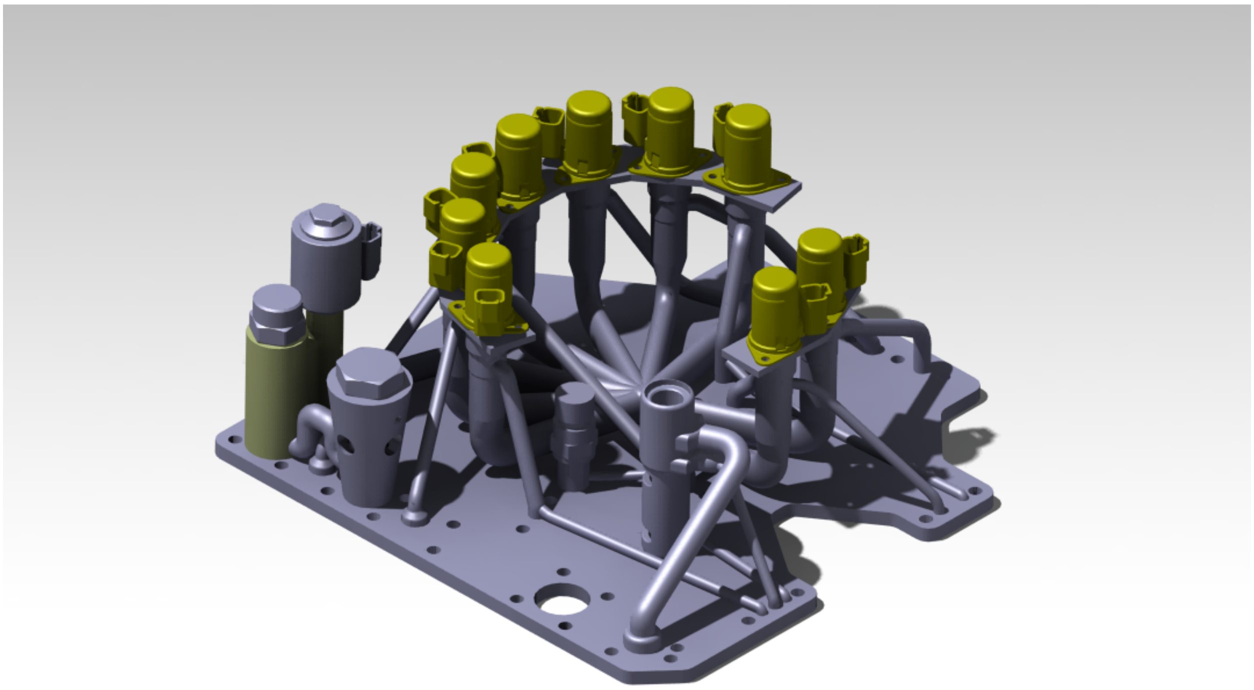

# Industrial implementation of additive manufacturing

Research and development of a component using additive manufacturing


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

Department of Mechanical and Nuclear Engineering
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BACHELOR'S THESIS 2018:IMSX15-18-35

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A photo of the chosen concept suitable for additive manufacturing can be seen on the front cover. This concept can substitute the current component in the PT9 transmission.

Gothenburg, Sweden 2018

# Abstract

Additive manufacturing (AM) is often claimed to be the manufacturing method of the future. The technique offers new design possibilities for manufacturing companies around the world as material is added rather than removed. Students from Chalmers University of Technology (Chalmers) and Pennsylvania State University (PSU) have in this report collaborated with the purpose to evaluate the possibilities for Volvo Construction Equipment (Volvo CE) to implement AM as a manufacturing technique for the control unit in Volvo CE's PT9 transmission. As it stands today, the control unit is a rather complex component that requires a wide variety of machining processes. The aim of the project was therefore to deliver a redesigned control unit suitable for AM that is better or equal in terms of performance and cost compared to the existing solution, reducing the need for complex machining. The report addresses the analysis of the existing component as well as the concept generation and analysis of a novel component that is designed with AM in mind. In addition, different AM methods were evaluated in order to find the most suitable AM-method for this application. The project followed a systematic development process that was adopted for the current situation, i.e, an iterative process where concepts and methods were evaluated and eliminated gradually, resulting in a final concept suitable for AM as well as a recommended AM-technique to be used.

The project resulted in a concept that utilizes the benefits of the AM-technique known as Powder Bed Fusion. The concept itself is a completely redesigned component which could be implemented into the PT9 transmission with a lower overall weight and a higher performance in terms of oil flow. The novel component is, however, more expensive than the existing solution due to the fact that the AM-method is currently not used for large scale production. In the future however, when the method becomes more widely spread and powder material is available at a significantly lower cost, AM will become more beneficial for Volvo CE. The team therefore recommends Volvo CE to use AM as a future manufacturing method for the control unit.

# Acknowledgements

Throughout the project the team have had help from several additional sources. We would like to thank everybody involved in this thesis. A special thanks to our supervisors Mikael Enelund, Lars Almefelt, Jessica Menold, and also our examiner Ola Isaksson for continuously providing us with constructive feedback and expertise.

Thanks to Herbert and Karin Jacobssons Foundation, the team could finally assemble in the United States, for which we are very grateful. We would also want to thank Arcam EBM AB and Swerea IVF AB for helping us gathering information regarding additive manufacturing. Lastly, we would like to thank our industrial partner Joacim Holmqvist from Volvo Construction Equipment for a great cooperation during the entire project.

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Christoffer Axelsson
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Gothenburg, May 2018

# Nomenclature

| | |
|---|---|
| AM | Additive Manufacturing |
| CFD | Computational fluid dynamics |
| CNC | Computer Numerical Control |
| DED | Direct Energy Deposition |
| DMLS | Direct metal laser sintering |
| EBM | Electron Beam Melting |
| EOA | Ease of assembly |
| EOM | Ease of manufacturing |
| PBF | Powder Bed Fusion |
| PSU | Pennsylvania State University |
| SL | Sheet Lamination |
| SLM | Selective Laser Melting |
| UAM | Ultrasonic additive manufacturing |

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# 1 Introduction

## 1.1 Background

In manufacturing, lowering production costs is a desire for all manufacturers. One way to do so is to reduce lead times on production and cutting material usage down. Another way to achieve this is to find an economically efficient manufacturing method that yields lower production costs. One option when choosing a manufacturing method to fulfill these goals is Additive Manufacturing (AM). AM is a manufacturing method where heated material is added to the component layer by layer to create the desired shape. By implementing this method the material is used more effectively.

AM is sought after in industries because of the opportunities to design more complex and optimized structures in components; this leads to enhancing the quality and performance (Gilbert & Thomas, 2015). With the implementation of Additive Manufacturing (AM), lead times can be reduced. Instead of casting, Computer-aided design (CAD) models can be created and printed directly as an almost finished product (Attaran, 2017). Volvo Construction Equipment (Volvo CE) are looking into how they can adapt to the changing technologies and incorporate these methods in their facilities. In this report, students from Chalmers University of Technology (Chalmers) and Pennsylvania State University (PSU) were therefore tasked to research and develop a novel component for Volvo CE using AM.

## 1.2 Purpose and objectives

The purpose of this project is to provide Volvo CE with the necessary information regarding AM as a potential manufacturing method. This project analyzes whether it is possible for Volvo CE to manufacture the control unit for the PT9 transmission using an AM method. Additionally, this project shall serve as a basis for Volvo CE to evaluate the possibilities to utilize AM as their means of production for their control unit in the future. The objectives of the project is to redesign the existing component so that:

- Performance is maintained or increased
- Cost of production is minimized
- The number of parts are reduced
- The need for excess machining is reduced

## 1.3 Description of the Existing Component

The component that was analyzed and redesigned in this thesis was a control unit shown in Figure 1.1 from Volvo CE, used in the PT9 transmission.

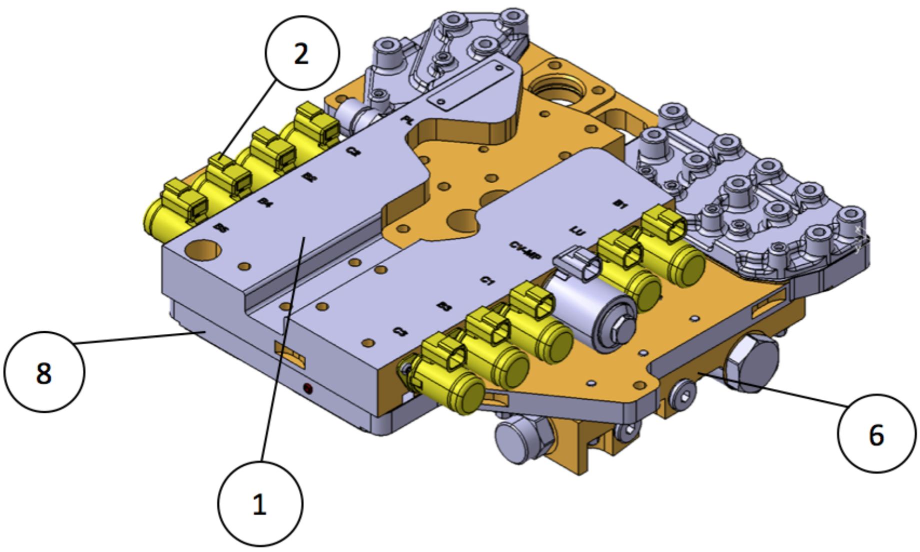


**Figure 1.1:** The assembled control unit with the oil distributor plate, gear changing unit, main pressure valve housing and solenoid valves marked

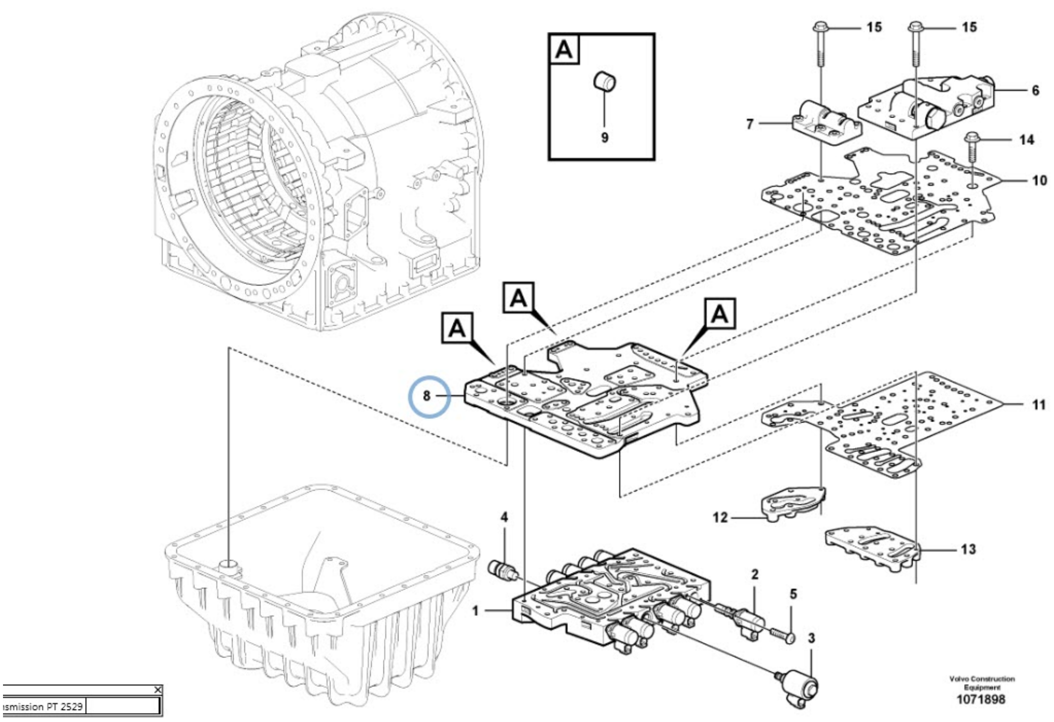


**Figure 1.2:** Exploded view of the control unit, planetary transmission and sump

The Figure 1.2 shows all the parts of the control unit along with the planetary transmission and the sump. Five of the parts will be of particular interest during this project. These are listed below along with their corresponding number in the figure. The seize of the control unit is 405x387x70 mm.

- Oil distributor plate (8)
- Gear changing unit (1)
- Lubrication valve housing (7)
- Main pressure valve housing (6)
- Solenoid valve (2)

A control unit's function is to enable activation of clutches and brakes in the system which leads to a gear change in the equipment. Signals are sent to the control unit which upon receiving these determines when a gear change should be performed. A complex network of oil-filled canals connect to valves. Each of the valves controls a specific clutch or brake. The valves open and close depending on the selected gear to let the oil flow through. When oil flows through, it reaches pistons which activate the clutch/brake with the help of the pressure applied. Combinations of activated clutches and brakes make for shifts to different gears. The oil in the system is constantly reused, being pumped from the sump into the canals. The function of the sump is, to put it simply, to gather the excess oil which is led back from the deactivated valves in the control unit. The oil in the sump is then repeatedly pumped into the system again. Gaskets are used in the control unit and they are made of steel and rubber. The gaskets serve as a mechanical seal between the aluminum parts to prevent the transmission oil from leaking into undesired areas. The metal parts of the unit are today primarily made of aluminum alloys.

A more in-depth description of the oil distributor plate is that is serves as the mounting plate towards the transmission as well as what the name describes, distributes the oil to the correct canals into the transmission. The gear changing unit holds the solenoid valves that have one inlet and two outlets. The inlet in the solenoid valve is connected to the main oil inlet in the control unit. The first outlet directs the oil through the valve and into the transmission to activate the clutches and breaks and the second outlet lets the return oil out in the sump when the valve is deactivated. The lubrication valve regulating the pressure of the lubrication oil that is transported into the transmission for cooling purposes. The main pressure valve housing holds the converter and the main pressure valve, a more specific and detailed description of how the valves and canals are connected can be seen in Figure 1.3

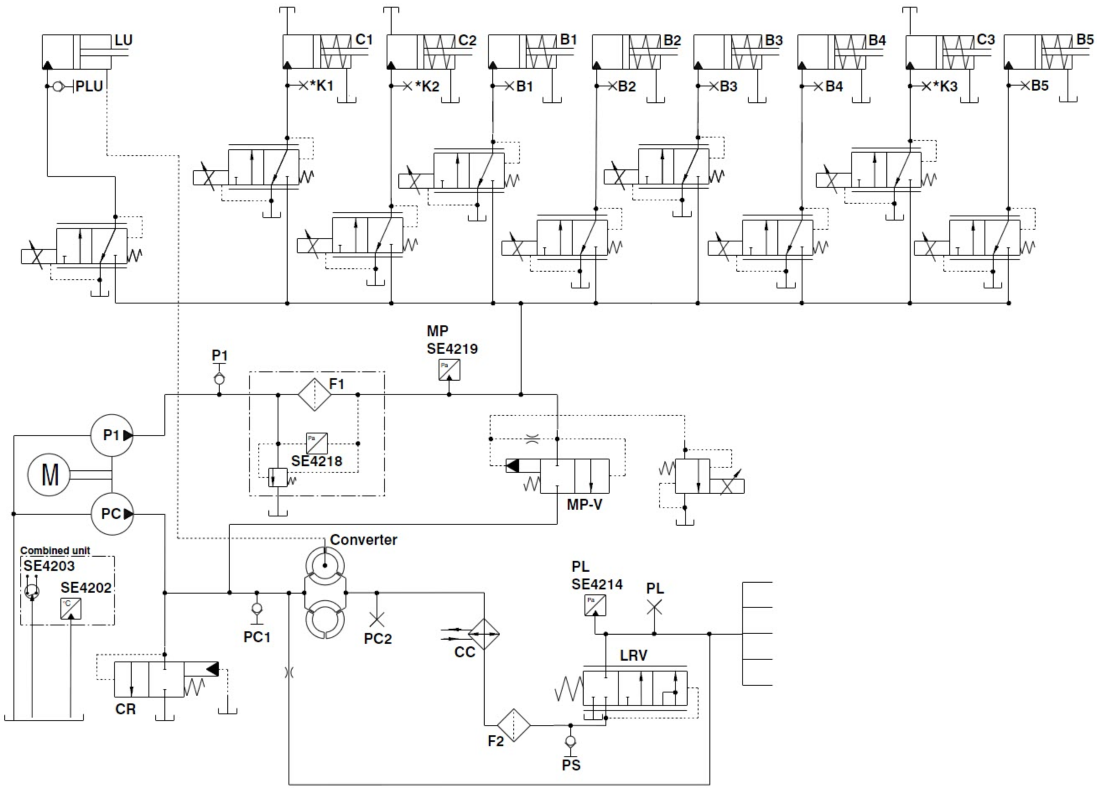


**Figure 1.3:** Hydraulic diagram of the control unit

## 1.4 Initial Problem Statement

As of today, AM is a rather slow and costly manufacturing method compared to traditional manufacturing techniques used for the control unit, as stated by Volvo CE. Therefore, it is crucial to evaluate the effects of a redesigned novel component with the existing component as a benchmark. The control unit is a rather complex component with many internal canals for oil flow. These canals are rectangular cross sections with perpendicular turns, thus not optimized for efficient flow. This is a result of the limitations with the traditional manufacturing methods. Theoretically, this could be solved by a new design that utilizes AM.

One of the main areas of interest that must be taken into consideration is component's ability to withstand a pressure of 6.0 MPa (60 bar) to meet Volvo CE's safety standards. The current solution originates from a solid aluminum block, and the geometry is therefore not entirely optimized for the internal pressure. The canals are separated by walls of different thickness and areas of the solid block that are untouched in order for the parts to be mounted together. The weight and size of the component are crucial for AM to be beneficial and cost effective (Atzeni & Salmi, 2012). With this in mind, the geometry should be oriented for AM to make it a viable manufacturing method for the control unit. The internal stresses and internal pressures must therefore be the constraints for the weight and volume optimization.

Another area of focus is to design the component with the surrounding environment in mind. The novel component must be able to fit into its predefined mounting points. Also, the design should be done with “Plug and Play” which means that the redesigned component should be easily interchangeable with the existing part. The size, connections, and mounting of the components need to be compatible. This slightly limits the possibilities to alter the size of the novel component.

