Application and Evaluation of Current Guidelines for Metal Additive Manufacturing

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2022

MASTER THESIS

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Published by
Department of Design Sciences
Faculty of Engineering LTH, Lund University
P.O. Box 118, SE-221 00 Lund, Sweden

Subject: Product Development (MMKM05),
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Examiner: Glenn Johansson

Abstract

The goal of this thesis has been to evaluate the design guidelines that currently exist regarding designing for metal additive manufacturing (AM). More specifically, this project has focused on the design guidelines regarding thin-walled features and how well they work when applied to adapt an industrial part for manufacturing with the AM process laser powder bed fusion (L-PBF).

Making the walls of features as thin as possible is a very important aspect of making designs that are cost-effective to produce with AM, as it reduces manufacturing time, and the manufacturing time is one of the biggest factors contributing to the total manufacturing cost. Metal AM is comparatively expensive, and hard to apply for mass production in a financially sound way. Therefore, it is important that designs for AM take full advantage of the benefits of the technology and for that, well-developed design guidelines are needed.

In this project, an industrial part from Alfa Laval that had previously been partially adapted for AM was redesigned by following the current guidelines as closely as possible. The goal was to see how well the guidelines work when applied in a realistic scenario and where further research can be done to improve them.

Guidelines were collected from various research experiments within the AMLIGHT project (Design and Material Performance for Lightweight in Powder Bed Metal Additive Manufacturing) and literature about AM, as well as from Alfa Lavals recommendations for the part. L-PBF was also researched to understand the process the part was being adapted for.

The redesign of the part uses much less material and would thus be much cheaper to manufacture, and some insights into where the design guidelines might be further refined were had.

Keywords: additive manufacturing, laser powder bed fusion, thin-wall structures, design for additive manufacturing, design guidelines

Sammanfattning

Målet med detta examensarbete har varit att utvärdera de designriktlinjer som för närvarande finns om design för metalltillverkning (AM). Mer specifikt har detta projekt fokuserat på designriktlinjerna avseende tunnväggiga detaljer och hur väl de fungerar när de tillämpas för att anpassa en industriell del för tillverkning med AM-processen laserpulverbäddfusion (L-PBF).

Att göra detaljers väggar så tunna som möjligt är en mycket viktig aspekt av att göra konstruktioner som är kostnadseffektiva att producera med AM, eftersom det minskar tillverkningstiden, och tillverkningstiden är en av de största faktorerna som bidrar till den totala tillverkningskostnaden. AM i metaller är jämförelsevis dyrt och svårt att tillämpa för massproduktion på ett ekonomiskt. Därför är det viktigt att konstruktioner för AM drar full nytta av fördelarna med tekniken och för det behövs det väl utvecklade designriktlinjer.

I detta projekt har en industridel från Alfa Laval som tidigare delvis varit anpassad för AM gjorts om genom att följa gällande riktlinjer så nära som möjligt. Målet var att se hur bra riktlinjerna fungerar när de tillämpas i ett realistiskt scenario och var ytterligare forskning kan göras för att förbättra dem.

Riktlinjer samlades in från olika forskningsexperiment inom projektet AMLIGHT (Design och materialprestanda för lättvikt vid pulverbäddbaserad additiv tillverkning) och litteratur om AM, samt från Alfa Lavals rekommendationer för delen. L-PBF undersöktes också för att förstå processen som delen anpassades för.

Den nya designen av delen använder mycket mindre material och skulle därmed bli mycket billigare att tillverka, en del insikter om var designriktlinjerna skulle kunna förfinas ytterligare kunde finnas.

Nyckelord: additiv tillverkning, laserpulverbäddsfusion, tunnväggiga detaljer, design för additiv tillverkning, designriktlinjer

Acknowledgements

Throughout this project, I have had the opportunity to work with a number of very knowledgeable and helpful people. Without their help and guidance, this project would not have been possible.

I would like to extend a big thanks to my thesis supervisor, Axel Nordin, for all his guidance and expertise throughout this past year. I also want to thank co-supervisor Satabdee Dash for her insightful suggestions and comments.

Thank you to all the people at Alfa Laval. To Joakim Öhlin and Johan Stenermark for all the feedback and help with the design and simulations, and to Per for helping this project get done. Thank you to the technicians who handled the prints.

Lastly thank you to the opponent, Emanuel Eliason, and the examinator, Glenn Johansson.

Lund, June 2022

Robin Bergman

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Introduction

This chapter introduces the field of research, the objectives of the thesis and outlines the project.

1.1 Background

Additive manufacturing (AM), or 3D-printing as it is often called, is still a relatively young manufacturing method and even though it is progressing fast and allows for a freedom of design that is unparalleled, it is still difficult to apply practically for mass production. This is especially true when it comes to working with metal materials. There are incredible opportunities to create more complex, more efficient, and lighter parts than what is possible with more conventional methods, such as casting and CNC (Computer Numerical Control). Designing or reworking a part for AM, however, can be complicated and requires a lot of work, and determining which parts are suitable candidates is difficult. Laser Powder Bed Fusion (L-PBF), one of the methods for metal AM, is a complex method with a large number of factors, ranging from design aspects to printing parameters and material choices to consider for a successful product.

The guidelines for how to successfully design a part for AM are still in development, among others in the research project AMLIGHT (Design and Material Performance for Lightweight in Powder Bed Metal Additive Manufacturing), of which this thesis will be a part. The research focus of AMLIGHT is how thin-walled structures should be designed and manufactured. This thesis will aim to apply what design guidelines currently exist to an industrial part in an attempt to provide insight into where further research might be needed.

1.2 Objectives

The main object of this thesis is to attempt to apply the current knowledge about designing for L-PBF and, more specifically, thin-walled structures in a real scenario. The guidelines will be applied as strictly as possible, with the hope of providing hints to what areas might need further research or clarification.

A big factor when designing for AM is to reduce the amount of material as much as possible. The material needed for AM often must be in a very specific form factor, such as a fine powder or thin filament, which often proves to be costly. The volume of a part also increases the time it takes to manufacture and, of course, the weight of the part. With many other manufacturing methods, reducing material is good, but it might not be paramount. With AM, it is one of the main driving factors of manufacturing costs in conjunction with the post-processing costs. Reducing material means that things get thinner and smaller, and thinner and smaller things are weaker. L-PBF works in very small dimensions, with layers as thin as 0.03 mm and melting pools of metal as small as 0.1 mm [1, 2 p.9]. At this scale, it can be hard to accurately predict what characteristics the finished part will have. This does not mean that it is possible to make details this small, however, as the process of the material melting at this scale is quite chaotic. At the moment, the recommended design guideline for minimum wall thickness at IKDC is 0.5 mm [3]. Other sources set the minimum as low as 0.3 mm, with a recommended minimum thickness of 1.0 mm [4 p.157]. Decreasing the minimum reliable wall thickness would allow for more cost-effective designs, and an important aspect of this thesis is to test the design guidelines regarding wall thicknesses and see if there might be room for improvement.

In this project, an in-and outlet pipe provided by Alfa Laval (figure 1) will be redesigned to take better advantage of additive manufacturing. The part can be thought of as several pipes put together into one part. Its role is to lead one liquid into a separator and to lead two liquids out. It does not serve a particularly complicated purpose, but there are complicated requirements on how it connects to other parts and the fluid dynamics of the liquids flowing through it. For the efficiency of the separator, it is crucial that the liquids inside move in an efficient and predictable way. The pipe has already been reworked to the point where it is possible to print it, but the design has yet to be optimized to reduce manufacturing cost and material use. Design guidelines for L-PBF will be collected and the in-and outlet pipe will be redesigned using these guidelines and specified requirements from Alfa Laval.

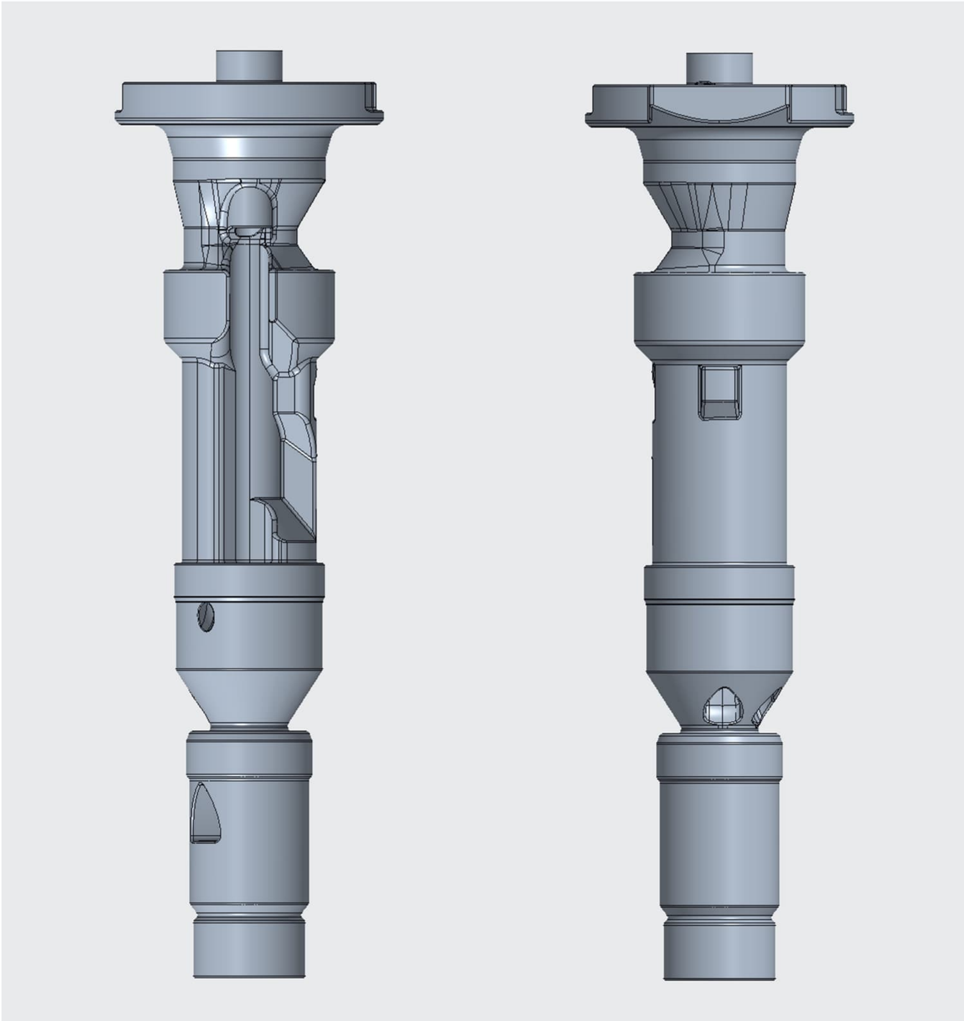


Figure 1, In-and outlet pipe from Alfa Laval, from two sides.

There is not much required of the part in terms of strengths as it will most likely not be subject to any forces worth considering. This makes it a good candidate for AM, as there is a lot of material inside the part that is not needed for the part to function. Leaving the external surfaces and removing the material inside the part would result in a hollow part with thin walls which would significantly cut down on the manufacturing cost of the part. As it is a fairly complicated part, the thin walls throughout the part would be at varying angles and intersect differently. Further adapting the in-and outlet pipe for AM should make for an interesting test for the guidelines for L-PBF regarding thin walls and hopefully give some valuable insights.

1.3 Limitations

As it will be difficult to evaluate the mechanical properties of the parts, measurements will be limited to dimensions and surface properties.

Alfa Laval uses a Trumpf TruPrint 5000 has a circular build chamber with a diameter of 300 mm and a height of 400 mm.

Previously, the part has been cast and therefore been very sturdy. The forces acting on the part have been deemed insignificant by engineers at Alfa Laval and have not been investigated. It is known that there is some force on the part axially and some rotational force, but they are thought to be small and not to require consideration.

Alfa Laval has not been willing to share much of the specific process parameters they use on their machines. This should not cause an issue as the project is mainly about the design process.

Not all parts of the pipe are very interesting to work on, as they might have simple geometry or not have any features that are likely to cause problems during manufacturing. To not spend money and time on manufacturing parts that would most likely not provide any valuable insights, the pipe will be divided into several segments and only the most interesting segments will be printed.

2 Methodology

This chapter outlines the methodology applied in this thesis project. Why this method was chosen is explained.

2.1 Development Method

The method chosen for this project is the double diamond design process adapted for DfAM (Design for Additive Manufacturing). It is a fairly general method for solving design challenges and leaves a lot of room for creativity and improvisation while providing guidance on how to move a project along. The first diamond consists of the two stages 'Discover' and 'Define' in which the challenge is understood, and the problem is defined. The two stages of the second diamond are 'Develop' and 'Deliver' in which a solution to the problem defined in the earlier stage is developed and delivered. As the blue arrow in the second diamond in figure 2 suggests, the solution might be delivered either as a final result, or it might be delivered back to the Develop stage for further improvement [5]. This method fits the project well, as the way the guidelines are evaluated is by how they work when applied in a design project.

2.1.1 The Double Diamond Approach

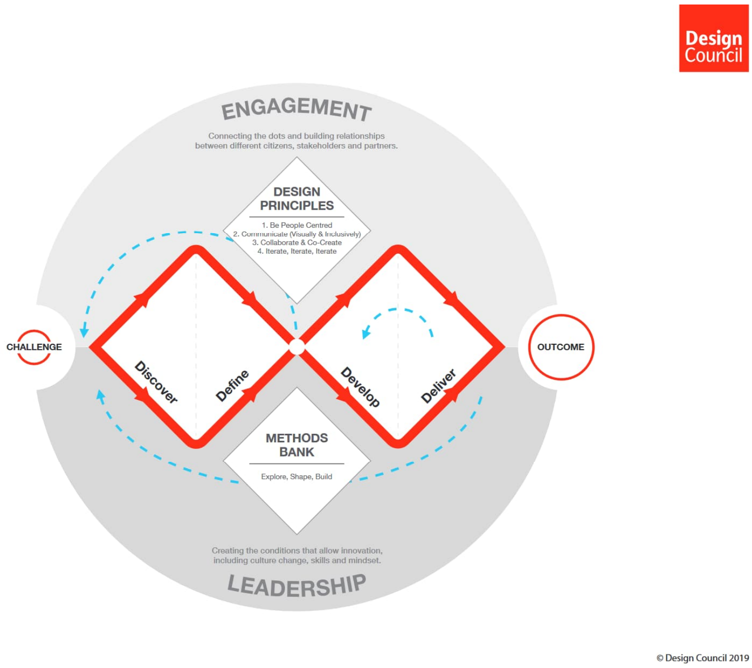


Figure 2, The Double Diamon approach, visualized. Courtesy of Design Council.

Discover

In the discover stage of the process, the goal is to build an understanding of the problem that is being solved. Research is made into the design aspects of AM and specifically what is required to design for L-PBF. To create smart solutions, knowledge is required of how the technology works and what the best practices are to design for it.

Define

At this point, with the knowledge gathered in the previous stage, the task at hand can be further specified. A more focused plan is made, and goals are specified for the development stage. During this stage, all the segments are printed to provide insights into the current state of the design and where to focus design efforts.

Develop

In this stage, the problem specified in the 'Define' stage is solved by working towards the established goals using what has been learned during the first two stages. For this project, that means that the in-and outlet pipe is redesigned for L-PBF as best as possible with the guidelines collected and what is known about the part and how previous prints of the part went.

Deliver

At this stage, the solution is presented and tested. Either the solution is accepted or there are issues to be resolved and the process is moved back to the 'Develop' stage, where the found issues are fixed. The project then moves forward to the 'Deliver' stage again, iterating until an acceptable solution is found. This project went through several iterations, where design mistakes were found by Alfa Laval that needed to be fixed. Simulations ran during this stage also showed some potential problems that warranted redesigns.

3 Discover

In this section, relevant technologies, analysis methods and guiding design principles are presented and explained.

3.1 Metal Additive Manufacturing

3.1.1 Additive Manufacturing

Many industries today use manufacturing techniques such as casting or injection moulding, both types of formative manufacturing techniques, and CNC-machining, a subtractive manufacturing method. When casting or moulding, a die is filled with liquid material which is then allowed to harden in the desired shape. Subtractive manufacturing starts with a block of material and the component is then carved out by removing material using machines (e.g., drills, lathes, or CNC machines) or by hand. These processes are highly developed, accurate and cost-effective, but there are strict limits to what can be manufactured. Moulding or casting require that the mould or die can be removed once the material has cooled and designing around this constraint can be very limiting. Subtractive methods can only remove material in areas that can be reached from the outside, which also severely limits what can be manufactured. With these methods, complex internal geometries, such as channels or thin internal walls, can be very difficult or expensive, maybe even impossible, to make.

Additive Manufacturing encapsulates technologies where components are manufactured by adding material incrementally, usually building the part layer by layer. There are many types of AM technologies. The perhaps most known type, and what usually comes to mind when 3D-printing is mentioned, is material extrusion methods such as Fused Deposition Modelling (FDM). Using FDM, parts are built by a heated nozzle through which a filament is fed. The nozzle moves across the build platform, depositing melted material along a predetermined path as it moves [4 p.19]. This works well when working in plastics, since the temperature needed is comparatively low (somewhere in the 180-250 °C span) and heating a nozzle to these temperatures is no problem. Metals, however, have a much higher melting point (close to 1400 °C for 316L stainless steel and almost 600 °C for the aluminium alloy AlSi10Mg), making them much harder to work with [6-8]. A visualization of the different manufacturing methods can be seen in figure 3.

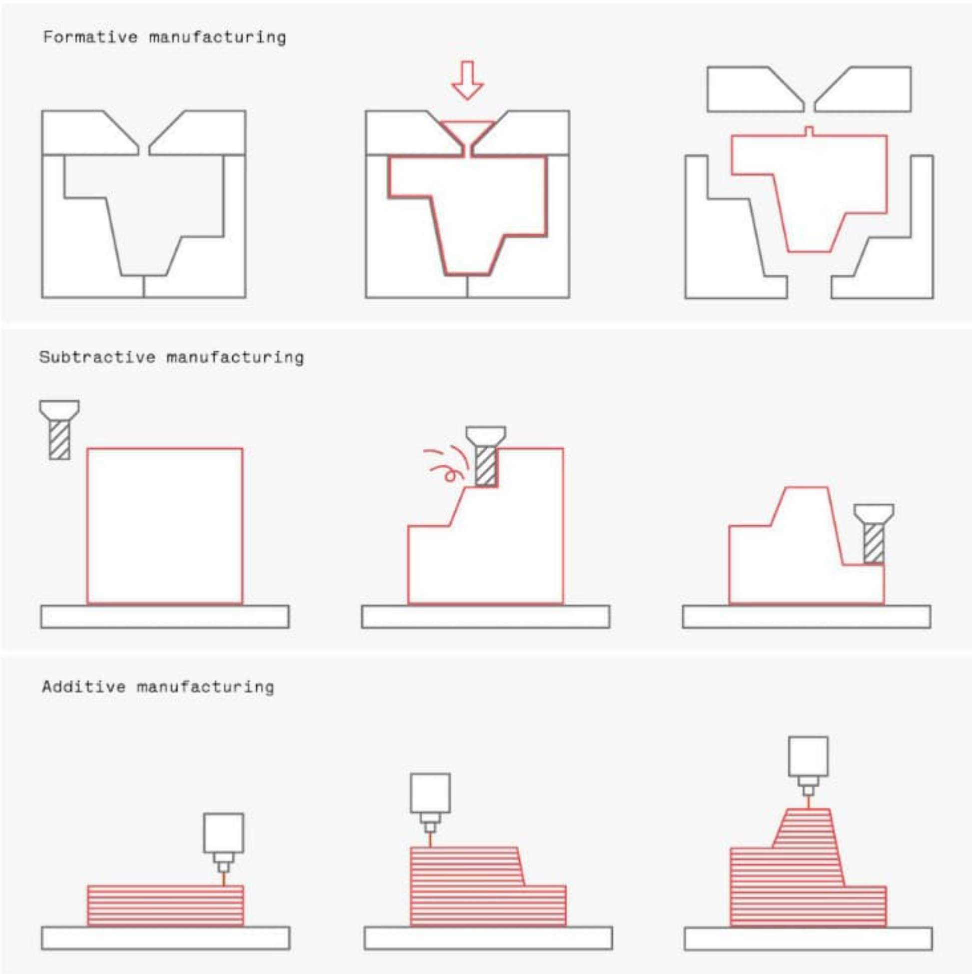


Figure 3, Visualization of different manufacturing [9].

