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3D Printed Oil Block

3D Concept and Cleanliness Study

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1 INTRODUCTION

1.1 Aim of the Thesis

The aim of the thesis is to create a concept for 3D-printed oil block utilizing the design freedoms and advantages gained from additive manufacturing concerning shape, weight and maintainability. The oil block needs to fit in the engine where the current one does not. The aim is also to improve the performance of the current component or at least keep it the same and to improve the maintainability of the part. In addition, a cost comparison between the traditionally manufactured part and the 3D printed part is to be made.

Fem simulations and flow properties of the parts will also be compared. The oil pressure changes, and flow speeds are the values that are compared between old and new design. The mass of the new concept and the part that is in use currently will be compared to see how much weight reduction there is. The maximum dimensions of the parts will be compared to see the difference in size.

The research aims to determine whether the cleanliness of metal-printed parts meets Wärtsilä's requirements regarding the cleanliness of components in contact with oil. Additionally, it will be investigated which cleaning methods would be wise to use for these kinds of parts.

1.2 Expected Results

The concept of 3D- Printed oil block should have gone through iteration rounds by the end of March. The part does not need to be ready for manufacturing at this point.

Also, the cost, mass and flow comparison should be made by the end of March comparing the current part to the new concept.

Oil channel cleanliness study should be done by the second week of April. It should also be valuated if the part meets Wärtsilä's cleanliness requirements. The test print and the surface analysis should be done by the first week of April.

1.3 About the Company

The commissioning party for the thesis is Wärtsilä Oy, which is a global leader in smart technologies and complete lifecycle solutions for the marine and energy markets. With strong focus on innovation and sustainability. Wärtsilä provides advanced solutions that enhance the efficiency and environmental performance of vessels and power plants worldwide.

The oil block that this project is focused on is from the Wärtsilä 9L W25 engine. The engine faces challenges in accommodating a traditionally manufactured oil block where 3D printing might provide a solution by reducing the size or adjusting the shape of the component to make it fit in the required space.

2 CONCEPT DESIGN PRECAUTIONS

2.1 Figuring out the Design Limiting Factors

In the beginning of the design process, the limitations of the part needed to be determined. This was done to help design the concept and avoid misunderstandings.

The limitations were figured by discussing with Wärtsilä's 3D printing expert, the thesis supervisor and other experts that know the limitations and function of the current part. This was done by arranging a kick-off meeting between the author, the supervisors of this thesis and Wärtsilä's experts.

2.1.1 Material

Material for the new oil block was discussed and chosen in the thesis kick-off meeting. When considering materials for 3D printing, it is necessary to think about how different materials affect printing process. For the intended purpose of the part, the material was chosen to be 316L stainless steel for its corrosion resistance and overall strength [1].

With stainless steel there are some limitations of which printers would be available for the project. Wärtsilä and its suppliers have printers that can print stainless steel but the size of the part that is able to be printed in one piece is smaller than with some other materials. [2]

2.1.2 Dimensions

As said previously the dimensions of the part are limited to the printers available to Wärtsilä's use. The maximum dimensions of the part are 240 mm x 240 mm x 320 mm. [2]

The part would preferably be smaller than the current part or the same size at least so it should fit in the required dimension range.

2.1.3 Interfaces between Parts

During the kick-off meeting, it became apparent that there is one interface between parts that cannot be changed. This interface is critical for the part and that is the key point for the concept design process, too. The interfaces are between oil block and manifold (Figure 1).

Other interfaces on the part are free to be changed to whatever is best for the oil block design.

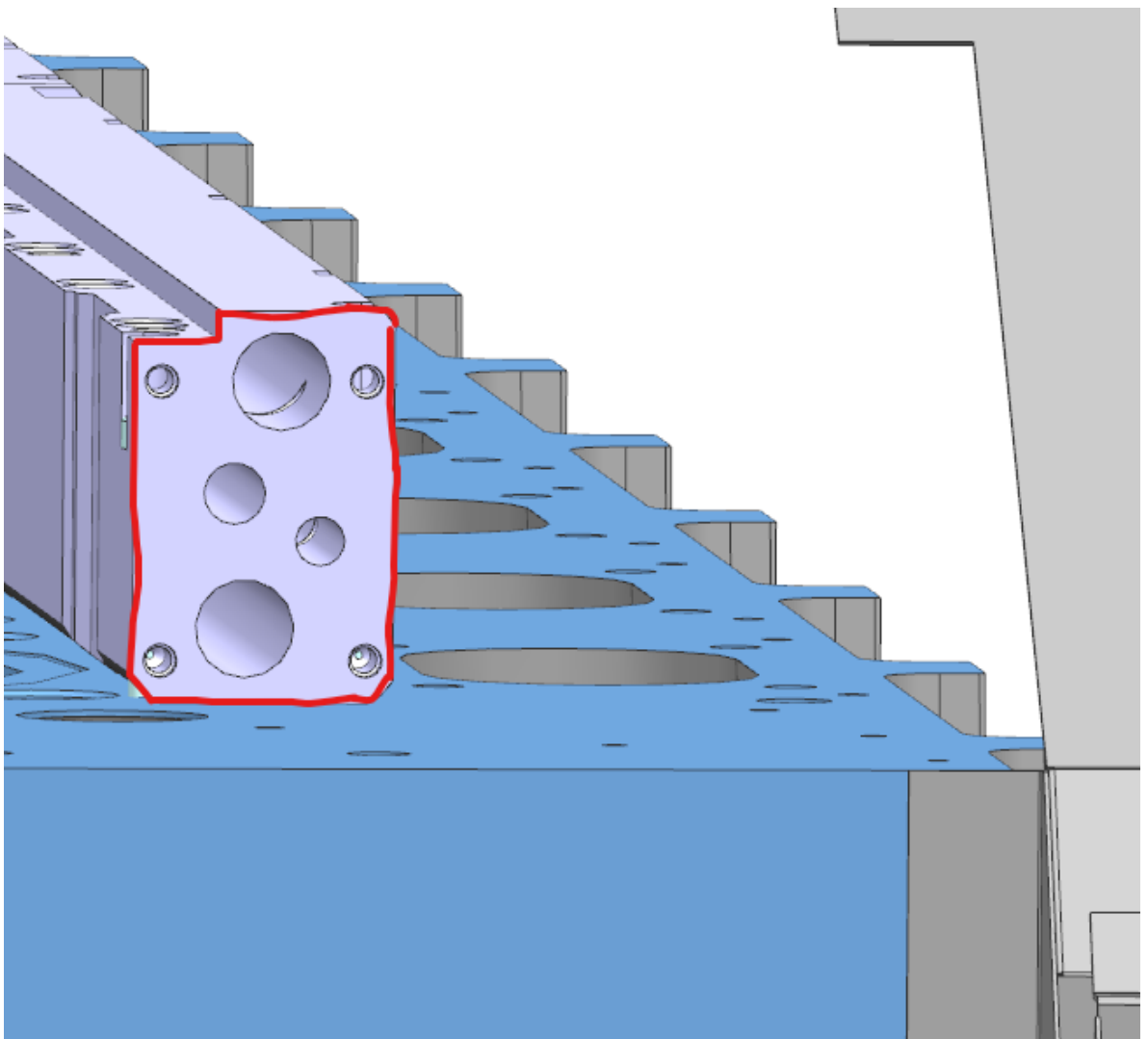


Figure 1. Interface between manifold and the oil block.

2.1.4 Maintainability and Manufacturing

Some other points that became apparent in the kick-off meeting was that maintenance and manufacturing should be kept in mind while designing the concept.

During maintenance the **VIC - solenoid and pressure sensors** should be removable without removing the oil block itself [3].

It was advised that the important surfaces on the part that need to be machined could be done with as little different attaching positions as possible.

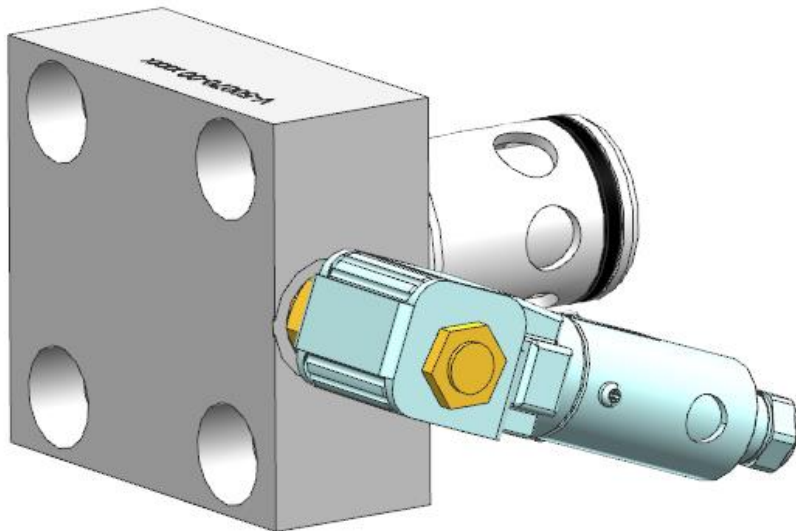


Figure 2. VIC - solenoid.

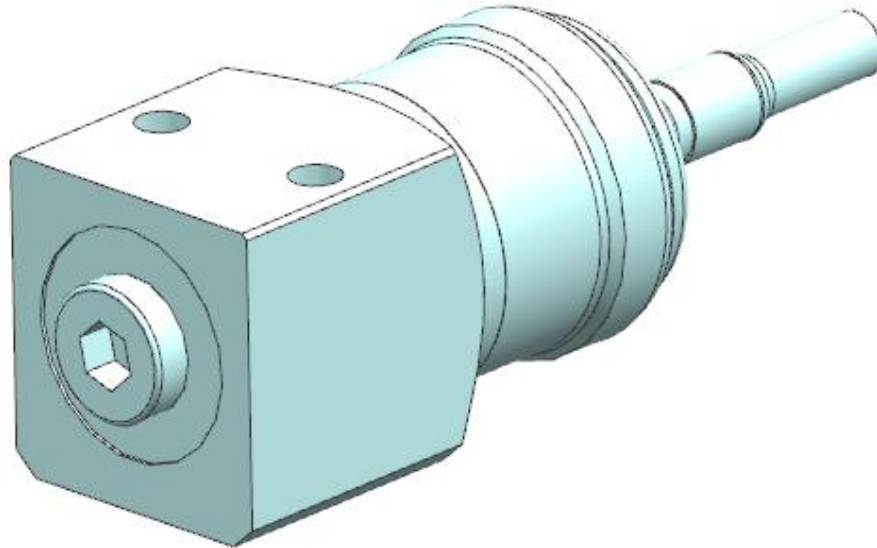


Figure 3. Pressure sensor.

2.1.5 Forces Affecting the Part

Before starting the design process, the forces and pressure that affect the part should be known and considered when designing the part.

The pressure of oil in the engine is separated to two different classes, high pressure and low pressure. In this case the oil in the block is low pressure, to be exact while in use approximately 8 bars maximum. The pressure which the part should withstand in testing is 12 bars and that value is what was used in simulations, too. [3; 4]

Forces that affect the part are the weight of the other components attached to the block. During the design, the forces need to be understood correctly in order to design a working concept and add some supports and material where it is needed.

2.2 Follow -up

During the kick-off meeting it, was decided that a weekly follow-up meeting would be arranged where the current situation of the thesis would be discussed. At the end of every meeting, the experts could give tips and thoughts on how to move forward.

When the design process starts, it is valuable information to get experts' thoughts about the concept and how to improve it since they have a lot of combined experience about different parts and design aspects.

3 CONCEPT DESIGN TIMELINE

3.1 Beginning

After the base line limitations were set in the design precautions part, the design process could begin. First, a copy from the 9L W25 engine assembly was created. This is what is called “help assembly” which is basically an assembly that helps with the design process. This was done by removing/hiding everything else from the assembly except the parts surrounding the oil block because these would be the parts that could limit the parts size and shape. [3]

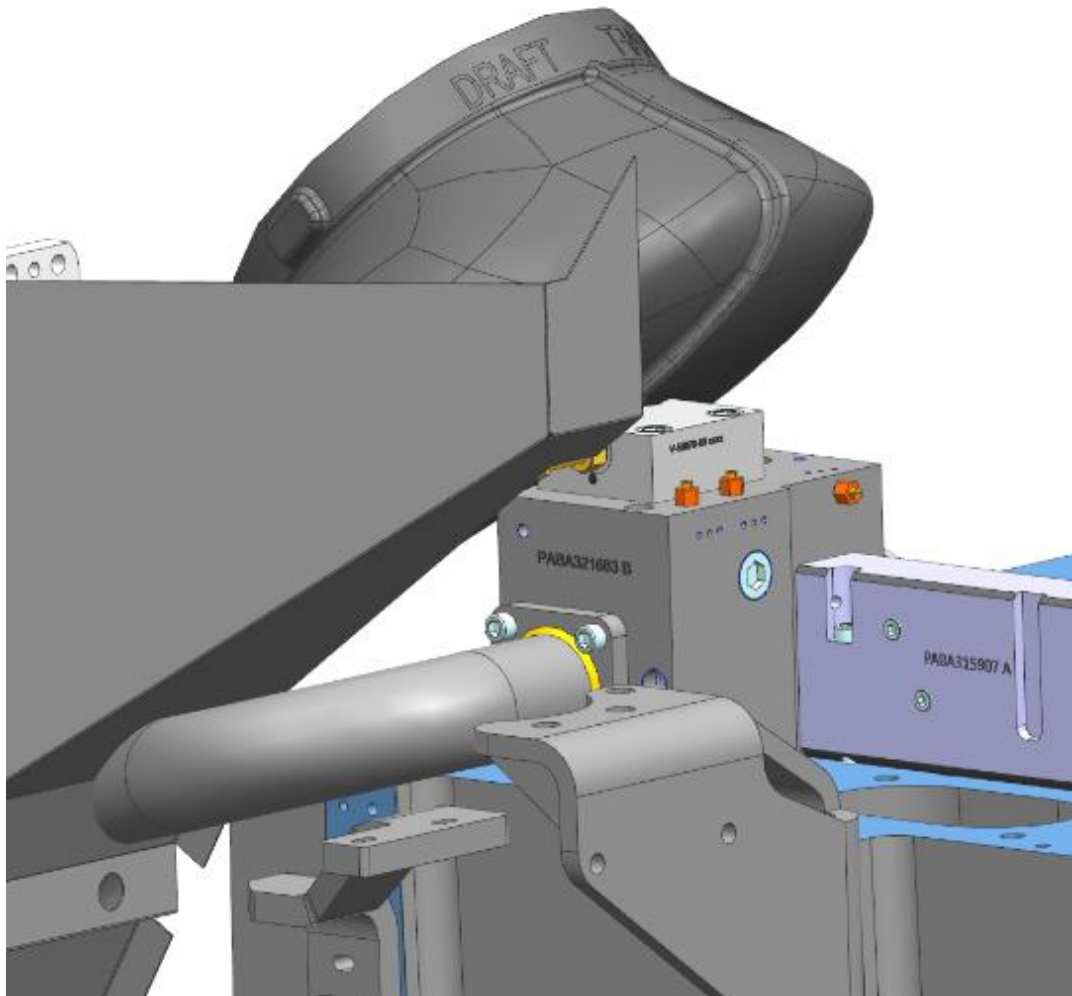


Figure 4. Help assembly with the current oil block that also shows the interference between current block and duct (part 1).

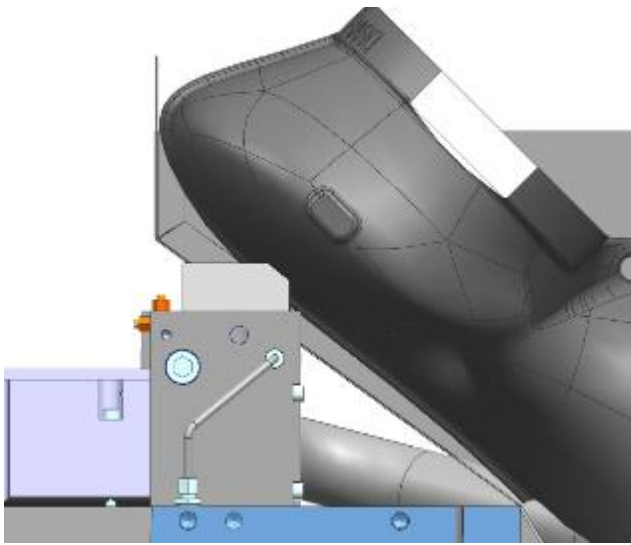


Figure 5. Help assembly with the current oil block that also shows the interference between current block and duct (part 2).

After the help assembly was created, it was important to understand how the oil flows in the part and which channels are connected. For this, an oil diagram was created (Figure 6) according to the flow result charts received from a senior engine expert. It shows how the oil flows in different channels and how much flow volume is in each channel. [5]

Oil diagram



Oil in red (300 l/min), booster oil in and out orange (40 l/min), oil in and out VIC main valve green (106 l/min), oil to turbo blue (102 l/min), oil to LISC black (4.5 l/min), VIC main valve drain oil yellow, Left over oil from oil in dark blue.

