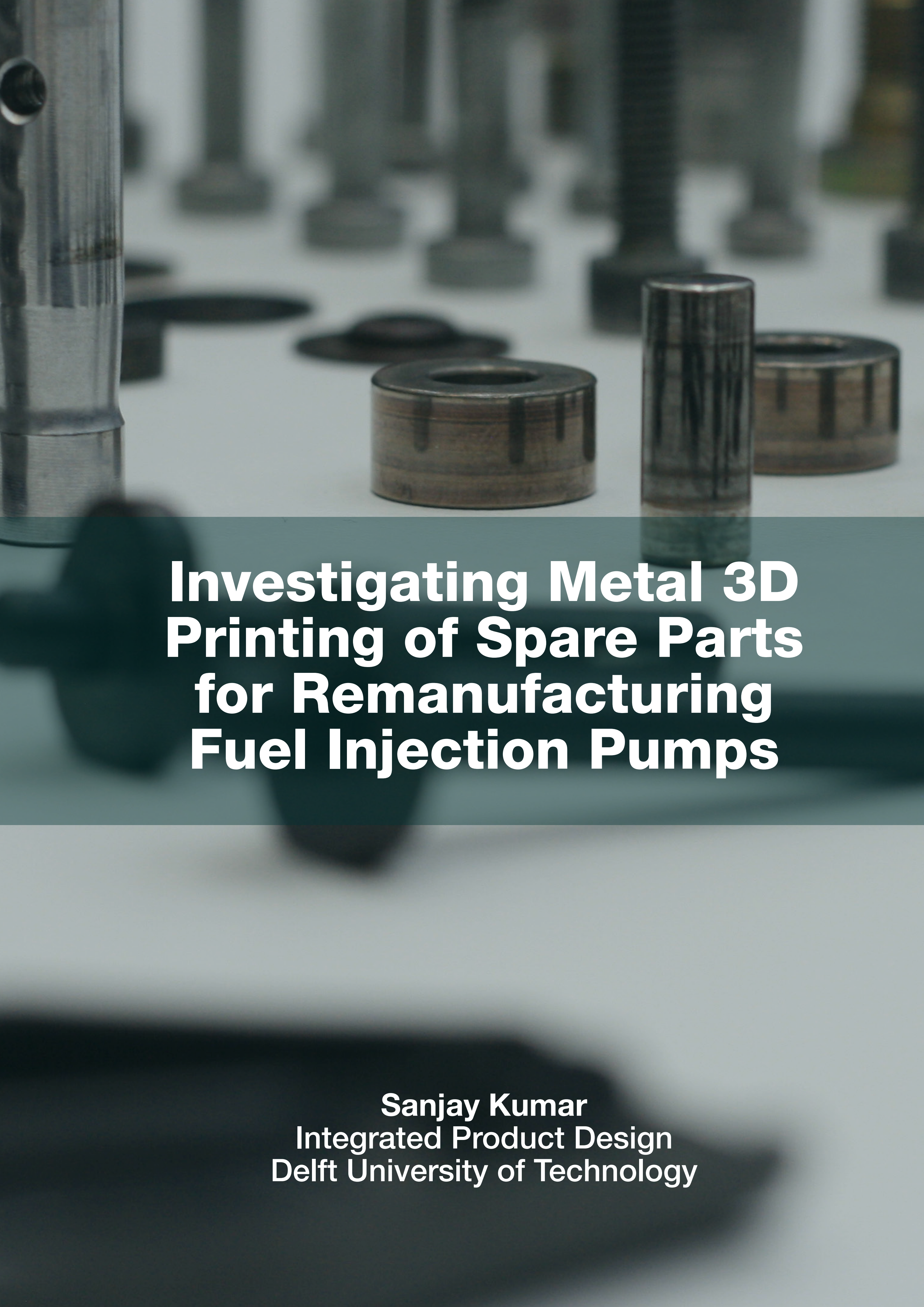

Investigating Metal 3D Printing of Spare Parts for Remanufacturing Fuel Injection Pumps

Sanjay Kumar
Integrated Product Design
Delft University of Technology

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Sanjay Kumar

MSc Integrated Product Design

Faculty of Industrial Design Engineering

Delft University of Technology

Landbergstraat 15, 2628CE Delft

the Netherlands

CHAIR

Prof. dr. ir. Conny Bakker

MENTOR

Dr. Jeremy Faludi

Robert Bosch GmbH

Postfach 10 60 50, 70049 Stuttgart

Germany

MENTORS

Mr. Christian Schindler

Mr. Dirk Lummer

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And to all the others, you know who you are, who have been a constant support and allowed me to achieve my goal. Thank you!

