Light Weight Additive Manufactured Mining Components

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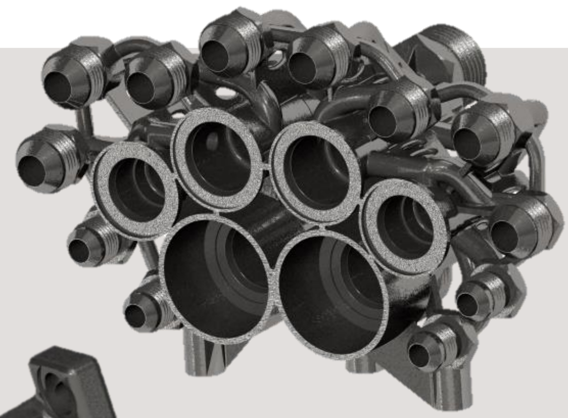
MASTER THESIS



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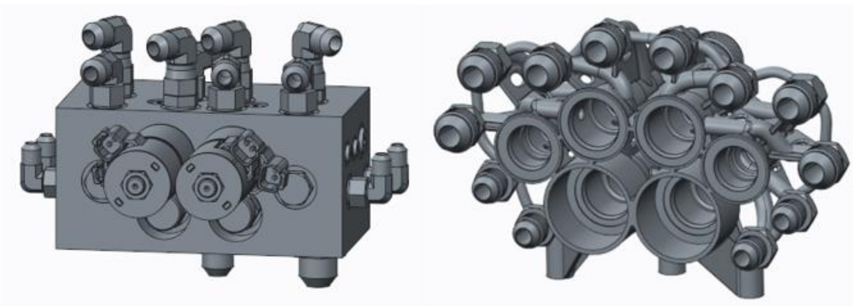
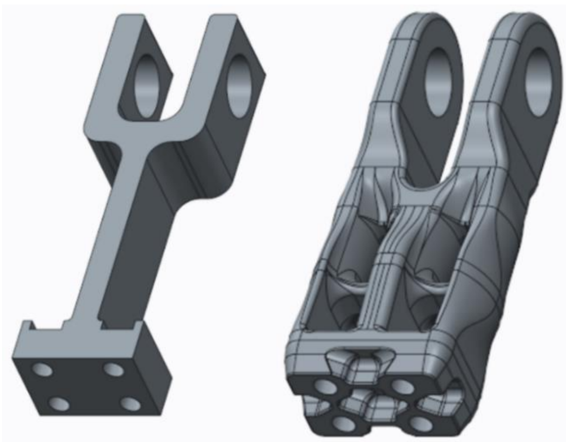
Abstract

Additive manufacturing in combination with topology optimization have been used to drastically improve the weight and performance of three mining components. A fourth component was analyzed but deemed not suitable for redesign at this stage.

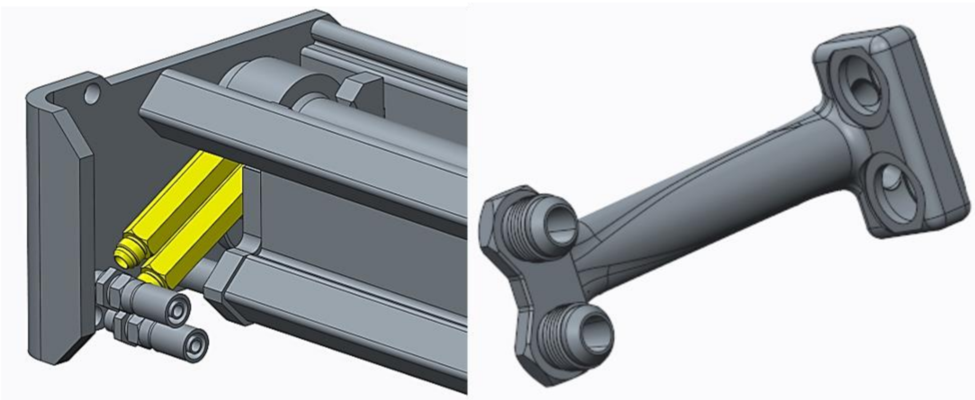
The first component was redesigned to get a better performance while simultaneously decreasing the weight with 92%. The first component is a hydraulic component containing six valves, two inlets and twelve outlets. See original design to the left and new design to the right in the figure below. This component was also printed in metal for further investigation.



The second component replaces a metal construction with a topology optimized plastic component, saving 78% of the weight. It’s placed between a hydraulic cylinder and the end of a feeder and attached using four M12 bolts. See original design to the left and new design to the right in the figure below.



The third component combines two parts into one, with a weight reduction of 34%. It would be troublesome to create the third component without using additive manufacturing. The third component should replace the connection between a hydraulic cylinder and two hoses on the feeder. The replaced connection was made up with various types of nipples. The nipples are prone to breaking and that's why a stronger component that fits the space was needed. See original design to the left and new design to the right in the figure below. The yellow parts in the left figure below are the nipples leading into the hydraulic cylinder.

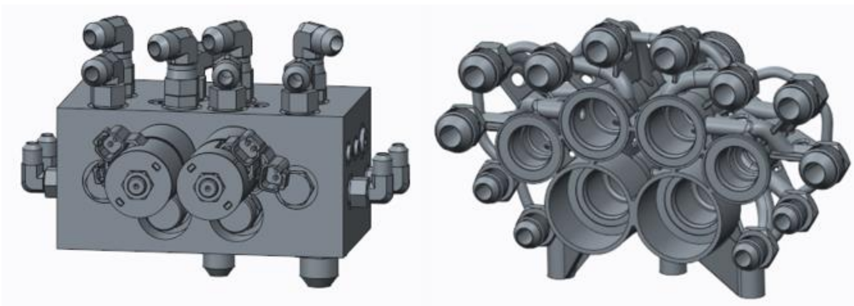


Keywords: Topology optimization, bracket, light weight, metal replacement, additive manufacturing, 3d-printing, Atlas Copco

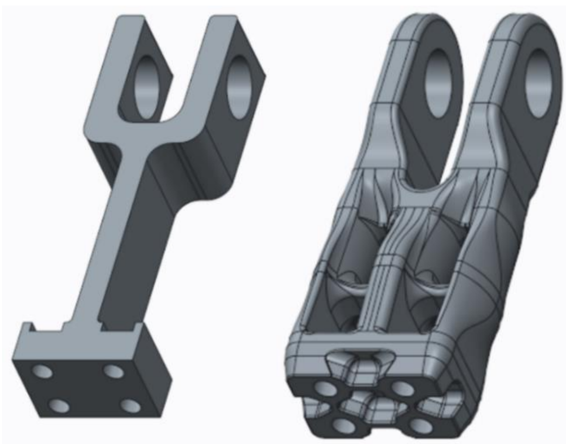
Sammanfattning

Additiv tillverkning i kombination med topologioptimering har använts för att drastiskt förbättra vikt och prestandan hos tre gruvkomponenter. En fjärde komponent analyserades men bedömdes inte värd att omkonstrueras.

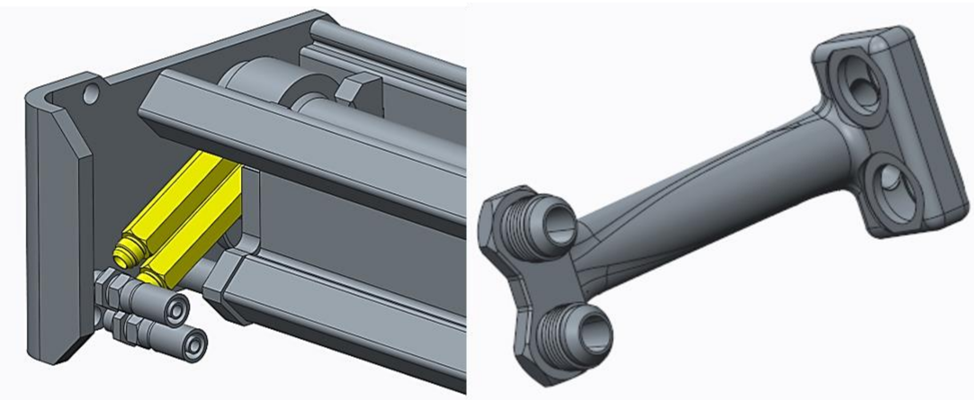
Den första komponenten konstruerades för att få bättre prestanda samtidigt som vikten minskade med 92%. Den första komponenten är en hydraulisk komponent innehållande sex ventiler, två inlopp och tolv utlopp. Nuvarande design kan ses till vänster och den nya designen till höger i figuren nedan. Denna komponent var också printad i metall för fortsatt utredning.



Den andra komponenten ersätter en metallkonstruktion med en topologioptimerad plastkomponent vilket sparar 78% av vikten. Den är placerad mellan en hydraulisk cylinder vid slutet på en matare och fastsatt med fyra M12 bultar. Nuvarande design kan ses till vänster och den nya designen till höger i figuren nedan.



Den tredje komponenten kombinerar två delar till en, med en viktreducering på 34%. Den vore besvärlig att tillverka den tredje komponenten utan att använda additiv tillverkning. Den tredje komponenten skulle ersätta kopplingen mellan en hydraulisk cylinder och två slangar på mataren. Den ersatta kopplingen bestod av olika typer av nipplar. Nipplarna är benägna att gå sönder och därför behövde man en starkare komponent som passar i utrymmet. Nuvarande design kan ses till vänster och den nya designen till höger i figuren nedan. Gula delarna i figuren till vänster är nipplarna som går till den hydrauliska cylindern.



Nyckelord: Topologioptimering, konsol, lättvikt, metallersättning, additiv tillverkning, 3d-printing, Atlas Copco

Acknowledgments

Thank you Sima Valizadeh and Magnus Karlberg at Atlas Copco for the confidence in me during this work. I wish to express my gratitude to the construction department at Atlas Copco in Örebro and to Professor Olaf Diegel at LTH for guiding and supervising me. All of you have been essential for this work.

Lund, June 2017
Henrik Nilsson

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List of acronyms and abbreviations

AC	Atlas Copco
AM	additive manufacturing
CAD	computer aided design
DMLS	direct metal laser sintering
DS	design space
LC	load case
PO	print orientation
SLM	selective laser melting
SLS	selective laser sintering
TO	topology optimization

1 Introduction

This introductory section should provide the reader with the underlying conditions for this master thesis.

1.1 Background

Additive manufacturing, AM, is growing exponentially. This thesis investigates the usage of AM primarily to reduce the weight of mining equipment. Mining equipment is used in a rough environment, with tight spaces and poor sight. This is why telescope booms, seen to the right in Figure 1.1 below, are commonly used. The hydraulic drills are mounted on the feeders. The weights from the hydraulic drills, booms and feeders are placed far ahead of the machine which results in large loads. Equipment is also commonly smashed into the mountain walls and rocks fall on the machines. The mining operation environment is humid and salty mine water is used by the machines. The temperature ranges from below zero to plus 50 degrees. Salty mine water together with high temperature makes the environment very corrosive. Vibrations and human safety are also important factors to account for.

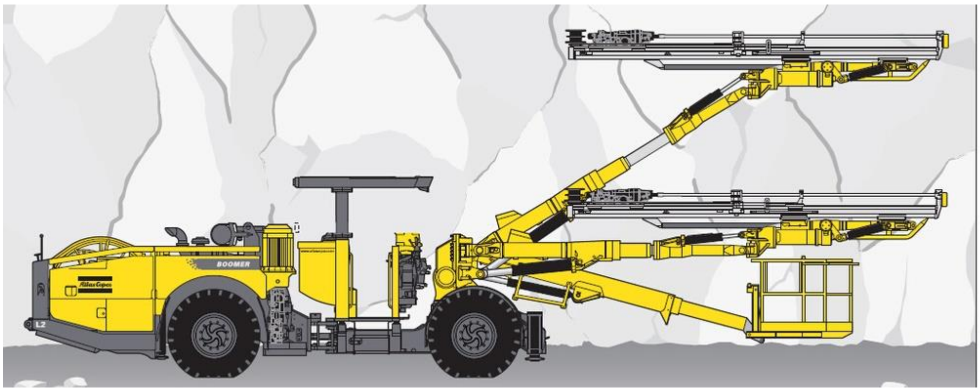

Figure 1.1 Example mining equipment

1.2 Company presentation

Atlas Copco, AC, is a Swedish manufacturer of industrial tools and equipment founded 1873 in Stockholm. AC has four main business areas: Compressor Technique, Industrial Technique, Mining and Rock Excavation Technique and Construction Technique. AC has customers in more than 180 countries and innovate and produce in more than 20 countries [1].

In January 2017, it was announced that AC will split into two companies. This split is expected in 2018 [2].

1.3 Goals

The goals are to reduce the weight of the booms and feeders, lower the prices and enhance performance. Some evaluation aspects are:

- Reduced weight but, at least, equivalent strength.
- Reduced hose wear.
- Stronger and more durable.
- Improved operator visibility.
- Reduced impact of the operating environment.
- Insights to where AM could be useful.
- Understanding when plastics AM or metal AM is useful.

1.4 Delimitations

This chapter will specify the delimitations for this thesis. All equipment is for underground mining and therefore surrounding conditions apply. Because of the construction and design nature of this thesis, no standard development process was used. All new designs will only be designed for AM. Broadness in design is perceived more important than detail in design. Only selected components will be analyzed and redesigned. Other larger components, in the selected components vicinity, will not be considered as changeable.

1.5 Method

The first step of the method consist of identifying suitable components to be analyzed and designed. Four, quite different, components were picked to give broad insights to understand where AM and topology optimization, TO, could be utilized and useful. These products will be presented in the coming section. The next step was to analyze the problem and generate design ideas using TO software. The software used to generate the design ideas was solidThinking Inspire. After generating the design ideas the CAD models were created by interpreting the generated design ideas. Creo 2.0 was used for generating the CAD models. The optimized CAD models was then analyzed using ANSYS. Polymer printing was done at LTH using EOS Formiga P110, a laser sintering 3D printer. See Figure 1.2 below. Iteration was done from generating CAD models, and printing them in EOS Formiga P110, to discussing with AC to verify and update the designs. Last step was to estimate the prices, for plastic and metal AM, and compare the newly created designs with the original ones.

Figure 1.2 EOS Formiga P110 [3]

2 Challenges

This section presents the selected components, i.e. the challenges, which will be looked into.

2.1 Selected components

Four different components has been selected for this thesis. Two components are suitable for TO and two are pure design challenges. The products suitable for TO are named dog bone and banana. The dog bone TO should be simple in comparison to the banana. The components that will be redesigned are called nipple-replacement and manifold. In the same manner, the nipple-replacement should be simple to design in comparison to the manifold. The product separation can be seen below.

- **Topology optimization**
  - Dog bone
  - Banana
- **Design challenges**
  - Nipple-replacement
  - Manifold

The selected components, and the background to their names, will be made understandable in the following chapters.

2.2 Dog bone

The dog bone is a component placed between a hydraulic cylinder and the end of a feeder, see yellow part in Figure 2.1 below. The component got its name from the original design looking similar to a dog bone. The dog bone is attached to the feeder with four M12 bolts and attached to the hydraulic cylinder with an expansion bolt. The dimensioning force used by AC from the hydraulic cylinder, at 65 bar, was 20kN. Since there are two ears, the load is divided by two. The dog bone is around 240mm long.