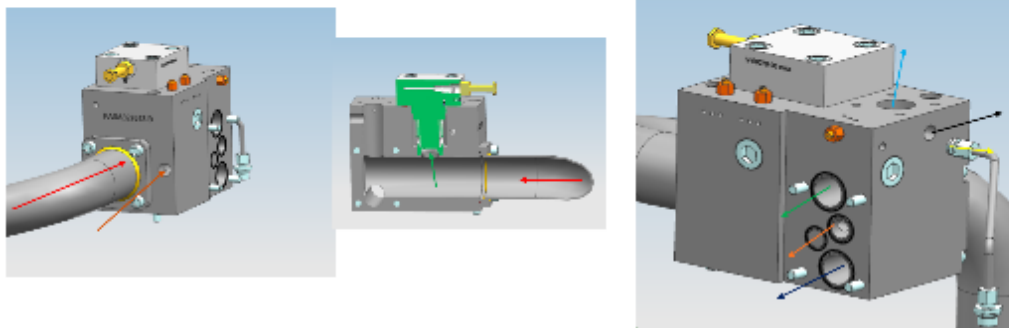


Figure 6. Oil diagram.

3.1.1 Placing Important Components

After the help assembly and oil diagram were created, it was time to start placing important components in the help assembly. These include the VIC – solenoid and the main oil inlet pipe. The oil pressure sensors are small enough to be placed later during the design process.

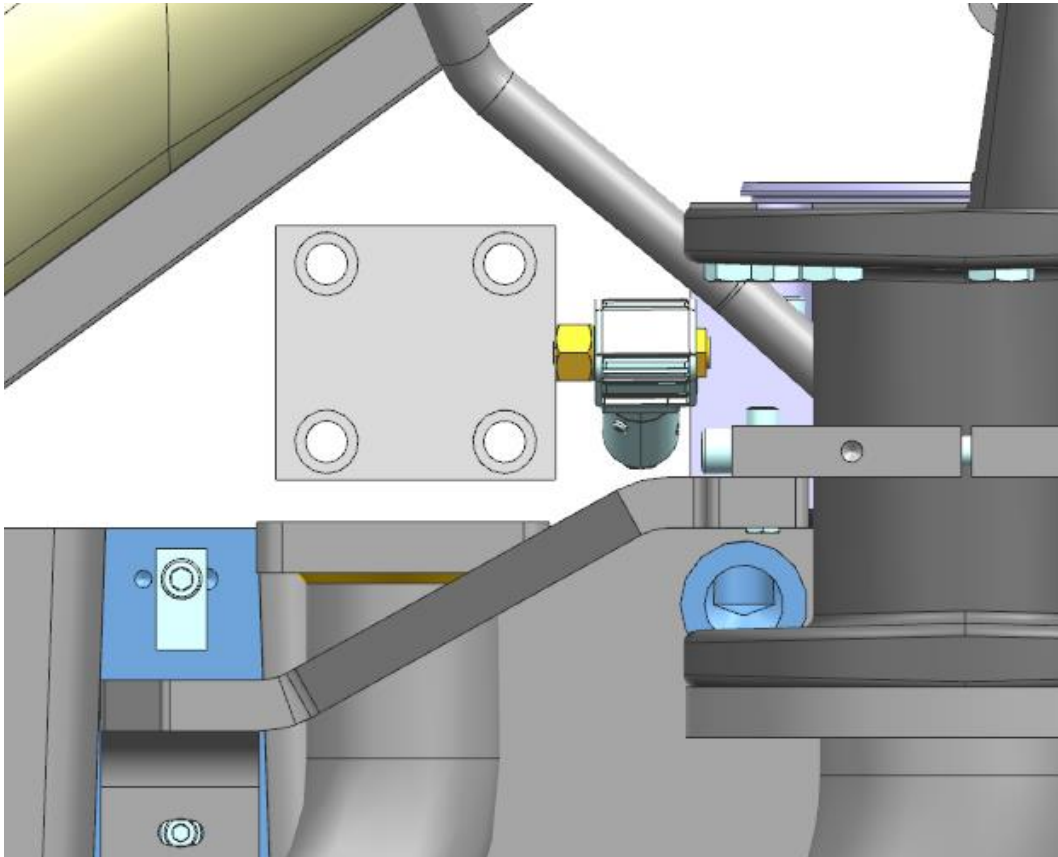


Figure 7. Placing VIC – solenoid and main oil inlet pipe.

It is important to keep in mind that the components need to be removable separately from the oil block, so there needs to be enough space around them. The ease of assembly needs to be considered too.

3.1.2 Creating the Part

The part was created using NX's new model command. After that the geometry of important components and the interface between manifold and the oil block was linked to the newly created part using the WAVE geometry linker. This command

copies the geometry of a chosen part to the file which then can be used to guide the design. These links were used to place the oil channels start and end positions.

3.2 Channel Design Process

The channels were designed so that the insides of the channels were modelled. The outer shell was created later by offsetting the faces. To get the channels hollow in the end, the inner parts of the channels were subtracted from the offset faces.

There were some limitations about the channel shapes that were dependent on which printer we could use for the project. These limitations only apply if the part needs to be printed without supports. In this case, the number of supports need to be minimized because of complex geometry which would make removing the supports rather time consuming and difficult.

After the components were placed in the first concept, it became apparent that it would not be possible to print the part with Wärtsilä's printer. That is why channels bigger than 10 mm in diameter needed to be a droplet shape instead of round [2]. This meant that almost every channel on the part needed to be a droplet shape. If the part could be printed with Wärtsilä's printer then the channels could be shaped round for up to 50 mm in diameter [2].

3.2.1 Sketches

Multiple datum CSYS were created to place the crosscut sketches for the channels. They were created by choosing center points of the channels from the WAVE linked geometries, then just moving them further away to make room for the shape to change from the droplet shape to round that is in the flanges (Figure 8).

Using datum CSYS makes changing the paths of the channels easier later if they need to be adjusted.

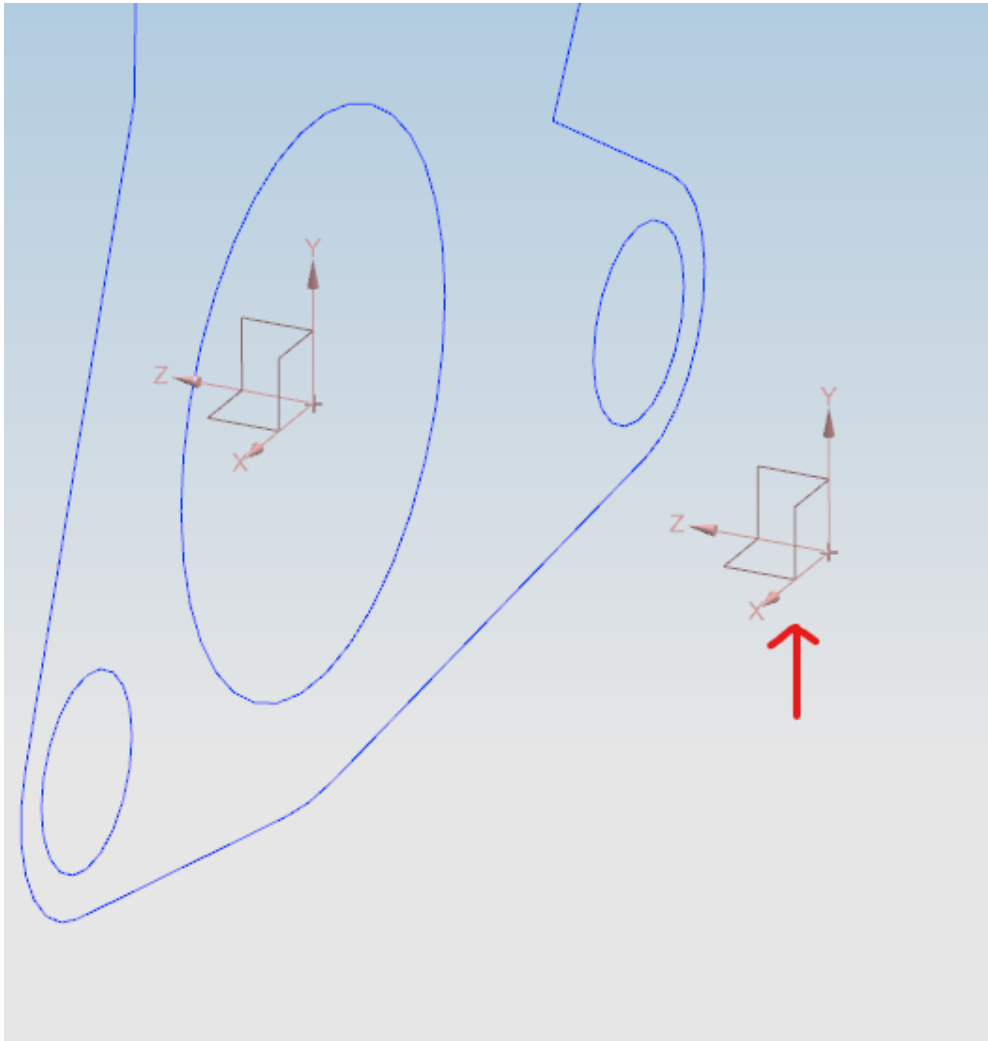


Figure 8. Datum CSYS moved from the center point of WAVE linked geometry.

After that the sketches were created using the planes of datum CSYS. The droplet shape had some limitations set by the printing method (LPBF). Those limitations were that the top radius had to be 1 mm and the angle of droplet sides had to be 40 degrees [6]. These limitations were to ensure that the print would be successful without supports in the channels.

The size of bottom radius was free to be changed to whatever needed to get a right size crosscut area for the channel.

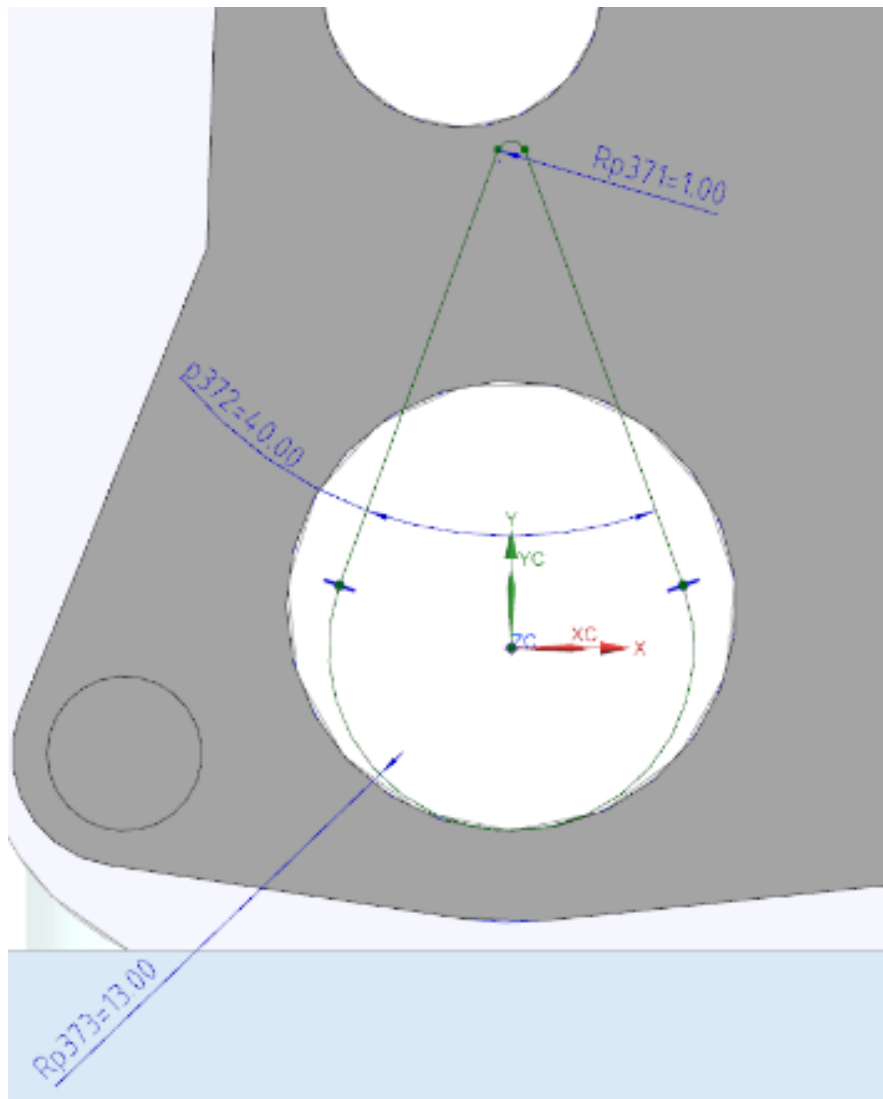


Figure 9. Sketch of droplet shape that is used in channels. The bottom radius (13mm) in the picture is free to be changed.

3.2.2 Combined Curve

To get the channels to flow smoothly and fit in the required space, the channels had to be converted to 3D.

This was done by a combined curve tool. The tool works by sketching curves on two different planes and then combining them to get a 3D sketch which then is used to guide the path of the channel. The curves used in the combined curve should both have the same start and end points so that the result has correct start and end points.

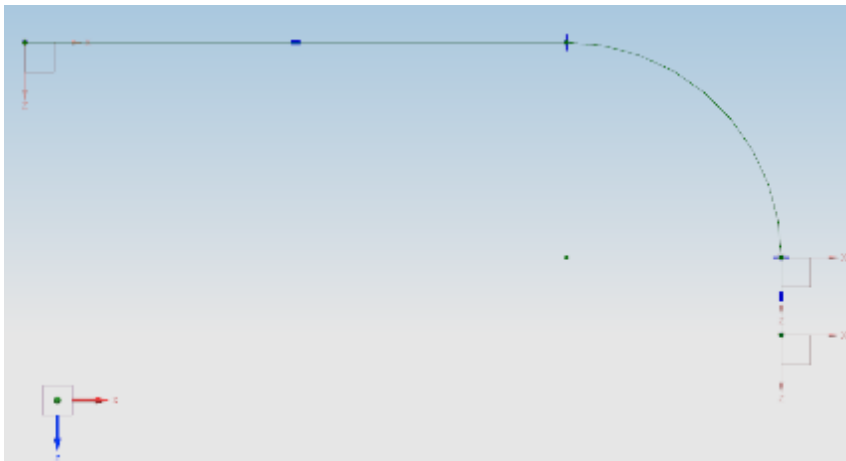


Figure 10. 1/ 2 Sketches used in combined curve.

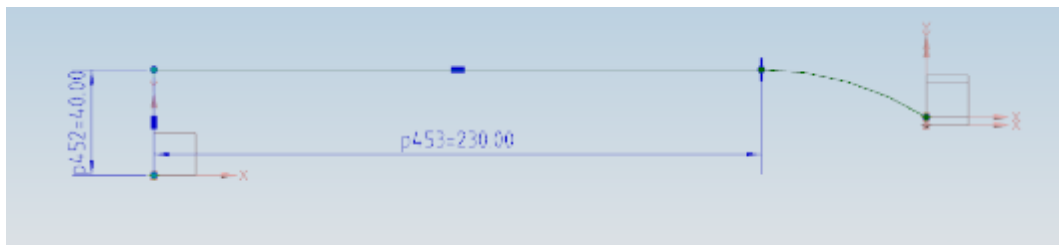


Figure 11. 2/ 2 Sketches used in combined curve.

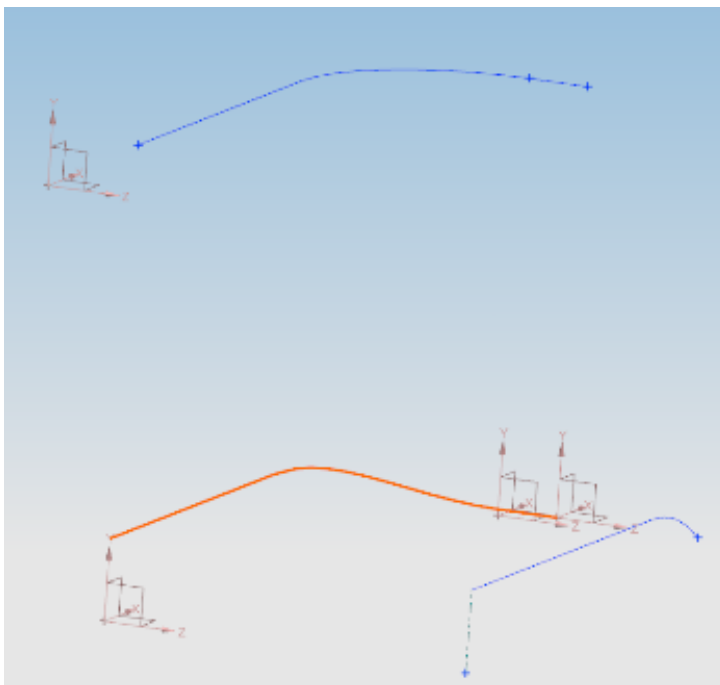


Figure 12. 3D Combined curve made from two separate curves. (Combined curve in orange and the component curves in blue).

3.2.3 Swept

To get the geometry between the crosscut sketches a swept command was used. For swept to work there needs to be sections which in this case are the crosscut sketches and guide which is our combined curve.

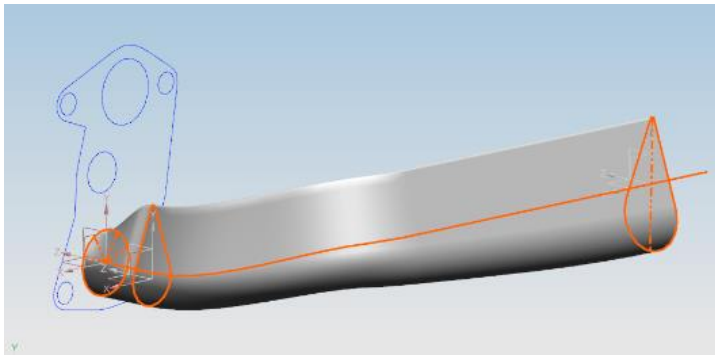


Figure 13. Swept with the guide and sections highlighted.