Executive Summary

The goal of this graduation project was to investigate if 3D printing could serve as a promising alternative for manufacturing spare parts needed for the remanufacturing of diesel injection pumps. This project was conducted under the EU ReCiPSS project, along with the support of Robert Bosch GmbH. Robert Bosch GmbH is, among other sectors, a large manufacturer of automotive components. It was in the interest of the remanufacturing industry as well as a sustainability standpoint to investigate this area. The proposition was investigated on three levels and posed the following research questions:

1. Can 3D printing produce spare parts for the pump at an acceptable cost and quality level compared to the existing manufacturing methods? (Feasibility)
2. Does spare part 3D printing make business sense for the Automotive Aftermarket Division of Bosch to pursue as a remanufacturing strategy? (Viability)
3. Is 3D printing for spare parts more environmentally friendly compared to the existing manufacturing methods? (Sustainability)

To answer these questions for the entire VP30 pump and fuel injection pumps in general would have been difficult, given the complexity of the product and time constraints. Thus, tools such as the Disassembly Map and the Hotspot Mapping tool were used to identify potential parts within the pump for which this initial investigation could take place. Using functional importance and environmental impact as criteria, the selection of two parts, an aluminium Locking Cover and an alloy steel Cam Plate were made.

The selected parts were converted from 2D technical drawings to living 3D models. PLA plastic test 3D prints confirmed the accuracy of these 'digital twins'. An exhaustive RFQ procedure followed and the order for metal 3D prints (using Direct Metal Laser Sintering) was placed. In the meanwhile, visits to the remanufacturing facility and Bosch's 3D Competence Centre opened doors to investigate the technology, its limitations, organisational barriers, and future potential. The metal printed parts arrived at our doorstep and were analysed on the three pillars mentioned earlier in the research questions.

The investigation found that metal 3D printed parts can meet the desired performance specifications. However, post-processing treatment such as annealing, case hardening and some machining might be required for specialised functions like the Cam Plate. The costs of metal 3D printing are not yet competitive with conventional manufacturing and are viable only for specific scenarios. These scenarios take the shape of lack of suppliers, urgent part demand, high tooling costs, and so on. Moreover, the non-competitive cost also brings to fore the organisational barriers within Bosch. Primarily, the automotive release procedure which requires significant investment of time and money to make a change. Lastly, on the sustainability front, middle volume production (~200-1000 units) was shown to be more sustainable than conventional manufacturing for the same volume. However, if the full life cycle of the tools and higher production volumes were to be considered, the opposite conclusion could be reached.

The investigation shows that in 2022, 3D printing metal spare parts is feasible but needs specific scenarios to be viable and sustainable. However, with improvements in technology and greater acceptance of 3D printing as a core industry technology, these pains can be resolved and allow for better and long-lasting products with lesser environmental impact. The advent of the 2030's will be exciting in this regard.

Report Structure

This report is structured in line with the double diamond design approach (Zijlstra & Daalhuizen, 2020).

The first section 'Introduction' introduces the various elements of the project and ends with a problem statement.

In the 'Part Selection' section, the product is analysed using design tools and methods to perform a selection of parts that are suitable for further development for 3D Printing.

The 'Design and Prototyping' section shows the processes and results of the design and prototyping segments culminating in the final version of the developed prototype complete with a technical data package.

The 'Testing and Evaluation' section evaluates the developed prototypes against the three pillars of design and sustainability as the fourth pillar to showcase the application of the results of this project in the broader context.

Lastly, the report ends with a conclusion and reflection of the entire project.

All citations in the report are in APA 6th edition style.

The appendices can be found in a separate document, listed alongside this main report. Confidential information that cannot be published in this report can be found in the separate Confidential Appendices document.

