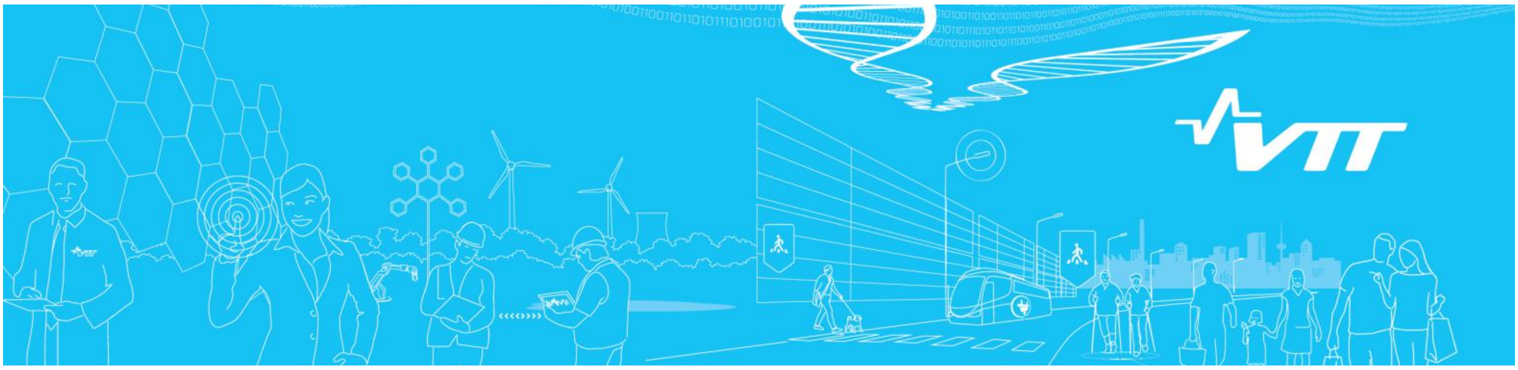

**RESEARCH REPORT**

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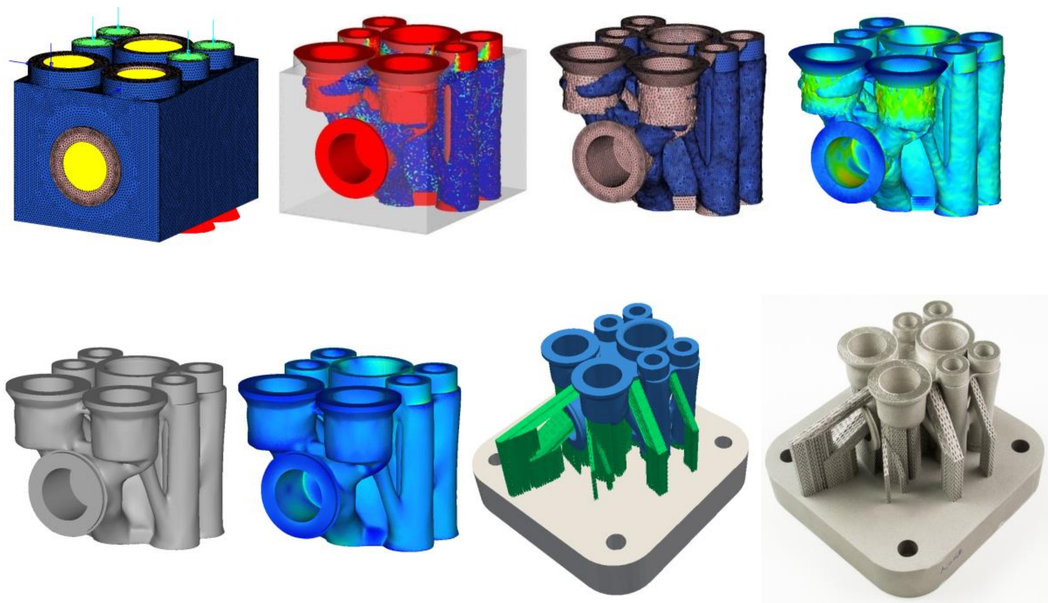

# Design for Additive Manufacturing


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**Summary**

Additive manufacturing (AM), also called 3D printing, enables the manufacture of nearly any geometry without the constraints imposed by traditional manufacturing techniques. As this technology advances and the costs of 3D printed parts continue to fall, AM will become a more prevalent and viable engineering and business solution. In order to take full advantage of this technology, new approaches to design need to be implemented in order to facilitate innovative and cost-effective solutions. The following describes some of the factors that need to be taken into consideration when designing metal parts to be created by the selective laser melting (SLM) method. Redesigns performed for two real industrial cases are included to demonstrate one approach to design, as well as some of the benefits gained.

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# Contents

# 1. Introduction

While previously considered a challenging and expensive way to manufacture metal parts, the long and varied list of advantages that additive manufacturing (AM) offers compared to traditional techniques (see Figure 1) coupled with rapid advances in the technology mean that companies are beginning to see the added value and business potential of AM [1, 2, 3, 4, 5, 6, 7, 8, 9]. With this in mind, VTT has coordinated a 2 year, approximately 3M€ research project with Tekes and seven Finnish companies (VTT project share ~1M€, project name AM-teknologiasta uutta liiketoimintaa). The primary objective of this project was to generate new business opportunities in Finland by utilizing AM technologies, with a focus on metal printing. One of the sub-tasks included in this work focused on the creation of design rules for metal parts created with the selective laser melting (SLM) method. This report focuses on one aspect of this sub-task – how to approach the job of designing for AM.

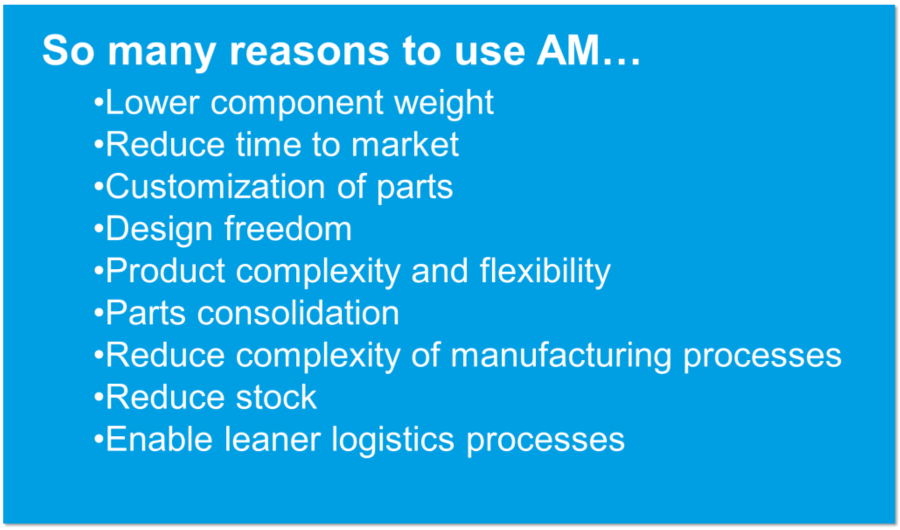



*Figure 1. Some of the many reasons that additive manufacturing is worth considering.*

# 2. Background – AM Processes and SLM Design Guidelines

Additive manufacturing is usually thought of as the process of joining material in a layer-wise fashion based on an interpretation of 3D model data, and is commonly referred to as 3D printing [10, 11, 1, 12]. AM processes can typically be divided into seven distinct categories, which are briefly described below in Table 1. The majority of the research conducted for the AM-Liiketoiminta project focused on one of the powder bed fusion processes known as selective laser melting (SLM).

