted using commercial software from Sculpteo[1]. Printing the original yoke and the new C6 would cost 3 390 SEK (395 USD) and 2 375 SEK (277 USD), respectively, per unit. Accounting for the maximum saving per yoke, to achieve an economical viability, a maximum cost per yoke would have to be 176.75 SEK (20.75 USD). This further attests to the economic limitation of using AM production as of now.

4.6 Method of Printing and Choice of Material

If it was desired to invest in AM for spare part production, the study found that DMLS by EOS would be the preferable option for the Volvo Group, as of now. Mainly because EBM currently does not officially support printing in stainless steel. Otherwise, EBM would probably prove more advantageous due to faster printing time and a higher density range. Methods of DED are usually preferable to PBF methods concerning the print time but only when printing single units.

Listed in Section 2.1.3 are selected metal powders, provided by EOS, that may be suitable for the yoke. Among them, the stainless steel PH1 is considered to be the best fit because of its high hardness, 45 HRC, as well as high yield and tensile strengths, >1440 MPa and >1300 MPa, respectively. The maraging steel MS1 has higher hardness and higher yield as well as tensile strength, but it also is rather brittle and therefore unfavorable. The other stainless steel, 316L, has lower yield strength, ultimate tensile strength and hardness, compared to PH1. The properties of 316L are however good enough according to the analysis, and therefore, depending on price difference between 316L and PH1, 316L could potentially replace PH1 as the best fit.

[1]Software found on `https://www.sculpteo.com/en/`.

4.7 Orientation of Components during Printing

To further optimize the print time and throughput of parts, the process of printing multiple components at once was investigated. The process, referred to as stacking, minimizes non utilized build volume, which decreases built time per unit compared to printing each unit individually. Stacking is especially effective when utilized for printing different spare part components, because there rarely is a demand for more than one unit at a time. This study investigated stacking of the injector yoke, seen in Figures 4.20 and 4.21. Although, stacking different spare parts together may pose a bigger challenge, the principal of decreasing print time per unit remains. The calculations that were made assumed the use of an EOS M 290 with a build volume of $250 \times 250 \times 325\,\mathrm{mm}^3$. Completely filling the build volume, a total of 700 injector yokes can be printed, utilizing 32% of the total build volume.

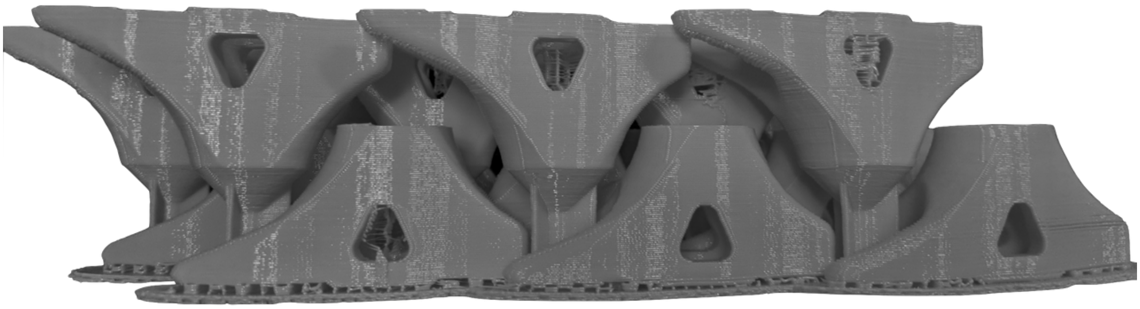

Figure 4.20: Side view of stacked and packed print. The custom support structure can be seen here. It is very easy to remove but strong enough to produce a quality print. Notice also that support structure for the top layer is not needed on the sides.

Figure 4.21: Top view of stacked and packed print. The parts can be packed extremely close to each other, due to the tapering from the design of C6.

5

Discussion

This section will mainly discuss the chosen concept, the need of a redesign and the difficulties in estimating the cost as well as suitable method and material for the yoke.

5.1 Analysis of Final Concept

The final concept was generated with the purpose of being more suitable for AM than the original yoke. AM gives a higher degree of freedom regarding design than conventional machining, and makes it possible to reduce the use of material, without compromising the performance of the component.

The original part was designed for manufacturing via pressing and sintering, and later even machining, giving certain design constraints. Without these constraints, the volume of the optimized yoke can be reduced to $9.75 \times 10^{-6}\,\mathrm{m}^3$, compared to $1.42 \times 10^{-5}\,\mathrm{m}^3$ for the original part and material, which equals a volume reduction of 28.4%. Although a method and preferred material, for the spare part production, have been suggested, it is important to note that neither an optimal material choice nor manufacturing method can be concluded. From this follows that the extent of post-processing also cannot be concluded. Most likely, more material will have to be added in certain areas to compensate for grinding, polishing etc. in order to print functional components. Furthermore, the degree of heat treatment also depends on the choice of material, and is therefore not taken into consideration in the redesign process.