High resolution images of all the figures in this report can also be found in a separate document named 'List of Figures' listed alongside this report.

Project Deliverables

The aim of this graduation project was to study the possibility of using Metal 3D printing for spare part production. Specifically, it studied a Diesel Injection Pump namely, the Bosch VP30.

To aid this study, this project delivers a Disassembly Map (de Fazio, Bakker, Flipsen, & Balkenende, 2021), a new design tool developed at the TU Delft and Philips to understand the product architecture and make a visual representation of how the various parts of a product are interconnected and the steps required to reach them.

Alongside the Disassembly Map, a Hotspot Map (Flipsen, Bakker, & de Pauw, 2020) has been created to detail the entire disassembly process in five categories: time, activity, functionality, environmental impact, and economic value. This allows us to see which parts of the pump are important in the context of spare part production and environmental sustainability.

A Life Cycle Assessment is also conducted to compare the existing (conventional) method of spare part production to the newer (additive manufacturing) method. This gives scientific proof if the new production method is more environmentally sustainable in comparison to the conventional method.

The project also aims to deliver some guidelines for designing for Metal 3D Printing which is derived from the learnings of the design and prototyping phase. A reflection on the utility of the Product Journey Map (Kooijman, 2022) is also included.

Lastly, the project delivers a technical data package for the selected spare parts which contain information such as the 3D Models. This goes hand in hand with the physical prototypes (both PLA plastic and metal) for the selected parts.

The final project brief, approved by the Board of Examiners can be found in *Appendix 1*.

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Chapter 1: Introduction

This chapter of the report introduces the various elements of the project namely the client organisation, their business motivations, the product i.e., the diesel injection pump, the context in which the project is set in and lastly, combines all of these into a succinct problem statement.

1.1 Stakeholders: About Robert Bosch GmbH

The client organisation for this graduation project was Robert Bosch GmbH, specifically the Automotive Aftermarket (AA) arm which falls under the Mobility Solutions division of the company. Robert Bosch GmbH (hereafter Bosch) is a 135-year-old manufacturer of automotive, household, and industrial equipment.

There are various other stakeholders with interests in the outcome of this project. These stakeholders range from Bosch's various third-party suppliers, their subsidiary organisations such as Koller + Schwemmer GmbH (hereafter KOSH) and 3D Competence Centre (hereafter 3D Centre) in Nürnberg, their large network of service locations and garages, their customers (in this case, mainly automotive manufacturers such as BMW and VW) and finally, the end consumers. The focus of this section however lies only on the organisation, namely Bosch's AA division itself.

Bosch is the largest automotive supplier in Europe (Taylor, 2021). Within it, the AA arm provides aftermarket shops and repair facilities in over 150 countries worldwide ranging all the way from spare parts to full scale diagnostic equipment. With more than 17000 partners, they deliver around 650,000 unique spare parts to customers around the world. Under the aegis of their 'Automotive Service Solutions' operation, they supply testing equipment, software, and training. They are also responsible for running 'Bosch Service', an independent repair shop chain with more than 16000 franchises ('About Us | Bosch Performance - Auto Aftermarket Division', n.d.).

Koller + Schwemmer GmbH (KOSH) is a subsidiary of Bosch in the automotive aftermarket business especially in the areas of repair and maintenance of diesel injection pumps.

The 3D Competence Centre in Nürnberg is a department within Bosch entrusted with the responsibility of researching new areas of application of 3D printing to Bosch's product lines. These organisations were involved and consulted throughout the duration of this project.

1.2 Business Case: The AA Division's Motivation

1.2.1 The Aftermarket Industry

The aftermarket sector refers to the sale and service of parts of automotive nature in parallel and after the initial sale from the OEM (Original Equipment Manufacturer). These include replacement parts, spare parts, compatible upgrade parts, routine maintenance work etc. According to research from Coherent Market Insights (2020), this industry in 2019 had a market size of US$ 515.5 Bn and is expected to grow at a CAGR of 5.7%. With a sizeable operation and clientele (the likes of BMW and the VW Group), the scale of the Bosch AA Division's work is large. This is especially evident by looking at the product that is the subject of this project.