*Table 1. Classification of AM processes, from EC AM Workshop report 2014 [11].*

| Process Type | Technique Definition | Example Technology | Material |
|---|---|---|---|
| **Vat Photopolymerisation** | Liquid photopolymer in a vat is selectively cured by light-activated polymerisation. | Stereo lithography (SLA), digital light processing (DLP) | Polymers and ceramics |
| **Material Jetting** | Droplets of build material are selectively deposited. | 3D inkjet printing | Polymers and composites |
| **Binder Jetting** | Liquid bonding agent is selectively deposited to join powder materials. | 3D inkjet printing | Metals, polymers, and ceramics |
| **Material Extrusion** | Material is selectively dispensed through a nozzle or orifice. | Fused deposition modelling (FDM) | Polymers |
| **Powder Bed Fusion** | Thermal energy selectively fuses regions of a powder bed. | Selective laser sintering (SLS), Selective laser melting (SLM), electron beam melting (EBM) | Metal, polymer, composites and ceramics |
| **Sheet Lamination** | A process in which sheets of material are bonded to form an object. | Ultrasonic Consolidation (UC) | Hybrids, metals and ceramics |
| **Directed Energy Deposition** | A process that focused thermal energy and fuses materials by melting as the material is being deposited. | Laser metal deposition (LMD) | Metals and hybrid metals |

## 2.1 Selective Laser Melting

Selective laser melting is a layer-based powder bed fusion technology used for the manufacture of metal parts. The geometry of the part to be printed is first defined in a 3D CAD file, which is then sliced into layers that are typically 20-100 µm thick, with a 2D image generated for each layer. Information from this file is then used to generate and assign necessary parameters used by the machine during the build, as well as for the creation of necessary physical supports. The actual build takes place within a chamber with a controlled atmosphere of inert gas, and the process is initiated with an even distribution of fine metal powder (particle size range is typically 10-60 µm) onto a build platform that is fastened to a table moving in the vertical direction. Once the powder layer is in place, one 2D slice of the part geometry is fused together by selectively (i.e. locally) melting the powder with a high-power laser beam. The laser energy is sufficient to melt the particles and form solid metal.

After some time for cooling, the build platform is lowered, a new layer of powder is deposited, and the laser is used to melt and solidify the next 2D layer of the part geometry. This process is repeated until completion of the build, as described in Figures 2 and 3.

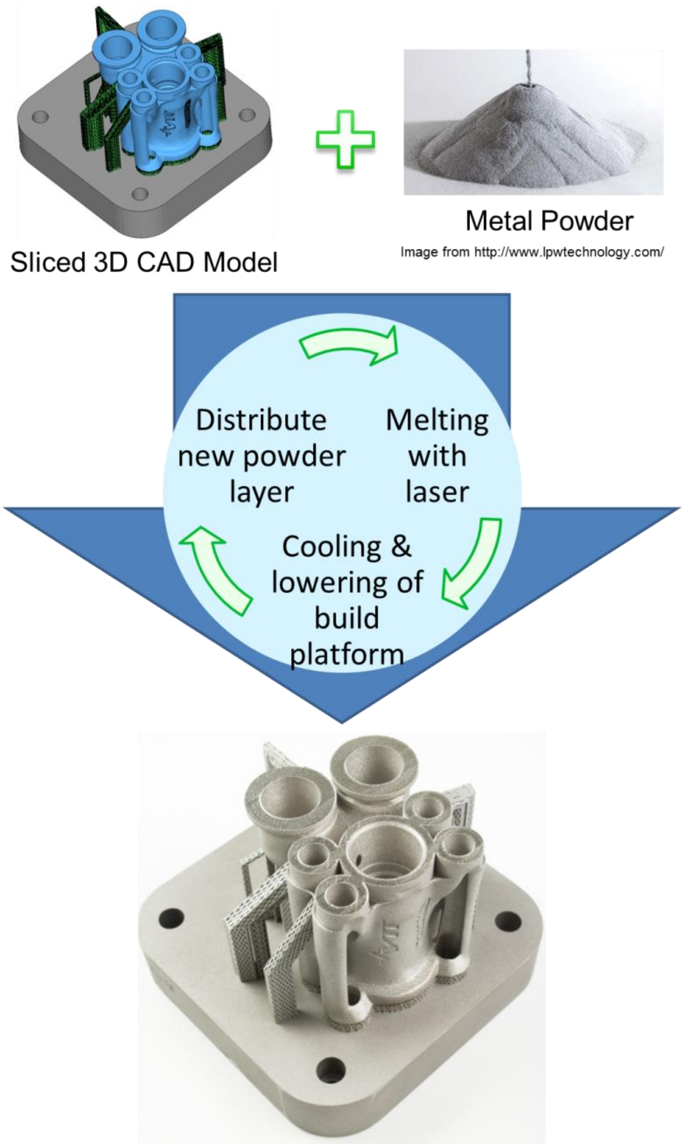



*Figure 2. Description of selective laser melting (SLM) manufacturing process.*

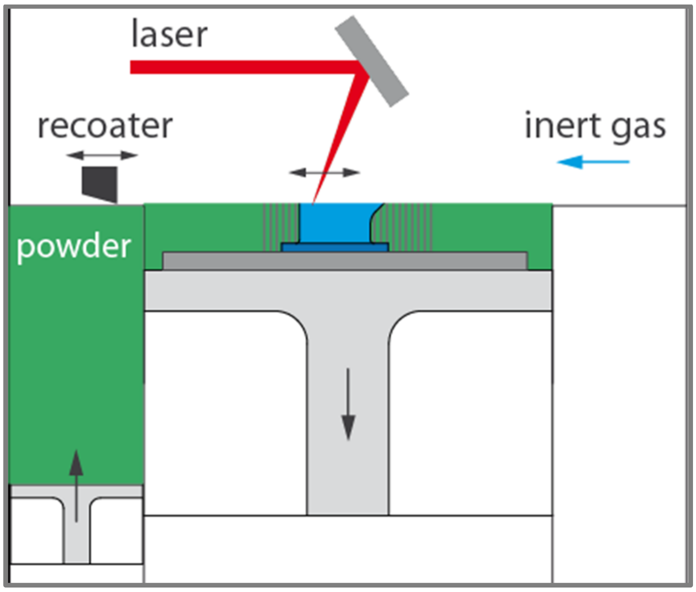



*Figure 3. Illustration describing selective laser melting process [13].*

## 2.2 Development of SLM Design Guidelines

While AM offers substantially more design freedom than traditional manufacturing techniques, these processes each have their own unique limitations. In order to evaluate the manufacturability limits of SLM, test series have been printed in several metals. Some of the topics considered in these tests include: inclination angle of parts relative to the build platform to test self-supporting limit angle, arch steepness, overhang limits, fillets and junctions with smooth transitions, printable hole size and orientation, wall thickness, surface quality variations for different surface angles. After printing, comparisons were made between the printed product and CAD model, and details such as surface roughness, defects, and porosity of the printed metal were investigated.

Some examples of the printed specimen geometry can be found in Figure 4, while Figure 5 shows one build platform of printed test parts [13]. The information obtained from these studies has been utilized in generating design guidelines for metal parts created by SLM, and have been used along with advanced design techniques such as topology optimization to design products specifically for production with AM.