A major advantage to AM is that complexity does not necessarily increase manufacturing cost or time. Instead, increasing the complexity of a design by, for instance, replacing a filled volume with a lattice structure would reduce material use and printing time, and bring the total cost for the part down. Parts can be made more functional, and lighter, as there is more design freedom, and more aesthetically pleasing designs can be considered without adding cost. With AM, it is also possible to, for instance, print parts that come out already assembled. More, simple parts can also be merged into one, more complex part, which can help cut assembly costs. Since there is no need for new tools such as dies, parts can also be highly customized, meaning that every single item can be changed to fit the customer's specific needs. This is especially useful in, for example, the medical field, for products like prostheses and dental crowns, where one-fits-all type of products are not very viable. [4 p.13]

AM is not, however, without limitations. No matter which AM technology is used, to get a successful print, there are many factors to account for. Parameters for the printing process itself, material considerations, and design choices all must work together. In figure 3, an Ishikawa diagram shows many different parameters that affect the part quality of metal AM parts. The design of the part is just a small part down in the right corner, but to make a good design for metal AM, many of the other parameters must be considered during the design process.

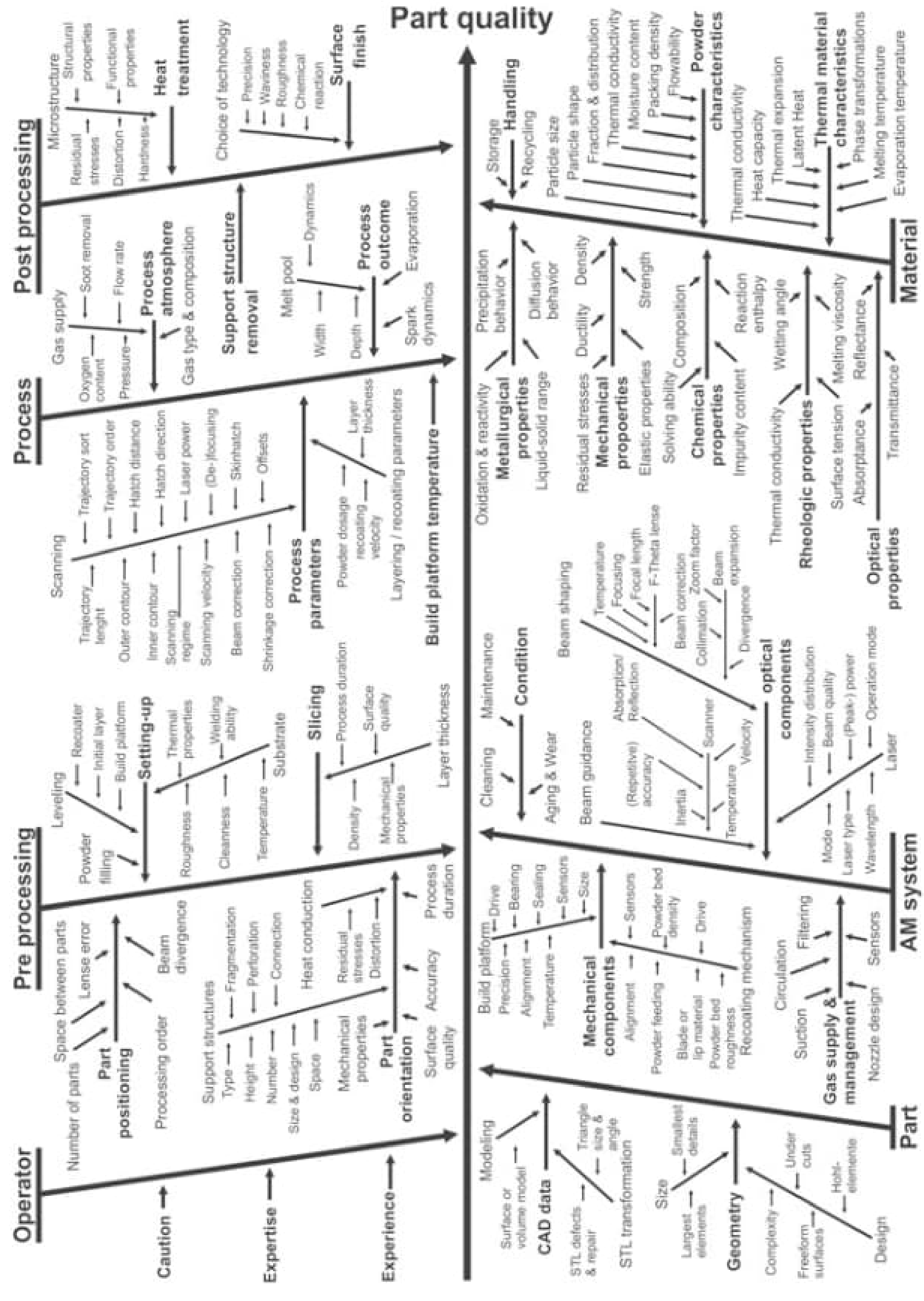


Figure 4, Ishikawa diagram for metal AM [4 p.127].

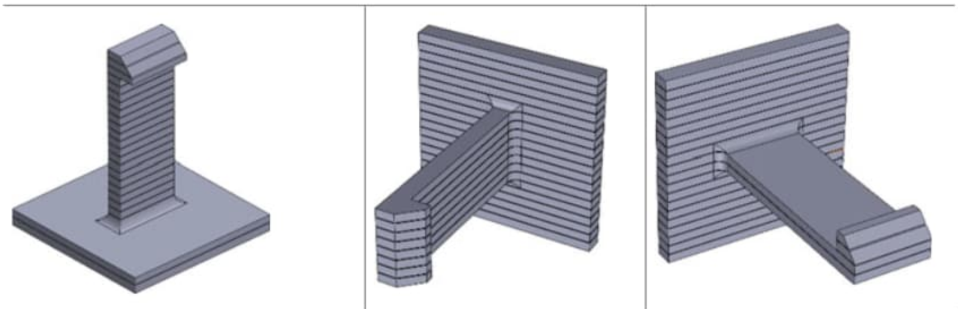
Producing parts with AM is also often comparatively expensive. The systems used can cost anywhere from US$500,000 to as much as US$1,500,000 for a high-end system printing in metal, which means the cost per hour to run the machine could be anywhere from $37 to over $100. Considering that the print time for a single part can run from a few hours to well over 100 hours, it is easy to see how expensive it can get [4 p. 49].

The material used must often come in a specific form, such as filament or a fine powder, which might be costly to produce or purchase. Handling of materials like fine metal powders also comes with certain health risks for the operator of the machine, so special training and precautions are needed [4 p. 125].

Even though the high cost per part might make it a less suitable manufacturing process in many cases, AM can play a key part in the development of a part. With AM, changes to the part do not require the creation of new costly tools or equipment, which allows designers to relatively easily and quickly create prototypes which can then, for example, be tested with other parts or used in demonstrations. This is known as rapid prototyping and is an area where AM can provide a great deal of value [4 p. 7].

3.1.2 **Anisotropy**

Due to the layer-by-layer process of AM, there might be a difference between the strength of the bond between layers and the strength of the bonds within individual layers. This can result in the finished part having differing mechanical properties in different directions. For this reason, it is important to not only consider the most convenient orientation to print a part in, but the function of the part should also be considered, to make sure that it is strong enough where it needs to be. That the mechanical properties of something are not the same in all directions is known as anisotropy, and it is more of a problem with some AM technologies than it is with others. Powder bed fusion technologies, for example, allow the material to hold on to heat for longer, creating stronger bonds between layers, and what anisotropy there is can often be eliminated with post-treatments. When extruding material, as with FDM methods, anisotropy can be more of a problem and should be considered when designing and choosing print orientation [4 p. 47]. An example of the importance of considering anisotropy can be seen in figure 5.



Clip will be weak and, almost certainly, break	Good compromise clip, with decent spring and strong hook	Clip has the best spring strength and flexibility but a weak hook

Figure 5, An example of how the print orientation can affect the function of a part [4 p. 94].

3.1.3 **Laser Powder Bed Fusion**

Laser Powder Bed Fusion (L-PBF) (figure 6) uses a chamber filled with a very fine powder which is selectively melted using a high power, high precision laser. The part is built-in thin layers only a fraction of a millimetre in thickness. After the laser has scanned the desired areas of the current layer, the build platform is lowered, and a new layer of un-melted powder is spread over the surface using a recoater. To prevent oxidation, the build chamber is filled with an inert gas, such as argon, and the oxygen level inside the chamber is monitored using a sensor. Because gases such as argon displace oxygen, it is recommended to also monitor the oxygen in the air outside the machine, to ensure that it does not drop below a safe level [4 p. 176]. After the build is finished the un-melted powder is collected, sieved to remove particles that may have been partially melted or deformed, and reused. Support material is removed from the part and post-processing such as machining, sanding and heat-treatment is done [2 p. 8].

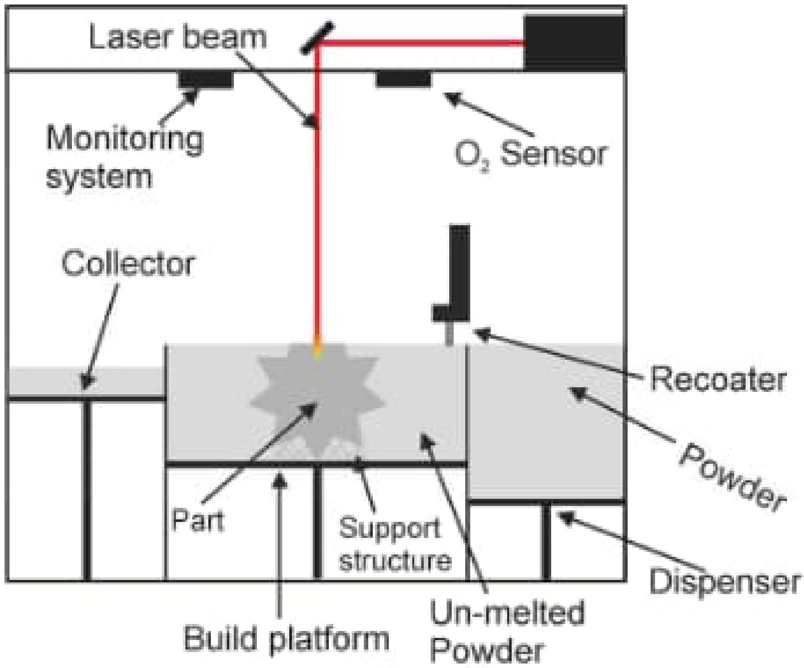
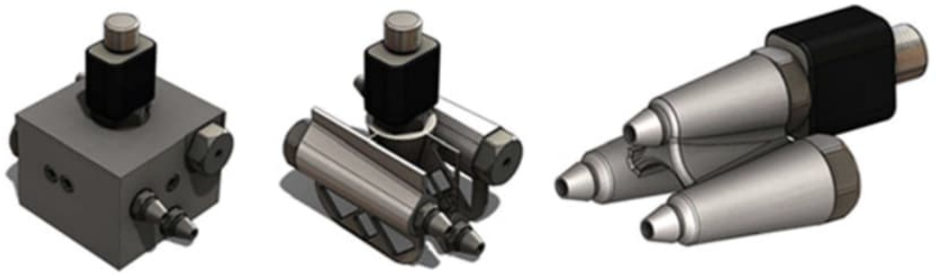


Figure 6, Overview of the components of a L-PBF machine [2 p. 7].

3.1.4 **Adapt for AM or design for AM**

When producing a part using AM, there is a spectrum for how much the part is designed to take advantage of what the process has to offer. For example, if the part is printed as a prototype that will later be manufactured using other methods, or as a replacement part, where getting the part quickly is most important, there may be no modifications made. This is known as direct part replacement. The next level would be to adapt a part for AM, where changes are made to the part to ease manufacturing, such as reduction of unnecessary material, but the function of the part and how it fits with other parts remain the same. When designing for AM, the part is completely remade to reap the full benefits of AM and the design freedom it offers. That includes changing surrounding parts if necessary to increase functionality [4, p.41]. In figure 7 there is an example highlighting how much of a difference the different levels of designing for AM can have on the weight of a part.



Direct part replacement	Adapt for Am	Design for AM
4.6 kg	1.0 kg 78% weight saving.	0.4 kg 91% weight saving. Improved fluid flow and fit within product. Less space required in product, and easier assembly.

Figure 7, An example of the different levels of design for AM and their effects [4 p. 42].

3.1.5 Distortion Compensation

During the manufacturing process, the parts are subject to very high temperatures, especially in the top layers where the laser is melting the powder. Some of the heat goes into the powder around the part and some is radiated away. Most of the heat, however, is transferred down through the part and into the base plate. This creates a heat gradient, with the top of the part being substantially warmer than the bottom. Areas with a lot of material such as filled volumes also take longer to cool than smaller, thinner parts, resulting in heat gradients between thicker and thinner areas as well. Because metal expands when getting warmer and shrinks when getting colder, these heat gradients can cause internal stresses in the part, which in turn cause the part to deform [9 p.162]. With the right design and process parameters, the deformation can be kept at a level that does not jeopardize the functionality of the part. Sometimes it is not possible to reduce the deformations down to an acceptable level with just smart design and tweaking of the process, however. In these cases, other tools are necessary. One tool for this is the process of distortion compensation, in which the deformation that occurs during printing is simulated and the part is adjusted to take the distortion into account. During printing, the adjusted part should then deform to the desired dimensions. An example of this can be seen in figure 8, where printing the original geometry would result in a part that bulges outwards at the top of the part. The compensated geometry takes this into account and the resulting part has “deformed” to the right dimensions [10].

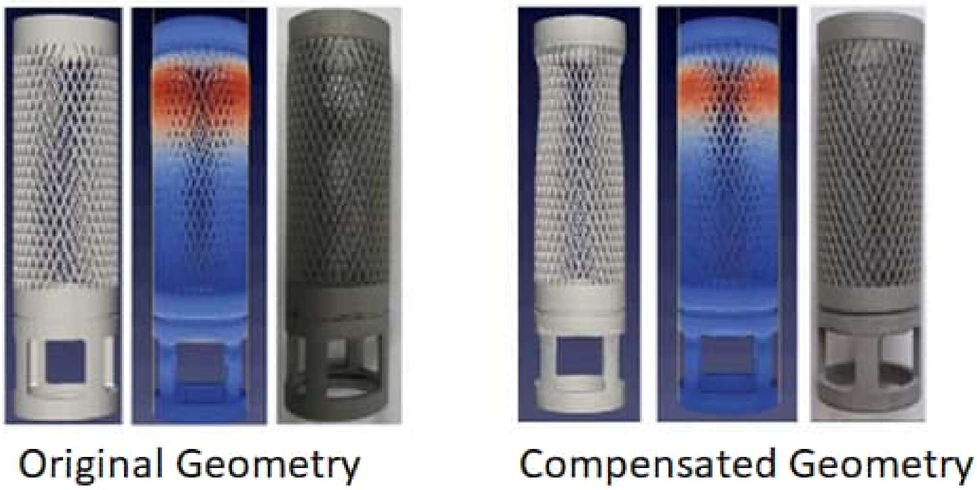


Figure 8, Original geometry, simulated distortion and resulting part to the left, and the same for the compensated geometry to the right [11].

The company Ansys provides simulation software for use in computer-aided engineering. Their software can be used to simulate things such as stresses, strains, and fluid dynamics as well as acoustics and electronics systems. They also have a simulations software suite aimed specifically at aiding in designing for AM, Ansys Additive. Besides simulating distortions and compensating for them, Ansys Additive also provides valuable information about potential problems that might occur during the printing process. Among other things, it can simulate the internal stresses in the material during printing and warn if there is a risk that the part deforms so much that it breaks or detaches from the build plate [12].

Another common failure that these kinds of simulations can predict is recoater blade crashes. If the part deforms upwards, there is a risk that the recoater blade collides with it while distributing a new layer of powder. This can either distort the part further or, more likely, it will cause damage to the softer material of the blade. A damaged blade (figure 9) will not provide an even new layer of powder (figure 10) for the laser to melt which will cause further problems.

Figure 9, A damaged recoater blade.

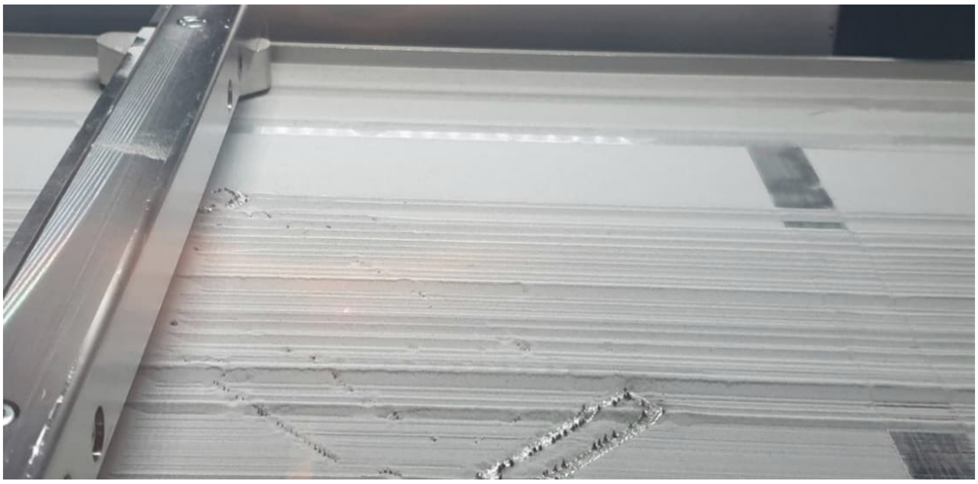


Figure 10, Uneven powder bed as a result of a damaged recoater blade.

Using these kinds of simulations can be a useful part of the design process as it might help uncover problems that would otherwise be revealed during printing. A caveat is, however, that you do the simulations right. For the program to be able to accurately simulate the entire process of printing a part, it needs to have all the right data. Providing the geometry of the part and support structures let the program know what to work on, but it also needs specific process parameters such as layer height and material specifications. Decisions must be made about the acceptable level of distortion and risk of failure. There are also two choices of mathematical models for simulating deformations, Linear Elastic being a simpler one and J2 Plasticity a more complicated and accurate model [13 p.31].

3.1.6 **Calibration procedure**

Distortion compensation analyses can be run without calibration, but for best results, machine and material-specific simulation parameters are preferred. For the program ANSYS Additive, two kinds of possible parameters can be defined, the Strain Scaling Factor (SSF) and Anisotropic Strain Coefficients (ASCs). The Strain Scaling Factor is simply a number that adjusts the simulation to better fit the reality of the specific circumstances that are being calibrated for. Anisotropic Strain Coefficients do the same, but they are more specific. ASCs factor the simulation of stresses in specific directions (parallel to the scan direction and perpendicular to the scan direction). Which of these parameters are needed depends on which simulations will be run. The SSF is the easiest to acquire and is all that is required to run more basic simulations like assumed strain simulations. Assumed strain uses a simpler way to calculate stresses, and while it might be less accurate it also takes less time. Calibration for more advanced simulations such as, for ANSYS Additive, scan pattern and thermal strain simulations require ASCs along with the SSF [14].