Reducing the weight and volume of the component is very crucial to the success of the project. In order to be able to mass produce the novel component, the production time must be minimized. The production time of AM lies almost completely in the ability to reduce the weight and volume of the component. The weight and volume of the component is also an important factor in the economical aspect. A reduced weight and volume means less material and shorter production time.

Lastly, another problem area that should be addressed is the ability to reduce the number of parts manufactured. AM techniques give huge possibilities to reduce the number of integrated parts of the components. As of today, the control unit consists of several parts mounted together with a large number of screws. This is done because it is difficult to design the component in other ways with traditional methods. Therefore, AM technologies provide the opportunity to manufacture these complex geometries as one solid part, thus reducing the number of parts required. Reducing the number of parts will help reduce costs and assembly times for Volvo CE.

## 1.5 Delimitations

The limitations of the project were split up between two different topics: project limitations and component limitations. The project limitations refers to the limits around the project, such as knowledge within the team and what the focus area was during the project. The component limitations refers to all the aspects the team would have to take into consideration when redesigning the existing component.

### 1.5.1 Project Limitations

The project team was limited to the three students from Chalmers and four students from PSU. The team has limited experience with AM technology. Some within the team have worked with AM before. For others, AM is a new method to use for manufacturing. Therefore, there will be a learning curve for team members who do not have experience, and that will cause initial delay of understanding and executing the project.

This project had a scheduled time limit with the final report needing to be completed at May 14th because of the conclusion of Chalmers’ semester. Due to the limited amount of time, the team would have to be consistent with making the deadlines. Due to this restriction of time for the project, the final prototype cannot be manufactured in metal by the project team because of the long lead times estimated by our industrial partner.

To get more information about the end result, the prototypes will be printed in plastic. This will give a physical model that can be analyzed accompanied by computer simulations. With a total project budget of 1000 United States Dollars (USD), there will be enough to spend on printing the novel component for visual inspections and also to test the design for supports and geometric orientation improvements.

Since the two universities are in different time zones, the communication between the project team members is limited as Sweden is ahead in time by six hours. To solve the time zone issue, the project team has decided to split up the work between the universities so daily contact does not need to be established. However, the team members meet multiple times a week via Skype to have complex and in-depth conversations with immediate feedback regarding the project.

### 1.5.2 Component Delimitations

According to the demands of Volvo CE, the AM component should fit in the existing space provided. Therefore, this constrains the size and dimensions of the design. The overall volume of the novel component is also limited by contemporary AM machinery, due to the fact that the component must be able to fit inside the AM method's build volume. Furthermore, the volume and weight of the novel component are limited from production costs and production time. The component could not be beneficial if the volume and weight are not optimized. This is because the volume and weight directly correspond to the cost of the component and the overall production time (Atzeni & Salmi, 2012).

Another limitation to the component is the oil flow. It is unlikely that Volvo CE would consider using a novel component with lower performance than the already existing component. Therefore, it is important to design the component so that the performance is as good as, or better than, the existing component. Performance in this case refers to pressure drop inside the canals. It is absolutely crucial that the pressure drop inside the control unit does not result in a net-pressure under 2.0 MPa. This is because the clutches and breaks require at least 2.0 MPa to be activated. The pressure drop will be analyzed using Computational fluid dynamics (CFD) simulations comparing the novel component with the existing solution. Lastly, it is also vital to consider the internal pressure as a limitation to the novel component design. The designed component must be able to withstand the pressure and stresses it is exposed to. For safety standards, Volvo CE desires the component to withstand a pressure of 6.0 MPa (60 bar). This affects the wall-thickness of the internal canals, as well as surrounding areas where pressures are applied. Finite element analysis will however not be performed in this project due to the limited time.

## 1.6 Work Procedure

The project followed a systematic development process, as shown in Figure 1.4, where the different phases of the project were iterative. The first step of this project was to research different methods of AM, along with an analysis of the existing component. This information provided the limitations, functions, and performance of the component. This phase ultimately resulted in a requirement specification.

The next phase of the project was an iterative concept generation phase where different concepts were generated, evaluated and eliminated with regards to the requirement specification.

The chosen concept was then analyzed further in yet another iterative process. More precise benchmarks was applied to the chosen concept to act like a basis for the concept design. The concept was then designed in CAD in order to be evaluated with regards to the requirement specification. In this phase, CFD simulations and economical calculations was made in order to determine whether the concept meets the requirements or not. If not, another iteration would follow where new calculations would have to be made. This iterative process provided necessary information for the redesign and reassured that no aspects of the redesign was overlooked.

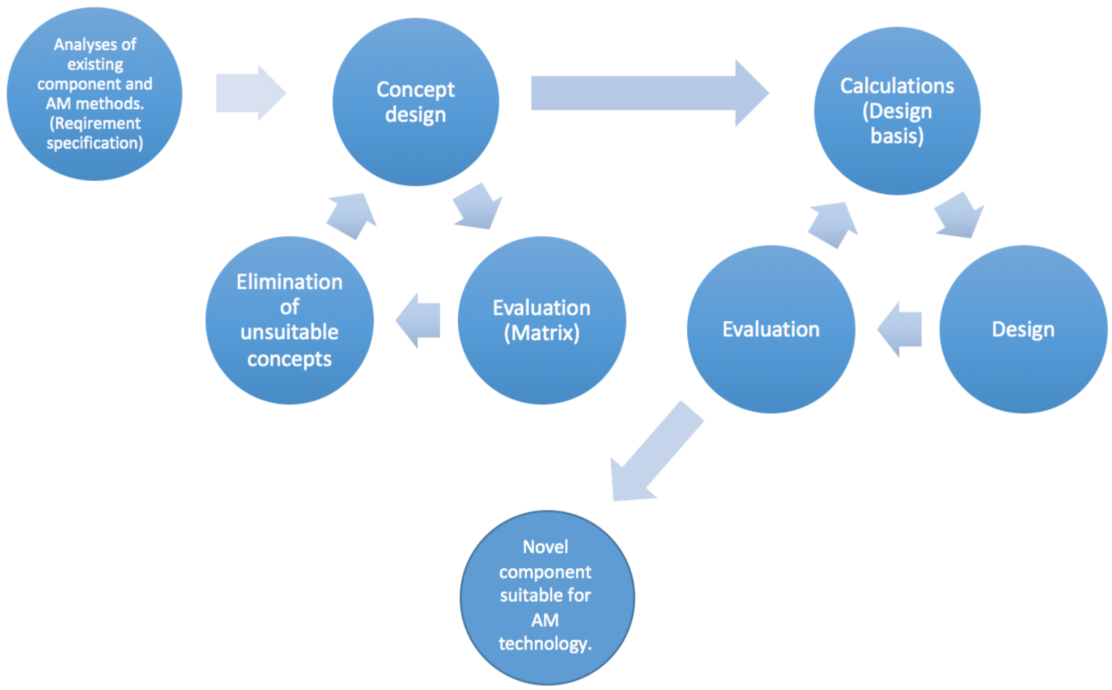


**Figure 1.4:** Iterative work procedure pattern

## 1.7 Ethical Aspects

To ensure that the ethical aspects of the project were respected, the Code of Ethics of Engineers was followed (American Society of Mechanical Engineers, 2012). Using a set of rules makes the ethics less abstract and easier to abide to.

Additionally, only facts from reliable sources was used throughout the project. Both positive and negative aspects had to be taken into account and biased opinions would have to be eliminated. The project was conducted with a critical perspective on possible consequences.

Since this project was a collaboration between Chalmers, PSU, and Volvo CE, decisions was made in consideration of all three parties. Questions and concerns are respectfully addressed in Skype meetings, emails, and messages.

An issue that concerns many parts of today's society is what happens when automated processes and machines "take over". Using AM to create a component reduces material handling (Attaran, 2017). This is favorable economically, however, it could have a significant effect on the work force in the future. A result of the reduction of operations could be that fewer people are required in production. The risk of people losing their employment will need to be considered and reviewed.

## 1.8 Environmental Aspects

One of the benefits of AM compared to traditional manufacturing is the reduced material waste. This is because material is added rather than removed from the work piece thus reducing the material waste. This can be achieved by optimizing the geometries and reducing the need to make adjustments like removing material after the component has been printed.

The environmental effect was reviewed as part of the volume sub-criterion in evaluation and is regarded as an important factor. This is especially important in a future perspective. Non-sustainable technologies are not regarded as worth investing in.

Life-cycle assessments on both the existing component and the redesign could be performed to investigate the environmental impacts the two different manufacturing methods have. A life-cycle assessment does not only examine the operations performed within the manufacturing process but analyzes all the stages in the product's life. These stages are according to The Global Development Research Center defined as everything from extracting the raw material to the waste disposal (Global Development Research Center, n.d.). Aspects such as shipping, packaging and customer use are therefore also included. This would offer an overall view on the actual environmental impact the components have.

# 2
# Analysis

In this chapter, analysis regarding different AM-methods are presented. This will include the evaluation of the methods as well as elimination of unsuitable methods. The analysis of the existing component is also included in this chapter. The analysis regards the fluid dynamics of the component as well as the cost and production time of the same. Different AM-materials are also explained in this section.

## 2.1 AM Methods

Due to the technological development of the AM industry, the number of different AM methods has increased rapidly the last years. The three methods that this project evaluates are the following: Direct Energy Deposition (DED), Sheet Lamination (SL), and Powder Bed Fusion (PBF). All methods that uses extrusion or plastic as part material are excluded in this project due to unsuitable material properties. Each of these methods contain some advantages and disadvantages. These advantages and disadvantages will be the basis of the elimination of unsuitable methods.

### 2.1.1 Sheet Lamination

The SL process includes ultrasonic additive manufacturing (UAM). The UAM process uses sheets of metal which are bound together using ultrasonic welding. The process requires additional CNC machining and removal of the unbound metal. One benefit of this method is that the metal used is not melted during the process and therefore less energy is required in that aspect.

### 2.1.2 Powder Bed Fusion

The AM methods that are using powder bed fusion are PBF, DMLS, SLM and EBM. Powder bed fusion (PBF) works by melting metal powder, that has been spread out by rollers or a recoated blade, by either a laser or an electronic beam. The subsequent layer is spread out onto the previous layer and the process is repeated. There are numerous examples exhibiting the use of DMLS, SLM, and EBM throughout the aerospace industry. The PBF methods provide several key advantages such as their geometric complexity benefits as well as near full density (99.5+%) when compared to conventionally manufactured parts. For illustration see figure 2.1.

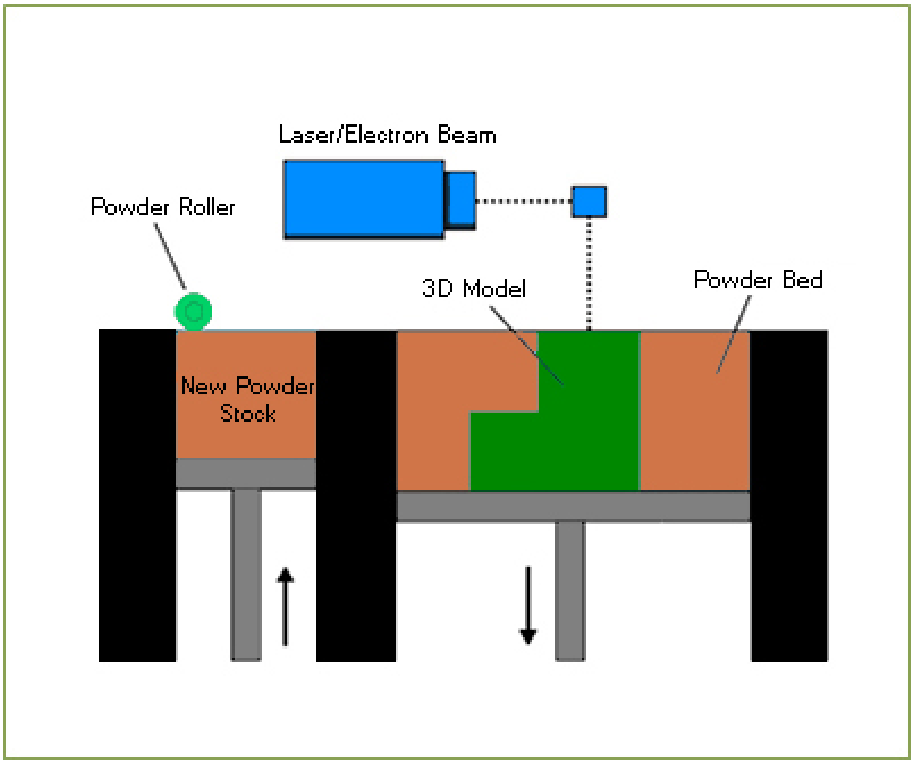


**Figure 2.1:** Illustration of Powder Bed Fusion method with powder roller

#### 2.1.2.1 Selective Laser Melting/Direct metal laser sintering

Selective Laser Melting (SLM) or Direct metal laser sintering (DMLS) is a particularly rapid AM technique designed to use a high power-density laser to melt and fuse metallic powders together. Unlike SL, the SLM and DMLS processes have the ability to fully melt the the metal material into a solid 3D-dimensional part.

#### 2.1.2.2 Electron Beam Melting

Electron Beam Melting (EBM) is very similar to SLM with the main difference being that EBM uses an electron beam instead if a laser beam when melting the powder. The EBM method benefits from being more efficient than laser systems since much of the energy of the laser is lost in reflection, instead of being absorbed by the powder. EBM therefore has a faster print speed than SLM and DSML. Another benefit with EBM is that the higher temperature during the process makes the part free from internal stresses and it does not require any heat treatment after the print is completed. The downside with EBM is that the residual powder gets quite hard and therefore post processing using a powder blaster is needed to get rid of the residual powder.

### 2.1.3 Direct Energy Deposition

The Direct Energy Deposition Method uses a metal wire or powder that is fed out of a nozzle and melted, by either a laser beam or an electronic beam, as it is deposited on the part. The feed nozzle moves in three dimensions across the part and melts a line of wire/powder with every pass, building a 3D geometry. However the DED process is limited in terms of producing complex structures as it needs dense support structures. In addition, DED suffers from poor surface finish values below 25 $\mu$m.

### 2.1.4 Elimination of Unsuitable Methods

After evaluating the advantages and disadvantages of all the AM techniques, the team selected Powder Bed Fusion as the preferred AM method. Other AM methods have some advantages, such as fast printing time, low cost, and quality, but the disadvantages outweighed the advantages. Therefore, PBF was chosen as the most suitable method, mainly due to its ability to print complex designs and overhang design, which are the most important limitations of our prototype due to the complex nature.

Within the Powder Bed Fusion method, there are three different printing methods, such as Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), and Selective Laser Melting (SLM). Among these different methods, our team is going to focus on the EBM and SLM methods, due to their remarkable advantages.

The two methods were chosen because they both have relatively fast printing time. With SLM, post processing is fairly easy while EBM provides high quality and good strength properties. However, after further evaluation of these two different methods, the team discovered that both of the methods have disadvantages that would make it tricky to print the novel component. The post processing that is required with EMB is not suitable for canals and therefore it can be difficult to ensure that no residual powder left in the canals. Of the mentioned methods, SLM and EBM are the most suitable methods for the control unit. However, further investigations in terms of test prints and evaluation of those are needed.

### 2.1.5 AM Materials

While AM is in its early stages of existence, there are still many applications and advancements. There is a large list of materials used for AM. This list ranges from the more common thermoplastics and metals to more unexpected materials such as stem cells and carbon fibers. However, due to the application of this project and component, our team decided to focus on the metals that could be used. According to “Materials for Additive Manufacturing” (2018), the most common metals that are used in AM are: aluminum alloys, cobalt-based alloys, steels, stainless steels, nickel-based alloys, and titanium alloys. The current component is machined from a shaped aluminum block, so using aluminum alloys in AM should be a viable option. However, the cost analysis is important to take into account when selecting a material. Performance is another criterion that needs to be taken into consideration after the material selection. Different materials’ properties have to be taken into account in order to have a favorable material.

## 2.2 Analysis of the Existing Component

The existing component needed to be analyzed in order to create a comparison of the concepts i.e the requirement specification. In order to better understand the component, iterations of CFD analyses were needed. Aside from performing CFD analyses, the cost and production time also needed to be evaluated. The concepts had to match or improve upon this component's performance, cost, and production time for the concepts to be feasible.

### 2.2.1 Computational Fluid Dynamics

To get a better understanding of the oil flow in the control unit, a CFD analysis was performed. The main canal of the PT9 transmission unit was chosen due to the fact that the majority of the oil flow is in this area. This area provides the pressure variations throughout the canal, which were necessary when choosing the new geometry of the canals. The initial fluid analysis was conducted on two geometries of the main canal. The first geometry was a rectangular cross section that was based on the original PT9 transmission canal. The second cross section was a cylindrical canal that was designed with regard to the existing canal. In both of these cases, the walls were taken to be real walls, and the flow was fully developed. It was necessary to obtain the pressure drops in the geometry because of the constraints given by Volvo CE. The current component does not subceed 2.0 MPa (20 bar), so in order to create a proper redesign, these values are critical when understanding the oil flow.

#### 2.2.1.1 Existing (Rectangular) Canals

The canal was recreated in SolidWorks based on the original part given by Volvo CE. The dimensions of the main canal are the same as the original as it was made by tracing over the part given by Volvo CE. Seven circular cut extrusions were created at the ends of the canal for the inlet and outlets. The design can be seen in Figure 2.2.