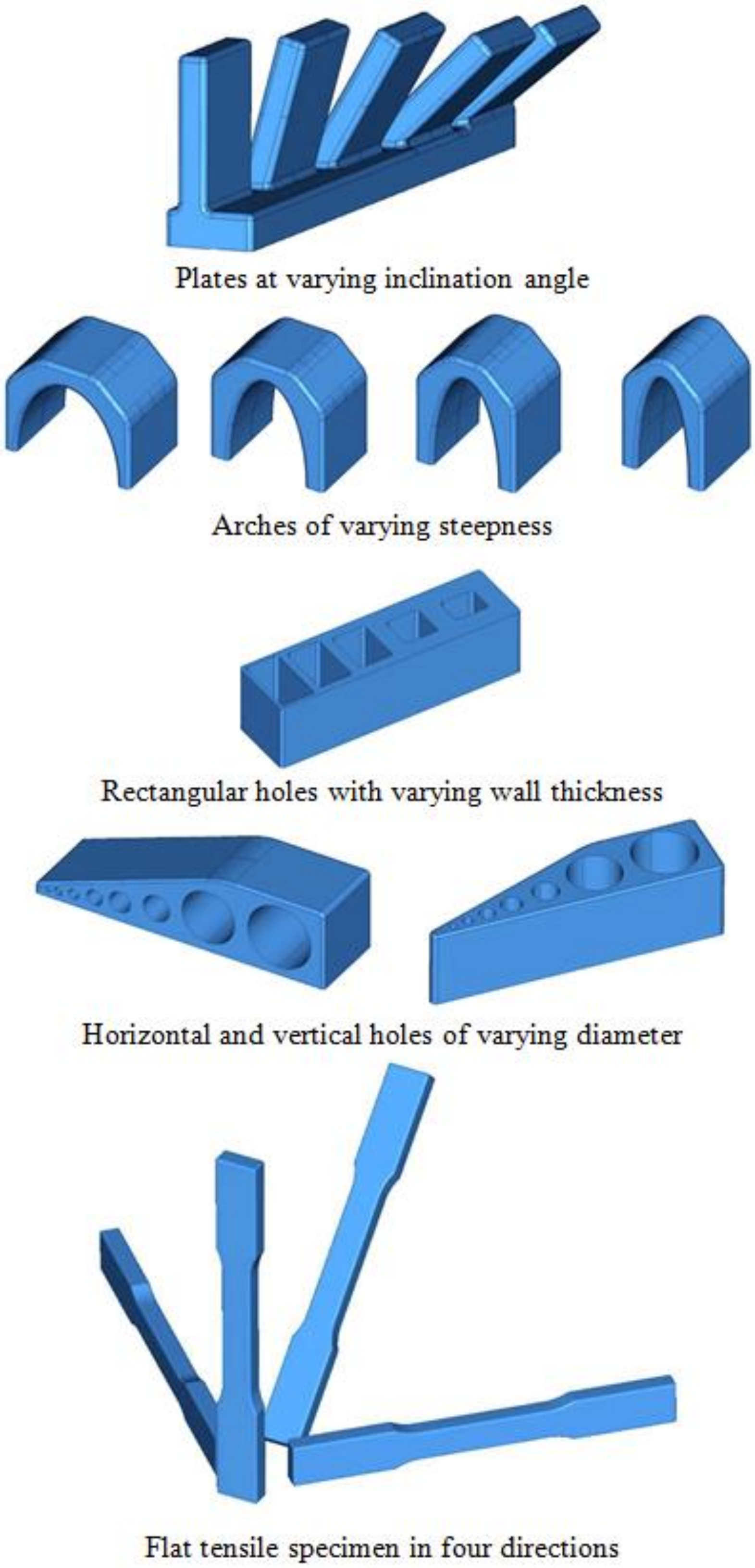



*Figure 4. CAD models of some of the test specimen used in SLM manufacturability tests for creation of design guidelines [13].*


*Figure 5. Printed test specimen used in SLM manufacturability tests for creation of design guidelines.*

## 3. Topology Optimization

Finite element based topology optimization is a technique used to find the optimal distribution of material and voids in a given design space, dependent on loading and boundary conditions, such that the resulting structure meets prescribed performance targets [14]. The typical optimization process is described in Figure 6, starting with the definition of the design space limits and proceeding with FEM model creation, optimization definition and calculation, results interpretation, and finally smoothing and validation of a potential design.

Used in the early stages of the design process for concept generation, topology optimization can help automate and expedite the traditional design process by reducing the number of necessary design iterations. Although this technique has been an available design tool for a few decades, restrictions imposed by traditional manufacturing techniques have severely limited its usefulness. This is changing now with the continuous development and increased use of AM in industry. With AM, it is possible to print almost any geometry – meaning that there are no longer harsh manufacturing restrictions limiting the potential for optimized design. Topology optimization is the natural design technology to pair with AM as it can fully exploit its potential [15, 16, 17, 18, 19, 20].

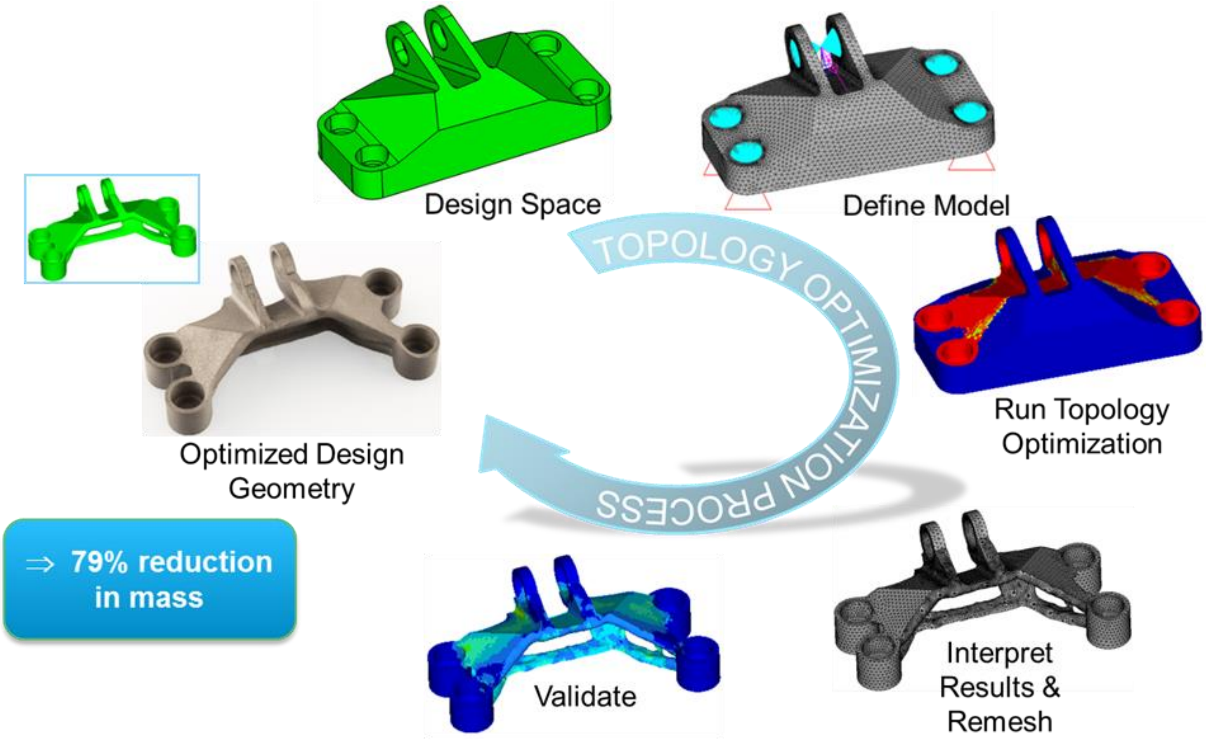



*Figure 6. Description of the topology optimization process; jet engine bracket shown as an example.*

In order to take full advantage of the tremendous potential offered by AM, it is not enough to simply start printing existing components that can be manufactured by more traditional techniques. Components should be designed (or redesigned) specifically for the AM process that will be used. This will allow the creation of a final product that is some combination of functionally superior, customized, and lower cost than a component designed for traditional manufacturing processes.

## 4. Case Studies

Within the scope of AM-teknologiasta uutta liiketoimintaa project, two customer cases have been studied with the goal of redesigning existing products for manufacture with SLM. The case studies are described by following the basic workflow described in Figure 7, with the manufacturing limitations specific to SLM being considered from the very beginning of the design process. Some key points of emphasis were to produce printable designs using the minimum required amount of material in order to save money by reducing necessary metal powder and printing time, to minimize the number of necessary external supports to reduce the time and costs associated with their removal, and to look for ways to improve performance and functionality due to relaxed manufacturing restrictions