For all parameters the basic procedure is similar. Calibration parts are printed and then measured for distortions. For SSF, only one part is needed. For ASCs, however, three parts in total need to be printed – two with different specific scan patterns, and one that uses the scan pattern that will later be used on the machine. The first two parts are used to procure the ASCs and the third part is for a final fine-tuning of the coefficients. If it is known what will be manufactured on the machine, it is best to choose a calibration part that has similar features to the parts that will be printed. Such features could be, for example, thin walls of overhangs. Choosing a custom calibration geometry could be a good idea if the machine is to be used to mass-produce a part, for example. For general use, though, something like the cantilever in figure 11 can be used [14].

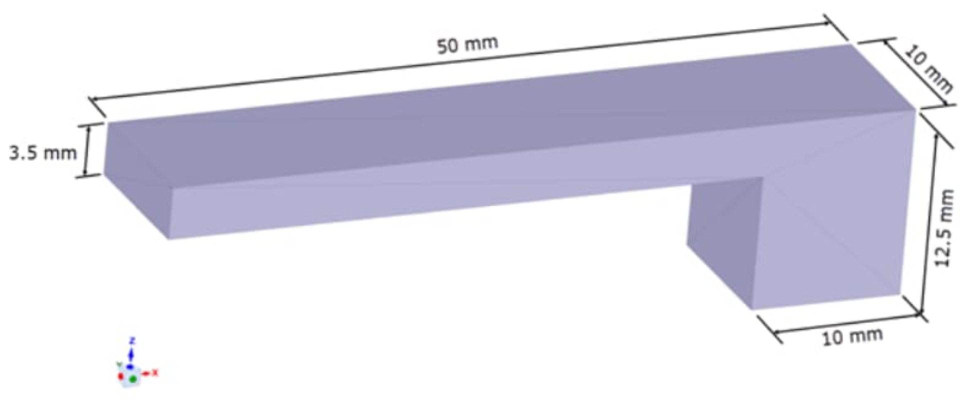


Figure 11, Cantilever geometry used for calibration of ANSYS Additive [14].

To get the values of the SSF and ASCs, the measured distortions on the calibration geometry are compared to distortions simulated by ANSYS Additive using default values for the parameters. The SSF and ASCs are adjusted depending on how the simulated distortions differ from the real, measured ones, and the simulations are run again with the new values. This iterative process is repeated until the simulated distortions are sufficiently close to the real ones [14].

Both SSF and ASCs will change depending on the process parameters (laser power, scan speed, layer thickness, baseplate temperature, hatch spacing, slicing stripe width, scan pattern, etc.). Calibration will therefore be best if parameters are the same for the printing of calibration parts as for the printing of the intended part. Ideally, any time something about the process changes, calibration should be redone. Even changing material supplier, even if the material used is the same, could be enough of a change for the calibration to be slightly inaccurate [14].

Having a perfectly calibrated machine is not always necessary, though, and depending on what the requirements are on the produced parts, a one-time calibration could be enough. Even without calibration, the simulations might predict problems and give insights that might be missed otherwise [14].

For the context of this project, the calibration procedure had already been done by Alfa Laval for their printer and SSF had been determined.

3.1.7 **Chamber placement**

Ideally, the angle at which the laser hits the part should, in most cases, be as close to perpendicular as possible. For some cases, such as walls that are slanted, having the laser parallel to the wall will yield a smoother surface (figures 12 and 13) [15]. Because the laser originates from the centre of the chamber, parts in the centre of the chamber will have closer to perpendicular angles during printing, whereas parts that are on a side or in a corner will have less favourable incidence angles. When producing parts using L-PBF, it is ideal to fit as many parts as possible in the chamber to cut down on print time and set-up and cleaning costs. Some parts will have to be placed in less-than-ideal locations in the chamber, which can have an undesirable effect on surface roughness.

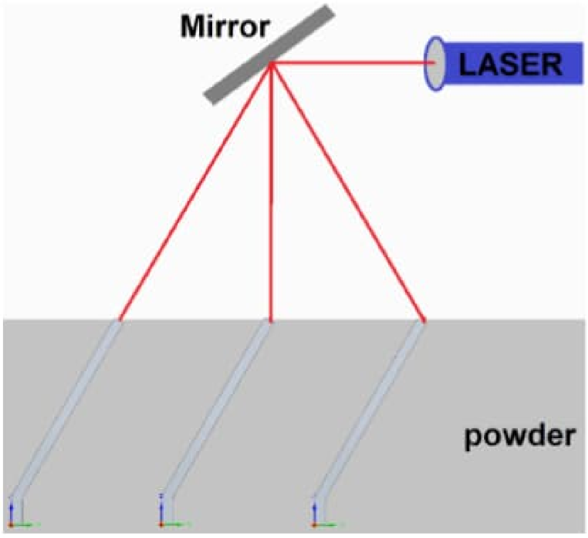


Figure 12, Illustration of how chamber placement affects the laser incidence angle [15].

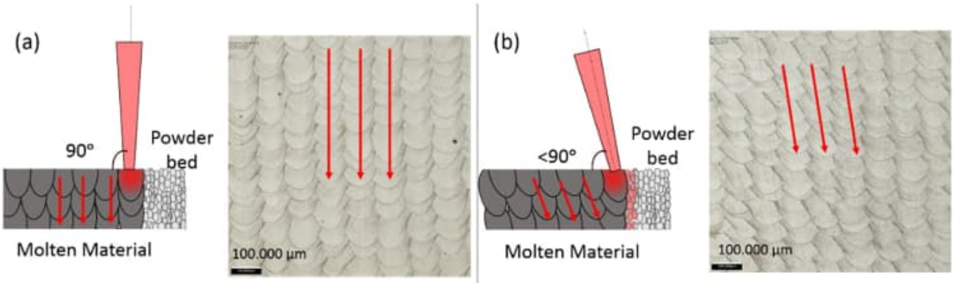


Figure 13, The effect of laser incidence angle on surface roughness, visualized [16 p.8].

3.2 Design Guidelines and Parameters

Here follows what guiding design principles could be found in various books and experiments. Some of them are more general good practices for AM, but most are more specific to L-BPF. Many of the guidelines have been discovered by setting up experiments with, for example, small walls with varying thickness, build angle and angle of impact with the recoater blade and then measuring the surface roughness of the walls. An example can be seen in figure 14. Experiments like these can be used to figure out the limit for where the risk of failure starts being too high.

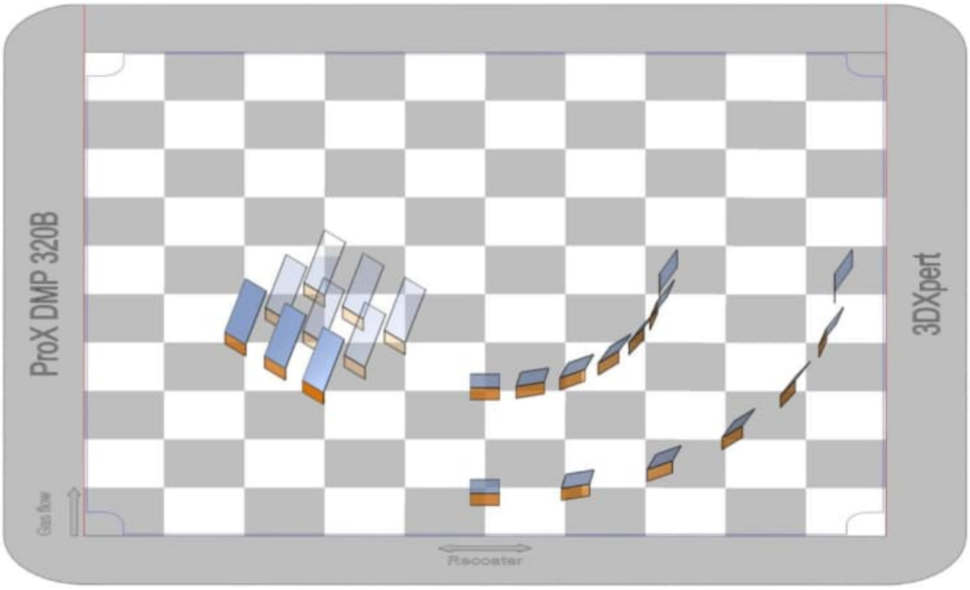


Figure 14, An example of a setup to test surface roughness depending on different placement angles and thicknesses of parts [3].

Following the recommendations for things such as overhang angles and wall thicknesses should lead to designs that should be printable, but it is not guaranteed. A design might still have to go through a few iterations of failure and redesign to become reliable. On the other hand, there might also be some missed opportunities if the guidelines are followed too closely in all cases. In the case of bridges, for example, a general guideline is that a flat, down-facing surface supported by at least 2 features should be no longer than 2 mm. 2 mm is a good rule of thumb, to play it safe, but if it is acceptable that the surface is a bit rough and the dimensions a bit deformed, larger gaps could be used to save on material or to simplify the design, although that comes with some risks [4 p 143]. (Figure 15)

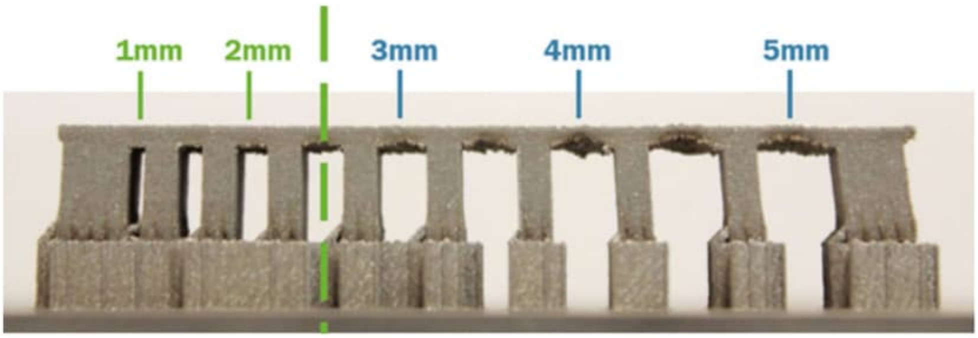


Figure 15, Results from an experiment testing bridge features with different sizes of gaps [4 p.143].

3.2.1 **Laser Parameters**

Laser Incidence Angle

The angle with which the laser hits the material influences the surface roughness and the dimensions for details with thin walls. Keeping the angle as close to perpendicular as possible yields the best results. The angle can be affected by how the part is positioned in the printing chamber as well as the angle of walls etc. [15].

3.2.2 **Parameters Related to the Recoater Blade**

Recoater Angle

The angle with which the recoater hits surfaces affects the dimensions and surface roughness, although it is not as great an impact as the laser angle. The recoater angle should preferably be at least 30 degrees [3].

Part Positioning

- Taller parts should be placed closer to the recoater blade [4 p.152-155].
- Parts should be placed in a way so that the recoater blade does not make first contact with them simultaneously [4 p.152-155].
- Avoid placing parts after each other in the recoater direction. If a part distorts or the recoater blade is damaged, parts behind might also be affected [4 p.152-155].

3.2.3 **Design Parameters**

Walls and thickness

- As a rule, walls have a minimum thickness of about 0.5 mm, but thinner walls can be successfully printed with the right settings and design, and thicker walls might be required in some circumstances [3, 4 p.157].
- Even wall thickness lets the material cool at an even rate and reduces residual stress. This is important in conventional manufacturing processes but even more so in AM. With L-PBF, residual stresses can usually be removed by heat-treating the printed part, but stresses that occur during printing can still cause the print to fail [4 p.157].

Other design parameters

- Overhanging surfaces over about a 45 degrees angle require support material. For stainless steel, titanium and cobalt chrome, an angle of up to 60 degrees could be acceptable. For this project, even though the parts will be printed in 316L stainless steel, 45 degrees will be considered the maximum angle, according to recommendations from Alfa Laval [4 p. 158].
- Downwards facing surfaces generally get rougher with a greater overhanging angle while upwards facing surfaces get somewhat smoother [3].
- Sharp edges and corners should be filleted to reduce stress concentrations. Filleting to ¼ of the thickness is a good rule of thumb [4 p. 157].
- Large masses of material will increase print time and material use and should be avoided. If large volumes of material are unavoidable, filling them with a lattice structure instead of solid material could be a good idea [4 p. 46].
- The minimum horizontal hole or slot size is directly related to the thickness of the part, the layer thickness, print orientation, as well as to the machine it is made on [4 p.43].
- The larger the surface area of the parts that are in close contact, the larger the gap between the moving parts must be [4 p. 43].
- Print orientation impacts, among other things, printing time, support material needed and surface roughness. Details can be somewhat distorted depending on the orientation they are printed in. Holes, for example, become slightly oval if printed vertically. Print orientation also affects anisotropy, the difference in material properties depending on direction. Anisotropy is less of a problem for L-PBF than for other printing methods and can mostly be eliminated using heat treatment and other post-processing but should still be considered. [4 p. 44-46].
- Circular, horizontal holes require internal support material over a diameter of about 8 mm.
- Holes with a larger diameter than 8 mm can be printed without support if the shape of the hole is changed from circular to, for example, oval, teardrop, or diamond-shaped [4 p. 151].
- The amount of support material should be minimized as it increases both printing time, material use, and post-processing time [4 p.47].
- Bridges (flat, down-facing surfaces supported by at least 2 features) can be up to about 2 mm without needing support structures [4 p.141].
- When making hollow parts, loose powder will be left in the hollow and will have to be removed. Salt-shaker holes should be made to allow removal of the powder. Two holes of at least 5 mm diameter is

recommended but smaller holes might be acceptable for parts with thinner walls [4 p.173].

3.2.4 **Support Structure**

Most parts require at least some support during the printing process. If the part has overhanging features which do not adhere to the 45-degree guideline, supports can be added that these features can be built upon [4 p.158].

During printing, the part is fused to the build plate and needs to be cut away from it. To keep the part intact and make removal of the part easier, a solid support structure of about 5 mm is added underneath the part [4 p.188]. Another function of support structures is to help lead off excess heat that is produced. Since most of the heat is transferred down through the part and into the build plate, a part that, for example, has some thinner sections might need additional material to do this effectively [17].

As with most design aspects of AM, there are several things to keep in mind regarding support structures:

- The support structure should preferably be easy to remove, as it can be very time consuming, especially in harder materials such as stainless steel.
- Support material can add considerably to the printing time and material use and should preferably be as small as possible without risking print failure.
- If the support is too dense, the support might grow out of the powder bed and interfere with the recoater blade.
- If the support is too small or thin, the rate of thermal transfer might not be enough which might result in delamination due to internal stresses.

Depending on the needs of the production, it might be better to overdo the support to ensure a successful build rather than spend time optimizing it. If the part will be printed in large volumes, optimizing the support structures of the part to reduce cost could be worth it. For lower volumes though, the added designing cost could end up being more than the savings of making the support slightly smaller [17].

3.2.5 **Laser Parameters and Scanning Strategies**

Even if the chosen part is well suited for L-BPF, all the right design choices are made, the part is well placed and sufficient support structures are created, the actual process of manufacturing the part also must be fine-tuned to get great results. In essence, it is about transferring the right amount of energy to the right place at the right time. If the material is not sufficiently melted, the part might end up with unwanted porosities and too much energy added can cause the material to vaporize which in turn creates defects [4 p.131].

Controlling the amount of energy deposited depends on several factors, such as the power of the laser, the size of the laser beam, how fast the laser moves over the area, how thick the layers are, how much the laser beam overlaps with previously scanned areas and how warm the material is when it is scanned (figure 16).

On a larger scale, the path that the laser takes over an area had to be chosen to provide the best possible material properties for the finished part, and for the efficiency of the process. To improve the surface quality of the part, the outline of the area is scanned separately [18]. This is called contour scanning and is performed either before or after the inner part of the area is scanned. Scanning patterns for the internal area, so-called hatch patterns, that follow the same path in the same place in overlapping layers (i.e. the first two examples in figure 17) have been shown to cause increased residual stresses [19]. To counter this, the pattern is usually rotated some amount every layer, most commonly 67°. It has also been shown that dividing a larger area into smaller ones, in a chess board like fashion, reduces residual stresses compared to larger areas [20]. With contour scanning, chess board division and rotation between layers, the resulting scanning strategy most commonly looks something like the one in figure 18, with the paths in the smaller squares rotating with every layer [4 p.130].

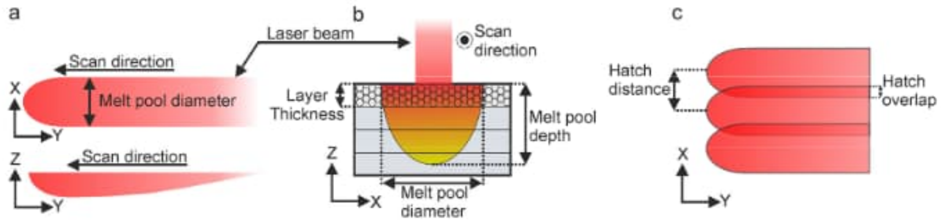


Figure 16, Common process parameters related to the laser [2 p.9].

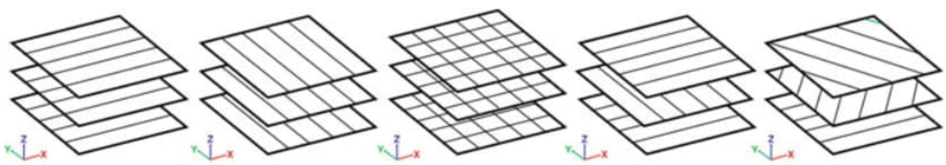


Figure 17, Examples of scanning strategies. [4 p.130].

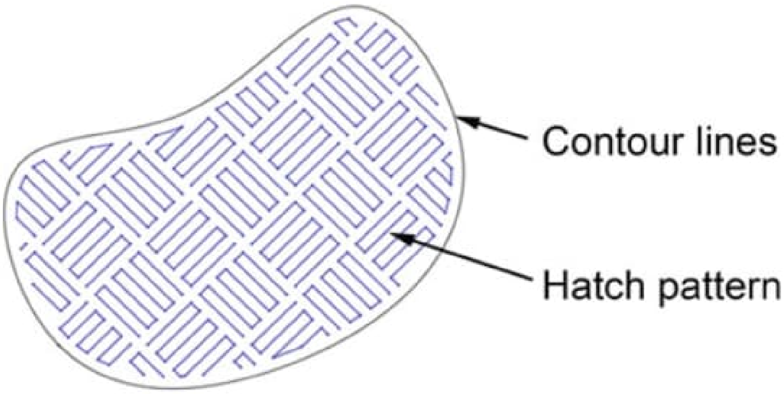


Figure 18, Commonly used scanning pattern for L-PBF [4 p.53].

3.3 Method for identifying details of a part that are suitable for redesign

When identifying which details of a part to choose for redesign, it helps to first consider the end-goals of the redesign, which are:

- Printed volume reduction
- Cost reduction
- Increased functionality
- Lower rate of print failure

In the case of this project, the part is being adapted for AM, not fully designed for AM, and part of the work has already been done. This means that all details of the part that connect to the surroundings (most outwards facing geometry) and all details that provide crucial functionality (inner channels, for example) must remain the same as before. The focus will therefore be on reducing the weight of the part as much as possible, without jeopardizing functionality. To figure out where the part needs work it is useful to understand which details of the part contribute most to unwanted properties of the part, i.e., where the most cost and risk are added. This can be done, for example, by going over the part and asking how specific details affect the manufacturing process and result:

Does this detail add unnecessarily to the printed volume of the part?

Details that typically add material to a part are large, filled volumes. Usually these can be hollowed out and support structures can be added to handle any problematic surfaces that this creates. The hollow can also be filled with a lattice structure, which serves as a support structure.