The result of swept is the inside geometry of the oil channels in the oil block.

3.3 Flanges, Screws and Tools

The flanges were made by linking the geometry of corresponding counterpart, meaning, the face from the VIC – solenoid, the face from the main oil pipe flange and the face from the manifold. The supporting flange that is against the engine block is sketched separately using the datum CSYS. After the sketch was done and the faces linked, the flanges were extruded.

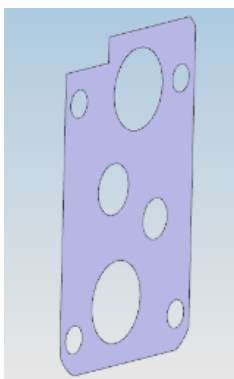


Figure 14. WAVE linked face of manifold.

During the design process, it must be considered that the screws fit and that there is enough space for tools to attach the part. So, the tools and screws were imported to the part to check if they fit and can be used.

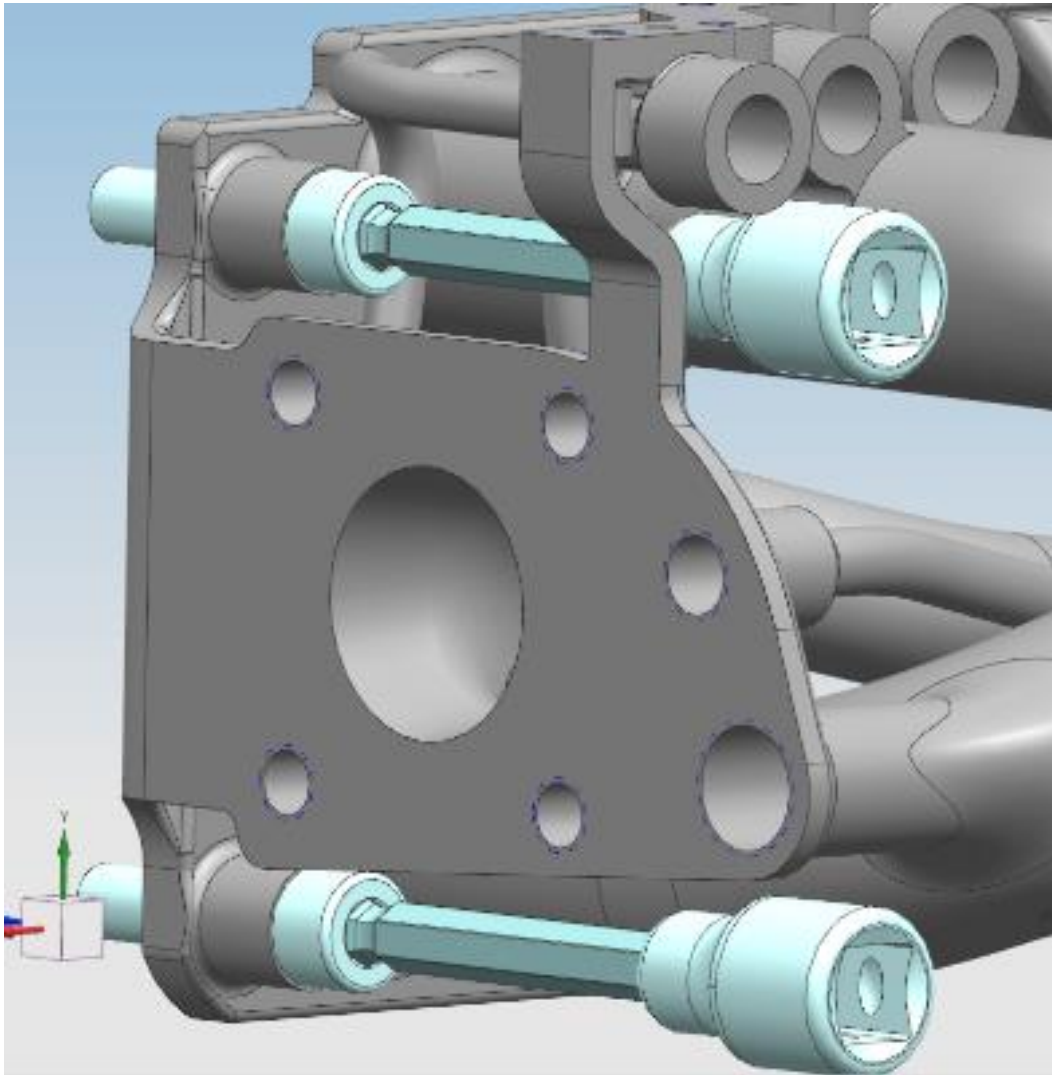


Figure 15. Checking that tools and screws fit.

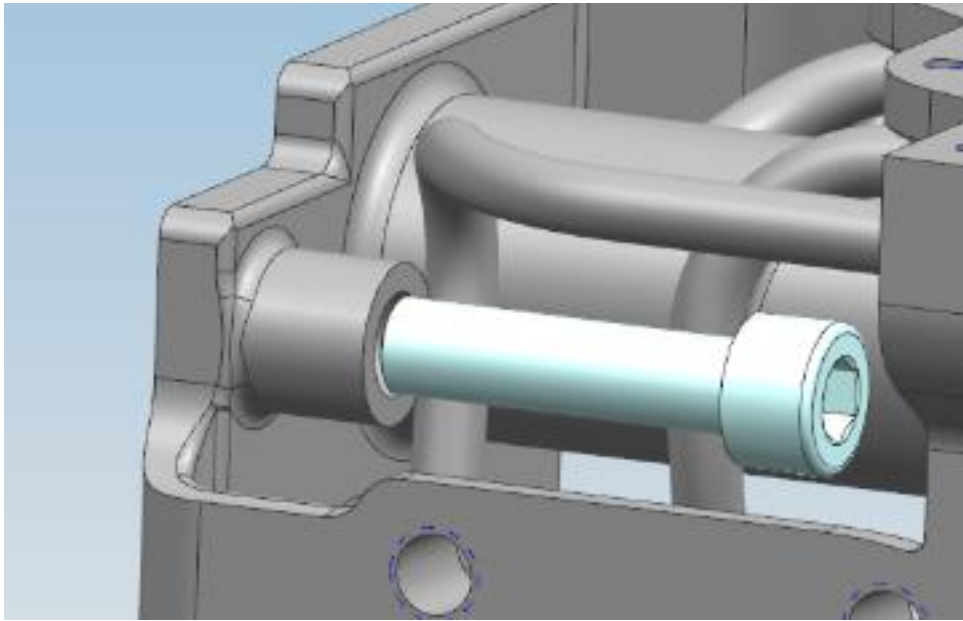


Figure 16. Checking that screws can be put in their holes.

3.4 Placement of Pressure Sensors

Pressure sensors have a few limitations which are that they need to fit the part, the cables that route into them need to have enough space to bend and pressure sensors need to be removable from the part without removing the block.

The sensor placement was discussed with Wärtsilä's automation expert and he tested to route the cables to see if there is enough space for bends.

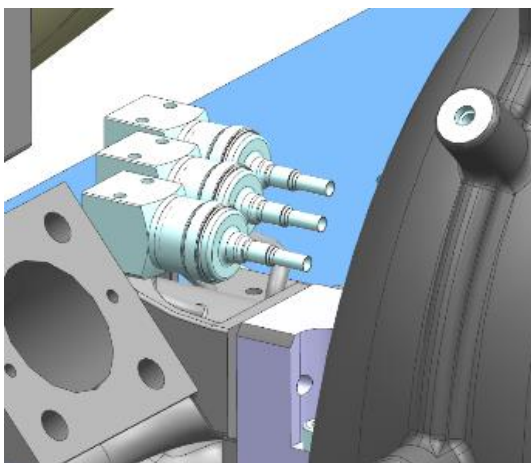


Figure 17. Placing pressure sensors so that they are removable from the part and that the cables have enough space to be routed.

3.5 First Concept

The first concept of 3D printable oil block was created using previous work methods. It met the limitations of removable VIC – solenoid and pressure sensors.

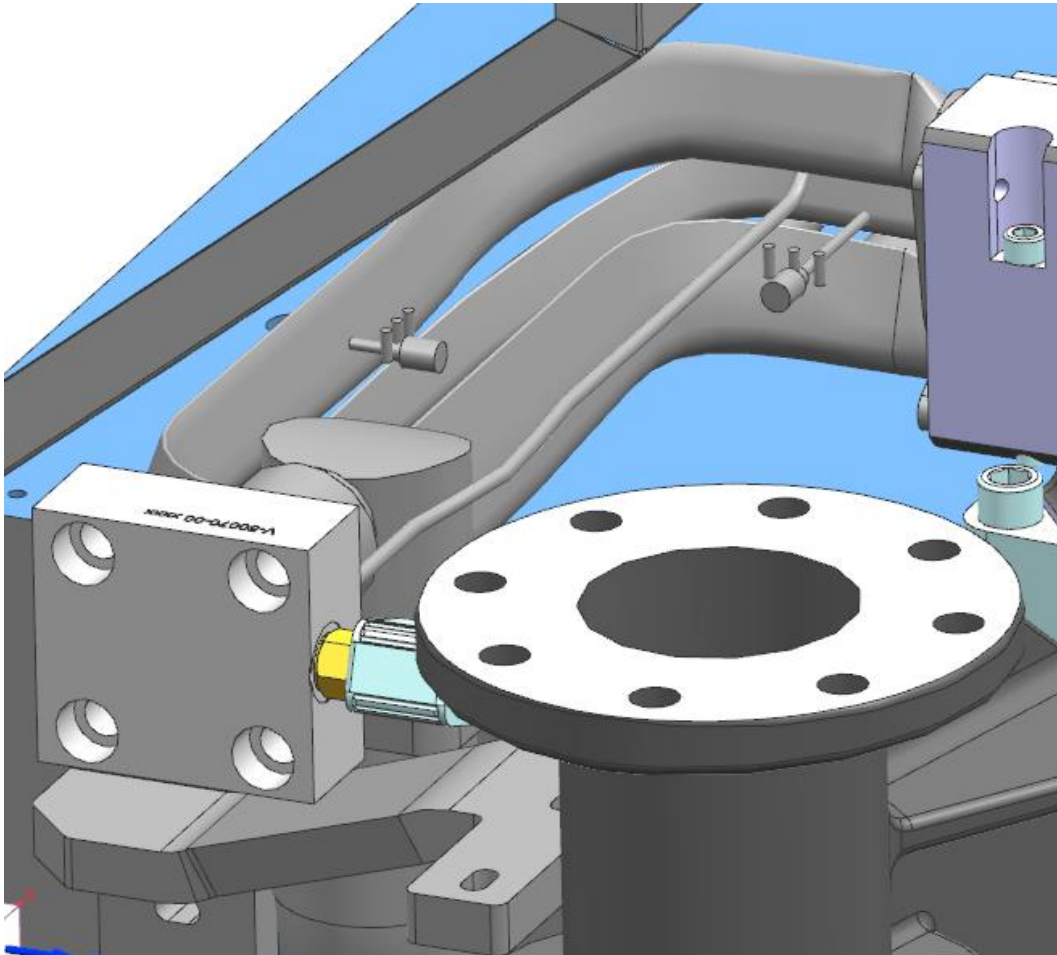


Figure 18. First concept in help assembly.

After discussing with Wärtsilä's experts, it was decided to try to make the design smaller since it was too big and bulky. It did not take advantage of the freedom that comes with 3D printing and it would be hard to get manufactured in Finland, since it cannot be printed with Wärtsilä's own printer and the suppliers of Wärtsilä would have trouble printing part so big, too. So, this concept was left unfinished.

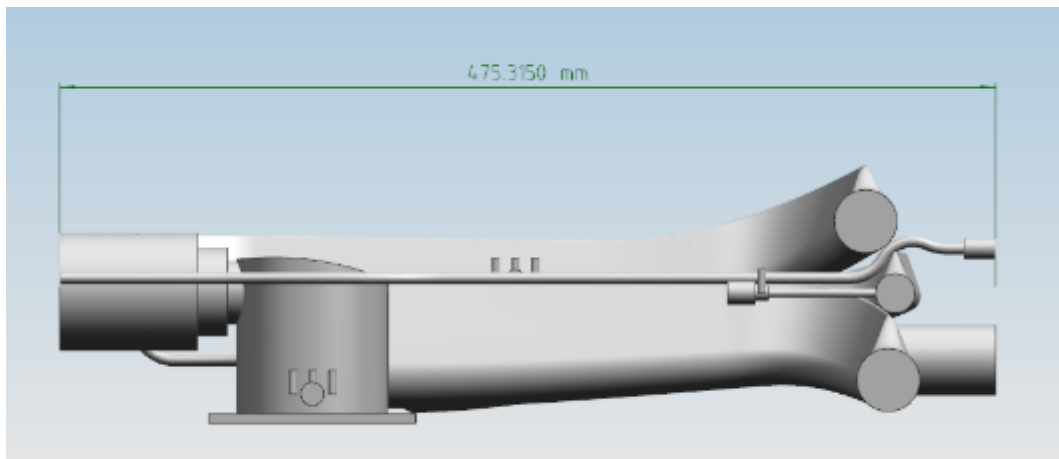


Figure 19. Length dimension of the first concept to show how big the part was.

This issue was due to poor placement of the VIC – solenoid and the main oil inlet pipe which led to part being too long.

3.6 Second Concept

After the first concept was left unfinished, the design process started all over again. This time the VIC – solenoid and the main oil inlet pipe placement was done more carefully. This ended up in finding a much better position for the VIC – solenoid and main oil inlet pipe (Figure 20).

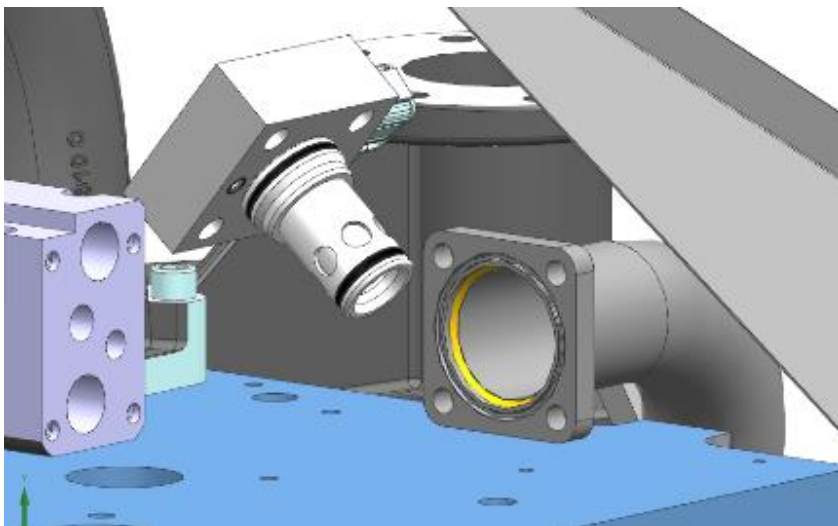


Figure 20. Position of VIC- solenoid and main oil inlet pipe in second concept.

The making of the second concept went considerably faster and smoother due to learning the right work methods and how to use the different commands more effectively.

Due to these improvements ,the second concept was a lot more compact and took advantage of 3D printing better. It was decided to continue developing this concept further.

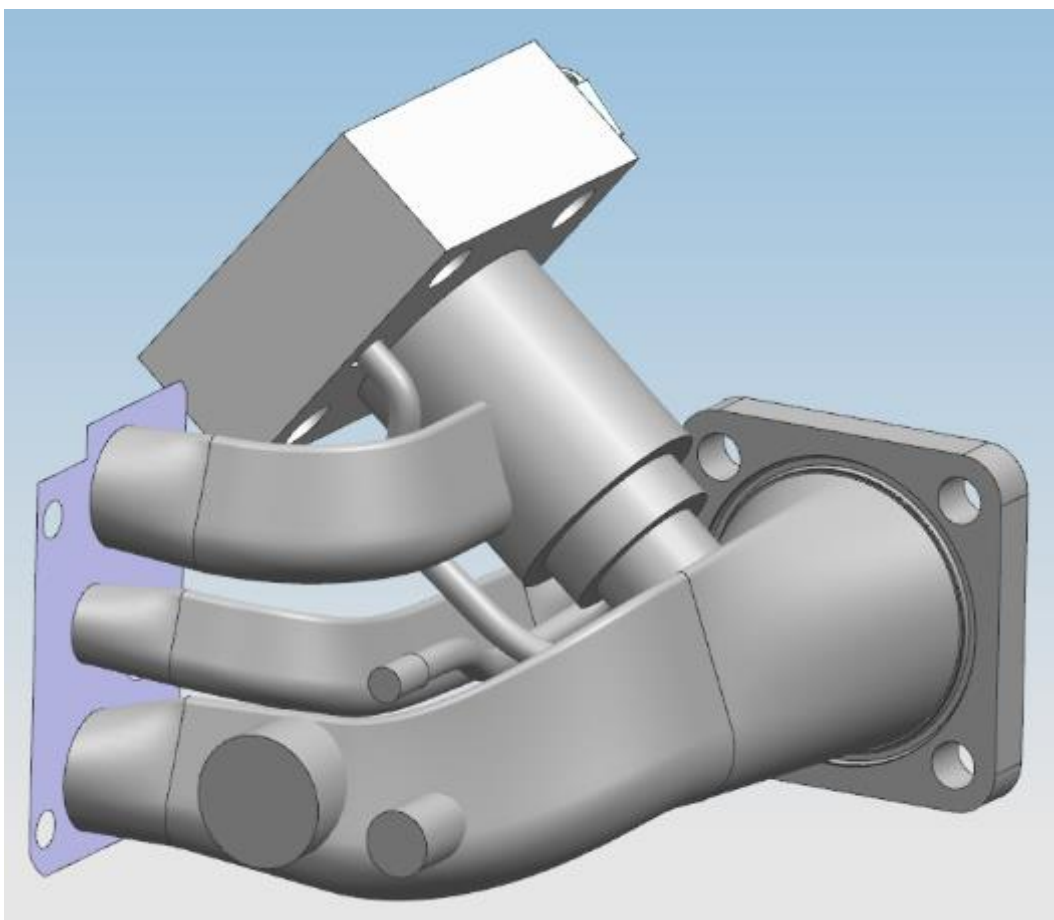


Figure 21. Second concept.