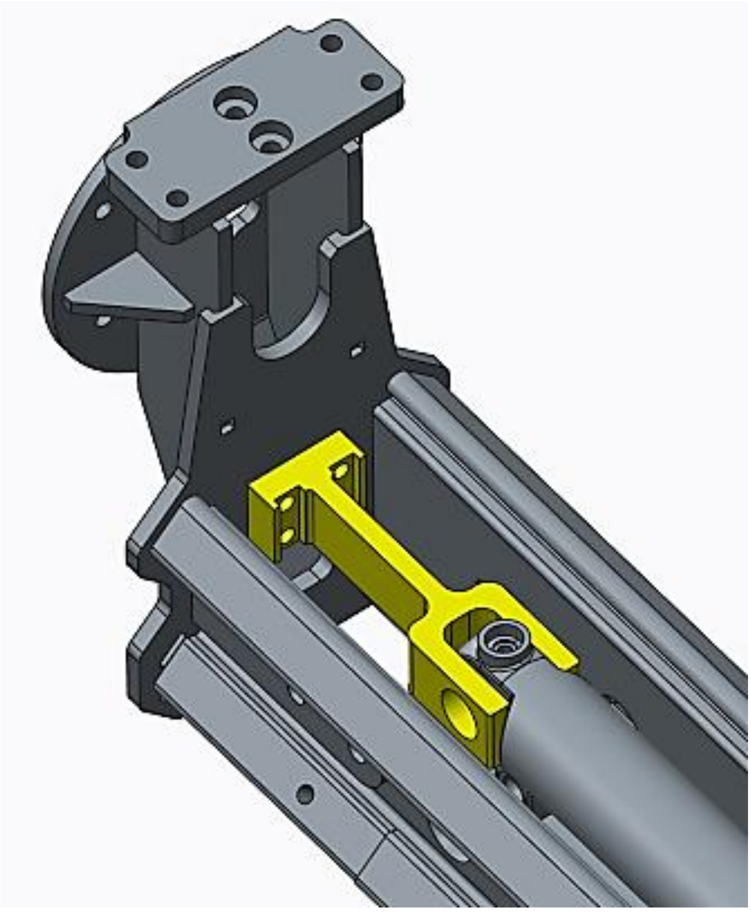

Figure 2.1 Dog bone placement

The challenge is to replace the original metal design with a TO plastic design, making the design substantially lighter while remaining equivalent strength. There also has to be enough room so that pieces of dirt can pass through and not get stuck. It would be beneficial if the dog bone could be produced in plastic instead of metal. The original AC Dog bone design is laser cut S355 steel and weights 2.41 kg.

2.3 Banana

The banana is a component between the feeder and the boom, making rotations possible. See yellow part in Figure 2.2 below. The component got its name from someone originally rendered the component yellow making it look like a banana. The banana is attached to a hydraulic cylinder, an axis and a bolted joint. In the bolted joint there are eleven bolts, not symmetric, as one was removed to make room for the banana to connect with the hydraulic cylinder. The banana is also connected to an axis which make forward and backward rotations possible. The banana is around 360mm long.

Figure 2.2 Banana placement

The challenge is to do a more comprehensive TO and create a design with reduced weight. Additionally the banana makes it more challenging by having several attachments and many larger surrounding components.

The original AC banana solution is made as molded S355 steel, see left of Figure 2.3 below, and weights 35.8 kg.

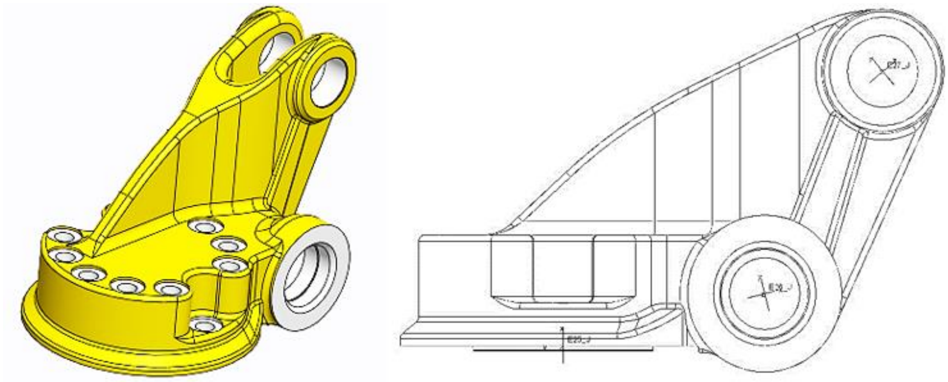

Figure 2.3 Banana

There are several LCs calculated in E25_J, E26_J and E27_J which can be seen to the right in Figure 2.3 above. LCs were given from AC and the LCs with the highest forces and moments were deemed as most critical and therefore selected. The selected LCs can be seen in Table 2.1 below.

Table 2.1 Selected LCs for the banana

Element 27 node J

	Element 27		Nod J			[kN,kNm]
Load Case	Fx	Fy	Fz	Mx	My	Mz
LC 1	-4,5	-152,2	-0,5	0,0	0,0	0,0
LC 2	10,2	-117,4	1,2	0,0	0,0	0,0

Element 26 node J

	Element 26		Nod J			[kN,kNm]
Load Case	Fx	Fy	Fz	Mx	My	Mz
LC 3	-91,2	143,7	43,0	1,9	-0,7	-0,2
LC 4	-89,4	103,4	37,3	-12,1	-14,1	-4,0
LC 5	-32,8	-8,3	12,0	3,2	-22,2	-6,3

Element 25 node J

	Element 25		Nod J			[kN,kNm]
Load Case	Fx	Fy	Fz	Mx	My	Mz
LC 6	3,4	31,0	2,1	-4,2	2,5	-25,3
LC 7	0,9	30,3	7,7	-21,5	10,9	-20,5
LC 8	-12,9	19,8	14,1	-24,2	-9,4	-3,1

2.4 Nipple-replacement

The nipple-replacement is a component that will replace the connection between a hydraulic cylinder and two hoses on the feeder. The component was named Nipple-replacement because that's what it's supposed to do. The original AC solution is prolonged nipples which can be seen in yellow in Figure 2.4 below. The prolonged nipples are around 150mm long.

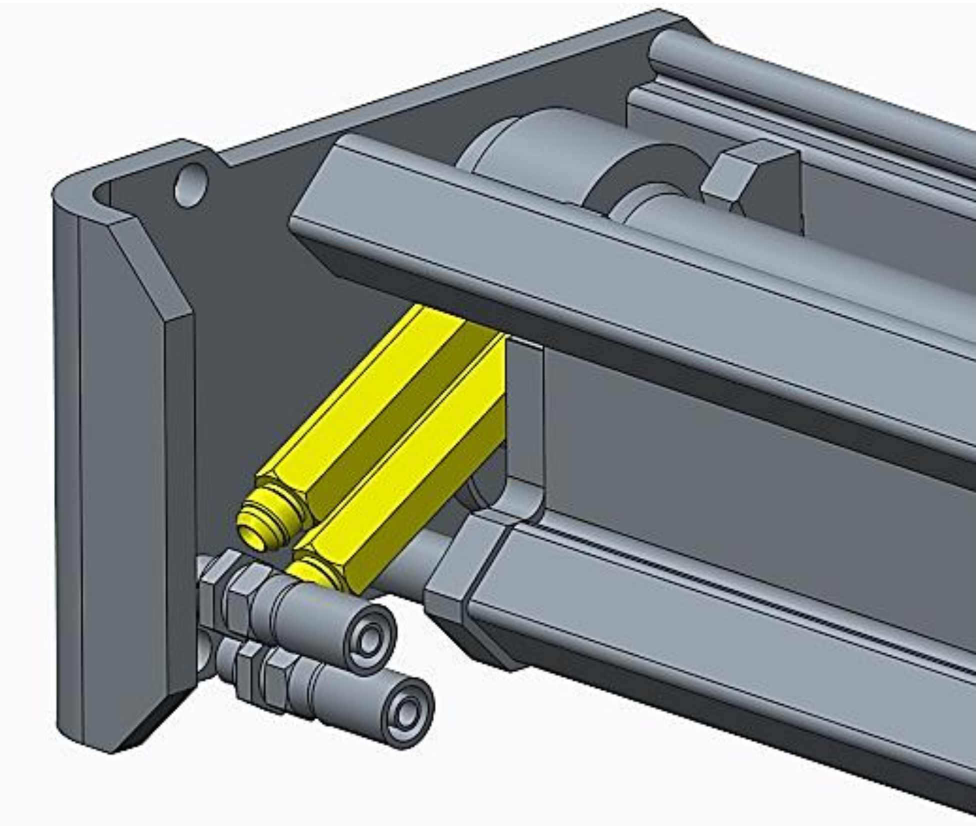

Figure 2.4 Original prolonged nipples design

The prolonged nipples often break as there are not enough space for them. The challenge is to create a design that fits the narrow space, does not break and should be easy to assemble. It's intended to use a banjo screw, a perforated hollow bolt for fluid transfer, to attach the new design to the hydraulic cylinder. Additional challenge is for the new design to be symmetric since it would otherwise result in two, right and left, replacement parts. The prolonged nipples are made of S355 steel and together they weigh 1.07 kg.

2.5 Manifold

The manifold is a hydraulic component containing six valves, two inlets and twelve outlets. See Figure 2.5 below. The original manufacturing method is drilling and plugging from a solid cylinder block. The challenge is to redesign the manifold using AM to improve flow, reduce weight and make assembling easier. The hydraulic scheme for this manifold is shown in Figure 2.6 below. The hydraulic scheme will stay the same, i.e. inlet and outlet positions on the valves will stay the same. The manifold is made of S355 steel and weighs 14.7 kg. The manifold is around 200mm long.

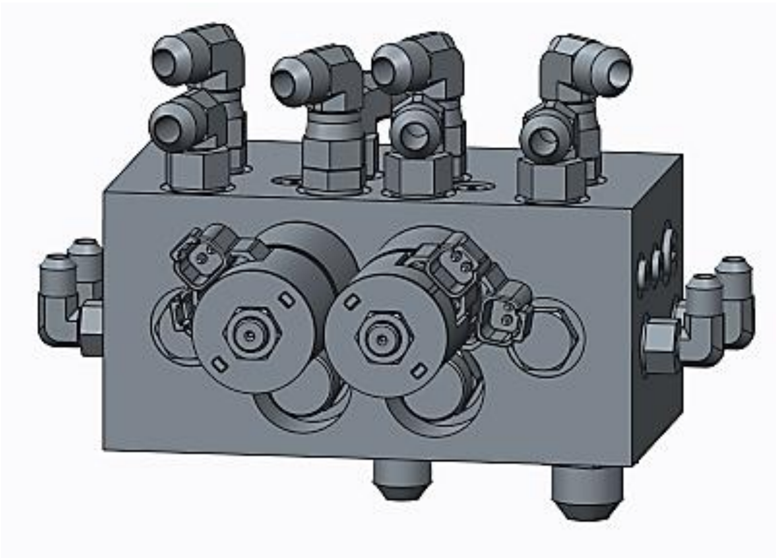

Figure 2.5 Original manifold design

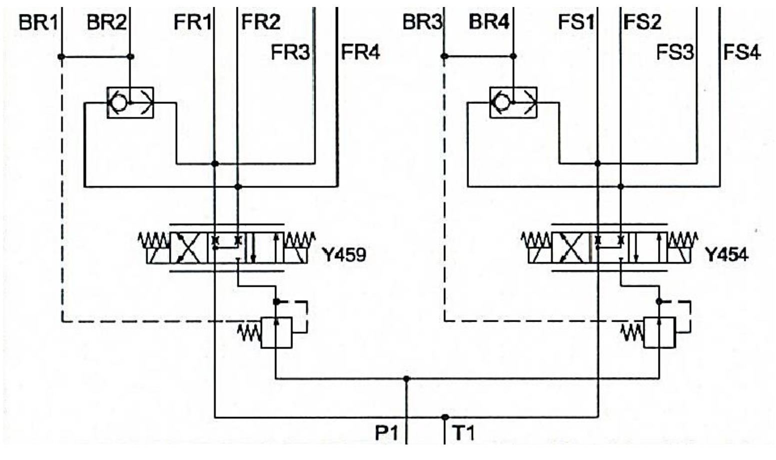

Figure 2.6 Hydraulic scheme for manifold

3 Theoretical background

This section should provide a theoretical background to the reader.

3.1 3D printing

3D printing is increasingly used synonymously to AM. AM is a process where digital 3D design data is used to build up a component layer by layer by depositing material [4]. TO software often suggest highly complex surfaces and internal structures which traditional manufacturing methods struggle to create. There are several different methods included in AM. Only the manufacturing methods used in this thesis will be explained in further detail later in this chapter. Other examples of AM are Stereolithograph Apparatus, Fused Deposition Modelling or Electron Beam Melting. For further information about AM technologies, the reader is referred to for example Ian Gibson et al. [5].

Other technical terms relating to AM are infill, layer height, support material, lattice structure and print orientation, PO. Infill is the percentage, of the inside volume of the part, that's filled with material. Layer height is the thickness of each layer which create the part [6]. Support material are often required to hold an object together while printing. The printed parts should not have an overhang beyond 45 degrees. If you print beyond 45 degrees the part may sag and then support material is needed. Lattice structure refers to the internal pattern that could be created. PO play a crucial role in where, and how much, support material is needed. Reducing the amount of support material reduces the costs. Surface quality can also be affected by PO [7]. One must consider both support material and PO when designing parts for AM. Parts produced by AM are anisotropic, different properties in different directions because of layer by layer production, which also has to be considered when designing parts.

3.1.1 **Selective Laser Sintering**

Selective Laser Sintering, SLS, fuses together a powder of plastic, ceramic or glass with heat from a high-power laser to form a solid, three-dimensional part [8]. The printing is done in a sealed box, see for example the machine in Figure 1.2 in chapter

1.5, so the temperature is just below the melting point of the material. The laser then only needs to create a slight increase to melt and fuse the powder together. The EOS Formiga P110 machine is using SLS technology. A piston moves the powder bed up, providing the building material for each layer. A roller then transports the powder to the building table. The building table is then lowered by a distance equal to the layer thickness. After manufacturing the part, the part is removed and excess powder is brushed away [9]. The SLS process is visualized in Figure 3.1 below.

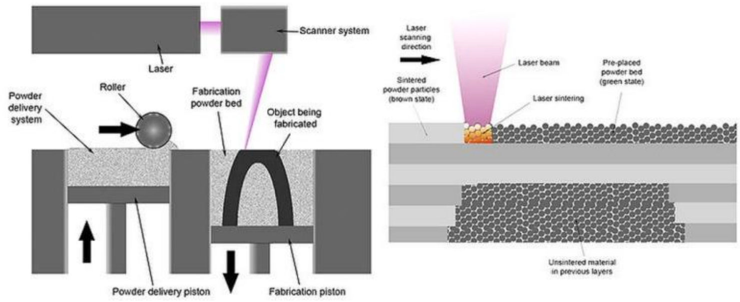

Figure 3.1 Schematic for a selective laser sintering system [8]

Tolerances for parts manufactured using SLS are ±0.3mm, with sandblasting or surface coloring as post processing alternatives [9]. There are post processing alternatives but parts manufactured using SLS usually don't require additional tooling once printed. Support material are not needed when using SLS, making SLS less time-consuming [8]. SLS possible materials are Alumide, Nylon (Polyamide PA2200), Glass Filled Nylon (Polyamide PA3200) PrimeCast (polystyrene based) and PrimePart (Polamide based) [9].

Nylon, PA2200, is the material used in the EOS Formiga P110 machine. Material properties are specified by producer material database. Notable values are shown in Figure 3.2 below. Tensile Modulus is the measure of stiffness for a material. Tensile Strength is the stress a material can take before failure, note that there is no specified yield point, and Strain at break is the strain a material can take before failure. The ISO standard specifies the testing. No temperatures are specified for the tensile tests. The density for PA2200 is 930 kg/m^3 [10]. PA2200 was selected since it's the polymer used in the Formiga P110 machine at LTH.