Does this detail add unnecessary cost to the manufacturing process?

For AM, the cost depends a lot on how much material needs to be used and how big of a volume needs to be scanned, so part of this question is the same as the previous. There are, however, other costs to consider. Post-processing can be a significant part of manufacturing costs, and it is important to keep all the manufacturing steps in mind when designing for AM. What requires post-processing is complicated and depends a lot on the function and requirements on the part. Heat treatment to reduce residual internal stresses in the material and removal of support structures are most common, and depending on the needs, machining and surface treatment might be required. Removal of left-over powder can be difficult. If any of these procedures can be eased or removed by design, it should be considered [4 p.205].

Can this detail be modified or redesigned to add functionality to the part?

The answer to this question will depend on the specific part and its function, but it is always worth considering. Maybe there is an opportunity to incorporate another part into the one being redesigned, and by doing that make assembly easier. Maybe there is a simple way to make the part more intuitive to use or assemble.

Does this detail have a risk of causing a print to fail?

Predicting whether a detail might cause the print to fail is not an easy task and is where the guidelines come into play the most. Avoiding failure during printing needs to be a top priority while designing for AM. A design that distorts or breaks during printing might result in large extra costs. The cost for preparation and cleaning of the printing machine persists if the part fails, and if, for example, the recoater blade gets damaged other parts that get printed simultaneously could also fail as a consequence. A little more material, weight and post-processing costs can be a small price to pay for a reliable, unproblematic design.

Understanding the printing process and its limitations deeply requires extensive research and experience. Luckily, plenty of experiments have been done to try to figure out where the limits are and there is plenty of literature on the subject. Following the guidelines outlined earlier in this chapter should be enough to at the very least get close to a printable design. There are too many factors at play for there to be a fail-safe guide for how to design for AM, and every new case could come with its own novel problems.

It is very important to gather any information about areas or details that have caused problems previously, especially if the part or similar parts have been manufactured using AM before.

4 Define

This section of the thesis presents the specific problem that this project sets out to solve. The part that is to be redesigned is introduced

4.1 Introduction of part and context

4.1.1 **Separators**

The part that will be redesigned is an in-and outlet pipe which is part of a centrifugal separator made by Alfa Laval. By spinning a liquid at high speeds, it is possible to separate the different components of the liquid based on their density. An early use of separators was to separate milk into cream and skimmed milk. Before centrifugal separators, milk was left to sit until the cream rose to the top and could be skimmed off. Spinning the milk sped up let the cream rise faster, and so milk could be processed much quicker and the risk of it turning sour was reduced. Together with Oscar Lamm, Gustaf de Laval, founded the company AB Separator in 1883, manufacturing and selling some of the first separators for dairy processing. AB Separator is now called Alfa Laval and the separators the company makes today (figure 19) are much more advanced and efficient, but they still follow the same principle as the cream separators. The applications of separators of course go beyond dairy, such as other food and beverages, oil, and fuel processing [21].

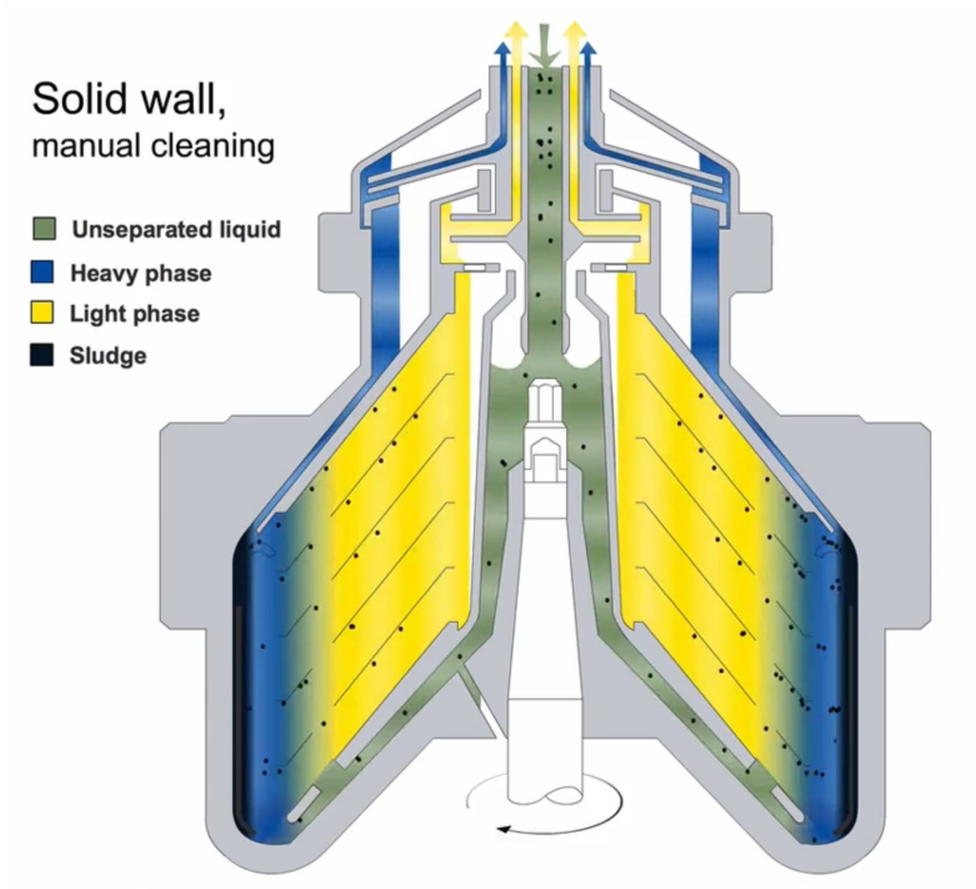


Figure 19, A illustration of a separator made by Alfa Laval [22]

4.1.2 **Role of the in-and outlet pipe**

The in-and outlet pipe is a central part of the separator. The unseparated liquid flows into the separation chamber through the pipes' central channel. And the separated liquids flow through the other, smaller channels in the part. (Figure 20)

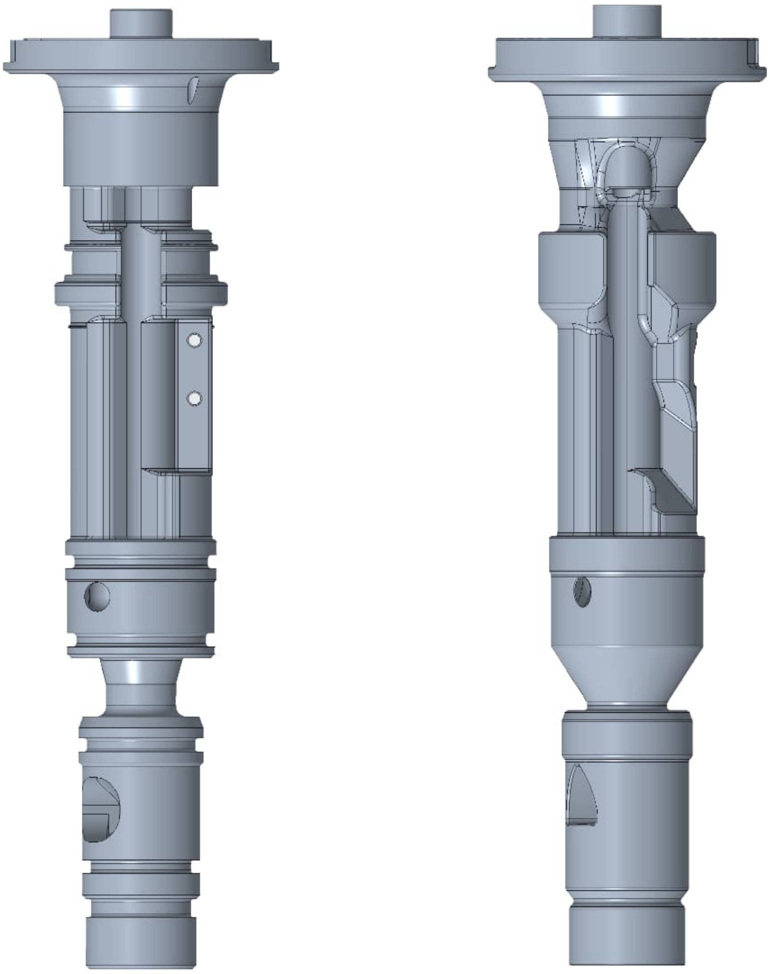


Figure 20, The part designed for casting (left) and the part partially adapted for AM (right).

4.1.3 **Previous adaptations for AM**

The pipe has previously been partially adapted for AM (see figure 20), to the point where it can be printed, but without taking full advantage of the benefits of AM. Throughout the part, there are overhanging areas that would need to be supported by support structures if the parts were to be printed without adaptations. Most of these have been reworked so that instead of being fully horizontal they are slanted surfaces that are printable.

However, two overhanging areas could not be changed so much that they could be printed without support structures. The smaller of them is where a channel entrance is located vertically. The entrance position cannot be changed without changes to connecting parts and so had to remain as is. As can be seen in figure 21, there was earlier a larger overhanging surface, which has been reduced to just the edges of the entrance to the channel. This surface does not have to be supported all the way down to the base plate, but a support can be constructed that goes down to a lower plateau, as illustrated in figure 22.

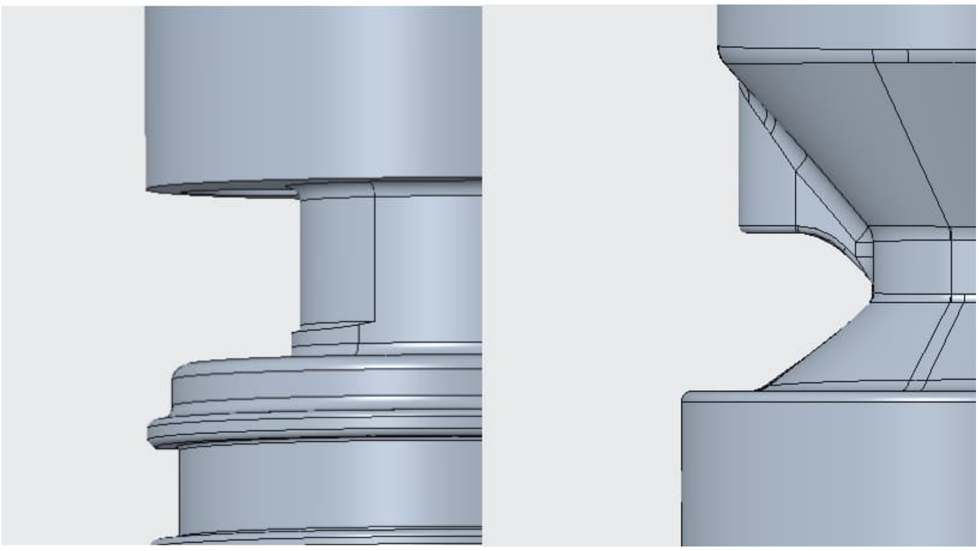


Figure 21, Smaller overhanging feature on segment 1.

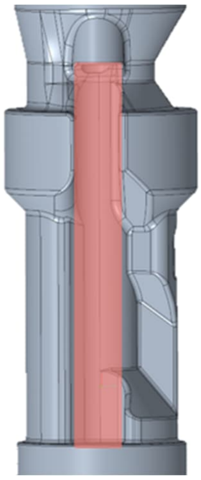


Figure 22, Image illustrating where the support structure would be to support the smaller overhang.

At the top of the part, there is a larger area that needs support. Unlike the smaller one, this one needs support that reaches all the way down the part to the base plate, if entirely vertical supports are used. This large support structure adds significantly to the manufacturing cost of the part. (Figures 23 and 24)

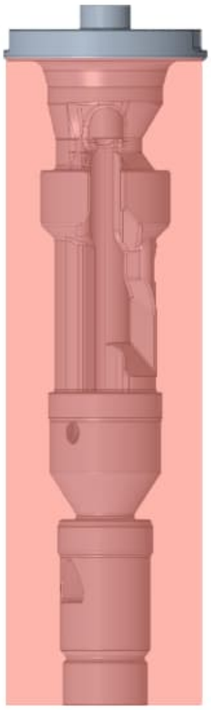


Figure 23, Illustration of support structure needed to support the overhanging feature in the top of the in-and outlet pipe.

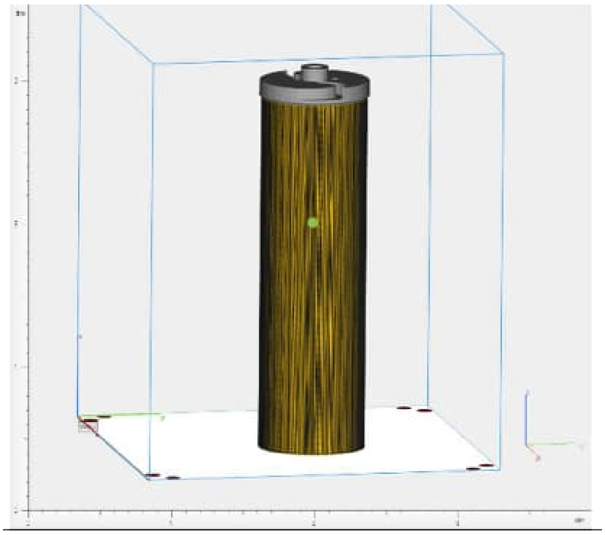


Figure 24, Support structure used when printing the partially adapted design, courtesy of Alfa Laval.

The channels of the part also had to be redesigned to be printable without supports. In figure 25, the entrance to one such channel can be seen. The opening has been changed from a circular one to an oval opening, as oval holes are better suited for AM. The more complicated opening in figure 26 was turned into two separate openings with teardrop shapes. In the old design, the inside channel would split in two at the top of the part, and in the new design, the channels are separated from the start. Another instance where an almost circular hole has been changed into a teardrop-shaped one can be seen in figure 27.

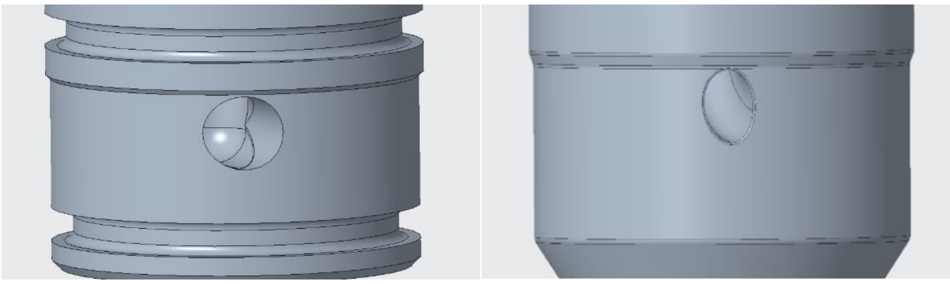


Figure 25, Circular entrance to a channel (left), and the adapted oval version (right).

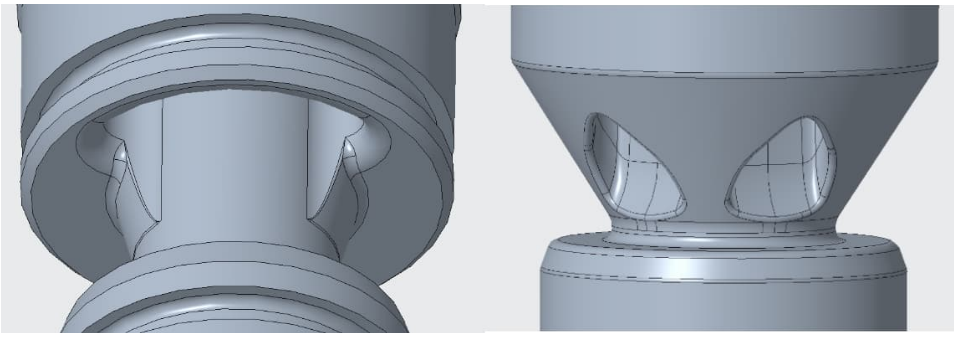


Figure 26, Entrance to a channel in the original design (left), and the version adapted for AM (right).

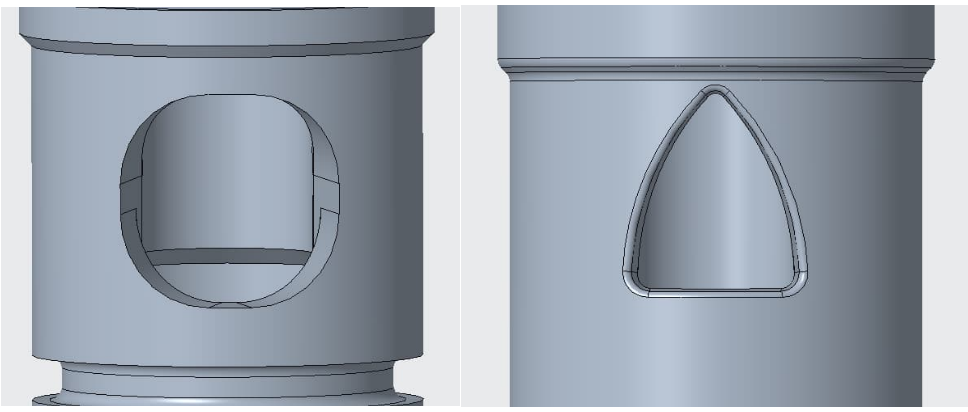


Figure 27, Entrance to a channel in the original design (left), and the version adapted for AM (right).

On a square, protruding feature on the part (figure 28), the formerly horizontal downfacing surface has been replaced with a slanted surface, following the 45-degree guideline for overhanging features.

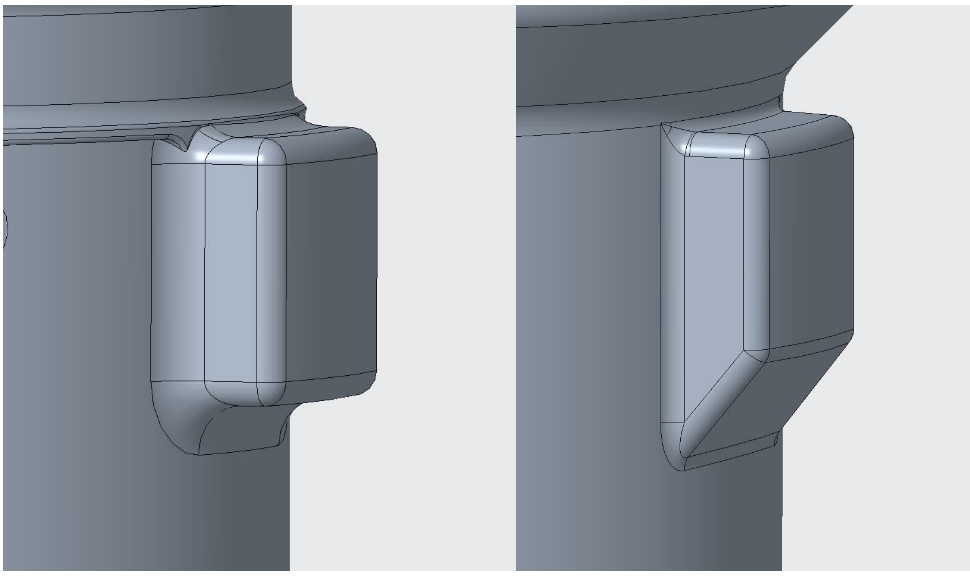


Figure 28, Original (left) and adapted versions (right) of a protruding feature.