It was so much smaller that it could be printed with Wärtsilä's own printer. This meant that the channels on the block could be round and not shaped like droplets [2].

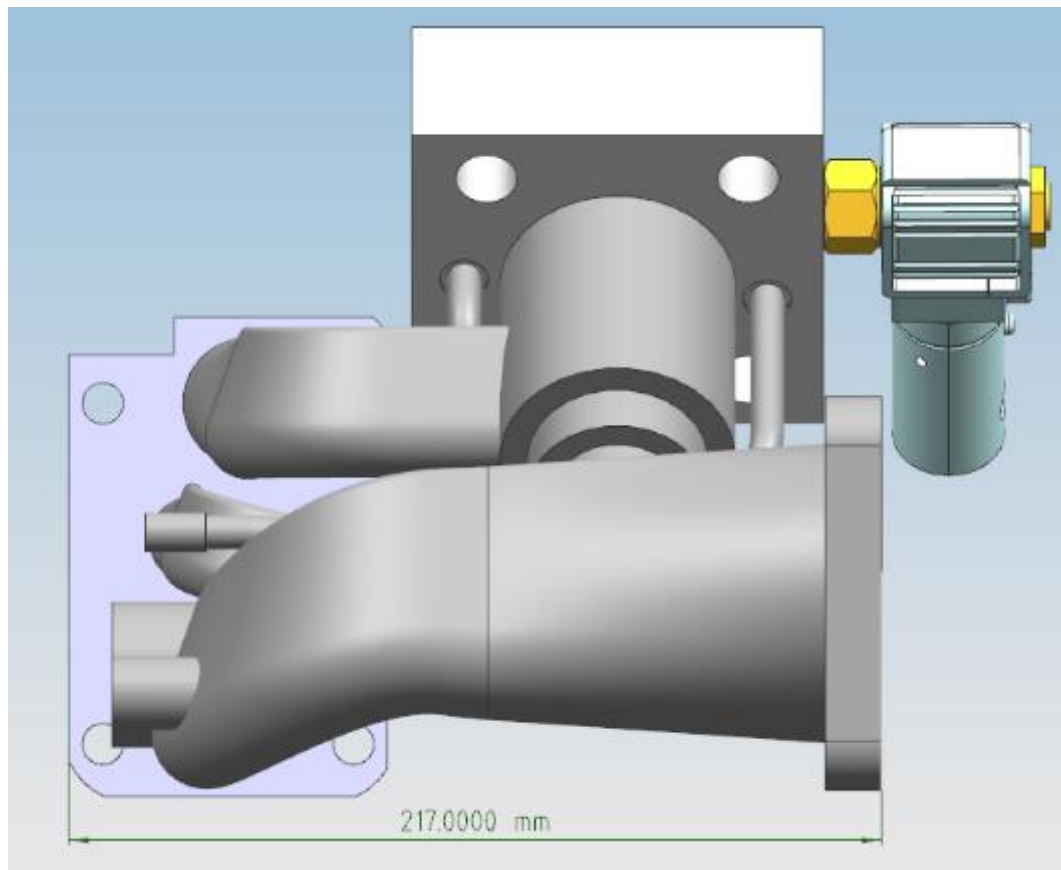


Figure 22. Second concept length to show the improvement in size of the oil block.

3.7 Third Concept

The third and final concept began where the second concept was left off. The crosscut sketches of the channels were changed to a round shape and the paths of the channels were further improved.

After the pressure sensors were placed, it was time to start creating other structures for the part.

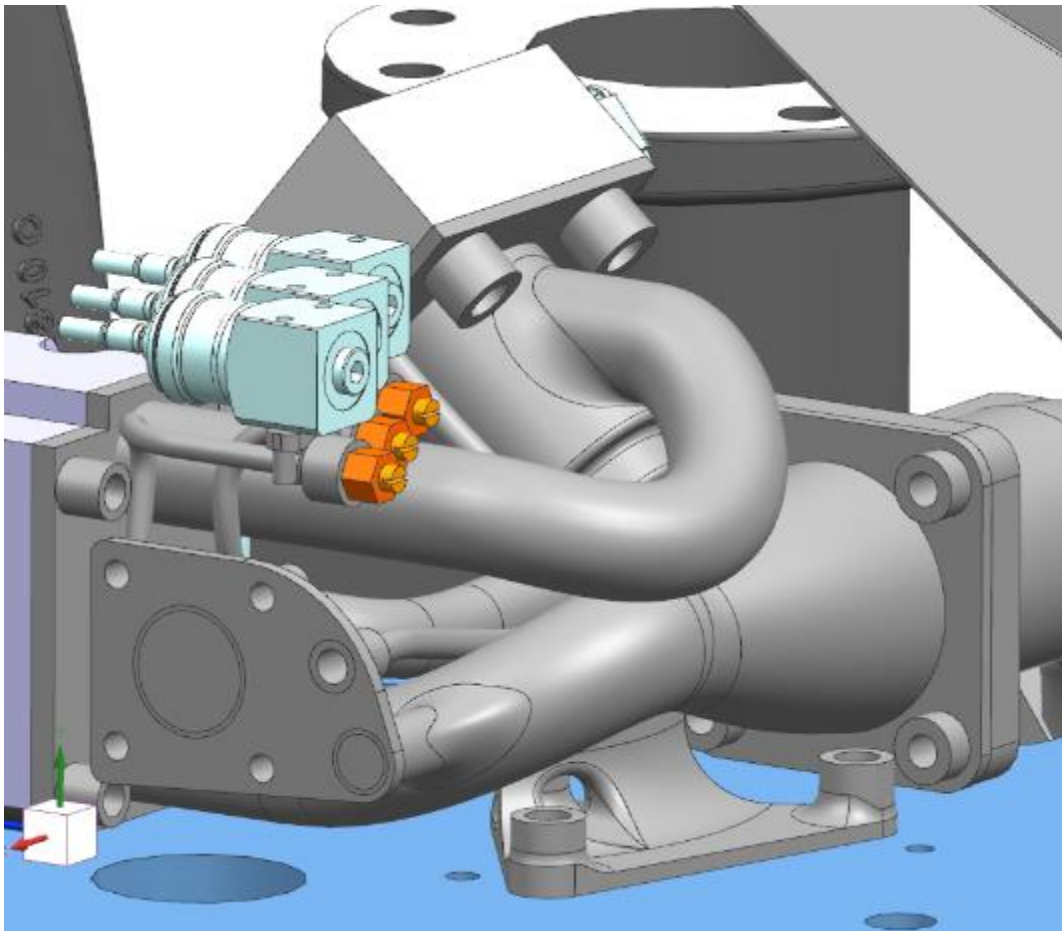


Figure 23. Third concept with pressure sensors placed and bottom plate added for support.

3.7.1 Creating the Outer Shell of the Oil Channels

After the concept was coming together, it was time to create the outer shells of the channels. This was done by offsetting the swept faces outwards by a certain amount. Before offsetting the faces, the extracted body command was used to copy the geometry of the created sweeps and then the copied geometry would be the one which was offset.

The wall thickness of channels was decided with the 3D printing expert that was part of this project. The thickness ended up being 1.5 mm which would have suitable strength without extra material that is not necessary [2].

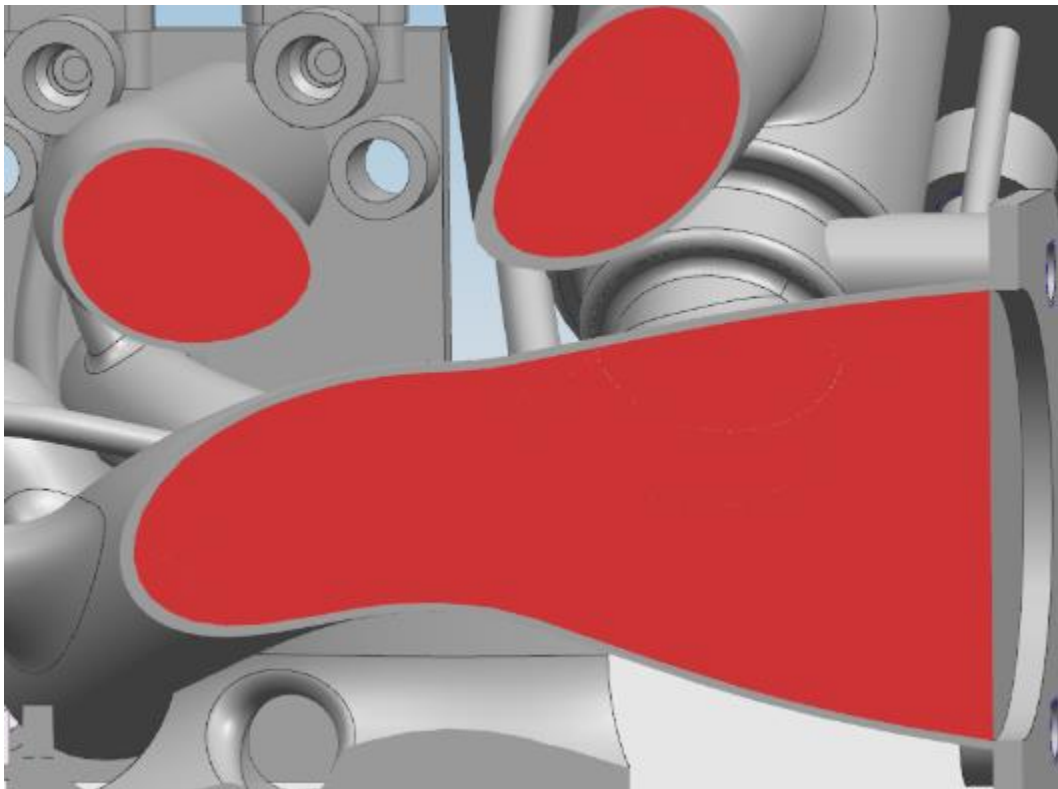


Figure 24. The outer shell of channels in grey and the sweeps that were created earlier in red.

3.8 Support Structures

Since the channels do not have too much structural strength by themselves, they need supports to hold up during use. When the channels were ready and the components found their place, it was time to start creating support structures for the oil block.

The supports were placed so that the flanges would be connected by the supports to give the part extra rigidity. There was one structure bridge modelled to connect two of the biggest channels on the part together and to the bottom flange which sits against the engine block.

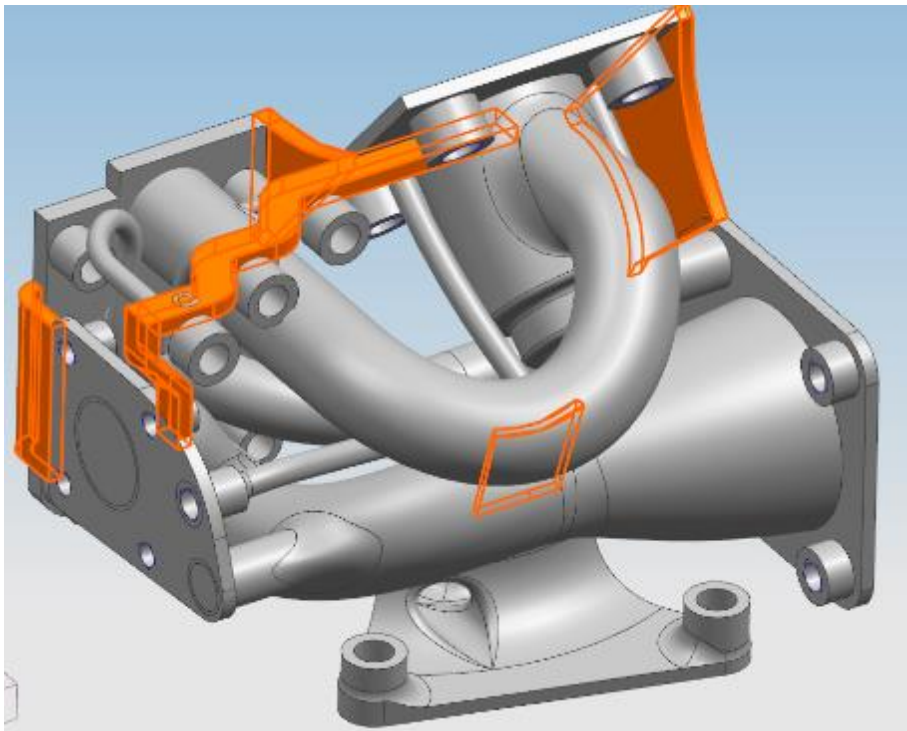


Figure 25. 1/2 Support structures of the block which are highlighted (orange).

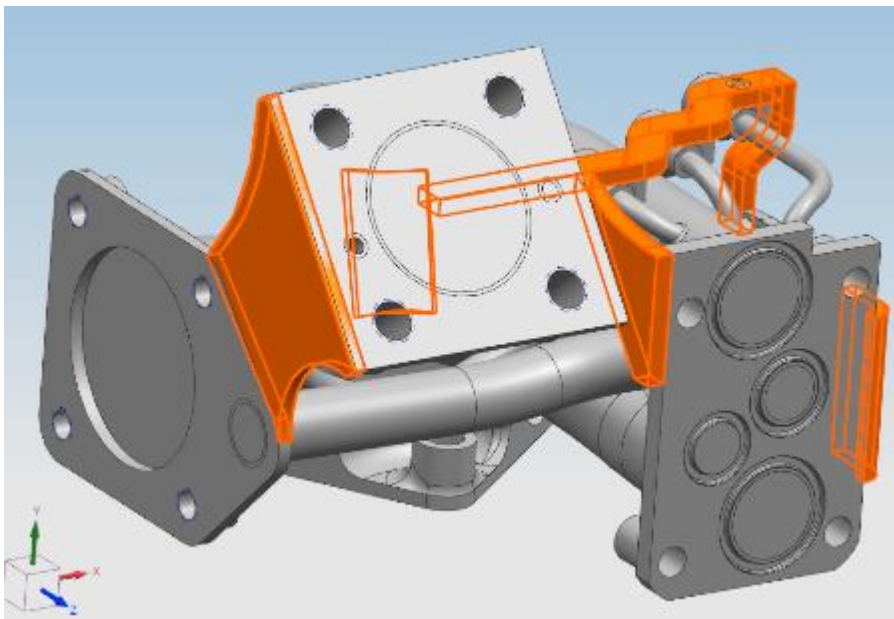


Figure 26. 2/2 Support structures of the block which are highlighted (orange).

3.9 Combining the Part and Subtracting the Channels

3.9.1 Combining the Part

When all the geometry on the part was created and in place, the next step was to start combining the different geometries together. For this we used the unite command where the main body of the part was chosen as a parent and all the other geometries and features as tools.

This resulted in one single body instead of many separate geometries. Note that these geometries that we are combining are the ones that were created using the extracted body command.

3.9.2 Subtracting the Channels

Now when the part was just one single body, it was time to start cutting the inside geometries of the channels from the part. Since the extracted body command was used earlier the original bodies (for example, sweeps, and extrudes) will now be used to cut the body. By doing this all the possible extra geometry and interference that could be in the channels from support structures were subtracted away.

The end result of this command is that the channels will now be hollow as they should be.

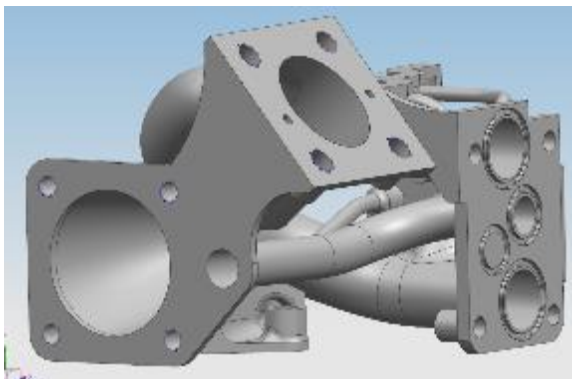


Figure 27. The body after subtracting the inside geometries of the channels.

3.10 Finishing Touches

Now when the main geometry was ready, it was time for some finishing touches to make the part look nicer and to improve its properties.

3.10.1 Screw Holes

The screw holes were added to the flanges where needed. Some holes have threads and some holes are just cut through. The screw holes needed extra material modelled for them to have enough depth for threads.

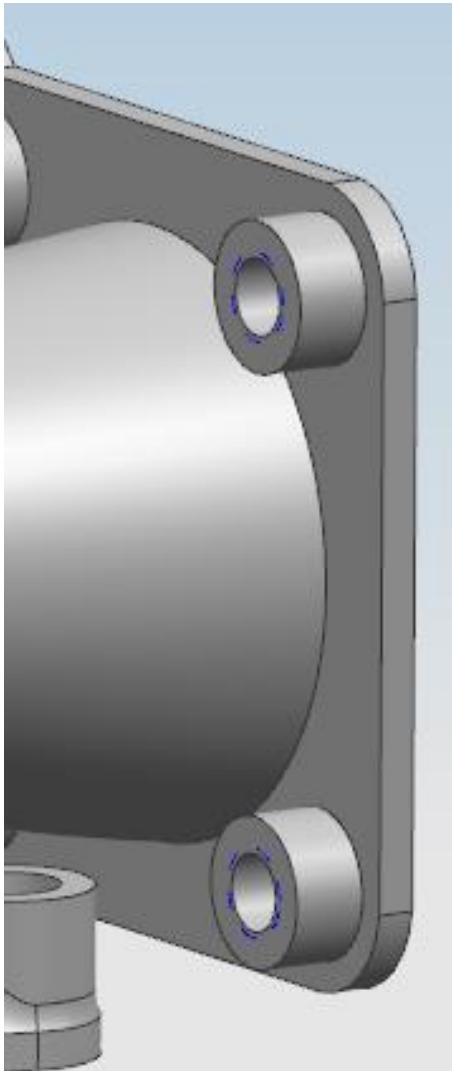


Figure 28. Added material for the screw holes.