Tensile Modulus			ISO 527-1/-2
X Direction	**1650**	MPa	
Y Direction	**1650**	MPa	
Z Direction	**1650**	MPa	
Tensile Strength			ISO 527-1/-2
X Direction	**48**	MPa	
Y Direction	**48**	MPa	
Z Direction	**42**	MPa	
Strain at break			ISO 527-1/-2
X Direction	**18**	%	
Y Direction	**18**	%	
Z Direction	**4**	%	

Figure 3.2 Notable material properties for PA2200 [10]

3.1.2 **Selective Laser Melting**

Selective Laser Melting, SLM, melt metallic powder together with the heat from a high-power laser to a part from 3D CAD data. In contrast to Direct Metal Laser Sintering, DMLS. SLM melts the metallic powder and DMLS sinter the metallic powder. The SLM and DMLS process is similar to the SLS process. SLM manufactures parts that are very dense and strong [11].

Tolerances for SLM are around ±0.05mm, with required heat treatment and post processing. DMLS tolerances, in contrast, are around ±0.1mm [9]. Both methods require support material and post processing. SLM made parts require heat treatment because of introduced stress from the melting process. SLM possible materials are Stainless steel 316L including 17-4PH, H13 tool steel, aluminium Al-Si-12, titanium CP, Ti-6Al-4V and Ti-6Al-7Nb, cobalt-chrome (ASTM75) and inconel 718 including 625 [9].

Material properties for example EOS StainlessSteel GP1 can be seen in Figure 3.3 below. Minimal yield stress is 530 MPa and the density is 7800 kg/m^3 [12].

	As manufactured	Stress relieved (1 hour at 650 °C)
Ultimate tensile strength		
- in horizontal direction (XY)	min 850 MPa (123 ksi) typical 930 ± 50 MPa (135 ± 7 ksi)	typical 1100 MPa (160 ksi)
- in vertical direction (Z)	min 850 MPa (123 ksi) typical 960 ± 50 MPa (139 ± 7 ksi)	typical 980 MPa (142 ksi)
Young's modulus	170 ± 30 GPa (25 ± 4 msi)	typical 180 GPa (26 msi)
Elongation at break		
- in horizontal direction (XY)	min 25 % typical 31 ± 5 %	typical 29 %
- in vertical direction (Z)	min 25 % typical 35 ± 5 %	typical 31 %

Figure 3.3 Notable material properties for EOS StainlessSteel GP1 [12]

3.2 Topology Optimization

Structural optimization is divided into sizing optimization, shape optimization and TO. TO is the most general form of structural optimization [13]. The goal of TO is to optimize material layout within a design space, DS, for certain boundary conditions and constraints. Boundary conditions are for example forces, displacements and temperatures. A model with DS have to be created in CAD and then imported to the TO software. In the software you apply boundary conditions, optimization objective and select constraints. Optimization objective are maximize stiffness or minimize mass. Constraints are for example either a mass target or a minimum safety factor. It's possible to set frequency constraints and thickness constraints, along with accuracy, contact, gravity and different LCs.

TO software commonly utilize finite element method to evaluate the design and then a nonlinear programming technique to iterate forth a satisfactory solution. For further information about structural optimization theory the reader is referred to for example Peter W. Christensen and Anders Klarbring [13].

4 Generating design ideas

This section presents a short software discussion and the generated topology optimized design ideas for the dog bone and the banana.

4.1 Software discussion

The chosen TO software for this thesis was solidThinking Inspire. There are several TO software packages available with different capabilities that suit different users better. Simulia Tosca, Abaqus ATOM and Altair OptiStruct are some other examples for TO software. SolidThinking Inspire is using the same finite element solver as Altair Optistruct. The simplified interface of Inspire in combination with automatic meshing reduce Inspire to essentially black box functionally [14]. For a more detailed TO software review the reader is referred to for example Ian Ferguson [14].

SoildThinking Inspire was selected as TO software firstly because of its simple interface and secondly because of the boundary conditions for the chosen components were of simple characteristics, i.e. only forces, moments and displacements.

4.2 Material

The PA2200 was modeled using the parameters in Figure 3.2 in chapter 3.1.1. The parameters in Inspire can be seen in Figure 4.1 below. The Poisson's Ratio was assumed to be 0.3. Note that the lowest, in Z-direction, was selected as Tensile Yield Strength.

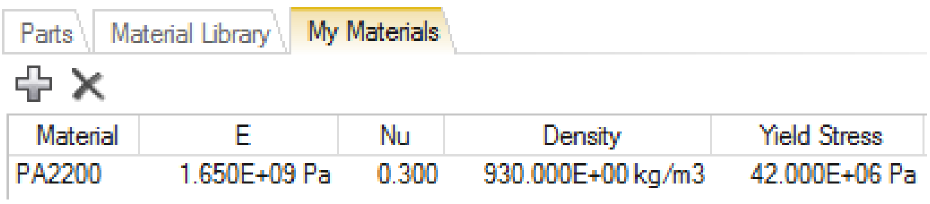

Figure 4.1 PA2200 material properties Inspire

Steel material properties are shown in Figure 4.2 below. The properties are similar to EOS steel except the yield stress. The TO designs will be regarded as inspiration and designed components will be analyzed further in ANSYS.

Parts | Material Library | My Materials

Material	E	Nu	Density	Yield Stress
Steel (AISI 316)	195.000E+09 Pa	0.290	8.000E+03 kg/m3	205.000E+06 Pa

Figure 4.2 Steel material properties Inspire

4.3 Dog bone

To generate the TO design, a DS was created. The DS for the dog bone is created from the assembly which can be seen in Figure 2.1 in chapter 2.2. The four bolts, needed to attach the dog bone to the feeder, must be considered when creating the DS. The bolts are 40mm long and they are mounted from the dog bone into the feeder. The space needed for the hydraulic cylinder is the same as for the original dog bone design. The expansion bolt dimensions are also the same as for the original design. This means that the two ears, attaching the hydraulic cylinder through the expansion bolt, will also be limited in thickness. The DS, in brown, can be seen in Figure 4.3 below. The dog bone was simulated using PA2200, and the weights specified in the figures are for PA2200.

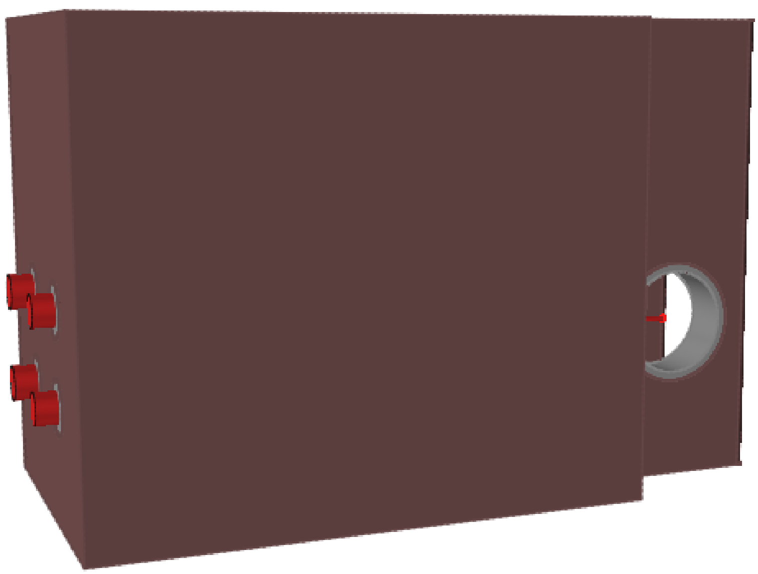

Figure 4.3 DS for the dog bone (3.04 kg)

The boundary conditions for the dog bone are the forces in the ears, from the hydraulic cylinder, and the supports for the bolts. The force in each ear is estimated to 10kN. The boundary conditions can be seen in Figure 4.4 below. Temperatures have not been included in the analysis.

Figure 4.4 Boundary conditions dog bone

When a DS is created and boundary conditions are set the next step is to set up the optimization, i.e. to set optimization criteria and constraints. Maximize stiffness was selected as optimization objective with a mass target of 20%. This mass target means that 80% should be carved away from the design space. The optimization objective and constraints can be seen in Figure 4.5 below.

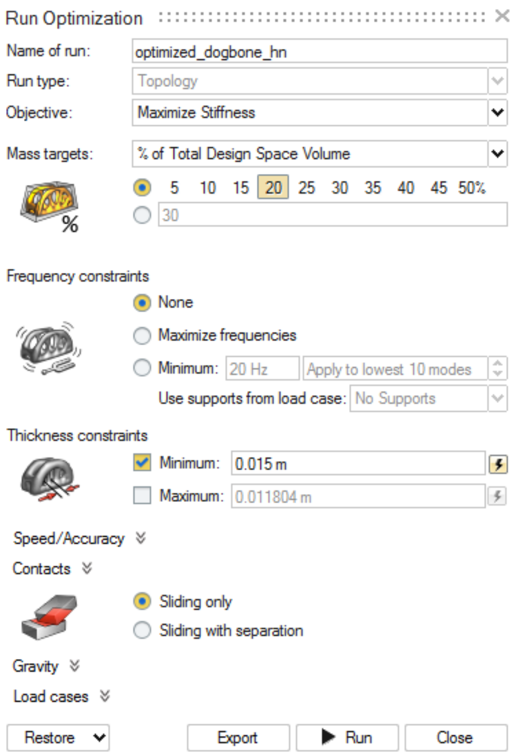

Figure 4.5 Dog bone optimization objective and constraints

This setup generated a TO design which can be seen in Figure 4.6 below.

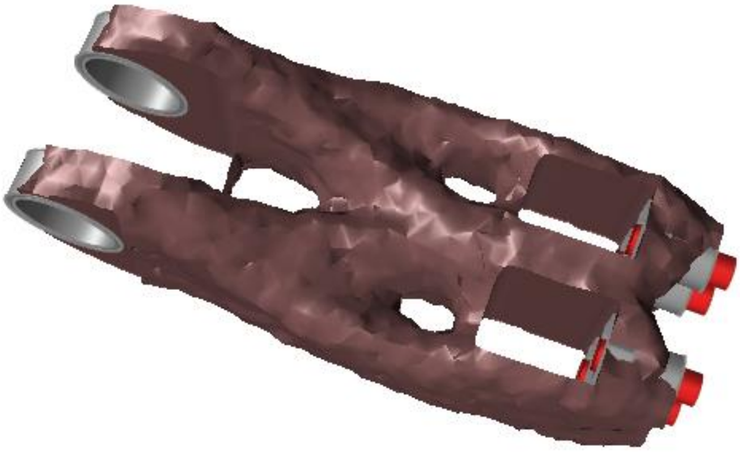

Figure 4.6 Initial TO dog bone design (0.54 kg)

4.4 Banana

The banana was TO using the same work order as for the dog bone. A DS was created as seen, in brown, in Figure 4.7 below. The banana was simulated using steel, and the weights specified in the figures are for steel.

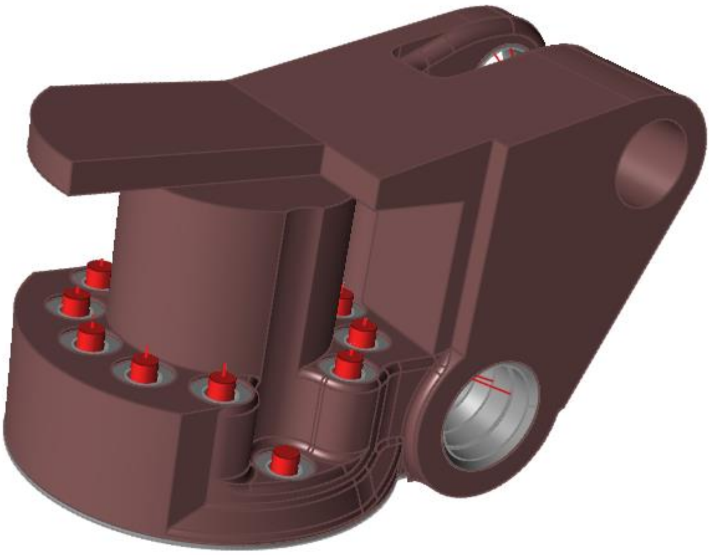

Figure 4.7 DS for the banana (87.8 kg)

Figure 4.8 below shows where the boundary conditions are applied. The magnitude is not shown since the banana have several LCs, which are specified in chapter 2.3 Table 2.1.

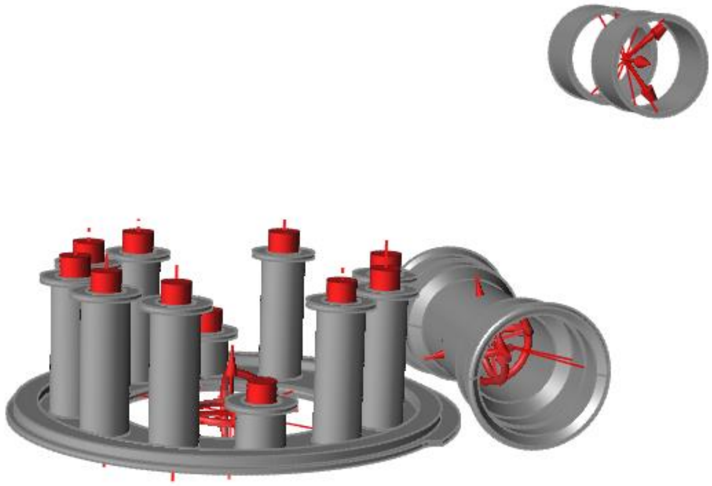

Figure 4.8 Placement for banana boundary conditions

Maximize stiffness was selected as optimization objective with a mass criteria of 30%. LC 1, LC 5, LC 6 and the combination LC 2+LC 5+LC 8 is shown in Figure 4.9, Figure 4.10, Figure 4.11 and Figure 4.12 respectively. LC 1 is for the hydraulic cylinder, LC 5 is for the axis and LC 6 is for the bolt fastening. Other TO using other LCs with the same objective and criteria are shown in Appendix A.