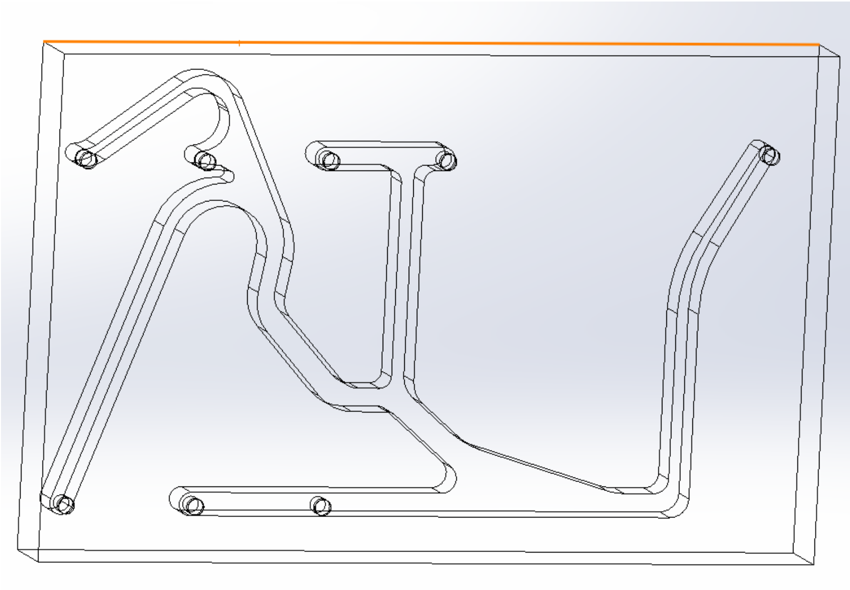

**Figure 2.2:** Existing component section view for CFD simulation. The second hole from bottom left is the inlet. The outlet is the top right hole

The conditions, which were provided by Volvo CE, to run the simulation were as follows:

- Inlet volumetric flow rate: 0.0005833 $m^3$/s
- Outlet pressure: 2.0 MPa (20 bar)
- 6 outlet holes at the end of the channels

The goal of the analysis was to obtain the changes in pressure for each outlet, as well as obtain a plot of the flow trajectory throughout the canal. From the analysis, we were able to visualize exactly where the oil was flowing to. The flow was flowing to the outlets (end canals) as expected. Figure 2.3 shows exactly how the oil was flowing throughout the system.

A cut plot was generated to get a visual representation of the pressure variation through the canal. From the cut plot, we were able to obtain pressure values between the inlet and outlets. Figure 2.4 demonstrates the pressure variation throughout the component. The pressure drop between the inlet and outlet was found to be about 0.2 MPa (2 bar).

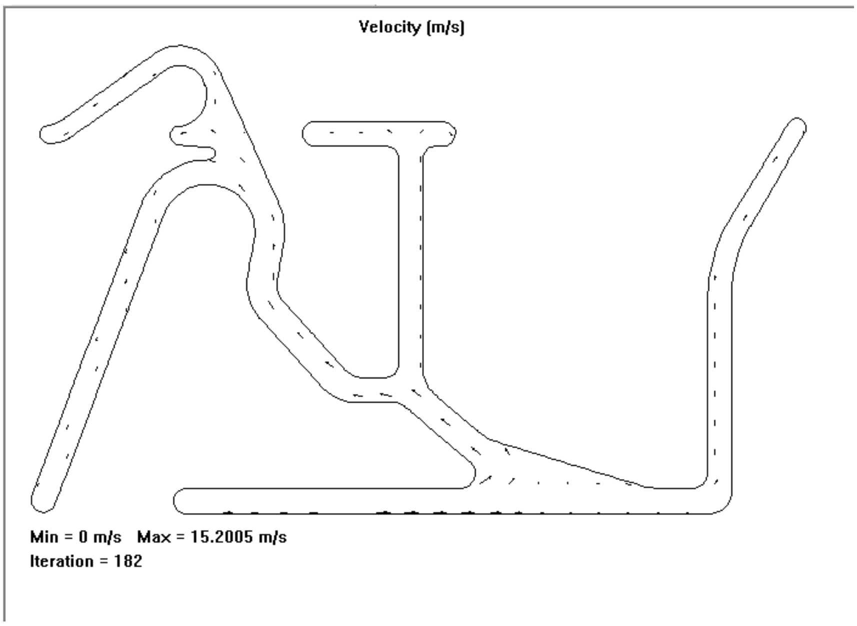


**Figure 2.3:** Component flow trajectory, the arrows point at the direction of the flow

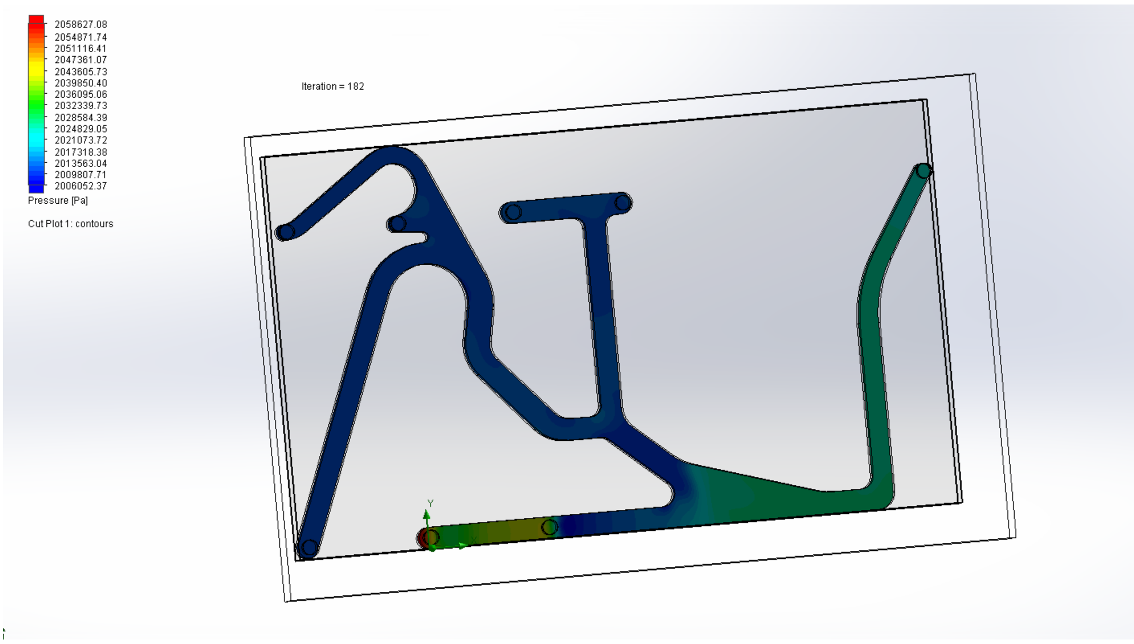


**Figure 2.4:** Pressure Plot of Existing Canals where red indicates higher pressure and blue indicates lower pressure

#### 2.2.1.2 Cylindrical Canal

The second analysis was done on the same canal but with a cylindrical cross section. This is the zeroth prototype, since this was the initial design even before the alpha prototype. This canal was created to have roughly the same design with similar dimensions. This was to portray a better visual of what could be going on with the pressure on the original part. The cylindrical cross section provides a more realistic value since the original part uses the same geometry. Similarly, seven holes were placed on the canals for the inlet and outlets shown below. Figure 2.5 demonstrates the design of the cylindrical canal.

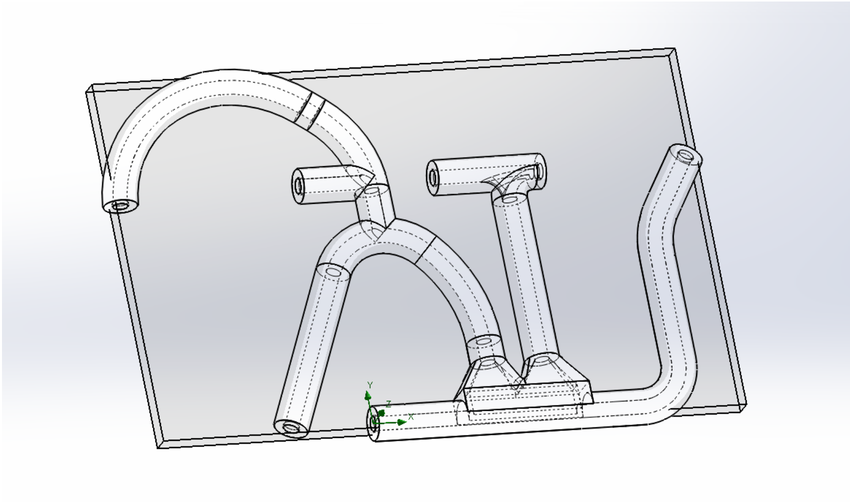

**Figure 2.5:** Cylindrical channel based off the existing component

For the analysis, the same conditions as for the rectangular canal were used to run the simulation. The goal, again, was to determine the change in pressure and visualize how the flow is moving throughout the canals. This cylindrical redesign demonstrated very similar results when compared to the rectangular canal. The pressure drop was almost identical. This is probably due to similar canal lengths and paths. Figure 2.6 and Figure 2.7 show the analyses of the cylindrical canal.

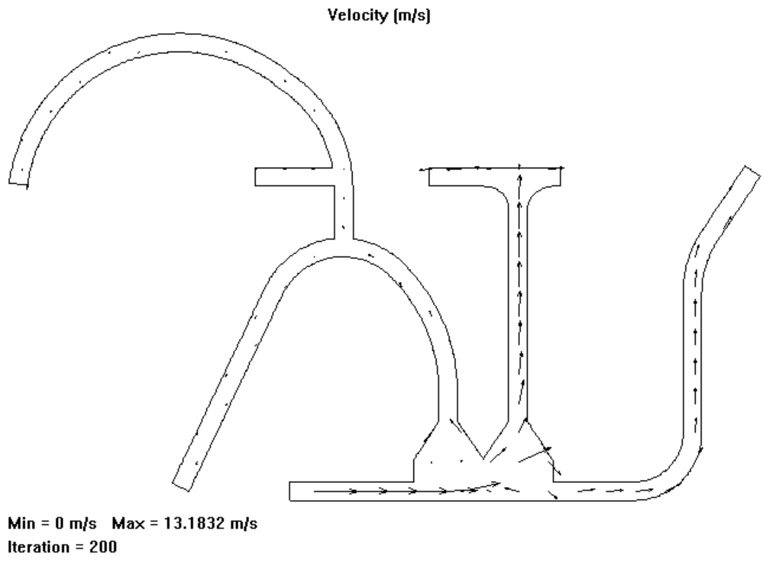


**Figure 2.6:** Cylindrical Canal Fluid Direction. The arrows shows the flow direction

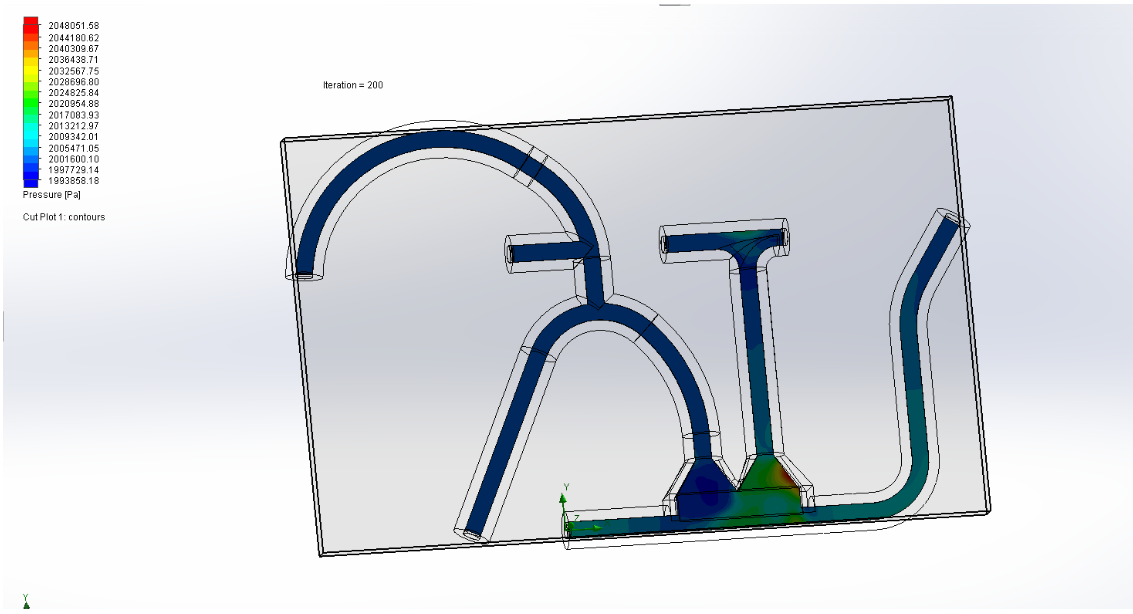


**Figure 2.7:** Cylindrical Canal Pressure Plot. Blue and red colours indicates low respectively high pressure

### 2.2.2 Cost and Production Time

In order to successfully design a novel component for Volvo CE, the overall cost and production time of the existing component needed to be evaluated. This is important because it should act as a benchmark for the novel design. Volvo CE uses internal trade as a way of tracking the cost of the different articles along the construction line. Thus it is impossible to properly compare the different contributions to the overall cost as it is not documented. Therefore, the comparison between the existing component and the novel component must be on the overall price where the contribution to the total price of the novel component had to be estimated.

The industrial partner supplied the overall cost of the existing component, see Appendix A.1. The cost was separated as a manufacturing cost for the included parts and an assembly cost for the entire component. To be able to compare the estimated cost of the generated concepts, the total cost of the existing component had to be a result of the assembly cost and the manufacturing cost. Because the manufacturing cost was given as an internal selling price for the included parts of the component, the screws and washers needed were not included.

# 3

# Concept Generation

This chapter describes the concept generation process of the project. The concept generation was divided into two sub-categories, namely structural redesign and canal redesign. The structural redesign is the concept generation based on the existing parts of the component while the canal redesign focuses on the canal cross-section. The chapter includes an in-dept description of the concept generation process as well as CFD analyses on different cross-section concepts. The concept generation of both the structural system and the canal system are based on the requirement specification that is also included in this chapter.

## 3.1 Requirement Specification

The requirement specifications that were set up are based on the customer needs. In this project, the customer is Volvo CE. They wanted to see if AM could reduce the number of included parts and if the manufacturing method could result in easier manufacturing. Volvo CE also stated that it was crucial that the pressure drop was less or equal than the existing solution and that the cost and production time was not significantly increased. The analyses of the existing component resulted in benchmarks regarding cost/time and pressure drop.

### 3.1.1 Constraints

The component's functions could not be changed or deleted. This means that the new concept must be able to perform all things the existing component can. Performance in terms of flow should not be impaired on behalf of any change in design. Several of the parts of the component have geometries that are non-changeable due to their function. The valves are an example of parts that could not be altered.

The geometries and functions of following parts could not be changed:

- Main pressure valve
- Control valve
- Proportional Valve (9 parts)
- Proportional Valve CV-MP
- Pressure Switch
- 6 point socket screws M5x12 (18 parts)

The position of the holes on the transmission are set and because of the plug-and-play connection the interface of the control unit had to be adapted to that. All concepts must be adapted so that they can meet the holes to the transmission.

The pressure drop inside the canals must not lead to a pressure of less than 2.0 MPa at the solenoid valve outlets. This is an important demand as the pressure from the solenoid valves to the clutches and brakes requires 2.0 MPa to be activated. Thus, each design must not lead to a pressure drop resulting in the pressure subceeding the 2.0 MPa mark.

### 3.1.2 Needs and Requirements

The surface roughness that is required for the seals inside the valve housing is 3.2 $R_a$. This is however not possible with contemporary AM-methods, excess machining is therefore needed for this purpose. It is therefore essential to minimize the excess machining so that the redesigned component is as easy as possible to machine.

Because of the 2.0 MPa pressure limitation, the concepts generated should be designed so that the canal length could be minimized, and evaluated on the same requirement. Preferably, the pressure drop should not be greater than the existing solution, namely 0.2 MPa given from the CFD analysis on the existing component.

Volvo need to consider the profitability of their investments. Cost could therefore be seen as an aspect in the requirement specification. The new concept should have a reasonable production cost. It should preferably be as low as possible as long as it does not have a negative impact on the other requirements. The concepts should therefor be designed so that they cost as little as possible, i.e. limiting the weight and volume that has to be printed. The price of the existing component was given to XXX USD.

One advantage with AM that Volvo CE want to utilize is the ability to reduce the number of parts required. Thus, decreasing the number of integrated parts of the components is preferred. The current number of parts is 41.

The specific constraints, customer needs and requirements are listed in Table 3.1.

**Table 3.1:** Requirements, customer needs and constraints for the component

| **Requirements** | **Customer Needs** | **Constraints** |
|---|---|---|
| Minimum pressure of 2.0 MPa at solenoid valves | Ease of manufacturing | Must connect holes to transmission |
| Surface roughness below 3.2 $R_a$ | Ease of assembly | Must fit inside the predetermined space |
| Cost below XXX USD | | |

## 3.2 Concept Generation of Structural System

The concept generation phase consisted of four steps in an iterative pattern. A list of requirement specifications based on the customer needs was initially set up. These specifications worked as the basis for the concept generation where the specifications had to be achieved. Thus, each generated design was generated and evaluated based on the requirements. The concepts were then eliminated based on how well they fulfilled the customer needs.

### 3.2.1 Initial Concept Designs

In order to generate the appropriate concept, the design spectrum needed to be separated into different sub-functions (titled A,B,C and D below). This was helpful for the team to analyze the best solution for each design aspect and combine these to receive a suitable concept. The sub-functions were chosen because the team considered these to be the most valuable to redesign in order to reduce the overall cost of the component as well as improving the performance. It was also necessary to redesign these sub-functions due to the fact that the current solutions could not be manufactured using AM. The sub-concepts (named 1,2, and 3 under each sub-function) were generated via an idea generating session where the team discussed solutions for the different sub-functions. These sub-functions are listed and described below as well as the description of the generated sub-concepts corresponding to each sub-function.

A. **How to design for the holes to the transmission**
   The connection between the control unit and the transmission is pre-defined and can not be changed. What could be changed is the manufacturing method for this connection. It is vital to determine whether the connection points must be a traditionally made plate or if it is possible to manufacture the connections using AM.

   1. **Concept with flanges**
      The concept with flanges, Figure 3.1, is based on the assumption that no base plate is needed and only the connections to the transmission would be printed. As seen in picture below. All the green areas would be printed as flanges and then be bolted to the transmission with a gasket between. The whole valve unit would be printed on a printer plate and after the print is ready the unit be separated from the printer plate.