3.10.2 Edge Blends

Edge blends were added to improve the appearance of the part and to prevent breaching. The blends were added to all other edges than on the faces that will be machined before use.

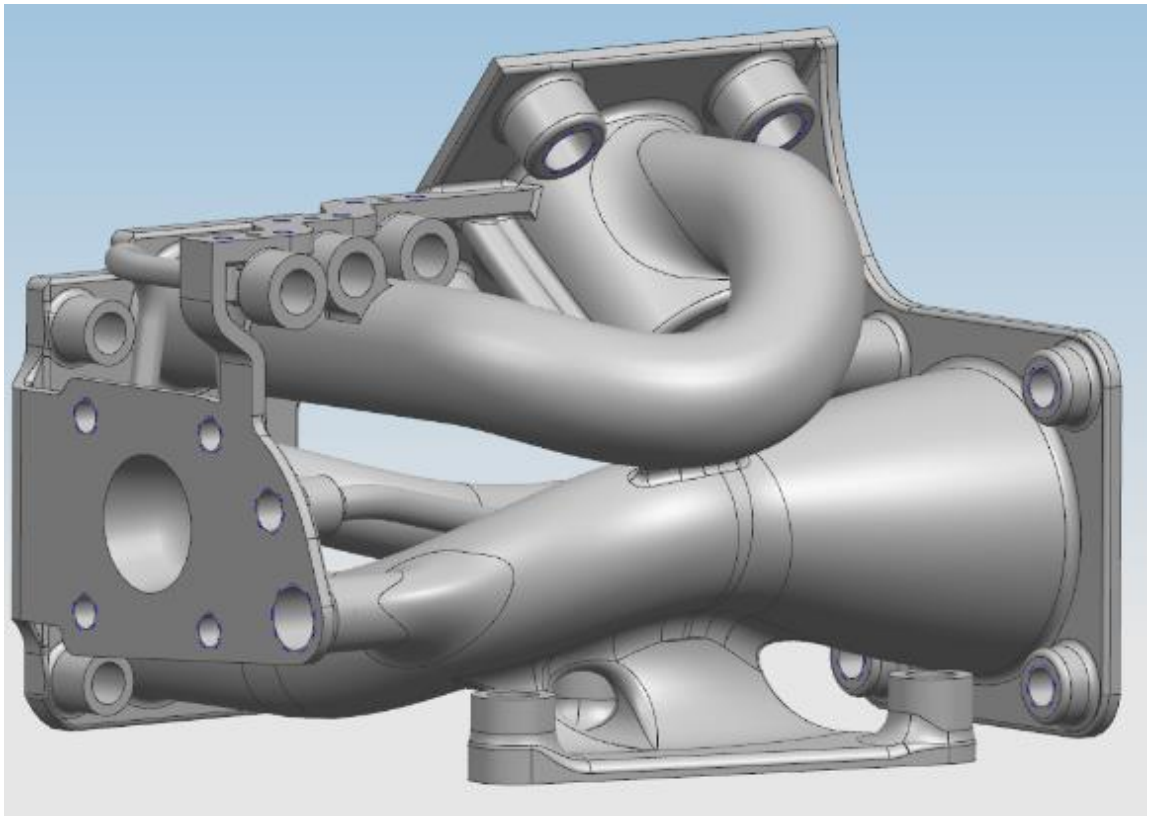


Figure 29. The concept after edge blends were added.

3.10.3 O – ring Grooves

O – ring grooves were added on the flange that is against the manifold. The grooves will not be printed though, since they need to be machined for a better surface finish. This will not cause any extra cost for the part since the face must be machined before use anyway.

4 FEM SIMULATIONS AND COMPARISONS

4.1 Computational Fluid Dynamics Simulation

The flow simulations were done using the inside geometries of the oil channels on both parts to see if there is any improvement on the 3D printed version over the current one. Simulations were done in Siemens NX.

4.1.1 Flow Velocity

Before the flow velocity simulations were created, the maximum and minimum velocity limits needed to be determined. Fortunately, there was a sheet for the maximum flow velocity speeds for different type of parts made in Wärtsilä already. From that sheet the maximum flow velocity was set to be 4.5 m/s. There was not any minimum velocity speed but if the velocity is really low, it informs that the channels might be too big and that the part is not cost effective. [7]

The flow to each channel needed to be known in order to create the simulation. For this following sheet was created.

Table 1. Oil flow sheet.

Oil flow (l/min)	Location
300	Oil in
40	Booster oil in and out
106	VIC main valve in and out
102	Oil to turbo

First, the flow velocity of the current part was simulated and the results showed that the current part is actually not bad with regard to velocity.

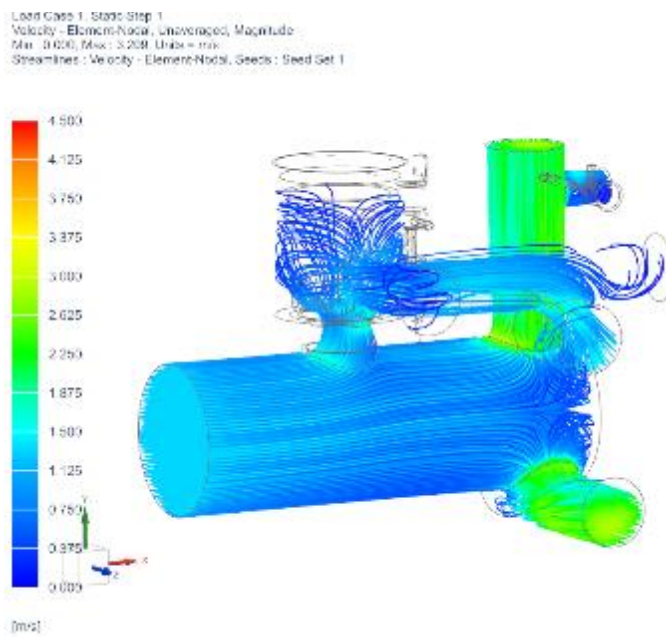


Figure 30. 1/2 Flow velocity simulations of the current part.

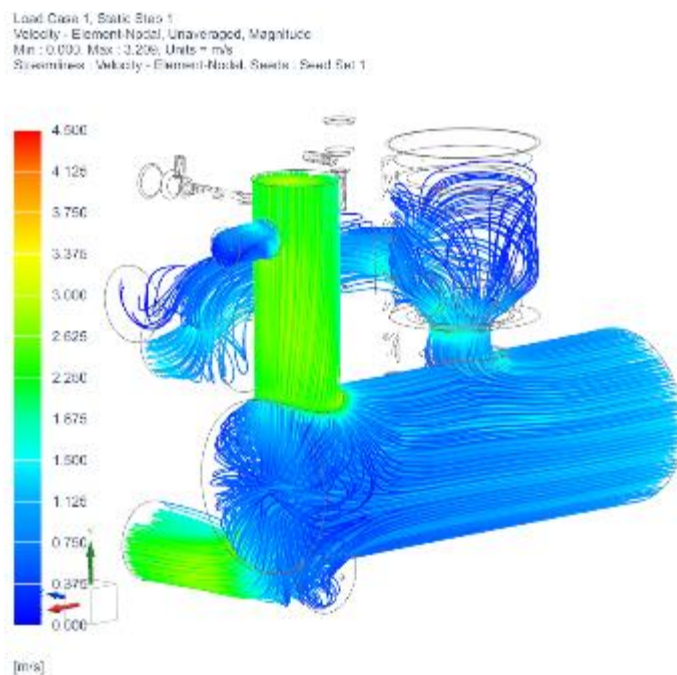


Figure 31. 2/2 Flow velocity simulations of the current part.

The part had around 1-2.5 m/s flow velocity at the end of the channels and on the big channel and on the VIC – solenoid channel the velocity was really low, close to 0 m/s. This indicates that the VIC – solenoid channel introduces a lot of restriction, and the big channel could be smaller.

The new concept created during this thesis showed little improvement over the current oil block regarding the flow velocity.

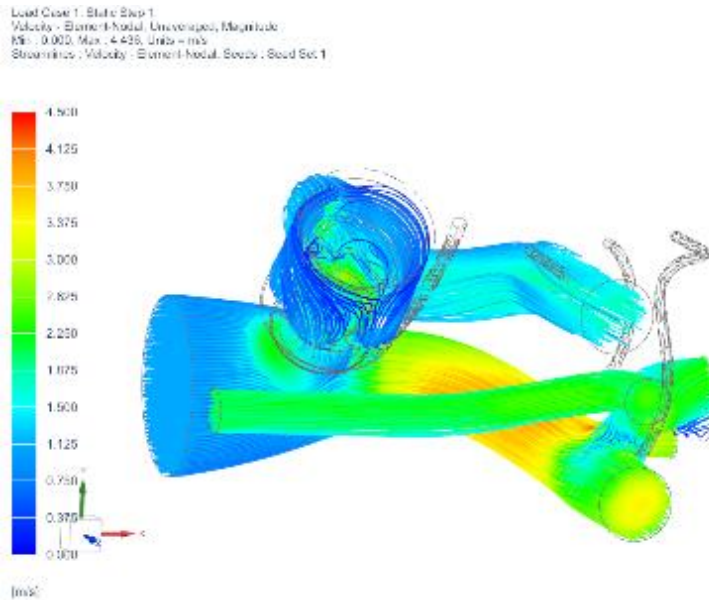


Figure 32. 1/2 Flow velocity simulations of the new concept.

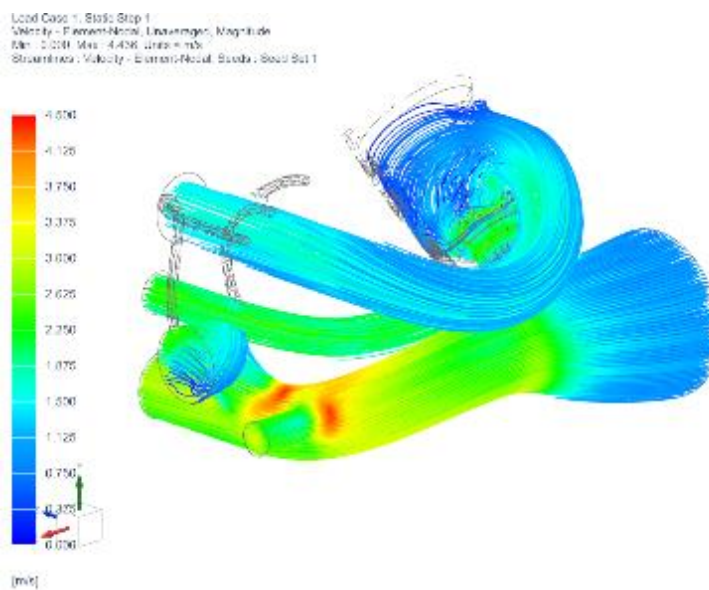


Figure 33. 2/2 Flow velocity simulations of the new concept.

The velocity at the end of the channels were a bit higher than the current one (1.5–3.3 m/s) but at the big channel and VIC - channel the velocity did not drop as low as in the current part.

All in all, the improvements were that there are less places on the new design where the flow is really slow. This is due to smoother channel geometry, but it does not have as big of an impact since this part is low pressure.

4.1.2 Total Pressure

The total pressure simulations were done by setting the oil temperature to 80 degrees Celsius, using the oil in flow amount of 300 l/min and the external pressure of 8 bars, which is the maximum value that this oil block should face when mounted on the engine. [4]

The total pressure of the parts showed little to no differences between the current part and the new concept. This is due to the minimum values being on the VIC – solenoid channel since it is restricting the flow.

This total pressure simulation shows the pressure of the oil in different parts of the channels. This way it can be seen how much pressure losses there are in the part. The higher the minimum value, the less pressure loss there is in the part. The less pressure loss there is better. The part with a higher minimum value in this simulation is better in this regard.

Both parts showed the same places where the pressure loss was highest. The most amount of pressure loss was created by the VIC - solenoid and it is unavoidable in this case.

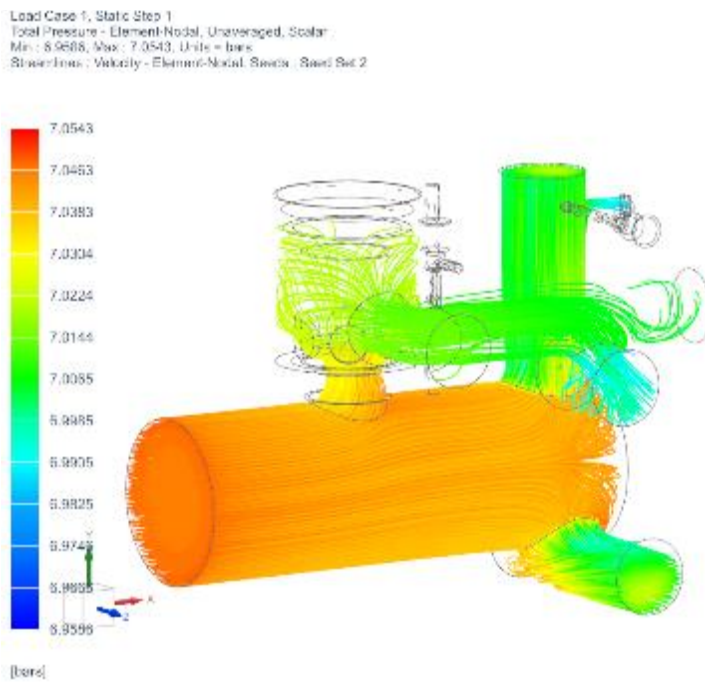


Figure 34. 1/2 Total pressure simulations of the current part.

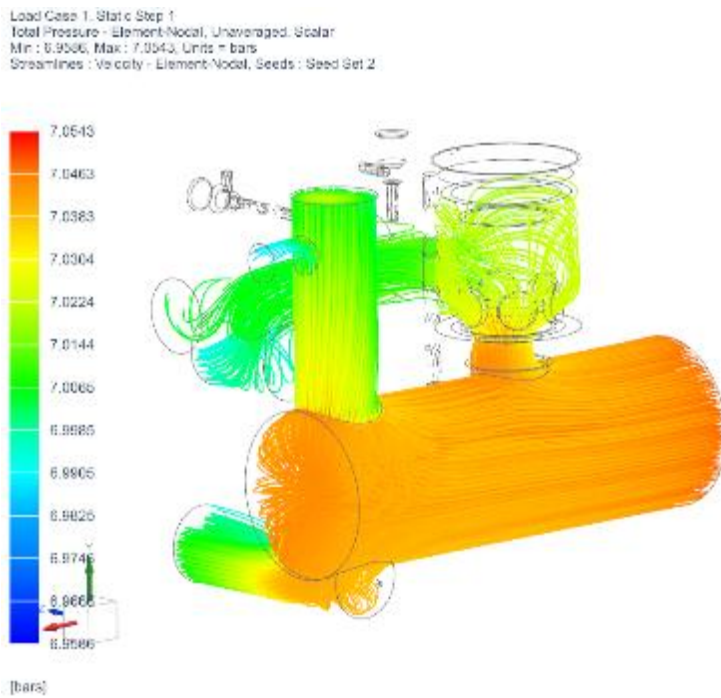


Figure 35. 2/2 Total pressure simulations of the current part.

The current part had a minimum total pressure value of 6.9586 bars and maximum of 7.0543 bars. So, the part had at least 0.9457 bars of pressure loss.

The new concept showed a bit worse (lower) minimum value over the current part in this regard.

Load Case 1, Static Step 1
 Total Pressure - Element-Nodal, Unaveraged, Scalar
 Min: 6.954, Max: 7.093, Units = bars
 Streamlines: Velocity - Element-Nodal, Seeds: Seed Set 1

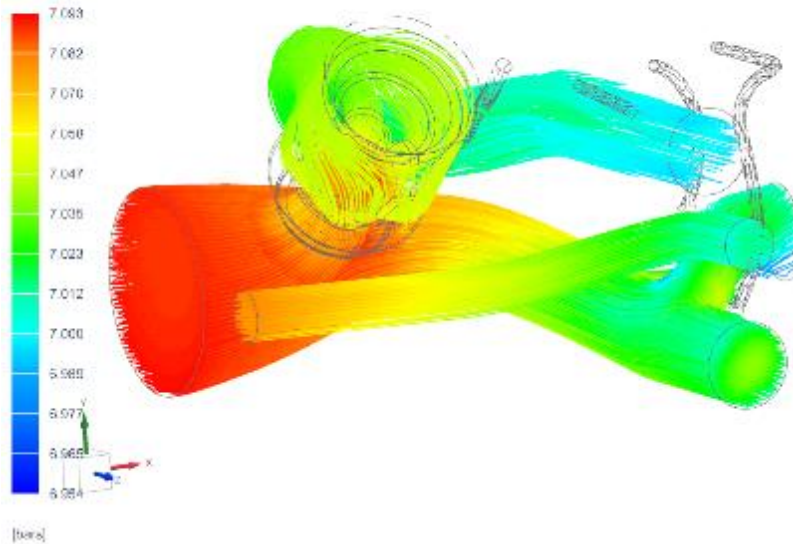


Figure 36. 1/2 Total pressure simulations of the new concept.