The Bosch Diesel Injection Pump line has sold more than 45 million units in the period from 1962-2002 (Robert Bosch GmbH, 2003). Thus, this extensive scale provides Bosch the influence to create impact in the automotive industry. The automotive industry, due to higher costs of vehicles and less disposability has, over the years, developed a framework and culture for aftermarket works such as repair, refurbishment and service, something that is conspicuously absent in consumer electronics today. Given the longer lifetimes of automotive and industrial components (10-15 years on average), there is a constant need for replacement and maintenance for these machines. With Bosch's position as one of the leaders in this industry, their aftermarket business is an important arm of their business model.

According to the Bosch Annual Report 2021 (Robert Bosch GmbH, 2022), the Mobility Solutions division which the AA arm is part of is responsible for 58% of the revenue of the organisation, thereby having great influence

on the financial performance of the company. The report also stated that the 'development of the AA sector was pleasing.' As a result of this recurring revenue stream, the aftermarket industry is important to Bosch for their financial bottom line.

On a parallel note, the mobility sector might evolve to become more electrified in the future. However, the needs of developing countries and other industrial applications will still need diesel power before they make the transition to fully sustainable power (Elliott, 2021). These diesel power units have a long life and thus, keeping them well-maintained and efficient goes a long way in ensuring their environmental impact is reduced. This can be achieved through the re-manufacturing of these pumps and producing spare parts needed for their upkeep.

1.2.2. The Remanufacturing Industry

Re-manufacturing is one of the product life extension strategies of the circular economy where used products are restored to as-new product quality. Remanufacturing is the process of receiving old/used components, reusing parts that are still functional, replacing the non-functional parts with newer ones, packaging them again and selling them again in the market (Shumon, 2011). This can be understood clearly from *Figure 1*. Today, re-manufacturing is widely performed (in automotive and other industries) as a means of prolonging life of manufactured products and evidence shows this meets both environmental and financial bottom lines for organizations (Ahuja & Terkar, 2020; Liu et al., 2016). Remanufacturing is one of the strategies used by Bosch for the AA sector.