Comparing the concepts in strength, the original design is subjected to lower stress levels as well as slightly smaller plastic zones than the chosen concept C6. Nevertheless, the stress levels of both C6 and the original design are below the yield strength and both components exhibited tolerated plastic zones, thus both designs fulfill the requirements regarding strength. The maximum deformation of the redesigned yoke was very small, only 0.06 mm. However, this deformation is considerably larger than the deformation of the original yoke, which was 0.0036 mm.

The effect from shape optimizing the yoke was negligibly small. The maximum von Mises stress was only reduced by 1 MPa, and additionally, the SO even resulted in a slightly higher mass, however, only 0.3 g. The conclusion to be drawn from this is either that the engineer intuitively made an optimized yoke using only the TO or that the gains from a SO are relatively small for small components. Either way, SO is a good way to conclude how optimal a design is.

5.2 Redesign

The component went through the SDO process described in Section 2.2, all of the steps were executed and the chosen concept fulfilled the requirements. The method can therefore be considered to be suitable for optimizations of this kind. The development as well as the quality assurance is however time consuming and the man hours for the design process are expensive. Therefore, the profit made from reducing the mass of the part may not compensate for the cost of development. However, reduction of build volume enables the possibility to fit more yokes on the build plate, and therefore reducing cost per unit. Presuming AM will be used, the reduction of volume could therefore be a vital argument to why an SDO should be made.

5.3 Materials and Methods

As discussed, there are too many insecurities and not enough information to make a qualified conclusion regarding the most suitable material and method. A conclusion can first be made after companies of interest are involved and can consult the manufacturing production. The recommendation is basically for the Volvo Group to reach out to EOS, SLM Solutions, Arcam, etc. with a business proposition presenting Volvo Group's desire to print a yoke with the demanded properties. The AM printer manufacturers can then respond with recommendations of equipment, material and post-processing including information of price, printing time and equipment life time. With this information the Volvo Group can make the necessary conclusions and decide the most suitable process of production.

Even though the Volvo Group can get their hands on the information needed, it does not guarantee that it will be economically beneficial to manufacture the yoke. A problem for AM to become efficient in the regular automotive industry is the lack of an inexpensive, but strong metal powder. This type of cheap structural material is non-existent as of now.

5.4 Limitations of Production and Distribution

It becomes obvious that AM for production of spare parts, in this case especially the injector yoke PN 469797, is not suitable for on demand printing of individual parts. Taking the customer needs *print time* and *post-processing* into consideration will implicate high demands on the supply chain of the Volvo Group. The desire to decrease the lead time will be limited by the print time of the printer. To achieve similar lead times as the traditional production and delivery routes would require AM printers on site at the distribution centers, mainly the CDCs.

A possible problem with printing components in different orientations is the arise of different surface finishes. When printing in PBF, upward facing surfaces will always be smoother than downward facing surfaces. This is due to a basic mechanical problem in PBF technology. The problem being that a downward facing surface is in contact with the powder below it while it cools, resulting in the powder partially melting together with the downward facing surface. This gives a substantially rougher surface than for upward facing surfaces, which are naturally smoothed out during cooling by gravitation. Printing multiple yokes stacked like Figure 4.20 will most likely mean that half of the yokes will need further post-processing, depending on the demand on surface finish. Another problematic aspect, of printing components in different orientations, is the difference between vertical and horizontal mechanical properties, vertical properties being stronger. The yoke, for example, is heavily loaded vertically, and therefore they should be printed like Figure 4.20. When printing different spare parts together, it may be difficult to minimize build volume without compromising the mechanical properties of some components.

5.5 Cost Estimation

Firstly, it is very hard to find price information on powders and other expendables from companies if you do not represent a company looking to invest. Meaning, even though we can calculate the amount of powder needed, we cannot calculate the cost. We can estimate the cost of the machine, but we cannot put this cost in relation to the printed objects. Especially when we do not know how long the machine can function or how much it costs to maintain. It is also fairly hard to estimate the cost of educating staff and work hours necessary per print.