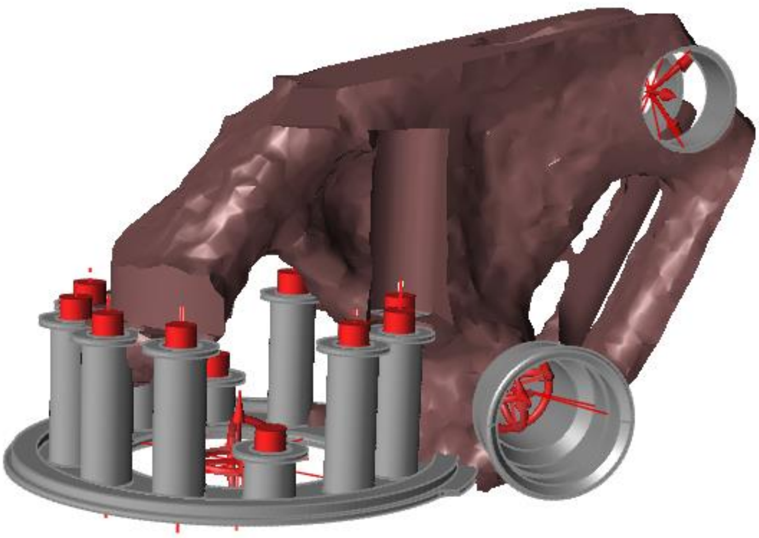

Figure 4.9 Optimized banana for LC 1 (28.7 kg)

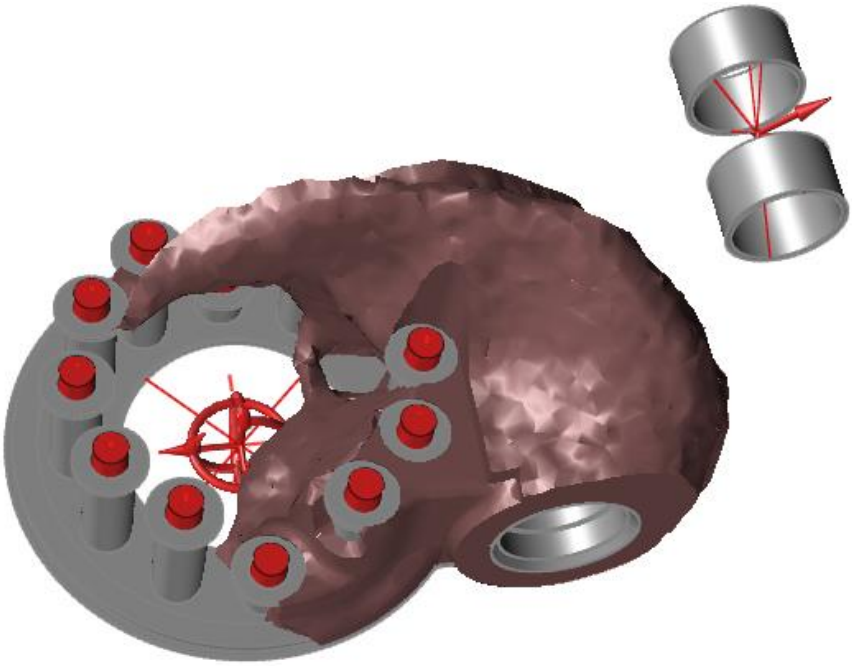

Figure 4.10 Optimized banana for LC 5 (28.6 kg)

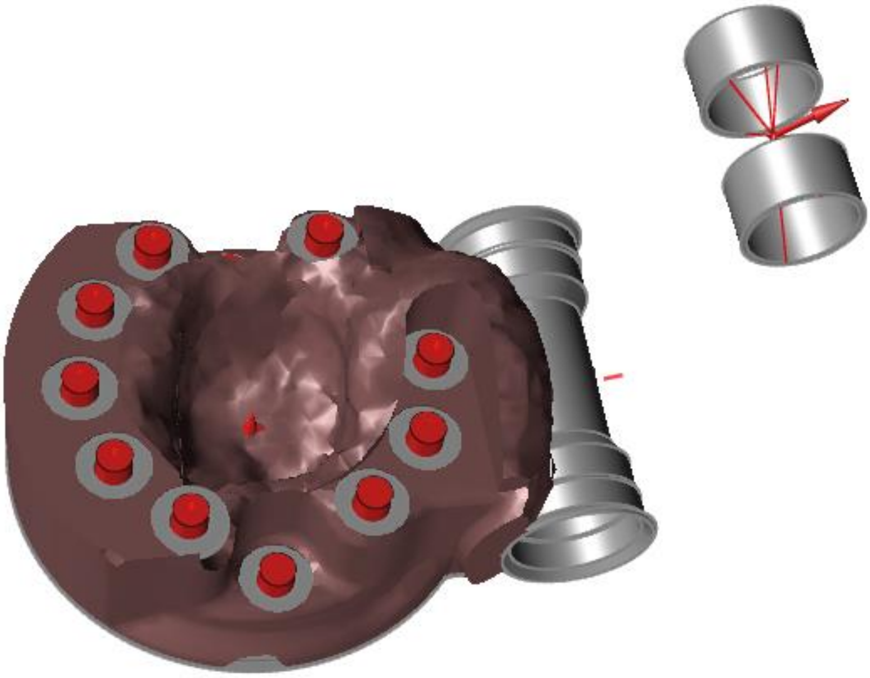

Figure 4.11 Optimized banana for LC 6 (28.2 kg)

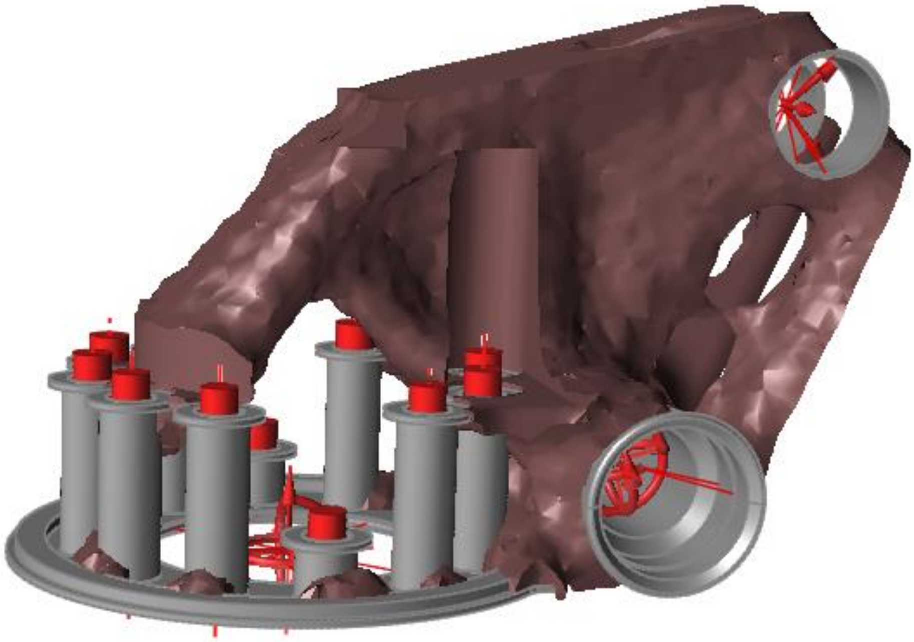

Figure 4.12 Optimized banana for LC 2+LC 5+LC 8 (29.1 kg)

5 Design process

This section presents the design process for the four challenges.

5.1 Dog bone

The initial design was created using the optimized design, seen in Figure 4.6 in chapter 4.3. The initial CAD design is seen Figure 5.1 below.

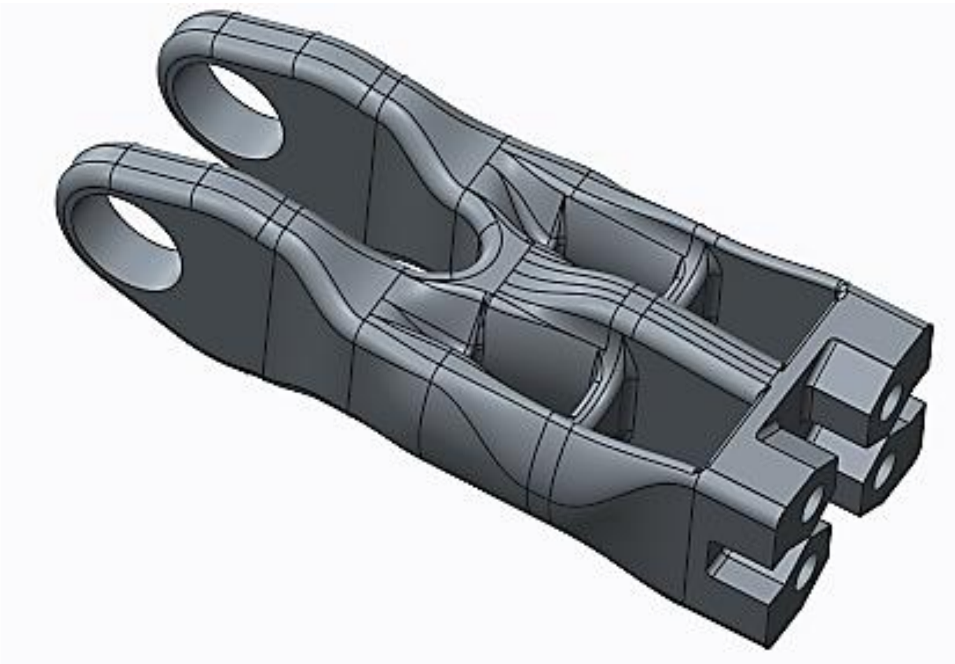

Figure 5.1 Initial CAD dog bone design

From the initial design, only created from the TO design, it was realized that the ears were too weak for an expansion bolt and the hydraulic cylinder fastening. This initial design was anyhow printed and brought up to AC for further discussion before creating the next version. The printed initial dog bone design can be seen in Figure 5.2 on the next page.

Figure 5.2 Polymer printed initial dog bone design

The next version was made bigger and with a square reinforcement for the ears. The rounds were also increased. This version can be seen in Figure 5.3 below.

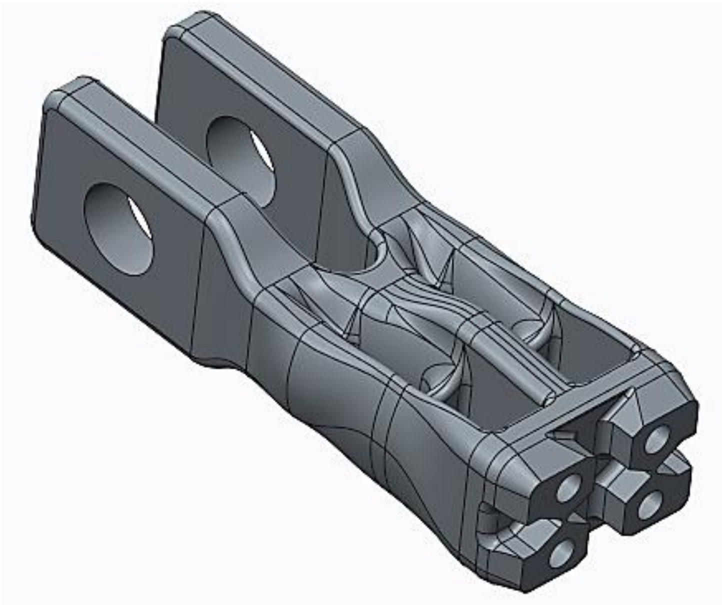

Figure 5.3 Square reinforced dog bone

The ear reinforcement was changed to a circular reinforcement. Ribs were added to the bolt attachment and rounds were increased even more. Diameter, for the bolt holes, were increased from 12mm to 12.5mm to account for SLS AM tolerances. The final dog bone design was trimmed 1mm to fit the SLS machine. The circular dog bone design can be seen in Figure 5.4 below. The printed initial dog bone design can be seen in Figure 5.5 on the next page.

Figure 5.4 Circular reinforced dog bone

Figure 5.5 Polymer printed circular reinforced dog bone

5.2 Banana

No new design has been created for the banana. This will be discussed in chapter 10.2.

5.3 Nipple-replacement

The initial design was created by looking at the assembly, see Figure 2.4 in chapter 2.4, and creating something that could solve the problem. An initial nipple-replacement design can be seen in Figure 5.6 below.

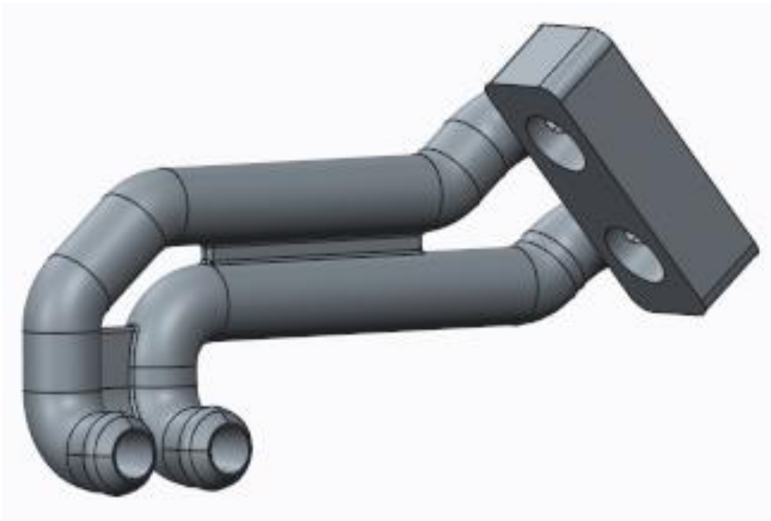

Figure 5.6 Initial nipple-replacement design

This initial design was also printed, which can be seen in Figure 5.7 on the next page, and brought to AC for discussion.

Figure 5.7 Polymer printed initial nipple-replacement

After discussion with AC, a new design was made. The design is now symmetric, more compact and also angled forward to get more space. The initial symmetric design can be seen in Figure 5.8 below. The hose fastening was made to be tapped afterwards.

Figure 5.8 Initial symmetric nipple-replacement

The initial symmetric design, placed where it should be, can be seen in Figure 5.9 below.

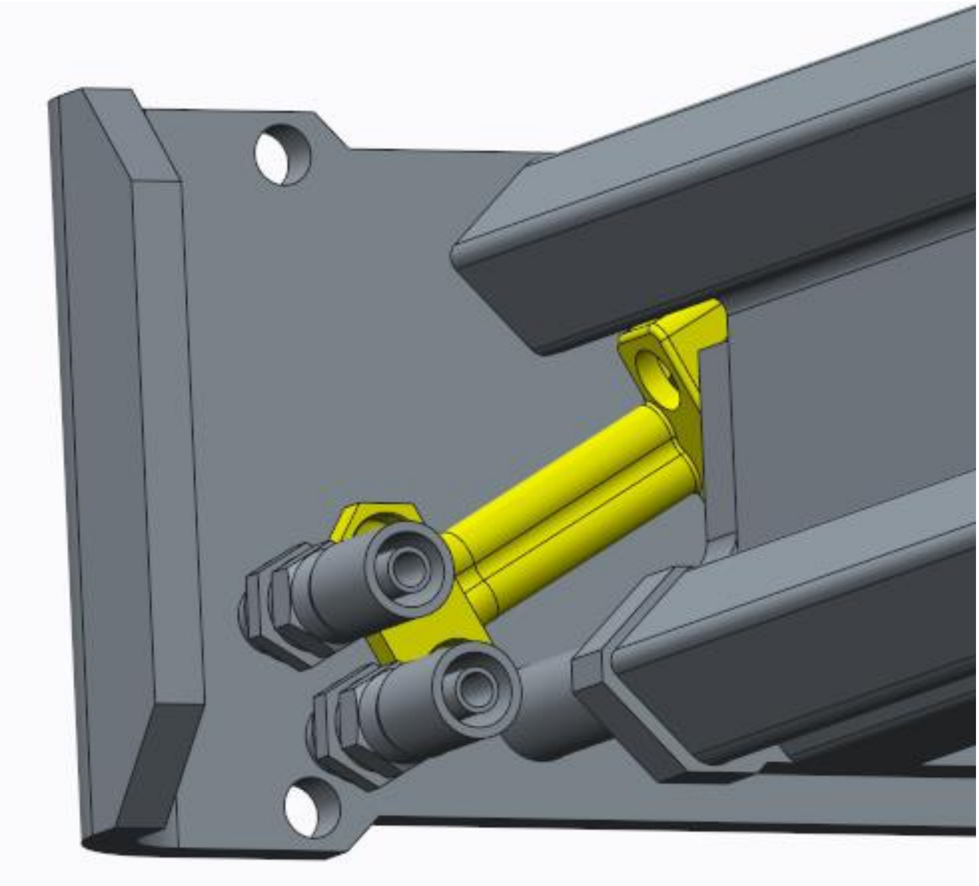

Figure 5.9 Symmetric design placement

After further discussions the design was changed for a proper design for fastening a banjo-screw. Also changed the design idea to create the threads directly instead of being tapped afterward. The threads for the nipple-replacement are G7/8”. Thread profile and dimensions are specified in Appendix B. A reinforcement was also added. The reinforced design can be seen in Figure 5.10 on the next page.