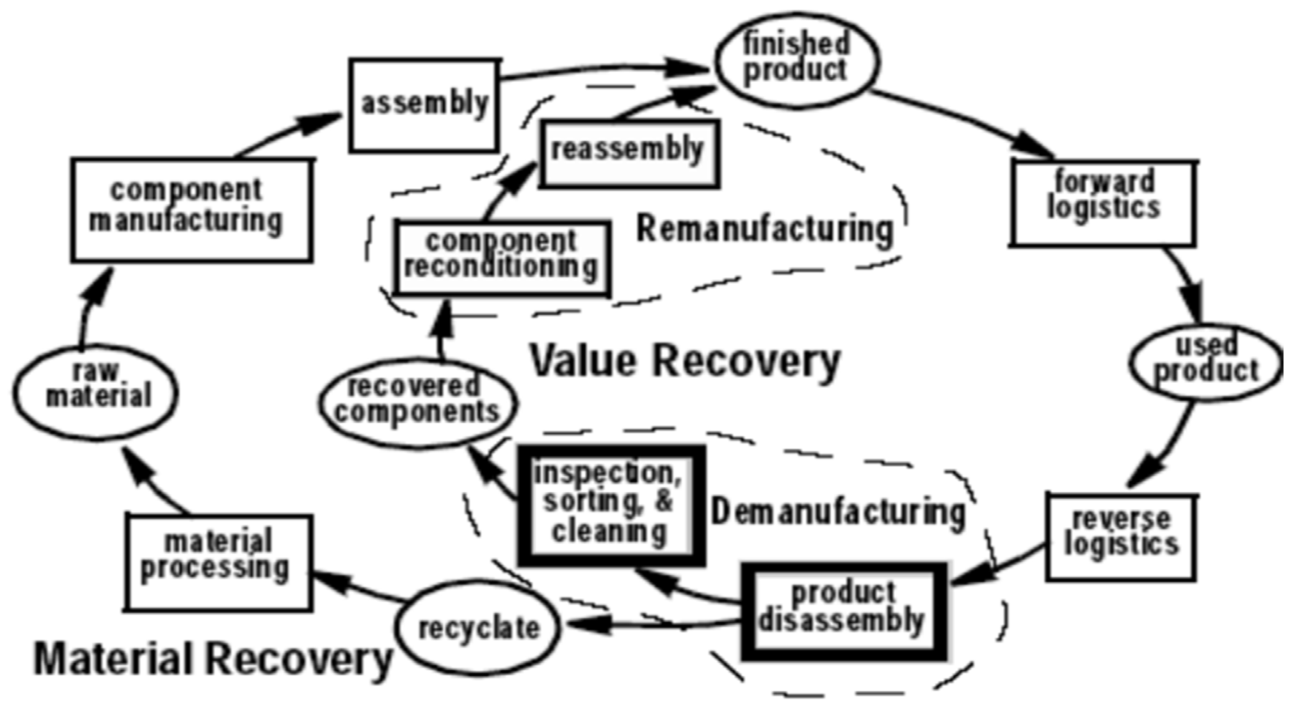


Figure 1: A typical manufacturing - remanufacturing system (Shumon, 2011)

Figure 2: Covering Cap

1.2.3 The Value Proposition

Spare parts need tooling setups and a considerable inventory to be maintained to allow for a smooth supply to meet the demand. Keeping the tooling and inventory live for these spare parts increases the costs, leading to higher part prices. This was especially evident when we took the example of a covering cap (see *Figure 2*) for the VP30 pump. With the help of data gathered from Mr. Dirk Lummer at Bosch, it was found that fewer than 10 units of this part were ordered in the year 2020. As a pressure die cast aluminium part, the cost of tooling is high for such a small order quantity. If spare parts are not readily available or suppliers are no longer producing the part, the dies must be newly produced leading to high incurred costs. On the other hand, not keeping these supply lines live would mean that Bosch would be unable to meet the demand for the parts. This leads to either fully new products being manufactured, or the existing products being scrapped. This could be a hindrance to the movement toward the circular economy for the automotive industry.

By utilizing new and advanced manufacturing methods that can scale better with the demand projections and allow for just-in-time production, the tooling and inventory costs can be reduced. Auto manufacturers such as VW and GM have already benefitted from reduced tooling costs to the tune of $300,000 by using 3D printing (Jackson, 2017, 2018). If these new manufacturing methods allow spare parts to be produced to the existing quality levels at a comparable cost, the cost and space saving potential for Bosch could be significant. This was the primary interest for Bosch to pursue this project.

1.3 Product: The VP30 Distributor Pump

The focus of the project was the manufacturing of spare parts for re-manufacturing the Bosch Diesel Injection Pump line. Specifically, it was concerned with the VP30 inline pump (see *Figure 3*). This pump is an inline distributor pump designed for passenger/commercial vehicles with four-to-six-cylinder diesel engines. The pump is used in conjunction with direct injection engines where higher fuel pressures can be obtained and thus, better atomization of the fuel takes place. This leads to better thermal efficiency of the engine.