There is an additional pipe that attaches to a small bracket which in turn connects to the in-and outlet pipe with two pairs of bolts and nuts using two holes. In the adapted design these two holes have been replaced by an indentation, where one hole can be made for the attachment of a smaller part replacing the bracket. (Figure 29)

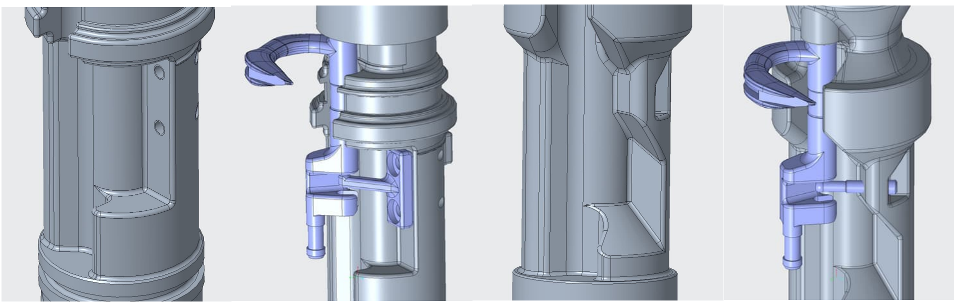


Figure 29, Adaptation of attachment point for other parts.

4.1.4 **Design Requirements**

Several design requirements were provided by Alfa Laval:

- To ensure that the part can still be assembled in the separator, outward surfaces should remain the same. However, since much of the outside needs to be machined to meet tight tolerances, adding material on the outside would not create a problem.
- Any changes to the channels inside the part and the entrances for those channels will affect the fluid dynamics of the liquids running through them. For the part to remain predictably functional without having to redo fluid dynamic analyses, the walls of the channels should also remain the same as before.
- In the case of the part breaking, any powder inside the part would run a risk of mixing with the fluid being processed, which cannot be allowed to happen. Therefore, all powder must be removed from the inside of the part.
- The fluid moving around the part causes a rotational force on the disc of the part. It is, however, hard to estimate how big this force is, and no effort to do so has been made by Alfa Laval. This is because it is not likely to be large enough to be of any concern.

When printing the adapted part, there were issues of the support structure cracking due to over-melting of the material near the overhanging area (figure 30). Engineers at Alfa Laval have proposed to further redesign the part to avoid having so much support. The proposed solution for the large area is to add material in the upper part so that the overhanging surface is instead at an angle and does not need support. It is also proposed to redesign the vertical channel entrance so that it also can be built without support (Figure 31).

Figure 30, Image of over-melted area and cracking of support structure, courtesy of Alfa Laval.

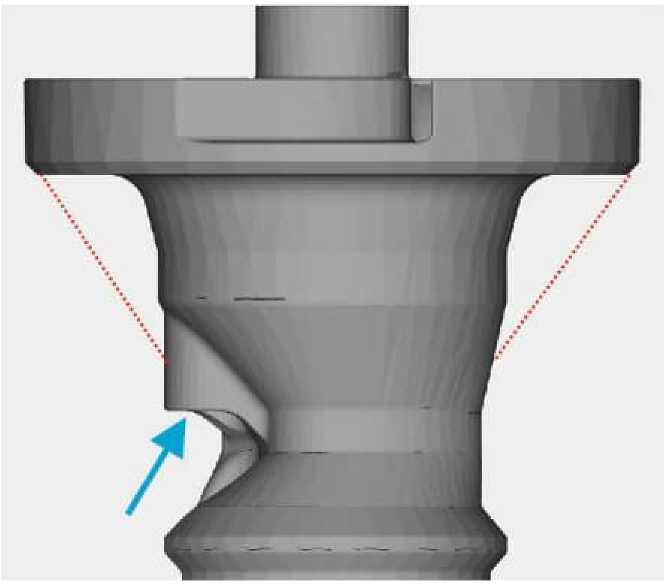


Figure 31, Proposed solution to reduce the support structure on the outside of the part. The red lines show where material can be added to create a slanted surface that does not need support.

4.2 Part segmentation

The part is long and has varying levels of complexity in different areas. For example, a section at the very bottom of the part in the print orientation is just a cylinder with a hole, without any slanting surfaces. Printing this segment of the part would be trivial and not much information of value would be gained. The top of the part, however, is much more complex and has areas that require support structures and channels for liquids. It is also at the top of the part where the support structure broke during printing. Because of the cost of printing, it was decided that the part should be divided into several segments so that only the interesting parts can be printed. This will make it possible to print designs at a lower cost to make sure that they are functional before attempting to print the entire part.

4.2.1 **Unnecessary Material**

Since the part is originally manufactured with casting, there was previously little choice but to fill all volumes with material. Throughout the part, there are filled volumes which can be removed. Removing this material would create many details inside the part that would need to be handled to ensure that they follow the guidelines. Most likely, large parts of the interior will need to be supported with either thin walls or something like a lattice structure.

4.2.2 **Choice of segments**

When dividing the pipe into segments, it is important that the interesting details are printed as a whole and not divided between the sections. A rough method with four steps was developed for the choice of how to divide the part:

1. Identifying critical details that should ideally not be between segments
2. Identifying areas with few critical details, where the part could be divided without many issues
3. Create segment candidates depending on the number of segments wanted and whether to leave out uninteresting parts or not
4. Choice of segments

Different areas of the part were put in three different categories depending on how critical the features in those areas were deemed to be.

The preferred areas of the pipe where the part could be split were areas that have mostly vertical surfaces, as it is unlikely that any issues would arise when printing them.

The not preferred areas are areas that contain slanted surfaces and internal channels bending inside the part. These areas should not be much of an issue to manufacture either, but they are a little more complicated and it would be better to avoid them.

The areas deemed to not be suitable for a split between segments are the areas with the features most critical to the parts' function and where problems are more likely to occur. This includes any openings in the part for channels, overhanging features that will need support structures and the areas where these support structures will most likely be. These categorized areas were coloured for visual aid, as can be seen in figure 32.

Figure 32, Colouration of how suitable areas are for segmentation. The green areas are the preferred ones, the yellow are not preferred and the red are not suitable for segmentation lines.

Since there is an area in the top of the part of about 64mm where it would not be suitable to divide the part, having segments much shorter than that would not significantly lower the overall print time, as the recoater would still have to make a pass for every layer until the tallest part is finished. Every part being printed also requires foundational support structures to bind it to the build plate, which adds to the build time for every additional segment. With this in mind, four alternatives for the segmentation were considered, with two choices to make. The first one was how many segments the pipe should be divided into. The second one was whether to print the entire part or leave out a section at the very bottom where the geometry is not complex enough to be of interest.

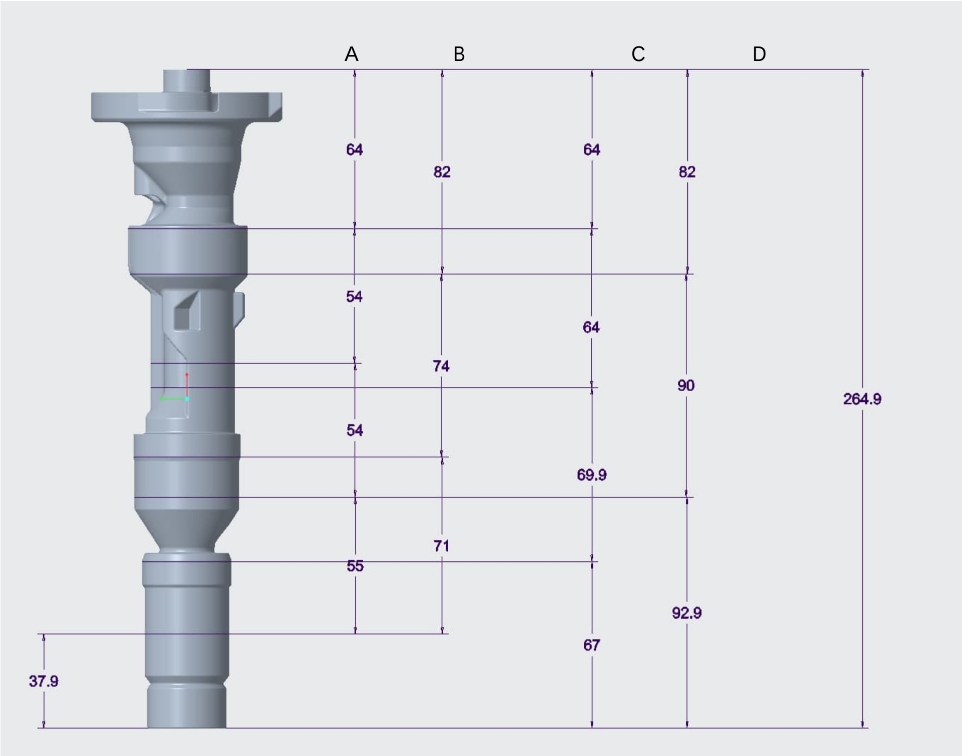


Figure 33, The considered options for the segmentation of the part.

As the lowest 37.9 mm are only circular sections with some rounded and chamfered edges, which should be trivial to adapt for AM it was decided that it should be left out of the print to save on material and to lower the printing time.

Option D (fig.33) was the chosen option in the end for a number of reasons. Firstly, all division lines for the segments are in preferable areas, without slanted walls or complicated geometry. Secondly, it provides the shortest tallest segment, meaning that the number of layers for the total print is the lowest, assuming all the segments will be printed together. The five segments of the part can be seen in figure 34.

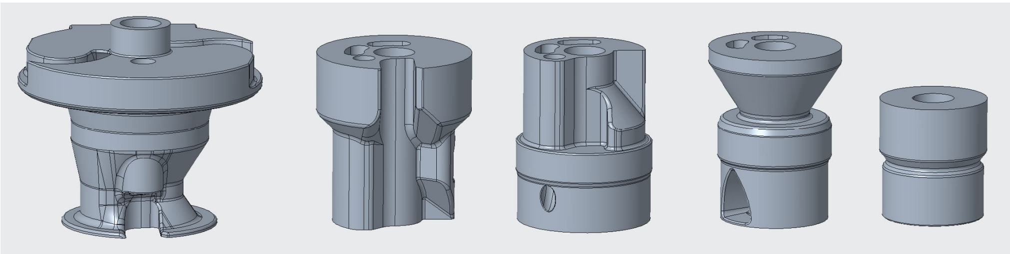


Figure 34, The in-and outlet pipe divided into five segments.

4.3 Unmodified Round of Printing

All the segments except for the lowest one were printed on Alfa Lavals printer. This round of printing was done so that any problems printing the segments separately could be discovered, and so that it would later be possible to make comparisons between the original adapted design and the design that would be developed during this project. The initial plan was to print all the parts for this project at LTHs facilities at IKDC, but unfortunately, the printer broke down when the print was started and was not functional again until the very end of the project. Before it was discovered that the printer was not working, the files for the segments were prepared so that they were in the right format, they were imported into the dedicated program for preparing files for printing and support structures were added for the areas which required it. Some work was also done to place the parts in the print chamber according to the relevant guidelines.

4.3.1 **Print Chamber Placement**

The following guidelines are relevant when creating a suggestion for the placement of the parts in reference to each other:

- The angle with which the recoater hits surfaces affects the dimensions and surface roughness, although it is not as great an impact as the laser angle. The recoater angle should be at least 30 degrees.
- Taller parts should be placed closer to the recoater blade.
- Parts should be placed in a way so that the recoater blade does not make first contact with them simultaneously.
- Avoid placing parts after each other in the recoater direction. If a part distorts or the recoater blade is damaged, parts behind might also be affected.
- "Clearance between parts built separately and assembled later must be at least equal to the general build tolerance of the system" [4 p.158]

As the part is mostly circular, it is impossible to keep the angle the recoater hits all surfaces over 30 degrees. For some details, such as channels and cut-outs, however, it is possible to angle the parts so that lower angles are avoided for the most part.

The parts were placed with a staggered layout in increments of 5 mm in the direction of the recoater with 5 mm between the parts. The parts were rotated to best avoid flat surfaces perpendicular to the recoater blade. The suggested part placement can be seen in figure 35.

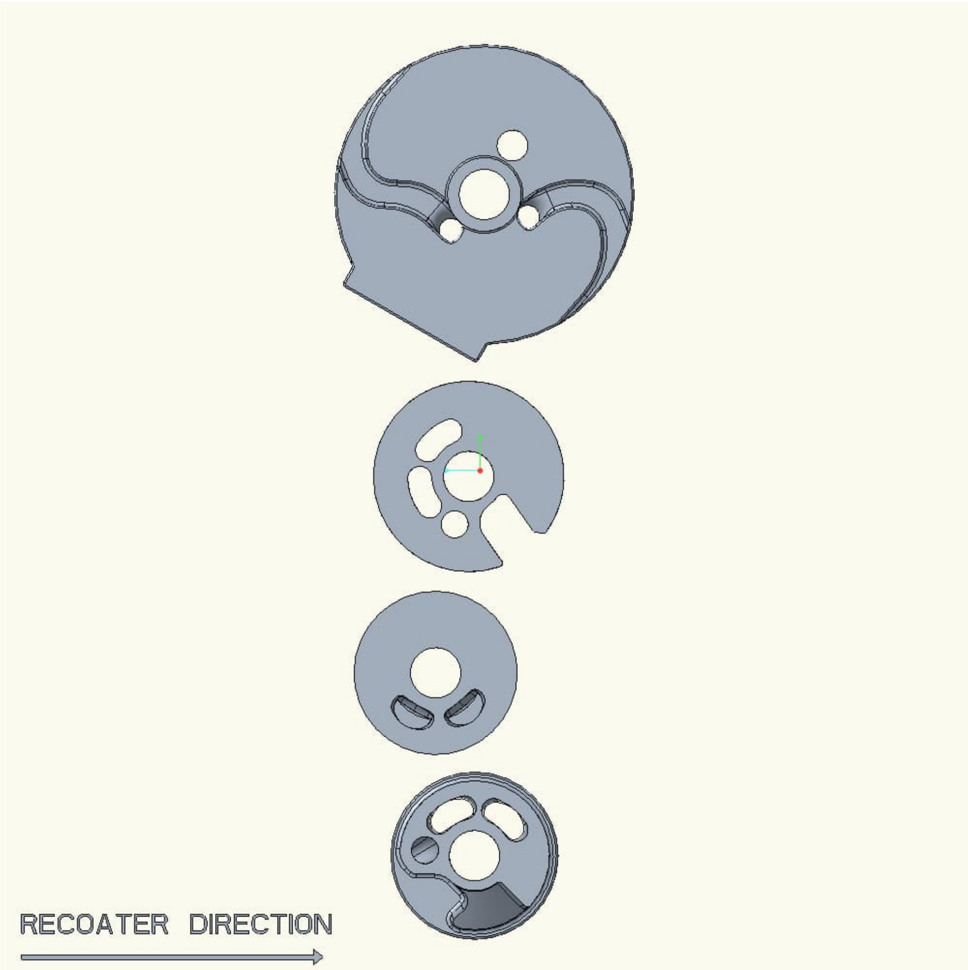


Figure 35, Suggestion of chamber placement for the four segments.

It is unknown if this proposed placement was followed when printing the parts, as the printer Alfa Laval uses is a different model than the one at IKDC and has a circular print chamber instead of a square one. There were also other parts in the chamber at the same time, so the placements were likely changed.

4.3.2 **Support Structures**

The bottom area of all segments will be supported by a 4 mm solid support. This support is needed to make it possible to remove the part from the base plate after printing without damaging the part. Out of the four segments, only segment 1 requires additional support, which was added similarly to how it had been added when the whole part was previously printed. The support structures were made according to the instructions of the machine technician at IKCD, with a wall with holes supporting the peripherals of the supported areas and a hatch pattern filling the areas, as can be seen in figure 36. The support structure that was actually used when printing the segment might have differed a bit from the one created here, but they are most likely fairly similar.

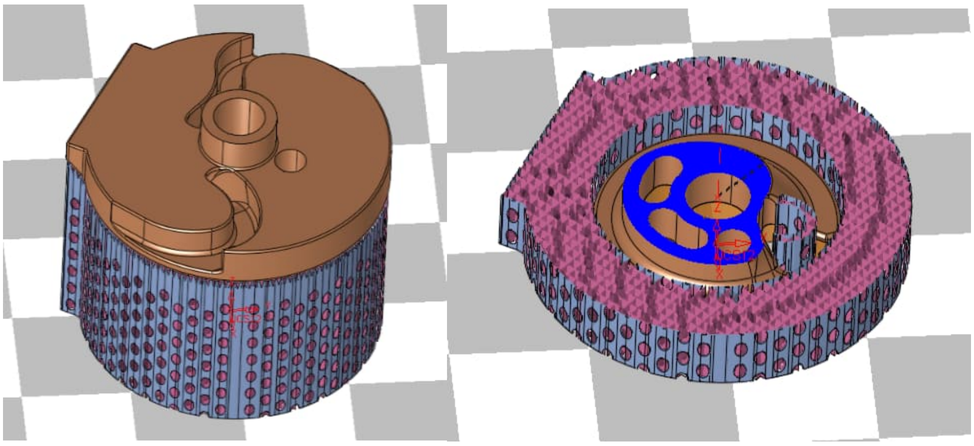


Figure 36, Supporting structures for segment 1.

5 Develop

In this chapter, the part is redesigned using the knowledge obtained in the research phase and process simulations are run to further refine the design.

5.1 Modifications/Improvement

5.1.1 **Identifying details of the part that are suitable for redesign**

Following the method from previous chapters for identifying details for redesign resulted in finding some clear candidates for design improvements. Predicting print failures at this stage would be very difficult as there is a requirement that the part remains functionally the same. Improving or adding functionality was not worth considering either. The part is, however, filled with material, much of which can be removed, as the physical requirements on the part do not go further than that the shape of the part and that liquids do not end up inside the part. Reducing the amount of support material needed is another thing to consider. Almost the entire part is surrounded by support structure, even though only two areas at the very top of the part require support. Changing the surface of the part so that it does not need support at all would be ideal, but that is not possible because of the requirements on the part. The support could, however, be significantly reduced by supporting these areas, not from the base plate but anchoring the supports higher up in the part. Removing internal material and reducing support structures should come with a significant reduction in manufacturing material and time costs.

5.1.2 **Reducing overhangs and surrounding support material**

There are two areas in the uppermost region of the part that need support. The top ring has a horizontal surface that requires support structures. Because the ring is so far up in the print direction and is also the widest section of the part, the entire part needs to be surrounded by support structure if the area is to be supported straight down. It is possible, however, to make surfaces at about a 45-degree angle. It should therefore be possible to build out from the part at an angle and intersect with the overhang.

The other area that needs to be supported is a smaller area by the entrance to one of the channels. Similarly to the other area, it should be possible to build out from the part instead of supporting it straight down. These two proposed solutions can be seen in figure 37.

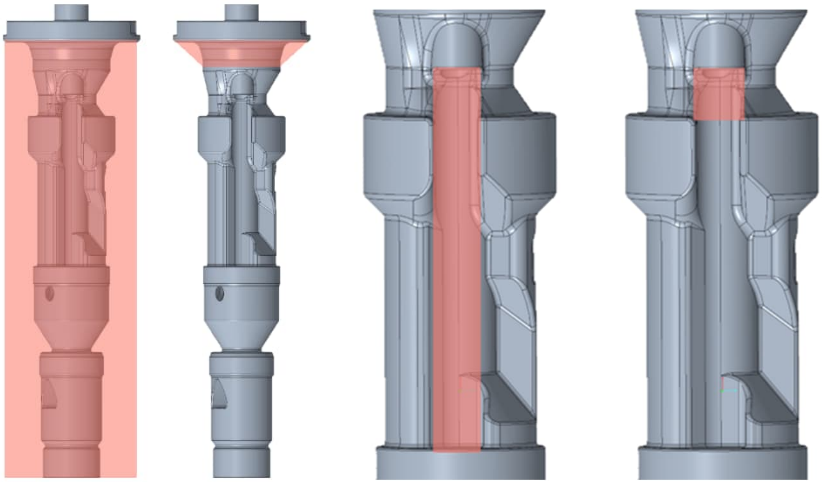


Figure 37, Support structures required before the redesign and proposed new supports.