Load Case 1, Static Step 1
 Total Pressure - Element-Nodal, Unaveraged, Scalar
 Min: 6.954, Max: 7.093, Units = bars
 Streamlines: Velocity - Element-Nodal, Seeds: Seed Set 1

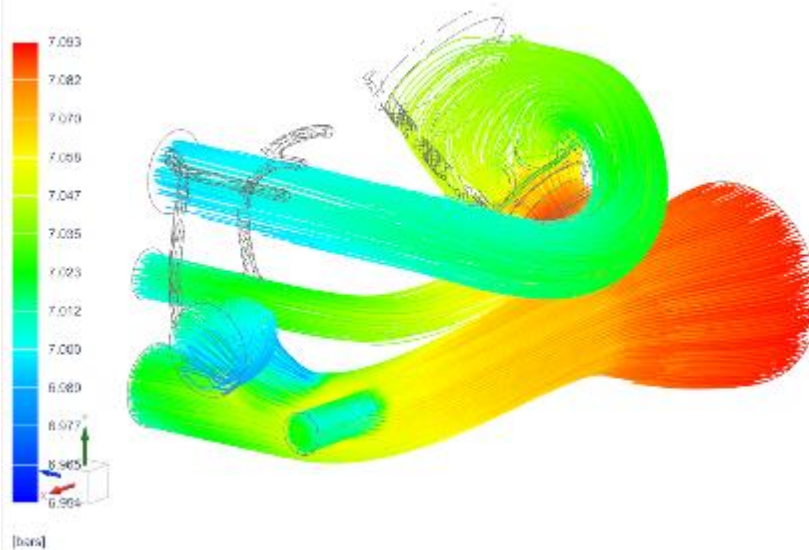


Figure 37. 1/2 Total pressure simulations of the new concept.

The new concept had a minimum total pressure value of 6.954 bars and maximum of 7.093 bars. So, the part had least 0.907 bars of pressure loss.

So, the new concept had 0.0046 bars worse minimum total pressure value. This probably falls in the margin of error. The maximum value, so the least pressure loss was in the new concept although this difference was only 0.0387 bars, also this would fall in the margin of error.

In conclusion, the parts showed little to no differences in this regard and the differences would fall into the margin of error. This situation could be different if the oil pressure was higher. Then the new concept would probably have edge over the current part because of smoother channel geometry achieved with 3D printing design freedom.

4.2 Natural Frequency

In Wärtsilä the parts need to have a natural frequency over 120 Hz in order to withstand the vibrations from the engine running at 1000 rpm. Everything over 200 Hz is considered good from this simulation since then there is a lot of safety factor. [4]

New_concept_final_dyna_sim1 - Solution 1 Result
SOLUTION 1, Mode 1, 237.68Hz
Displacement - Nodal, Magnitude
Min : 0.000, Max : 0.674, Units = mm
Deformation : Displacement - Nodal Magnitude
Animation Frame 1 of 30

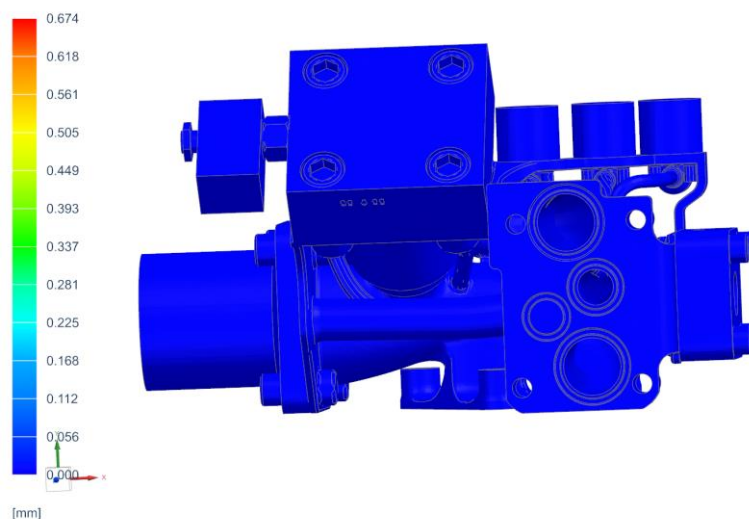


Figure 38. Lowest natural frequency of the new concept oil block.

The current part did not need testing in this regard since it has already been in use and this feature does not need comparing between the old and new design since the most important thing in this regard is that the natural frequency is over 120 Hz.

The part was constrained from the screw holes of the manifold flange and from the flange that is against the engine.

The lowest natural frequency of the new design was around ~238 Hz which is much over the value that is considered good in Wärtsilä. So, the new design does not need any changes in this regard.

4.3 Mass Comparison

In 3D printing weight reduction is almost guaranteed since material is only added where it is needed.

The current part is bulky and heavy, so the new design can really take advantage of weight savings on the new part. The current part weights 33.2 kg which means it is above the 25 kg mark. That means that the current part needs a lifting tool to be assembled.

With the new concept the weight of the part was able to be cut down to just 4.2 kg, which means weight reduction of ~87 percent.

4.4 Dimensions Comparison

The maximum length, height and depth will be compared between the current part and the new concept. The dimensions of the current part are 220 mm x 182 mm x 148.5 mm.

The dimensions of the new concept are 226 mm x 176 mm x 200 mm. The new concept is a bit longer and deeper than the current one, but it is 6 mm lower. The height is the most important dimension out of these since the fitment problem

with the current part is caused by the part being too tall and because of the VIC – solenoid on top of the part.

4.5 Cost Comparison

The cost of the current part was compared to the new 3D printed concept. Cost comparison is important part when thinking about changing traditionally manufactured part to 3D printed part. It needs to be considered that printing single part will cost more than if multiple parts were printed.

Because of Wärtsilä's privacy the exact prices will not be revealed but the new 3D printed concept would be approximately 2x – 2.5x the price of the current part.

3D printing might still be the only viable option to make the part fit in the space provided and still have good enough performance and maintainability. So, the price increase is somewhat justified since the current part is not usable and does not fit the engine as shown previously. In addition, there is no way to remove the VIC – solenoid making it not serviceable.

When thinking about this cost difference, one point of view to consider is that the new concept can be lifted without any tools so if we consider the cost of the tool and the inconvenience it causes, the difference might not seem so dramatic after all.

4.6 Comparison Summary

In summary the flow characteristics of the part were quite similar and most of the differences fall into the margin of error. There was a slightly better flow velocity overall in the new concept compared to the current one.

The mass of the oil block was majorly improved on the new concept with weight reduction of almost 90 percent (Table 2).

New concept is 2x – 2.5x the price of the current part so the cost increase is significant (Table 2) [2].

The size of the block is a bit larger in length and depth than the current part (Table 2) but the most important dimension, the height, was 6mm lower which gives more room for the VIC – solenoid.

Table 2. Comparison sheet between current and new concept.

Oil block design	Current	New
Mass (kg)	33.2	4.2
Cost	1x	2.5x
Dimensions (mm)		
Length	220	226
Height	182	176
Depth	148.5	200

5 FEM ANALYSIS (PRESSURE STRESSES)

After the flow simulations were created, it was time to do a FEM analysis to make sure that the part can withstand the pressure of 12 bars that is used in testing and simulations. The analysis was done in NX by loading all the channels with 12 bars of pressure and measuring the stress of the part. Fixed constrains were added to all the screw holes on the flanges to limit the amount of warping that might change the results. [8]

Before examining the results, it was crucial to know the properties of printed 316L stainless steel and the safety factor required for the oil block. Most important strength properties for this analysis are yield strength and tensile strength. Since 3D printed parts are usually a bit porous, they tend to be quite brittle, which is why the yield strength and tensile strength values are quite close to each other.

Mechanical Properties as Manufactured¹

Typical properties as manufactured ISO 6892-1

	Yield strength $R_{p0.2}$ [MPa]	Tensile strength R_m [MPa]	Elongation at break A [%]
40 μ m horizontal	500	600	35
40 μ m vertical	450	550	50
80 μ m horizontal	500	600	35
80 μ m vertical	450	550	45

Figure 39. Properties of 3D printed 316L stainless steel. (Picture from EOS data sheet.)

From Figure 40 we can see that the yield strength is 450 MPa and tensile strength is 550 MPa [9]. Because these two values are close to each other, the maximum value of 450 MPa will be used to calculate the maximum stress allowed for the part. This will be done by dividing 450 MPa by two to have safety factor of two for the part. The maximum allowed stress will then be 225 MPa. [4; 8]

During the analysis the part will be examined for any weak points or points that have concentrated stress on them and if it is possible to try to improve those points.

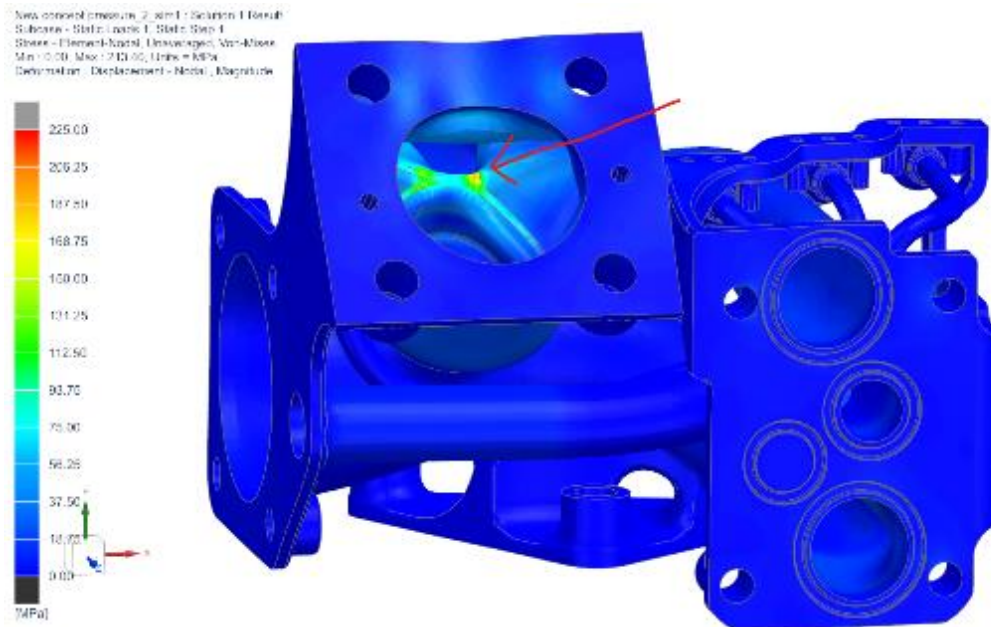


Figure 40. Stress analysis of new concept when loaded with 12 bars.

The maximum stress that affects the part at the set pressure is ~ 213.4 MPa, which is less than the maximum amount that was set earlier (225 MPa). The arrow shows (Figure 42) where the stress is concentrated on the part around the chamber for the VIC – solenoid. This is the only spot that has stress values more than 0-50 MPa.

This tells that in that spot there could be room for improvement, even though the part does pass the analysis on the required test pressure. The results indicate that the wall thickness of the channels could maybe be less than 1.5mm since the stresses are only concentrated on one spot on the part and the rest of the block has stresses around 0-55MPa. This way the weight of the part could fall below 4kg which would result in weight savings over 90 percent.

6 CLEANLINESS STUDY

The new 3D printed concept needs to meet Wärtsilä's cleanliness demands for it to possibly go into production. The part falls in filtered oil category which has cleanliness class of 1 or better. This means that the following requirements need to be met for the part to pass the cleanliness requirements. [10]

CLEANNES REQUIREMENTS	
Not allowed:	
<ul style="list-style-type: none"> - Dirt, slag, welding remains, burrs, curls; - Remains of grid blasting; - Sand penetration, sand particles; - Casting fins: <ul style="list-style-type: none"> >3mm (see Note 1); ≤3mm that could come loose during running; - Rust on machined surfaces; - A layer of rust, or rust attack on unpainted not-machined surfaces, allowed slight spots of rust 	
<u>Cleanness Class required:</u>	
Class 3 or better	
<hr/> <u>All previous requirements, plus:</u>	
Not allowed:	
<ul style="list-style-type: none"> - Casting fins; - Rust 	
<u>Cleanness Class required:</u>	
Class 2 or better.	
<hr/> <u>All previous requirements, plus:</u>	
<u>Cleanness Class required:</u>	
Class 1 or better. Or component/system specific documentation.	

Figure 41. Cleanliness requirements.

Class	Description of particles size
0	Particles not visible under 10x magnification
1	Particles visible under 10x magnification but not with normal or corrected vision (usually particles less than <u>50 μm</u> in diameter)

Figure 42. Cleanliness class specification.

6.1 Gathering Information

During this thesis the information about the cleanliness was mostly obtained from Wärtsilä's experts and Wärtsilä's supplier's experts since they have a lot of data and knowledge about the cleanliness of 3D printed parts.

At the kick-off meeting, it was advised to try to get information about previous 3D printing projects that have been done in Wärtsilä since there would be a lot of information that can be implemented in this project. So, after the meeting an interview was arranged with Wärtsilä's 3D printing expert.

6.1.1 Interviewing Wärtsilä's 3D Printing Expert (Francesco Trevisan)

During the interview with the expert, it became clear that they have successfully met Wärtsilä's cleanliness demands during previous 3D printed projects [2]. However, he could not say for sure that this part will pass the cleanliness demands since the parts have been different but within same cleanliness class of 1 or better.

He showed previous reports from old projects and even showed one fast concept he had done previously about the same part that this thesis is about.

Different cleaning/ post processing methods were discussed and that there are multiple good methods available for the part if it is not too large. One of the methods discussed was Thermal Deburring Technology (TEM) which usually yields in pretty good results. It is an affordable and fast method which then would reduce the overall cost of the part which would be good of course. There are also methods such as electro polishing and electro chemical polishing that allows to get complete cleanliness [2].

He advised to try to stay away from designing any deep pockets or any other geometry which would be prone to have metal powder and other debris from printing trapped into it.

6.1.2 Interviewing Wärtsilä's Supplier's 3D printing Expert (AMEXCI), Masi Tammela)

Mr Trevisan suggested that it would be wise to interview one of Wärtsilä's supplier's 3D print expert Masi Tammela (AMEXCI).

He gladly accepted the interview and was happy to answer questions and give his thoughts on this subject. He agreed with Mr Trevisan that the part could be possible to get clean enough for the cleanliness requirements, but he could not say for certain neither [11].

Amexci has done a lot of testing about the cleanliness of 3D printed parts but none with a part that is similar with this oil block. Therefore, he was interested in this study too and was willing to print test pieces if needed for this project.

He also mentioned another cleaning method which we could use to achieve the cleanliness needed to meet Wärtsilä's requirements. This was ultrasound cleaning that is widely used in the field of 3D printing and is quite fast and affordable. [11]

6.2 Processes between the Print and Post Processing

After the part is printed, it goes through different steps before post processing. These steps include powder removal, sand blasting, heat treatment, platform removal and supports removal. [2; 12]

1. Powder Removal

The powder in the powder bed is vacuum cleaned and collected by the LPBF operator [12]. Operator needs to be careful during this step since there might be residual powder inside the part, particularly inside internal channels and supports.

2. Sand Blasting

High energy levels involved in the laser melting cause the powder close to the part to attach and sinter on the surface. To reduce this effect, the part is sand blasted

using conventional sand blasting stations [12]. Usually during blasting agents such as glass, alumina or steel balls are used.

3. Heat Treatment

Due to elevated temperatures and very fast cooling rates involved in the LPBF process, the printed parts have high thermal residual stresses that need to be relieved [12]. The part can be removed from the platform only after the thermal stresses have been relieved. This is because the residual stresses would deform the part otherwise.

4. Platform Removal

The part is basically welded on the building platform and need to be mechanically removed after the stress has been relieved from the part. Usually parts are removed by manual operation, band sawing or Electric Discharge Machining (EDM) cutting. [12]

5. Supports Removal

After parts is detached from the platform, the supports can be removed from the part by manual operation [12]. The support structures are not allowed on the final part. After this step the part is ready to go into surface post processing.

6.3 Test Print and Thermal Deburring Technology (TEM) Testing

Mr Trevisan suggested that we would print a test piece of the new concept. For this we used the third concept. Only a small part of the oil block was printed due to time limitations but that was enough to get information and do testing on the part about the cleanliness of the internal surfaces of oil channels. The printing method used was LPBF (Laser Powder Bed Fusion).

The printing was done by Wärtsilä's supplier (Amexci). The post processing technology used (TEM) was chosen for its fast speed and cheap price. The testing was

done to determine if this technique would yield in good enough results for this application without much cleaning after the process is done.

This technology works by placing the part in pressurized chamber and filling it with methane gas. The combustion of this methane gas will clean the part through an oxidation reaction. [13]

Following are pictures of the printed samples which will be analyzed later in the surface analysis.



Figure 43. Test print reference point without any thermal deburring.



Figure 44. Closer look at the surface of the print without any thermal deburring.

As we can see, the surface of the channels is quite rough from the printer and there are some big particles left. The desired result of this deburring process was to get smoother surfaces and less particles.

Figures 46 and 47 are pictures of deburred pieces that have been marked by the supplier to show different iterations of the tests and refer to “power” used in these tests.



Figure 45. Print that was the starting point “normal” of their tests.



Figure 46. Closer look on the surface of the starting point “normal” of the print.

After they had done the standard deburring process for the part, the tests with different “powers” begun. This was the start point of these following tests.