Figure 5.10 Reinforced nipple-replacement design

This reinforced design was also printed, which can be seen in Figure 5.11 below. The PO has to be such that the threads are printed vertically.

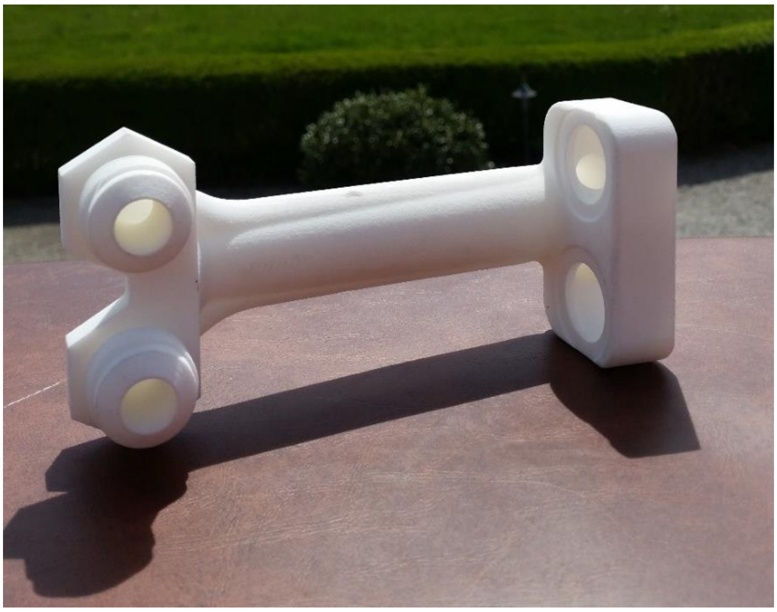

Figure 5.11 Polymer printed reinforced nipple-replacement design

5.4 Manifold

The manifold is manufactured by drilling and plugging from a solid cylinder block. The paths inside are shown in Figure 5.12 below.

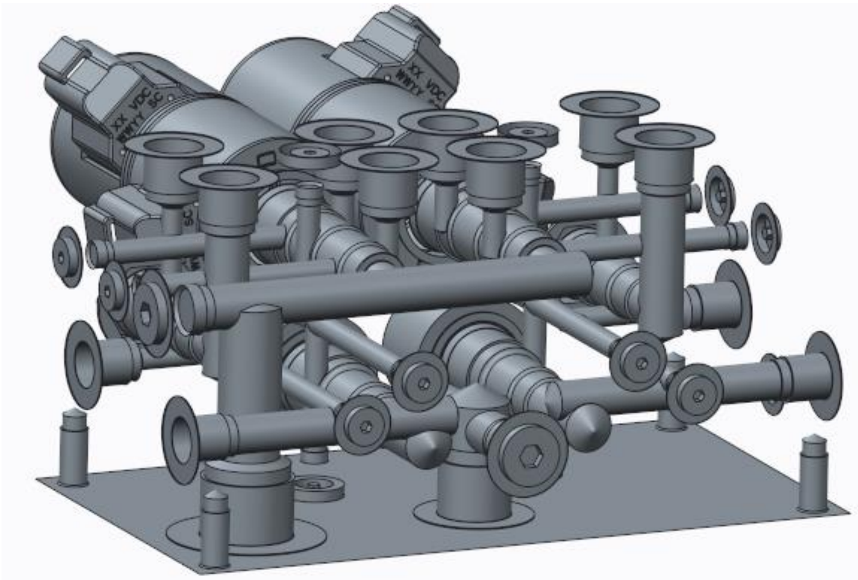

Figure 5.12 Paths inside manifold

The first idea design was made using the same valve outlets which can be seen in Figure 5.13 below.

Figure 5.13 New manifold idea

Further development of this concept became the initial design. The hose attachments were threaded and three fastening points were added. The manifold have four different threads. The threads are G7/8”, G1 1/16”, G3/4” and G9/16” for P1, T1, FR and BR outlets respectively. See the hydraulic scheme in Figure 2.6 in chapter 2.5. The G1 1/16” thread is not found in Appendix B but is found on [15]. The fastening points needs to be tapped afterwards. The initial design can be seen in Figure 5.14 and Figure 5.15 below.

Figure 5.14 Initial manifold design

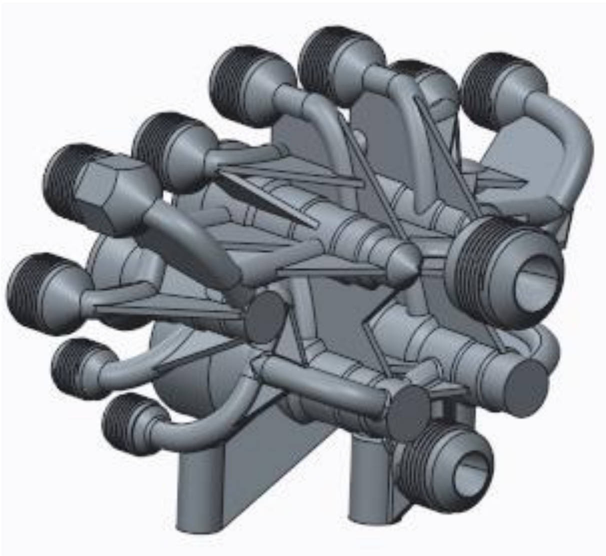

Figure 5.15 Initial manifold design

Increased the valve thickness slightly and added another reinforcement for the two fastening points on the sides. Added another reinforcement linking all outlets together. Added holes in reinforcements to further decrease the weight. The reinforced version can be seen in Figure 5.16 and Figure 5.17 below.

Figure 5.16 Reinforced manifold design

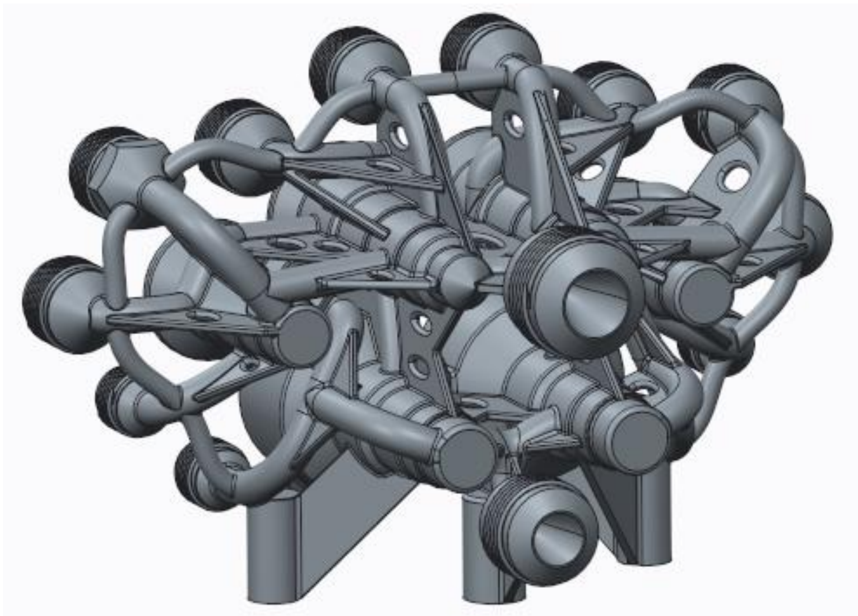

Figure 5.17 Reinforced manifold design

The reinforced manifold design was printed, which can be seen in Figure 5.18 below. The PO has to be such that the threads are printed vertically.

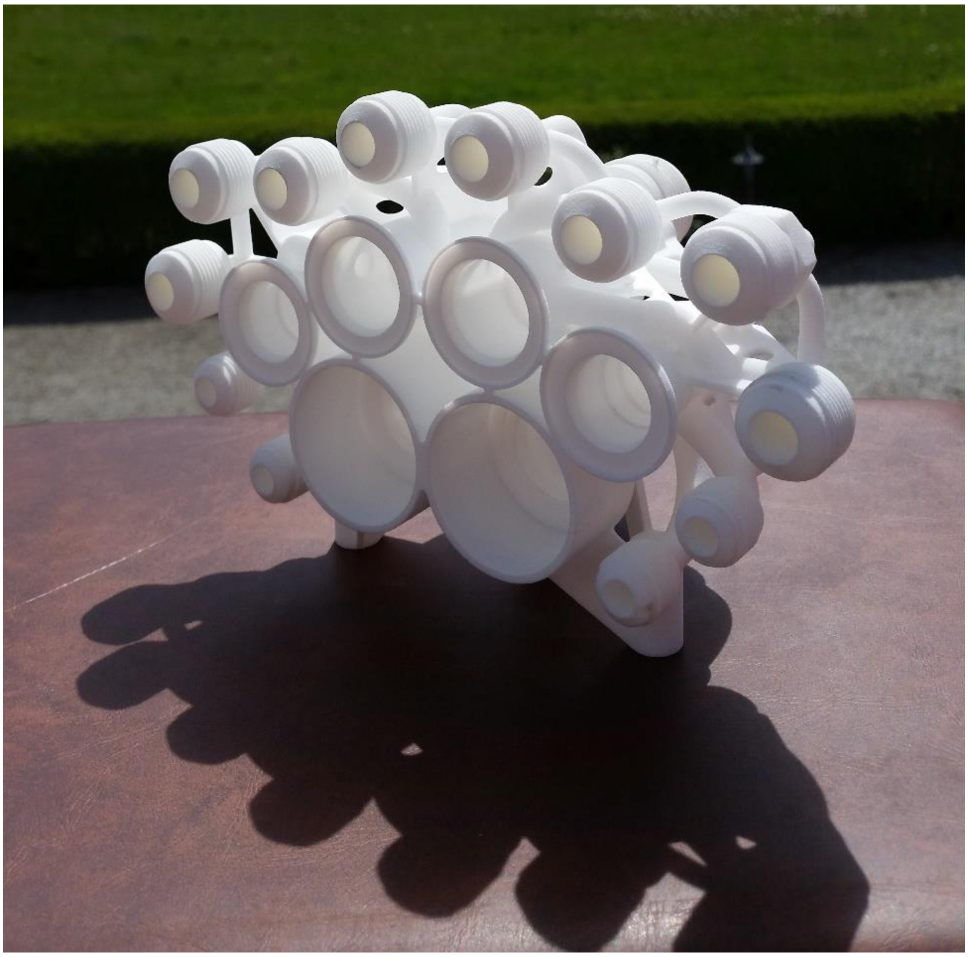

Figure 5.18 Polymer printed reinforced manifold design

6 Analysis and initial testing

This section presents the finite element analysis of the dog bone and initial component testing for the dog bone and the nipple-replacement at AC.

6.1 Dog bone

The circular reinforced dog bone design was analyzed in ANSYS, to verify that there wouldn’t be any weak points. The following subchapters are the ANSYS set up and solutions. Temperatures, fatigue and buckling have not been included in the analysis.

6.1.1 **Material**

The PA2200 was modeled as isotropic elastic using the parameters in Figure 3.2 in chapter 3.1.1. The parameters in ANSYS can be seen in Figure 6.1 below. Poisson’s Ratio was selected to 0.4 according to [16]. Note that the lowest, in Z-direction, was selected as Tensile Ultimate Strength. The lowest Tensile Ultimate Strength was selected to not overestimate the capability of PA2200.

Property	Value	Unit
Density	0,93	g cm^-3
Isotropic Elasticity		
Derive from	Young's Modulu...	
Young's Modulus	1,65E+09	Pa
Poisson's Ratio	0,4	
Bulk Modulus	2,75E+09	Pa
Shear Modulus	5,8929E+08	Pa
Tensile Ultimate Strength	4,2E+07	Pa

Figure 6.1 PA2200 material properties ANSYS

6.1.2 **Mesh**

The dog bone was meshed using ANSYS default settings. The model consists of 31232 nodes and 17876 elements. The mesh can be seen in Figure 6.2 below. There was a limit on the amount of nodes since the student version of ANSYS was used. The limitation on nodes is why no mesh convergence study has been made.

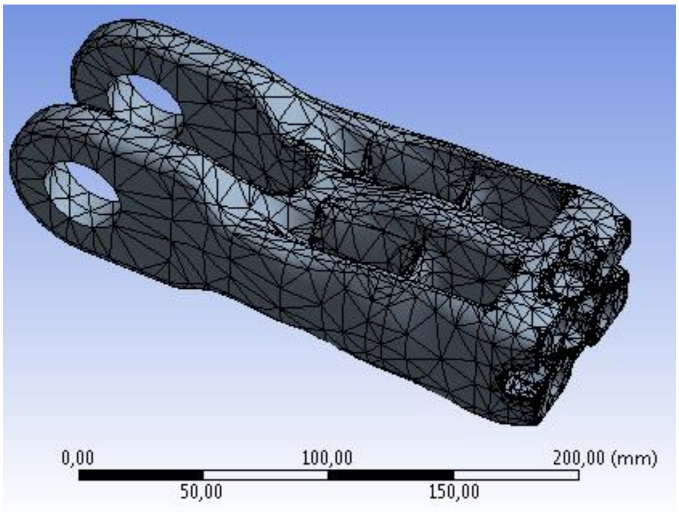

Figure 6.2 Dog bone mesh

6.1.3 **Boundary conditions**

The modeled boundary conditions for the dog bone are the bearing loads from the hydraulic cylinder, 10kN in each ear, and the M12 bolts holding it to the feeder. The boundary conditions can be seen in Figure 6.3 below.

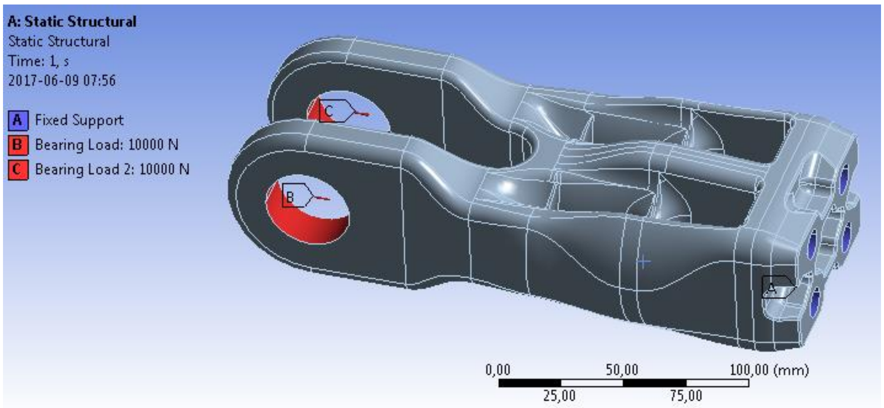

Figure 6.3 Boundary conditions dog bone

6.1.4 **ANSYS dog bone results**

The equivalent stress is shown in Figure 6.4 below, note that most of the structure is the same color. This indicates a proper topology optimization.