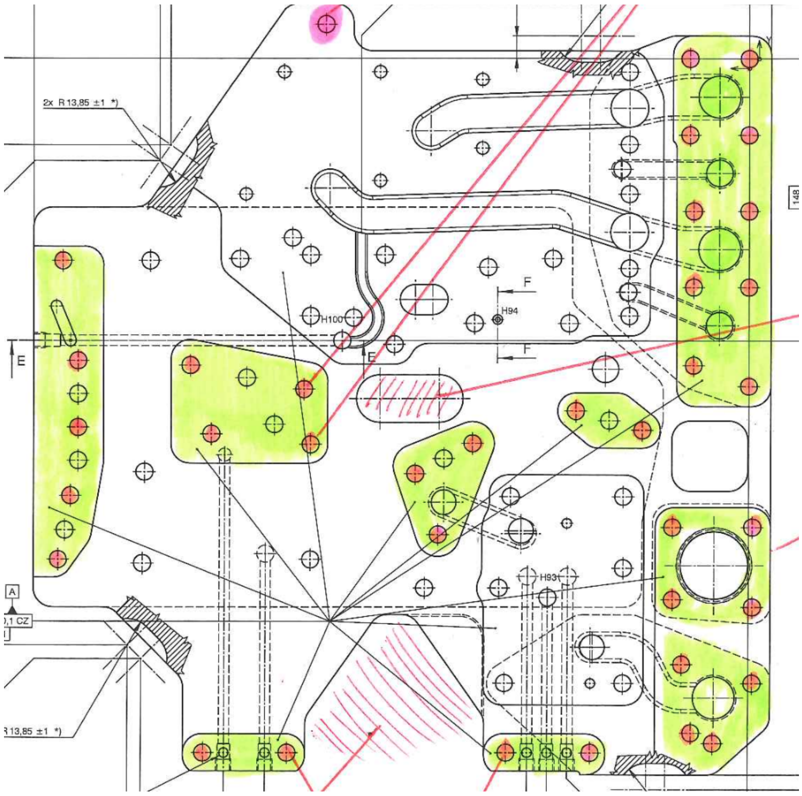


**Figure 3.1:** Drawing of oil distributor plate were the green areas would be the flanges

2. **Concept with base plate**
   The printer plate would be used as the connection between the control unit and the transmission. The canals that connect the transmission and the control unit would be machined after the print is done. A gasket between the transmission and the control unit would be needed.

3. **Concept printed directly onto printer plate**
   This concept would be printed on a printer base plate and after the print is done the whole printer plate would be machined to the specific geometry.

B. **How to rearrange the solinoid valves**
The valves must be present in the novel component but their arrangement could be changed, as could the arrangement of the existing canals inside the control unit. The arrangement of the canals is a result of the boundaries of traditional manufacturing techniques. Thus, it would be possible to rearrange the layout of the canals by rearranging the valves. The aim of the rearrangement is ultimately to reduce the canal length, thus optimizing the performance.

1. **Concept with the valves standing perpendicular to the existing orientation**
   For this concept the valves are standing in a certain pattern that would minimize the length of the canals. The main reason for having the valves standing

upright is that the holes that the valves would be mounted in may need machining after they having been printed.

2. **Concept with a polygonal valve housing**
   The valve housing would be redesigned into a polygonal shape with eleven sides where each has a valve. The canals would connect in the middle and lead to the different valves symmetrically.

3. **Concept with existing arrangement**
   If the canals could be rearranged and/or changed, there might be no need to rearrange the valves. Therefore, this concept is basically to keep the arrangement as it is.

C. **How to design the lubrication valve housing**
The lubrication valve must be incorporated into the new design. Because of the extended design opportunities that AM-technology provides there are new possibilities to change how the valve is incorporated.

1. **Concept without redesign of the lubrication valve housing**
   This concept is based on a plug and play solution for the lubrication valve housing. The existing lubrication valve housing would be bolted onto a printed base plate on a canal, as shown in Figure 3.2.

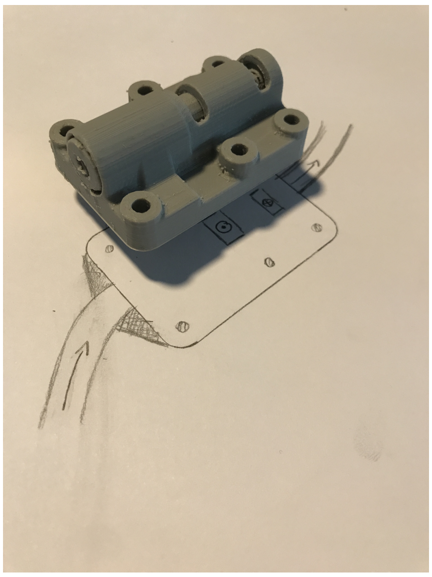

**Figure 3.2:** Concept without redesign of the lubrication valve housing

2. **Concept with redesign of the lubrication valve housing**
   The concept that is based on a redesigned lubrication valve would be printed on one of the canals/tubes that transfer the oil. The actual lubrication valve, and the spring would be mounted on the canal after the print is finished. This way of designing the valve housing may need some machining to get the threads and the tolerances correct. This concept is sketched in Figure 3.3.

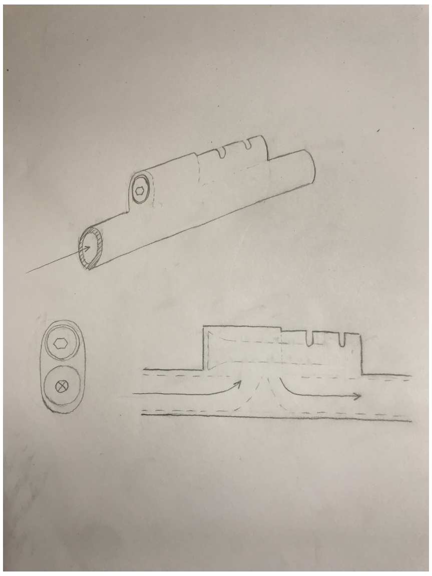

**Figure 3.3:** Concept with redesign of the lubrication valve housing

3. **Concept with the lubrication valve housing bolted to the base plate**
   For this concept the lubrication valve housing would be bolted onto the reversed side of where the valves are located, see Figure 3.4. The canal/tube that would transfer the oil would be printed on one side of the base plate and then connected to the lubrication valve housing through holes drilled in the base plate.

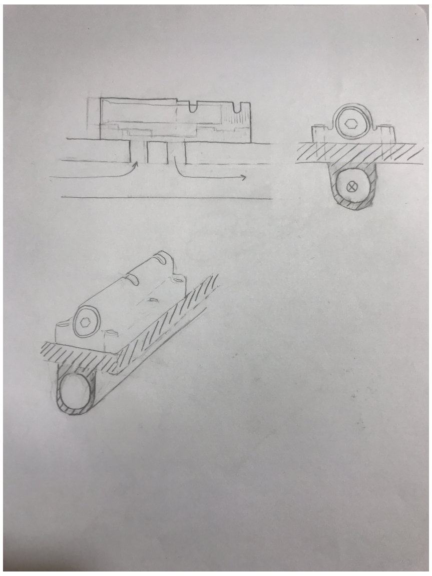

**Figure 3.4:** Concept with the lubrication valve housing bolted to the base plate

D. **How to design the main pressure valve housing**
   The same as for the lubrication valve housing goes for the main valve and the main valve housing. The main valve must exist in the novel design, but this is not the case for the housing. The housing can be changed or completely re-

moved as the main valve can be incorporated directly into the connecting canals.

### 3.2.2 Sub-concept Merging and Initial Elimination

To generate possible concepts a Morphological Matrix was used. The matrix set up all the design aspects and their solutions, the sub-concepts. From this, combinations with one sub-concept from each design-aspect were made into design concepts for the whole component. A large number of concepts could be generated from this. In this case there are four design aspects with three sub-concepts each. The total number of concepts could therefore be 81 but some combinations of the sub-concepts cannot be executed. The reason is that there are certain component requirements for each of the sub-concepts and in some cases these requirements contradict each other. The sub-concepts for the redesign of the lubrication valve housing and the main pressure valve housing are based on the sub-concepts regarding the connection to the transmission. They are either adapted to the idea of using a base plate or not using a base plate. The combinations with contradicting sub-concept ideas are therefore useless and are eliminated before the actual concept generation process begins since it serves no purpose to include them in further investigations. Because of the similarities between the lubrication valve housing and the main pressure valve housing the generated sub-concepts for C and D are based on the same ideas. They were only be combined with the corresponding sub-concept. An evaluation of which of the design options is the most suitable was therefore made with both the lubrication valve housing and the main valve housing in mind.

The concepts that are realizable were set up against each other and evaluated, See Appendix B.

The Morphological Matrix generated 18 unique concepts. To further evaluate the 18 concepts an elimination matrix which can be found in Appendix C was set up with three points of interest:

- Ease of manufacturing
- Cost/Time
- Performance

In the matrix the concepts were given scores from 1 to 6 with regards to these three aspects. The higher the score, the better the concept is expected to be.

The ease of manufacturing point shows how easily the concept could be manufactured. This is determined by how much support structures that would be needed to keep the print stable, if the concept would need any machining after it has been printed and if that machining would be complex or not.

Cost/time refers to an estimation of how long the component would take to print. The main factor here is the volume/weight of the printed part. Naturally, the size of the print determines both the time it takes to print it as well as the cost of the component. Building height is another factor that affects the printing time but it has a lesser influence.

The different concepts' performances were in this stage evaluated with a discussion of the canal-arrangement that will accrue with the different concepts. The scores were based on estimations as it was impossible to make exact calculations at this stage. This makes the evaluation a bit uncertain but more advanced calculations would probably have rendered roughly the same results.

When all the concepts had been evaluated, six concepts had received a total score of 15 points or more. The concepts that had lower scores than 15 points were eliminated. The six remaining concepts were those that seemed the most worthy of performing more evaluations on.

#### 3.2.2.1 Descriptions of Remaining Concepts

The basics of the six concepts with the highest scores from the elimination matrix are described below.

1. **Concept 2**
   The control unit and the transmission would be connected by flanges. The absence of a base plate forces the lubrication and main pressure valve housings to be incorporated into the design in a different way than in the original component. Instead of being separate parts bolted onto the base plate, the housings would be printed directly onto the canals.

   The valves in the gear changing unit would be standing vertically, perpendicular to the original orientation. The change in orientation compared to the original design would make for shorter canals which is desirable because it improves the flow through the canals. With the vertical valves the available space is utilized more efficiently than in the original component.

   The decreased volume and weight that come with removing the base plate is another benefit of this design. The integration of the valve housings onto the canals also reduces the volume/weight to some extent.

2. **Concept 7**
   Similar to the existing component, there would be a base plate that connects the control unit to the transmission. In comparison to the original design the new base plate would be of lower weight and unnecessary features would be removed.

   The gear changing unit valves would be standing vertically like in Concept 2, described above. The vertical orientation of the valves minimizes the length of the canals which improves the performance in terms of flow.

The lubrication valve housing and the main pressure valve housing would be redesigned in the same way as in Concept 2. With the inclusion of the base plate they could be mounted onto the plate like in the original design but that is not necessarily a better design solution. Therefore, this concept involves both the base plate and the incorporated valve housings.

The difference from Concept 2 is the base plate. With this, the overall volume and weight of the component would increase. Some material can be spared with the integrated housings instead of the bolted-on equivalents but not a significant amount.

3. **Concept 8**
   In this concept the base plate and the vertical gear changing unit valves remain the same as in Concept 2 and 7.

   The lubrication and main pressure valve housings would in this concept be bolted onto the base plate. The canals would be printed on the base plate on top of machined holes that go through the plate. The valve housings would then be attached to the other side of this plate. The whole plate would be flipped when it is connected to the transmission.

   The principal with bolting the valve housings onto the base plate makes this concept more similar to the original design than the previous concepts. The lubrication valve housing and main pressure valve housing add some volume/weight.

4. **Concept 9**
   This concept also includes the base plate. The lubrication valve housing and the main pressure valve housing would be integrated into the design of the canals just like in Concepts 2 and 7.

   Instead of the vertical valve housing used for the previous concepts, this one would have a polygonal valve housing. An eleven-sided polygon would house one valve on each of its sides. The polygonal valve housing is designed to keep the canals in the center. The shape and symmetry of the valve housing enable short distances to each of the inlets. Again, minimizing the length of the canals optimizes the flow.

5. **Concept 13**
   Here the sub-concept for the base plate is slightly different. The printer plate

is a non-printed, pre-cut metal plate that would be used as a base to prevent deformation which can occur during metal printing due to the tensile stress that can emerge in large prints.

The printer plate sub-concept would be combined with the polygonal valve housing and the integrated lubrication valve and main pressure valve housings.

In general, this concept is very similar to Concept 7. The only thing in this concept that differs from Concept 7 is the printer plate.

The main benefit of the concept is the “stability” the printer plate would provide during printing. Depending on which printing method that would be used it could be difficult to prevent the tensile stresses during printing and this would be a way around this problem.

One problem with the printer plate, however, is that it would have to be removed after the print is finished. The machining required for the removal can be considered to be a difficult operation when evaluating the concepts.

6. **Concept 15**
   This concept is basically the same as Concept 13 with the only difference being the design of the valve housing. Instead of the vertical valve housing, the sub-concept with a polygonal valve housing would be used. In terms of material use, there is no significant difference between those two options.

### 3.2.3 Final Evaluation and Elimination of Concepts

In order to determine which of the remaining concepts that is the most suitable for the described application a Kesselring Matrix was used. The matrix is a useful tool when it comes to evaluation and elimination of concepts. To have the matrix work, certain criteria had to be set up prior to the evaluation. These criteria represent the different aspects that must be considered based on the requirement specifications set by Volvo CE. The criteria were weighted due to the fact that some aspects of the concepts are more important than others. Each concept was thereafter given a grade based on how well they fulfilled the different criteria. This grade was multiplied with the weight to get the final score for each concept. Based on the final score, a concept was chosen.

A Kesselring matrix includes grading of the existing solution to act as a comparison of the concepts. In this case, however, the problem statement indicates that the project should focus on the possibilities to incorporate AM technology into Volvo CE’s manufacturing techniques. This limits the design scope to concepts that allows for AM. Because of this, the existing solution is excluded from the Kesselring matrix.

#### 3.2.3.1 Criteria of Kesselring Matrix

Four criteria were set up based on the requirement specifications, Ease of Manufacturing (EOM), Cost/time, Performance and Ease of Assembly (EOS).

The EOM criteria refers to the machining after the component has been printed. Due to the requirement specifications the surface roughness required for some faces is 3.2 $R_a$. None of the AM techniques are able to meet the requirement and therefore machining would be necessary. To evaluate the EOM between the different concepts the number of setups needed in a CNC machine was calculated for each of the concepts. The number of setups refer to how many times the operator would need to rotate the part in the CNC to enable the CNC machine to operate. In this case, it is assumed that a 3-axis CNC milling machine would be used. The machining itself would not be complex, the operations needed are mainly face milling, drilling and threading.
The extent of the operations was also evaluated. The amount of material needed to be removed from the component after the printing process vary. In those cases where a large amount would be removed from the printed part the operations can be considered more extensive and more difficult.

The actual difficulties that come with design for AM were not included in ease of manufacturing. This is because the different concepts have the same limitation when it comes to AM design.

For cost/time, the aspects evaluated were the printed volume, which directly corresponds to material cost, and the ability to arrange the canals in order to reduce the total canal length. In some concepts there are parts that are already used in the current solution. The costs of these parts were provided by Volvo and were used in order to calculate the cost of the concepts. Sketches of the sub-concepts that are supposed to be printed were modelled using CAD in Catia V5. For each of the six concepts, the sum of the sub-concepts' volumes was calculated.
Since the canals connecting the sub-concepts are not included, the possibility to reduce the total canal length had to be estimated. The canals would make up for the most part of the total printed weight of the different concepts, and it was therefore crucial that the canals were included in the cost criteria. The cost of assembly, however, is not included in this criteria as it is incorporated into the assembly criteria. The logistics costs for the different concepts are also not included as they all would be roughly the same size and weight.

The performance of our system is also one of the most important aspects of the design. The performance criteria was divided into three sub criteria namely length of the design, geometry of the system and the surface roughness of the inner contour of the system. The length of the geometry was considered because we wanted to come up with a design that would be able to fit in the housing of the existing control unit. Longer canals would also give us higher pressure drop across the channels.

After analyzing the given PT9 transmission unit we realized that the canals in it have a number of turns. We decided to reduce the number of turns to have a better and simpler flow in our canals.

EOA was the last criteria we picked for this project. This criteria was divided into three sub-criteria namely easy, medium and hard. Our concepts that would have mounting areas that are easily accessible by off the shelf machining tools, for example drill bits, were put in the easy criteria while the concepts that would have difficulties in accessing the mounting areas by off the shelf machining tools were put in the medium criteria and lastly, if our concepts required special tooling machines for example lathe to give it a final shape, they were put in the hard criteria. The other two features in our concepts to be considered were the weight and manual assembly. The weight of our components should be such so that it requires no external machine to pick it up as all this would increase the production time and would require extra man power. The manual assembly criteria was judged based on how difficult it would be to assemble the pieces together. If it would require no manual assembly it was put under the easy criteria but if it would require manual assembly after manufacturing it was out under the medium criteria and if it would require complex assembly, for example the assembly of the components require special training, it was placed under the hard criteria. As a team we considered all these criteria before making a final decision.

The points awarded to the different concepts' sub-criteria were 1, 2 and 4. This scoring was used instead of 1, 2 and 3 to give a more fair and logical result. The 1, 2, 3-scale does not show the superiority the best concepts have over the rest. With the 1, 2, 4-scale, the logic goes like this: 2 is the double value of 1 and 4 is the double value of 2. 3 is only 1.5 as much as 2 so it is can be seen as misgiving when adding the weighted sums together. To summarize, this point system is a better indicator of the concepts' actual value in terms of quality.

The sum of the weight of all criteria adds up to 10. The cost/time aspect is the most important factor to take into consideration. It was therefore given a ”weight” of 5 in the Kesselring matrix. The cost is thus considered to be as important as all the other criteria combined. This is due to the correlation of price of a component and the customer value. The customer will not buy a component where the price does not at least equal its value. The value could be described as the qualities of the component in which the performance, EOM and EOA are all included. Evaluation of the six concepts in Appendix D.

#### 3.2.3.2 Elimination using Kesselring Matrix

In Table 3.2 the result of the Kesselring matrix is shown. Concept 8 was rated the lowest in the process, the main reason being that it would be the least cost effective. Between the other concepts the scores were not very different from each other. The small difference in score between the different concepts shows that the six concepts that were selected from the first 18 really were the best concepts to go with. If the difference had been more significant the process of eliminating concepts from the first 18 would have had to be redone.