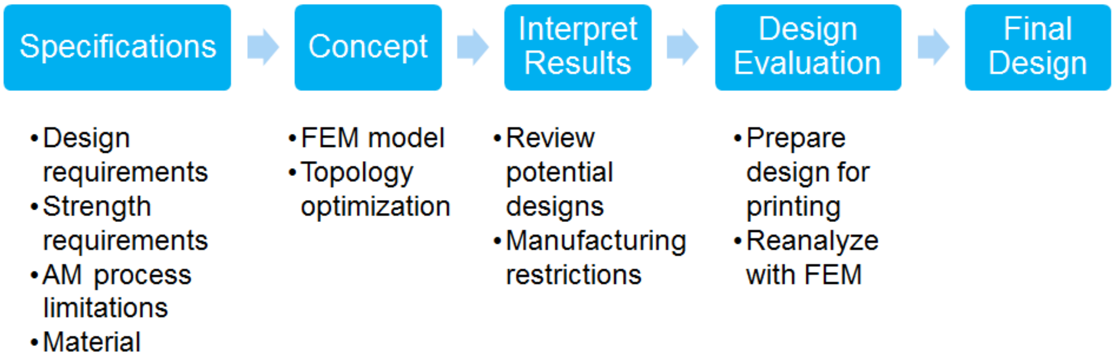



*Figure 7. Overview of the design for AM workflow (adapted from [15]).*

## 4.1 Nurmi Cylinders Oy Hydraulic Valve Block

Nurmi Cylinders Oy is a Finnish manufacturer of hydraulic cylinders for heavy-duty applications in offshore, industrial, marine and mobile environments. The design challenge presented was to redesign a hydraulic valve block to take full advantage of the benefits of AM. The traditional valve block is created using subtractive manufacturing techniques. Starting with a solid block of metal, all internal channels are produced by making straight, circular drillings. So-called blind drilling is necessary (where the internal channels need to change direction and the holes coming from two locations need to meet), which is difficult and often somewhat inaccurate. Additionally, a large number of auxiliary holes are necessary for the creation of the valve block. These auxiliary holes need to be plugged and create the potential for leaks. The sought-after advantages of utilizing AM for production of this part include optimizing shape and cross-section of internal channels for improved flow and space saving, reducing the chance of leaks by eliminating the need for the auxiliary channels, and the ability to produce small series that are tailored to meet customer's needs. The redesign process for this part further enhances the economic viability of using AM by reducing the amount of material needed to make the part, which thus saves money two ways by decreasing the amount of metal powder needed and cutting the total time necessary to print the part.

### 4.1.1 Specifications

Nurmi Cylinders provided an initial valve block geometry describing their vision of how the internal channels might look, the external boundaries of the design space, and defining the necessary non-design regions that include the location of the valve cartridge and bolt fixation points (Figure 8). The valve block requirements were also clearly defined. The standard internal operating pressure is 100 bar, the test pressure is 420 bar, and optimization should be done using an internal pressure of 300 bar. The yield stress and tensile strength safety factors were 1.8 and 2.7, respectively. A bolt preload of 17.9 kN was to be included in the FEM model, as well as various 100 kg side loads to represent potential misuse. A high-strength material with good corrosion resistance was also specified.

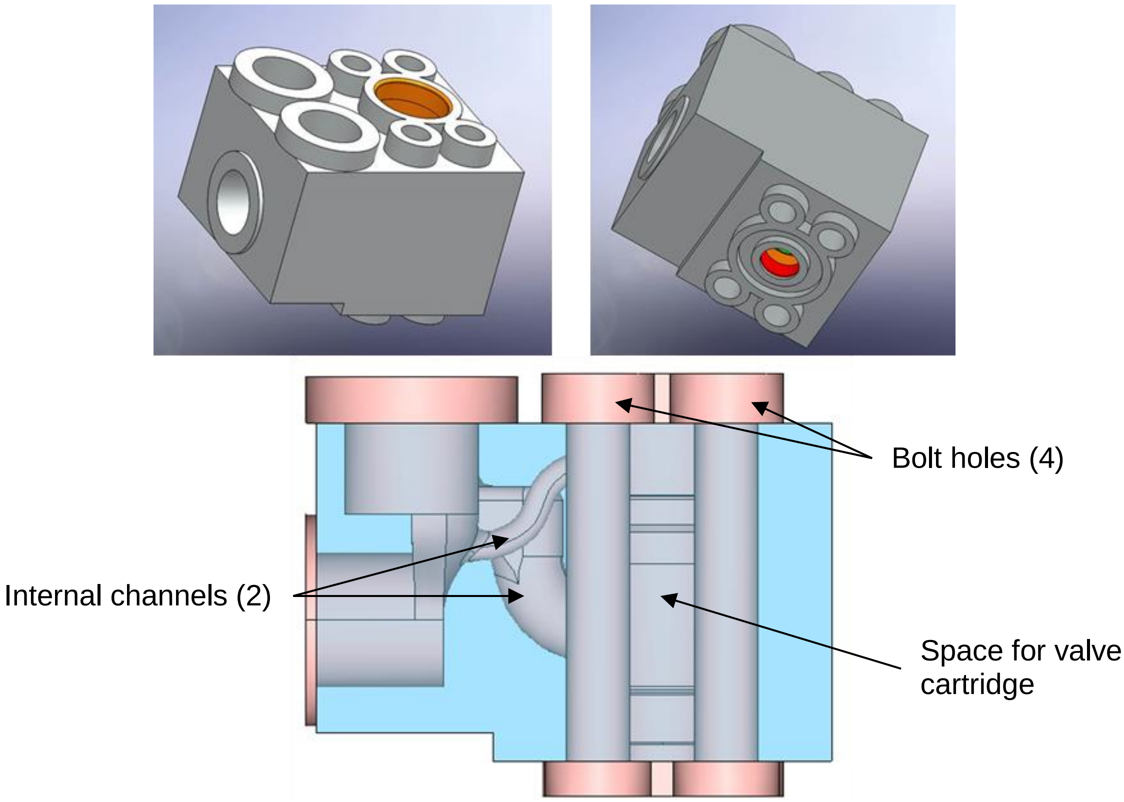



*Figure 8. Initial valve block design space provided by Nurmi Cylinders Oy.*

As SLM was the chosen manufacturing approach, process limitations needed to be taken into consideration. The suggested configuration of the two internal channels would require supports, regardless of the print orientation. This is problematic, as the removal of the supports would be impossible. It was also noted that the design space was limited needlessly on one side of the valve block, which might inhibit the optimal placement of material during the topology optimization step. Some small modifications of the design and non-design spaces were suggested, as shown in Figure 9. The cross-section of the internal channels changed from circular to elliptical shape having the same area, as this eliminated the need for internal supports. The path of the channels changed also, to be more direct and with an angle to the baseplate of approximately 45°. The idea was that it seemed likely that after optimization the outer surface of the valve block would follow the path of the internal channels. If this proved to be the case, then having this angle for the channels would help reduce the need for external supports as well.

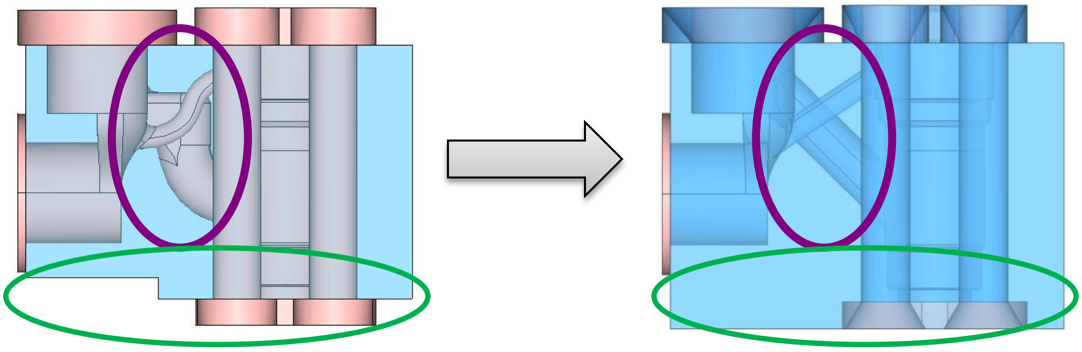


*Figure 9. Suggested changes for valve block internal channels and design space; internal channel orientation and cross-section were modified (purple), and allowable design space was extended (green).*