Figure 47. Print after first round of deburring with the “power” of 110.



Figure 48. Closer look on the surface of print after deburring with the “power” of 110.

The surface on the print is a bit smoother than at the start point but still rough. There are quite big particles left.



Figure 49. Print after second round of deburring with the “power” of 130.



Figure 50. Closer look on the surface of print after second round of deburring with the "power" of 130.

Now the print has a bit less of the bigger particles that were seen earlier but the surface is still quite rough. All in all, the deburring tests showed that the effect on surface is quite limited, but still better than the untouched surface. After testing was done at the supplier, the print was sent to Sustainable Technology Hub (STH) that is in Vaasa for a surface analysis.

6.4 Surface Analysis

The surface analysis was conducted by Wärtsilä's material expert at the material laboratory in STH. The pictures used in this section are taken by the material expert and the text is referred from the report that he made about the process.

The scope of these tests was to investigate thermal deburring as a possible cheap solution for post-processing the internal channels in 3D printed hydraulic blocks and whether the cleanliness demands will be met with this post processing method.

The surface investigation highlights the effect of the post-process over the printed surfaces. The focus will be on the presence of attached metal particles if there are any, WLI measurement and whether the wall thickness has changed from the deburring.

This analysis is crucial to know if the part is usable in the engine since 3D printed parts tend to have quite much residue and particles that are not attached to the print, which are usually slag remains from the metal powder being melted by the laser during LBPF process.

Total of five samples were inspected during the analysis, four of them being printed from 316L which were deburred and one sample which was printed from MS1 tool steel which was "blasted". The one printed with MS1 had different printing parameters with a layer thickness of 40 μm (other samples had layer thickness of 80 μm) and was more expensive due to longer printing time and material.

6.4.1 Visual Inspection

First, the parts were visually inspected where the expert observed that the part deburred with "power" of 130 showed more oxidation on the surface, especially on structures that have been heated more during the process. [14; 15]

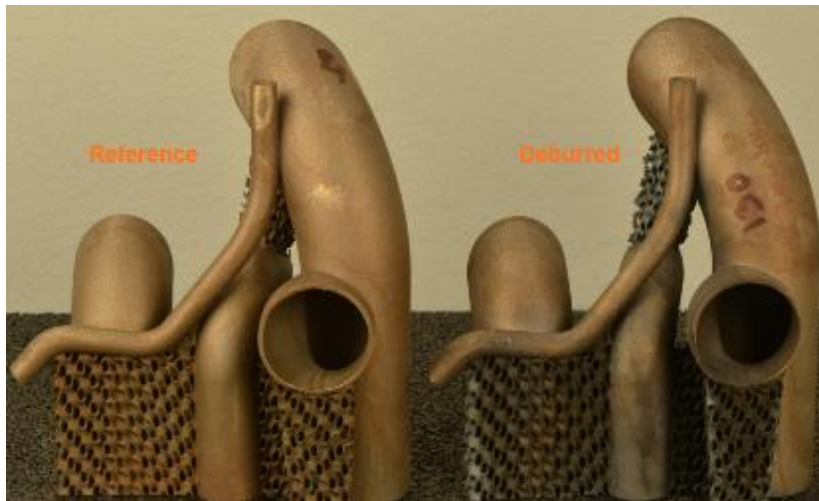


Figure 51. Reference part and deburred part with “power” of 130 side to side to see the oxidation.

Inside the channels there were not big differences visually at the smoother areas [15].

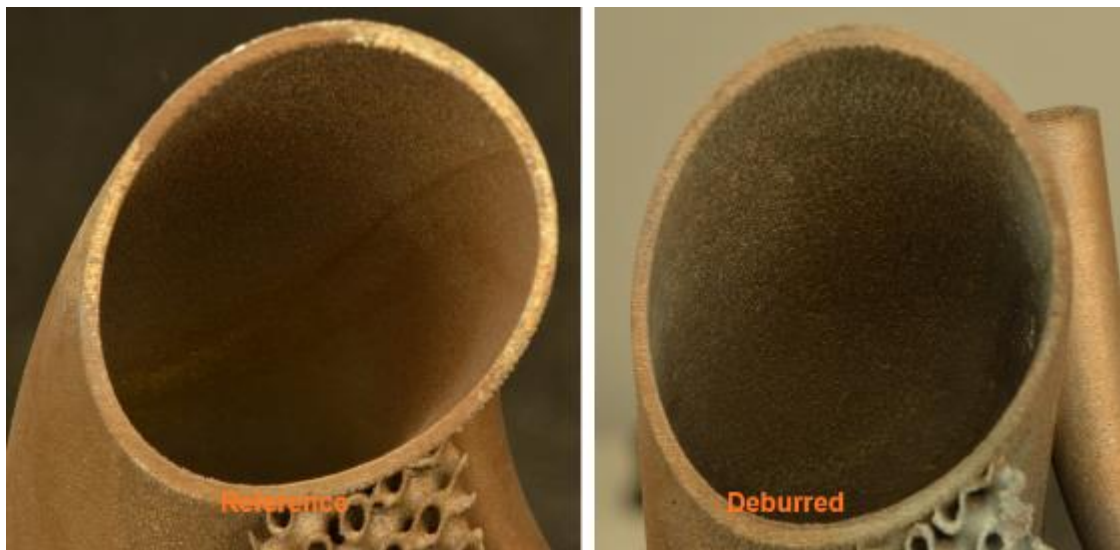


Figure 52. Side to side view of the channel smoothness.

On rougher surfaces the oxidation is more profound. There is more oxidation visible on the “130” sample inside the channels also [15].

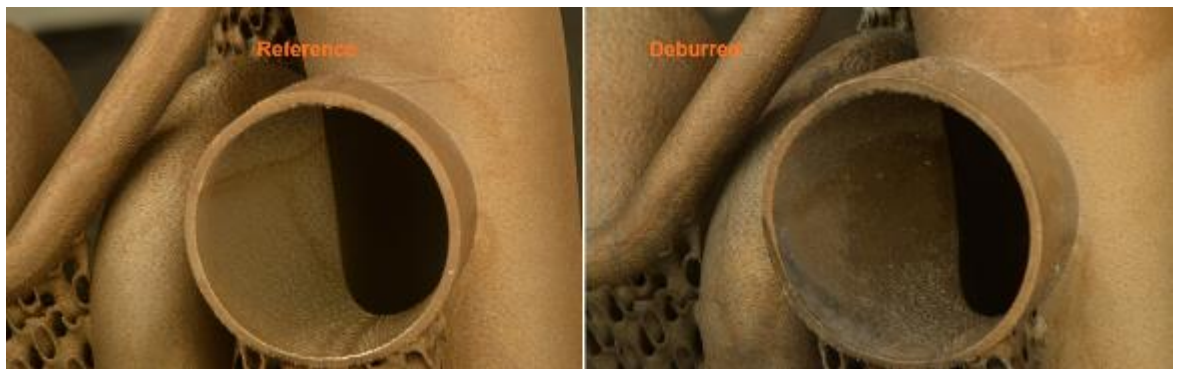


Figure 53. Side to side view of the oxidation of the inside surfaces of the channels.

6.4.2 Cutting the Samples

Before the White Light Interferometer measurement could be done two of the five samples were cut to smaller pieces [15].



Figure 54. Marking the lines where the part will be cut to smaller pieces.



Figure 55. Smaller pieces that were cut from the part.

During the cutting, the surfaces are exposed to cutting liquid flow and pressurized air drying/ cleaning after cutting [15]. These pieces would then be taken for the WLI measurement.

6.4.3 White Light Interferometer (WLI) Measurement on Cut Samples

During this operation a 3D scan is created from the part using white light scanning which enables accurate 3D models to be created so that the possible differences between different treatments could be investigated. [15]

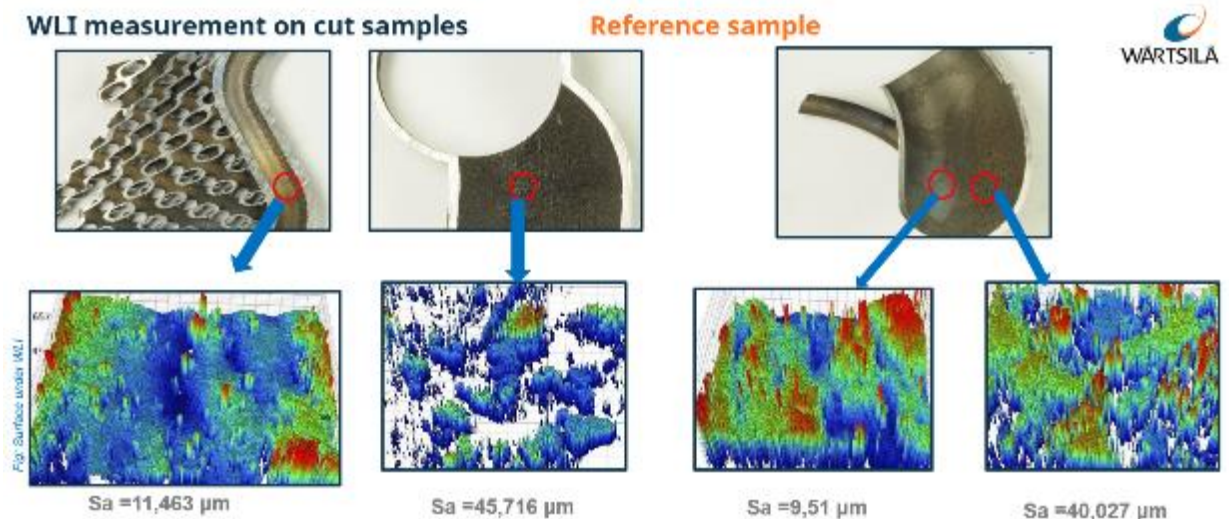


Figure 56. 1/2 WLI results from the reference and deburred sample.

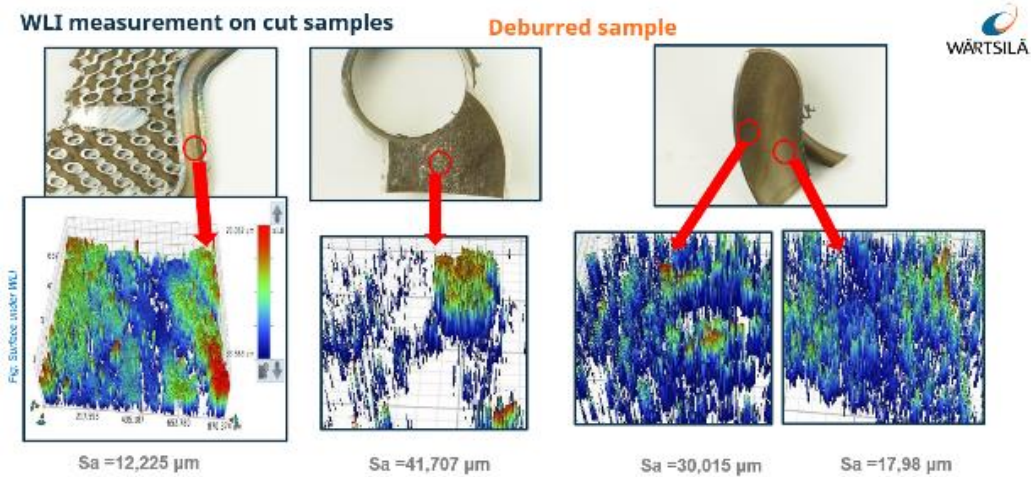


Figure 57. 2/2 WLI results from the reference and deburred sample.

Based on these measurements, there are slight differences in the surface parameters Sa (Arithmetic mean of height of an area) that can be observed throughout the reference and deburred surface. The sample that was deburred with the “power” of 130 delivered somewhat smoother surfaces. [15]

6.4.4 Thickness Measurement

For thickness measurement, cross section samples were cut from the large channel intersection and from the smallest channel, the same locations from both samples. The measurements are varying on the same levels in both samples ($\sim \pm 50$ µm). No difference can be found related to the deburring process parameters. [15]



Figure 58. Cross section cuts from the samples.

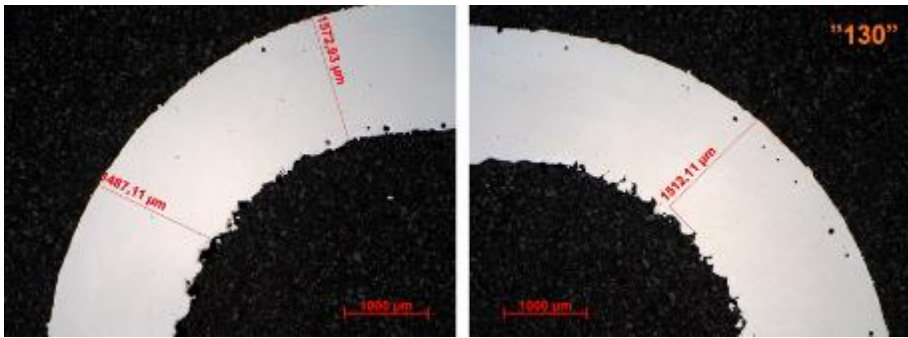


Figure 59. 1/2 Thickness measurements from different parts of the walls.

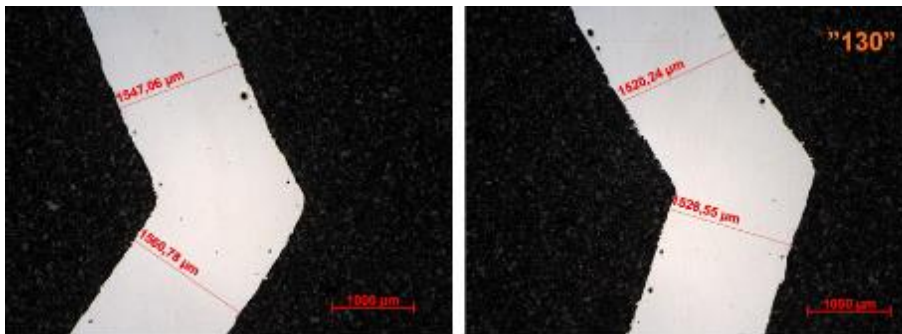


Figure 60. 2/2 Thickness measurements from different parts of the walls.

6.4.5 Cleanliness Investigation

During the visual analysis, it was noted that the parts had quite a lot of oxidation and debris on them. Therefore, the parts needed to be cleaned before the analysis. This was done with a soft toothbrush which removed a lot of loose material from the test pieces. The cleaning was done on top of white sheet of paper to see how much particles are released. [14; 15]

The tests were performed by wiping the large channel inside surface with clean a white cotton cloth, then analyzing how much contamination and particles are on it [14]. To pass the cleanliness demands the cloth should not have visible particles with bare eye but can be visible at 10x magnification [10]. It must be taken into consideration that the “ref” and “130” brushing results are slightly controversial since some debris is left from the cutting process [14; 15].



Figure 61. 1/3 Results of the "ref" sample.



Figure 62. 2/3 Results of the "ref" sample.

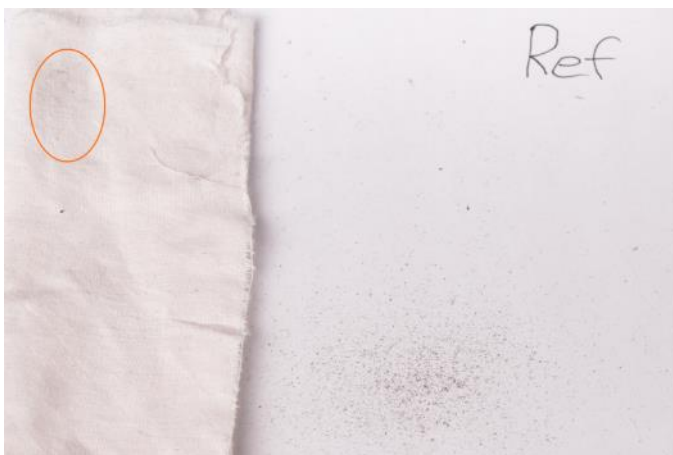


Figure 63. 3/3 Results of the "ref" sample.

These results showed that the cotton cloth had some black residue and a few particles visible with a naked eye. During brushing, a lot of small particles fell on the paper (most likely cutting debris). [15]



Figure 64. 1/2 Results of the “130” sample.



Figure 65. 2/2 Results of the “130” sample.

The cotton cloth had some black residue and some larger particles. There were many small particles on the paper (most likely cutting debris). [15]



Figure 66. 1/2 Results of the “110” sample.