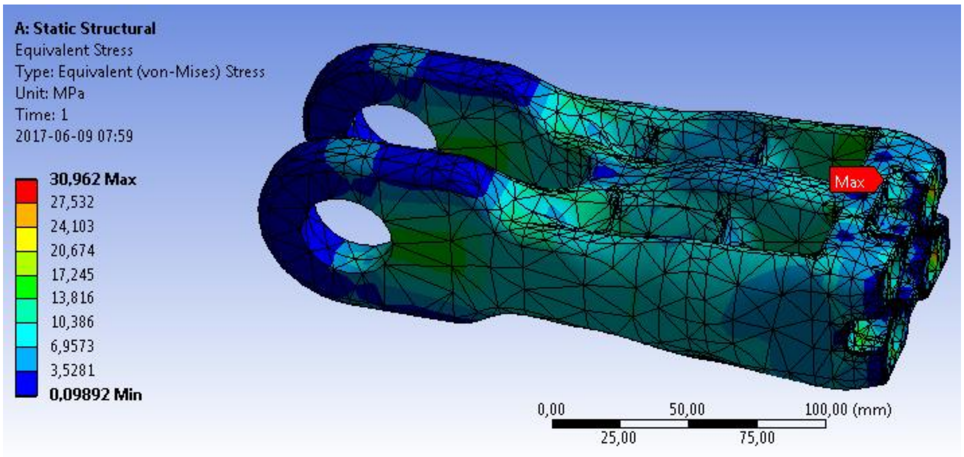

Figure 6.4 Equivalent (von-Mises) stress dog bone analysis

The max stress shows up, see Figure 6.5 below, along the edge of the support boundary condition.

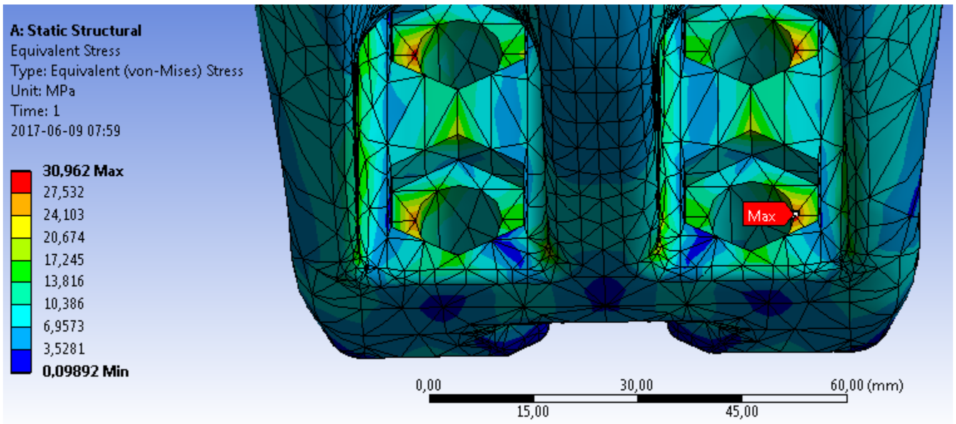

Figure 6.5 Max stress dog bone analysis

The total deformation for the dog bone is shown in Figure 6.6 below.

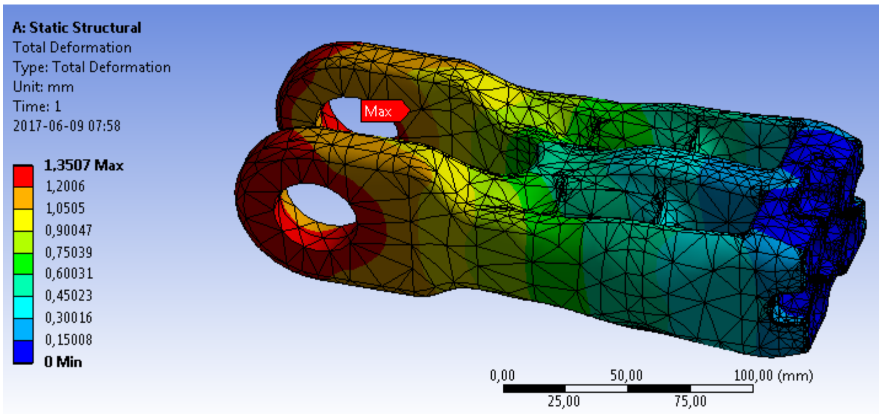

Figure 6.6 Total deformation dog bone analysis

6.1.5 **Testing**

After some initial doubts about using plastics an expansion bolt was inserted and tightened, see Figure 6.7 below.

Figure 6.7 Inserting and tightening an expansion bolt

The dog bone withstood the force from the expansion bolt without any apparent difficulties.

The dog bone was then mounted on the feeder, see Figure 6.8 below, to make sure that it could be properly fastened. There were no possibility to connect a hydraulic cylinder for a functional test.

Figure 6.8 Mounting dog bone on feeder

6.2 Nipple-replacement

It was immediately obvious that the nipple-replacement lacked the correct length. The threads were also tested with a ½" hose which revealed that the threads were incorrect. The problem was a misinterpretation about the internal and external thread dimensions and which diameter the nipple had without the threads. The threads were then needed to be changed in the final nipple-replacement design and also in the final manifold design.

There were no possibilities to test the component with the correct sized banjo screw.

6.3 Manifold

There was no possibility to test the manifold. The threads were however also incorrect for the manifold.

7 New final designs

This section presents the new final designs for the four challenges.

7.1 Dog bone

The initial testing yielded no new design changes so the reinforced circular dog bone is the final design. See design in Figure 5.4 and polymer print in Figure 5.5 in chapter 5.1.

7.2 Banana

No new final design has been created for the banana. The banana will be discussed in chapter 10.2. The dog bone was printed in 1/3rd scale for presentation purposes. The printed banana can be seen in Figure 7.1 below.

Figure 7.1 Polymer printed AC banana

7.3 Nipple-replacement

After printing the reinforced design and bringing it to AC it was obvious that the design could not be shortened. The final design is therefore longer and the threads were changed. The final design can be seen in Figure 7.2 below and in the assembly in Figure 7.3 below.

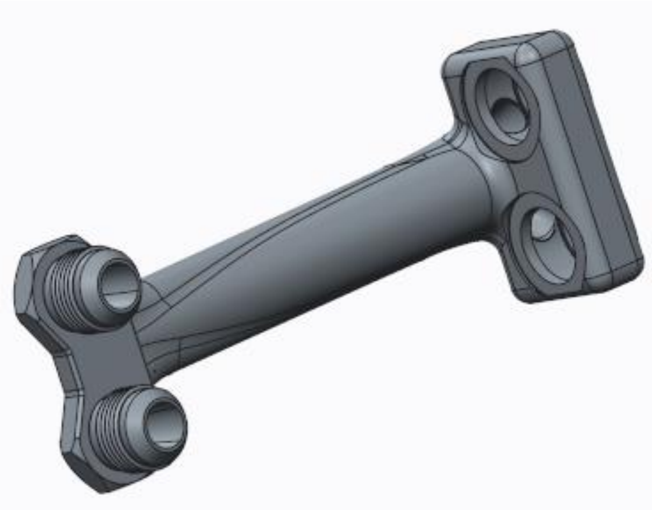

Figure 7.2 New final nipple-replacement design

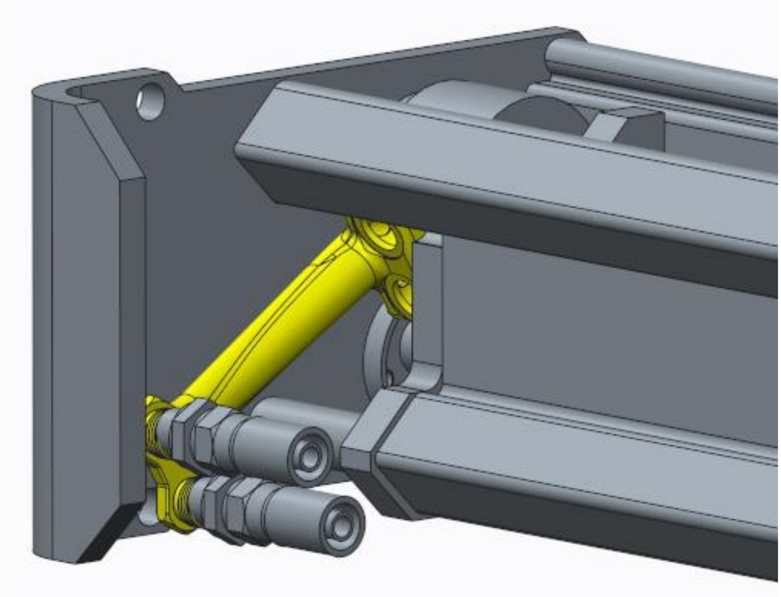

Figure 7.3 Position of new final nipple-replacement design

A cross section of the nipple-replacement is shown in Figure 7.4 below.

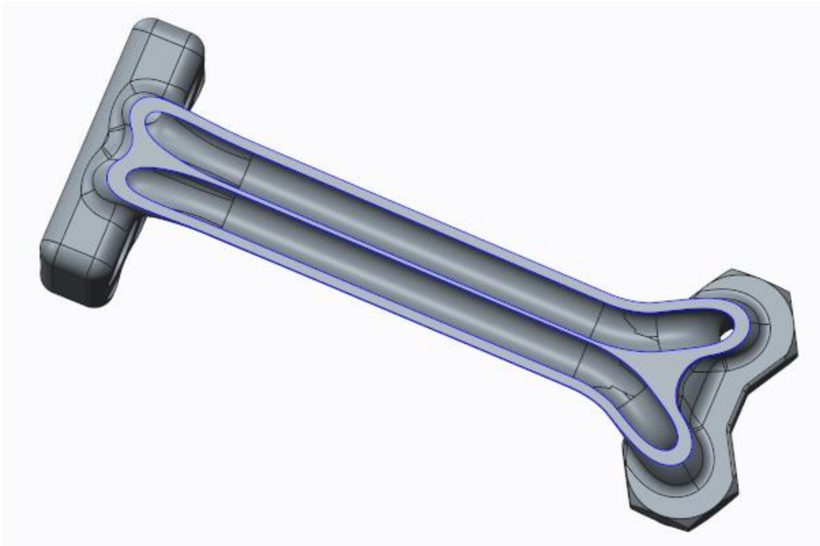

Figure 7.4 Cross section of new final nipple-replacement design

The final nipple-replacement design was printed, which can be seen in Figure 7.5 below.

Figure 7.5 Polymer printed final nipple-replacement design

7.4 Manifold

The threads were changed for the final manifold design. Added wrench grippers to all inlets and outlets and added another reinforcement for one inlet. The wrench gripper dimensions were selected to 17.5mm and 27mm, example wrench openings from Appendix C. The final manifold design can be seen in Figure 7.6 and Figure 7.7 below.

Figure 7.6 New final manifold design from front

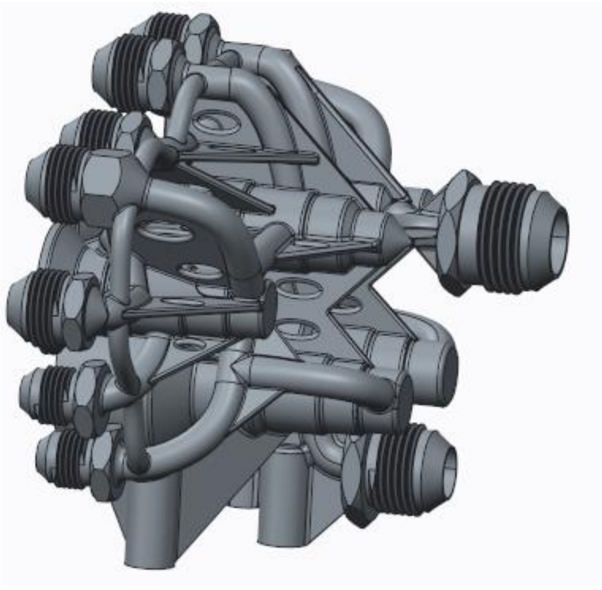

Figure 7.7 New final manifold design from side

8 Component prices

This section presents the component price offers.

8.1 Prices from the web

Two web-based companies, Shapeways and iMaterialize, were selected to gather price offers from. By uploading the designs in STL-format, the price offers are received depending on the material that you want to use. One has to be careful and check the manufacturing method that will be used. Shapeways and iMaterialize do not offer DMLS or SLM manufactured steel components. Shapeways offer DMLS for aluminium, Al, and iMaterialize offer DMLS for aluminium and titanium, Ti. Both companies can print in nylon, polyamide (PA), using SLS. The prices from Shapeways can be seen in Table 8.1 below. The dollar to kronor ratio at the time was 8,81.

Table 8.1 Price offers from Shapeways

	Shapeways	
Dog bone (PA)	$357,79	3 152 kr
Nipple-replacement (Al)	$973,88	8 580 kr
Manifold (Al)	$2 447,48	21 562 kr

The prices from iMaterialize can be seen in Table 8.2 below. The euro to kronor ratio at the time was 9,62.

Table 8.2 Price offers from iMaterialize

	iMaterialize	
Dog bone (PA)	142,71 €	1 373 kr
Nipple-replacement (Al)	764,14 €	7 351 kr
Manifold (Al)	1 390,90 €	13 380 kr

8.2 Prices from local company

Lasertech was selected as the local printing company. Their price for printing the manifold in Al is 26 800kr using SLM. Their offer for printing the manifold in steel using SLM was around 40 000 kr.

9 Comparison

This section presents the comparison between the original designs and the new designs.

9.1 Original and new components

The material, weight and volume for the components will be compared. Table 9.1 below shows the comparison between the original and new design. The star in the table is explained below the table. The banana design was not changed and therefore set to not applicable, N.A. The new weight is shown with the percentage of the original design weight in parenthesis. No exact prices for AM steel components were gathered.

Table 9.1 Comparison between original and new designs

	Dog bone		**Banana**	
	Original	New	Original	New
Material	S355 steel	PA2200	S355 steel	N.A.
Weight	2,41kg	0,54kg (78%)	35,8kg	N.A.
Volume	3,1e+5 mm^3	5,8e+5 mm^3	4,6e+6 mm^3	N.A.
Cost	*	1 373 kr	*	N.A.
	Nipple-replacement		**Manifold**	
	Original	New	Original	New
Material	S355 steel	EOS Steel	S355 steel	EOS Steel
Weight	1,07kg	0,71 (34%)	14,7kg	1,25kg (92%)
Volume	1,37e+5 mm^3	9.2e+4 mm^3	1,9e+06 mm^3	1,6e+05 mm^3
Cost	*	-	*	-

(*): Confidential

10 Discussion and conclusions

This section presents final assessment for the challenges with a simulations and comparison discussion and finally goal fulfillment and further work.

10.1 Dog bone

According to the initial analysis and testing the plastic AM dog bone seem to be able to replace the metal dog bone. More testing would be needed to reassure that this is the case. Many parts could then likely be changed, and thereby reduce the weight and possibly cost, if this is the case.

10.2 Banana

The weight loss, which was simulated using TO software, was deemed not enough for the extra cost that AM brings. The banana DS is not the ideal scenario for a TO. See the difference in DS between the banana and the dog bone in Figure 4.7 and Figure 4.3 respectively. A big and undisturbed DS is preferable. The banana component is assembled with many other parts. If one could reimagine and redesign the whole system as one component it might be considered proper to use AM.

Using different lattice structures one could possibly get a stiff and low weight component good enough to be considered for AM. Like bone, one would want the optimized structure to have different regions with different internal structure.

One should remember that not all components are suitable for AM.

10.3 Nipple-replacement

The nipple-replacement would be troublesome to create without AM. To fit into the tiny space where the prolonged nipples are and without several manufacturing steps. The nipple-replacement will cost significantly more than the original design but the supply chain could be significantly improved by using this new design. This design shows that parts needed which are difficult to manufacture with traditional methods AM could prove useful.

The nipple-replacement also get improved flow when you remove the 90 degree connections.

10.4 Manifold

Removing 92% of the weight while increasing performance is a great improvement. The weight for a machine could be significantly lowered depending on how manifolds the machine has. Simpler manifolds are probably not suitable for AM and would be a lot more costly to produce.