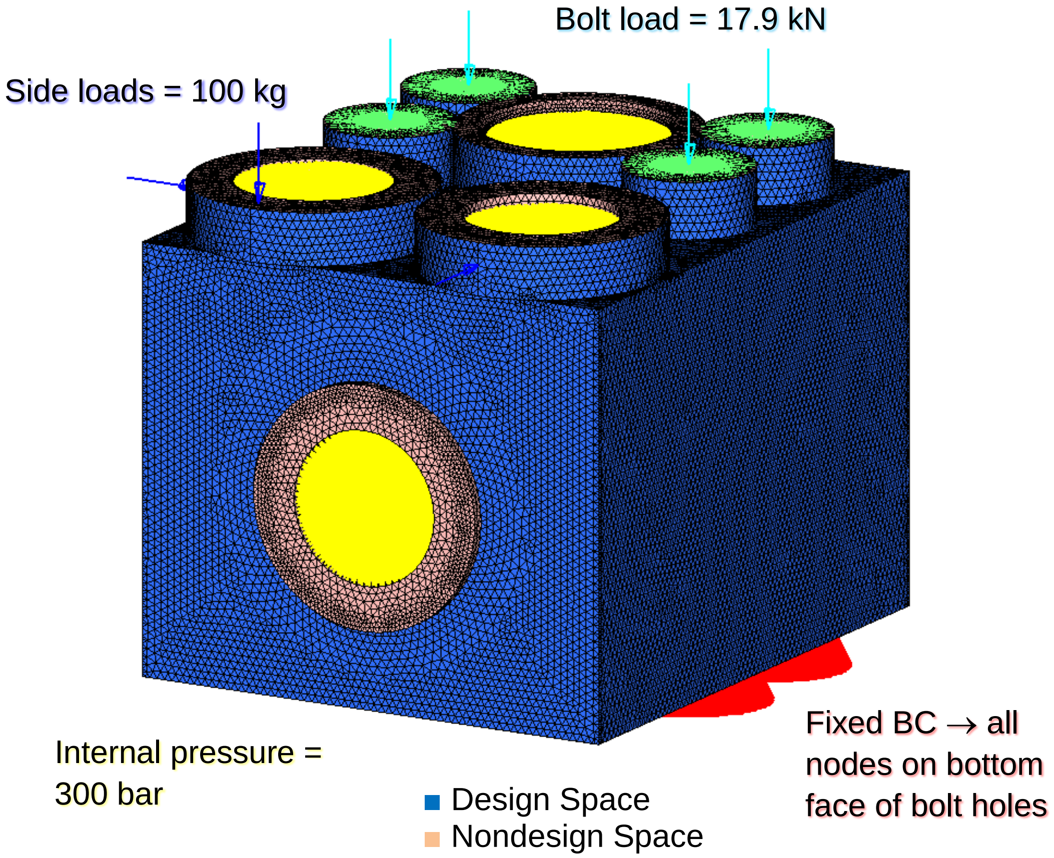
### 4.1.2 Concept

Altair HyperMesh software was used to import and modify the valve block geometry, mesh the part, and do all FEA and topology optimization pre-processing. After some initial tests, an element size of 1 mm was chosen. The choice of element size within the design space of a topology optimization problem is linked to the minimum and maximum member size (if specified in the optimization). It is recommended that between 3-10 elements fit along the minimum member distance, and the maximum member size must be at least twice that of the minimum member size (or at least 6 times the average element length).

The loads and boundary conditions described by Nurmi were applied as shown in Figure 10. A fixed boundary condition was applied to one end of the bolted region (red), a 300 bar internal pressure was applied over the inner walls of the channels and valve slot (yellow), a 17.9 kN bolt preload was applied over the four bolted regions (light blue), and several 100 kg side loads were tested (dark blue).

A topology optimization case was created on this FEM model, with an objective to minimize the total mass. Constraints were set on the maximum allowable stress and the minimum member size. In the initial simulations, the material chosen was H13 tool steel. This is a high strength steel that was easily available at the time of the study. The intention was to eventually change the material to a high-strength material that is also corrosion resistant later in the project. Throughout the course of the project, variations on the optimization objective and constraints, design space and material were also tested.

The result of the described topology optimization can be found in Figure 11, where a colormap of scaled element density values is displayed. Elements with density values below 0.3 have been filtered out and removed from the figure to give an idea of what the optimized design might look like.



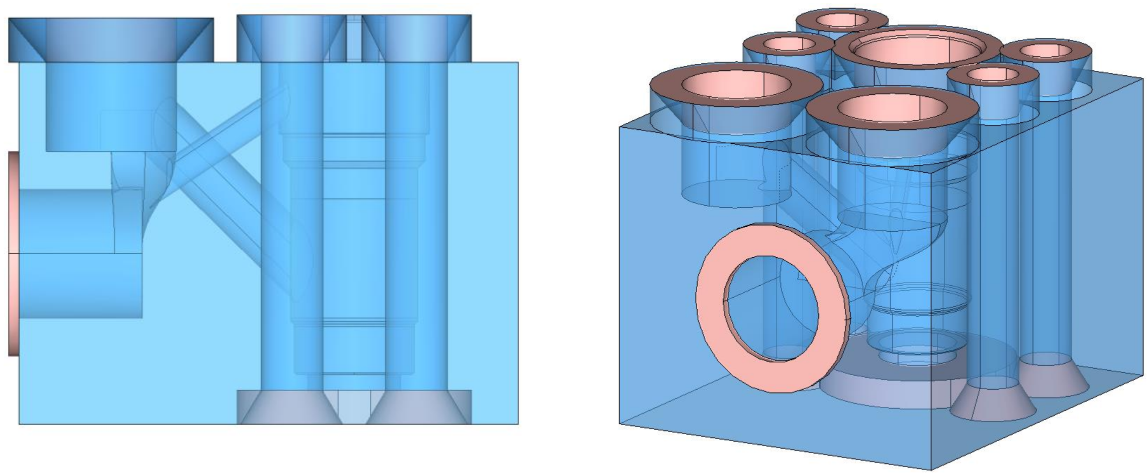



*Figure 10. Finite element model of the valve block. Blue elements indicate design space, peach elements are non-design space.*

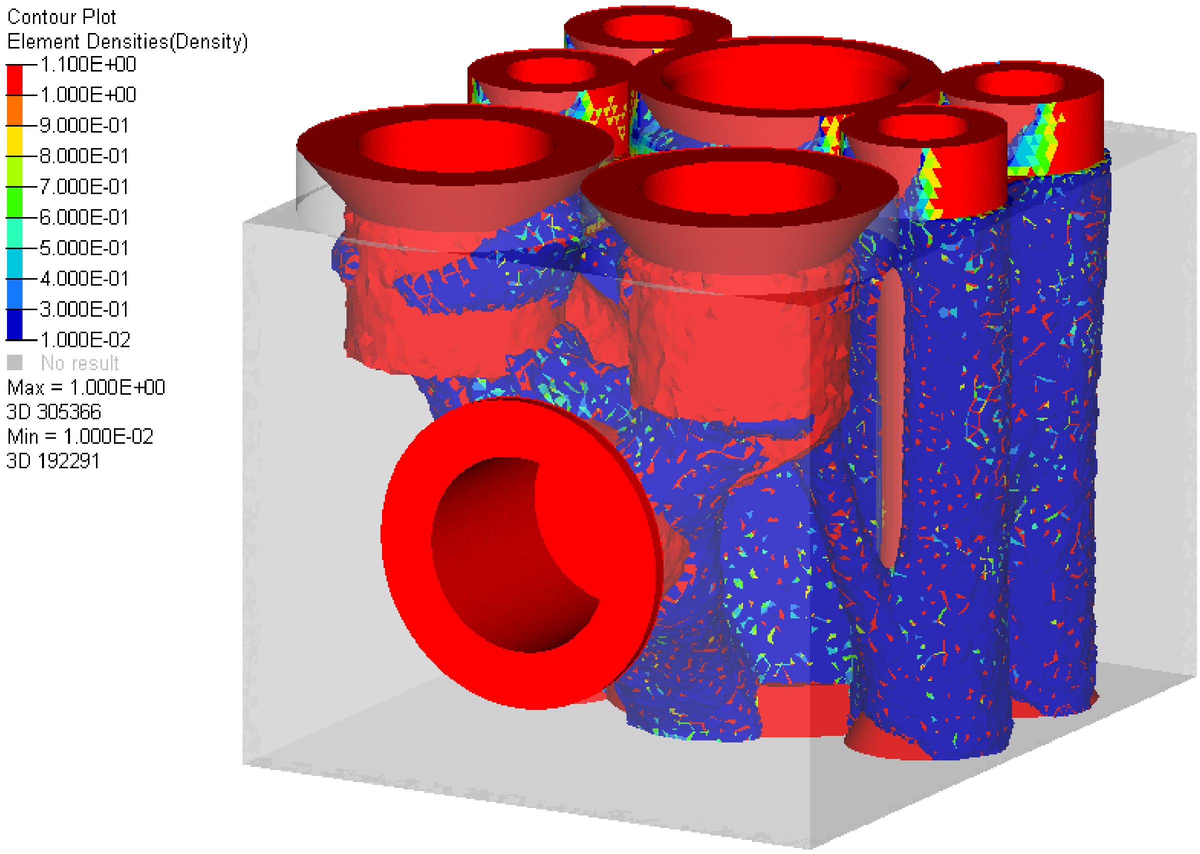



*Figure 11. Topology optimization result showing colormap of scaled element densities; elements with density values below 0.3 have been hidden.*