5.1.3 **Removing material**

The very first step in the process of weight reduction was to “shell” the part. As the name implies, this means that the part is hollowed out, leaving only a shell. Any surface that “touches air” is turned into a thin wall of a specified thickness. Following the guideline about minimum thickness, the walls after shelling were 0.5 mm thick. In figure 38, the result of shelling segment 2 can be seen.

This step removes a large portion of the total volume of the part, reducing the amount of material down to around 14.5% of the original volume.

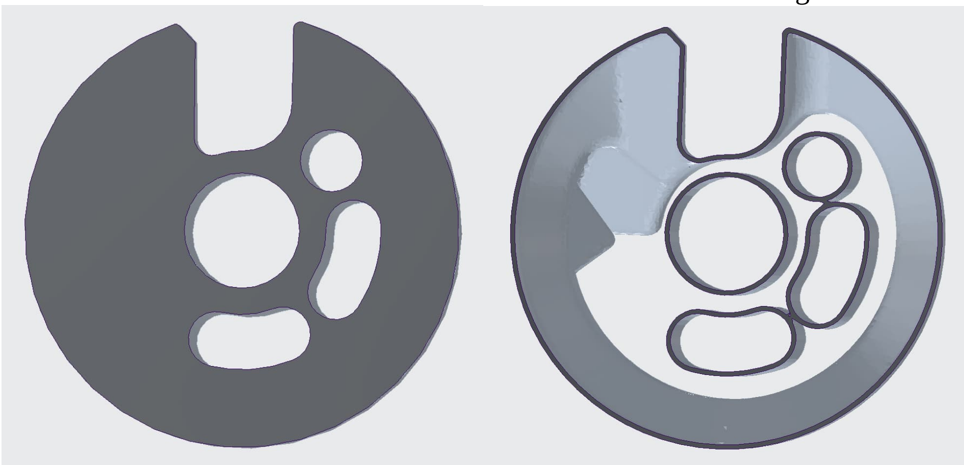


Figure 38, Segment 2, before and after shelling.

5.1.4 **Fixing problems created by removing material**

The outside of the part had largely been adapted for AM so that most of the surfaces on the exterior of the part follow the guidelines. Consequently, as many of the surfaces on the inside are parallel to the outside ones, many interior areas do not need to be adapted. Upwards facing surfaces, however, become downward-facing surfaces on the inside and need to be supported. Two main solutions were considered for how to handle these surfaces. The simple one would be to simply fill the entire internal volume with a lattice structure. This would provide support for all surfaces and be fairly easy to do. The weight of the part would be reduced along with material use and printing time. The powder inside the part might, however, get stuck in the lattice to a high degree and getting it all out could be problematic.

The more complicated solution would be to handle each surface individually. This would require a more detailed inspection of the part as the surfaces have to be identified before they can be handled. Creating the supports for the surfaces manually would take quite a bit more time and effort, but it would provide more control and allow for even more material reduction. It is also likely that removing internal powder would be significantly easier.

The two solutions can be compared to using the more straightforward support structure on the outside that covers the whole part or making smaller, specifically designed supports. Both solutions have their place, as sometimes it is too much work to create manual supports, and it is more important to print the part fast than to reduce the cost as much as possible. If the plan is for the part to eventually be produced using AM, as with the pipe in this project, the extra design work could result in substantial savings down the line.

The requirement to not change the outside of the part and the requirement to remove the powder from inside the part are in conflict as holes in the surface would be necessary to remove the powder. Since the part will be printed in segments during this project, the powder will be easily removable. If the whole part is to be printed, possible locations for holes for removal of powder is in either the top or the bottom of the part, where potentially an area could be left open. There is also an area (figure 39) where another part is to be attached, which would require a hole. The part that would fit in that hole has a diameter of 4 mm, which is under the recommended 5 mm, but it could be enough to remove the powder.

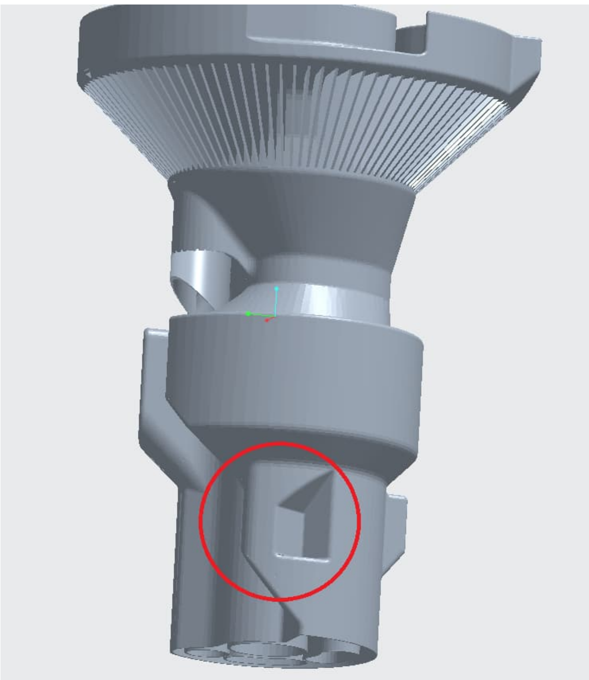


Figure 39, Potential location for powder holes.

5.1.5 **Supporting inner surfaces**

Even though creating the supports manually required more time and effort than it would require to fill the void with a lattice structure, doing so made it easier to follow the guidelines more accurately and further minimized the weight and print time of the part. Manual supports also give more control over the structures to ensure that, for example, powder will not get stuck inside the part.

The inner surfaces were mostly handled similarly. The maximum angle for an overhanging surface is 45 degrees. This means that instead of a vertical support structure, support structures could be built at a 45-degree angle and ‘anchored’ to closely located features. The maximum distance for a bridge is about 2 mm. That means that every 2 mm there must be something supporting the surfaces. With these two things in mind, the simplest solution was to add thin walls at about a 2 mm distance and have them at an angle of 45 degrees towards the nearest feature. Following the guidelines about a minimum wall thickness of 0.5 mm and that it is preferable to have an even thickness throughout the part, the walls were set to be 0.5 mm. The pipe has many circular features, with the same centre. Because of this it was often easiest to create one of these supporting walls and then create copies at evenly spaced intervals revolving around the centre line of the pipe. (Figures 40, 41 and 42) In other cases, each wall had to be created separately, depending on the specific area. Segment 1 posed a particular challenge, as a large internal area with a complicated surface had to be supported without, in some cases, having access to good nearby features to ‘anchor’ the supports to (figure 43).

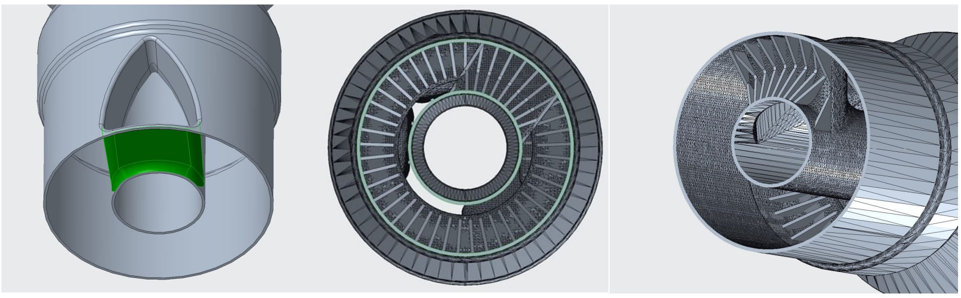


Figure 40, Channel entrance on segment 4, without support to the left and with added custom support structure in the middle and on the right.

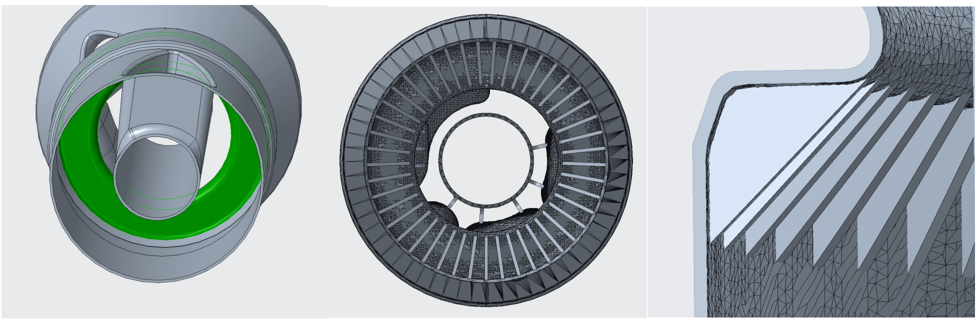


Figure 41, Overhanging area on segment 4, without support to the left and with added custom support structure in the middle and on the right.

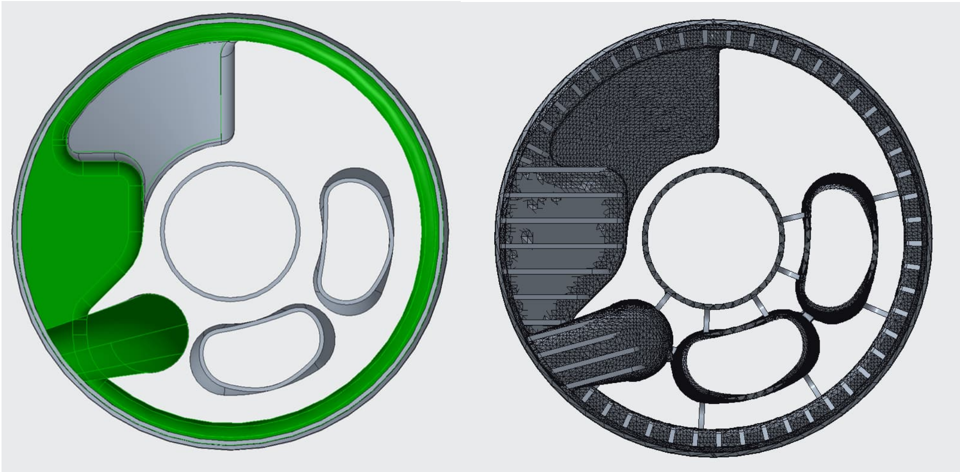


Figure 42, unsupported area in segment 3 on the left, and custom supports added on the right.

Figure 43, A large area in segment 1 in need of support structure (left and middle) and the same area with added support.

In some instances, the supports added ended up between segments. This is not ideal as it would be good to see the supports printed in full to ensure that they work as intended. The supporting walls are, independently, simple features, and should not have a very high risk of failure. Together, though, they form a more complex structure, which might be prone to deformations due to high heat, for example.

Hollowing out the part resulted in the inner channels being separated from the rest of the part for most of their length. This might cause problems, since the part is likely to deform, at least a little bit, during printing due to heat. To prevent the walls of the channels from ending up being misaligned with where they reconnect with the outer walls of the part higher up, some walls were added between the different channels and the channels and the outer walls, as can be seen in figure 42.

The overhanging features on the outside of the part, which previously required huge support structures, were supported in a similar fashion (figure 44). The larger of the overhangs needed only walls 'anchoring' to the outside of the part further down.

The smaller surface, however, where a channel has its entrance, required an additional supporting wall to which smaller walls could ‘anchor’ (Figure 45).

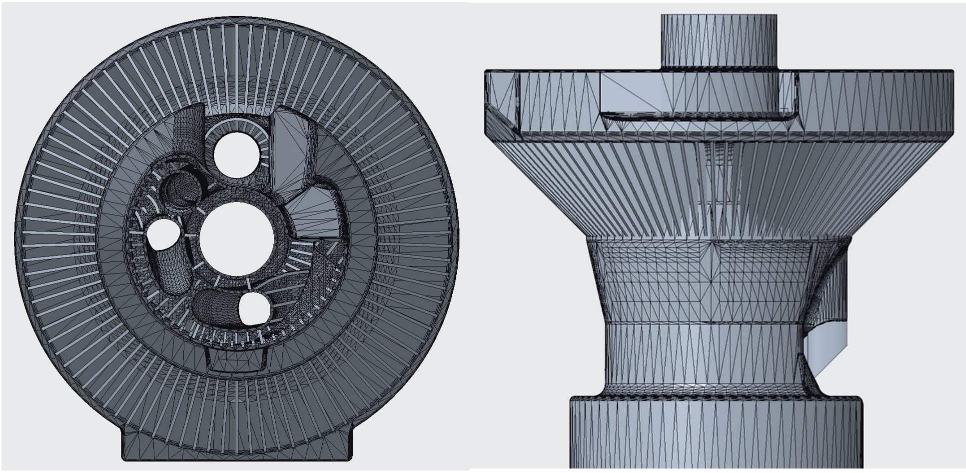


Figure 44, The supporting walls for the large overhanging feature.

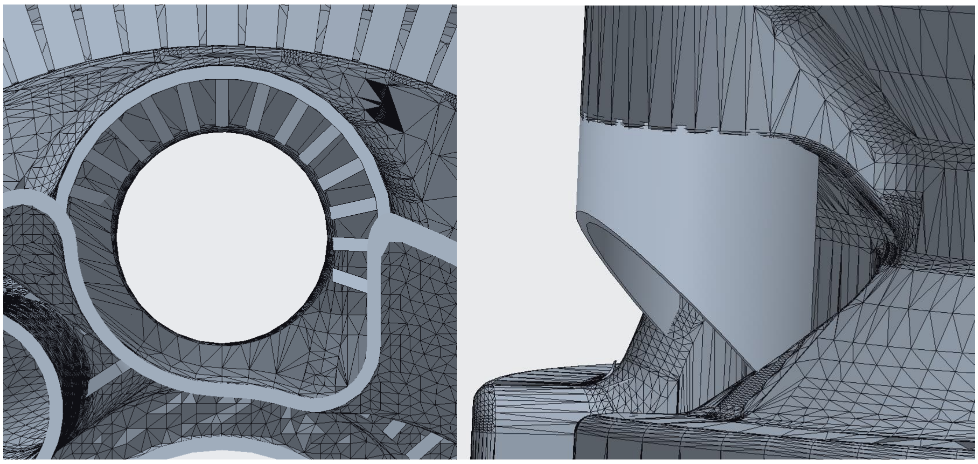


Figure 45, Supports for the overhanging entrance to a channel

Some more details of the supports between the channels and supports for an internal surface can be seen in figures 46 and 47.

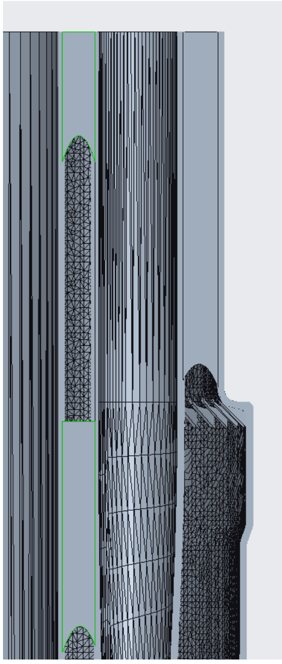


Figure 46, Supporting features between the inner channels.

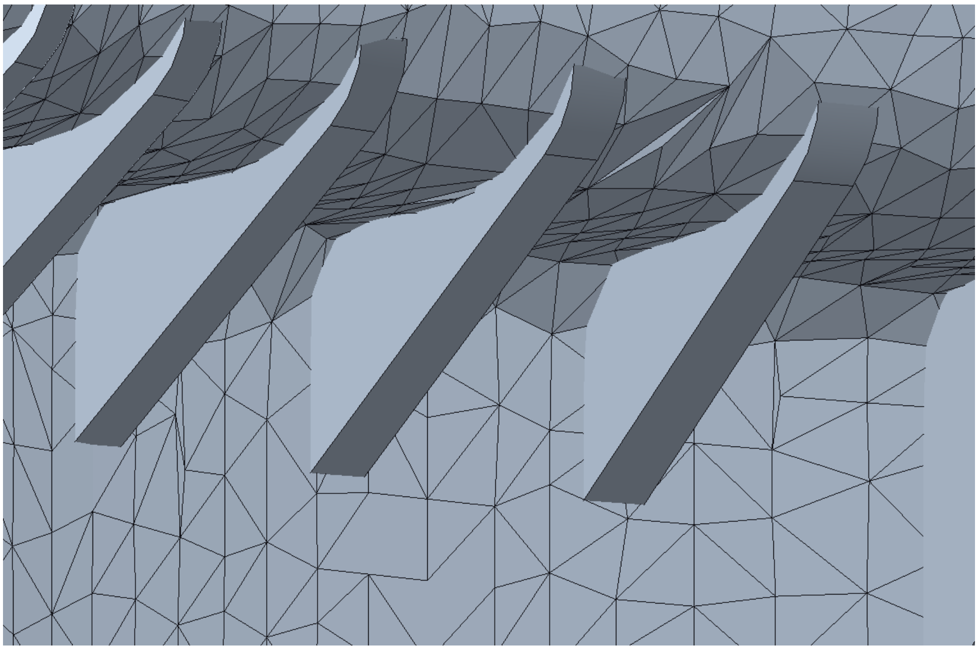


Figure 47, Supporting walls for an internal overhanging surface.

5.2 Distortion Compensation Analysis

5.2.1 **Distortion Compensation Simulations**

When running any simulations that are calculating stresses and strains in a material, the properties of the material must be accurately specified to get good results. 316L is an alloy made up of mostly iron, with some added amounts of chromium and nickel, as well as a smaller percentage of molybdenum. Some other materials, such as silicon and carbon might also be added in even smaller amounts [7]. All the materials contribute in different ways to the properties of 316L, the chromium, for example, together with a low carbon content, imparting resistance to corrosion and heat [23]. For distortion compensation simulations, properties relating to how the material performs when heated are important, as well as properties specifying how the material deforms when strained and how much stress it can take before breaking. For example, the Thermal Expansion Coefficient stated how much the material expands when heated by one degree Kelvin [24]. the Elastic Modulus states how much the material deforms elastically when strained and the Material Yield Strength stated how much stress the material can take before it deforms permanently [25, 26]. (Figure 48)

For simulations in Ansys Additive in this project, a custom version of 316L stainless steel was created with the value for SSF provided by Alfa Laval replacing the standard value of 1.0. Besides changing the SSF, all other settings were left at default values. The more accurate mathematical model for simulation of deformations, J2 Plasticity was chosen for the simulations.

There is a setting for voxel size that was left at the default value of 0.5 mm. A voxel can best be explained as the 3D equivalent of a pixel, and just like having more, smaller pixels for an image result in a more detailed image, having more, smaller voxels would result in a more detailed representation of a 3D object. 0.5 mm was probably too big of a value for these simulations, as most of the walls have a thickness of 0.5 mm and the program might have issues accurately representing them with such large voxels. A recommended value for voxel size is at least a fourth of the minimum feature size, which in this case would be 0.125 mm [27].

There is a choice of outputs for the simulations, and for this project, the outputs chosen were distortion compensated versions of the parts, information about potential recoater blade crashes and information about strain in different areas of the parts. (Figure 49)

Properties

Powder Absorptivity	0.76
Solid Absorptivity	0.45
Thermal Expansion Coefficient (K^{-1})	0.0000165
Elastic Modulus (GPa)	185
Poisson Ratio	0.25
Material Yield Strength (MPa)	530
Hardening Factor	0.0018
Support Yield Strength Ratio	0.4375
Strain Scaling Factor	0.6
Anisotropic Strain Coefficients (‖)	1.5
Anisotropic Strain Coefficients (⊥)	0.5
Anisotropic Strain Coefficients (Z)	1

Figure 48, Material properties for 316L stainless steel used for simulations in Ansys Additive.