The highest scoring concept was Concept 7. It was one of the best concepts in the Cost/Time criterion which is crucial as that can be regarded as the most important factor. It also gained a high score for the ease of manufacturing. One thing to point is that the sum of the concept scoring for Concept 7 is not the highest out of the six, but the weighted sum is. This shows the importance of using a weighted matrix when the criteria differ in importance.

**Table 3.2:** Kesselring matrix with criteria stated in 3.1

| Criteria | Weight | Concept 2 | Concept 7 | Concept 8 | Concept 9 | Concept 13 | Concept 15 |
|---|---|---|---|---|---|---|---|
| EOM | 2 | 4 | 3 | 1,5 | 3 | 2,5 | 2,75 |
| Cost/Time | 5 | 2 | 3 | 1,5 | 2,5 | 3 | 2,5 |
| Performance | 3 | 2,125 | 2,25 | 2,75 | 2,25 | 2,25 | 2,25 |
| EOA | 1 | 3 | 2,75 | 2,25 | 3,25 | 2,5 | 3 |
| Sum | | 11,125 | 11 | 8 | 11 | 10,25 | 10,5 |
| Weighted Sum | | 27,375 | 30,5 | 21 | 28,5 | 29,25 | 27,75 |

## 3.3 Concept Generation of Canals

The control unit in the PT9 transmission is a very complex model with oil flowing in its canals and therefore it required us to analyze various geometries of canals. In AM, making canals is considered as one of the most complicated processes because not every geometry can be easily printed. Most geometries require support structures but we cannot have that in our canals as they are internal. It would be difficult to machine the support structure out of the canals after printing it. Therefore we wanted to find geometries that would require the minimal amount of support structure inside, preferably none. We also wanted to have the flow of the oil to be as smooth as possible inside the canals so that it causes no system turbulence. Therefore this section is dedicated to find the best geometry of canals based on ease of AM and having the best fluid flow.

### 3.3.1 AM Geometries

As a team, four different cross-sectional geometries were developed. There were two major goals with these cross-sectional geometries: to provide adequate fluid dynamics and to have the ability to be printed without any internal supports. The four geometries are pictured in Figure 3.5:

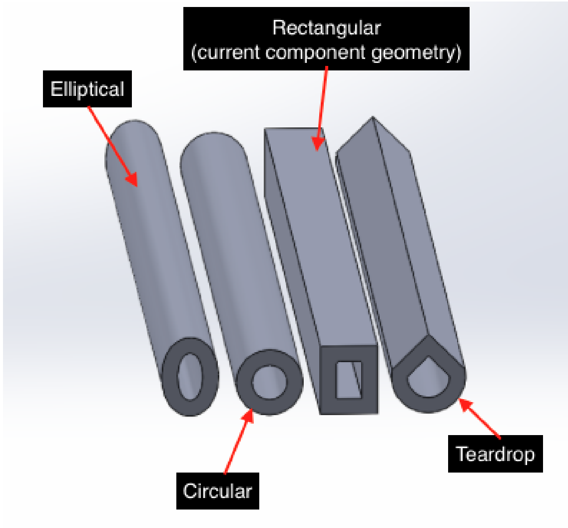


**Figure 3.5:** Four concepts of different cross-sectional geometries

#### 3.3.1.1 Fluid Dynamics

CFD analyses were performed on four different cross-sectional geometries. A straight path was chosen for this type of analysis to make the calculations easy. The second reason for this was because it was easier to keep the areas of all four geometries within five percent of each other to have accurate calculations. These tests were conducted to visualize the pressure drops across the pipes for different geometries and to calculate the pumping power to obtain a rough knowledge about the friction along the length of the pipe. For this calculation we made three assumptions and they were steady state, in-compressible flow and one surface roughness. Incompressible flow was picked because the density of the fluid will remain constant throughout the flow. The calculations in Figure 3.7 were done with an assumption of surface roughness zero but that would not be the case with canals because it is nearly impossible to make smooth canals. This assumption was chosen to make the calculations simple. Having Ra surface roughness more than one will only increase the pressure drop and the pumping power by the friction factor obtained from the moody chart corresponding to the obtained Reynolds number and surface roughness.

Four different shapes of pipes were analyzed using SolidWorks. The geometry of the pipes tested were circular, elliptical, tear drop and rectangle. The rectangular cross section was tested so that the other three geometries of the pipe could be compared to the original shape. All the pipes had approximately the same area or within 5% of one another. The fluid flow analyses were done to check the pressure drop at the inlet and outlet of the pipe. Through the pressure drop we could estimate the pumping power needed for the oil to flow across the pipes. Pumping power is directly proportional to the friction in the pipe and the pipe with the least pumping power is preferred. Figure 3.7 shows the pressure plot across the four cross sections of the pipe.

The pressure cut plots of the pipes shown in Figure 3.7 show that the pressure drop across the pipes falls in the range of about 1.5-2.5 kPa when the applied pressure across the pipes is 2.0 MPa. Hand calculations were then performed to check if the pressure drops are close and to find the pumping power. See the calculations for each pipe geometry in Appendix E.

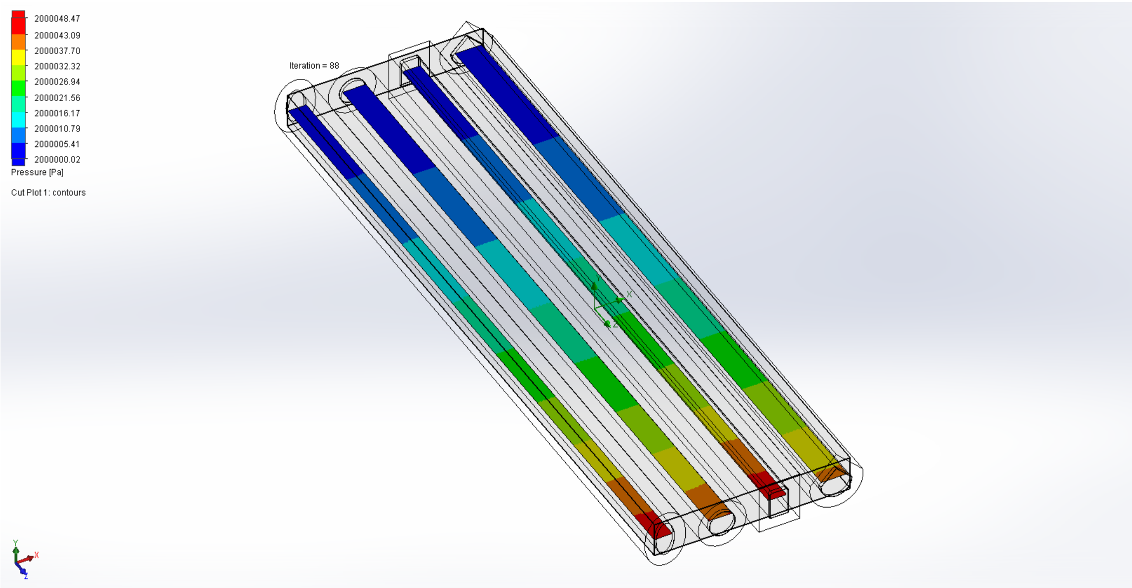


**Figure 3.6:** Pressure map across the pipes for the different geometries where red indicates high pressure and blue indicates low pressure

As mentioned earlier, the pipe geometry with the least pumping power would be the best for our project as we were looking for a pipe with the least friction to achieve a smooth flow.
After conducting the computational fluid dynamics on these geometries, the pressure drop was extracted from each geometry. This pressure drop was then used to calculate the pumping power $W$

$$W = V \cdot (\delta p)$$

where $V$ is the volumetric flow rate of the fluid and $\delta p$ is the pressure drop. The pumping power for our project is directly proportional to the pressure drop since the volumetric flow is a constant factor which was given to us by our industrial partner. Among the four geometries, rectangular cross-section (the current design) had the largest pumping power, 14.48 W, because the obtained pressure drop for that geometry was the highest and circular cross-section had the smallest pumping power, 8.55 W. Elliptical and tear drop pipe had pumping powers of about 12.39 W and 13.37 W respectively. To interpret the calculations better, it is necessary to know that friction will be lower across the length of the pipe with lower pumping power. Hand calculations are present to explain pumping power analytically in Appendix E.

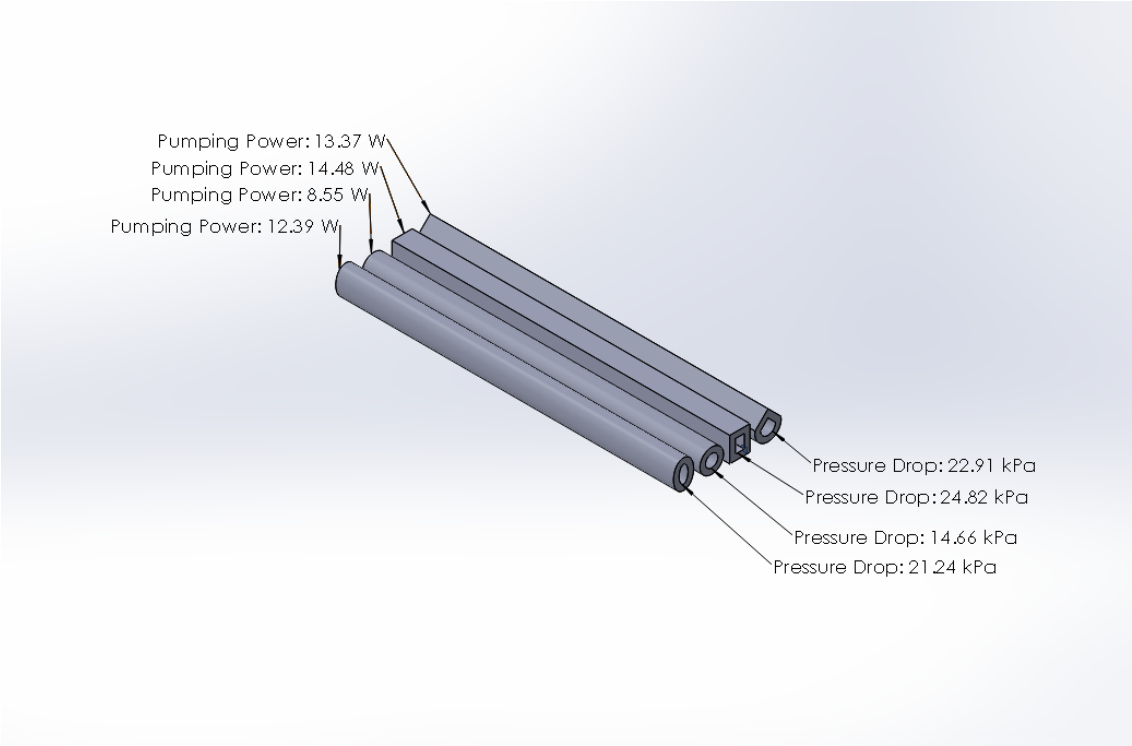


**Figure 3.7:** Pressure drop and pumping power for each cross-section geometry

#### 3.3.1.2 AM Restrictions

Due to the limitations of AM, overhangs on the outer geometry should be avoided if possible to minimize unnecessary material in form of supports. To avoid any part failure, AM recommends the use of support structures in the critical areas. However, for internal canals, this is not an option. Support structures on this component would require machining in difficult, if not impossible, to reach areas.

Rectangular cross-sections are most likely to fail without supports. The top overhang is very susceptible to sagging, which will result in failure during manufacturing or extensive machining. Circular cross-sections may have some issues at the top. Sagging is possible and could lead into failure during manufacturing. The sagging will make the circular shape not uniform and may also have the need to be machined. Elliptical cross-sections are much better than circular ones. Sagging is unlikely so the need for machining will be all but removed for the canals. Teardrop cross-sections will have no sagging. With 45° walls, the teardrop shape will be adequately self-supporting.

### 3.3.2 Concept Selection

The cross-sectional geometries were selected using a simplified Kesselring matrix, see Table 3.4. The two criteria were the ability for the geometry to be manufactured using AM methods and the flow dynamics. To rank the concepts, the AM was taken into account and is described in Table 3.3. The flow dynamics criteria used ranking from calculated pumping power and pressure drops aforementioned.

**Table 3.3:** Criteria corresponding to the Kesselring matrix in Table 3.4

| | 0 | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Additive Manufacturing | Needs supports | Potential failure | Possible failure, Noticeable sagging | Minimal sagging | Doesn't need support structures, doesn't sag |
| Flow Dynamics | The circular cross-sections will require less pumping power (less friction resistance) so ranked from most circular to least | | | | |

**Table 3.4:** Kesselring matrix for cross-sectional geometries, teardrop and circular got the best score

| | Rectangular | Circular | Ellipse | Teardrop |
|---|---|---|---|---|
| Additive Manufacturing | 1 | 2 | 3 | 4 |
| Flow Dynamics | 1 | 4 | 3 | 2 |

From these matrices, it can be resolved that the circular cross-section would give the best performance. However, circular geometry is vulnerable for sagging and failure. The ellipsoid cross-sections would be the safer choice with the next highest calculated performance. The teardrop cross-section is the safest choice. But with the safest choice comes a decline in performance. Lastly, the rectangular cross-section is not a viable option because it has the poorest performance and greatest risk for AM failures.

# 4

# Selected Concept

Based on the Kesselring matrix, a structural concept was selected. The matrix indicated a close scoring between the different concepts, thus the team deemed it necessary to cross breed the highest scoring concepts. Subconcepts B1 and B2 were crossbred in order to receive a polygonal main gear selection unit with perpendicular valves. This is because the polygonal structure gives the opportunity to minimize the canal length for the main canal, and the perpendicular valve placement makes the machining much easier. The selected concept is therefore Concept 7 with an incorporated polygonal design. The design shows the possibilities with AM to reduce the number of parts, as the novel concept only has three integrated parts instead of the original 41 thus making the component much easier to assemble. The concept uses circular crossection for the vertical canals and elliptical crossection for the horizontal canals. The selected concept prints either on a pre-machined baseplate or the baseplate will be machined after the print is done. The lubrication valve housing as well as the main valve housing will be incorporated into the main canal and printed directly on top of the main inlets. This will result in more efficient oil flow as the canals will be much shorter compared to the original component design. Figure 4.1 shows the redesigned concept and Figure 4.3 shows the redesigned concept in the basic assembled setting.

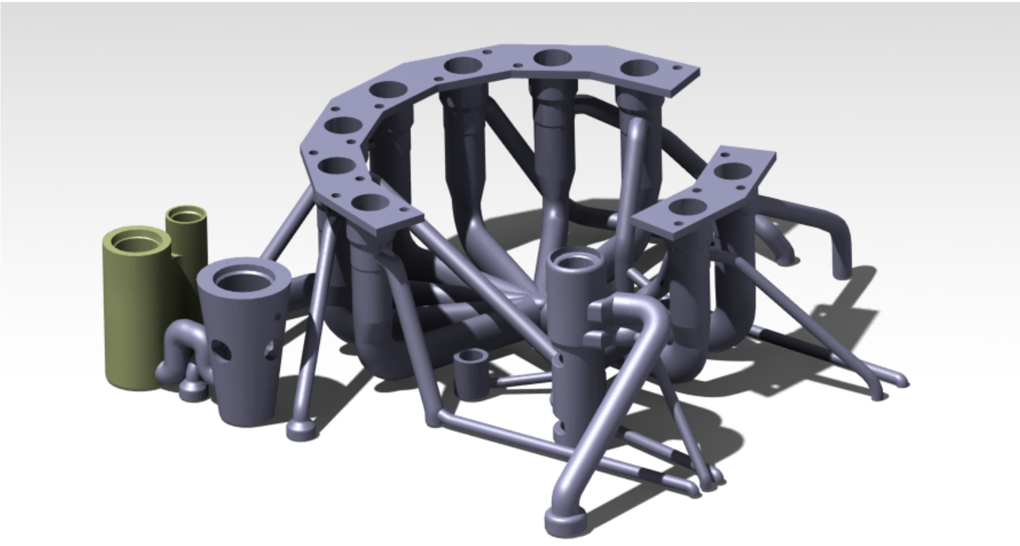

**Figure 4.1:** Final concept that would be additively manufactured on top of the baseplate

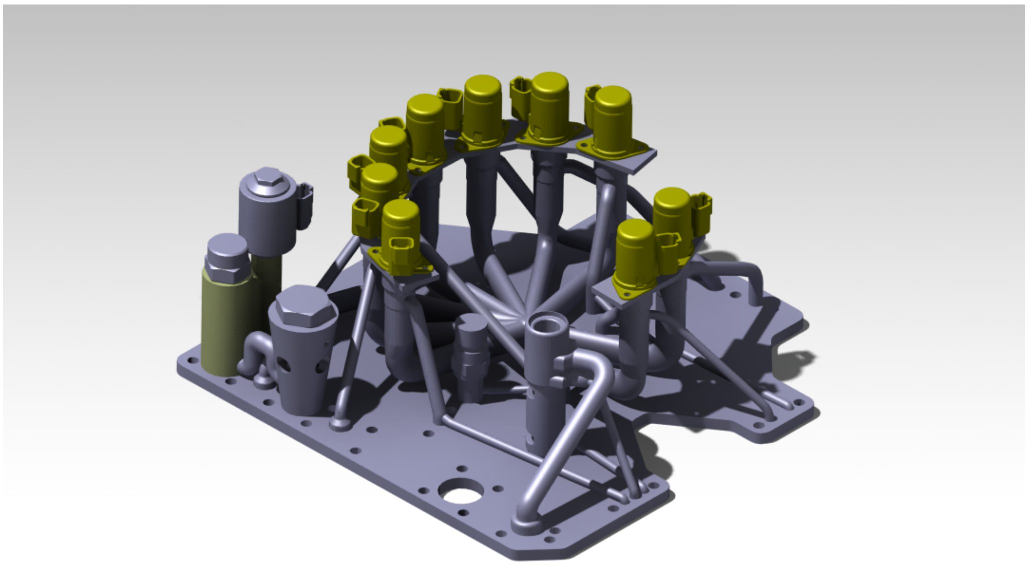

**Figure 4.2:** Final concept in the final assembly of the component

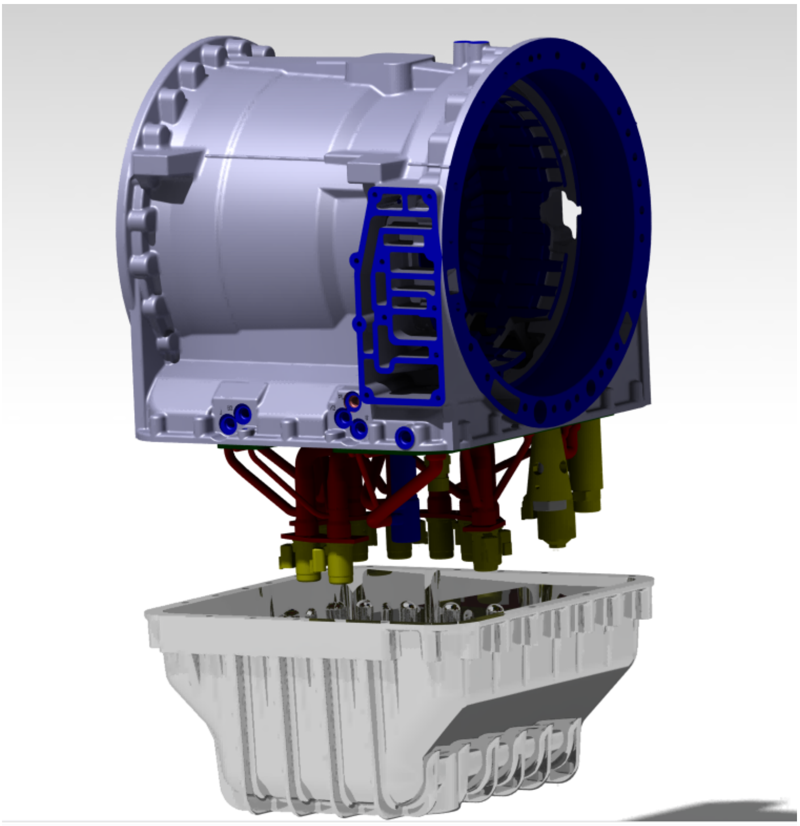

**Figure 4.3:** Final concept assembled into the transmission

### 4.0.1 Computational Fluid Dynamics

To perform the CFD for the novel component our team had to redevelop the canal structures on Solidworks. This was done to reduce the complexity of the model to facilitate the meshing across the canals in Solidworks.
To conduct the computational fluid dynamics, transmission oil was used as the fluid. Solidworks does not have transmission oil available in their directory meaning that the fluid had to be custom made. The properties of the fluid were given to us by Volvo. The list below shows the custom made fluid.