### 4.1.3 Interpret Results

The result of the topology optimization is the assignment of scaled material density values to each element of the mesh in order to indicate where material is needed and where it is not. For elements where the density value is 1, material is necessary; and where the value is 0, material should be removed. However, the result is open to interpretation at all intermediate values. The design interpretation software OSSmooth was utilized to interpret the topology optimization results and automatically generate a new FEM mesh, while preserving all boundary conditions and load cases from the original model. This step allowed a “rough” initial version of the optimized design to be reanalysed automatically to verify that the suggested design was capable of meeting all design constraints. The mesh corresponding to the initial result interpretation can be found in Figure 12.

An analysis was performed on the design interpretation in order to check that the maximum stress limit was not exceeded. For this case the maximum allowable stress was 640 MPa when using H12 tool steel and taking customer specified safety factors into consideration. The result of the analysis is displayed in Figure 13. The stress levels only exceeded the allowable levels for a few elements, where stress concentrations existed mainly due to the sharp edges generated during the automatic mesh creation procedure.

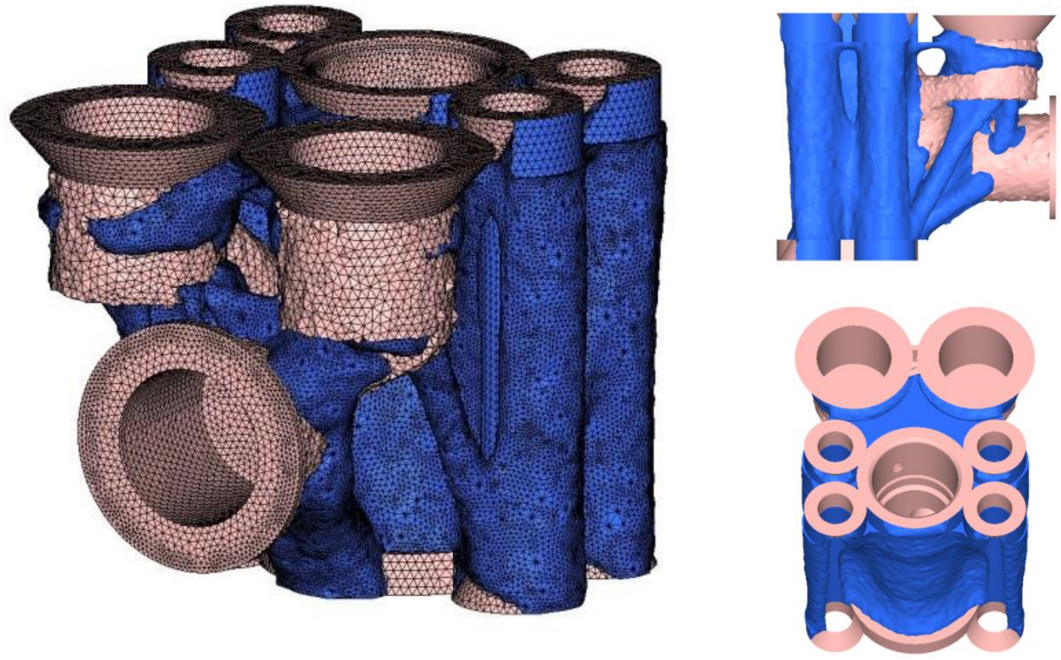


*Figure 12. Topology optimization result interpretation and remeshing, as performed automatically with OSSmooth software.*

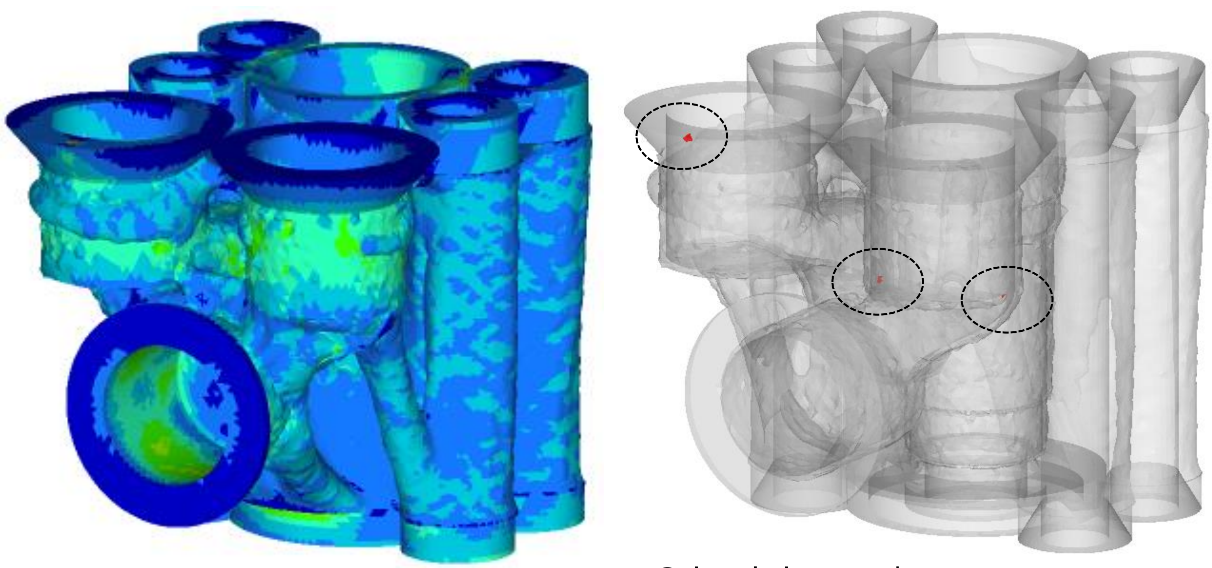



*Figure 13. Stress levels resulting from reanalysis of initial topology optimization design interpretation.*

As this first design reanalysis gave a promising result, the printability of the design was checked. The build direction and orientation of the part on the build platform were considered, and Magics software was used to estimate the size, location and quantity of necessary supporting structures [13].

4.1.4 Design Evaluation

After the design was deemed to be printable, the task of finalizing the design was undertaken. A software package called 3-Matic[STL] was used to smooth the finite element mesh and create the STL file type that is necessary for printing the part. Images of the design after the smoothing procedure can be found in Figure 14. The new, smoothed geometry was then imported into OptiStruct where it was meshed and analysed one final time. For this final analysis, the internal pressure was increased to the test pressure of 420 bar. The resulting stress levels can be seen in Figure 15, where it can be seen that stress levels only exceeded 500 MPa in a few small regions (mostly in the non-design space), and that the design meets all of the initially prescribed performance criteria. The final version of the part was 76% lighter than the traditionally manufactured valve block, and 66% lighter than the initial design space.