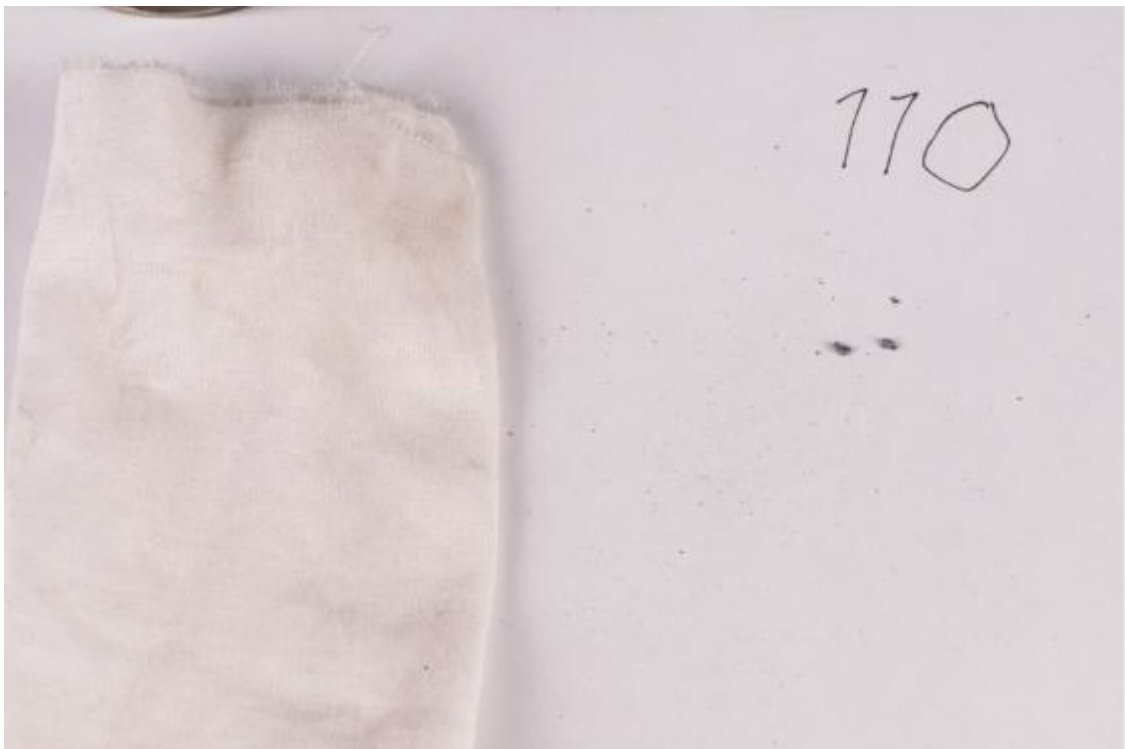


Figure 67. 2/2 Results of the “110” sample.

The cotton cloth had less residues than first two samples. Some larger particles were removed during the brushing (oxidation/slag). [15]



Figure 68. 1/2 Results of the “normal” sample.



Figure 69. 2/2 Results of the “normal” sample.

The best results came from the 316L samples. The cotton cloth was almost clean but with some visible particles found. Several large particles were removed with brushing (oxidation/slag). [15]



Figure 70. 1/2 Results of the “blasted” sample which was printed from MS1.



Figure 71. 2/2 Results of the “blasted” sample which was printed from MS1.

The cotton cloth had some dark spots and had individual larger particles visible for the naked eye without magnification. Some large particles removed with a brush (oxidation/slag). [15]

6.5 Conclusion

It must be noted that in Wärtsilä the parts are tested for cleanliness after they have been machined and chemically cleaned after the machining process. These test prints were not cleaned well after the thermal deburring and they did not go through the chemical cleaning process. These could be the changing things that define whether the parts pass the cleanliness or not. [4]

The parts had partially rough surfaces which are more difficult to clean and can trap particles that are later detached during use. This is why smoother surfaces are preferred when considering cleanliness. [16]

Current state of the printed parts do not pass the cleanliness demands of Wärtsilä. Positive in this is that the parts were successfully printed and that some of the results are close to passing the demands.

By changing the printing parameters and using some other post processing methods and by cleaning the parts well after the process, it is likely that the parts would be able to meet the cleanliness demands but this needs more testing.

7 TEST PRINT FROM PLASTIC

After the metal test prints had been ordered from the supplier, it was decided that a plastic print from the whole oil block was going to be printed on Wärtsilä's own printer. This was done to see how the part would look in real life and how it could be printed as a single piece. Pictures of the printed plastic oil block are shown below.

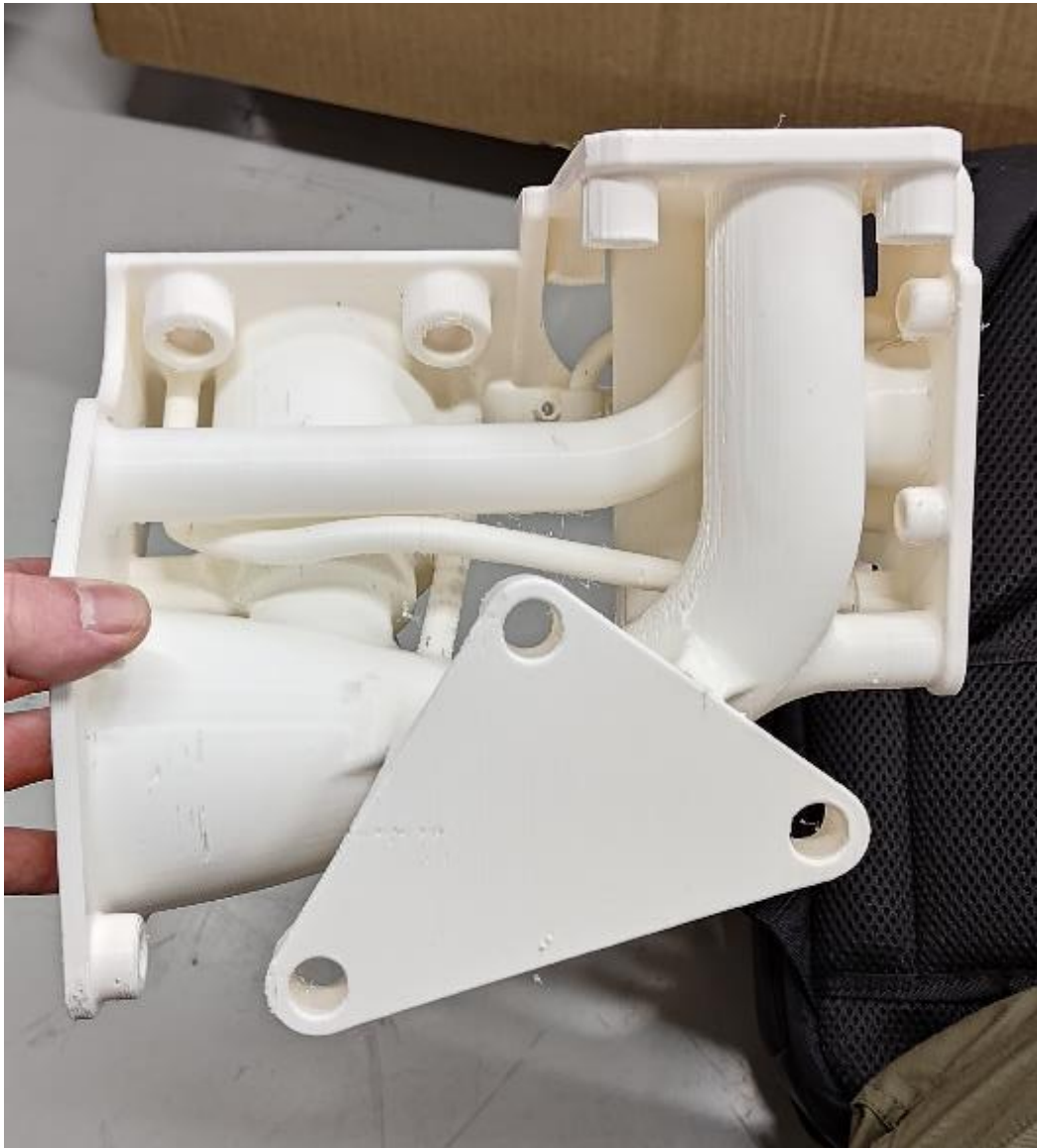


Figure 72. Plastic 3D printed oil block of the new concept (bottom side up).

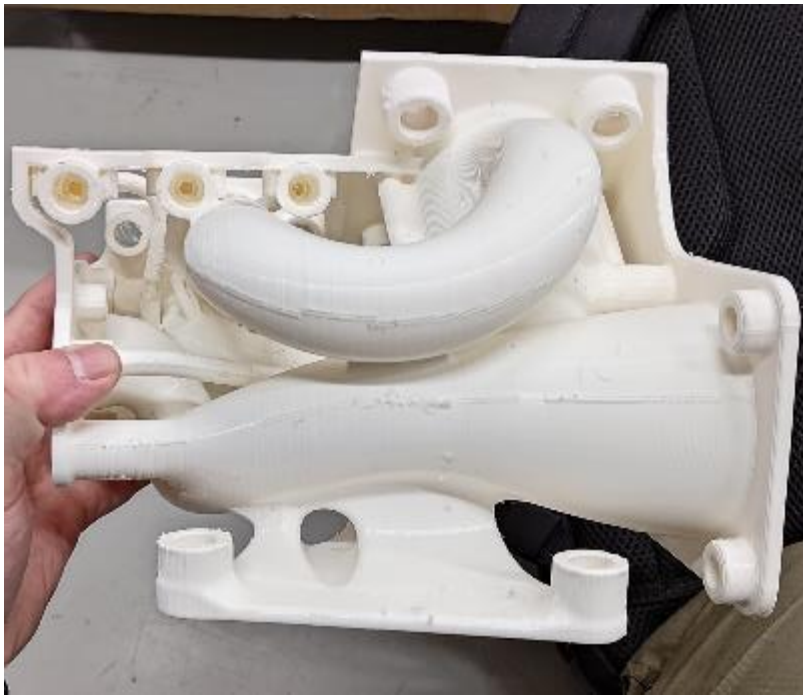


Figure 73. Front side of the plastic printed oil block.

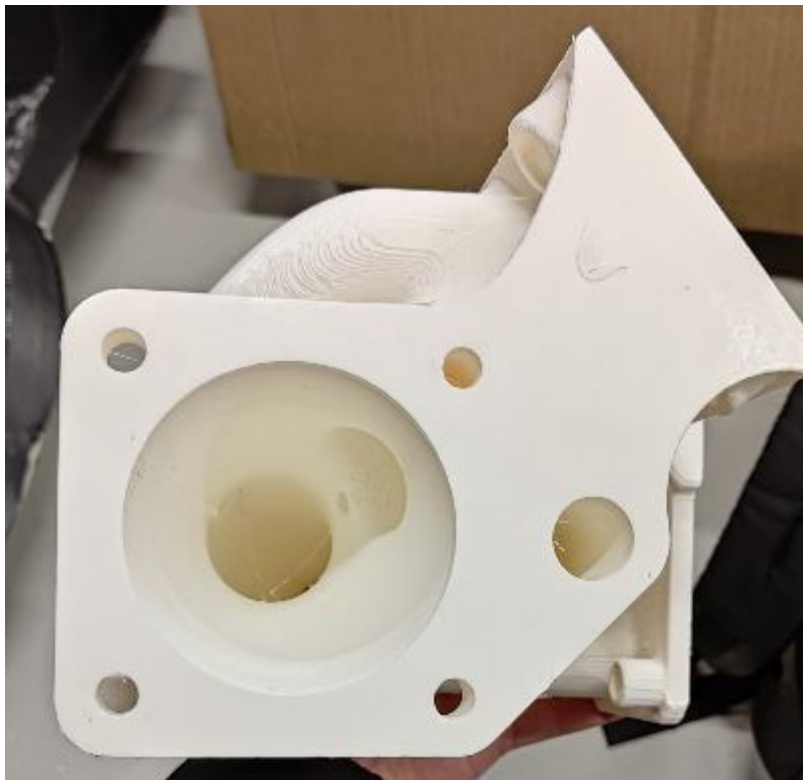


Figure 74. Plastic printed oil block (face that is against build surface).

The print is quite rough since the quality of the print is not important in this case. There were also some places for improvement that became apparent from the test print. For example, there is not enough material around the screw holes on the pressure sensor attachment points.



Figure 75. View which shows that there is not enough material around the screw holes of the pressure sensor attachment points.

The placement of pressure sensors caught the eye of Wärtsilä's experts, since they have little channels coming from them (Figure 76) which need supports when printing. This increases the cost of the part because support removal takes a lot of time. With better placement the need of supports could be avoided.

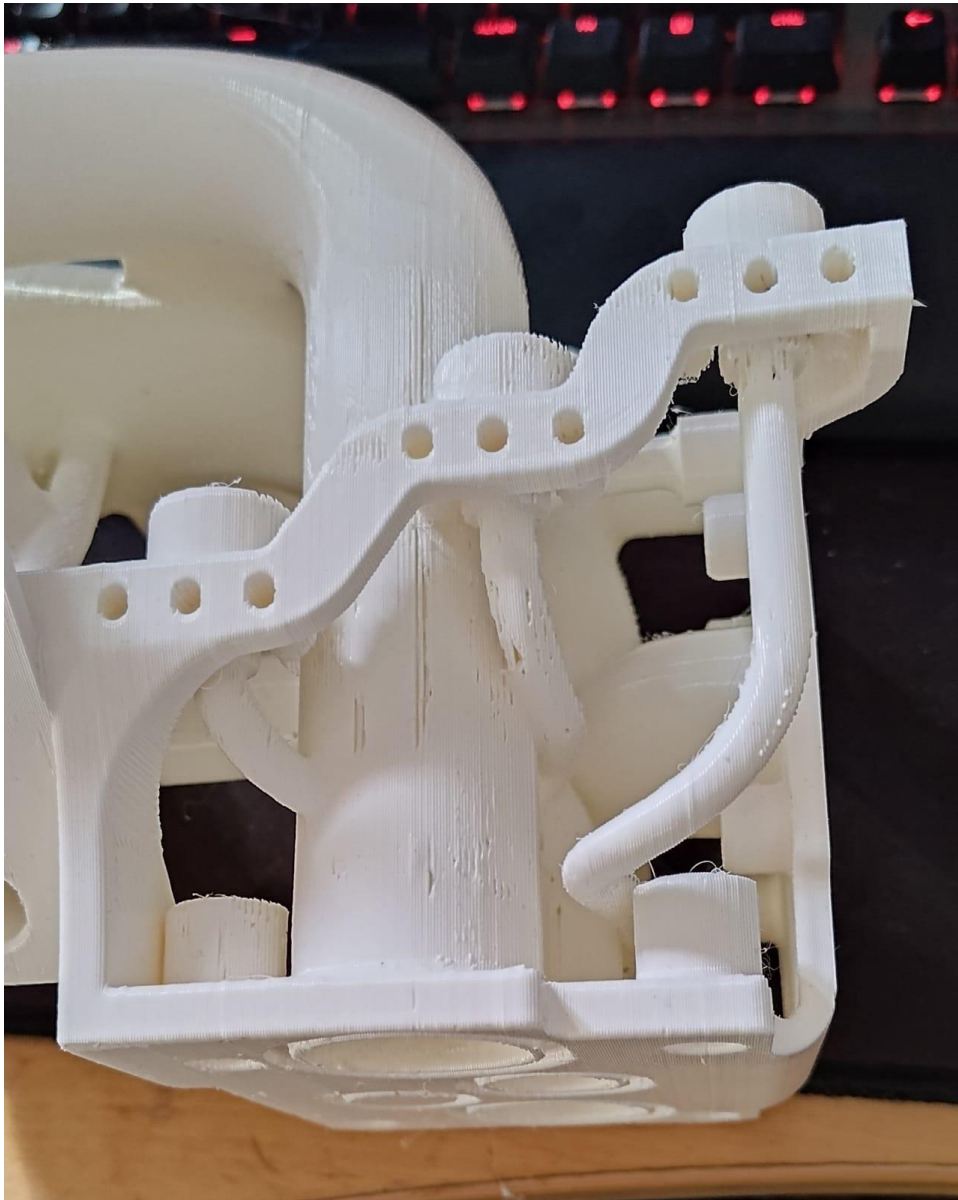


Figure 76. Closer look at the pressure sensor placement.

Overall, the test print was successful and the part turned out good. Insides of the channels printed fine and there were not any critical flaws about the concept that became apparent from this test print. It gives a good insight about how the part would look different than when printed from metal.

8 FURTHER IMPROVEMENTS

Before the new concept can be taken into production, there is still a lot of points for improvement.

The usefulness of this new concept and its cost increase could be validated by creating the new concept of the block with traditional manufacturing methods to see how these two would compare (new additive manufacturing concept vs new traditional concept).

8.1 Concept

Some attachment points for machining should be added on the part. Due to the time limitations, they were not designed yet. This problem needs to be solved with Wärtsilä's machining experts in the future.

The placement of pressure sensors could be investigated if there still were better positions available to improve the serviceability of the pressure sensors.

The problem that became apparent from plastic test print should also be addressed, so more material around screw holes should be added.

The concept needs to be fine-tuned to get rid of the need of supports in spots that can be seen in **Figure 71**. This can be done by changing the angles of the channels or adding some kind of lattice or edge blend to the part [17].

There were not more critical points of improvement that became apparent during this project considering the 3D concept but there is for sure more points of improvement that will become apparent in the future if this concept is to be taken into production.

8.2 Cleanliness

Since the test prints did not pass the cleanliness demands of Wärtsilä [10], the cleanliness needs to be tested further with different kinds of printing parameters, materials and post processing techniques.

Mr Trevisan suggested that the oil block could be printed using DED (Directed Energy Deposition) method, as well and analyzed if it would be suitable for this application. This method works by melting material as it is being deposited, often referred as “metal deposition” technology [18].

There is already talk with AMEXCI to find a proper post-process to pass the cleanliness.

9 CONCLUSIONS

Overall, the thesis was quite successful and the expected results were met. Even though the test prints that were post processed using TEM did not meet the cleanliness demands, it gave valuable information for Wärtsilä. It is also quite certain that the prints will meet the demands with a bit of testing around with different printing parameters and different post processing methods.

A new concept for 3D printed oil block was created which met the limiting factors that were set beforehand. It allows the VIC – solenoid to be mounted so it is removable and serviceable separately without removing the whole oil block. Most importantly, the new concept oil block fits the space provided in the engine where the current solution does not.

Comparisons between the current oil block and new concept were created successfully and it gave good information about the benefits and downsides of 3D printing in this situation. Most importantly, the weight was reduced by almost 90 percent. The cost of the part is more than the current part but the fact that the oil block now fits the engine outweighs the cost increase.

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