1. Transmission Oil Characteristics
    - Density - 815 kg/m$^3$
    - Dynamic Viscosity - 0.0102 Pa
    - Specific Heat - 0.0021 J/(kg k)
    - Thermal Conductivity - 1.3 W/(m k)

Inlet volumetric flow of 0.0005833 m$^3$/s and pressure of 2.0 MPa (20 bar) were given to us by Volvo CE. We also applied a real wall condition on top, bottom and side of the canal. This was done because the walls of the canals will have some friction and won't be perfectly adiabatic. After applying all these conditions the analysis was ran on the novel component and Figure 4.4 below shows the pressure map of the system.

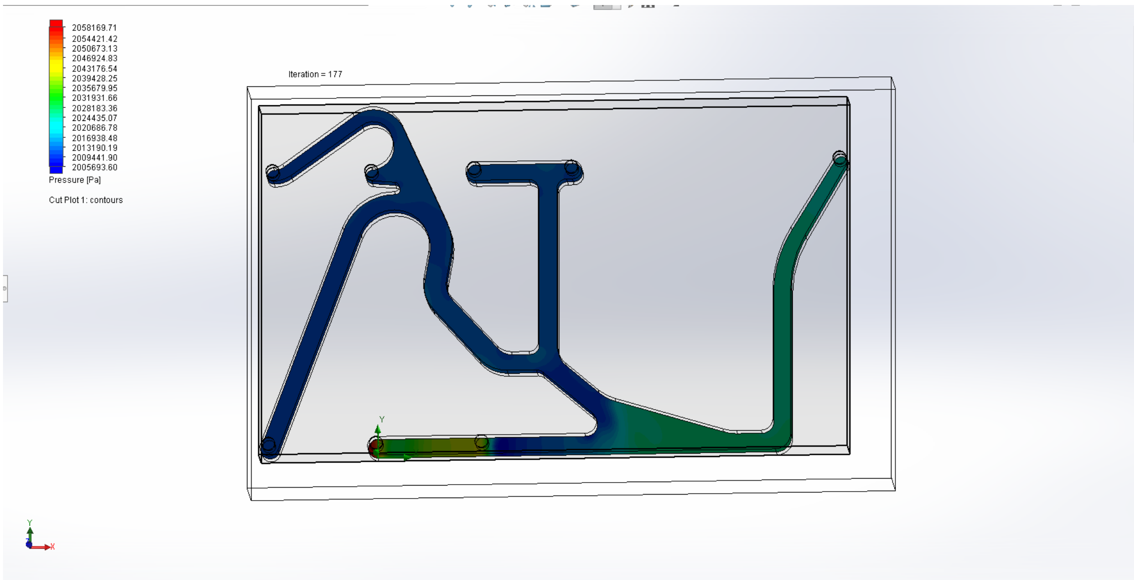


**Figure 4.4:** Pressure Map of the Novel Component where red indicates high pressure and blue indicates low pressure

As previously mentioned, the canal was redesigned along with the system redesign. The main purpose for this was to have a more symmetrical pressure map on the system. Figure 4.5 shows the pressure map of the system we redesigned.

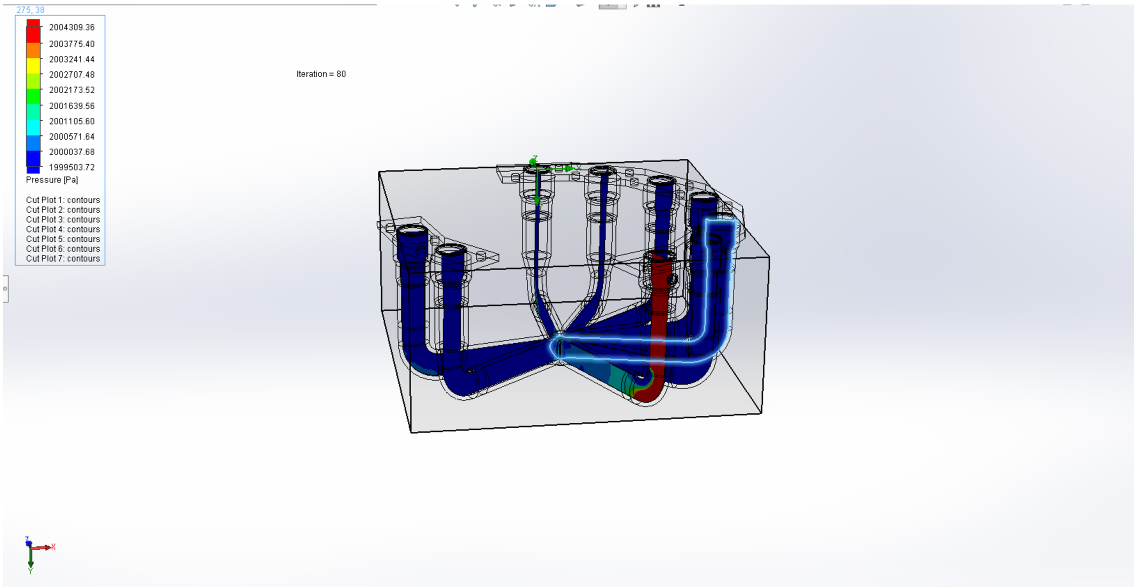


**Figure 4.5:** Pressure Map of the redesigned component where red indicates high pressure and blue indicates low pressure

Studying Figures 4.4 and 4.5 we can make a conclusion that the pressure map of the redesigned component is much cleaner and does not change from canal to canal, even though the inlet is not in the correct position due to difficulties. Whereas in the existing component, the canal system has so many turns that there are pressure changes across each turn. One interesting thing to notice is that the change from circular to ellipsoid shape has no effect on the pressure in the redesigned system. The maximum pressure recorded in the existing component ranged between 2.05 to 2.07 MPa (20.5 to 20.7 bar) when the boundary condition was set to 2.0 MPa (20 bar). While for the new system the maximum pressure ranges between 1.99 to 2.0 MPa (19.9 to 20 bar) when the boundary condition was set to 2.0 MPa (20 bar). After observing these differences it is safe to say that the redesign has better performance than the existing component.

There are two ways of developing a model. The first method is to develop a model to show what a real design looks like. The second method is to develop a model to perform simulation and analysis on it. The first method can have detailed fillets, chamfers and have a complicated geometry while the second method needs to have a cleaner and simpler model. Figure 4.1 shows the actual redesigned model and Figure 4.6 shows the model we could conduct our flow analysis on.

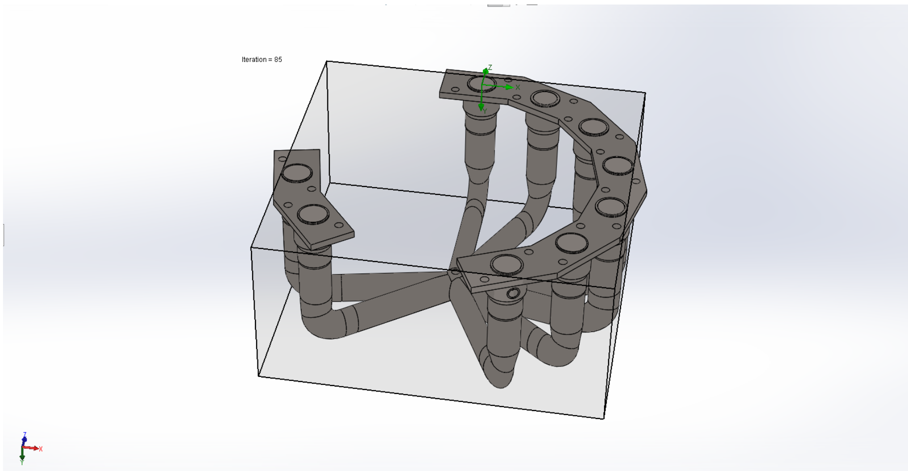

**Figure 4.6:** Model Used for CFD

### 4.0.2 Cost Evaluation

The costs of the existing component were provided by Volvo. In Table 4.1 the prices for the different components are shown and summarized. The total cost for manufacture the existing component is XXX $.

The difficulties when estimating a price for the novel component is that the price depends on a variety of of factors. The ability to negotiate with the company that will provide the component, different labour cost between countries and so forth. The estimation of the cost of the novel component was accomplished by two different methods. The first with only labour cost and powder cost taken in consideration, and the second including the machine cost.

When estimating the time it would take to print one control unit, Materialise Magics software was used. Due to the size of the control unit it had to be downsized to fit the workspace in the software. Four different time estimations were made with four different scales of the component. It could be seen that the time and scale was linear and the print time for the 50% scale model could be multiplied by two to get the actual print time for the noval component. For print parameters 0.3 mm layer height was used. The calculations were made to fit the EOS M 290 Printer. The software estimation of the print time was 22 hours and 26 minutes.

A speculative demand of control units today was given by Volvo CE. Approximately XXX units are manufactured each year, that corresponds to XX AM machines needed if 300 workdays are assumed and the print time is 22 hours and 26 minutes. An SLM M290 machine costs approximately 860000€, according to (Sebastian Hallgren, 2016), thus 14 such machines would add up to an investment price of 12 million €. This machine would however not be able to print the novel component due to the size of the component. A larger printer will be needed and therefore the cost will also increase. Within this project the team have not been able to get pricing for such a large printer and therefor estimates investments cost with EOS M

290 as a reference.

Aluminum powder cost is estimated to 130 $/kg (Sebastian Hällgren, 2016) with 10% powder waste that is not reuseable. For the novel component that has a weight of 1.73 kg the total powder cost estimates to 272 $. Labour cost for a CNC-operator is estimated to 34 $/h including tax and insurance and the same amount is used to estimate the costs for a printer operator (payscale.com, 2017).
Preparation and cleaning time for one print was estimated to roughly two plus three hours. Adding the oil distribution plate and a gasket the overall price is estimated to 1 142 $. One thing to have in mind is that in this estimation neither the cost of the printer nor the machining costs are taken in consideration. Those costs will add up to a higher overall price for the novel component. The calculations are shown in Table 4.1.

When taking the printing machine cost in consideration the price estimation differs from the previous. Assuming costs from (Sebastian Hallgren, 2016), were investing in one machine estimates to 86000 €and write of years is three. When taking those assumptions in considerations the machine and labour cost estimates to 120 $/h and overall price estimates to 3 207 $ for one control unit.

**Table 4.1:** Cost estimation for existing component and novel component using only labour costs

| | | | | |
|---|---|---|---|---|
| Existing component with manufacturing cost | | | | |
| Art. Nr | Definition | Price Part | Price Blank | Volvo Materal |
| 11430048 | Cover | [redacted] | | VAC43100+KF |
| 11430461 | Cover | [redacted] | | VAC43100+KF |
| 11430633 | Lubrication Valve Housing | [redacted] | | VAC43100+KF |
| 17222494 | Gear Selector | [redacted] | [redacted] | AW6082+T6 |
| 17222539 | Housing | [redacted] | [redacted] | AW6082+T6 |
| 17222554 | Oil Distributor Plate | [redacted] | [redacted] | VAS6082+T6 |
| 17236391 | Gasket | [redacted] | | Steel/rubber |
| 17236389 | Gasket | [redacted] | | Steel/rubber |
| | | [redacted] | | |
| Assembly cost | | | | |
| Direct cost (worker + machine) = 117,75 SEK | | [redacted] | | |
| | | [redacted] | | |
| Total cost | | [redacted] | | |
| | | [redacted] | | |
| Novel component with manufacturing cost | | | | |
| | | Price | | |
| Powder cost | 110 eur/kg | 2 124,05 kr | | |
| 17236389 | Gasket | 40,50 kr | | Steel/rubber |
| 17222554 | Oil Distributor Plate | 1 109,31 kr | 562,15 kr | VAS6082+T6 |
| Print time | 22.4 hours 34 USD/hour | 6 547,00 kr | | |
| Total cost | | 9 820,86 kr | | |

# 5

# Discussion and Recommendation

In this chapter the team will provide to the reader the conclusion of the report, as well as discuss the results of the project. The final section of this report will be recommendations for Volvo CE regarding the redesign of the component as well as implementation of AM-technology into Volvo CEs's production techniques.

## 5.1 Conclusion

This project shows that AM-technology provides new design possibilities that would be impossible to manufacture with traditional techniques. In this case, the canals in the control unit are designed for optimal flow with little restrictions. The canals are shortened with smoother bends and an optimized cross-section. These factors all contributed to a lower pressure drop in the control unit.

Redesigning the component with AM-technology allows for the control unit to be easier to manufacture and assemble due to a decreased amount of machining. Parts that were previously bolted together can now be printed as one solid part, therefore reducing the number of parts required. The canals can be printed without supports if done correctly, thus getting rid of the need for cross-drilling and similar operations. Another advantage with AM technology in this case is that the overall weight of the component was reduced. Originally the weight was 13.8 kg, and after redesigning it for AM the weight is only 5.2 kg.

However, the cost of production was greatly increased as the redesigned unit would have an estimated cost of 1 142 $ whereas the existing solution only costs about XXX $ for the component alone. This is taking only the material costs into account.

The cost to transition away from machining and into AM would be very high. This cost would include a new training program for employees, new machines and new unpredicted costs and problems. Therefore it is not suitable to use this concept from the current cost perspective. However, it could be a very viable concept to use in the future when AM technologies become more common and economical.

## 5.2 Result Discussion

The results indicate that AM technology opens up new design possibilities for Volvo CE. It allows Volvo CE to manufacture parts with much less weight and with complex geometries. In this case, however, the weight of the component itself was not the main priority due to the price and performance being the most important aspects of this project. Today, AM is mainly used in low-volume production where the parts are usually small and complex to machine. The most common usage of the method is when low weight is desired. It is also more profitable when components are printed in batches as the overall print time can be reduced significantly. This is impossible for the novel component as it is too large to be printed in numbers simultaneously. This might be an important factor as to why the price ended up being higher than the original solution.

It should be added, however, that the decreased weight of the component may have a positive impact on the price in other areas that are not calculated in this project. Having a lighter novel component makes it easier to handle in an assembly as it limits the need for lifting equipment. This might make the concept cheaper than the calculated price shows because of the fact that it requires fewer workers and no lifting devices. Compared to the existing solution, more components can be transported to the assembly line at once. Ultimately, transportation and logistical costs can be eliminated, or greatly reduced, if the component is printed in Köping where the component is assembled to the transmission as of today. This will however require investments in AM-machinery for their manufacturing plants, leading to a much higher price per component in the near future.

The main reason for the high price is due to the price of the metal powder. Since AM is a rather new method, the material usage is limited, and the material price can therefore be held high. When the method becomes more common, the price of the metal powder used for AM will probably become lower with time. It is also likely that the continuous research on AM will result in more available types of metal powder that might suit this component better.

When it comes to the fluid dynamics in this project, the redesigned model had a better pressure map and lower pressure drop compared to the original model given to us. The results for the main canals we developed were compared to the original canals in the transmission unit. The fluid analysis could only be conducted on the main canal as seen in the computational fluid dynamics sections. Also, the main inlet in these simulations differ from the actual main inlet. This was because the model developed was too complex for SolidWorks or ANSYS to handle because it was developed to illustrate our final design. In the future, the results of flow simulation might change if the entire model could be simplified for flow dynamics purposes. One could not make any final conclusions based on these fluid analyses, they do, however, hint that the pressure drop in the canals is reduced compared to the existing design. This is also proven by theory as shorter canals, less edgy turns and a different cross-sectional geometry should lead to less pressure drop.

In the future, this concept can be refined in order to make it even more suitable for the application. It is also likely that the AM-methods will become better with time, giving the opportunity to design the canals with less internal friction due to a finer surface. Having refined canals should result in this concept being significantly better when it comes to oil flow in the canals.