Valve example tolerances can be seen in Appendix D. SLM could produce parts with this tolerance but not with the surface finish. If that quality of surface finish is required the valves would need after-treatment.

The manifold also get improved flow when you remove the 90 degree connections.

Lasertech SLM steel offer at 40 000 kr was deemed too expensive by AC and therefore the manifold was printed in Al for further investigations.

10.5 Simulations discussion

Boundary conditions for the dog bone and banana have not included bolt pretensions. This is because at this stage it was deemed too detailed and would only add more complexity. The expansion bolt, for the dog bone, was not simulated either because the exact pressure created was unknown.

One would like to have software capable of setting different lattice structures for different regions. Using a different software it might be possible to do this and get proper simulations for the banana for example.

In the ideal world one would also like to be able to perform solid mechanics calculations with these different regions of lattice structures. These calculations are too time consuming using the computing power that is available today.

10.5.1 **Inspire**

Maximize stiffness was selected as objective because it’s the main purpose for the component. The secondary purpose is minimized weight. A minimized weight objective for the dog bone can be seen in Figure 10.1 below. One could use this to create a new laser cut metal design. For metal replacement maximized stiffness would be recommended. This minimized mass simulations weights 1.49kg in steel and 0.17kg in PA2200. One must pick carefully when using TO software and use the results as design inspiration.

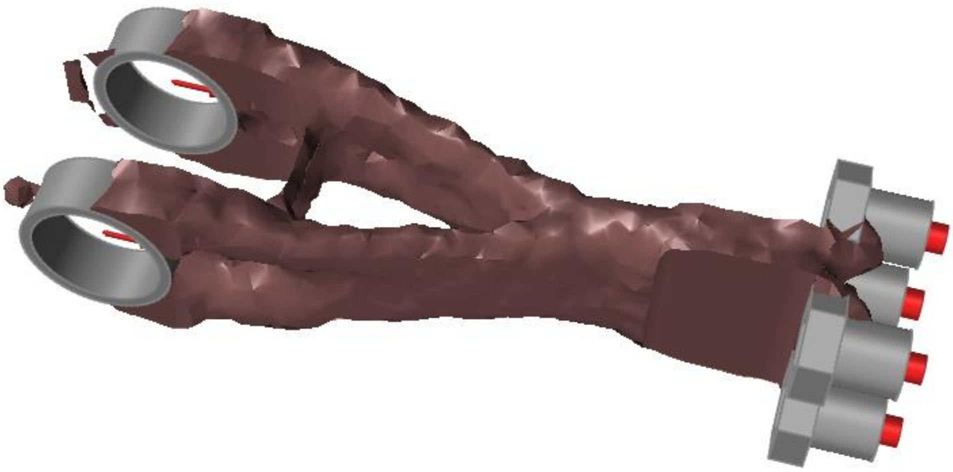

Figure 10.1 Minimized mass objective dog bone

10.5.2 **ANSYS**

Since Inspire performs a finite element analysis, only one extra simulation was done. The PA2200 was modeled using a linear elastic model. AM components are not isotropic but it was modeled this way to get a faster set up and only a rough estimate was needed. The mesh was limited by the student version of ANSYS so very exact simulations could not be done. Still a result under yield stress emerged. Figure 6.5 in chapter 6.1.4 shows a presumed stress concentration because of boundary condition set up. One could instead imagine that the whole bottom plate, as a result of the four bolts, would be considered fixed.

10.6 Comparison discussion

The dog bone volume increases so the weight reduction comes greatly from the lower density of PA2200. S355 steel and EOS steel have the same density so the weight reduction for the nipple-replacement and the manifold is only from the new design. Large SLM manufactured components in steel are expensive. The offer from the local company, Lasertech, was deemed too expensive by AC. The polymer dog bone costs less to make using SLS polymer instead of laser cut steel.

Prices always depends greatly on order amount and is therefore hard to draw any hard conclusions from.

10.7 Goal fulfillment

The goals can be seen in chapter 1.3. Reducing the weight of the booms and feeders have been fulfilled. Lowering the prices are exceptionally challenging for AM components but the dog bone could potentially be cheaper in PA2200. Enhanced performance is fulfilled considering easier hose handling and improved flow.

Only the dog bone was analyzed but it could be said to have equivalent strength. Hose wear was reduced for the manifold. The nipple-replacement is stronger than original design however durability was not evaluated. Operating visibility was not applicable for the selected components. Impact of operating environment was not evaluated. Insights to usefulness of AM have been fulfilled. Understanding when plastics and metal AM is useful is also considered fulfilled.

Overall satisfactory goal fulfillment.

10.8 Further development

AM is useful for prototyping and rapid development and should at least be considered for that purpose alone.

The new designs requires more testing. Preferably real physical testing in machine and fatigue testing. One should also consider testing with changes in infill and different lattice structures. More precise simulations, with bolt pretensions and expansions bolts, could also be useful. The thread tolerances and quality should also be assessed. More price offers should also be collected to fully understand the price situation for plastic and metal AM components.

One could also imagine chips or other electronics easily being put into the component when it’s being created. In such a way one could get extra functions into an AM component.

The main development issue would be figuring out the whole supply chain reaction when changing from traditional manufacturing methods to AM. Estimating the extra time needed from designers to create more advanced models would also be useful. One cannot simply look at the new component price and draw conclusions from that. AM components bring with them other customer values and changes to the logistics situation. Decision making will remain unclear until the true price of changing to AM components have been investigated.

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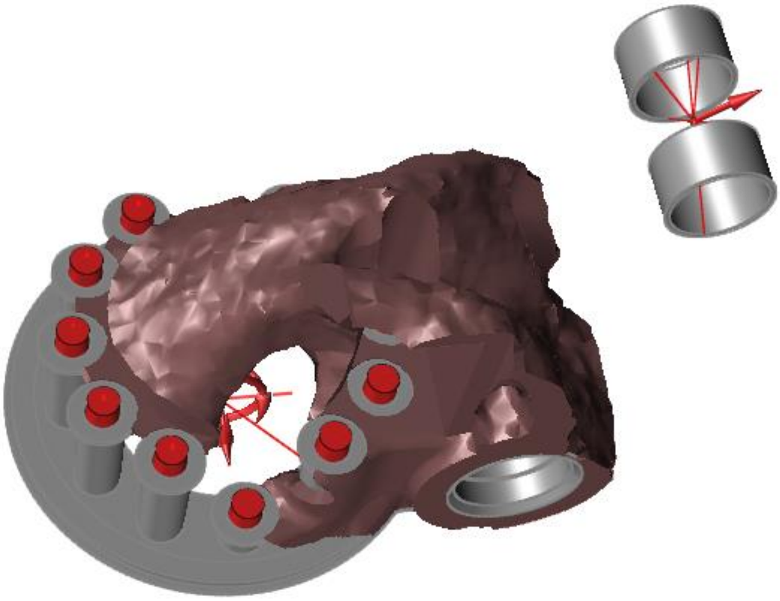
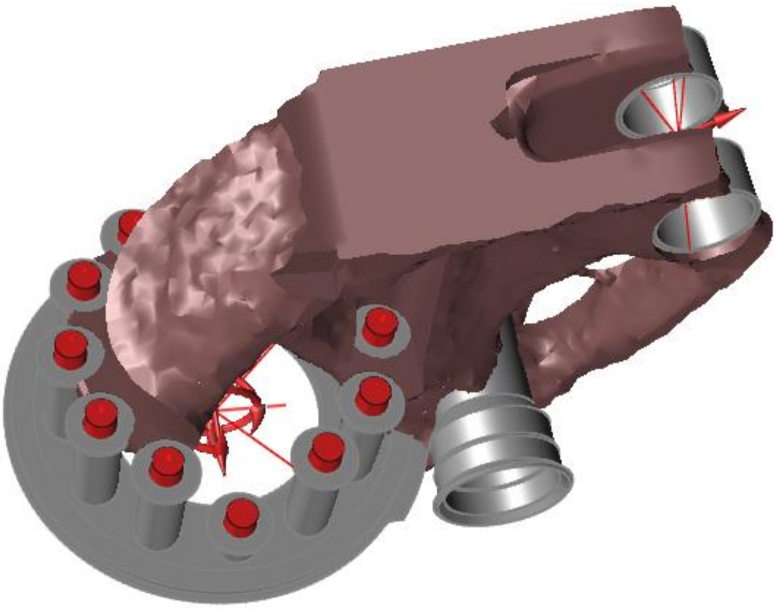
Appendix A – Banana TO for other LCs

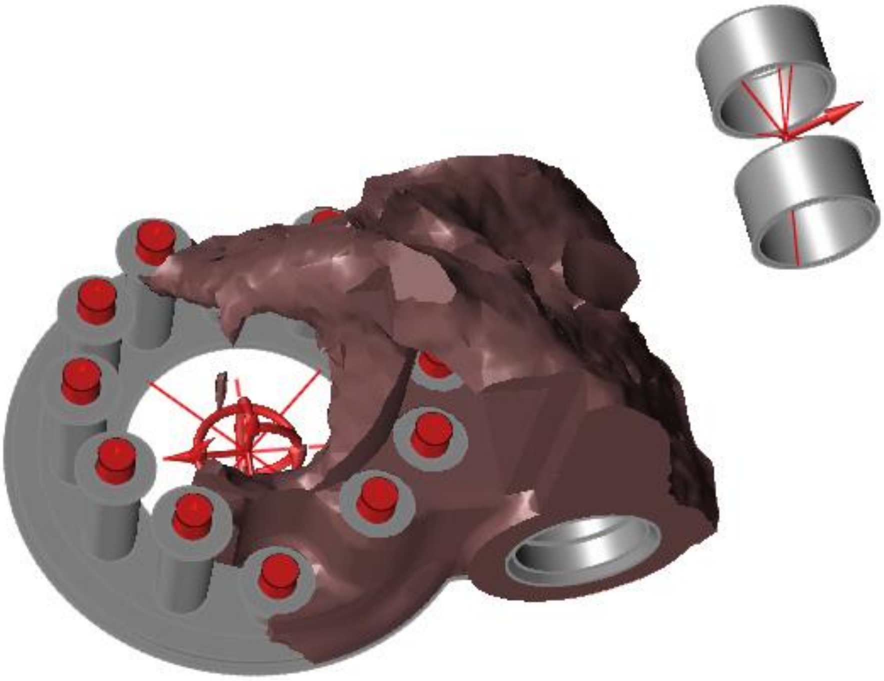


LC 3 (28.8 kg)

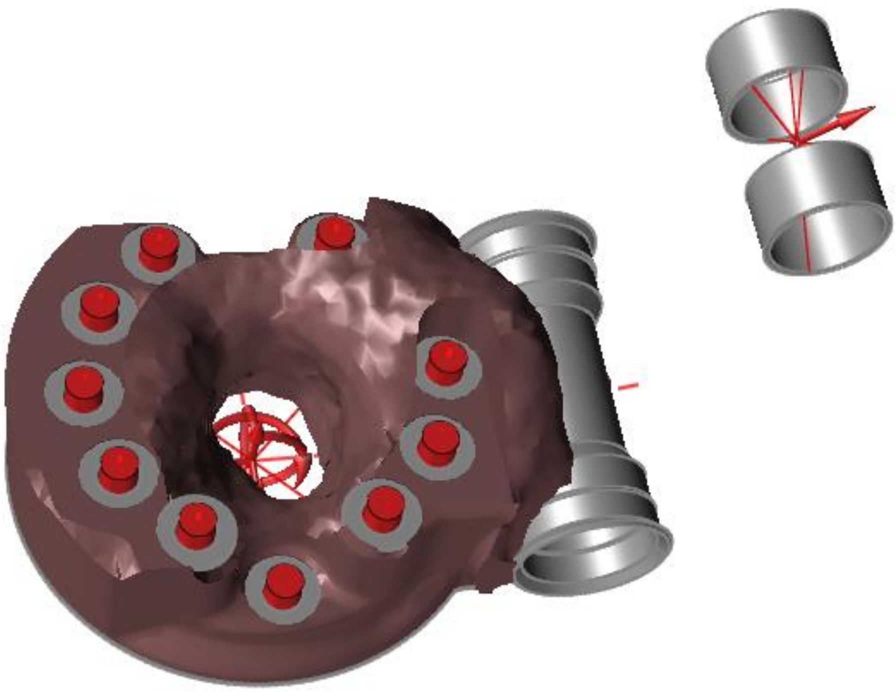


LC 2 (28.7 kg)

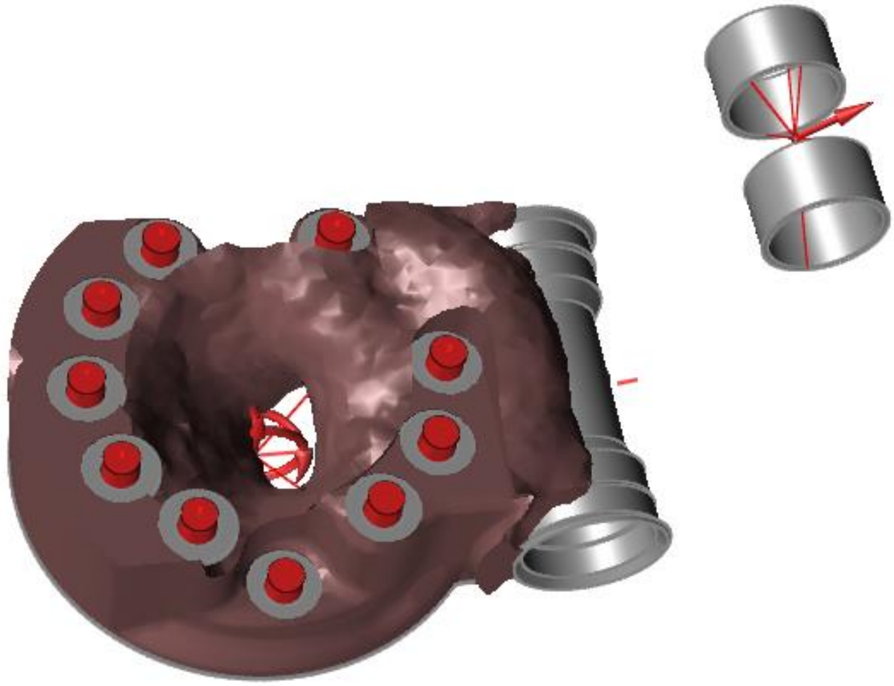
Appendix A



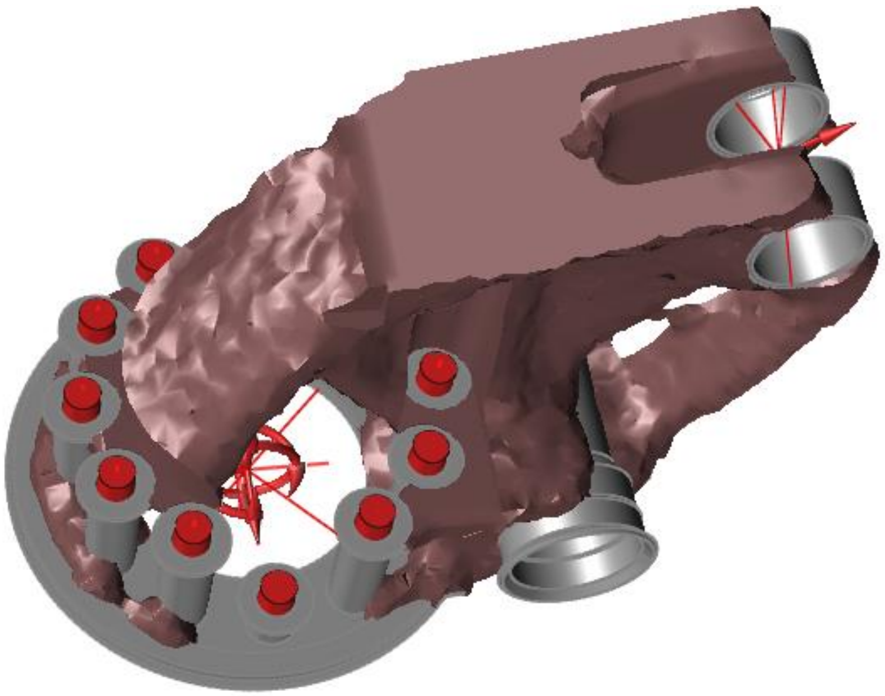
LC 4 (28.6 kg)