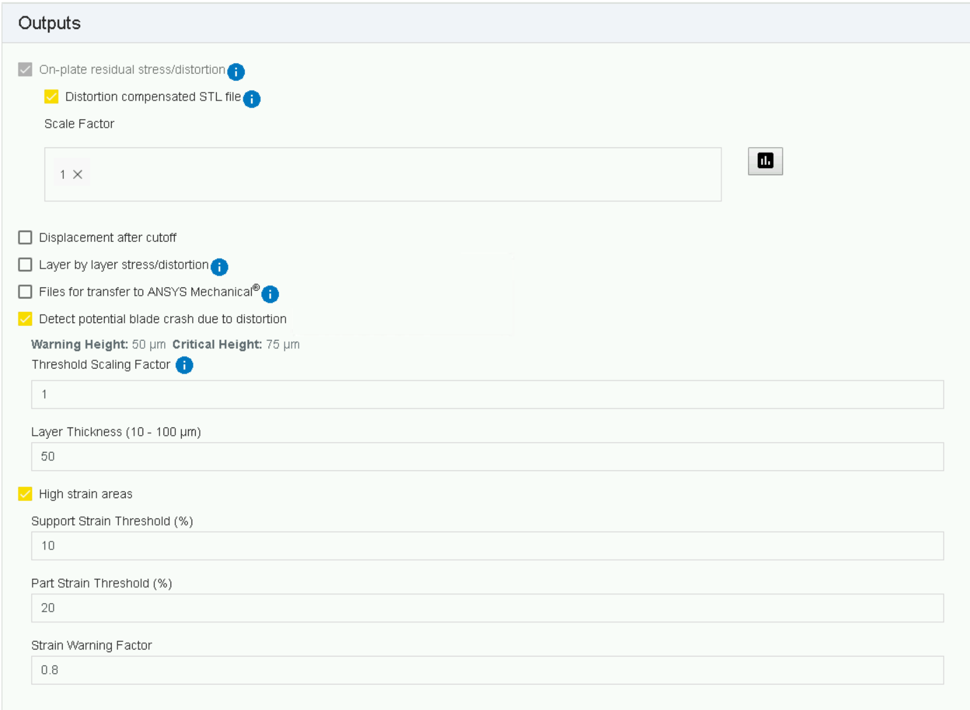


Figure 49, Output setting used for the simulations.

5.2.2 **Simulations results**

The simulations revealed that the parts would deform quite a bit during the printing process, in some parts as much as 0.44 mm (table 6.1). These deformations could be big enough to cause problems assembling the pipe with other parts, and if printing the compensated versions could reduce the deformations, these problems might be averted.

Table 6.1 Maximum distortions in the different parts.

Part	*Maximum distortion (mm)*
Segment 1	0.31
Segment 2	0.16
Segment 3	0.09
Segment 4	0.08
Segment 5	0.06
Full part	0.44

The simulation results also warned that there was a potential risk for recoater blade interference in segment 1. In fact, the results highlighted a total of 1075 possible blade crash locations for the simulation of segment 1, and 1035 for the simulation of the full part. The distortions of segment 1 can be seen in figure 50, and the areas at risk for blade crashes were located where the supporting walls meet the overhanging surface, out towards the edge of the part.

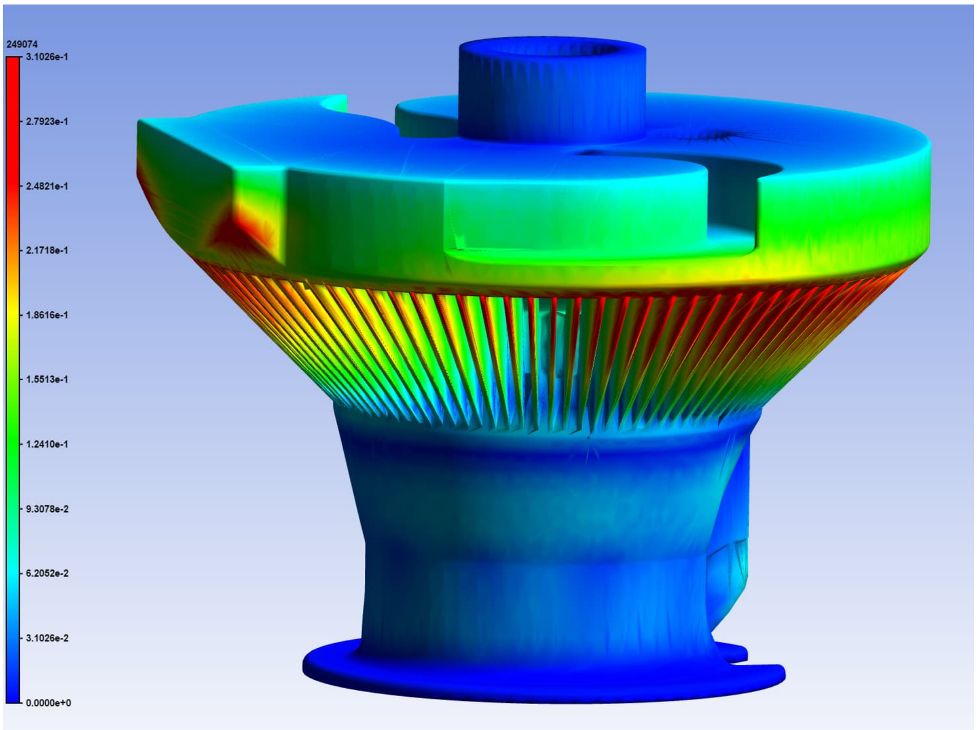


Figure 50, Simulation results showing distortion for segment 1.

The deformation of the supporting walls is most likely due to there being too much heat in the walls, causing them to expand upwards. To reduce the heat in these areas, two design solutions were proposed:

- Add holes to the supporting walls on the outside with the idea that less material leads to less distortion due to less build-up of heat.
- Make the outer supporting walls thicker, giving the heat more material to absorb into and reducing deformations.

Another possible solution would be to slow down the printing process, to give the part more time to cool down between layers.

Both design solutions were modelled, and new simulations were run on segment 1. Adding the holes to the supporting walls increased the number of blade crash warnings to 1204 while doubling the thickness of the walls from 0.5 mm to 1.0 mm decreased the number of warnings down to 224. Further increasing the thickness to 1.2 mm (figure 51) and replacing the walls with a solid support removed all blade crash warnings. Such thick walls go against the guidelines of even wall thickness throughout a part, and regions of solid material are generally undesirable and should be removed if possible. The solid support does not seem to increase the distortion of the part and keeping the solid support would make it easier to cut away the support in post-processing.

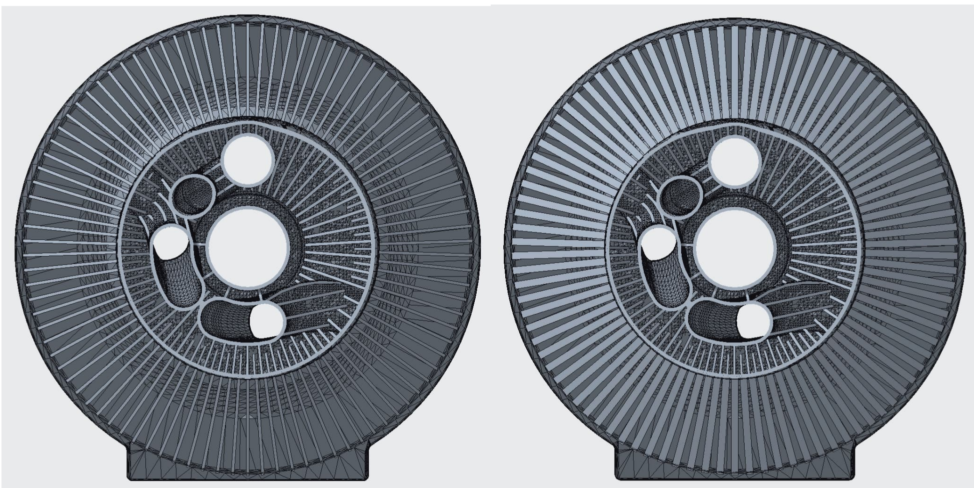


Figure 51, The design with supporting walls with a thickness of 0.5 mm to the left and the version with 1.2 mm to the right.

At this point, these simulations have already yielded some valuable results, as they potentially prevented a failed print due to recoater blade crashes in segment 1. Using the compensated geometries output by Ansys Additive instead of the original files should make the result more dimensionally accurate.

5.3 Modified Round of Printing

Out of the segments, only the redesigns of segments 1 and 2 were printed, as they were the most interesting. Segment 1 is the most complicated of the segments, with more complex surfaces and supports on the inside and outside, and segment 2 has some more complex outside surfaces and the attachment point for other parts. Both parts were heat-treated after printing (figure 52).

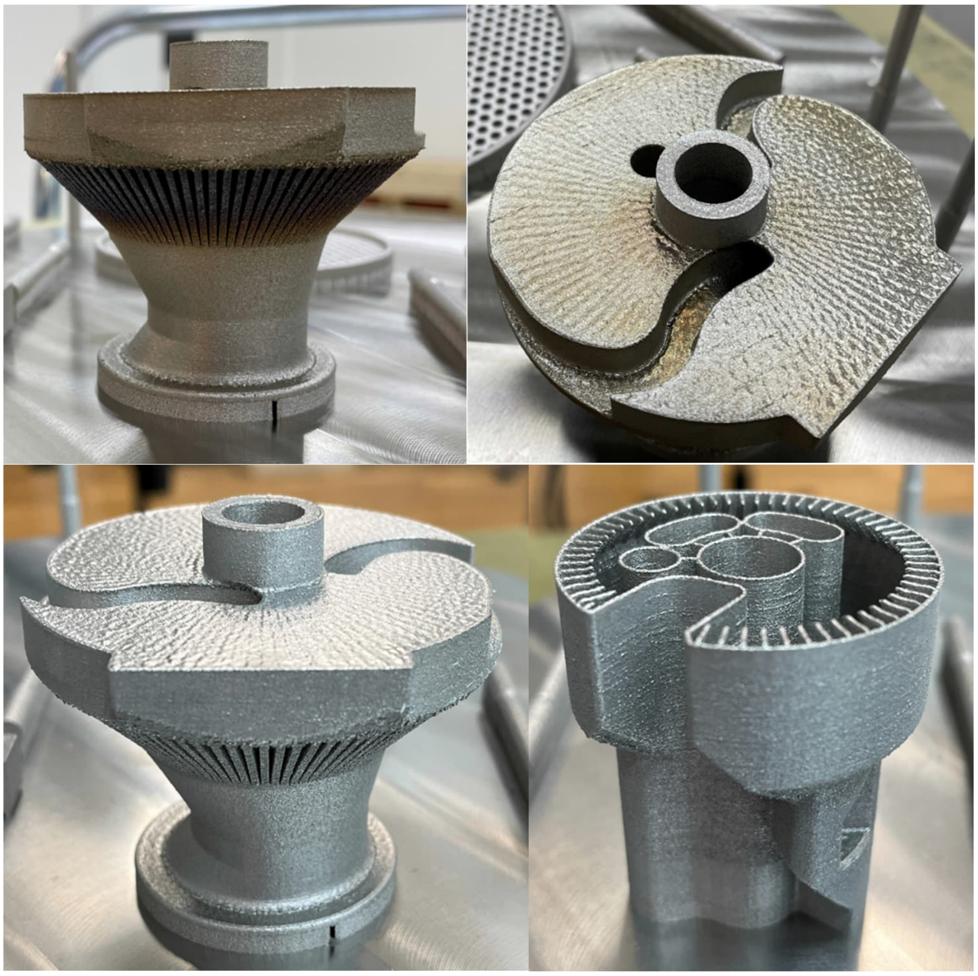


Figure 52, Segment 1 before heat-treatment to the top, and segments 1 and 2 after heat treatment on the bottom.

At first, only the uncompensated versions of segments 1 and 2 were printed, and besides some rough surfaces, the print was a success. Segment 1 was the only segment of which the distortion compensated geometry was printed, and while the part did print in its entirety, there were quite a few defects. Some walls had holes in them, the outer supporting walls had some very rough surfaces and there were distinct lines on the large top surface, as can be seen in figure 53. In figure 54 the probable reason for the defects is shown. Some surfaces seem to have taken on unusual shapes when being compensated making them very pointy instead of their original flat appearance.

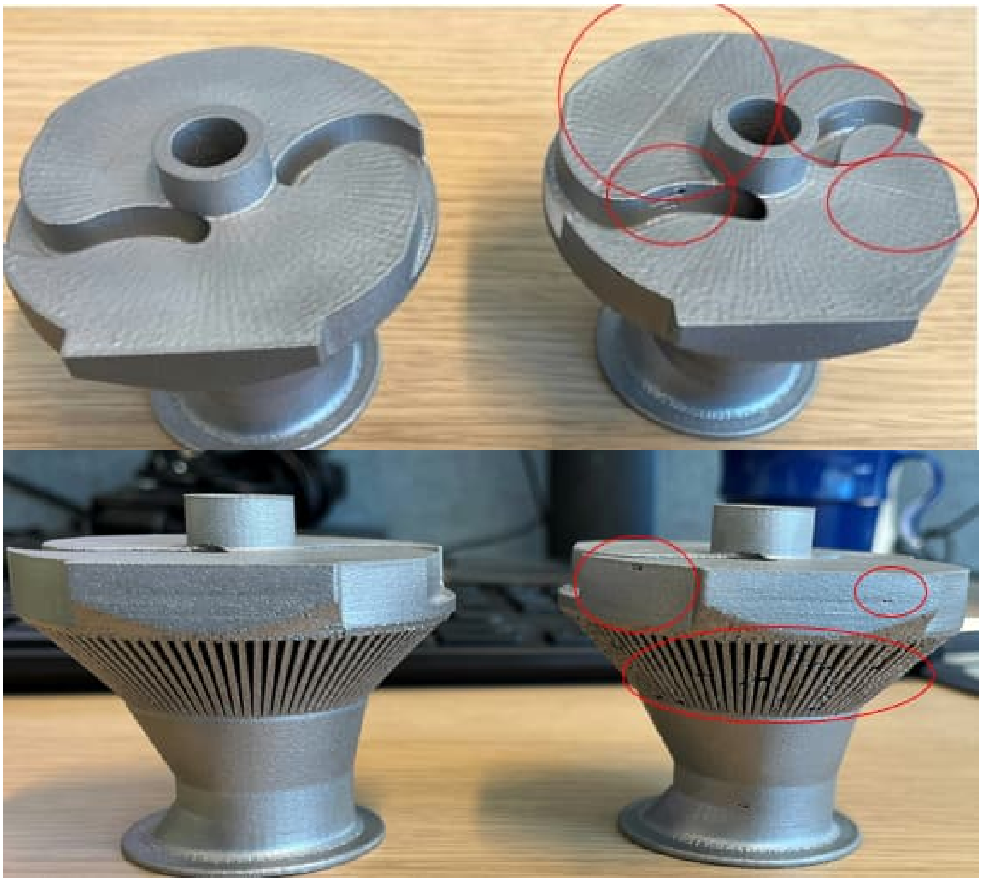


Figure 53, Print of segment 1, uncompensated to the left and compensated for distortion to the right. Defects are highlighted with red circles. Courtesy of Alfa Laval.

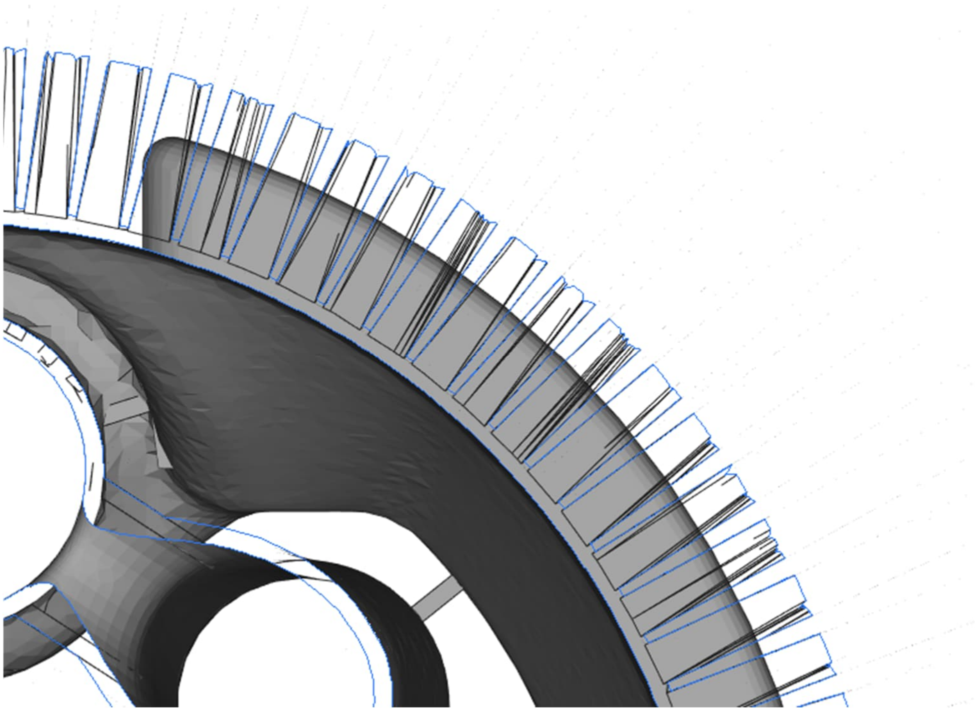


Figure 54, Jagged geometry of the outer supporting walls on segment 1, courtesy of Alfa Laval.

6 Deliver

This chapter presents the time and cost reductions that were achieved for the part, based on process simulations.

6.1 Results

Not all segments were printed, so exact values for the time it takes to print the parts and how much it would cost could not be obtained. Programs used for preparing parts to print do, however, have the functionality to simulate the printing process and calculate printing time, material use and the cost of a part. After adding the foundational support structures between the parts and the build plate and supports for the overhanging regions, simulations were run for the entire pipe and the individual segments, both the original adapted version and the further adapted design developed during this project. Unsurprisingly, there were significant reductions in the material use and printing time in the new design compared to the old one. Due to the amount of internal material and the large support structure needed in the original adaptation, the material use of the whole part could be reduced by over 90% and the printing time could be reduced to about a third. Simulated values for the original adaptation and the redesign can be found in tables 7.1 and 7.2, respectively. Comparisons of these values can be found in table 7.3. All cost calculations were done using cost values provided by Alfa Laval.

Table 7.1 Simulated print times, printed volumes, and costs for the original adaptation of the pipe.

Model	*Print time (h)*	*Part volume (cm^3)*	*Support volume (cm^3)*	*Total volume (cm^3)*	*Cost per part (SEK)*
Segment 1	11.7	88.8	21.4	110.2	9,068
Segment 2	6.8	2.7	49.9	52.6	5,220
Segment 3	6.4	45.5	5.7	51.2	4,924
Segment 4	5.6	40.3	3.9	44.2	4,345
Segment 5	3.4	24.0	1.6	25.6	2,652
Full part	45.8	248.6	340.0	588.5	36,103

Table 7.2 Simulated print times, printed volumes, and costs for the redesign of the pipe.

Model	*Print time (h)*	*Part volume (cm^3)*	*Support volume (cm^3)*	*Total volume (cm^3)*	*Cost per part (SEK)*
Segment 1	7.3	32.4	1.46	33.9	5,589
Segment 2	3.0	8.5	0.7	9.2	2,278
Segment 3	6.4	7.8	0.6	8.4	2,150
Segment 4	5.6	5.3	0.4	5.6	1,638
Segment 5	3.4	3.3	2.0	5.3	1,141
Full part	15.9	51.6	2.0	53.6	12,048

Table 7.3 Differences in print times, printed volumes and costs between the original adaptation and the redesign.

Model	*Print time reduction (%)*	*Material use reduction (%)*	*Cost reduction (%)*
Segment 1	62.8	30.8	61.6
Segment 2	44.4	17.6	43.6
Segment 3	44.4	18.4	43.7
Segment 4	38.9	12.7	37.7
Segment 5	43.7	20.8	43.0
Full part	34.6	9.1	33.4

Note: Reductions are presented as a percentage of how much print time, material or cost would be required to produce the new design compared to the original adaptation.