Not knowing prices of powders makes it hard to choose one. Different powders in different materials need different post-processing. Post-processing is also fairly expensive and time consuming. All products do not need surface treatment, but all materials will need some heat treatment, due to the non-homogeneous structure accomplished from layer-wise printing. As the complexity of manufacturing rises it would be preferable to ask manufacturing companies what they would charge to produce the yoke using AM. Once again it proves hard to find this information if you are not a company seeking to invest. The best estimation available was found to be through Sculpteo. As previously mentioned, according to Sculpteo, a single unit of the original yoke would cost 3 390 SEK (395 USD) and the chosen concept C6 would cost 2 375 SEK (277 USD) per unit. Simply using Sculpteo's service, without knowing how they calculate their prices, is not very scientific and makes the results fairly unreliable. Although, as mentioned in Section 2.4, cost estimations vary a lot between current AM suppliers.

The initial problem statement was that the logistical costs of injector yoke were high. This turned out to be untrue. The fact that the yoke sells 500-600 units per year means that it is not a low frequency spare part. The stock is replaced 5-6 times a year meaning storage space is used efficiently enough. The fact that the component weighs 102.24 g makes shipping fairly cheap. Knowing this, it was established that any attempt at comparing the current yoke to AM would without doubt conclude a favor towards the current method. It was thereafter attempted to find other spare parts with lower frequencies. This turned out to be problematic. Firstly, the current database of spare parts does not provide enough parameters to establish search criterion to find components with a potential to be produced using AM. Also, low frequency spare parts are often fairly old and documentation of old components is often incomplete, at least to modern standards. An important piece of documentation for validating AM suitability are digital CAD models. In this period of time, computer simulations were not used and therefore there are rarely digital 3D models of any sort. It is fairly easy to conclude which parameters make AM expensive or cheap, but comparing these parameters to each other is a lot more difficult. Should the volume of the yoke be reduced as much as possible or is the cost of volume negligible in comparison to post-processing? Is it cheaper to buy multiple machines and place them in every CDC or is it cheaper to ship from one or two? Questions like these may not be answerable without trial and error.

With all this said, in time AM will become cheaper, as forecast in Section 2.4, and the yoke will become more expensive to manufacture. Therefore the recommendation of this report is still to invest in AM for the ability to adapt to the future AM market. There will come a day when AM completely changes the way we manufacture and companies stuck in old ways of production are likely to be outcompeted.

5.6 Business Case

The main conceptual problem with manufacturing spare parts using AM is that there rarely is a demand for more than one or a couple of units at a time. In order to make AM profitable for spare parts, it is suggested that all spare parts suitable for AM should be gathered in a pool. Incoming orders for parts in the pool could then be printed together. Using PBF, this would decrease the cost of printing, substantially, because printing multiple units is far less expensive than printing single units, due to the cost of unused volume in the printer being carried by multiple parts.

The infrastructure for such a production route would include a printer placed in one or multiple CDCs, depending on how frequently parts from the AM pool are ordered. Orders taken for spare parts included in the pool are saved until the total volume of all orders is enough to fill the entire or a large portion of the build volume. Examples of this concept, previously referred to as stacking, can be seen in 4.20 and 4.21.

One could say that this method of manufacturing spare parts eliminates the concept of low frequency articles replacing it with a frequency of the pool. If there are enough different spare parts in the pool the frequency of orders will become high enough to limit waiting time for the customers. All the while limiting storage space needed only to the machine and the storage of powder and other expendables.

5.7 Further Research

The chosen concept is not ready for manufacturing, before it can be taken into production further analyses has to be made, such as buckling and fatigue analyses. Real break load testing should also be executed. Due to the high price of AM, the team was unable to conduct their own physical tests. Ideally, the part would be printed in different machines, using different powders and different orientations, conduct a series of different post-processes and finally test the strength of the components assuring the perfect design. Instead the concepts were printed in plastic, only as representative prototypes.

Also, the design must be adjusted to the chosen AM method and material choice to compensate for necessary grinding and polishing. A suggestion for further research in the area is an optimization with the main target to minimize print time. This is an extensive adjustment, that was not within the scope of this project.

Because AM is an expensive manufacturing method most research for manufacturing is conducted in fields that can show immediate profit, such as aerospace and orthopedics. The lack of research of similar products made our conclusions regarding method and material very general and non-specific to our task. Therefore, a study regarding the possibilities of optimizing the supply chain for AM is recommended.

5.8 Conclusions

From this thesis it can be concluded that, by taking advantage of the design freedom that comes with additive manufacturing, it is possible to redesign the component so that the volume is minimized with 28.4%, while maintaining the mechanical properties. However, the design is not complete since the post-processing has not been taken into consideration and therefore, more material has to be added in places where grinding and polishing are needed. Also, it can be concluded that the reduction of volume makes it possible to utilize up to 32% of the build volume by stacking the injector yoke effectively.