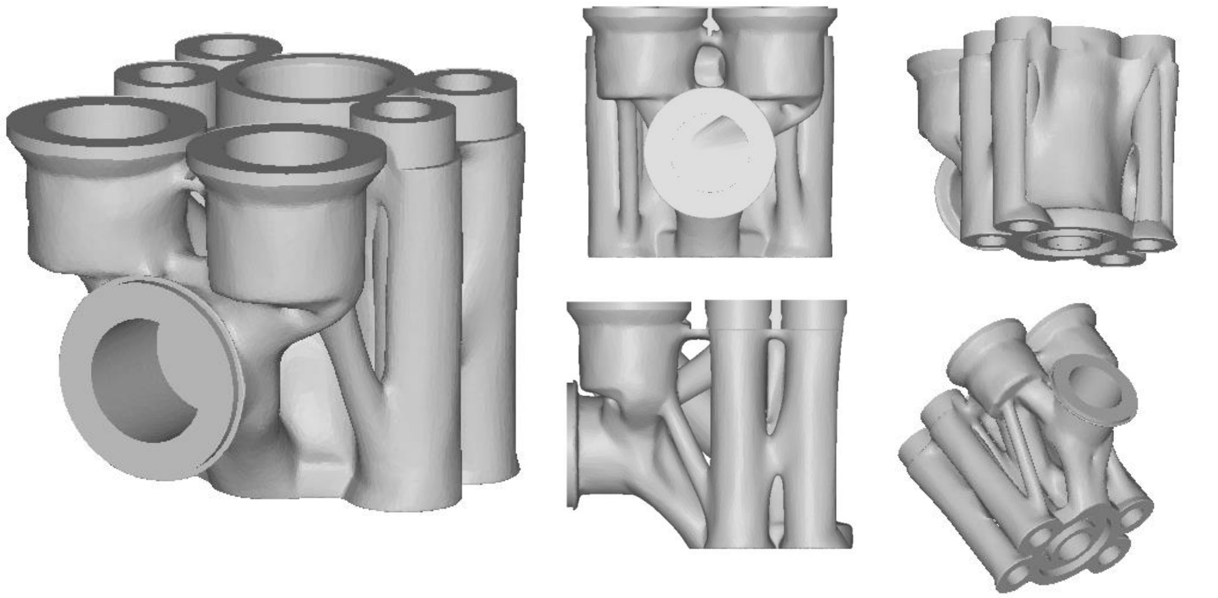
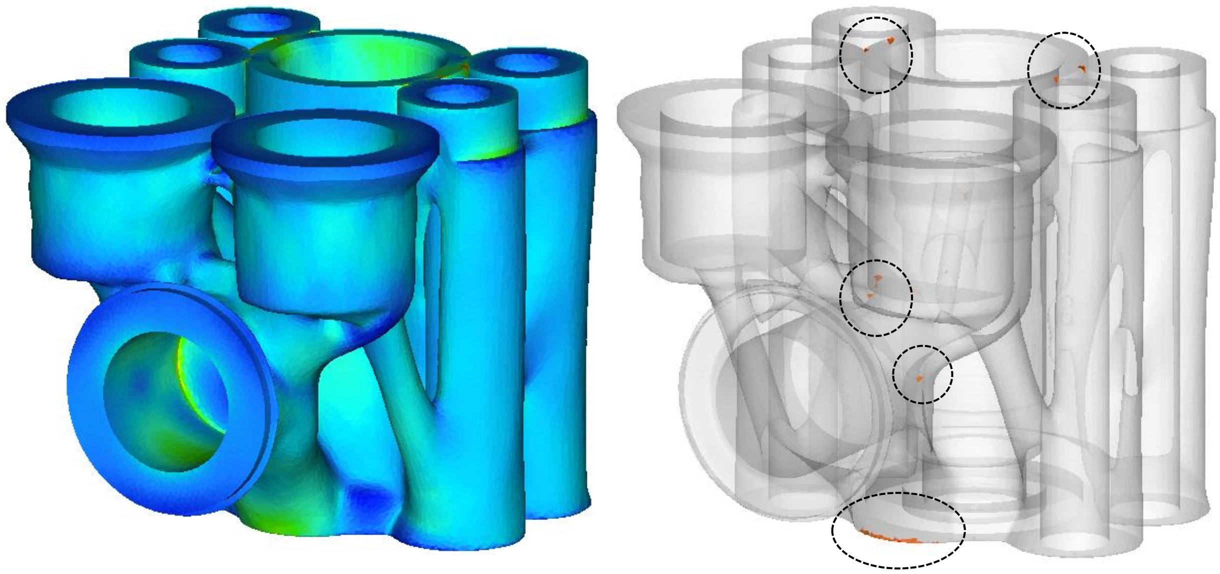


*Figure 14. Smoothing of topology optimization result in preparation for printing.*



Colored elements have stresses exceeding 500 MPa

*Figure 15. Final analysis of valve block design.*

### 4.1.5 Final Design

After the FEM analysis of the design showed that it would meet all specifications, the corresponding STL file was loaded into Magics software to prepare for printing. The computer model describing the orientation of the part on the build platform, along with the necessary support structures, can be seen in Figure 16. Several images of the printed part after support removal can be found in Figure 17.

*Figure 16. Creation of necessary support structures in Magics software (left), and printed component (right).*

*Figure 17. Images of the valve block after support removal and other post-processing procedures.*

## 4.2 Meconet Oy MC Component

A second redesign effort was done in collaboration with Meconet Oy. The case was a welding head bracket from a multi-center machine, as shown in Figure 18. In this example, the goal was to reduce the mass of the component and thus the operating costs of the machine.

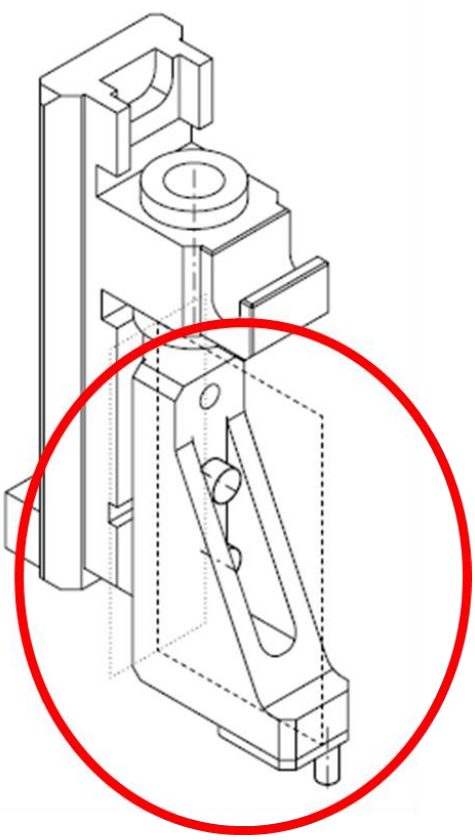


*Figure 18. Welding head bracket from multi-center machine.*

### 4.2.1 Model Details

A description of the available design space for the bracket was provided by Meconet, as depicted in Figure 19. Information about the boundary conditions and loads acting on the weld tip were also provided, and H13 tool steel was chosen as the desired material.

Altair HyperMesh software was again used to create the initial FEM and topology optimization models for this study. The loads on the welding head tip and the bolt preloads are described in Figure 19. An upper stress limit of 100 MPa was set after taking into consideration the fatigue limit of additive manufactured H13. Two approaches were taken for the topology optimization – the first with mass minimization set as the objective function, and the second objective was to minimize compliance while utilizing a volume fraction constraint to control the maximum amount of used material.