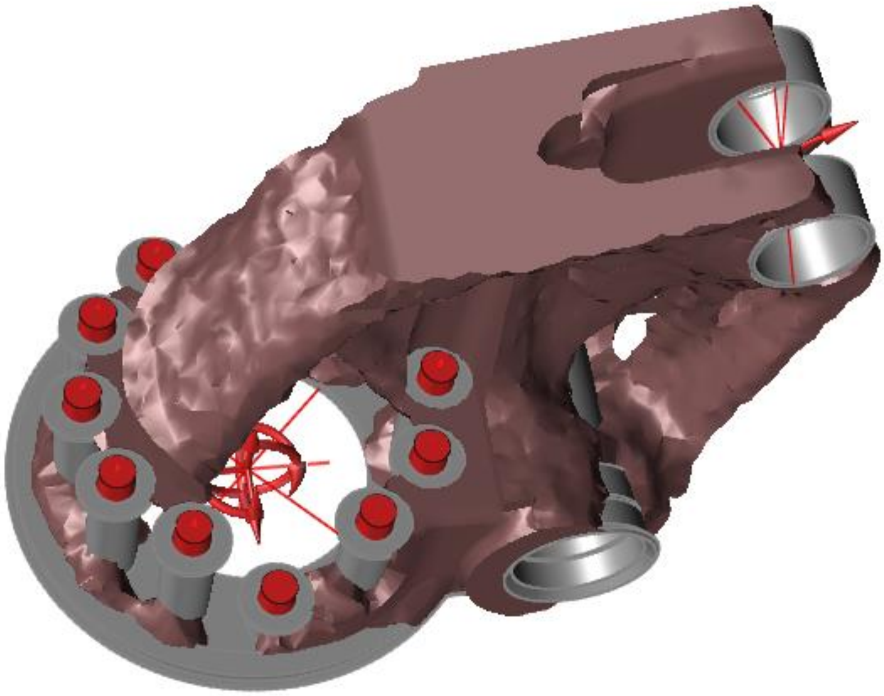
LC 7 (28.4 kg)



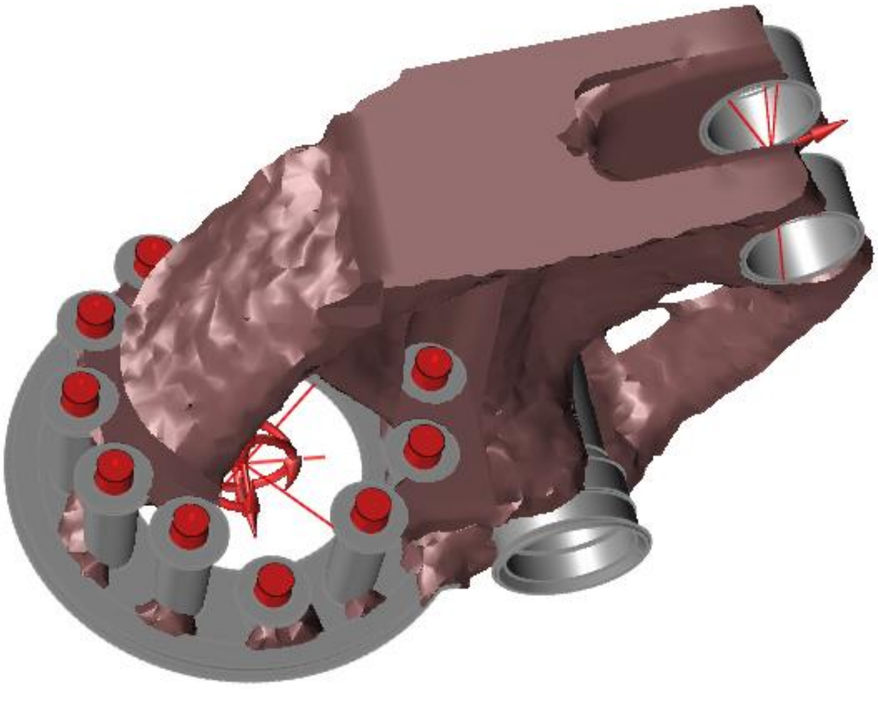
LC 8 (28.5 kg)



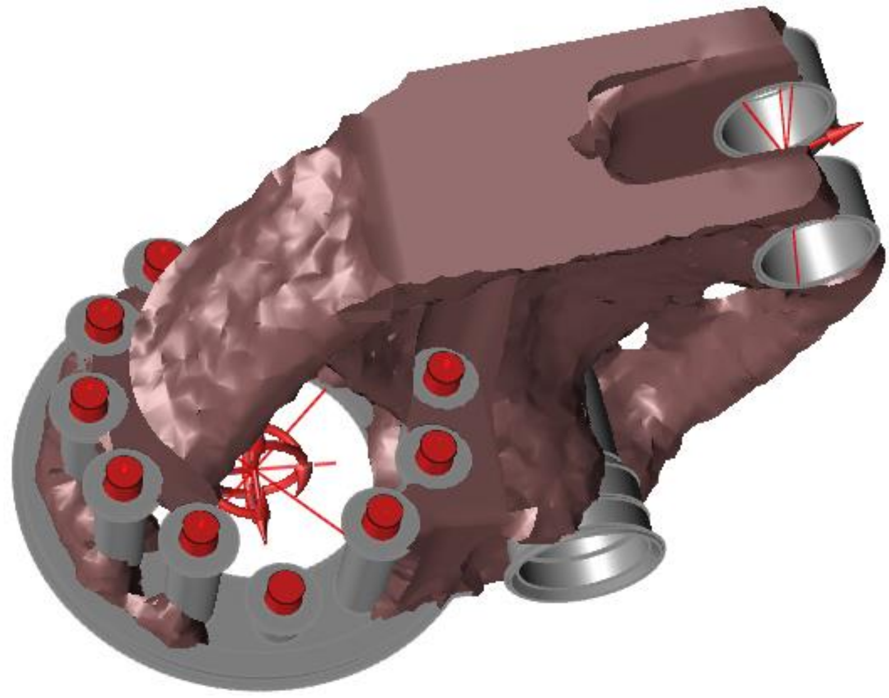
LC 1+LC 3+LC 6 (28.9 kg)



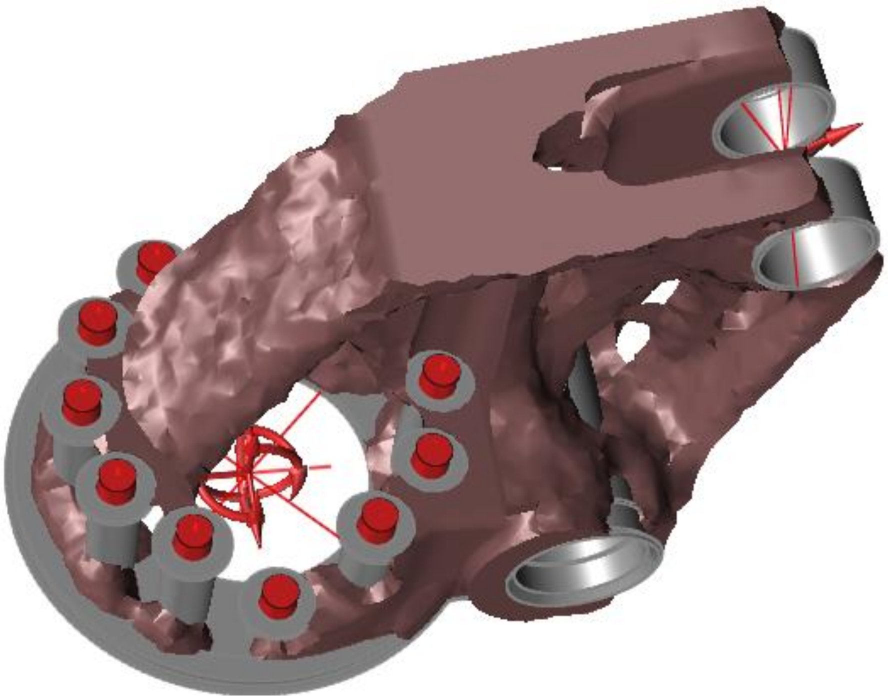
LC 1+LC 4+LC 7 (29.0 kg)



LC 1+LC 3+LC 8 (28.9 kg)



LC 2+LC 3+LC 6 (29.0 kg)



LC 2+LC 4+LC 7 (28.9 kg)

Appendix B – UNF JIC Threads

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Inch threads

BASIC DIMENSIONS

UNF (UNRF) threads

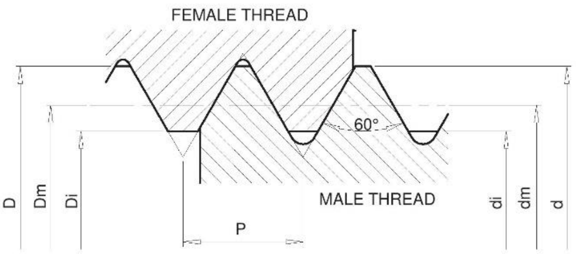
RESTRICTIVE

Threads according to this standard shall be used only when special reasons so require.

This standard is based on ISO 725:1978 and ANSI/ASME B1.1-1989.

1 THREAD PROFILES

The thread profiles for male and female threads are based on the basic profile which is valid for the thread according to the figure below. The figure also shows the diameters to which the thread tolerances are related.



2 BASIC DIMENSIONS

2.1 Threads for general use

Thread designation	Major dia.	No of threads per inch	Pitch	Nut and bolt		
D –n UNF	inch			Major diameter	Pitch diameter	Minor diameter
d –n UNF	D d	n	P	D d	D_m d_m	D_i d_i
1/4 –28 UNF	1/4	28	0,907	6,350	5,761	5,367
5/16 –24 UNF	5/16	24	1,058	7,938	7,249	6,792
3/8 –24 UNF	3/8	24	1,058	9,525	8,837	8,379
1/2 –20 UNF	1/2	20	1,270	12,700	11,874	11,326
5/8 –18 UNF	5/8	18	1,411	15,875	14,958	14,348
3/4 –16 UNF	3/4	16	1,588	19,050	18,019	17,330
7/8 –14 UNF	7/8	14	1,814	22,225	21,046	20,262
1 –12 UNF	1	12	2,117	25,400	24,026	23,109
1 1/4 –12 UNF	1 1/4	12	2,117	31,750	30,376	29,459
1 1/2 –12 UNF	1 1/2	12	2,117	38,100	36,726	35,809

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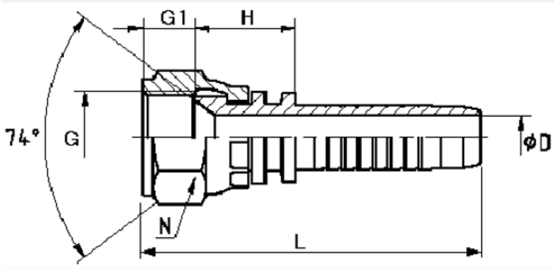
2.2 Threads for special use, which should be avoided.

Thread designation			Major dia.	No of threads per inch	Pitch	Nut and bolt		
D −n		UNF	inch			Major diameter	Pitch diameter	Minor diameter
d −n		UNF	D d	n	P	D d	D_m d_m	D_i d_i
7/16	−20	UNF	7/16	20	1,270	11,112	10,287	9,738
9/16	−18	UNF	9/16	18	1,411	14,288	13,371	12,761
1 1/8	−12	UNF	1 1/8	12	2,117	28,575	27,201	26,284
1 3/8	−12	UNF	1 3/8	12	2,117	34,925	33,551	32,634

xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Appendix C – Wrench opening dimensions



Properties Table

Nur	D	D2	For Hose Art	For Hose Ty	G,Thread-To	G-n	G1	H or B	Hose ID [mm]	Hose ID	L	L1	L2	N
	27.0	57.2	0075 5005...	R9R	UN	1 5/8 -12	15.8	26.70	31.50	1 1/4			68.50	47.80
	27.0	57.2	0075500564	En853-2SN	UN	1 5/8 -12	15.8	26.70	31.50	1 1/4			68.50	47.80
	5.6	20.6	0073 8522...	R2AT	UNF	9/16-18	16.5	9.70	6.30	1/4			30.50	19.00
	5.6	23.9	0570 0164...		UNF	9/16-18	16.5	9.70	6.30	1/4			30.50	19.00
	7.1	25.4	0073 8522...	R2AT	UNF	3/4 -16	18.7	10.60	10.00	3/8			32.00	22.00
	7.1	26.1	0570 0165...	R9R	UNF	3/4 -16	19.8	10.70	10.00	3/8			36.50	23.90
	9.7	28.6	0570 0153...	R1T	UNF	7/8 -14	20.3	12.70	12.50	1/2			34.00	27.00
	9.7	30.2	0073 8523...	R2AT	UNF	7/8 -14	20.3	12.70	12.50	1/2			34.00	27.00
	9.1	29.7	0570 0166...	R9R	UNF	7/8 -14	21.8	12.70	12.50	1/2			42.90	26.90
	15.5	38.1	0073 8523...	R2AT	UN	1 1/16-12	21.8	14.20	19.00	3/4			42.70	32.00
	15.1	36.8	0570 0167...	R9R	UN	1 1/16-12	23.1	14.20	19.00	3/4			50.00	31.80
	21.4	42.9	0073 8513...	R1T	UN	1 5/16-12	24.1	15.00	25.00	1			50.80	41.00
	21.4	46	0570 0160...	R2AT	UN	1 5/16-12	24.1	15.00	25.00	1			50.80	41.00
	21.0	46.0	0570 0168...	R9R	UN	1 5/16-12	25.9	15.00	25.00	1			60.20	38.10
	2.8	14.5	0075 1012...	PLASTIC	UNF	7/16-20	14.5	8.60	4.80	3/16			31.70	14.00
	33.3	57.2	0073 8513...	R1	UN	1 7/8 -12	25.9	18.50	38.00	1 1/2			63.30	60.00
	44.5	71.4	0073 8513...	R1	UN	2 1/2 -12	27.2	23.90	51.00	2			78.70	75.00
	13.1	31.8	1006-00-10	PZ 333	UNF	7/8-14	12.7	21.80	15.90	5/8			45.70	26.90
	9.1	28.6	1006-00-08	PZ 333	UNF	3/4-16	10.7	2.80	12.70	1/2			44.40	23.90
	13.1	33.3			UNF	7/8-14	12.7	20.30	15.90	5/8			36.80	26.90
	4.5	20.6		R2/DIN2	UNF	7/16-20	8.6	15.00	6.30	1/4			30.50	14.20
	7.1	25.4		R2/DIN2	UNF	9/16-18	9.7	16.50	9.50	3/8	55		32.00	17.50
	9.7	30.2		R2/DIN2	UNF	3/4-16	10.7	19.30	12.70	1/2			34.00	23.90

Appendix D – Example of valve tolerances