Due to expensive material and costly printing time, it is not possible to make AM profitable today. However, it could be important to invest in AM early, as it will prove to be advantageous in the future. Thus, it might be a strategic decision to proceed with setting up an AM production route for spare parts, even though it may prove unprofitable.

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A

Topology Optimization

Figure A.1: Topology optimization with a target volume reduction of 50%. The bottom plate were allowed to be removed.

B

Part Drawing of Chosen Concept

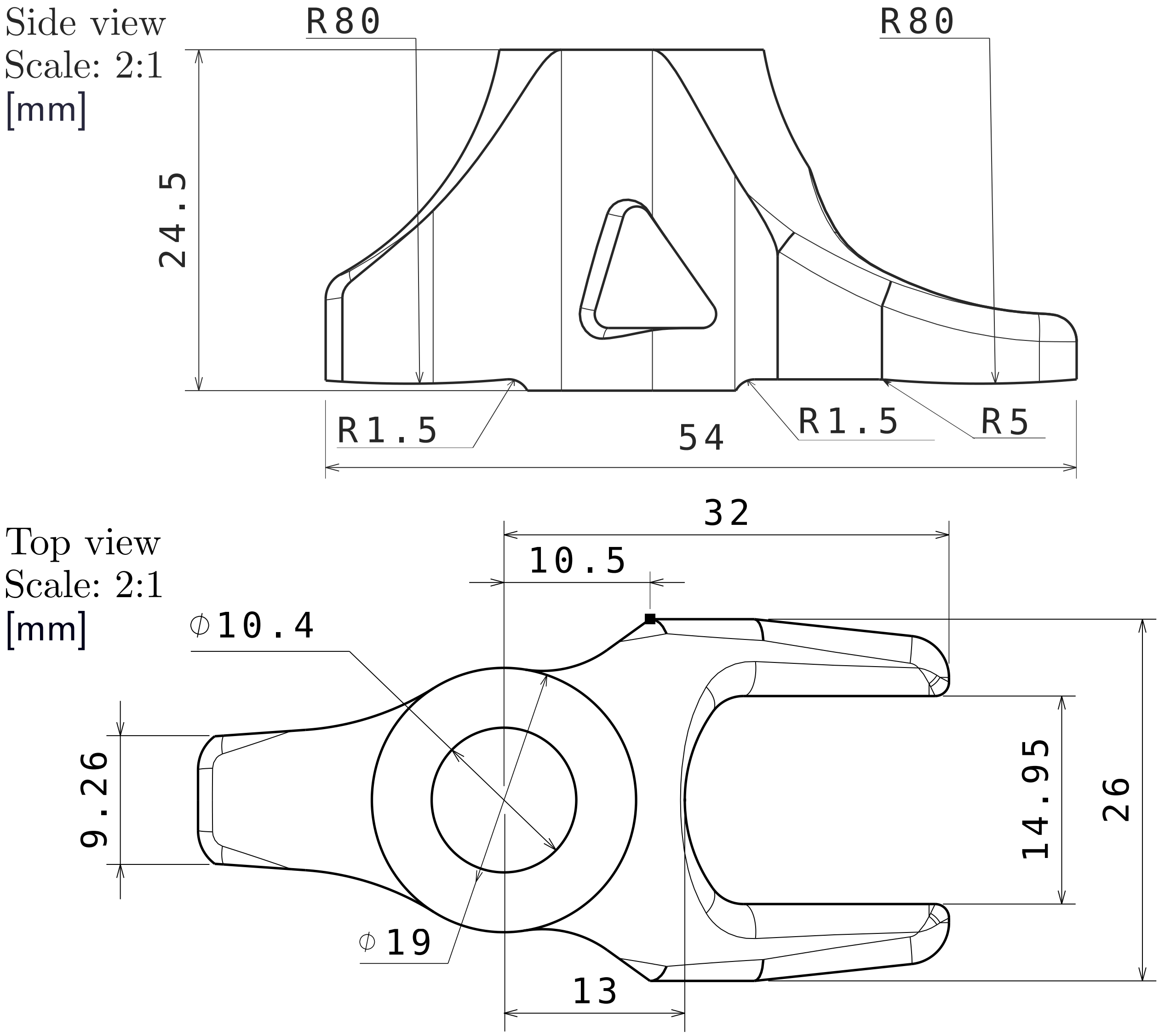

Figure B.1: Part drawings of the chosen concept seen from the side and top, respectively, in scale 2:1. All measurements are in mm.