A finer surface roughness value from the print might also result in less access machining needed for the print since tolerances for the holes and for the different surfaces can be met using AM only. This will decrease the cost as it reduces the need for manpower and machining time. The overall time for each component can also be reduced in this way. If other AM-techniques that do not require powder, but still meet the requirements, emerge in the future, it also reduces the issue with access powder being left in the canals. This is crucial as there cannot be any powder left in the canals when the component is installed in the transmission. In the future, it is likely that the concept would make more sense if the entire transmission was optimized for a AM solution.

There are some factors that might have altered the outcome of this project that should be mentioned. This concept is designed with PBF in mind, however, it is not entirely optimized. If new, more efficient AM-methods emerge, the component might have to be redesigned. This has not been taken into consideration in this project. Also, the limited time frame resulted in one concept for one AM-method. It would be interesting to compare two or more concepts designed based on different AM-methods to see the difference in performance and cost.

The cost of the metal powder used for the cost calculation is only an estimation from a 3D printing metals company. The values that they had given us represent their costs for the powders. The price of metal powders can vary between suppliers, which alters the cost of the component. In addition to that, the price estimation is based off of the current cheapest metal at the company. In the future, these prices will likely drop, as newer and cheaper powders emerge. Furthermore, not every aspect was taken into consideration for the cost estimate. The pricing only took account for the fabrication of the part. Costs such as transportation, and administrative costs were not taken into consideration.

The cost calculation did show two different scenarios, one with only the print taken into consideration, and the other with the machine cost incorporated. This was because it is unclear if it is intended to invest in AM-machinery or if the production will be outsourced. The cost calculation would benefit from more exact information regarding these aspects. What can be said, however, is that the investment of new AM-machines would be expensive and the transition from traditional machinery to AM-machinery would be problematic. Since approximately 14 machines are needed in order to keep the same production, the investment of these machines would be very expensive. Also it should be mentioned that the print time did not take into account the access work needed for finishing the print, which could alter the overall print time and price. Such an investment would make more sense if more of the production was made using AM, so that more parts could be manufactured with the same machines.

Transitioning to AM-technology would not be recommended with today's circumstances. However, it could be a very viable concept to use in the future when AM-technologies become more common and economical. An example of how AM could become more economically beneficial in the future is that the powder material used in the printing process is expected to become significantly cheaper as the use of AM expands as stated by Arcam EBM AB (personal communication, 2018).

## 5.3 Recommendations

This section will include the team's recommendations for what Volvo CE should do next regarding the redesigned component and implementing AM. These recommendations are areas where the team feels improvements can be made and where future problems can be avoided.

### 5.3.1 Redesigned Component Recommendations

The control unit is a complex component to redesign for AM. Within the limited time of this project, the team have not been able to optimize the concept completely. Moving forward, the team recommends a more optimized canal path with more gentle curves and canal shorter distances. This specific feature can be seen in Figure 5.1 with a single example circled in red. Shorter canals with more gentle curves would mean less pressure drop, thus increasing the performance. Another recommendation is that the valve house could be altered to use less material. There are two ways this could be altered, the first is making the valve house itself shorter, which is circled in blue in Figure 5.1. The second way would be to make the horizontal distances shorter, which is circled in green in Figure 5.1. Making the gear selection unit more compact would lead to less material usage, reducing the price. Another idea is that the valve connection could be shaped to match the valve connection; this is circled in pink in Figure 5.1.

It is also recommended that Finite Element Analysis are performed on the component, reassuring that the component can withstand the environment in where it is supposed to be fitted . From this analysis, a more appropriate material could be chosen as well as optimization of wall thickness, possibly lowering the overall cost.

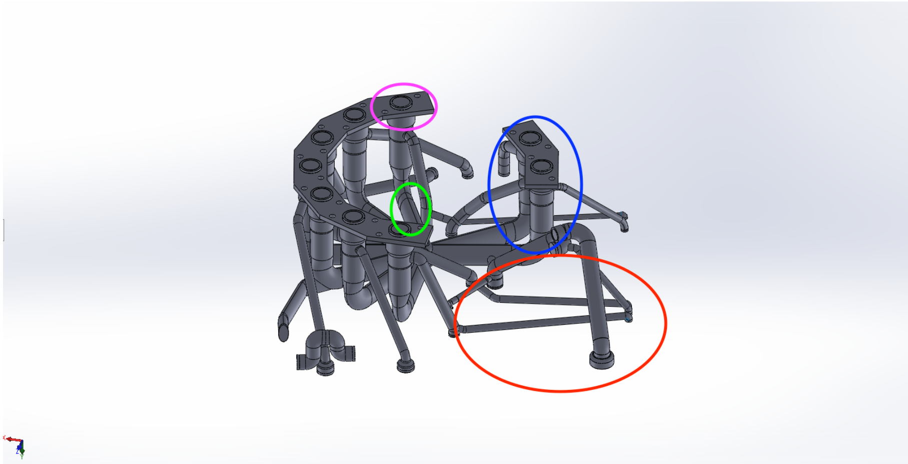

**Figure 5.1:** Final concept with areas circled to highlight recommended areas of improvement

### 5.3.2 Implementing AM Recommendations

Implementing AM for the redesigned control unit will be an expensive transition from traditional manufacturing methods. Due to the fact that the redesigned control unit is relatively big only one unit per time can be printed. Small parts can be made in rows and can be stacked on top of each other resulting in a large number of parts being printed simultaneously instead of just one large part and therefore more cost effective. This could be done by using a 3D printing software to allow you to orient and splice the parts as well as to create custom support structures manually, if needed. It gives more control to the user. One way to make use of this feature would be to divide the concept into smaller parts from which the final component could be assembled. In this way, it is possible to print more parts simultaneously, decreasing the print time. This will however require more assembly as the parts would need to be put together. Calculations on this matter is recommended in order to evaluate this as a viable production method.

Using PBF will result in “clean up time” to remove the excess powder from all surfaces including the internal cavities. This is a big problem when it comes to EBM as the powder becomes hardened by the high temperature during printing, resulting in chunks of unwanted material being left in the canals. The alternative method suggested to additively manufacture this component would be SLM. This is because this PBF method does not require as high temperatures during manufacturing, possibly leading to less hardened material being left in the canals. SLM does on the other hand require heat treatment after the print is done. A closer comparison between these PBF methods are therefor recommended in order to determine the most profitable one.

This thesis have not taken into account the difference in environmental impact between the existing component and the novel component. It is certain that the weight have been significantly decreased with the redesign, resulting in less material usage. However, this does not automatically reduce the environmental impact since the extraction and production of the respective materials differ. The team therefor recommend that Volvo CE perform a Life Cycle Assessment in order to determine if AM is a viable manufacturing method for the control unit when it comes to the environment.

With the recommendations aforementioned, the team would recommend Volvo CE to compare the performance benefits to the increased cost that the novel component results in. It is highly probable that the price for AM will greatly decrease with time, making the price of the novel component as cheap as, or cheaper than, the existing component in the near future. In that case, this concept could act as an example of the possibilities that come with AM. The team would also suggest to examine the possibilities to utilize AM for other components in Volvo CE's production as some components could benefit even more from AM. By other means, we would recommend Volvo CE to use this report as a basis for further evaluation of implementing AM in their production. The team believes that AM will become the future of manufacturing as it allows for more optimized components, and even if the control unit does not represent the most beneficial component to redesign, it is proven that the performance can be greatly increased with AM.

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# A

# Appendix 1

**Table A.1:** Existing component with manufacturing cost

| Existing component with manufacturing cost | | | | |
|---|---|---|---|---|
| Art. Nr | Definition | Price Part | Price Blank | Volvo Materal |
| 11430048 | Cover | kr | | VAC43100+KF |
| 11430461 | Cover | kr | | VAC43100+KF |
| 11430633 | Lubrication Valve Housing | kr | | VAC43100+KF |
| 17222494 | Gear Selector | kr | kr | AW6082+T6 |
| 17222539 | Housing | kr | kr | AW6082+T6 |
| 17222554 | Oil Distributor Plate | kr | kr | VAS6082+T6 |
| 17236391 | Gasket | kr | | Steel/rubber |
| 17236389 | Gasket | kr | | Steel/rubber |

# B

# Appendix 2

| Points of interest | Concepts | | |
|---|---|---|---|
| **How to design for the holes to the transmission** | A1 | A2 | A3 |
| **How to rearrange the valves** | B1 | B2 | B3 |
| **How to design the lubrication valve housing** | C1 | C2 | C3 |
| **How to design the main valve housing** | D1 | D2 | D3 |

**Figure B.1:** Concept 1(A1B1C1D1)

| Points of interest | Concepts | | |
|---|---|---|---|
| **How to design for the holes to the transmission** | A1 | A2 | A3 |
| **How to rearrange the valves** | B1 | B2 | B3 |
| **How to design the lubrication valve housing** | C1 | C2 | C3 |
| **How to design the main valve housing** | D1 | D2 | D3 |

**Figure B.2:** Concept 2(A1B1C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| **How to design for the holes to the transmission** | A1 | A2 | A3 |
| **How to rearrange the valves** | B1 | B2 | B3 |
| **How to design the lubrication valve housing** | C1 | C2 | C3 |
| **How to design the main valve housing** | D1 | D2 | D3 |

**Figure B.3:** Concept 3(A1B2C1D1)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.4:** Concept 4(A1B2C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.5:** Concept 5(A1B3C1D1)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.6:** Concept 6(A1B3C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.7:** Concept 7(A2B1C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.8:** Concept 8(A2B1C3D3)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.9:** Concept 9(A2B2C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.10:** Concept 10(A2B2C3D3)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.11:** Concept 11(A2B3C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.12:** Concept 12(A1B3C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.13:** Concept 13(A3B1C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.14:** Concept 14(A3B1C3D3)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.15:** Concept 15(A3B2C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.16:** Concept 16(A3B2C3D3)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.17:** Concept 17(A3B3C2D2)

| Points of interest | Concepts | | |
|---|---|---|---|
| How to design for the holes to the transmission | A1 | A2 | A3 |
| How to rearrange the valves | B1 | B2 | B3 |
| How to design the lubrication valve housing | C1 | C2 | C3 |
| How to design the main valve housing | D1 | D2 | D3 |

**Figure B.18:** Concept 18(A3B3C3D3)

# C

# Appendix 3

| Points of interest | Concept 1 | Concept 2 | Concept 3 | Concept 4 | Concept 5 | Concept 6 | Concept 7 | Concept 8 | Concept 9 | Concept 10 | Concept 11 | Concept 12 | Concept 13 | Concept 14 | Concept 15 | Concept 16 | Concept 17 | Concept 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ease of manufacturing | 1 | 3 | 1 | 2 | 1 | 2 | 4 | 3 | 4 | 3 | 2 | 3 | 3 | 2 | 4 | 3 | 2 | 1 |
| Cost/time | 4 | 6 | 4 | 4 | 6 | 4 | 8 | 6 | 6 | 4 | 4 | 4 | 6 | 6 | 6 | 4 | 2 | 4 |
| Performance | 4 | 6 | 6 | 4 | 4 | 4 | 6 | 6 | 6 | 2 | 2 | 2 | 6 | 4 | 6 | 4 | 6 | 4 |
| Total | 9 | 15 | 11 | 10 | 11 | 10 | 18 | 15 | 16 | 9 | 8 | 9 | 15 | 12 | 16 | 11 | 10 | 9 |

**Table C.1:** Structural concept elimination matrix

# D

# Appendix 4

**Concept 2**

Three setups are required for this concept to become completely finished. First, the base/printer plate is removed by sawing. After that, the flanges need face milling and the holes for the valves need to be threaded. The extent of the work the CNC machine would perform is considered small. Apart from the removal of the plate, the work needed is mainly finishing. During these operations, the amount of material removed is small, therefore, making for quick and simple operations.

The volume of this concept is the highest out of all the six final concepts, 1.10*10E-03 cubic meters. It is scored accordingly to this, with one point awarded. The reason for the volume to be this high is because for this concept, all the sub-concept parts are printed. The printing process leads to much higher material prices than the traditionally manufactured parts. There is an opportunity to improve the arrangement of the canals with the standing perpendicular valve housing along with the other valve housings printed onto the canals as the valves can be placed in more optimal places with this concept. On the other hand, compared with the polygonal valve housing, the main canal will be longer.

The overall performance of this concept will increase because the vertical valves will allow for a decreased canal length. The orientation of the valves can be optimized so that the oil flow can be as smooth as possible. Since the other parts of the concept do not regulate oil flow, it will not affect the performance.

Since this concept is mainly utilizing the flanges, the overall number of parts will decrease. The lubrication valve will also be printed directly on to the plate, further decreasing the number of parts. However, the only downfall comes from the fact that there will be a need for post machining for vertical valves. Since the number of parts decreased, this concept received the highest score.

**Concept 7**

For this concept there will be four different setups in the CNC machine. The plate is milled and holes are made in the first setup. The plate is then flipped and milled on the other side. These initial operations are performed the printing of the actual component to prepare the base plate. Finishing the holes for the valves is the last thing to be done, after the printing process. The extent of the operations is small since it is only finishing and drilling work that needs to be performed and the amount of material that is being removed during those is small.

The printed volume of this concept would be $0.96 \cdot 10^{-3}$ $m^3$ which is a medium sized volume. The given score for this sub-criterium is 2. Compared to Concept 2 the difference is the use of a base plate. The base plate is not manufactured using a 3D-printer and the price of it is significantly lower. The lubrication valve housing and main pressure valve housing are printed along with the rest of the component and therefore their volume is included in this calculation. They are however very small and do not affect this volume significantly. This concept also has the perpendicular standing valve housing and the integrated main pressure valve housing and lubrication valve housing. Because of this, it has the same pros and cons as Concept 2.

The performance of this concept will be increased due to the valve orientation. The baseplate and does not regulate the flow, therefore the performance will not be affected. The main pressure valve and lubrication valves will not directly affect the performance as whole.

The assembly time will increase slightly because the number of parts needed increases. Similar to concept 2, this concept will need extra machining for the vertical valves, due to support structures and inner canals. This leads to slightly a less desirable concept when scored against other concepts.

**Concept 8**
With the lubrication valve housing and main pressure valve housing bolted onto the base plate, the setups increase in number because a lot of work is needed on the valve housings. The total number of setups will be nine. The lubrication valve housing requires two setups and the main pressure valve housing requires three. Additionally, the same operations that would be performed on Concept 7 are needed for this concept as well because they both have the base plate sub-concept. The level of extent of the operations is medium. The operations themselves are relatively easy and only a small amount of material is removed with each setup but in correlation to the number of setups, the total of removed material will add up to a medium amount.

The volume would be 0.72*10E-03 cubic meters, which is categorized as medium. The standing perpendicular valve housing is what contributes to this volume as it is rather large. The standing perpendicular valve housing is used in this concept too. A difference with this concept is that the lubrication valve housing and main pressure valve housing will be bolted onto the base plate instead of being placed onto the canals. This makes the arrangement of canals more restricted and the score for this sub-criterium is lower than Concept 2 and Concept 7.

The overall performance of this concept is similar to the previous concepts because it incorporates the vertical valves for the oil flow. Having shortened canals increase the efficiency of the oil flow throughout the system. The scoring to this is similar to the previous concepts due to the fact that the only difference stems from the lubrication and main pressure valves being bolted into the baseplate.

Since this concept incorporates the main pressure valve and lubrication valve being bolted into the baseplate, the number of parts increase. The assembly therefore becomes more tedious. The need for machining is also required due to the valve orientation, hence why the scoring is similar to the previous concepts.

**Concept 9**
To finish this concept, four setups are needed. Two operations on the base plate will be needed. The surfaces need finishing and the holes to the transmission have to be drilled. The finishing work on the polygonal valve housing only needs one setup, and the finishing work on the lubrication valve housing and main pressure valve housing can be done in the same setup. The level of extent is low and classified as small. All parts of the component need finishing work but these are easily and quickly performed.

The volume of this concept is one of the lowest, 0.44*10E-03 cubic meters, and therefore given the highest score, 4, for this sub-criterium. The polygonal valve housing is designed with a very low volume which is beneficial in this evaluation. The redesigned valve housings which are printed onto the canals each only contribute with a small amount of volume. With the polygonal valve housing the main canal can be made shorter. This design aspect is a big improvement compared to the existing solution. However, the arrangement of the valves is much more restricted when compared to the standing perpendicular solution and the score for that sub-criterium is therefore lower.

The performance of this concept will be will increase slightly because the canals have less turns and a more symmetrical geometry compared to the original model. The flow would essentially be better in this concept. However, it is scored a bit lower because of the restrictions that the bolted main pressure valve brings. The canal connections would be further restricted.

The assembly of this product would be fairly simple, with the addition of the extra parts being needed. The polygon is easily printed and will not require extra machining to assemble with the other pats. The only necessary item is the extra bolts for the lubrication and main pressure valve. This leads to the concept scoring the highest when comparing assemblies to the other concepts.

**Concept 13**
Only two, or a maximum of three, setups are required for this concept. After printing, the printer plate would be reshaped and along with that, surface finishing is done. The valve housings would need one or two setups to be completely finished. Only three operations would be considered optimal, but on the downside, these they are very extensive because of the reshaping of the printer plate. A lot of material is needed to be removed and that is also more difficult and more time consuming than all other operations.

This concept is quite similar to Concept 7 and therefore it would also have same volume, 0.96*10E-03 cubic meters, and that volume is classified as medium. As for Concept 7, the standing perpendicular valve housing is what mostly contributes to the total volume here. For the length and arrangement of the canals the pros and cons are also the same as Concept 7 as the type of base plate used does not affect this sub-criterium.

The performance of this concept will rank similar to the previous concepts. This concept incorporates the use of the vertical valves, which can lead to higher performance values when compared to the original model. The other parts that are included with this concept will not affect the performance.

This concept incorporates printing directly onto the baseplate, which decreases the number of parts that are required. The redesigned lubrication and main pressure valves will be printed directly on the canals as well, further decreasing the number of parts needed. However, the need for machining from the vertical valve will make this assembly tedious.

**Concept 15**

Three to four setups in the CNC are needed to complete this concept. First, the printer plate is machined to the desired shape. The polygonal valve housing can be finished in one setup. The lubrication valve housing and main pressure valve housing would together need one or two finishing setups. With the reshaping of the printer plate, the operations are extensive because of the material removal. The valve housing requires finishing work that is easy to do, however, the amount of work is plentiful.

Like Concept 9, this concept would have a volume of 0.44*10E-03 cubic meters, and it is categorized as ”low” which gives it the score 4. It is also given the same score as Concept 9 for the other two sub-criteria; length of canals and arrangement of canals.