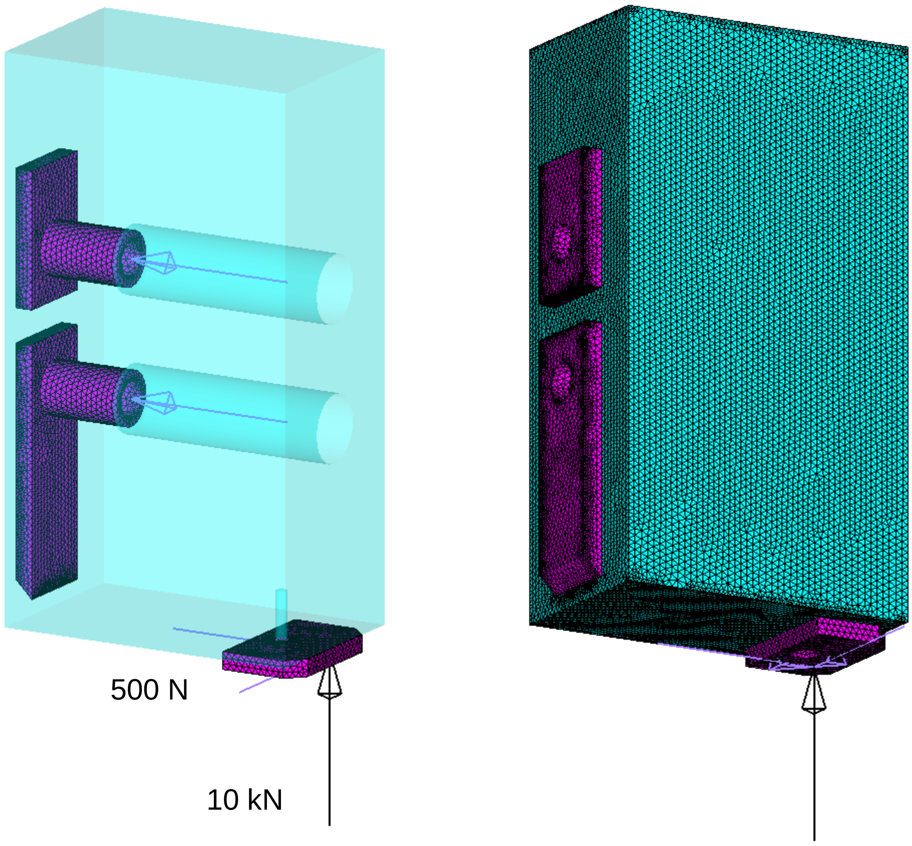



*Figure 19. Design space (■), non-design space (■), and loads defined for the redesign of the welding head bracket.*

### 4.2.2 Interpret Results

OSSmooth software was again used to interpret the optimization results and automatically generate a FEM mesh for reanalysis. Figure 20 shows the results of the mass minimization version of the optimization, in which the mass of the part was reduced by 91% compared to the original design. Figure 21 has the maximum stiffness (minimum compliance) results, where a mass reduction of 86% was achieved. In the initial FEM reanalysis of the designs, the stress levels exceeded the allowable 100 MPa in a few small regions of the first option (min. mass). It is expected that when the design is smoothed and finalised, that these stress concentrations would disappear. The stress levels of the second option (max. stiffness) were acceptable even before smoothing the optimized result. The results of the second option were utilized by Meconet as the basis for creation of their new SLM welding head brackets.

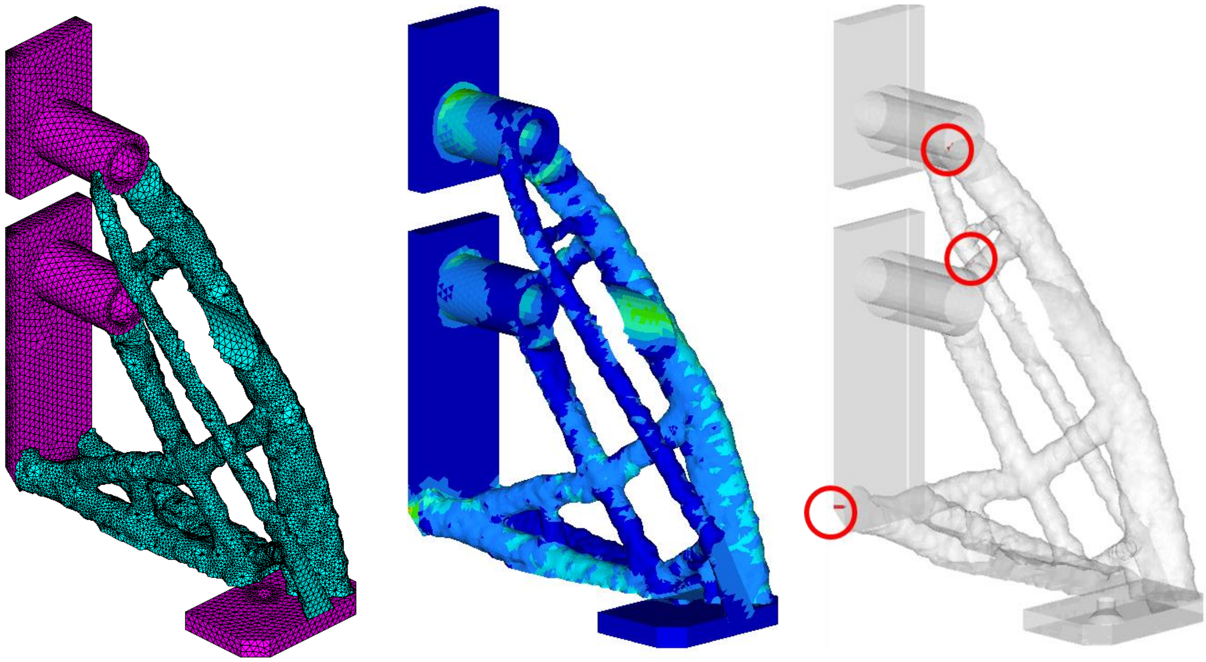


*Figure 20. Interpretation of topology optimization result (objective = minimize mass), reanalysis, and highlighted regions where stress exceeds 100 MPa.*

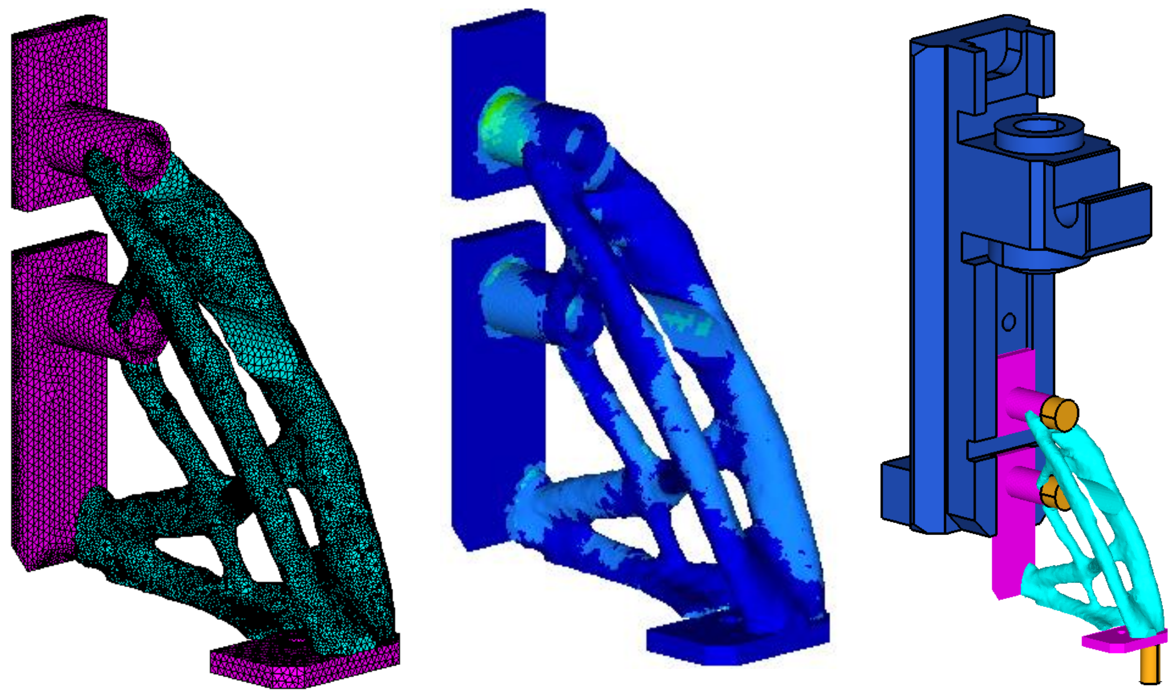


*Figure 21. Interpretation of topology optimization result (objective = minimize compliance, volume fraction constraint), reanalysis, and image of new design in the multi-center machine.*

## 5. Conclusions

The work done in the AM-teknologiasta uutta liiketoimintaa project has helped to highlight the possibilities and difficulties associated with creating additive manufactured metal parts. The creation and use of design guidelines for selective laser melting has proven to be invaluable when it comes to redesigning metal parts that are not only printable, but also have improved performance and functionality at a minimal cost. Topology optimization has also been shown to be particularly useful in the design process, as it gives clues to the optimal use of material.

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