The reductions in material use and printing time have a big impact on the cost of each part, bringing it down to about a third of the original for the full part.

The simulations were run as if each part would be printed separately, with no other objects in the printing chamber. Realistically, printing just a single part would not happen very often, as there are fixed costs associated with preparing the machine for a print and cleaning it out and handling the left-over powder afterwards. For every layer, adding a new layer of powder also takes the same time no matter how full the print chamber is. That means that the time estimations, and therefore the cost estimations, for the full part might not be entirely accurate in these simulations.

For more accurate cost estimations, an engineer at Alfa Laval also ran similar simulations for the full part, both for printing a single part and filling the chamber with nine at a time. The results of these simulations can be seen in table 7.4, and a comparison between printing a single part and nine at a time can be found in table 7.5. The results from Alfa Laval are more likely to be close to the real values if the parts were to be printed, and the cost also includes estimated costs for removal of supports and processing of the build plate. According to the Alfa Laval simulations, printing nine at a time reduces the print time per part down to about a third of the time it would take to print them individually, showing how much more efficient it is to fill up the print chamber when possible. The results from Alfa Laval show that the cost of the redesigned pipe only would cost about 39% of the original adaptation and that the build time per part would be around 39% of the original as well.

Table 7.4 Simulated print times, printed volumes, and costs for the original adaptation and the redesign of the pipe, done by an engineer at Alfa Laval.

Model	*Parts per print (pc.)*	*Print time (h)*	*Part volume (cm^3)*	*Support volume* (cm^3)*	*Total volume (cm^3)*	*Total cost (SEK)*	*Cost per part (SEK)*
Original adaptation	9	86.5	2,237.6	770.6	3,008.3	76,572	8,508
Original adaptation	1	26	248.6	85.6	334.3	24,028	24,028
Redesign	9	33.5	530.9	12.7	543.6	30,078	3,342
Redesign	1	13	59.0	1.4	60.4	13,670	13,670

*The support volume is the total volume of all supports, including foundational support.

Table 7.5 Comparison of print time and cost when printing a single part or printing nine at a time.

Parts per print (pc.)	*Print time reduction (%)*	*Cost reduction (%)*
9	38.7	39.3
1	50.0	56.9

Note: Reductions are presented as a percentage of how much print time, material or cost would be required to produce the new design compared to the original adaptation.

Some simulations were also run to see what difference it made to make the outer supporting walls thicker, and how much making the support solid would affect the print time, volume, and cost of the part. The results and a comparison can be seen in table 7.6.

Table 7.6 Comparison of the final design and other tested versions.

Model	*Print time (h)*	*Print time change*	*Total volume (cm^3)*	*Volume change*	*Cost per part (SEK)*	*Cost change*
Final design	7.3		33.9		5,589	
Thin supporting walls	6.6	-9.5%	27.2	-19.8%	5,032	-10.0%
Solid support	7.4	+1.3%	40.2	+18.6%	5,671	+1.5%

7 Discussion

In this chapter the results of the thesis are discussed, along with the circumstances of the project, missed opportunities and mistakes. Some suggestions for further development are also presented, both for the design guidelines and for the development of the in-and outlet pipe.

7.1 Design guidelines

One of the main goals of this thesis was to evaluate the guidelines regarding wall thickness, and the resulting design of the in-and outlet pipe consisted almost entirely of walls that were as thin as the guidelines would allow. Two other guidelines that came heavily into play during the design process were the guideline regarding bridges and the guideline about maximum overhang angle. The guidelines worked well, in that the parts were printed successfully. It is, however, possible to see the underlying supporting walls in the top surface of segment 1. It seems as if the areas between the supports have sagged down a bit, forming a wavy pattern on the surface. This might not be a problem if the surface is to be evened out anyway, or if the roughness of the surface does not matter. This implies that there might be room for improvement on the guidelines regarding bridges. In cases where the actual bridge is very thin, the supports might need to be closer together to avoid sagging, and in other cases where the quality of the downward-facing surface does not matter, it might be possible to expand the distance.

When it comes to the actual design goals for the pipe, the end goal was to reduce the manufacturing cost of the part, mainly by reducing the amount of material that needed to be printed. By removing much of the material inside the part and also drastically reducing the support structure on the outside of the part, a significant cost decrease could be achieved. However, the AM-adapted design that the design created during this project was based on has extra material added to the exterior that should be removed in post-processing to meet requirements for surface finish and create details needed for the pipe to be assembled with other parts. About 1 mm had been added radially to the part in most places, and more in some places. Due to miscommunications at the beginning of the project, this was not known until much of the work on the redesign had already been done. If it had been known, the outer walls of the part would have been made substantially thicker, probably around 1 mm or more. If the outer walls were thicker, all the supporting walls have to be too, if the guideline about even thickness is to be followed.

As it is, if the redesign were to be produced, it would not be possible to cut away the material needed to form the details required on the outside of the part, because the walls are too thin. It could be possible to add material on the inside of the outer walls to make them thick enough for the needed material to be removed. Even if that is not possible, and the part has to be redesigned yet again, the work done during this project has hopefully provided some insight into how much the manufacturing costs of this part can be reduced.

The design guideline from Alfa Laval about having a maximum overhang angle of 45 degrees was followed strictly when deciding which areas required supports and when designing the supports. The supports do not, however, need to have high-quality surfaces or look nice, since they are either on the inside of the part or are to be removed in post-processing. All they need to do is provide adequate support. Considering that the general guideline is a maximum of 60 degrees, it could be possible to increase the maximum angle at least up to 60 degrees for these kinds of supporting features.

It became quite clear that even though an attempt can be made to follow the design guidelines closely, there will almost certainly be a reason to, at least to some extent, divert from them to handle an issue separate from the one that the specific guideline is addressing. For example, the supporting walls on the outside of segment 1 did follow the guideline about even wall thickness throughout the part in the first iteration, but analyses revealed a potential recoater blade issue which was resolved by more than doubling the wall thickness.

If some of the design guidelines are adjusted so that more leeway is given for features that only serve as support, further reduction in manufacturing costs can potentially be had.

There may be some research that has been done specifically on designing support structures, which could have been used when designing the supporting walls. This could have been investigated during the research phase of the project but was not considered as the specifics of how the part would be redesigned were not fully known.

The design guidelines that were found and used during this project worked well. Someone with very little experience in additive manufacturing could follow them and design a part that could be successfully printed.

7.2 Distortion Compensation

The compensated version of segment 1 did print fully, but there were some serious issues with holes in some walls and deep grooves in some surfaces. This was most likely due to the geometry getting corrupted in some way during the simulation. Because the geometry is being changed when being compensated, it makes sense that the flat surfaces of the walls would not remain so flat, but that the shapes of the outer supporting walls became so jagged as they are in figure 45 mean something went wrong. The reason for this could be that when setting up the simulations, the voxel size setting was left at the default value of 0.5 mm. Since the walls in most of the part have a wall thickness of 0.5 mm, the program likely had trouble accurately representing the features. If the voxel size had been lowered to the recommended value of 0.125 mm, the simulations would have had better resolution and the features in the outputted files might have worked better.

The simulations did show that the part will deform quite a bit during printing and that using distortion compensation simulations could help manufacture parts of higher quality. Another valuable factor of these simulations is the ability to find points of failure, such as blade crashes, before they occur.

7.3 Project plan

The original project plan had the project taking place during the fall semester of 2021, with the report being finished in the middle of December and the presentation taking place in January. In reality, it also took the entire spring semester of 2022 to complete the project. A main reason that it took so much longer is that the printer that was intended to be used during the project broke down when the first round of printing was started. It was not up and running again until the end of May 2022, by which time the project was concluding and there was no time for or reason to use it. The intended printer was in Lund University's facilities at IKDC. Using that one, the preparation of the prints could have been done independently, and then printed with the aid of the technicians there. Instead, all prints were handled by Alfa Laval. This removed a great deal of autonomy from the project, as preparations, printing and post-processing had to be handled by Alfa Laval employees when there was time and capacity. While this did slow down the process considerably, it also meant that the designs were more thoroughly looked over by engineers and technicians at Alfa Laval, and some issues with the design that might have gone unnoticed were found. This extra involvement from Alfa Laval probably resulted in a more refined design being developed.

Another contributing factor to the delay is that there initially were some issues handling the CAD files that were given. The first step in the redesign process was to shell out the part. However, the shell function in the program that there was the most experience with did not work for the files. It took quite some time to figure out a way to work around this using several different other CAD programs and file formats. This led to the first draft of the redesign being delayed by a few weeks.

The original project plan and the outcome can be seen in appendix A.

7.4 Other considerations

Throughout the project, many different programs and file formats were used. Different simulation software was needed for different applications, software for viewing the outputted simulation results, and several different CAD programs were used, as they had different specific features that were needed. In some cases, the CAD program did have the needed feature, but it just did not work in that specific program for that specific file. A lot of time was spent troubleshooting and trying to figure out how to get things to work. With more experience, the workflow could have been more efficient, and more time could have been spent on refining the design.

In the beginning, not much information about the part, its function, and how it fits with other parts were provided. Because of that, some things had to be guessed about the part. This led to some misunderstandings about the part and the conditions for the design of the part.

The choice of segments might not have been ideal. In an attempt to not have already existing details between segments, many of the supporting walls on the inside of the part ended up being divided between parts, which was not optimal. The divisions were based mostly on the original design and not what the further AM-adapted design would look like. Had the segments also been based on what the part might look like when finished, perhaps better options had been chosen.

The recoater blade impact angle can influence print failure rates. The added interior support walls could potentially have been designed with this in mind, for example by striving to keep the parallel with each other and perpendicular with the recoater blade direction. This would, however, require that the print orientation of the part was decided beforehand.

A concern arose that the many thin structures of the supporting walls could cause an increase in printing time due to the way that the areas of each layer are printed. Even though the total scanned area for each layer is smaller than it would be with a solid support structure, each small area must first have its outlines scanned, after which the inside is scanned in a pattern. This would result in a less time-efficient scan as the laser would have to jump between areas instead of scanning continuously over one, larger area.

Because the area that needs to be scanned is so much smaller, having a solid support will probably not be more efficient. Furthermore, having a solid support would result in a large, filled volume on the part. This large volume would not be in accordance with the guidelines regarding even wall thickness throughout the part and could result in stresses and distortions due to build-up of heat.

The support structure on the outside of the part would be cut off during post-processing. The evenly spaced walls could result in vibrations when cutting them off using a lathe. A solid support would resolve this. Considering that the walls had to be made significantly thicker to reduce the risk of blade crashes, the solid support could be worth considering.

7.5 Further Research Suggestions

7.5.1 **Regarding Design Guidelines**

There are guidelines for maximum distance for unsupported bridges is at around 2 mm, but wider ones are possible. Is that the widest that can be consistently printed or the widest that can be consistently printed with a high quality downwards facing surface? Does the surrounding area affect how long the bridges can be? Does the bridge gap need to be adjusted depending on how thick the bridge is to prevent sagging? Is there anything to consider regarding the supports on either side of the bridge?

Some guidelines can be further developed to include different grades of quality so that they can be applied in different ways in different situations depending on design needs. For example, there are essentially no requirements on the inside surfaces of the part used for this project, as long as the part is structurally stable.

The guidelines for thin walls, with a minimum thickness of 0.5 mm worked well. This thickness seems to be safe, at least it was for this part. Walls can, however, be made thinner, but it is hard to know where and how they can be made thinner. Just like with the guidelines about bridges, it could be good to have some more broad guidelines about under which circumstances walls should be thinner or thicker. This could be accomplished by figuring out in what situations 0.5 mm is too thin, and in what situations thinner walls worked well.

7.5.2 **Further Development of the In-and Outlet Pipe**

This thesis proves that there are substantial cost reductions to be had for this part by removing the internal material and making smarter, more minimal support structures. Further developing this design by adding material to the outside walls so that material can be removed to get the desired shape of the part would be a good first step. The support structures can also be refined to make them smaller or replaced with, for example, small lattice structures.

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Appendix A Project Plan and Outcome

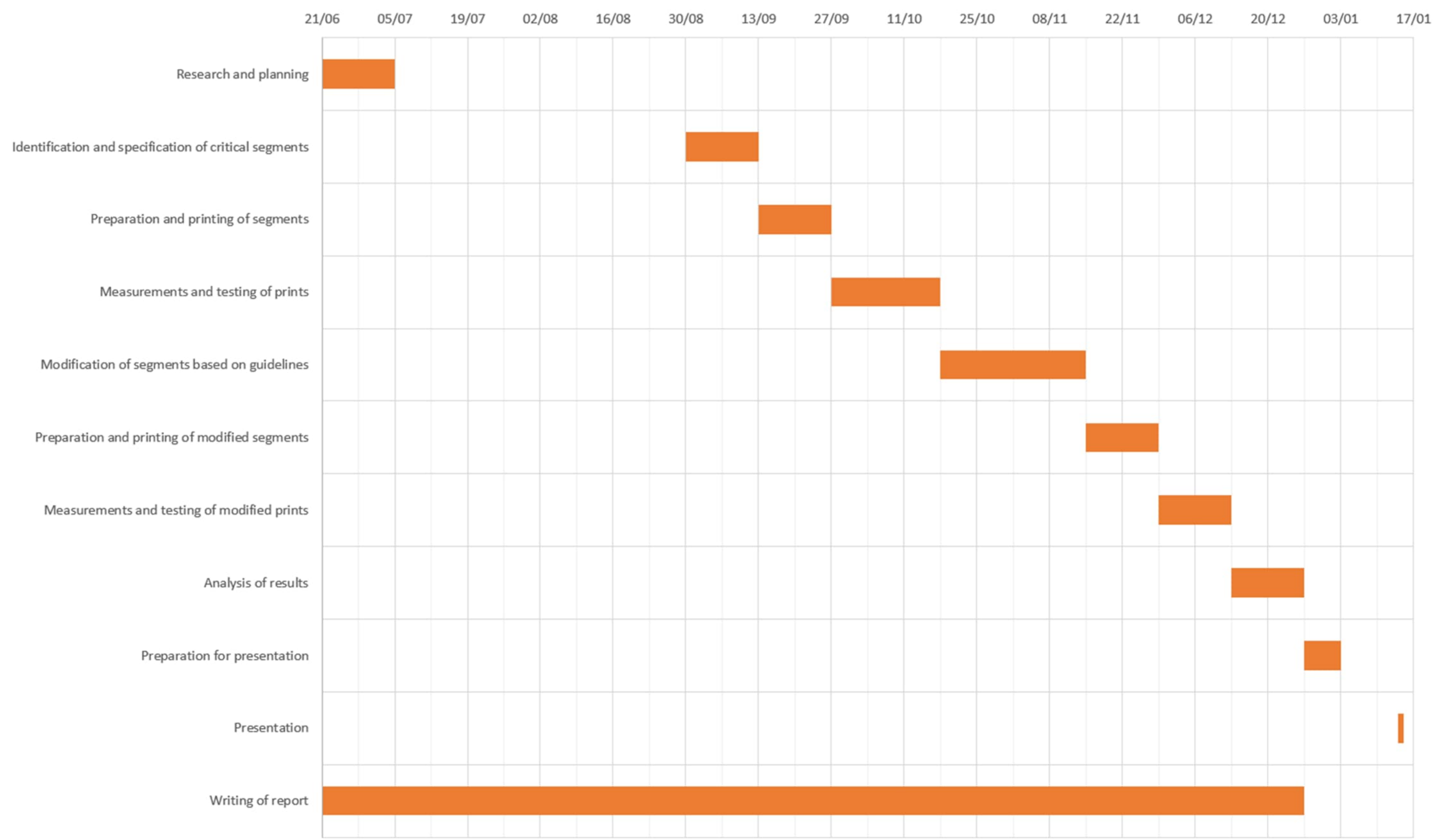

Figure A.1 Original time plan.

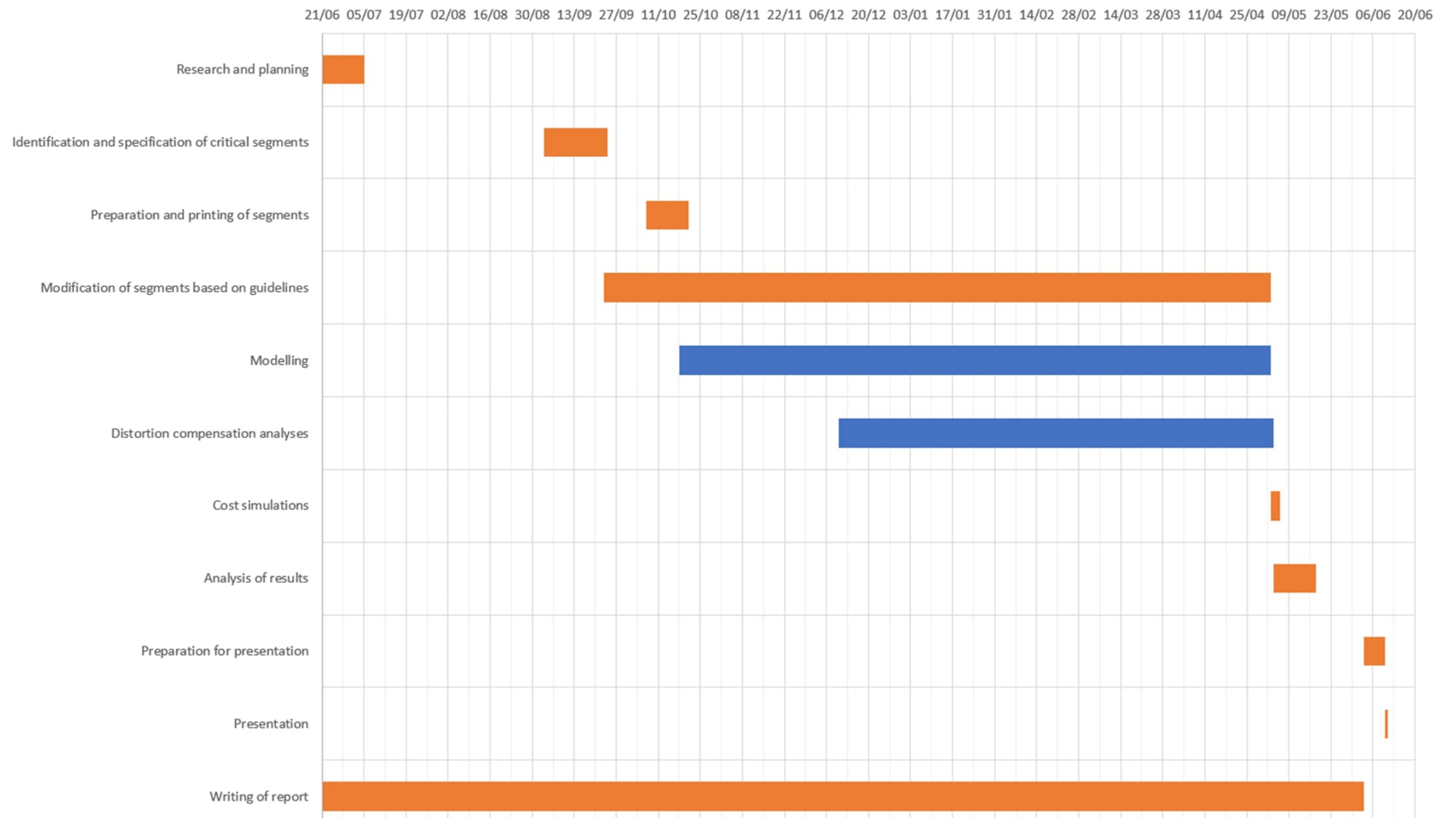

Figure A.2 Actual time plan.