The performance will be better than the original concept, but similar to concepts 7 and 13. The redesigned of valves allow for a more symmetrical flow, leading to a more efficient oil flow. The other parts included with this concept will not affect the performance.

The assembly of this received a higher score because the parts will be printed directly onto the baseplate. The polygon design of the valves allow for an easy assembly due to the fact that extra machining will not be needed. In addition, the redesigned main pressure valve and lubrication valve will be printed onto the canals, which will make it easier when mounting on to the baseplate.

# E

# Appendix 5

<u>Assumptions made for this calculations</u>:

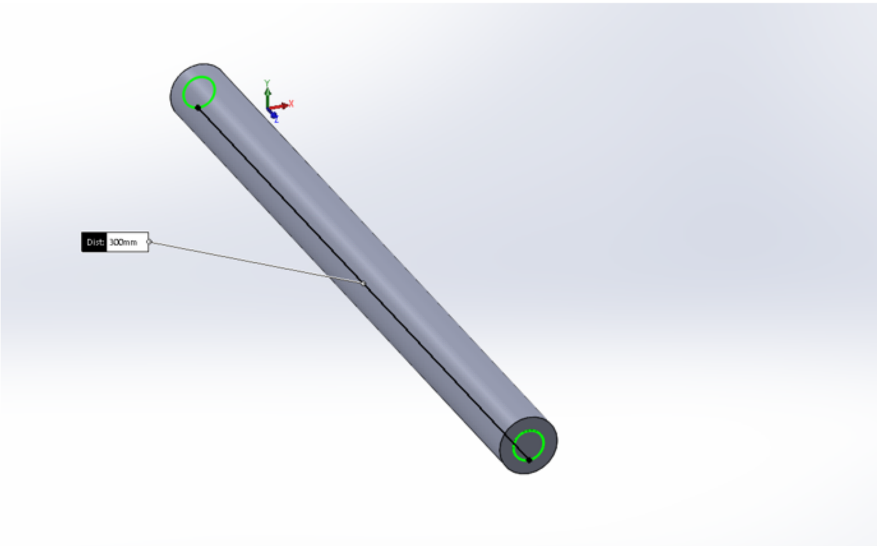
- Incompressible Flow
- Fully Developed
- Surface Roughness is zero across the length of the pipe

<u>Given information about the oil</u>:

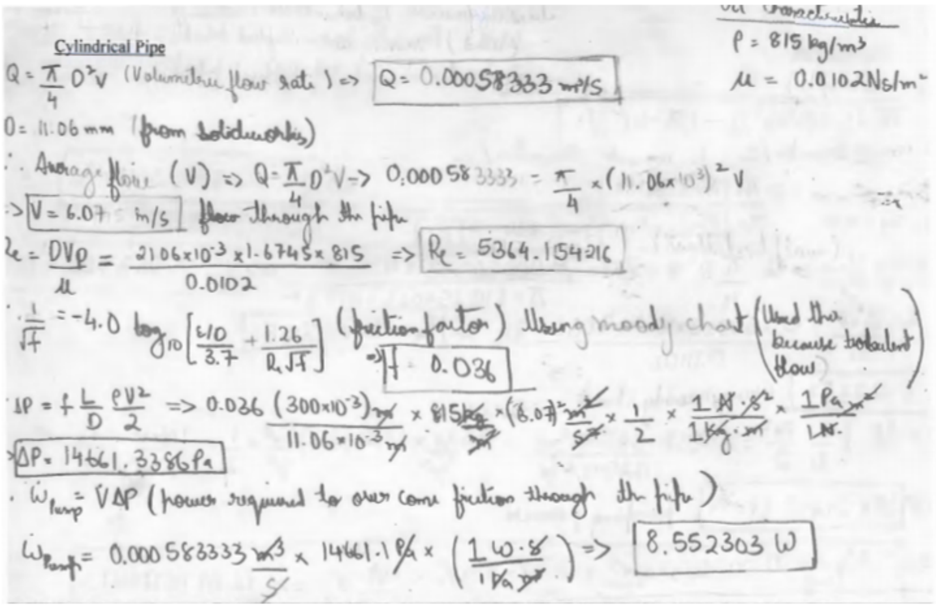
Density (r) – 815 $\frac{kg}{m^3}$

Dynamic Viscosity (m) - 0.0102 $\frac{N*s}{m^2}$

<u>Cylindrical Pipe</u>




Diameter of the pipe is 11.06 mm



Cylindrical Pipe

Oil characteristics

$\rho = 815\ kg/m^3$

$\mu = 0.0102\ Ns/m^2$

$Q = \frac{\pi}{4} D^2 V$ (Volumetric flow rate) => $\boxed{Q = 0.00058333\ m^3/s}$

$D = 11.06\ mm$ (from solidworks)

∴ Average flow (V) => $Q = \frac{\pi}{4} D^2 V$ -> $0.00058333 = \frac{\pi}{4} \times (11.06\times10^{-3})^2 V$

=> $\boxed{V = 6.07\ m/s}$ flow through the pipe

$Re = \frac{DV\rho}{\mu} = \frac{2106\times10^{-3} \times 1.6745 \times 815}{0.0102}$ => $\boxed{Re = 5364.154216}$

∴ $\frac{1}{\sqrt{f}} = -4.0 \log_{10}\left[\frac{\varepsilon/D}{3.7} + \frac{1.26}{Re\sqrt{f}}\right]$ (friction factor) Using moody chart (Used this because turbulent flow)

=> $\boxed{f = 0.036}$

$\Delta P = f \frac{L}{D} \frac{\rho V^2}{2}$ => $0.036 \frac{(300\times10^{-3})\cancel{m}}{11.06\times10^{-3}\cancel{m}} \times 815\frac{kg}{m^3} \times (6.07)^2 \frac{m^2}{s^2} \times \frac{1}{2} \times \frac{1\ N\cdot s^2}{1\ kg\cdot m} \times \frac{1\ Pa\ m^2}{1\ N}$

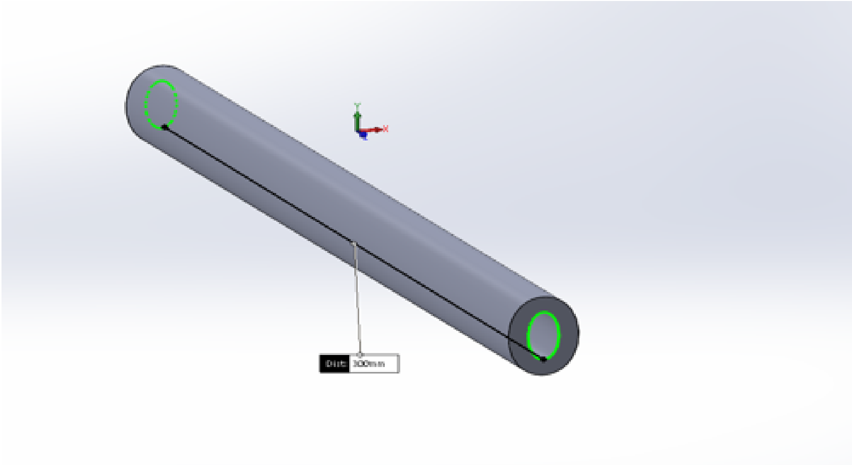
=> $\boxed{\Delta P = 14661.3386\ Pa}$

∴ $\dot{W}_{pump} = \dot{V}\Delta P$ (power required to over come friction through the pipe)

$\dot{W}_{pump} = 0.000583333 \frac{m^3}{s} \times 14661.1\ Pa \times \left(\frac{1\ W\cdot s}{1\ Pa\ m^3}\right)$ => $\boxed{8.552303\ W}$

**Figure E.1:** Calculations for pressure drop and pumping power

Ellipsoid Pipe:




Major Diameter: 15.28 mm

Minor Diameter: 8 mm

Surface Area from Solid Works = 96.05 mm²
Wetted Perimeter from Solid Works = 37.47 mm
(Hydraulic diameter of elliptical pipe)

Ellipsoid Pipe:

$$= \frac{4\times(\pi\times a\times b)}{\pi\times\sqrt{[(2\times(a^2+b^2)) - ((a-b)^2)/2]}}$$

a = major diameter/2 ; b = minor diameter/2

a = 7.64 mm

b = 4 mm

$$\Rightarrow \frac{4\times(\pi\times 7.64\times 4)}{\pi\times\sqrt{[2\times(7.64^2+4^2)) - ((7.64-4)^2/2)}} \Rightarrow \boxed{D_e = 10.254023\times 10^{-3}\,m}$$

Average flow $\Rightarrow Q = \frac{\pi}{4} D_e^2 V \Rightarrow V = \frac{0.00058333\times 4}{\pi\times(10.254023\times 10^{-3})^2} \Rightarrow \boxed{V = 7.063758\ m/s}$

$R_e = \frac{D_e V \rho}{\mu} = \frac{10.254023\times 10^{-3}\times 7.063\times 815}{0.0102} \Rightarrow \boxed{R_e = 5787.45}$

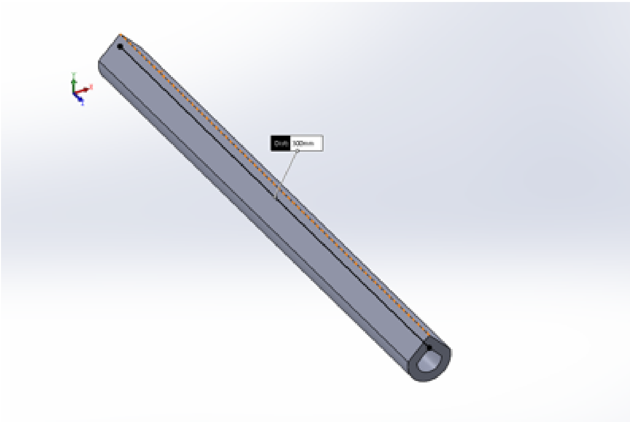
$\boxed{f = 0.0357}$ using moody chart

$> \Delta P = f \frac{L}{D}\frac{\rho v^2}{2} \Rightarrow 0.0357\ \frac{300\times 10^{-3}\ m}{10.25\times 10^{-3}\ m} \times 815\ \frac{kg}{m^3} \times (7.063758)^2 \frac{m^2}{s^2} \times \frac{1}{2} \times \frac{1\ N\times s^2}{m\cdot kg} \times \frac{Pa\ m^2}{1\ N}$

$> \boxed{\Delta P = 21248.89\ Pa}$ pumping power

$> \boxed{\therefore \dot{w}_{Pump} = 0.00058333\ \frac{m^3}{s} \times 21423.925\ Pa \times \frac{1\ W\cdot s}{1\ N\cdot m} \Rightarrow 12.39307772\ W}$

Tear Drop Pipe:



Tear Drop Pipe

Surface Area from SolidWorks = 105.11 mm$^2$

Wetted perimeter from Solidworks = 41.29 mm

$D_e = \dfrac{4 \times \text{Cross Section area}}{\text{Wetted Perimeter}}$

$\Rightarrow D_e = \dfrac{4 \times (105.11)}{41.29} \Rightarrow \boxed{D_e = 10.1826 \times 10^{-3}\,m}$

Pumping flow $Q = \dfrac{\pi}{4} D_e^2 V \Rightarrow V = \dfrac{0.00058333 \times 4}{\pi \times (10.1826 \times 10^{-3})^2} \Rightarrow \boxed{V = 7.163199\ m/s}$

$Re = \dfrac{D_e V \rho}{\mu} = \dfrac{11.9263 \times 10^{-3} \times 7.163199 \times 815}{0.0102} \Rightarrow \boxed{6826.061283}$

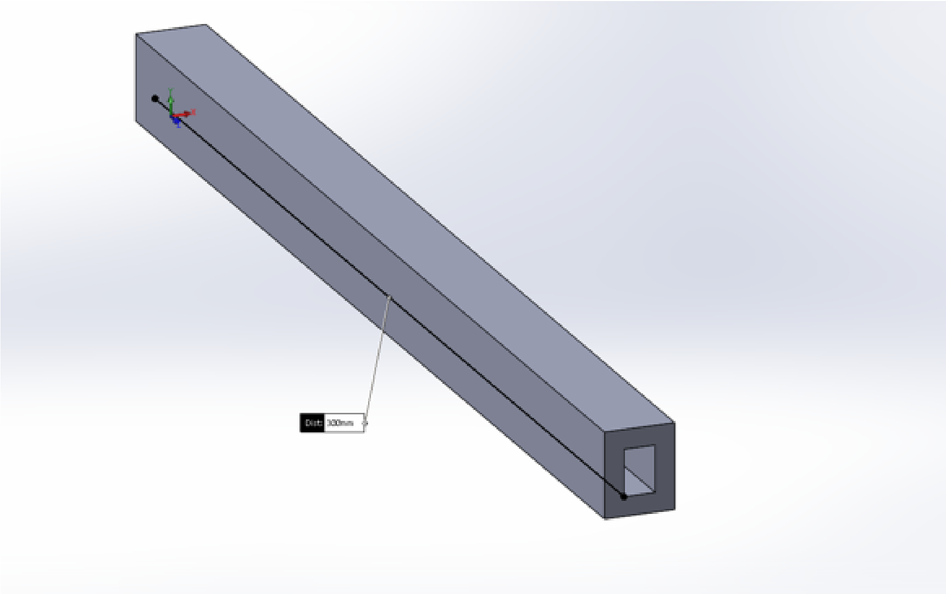
$\boxed{f = 0.035}$ (from moody chart)

$\Rightarrow \Delta P = f \dfrac{L}{D} \dfrac{\rho V^2}{2} \Rightarrow 0.035 \times \dfrac{300 \times 10^{-3}\,m}{10.1826 \times 10^{-3}\,m} \times 815\,\dfrac{kg}{m^3} \times (5.22171)^2 \dfrac{m^2}{s^2} \times \dfrac{1}{2} \times \dfrac{1\,N\,s^2}{m\,kg} \times \dfrac{Pa\,m^2}{1\,N}$

$\Rightarrow \boxed{\Delta P = 22919.67601\ Pa}$

$\dot{W}_{Pump1} = \dot{V} \Delta P = 0.00058333\,\dfrac{m^3}{s} \times 22914.67601 = \boxed{13.366\ W}$

Rectangular Pipe (Current Design):




ectangular Pipe :

Cross Sectional area from SW = 101.85 mm$^2$

Perimeter (wetted) from SW = 41.15

$$D_e = 4 \times \frac{\text{Cross Sectional area}}{\text{Wetted Perimeter}}$$

$$\therefore D_e \Rightarrow \frac{4(101.85)}{2[41.29]} \Rightarrow \boxed{D_e = 9.9003 \times 10^{-3}\,m}$$

Average flow $\Rightarrow Q = \frac{\pi}{4} D_e^2 V \Rightarrow \frac{0.000583333 \times 4}{\pi \times (9.26315 \times 10^{-3})^2} \Rightarrow \boxed{V = 7.5775\ m/s}$

$$= \frac{D_e V \rho}{u} = \frac{9.26315 \times 10^{-3} \times 8.655 \times 815}{0.0102} \Rightarrow \boxed{R_e = 5450.9303}$$

using moody chart ; $\boxed{f = 0.035}$ (depends on reynolds number)

$$= f \frac{L}{D} \frac{\rho V^2}{2} \Rightarrow 0.036 \times \frac{(300 \times 10^{-3})\,\cancel{m}}{9.26315 \times 10^{-3}\,\cancel{m}} \times 815 \frac{\cancel{kg}}{\cancel{m^3}} \times (8.655)^2 \frac{\cancel{m^2}}{\cancel{s^2}} \times \frac{1}{2} \times 1 \frac{\cancel{N} \cdot \cancel{s^2}}{\cancel{kg} \cdot \cancel{m}} \times \frac{1\,Pa\,\cancel{m^2}}{1\,\cancel{N}}$$

$$\boxed{\Delta P = 24815.3524\ Pa}$$

$$\boxed{\therefore \dot{W}_{Pump} = 0.0005833 \times 71179.80796 \Rightarrow 14.47553\ W}$$

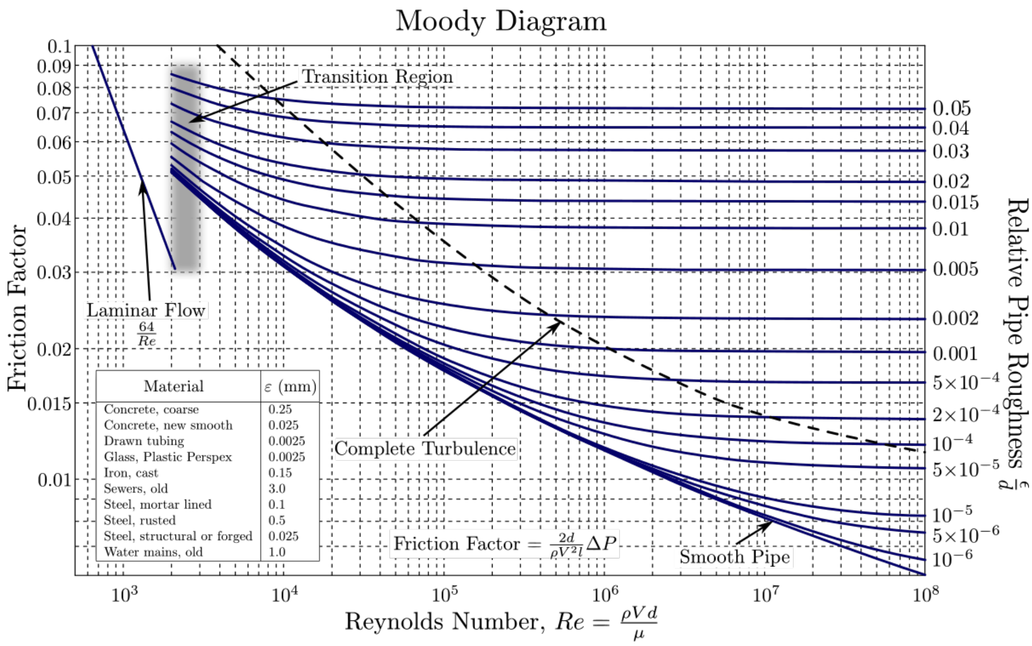



**Figure E.2:** Moody Chart used for friction factor [8]