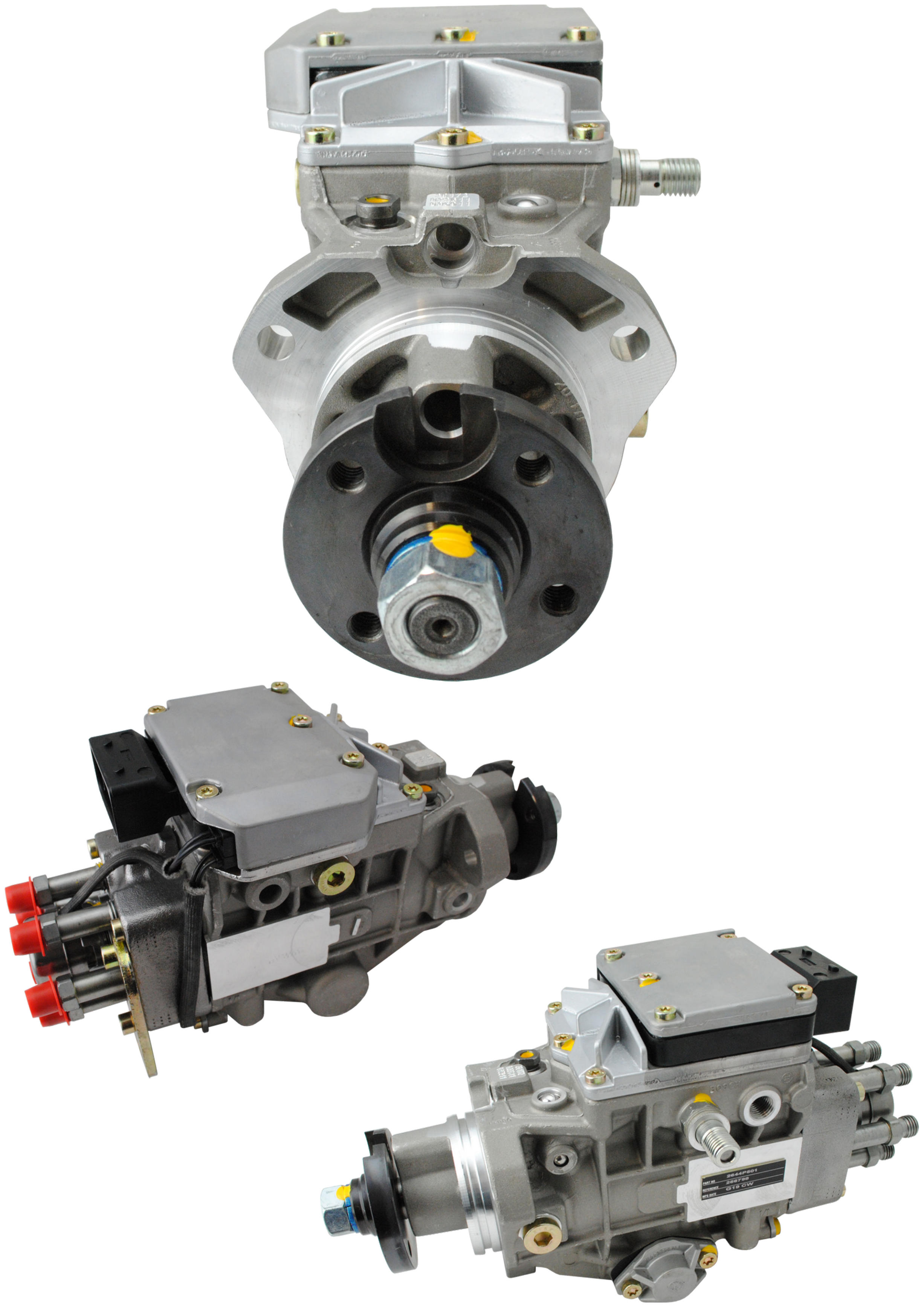


Figure 3: Bosch VP30 Diesel Injection Pump

1.3.1 A Brief History

The Diesel Injection Pump line was first introduced in 1962 with a completely mechanical design and has been in constant development with newer revisions to its design making it more efficient and accurate. Today, the pump can deliver fuel with fractional accuracy. The designs of its auxiliary control mechanisms have also evolved moving from mechanical controls to electric to solenoid-based systems which offer tremendous sensitivity in performance.

The 'solenoid-valve controlled' VP29/30 pump that we are focussed on was first introduced to market in 1998. Its close cousin, the VP44 powered the BMW 320d to a victory in the 24hr Nürburgring race in 1998 proving to the world that diesel powered cars can be powerful and reliable (Robert Bosch GmbH, 2003). The VP30 line has since developed a reputation of being a reliable workhorse. The Distributor Pump series has grown alongside the automotive industry at large and has had more than 45 million units shipped in its active lifecycle from 1962-2002.

1.3.2 The VP30 Pump: Details and Workings

The specific pump that we are using is labelled VE6/12M1250R1 which means that it is a distributor injection pump with an axial piston pump for a 6-cylinder engine that has a pump plunger diameter of 12mm controlled by a high-pressure solenoid valve with an upper nominal speed of 1250RPM in clockwise rotation (see *Figure 4*).

The pump is part of the diesel powertrain and feeds the fuel to the nozzles which inject the fuel into the cylinders of the engine. An understanding of the context in which the pump operates can be obtained through *Figure 5*. The pump shown is a VP44 pump but the VP30 operates in the same context.

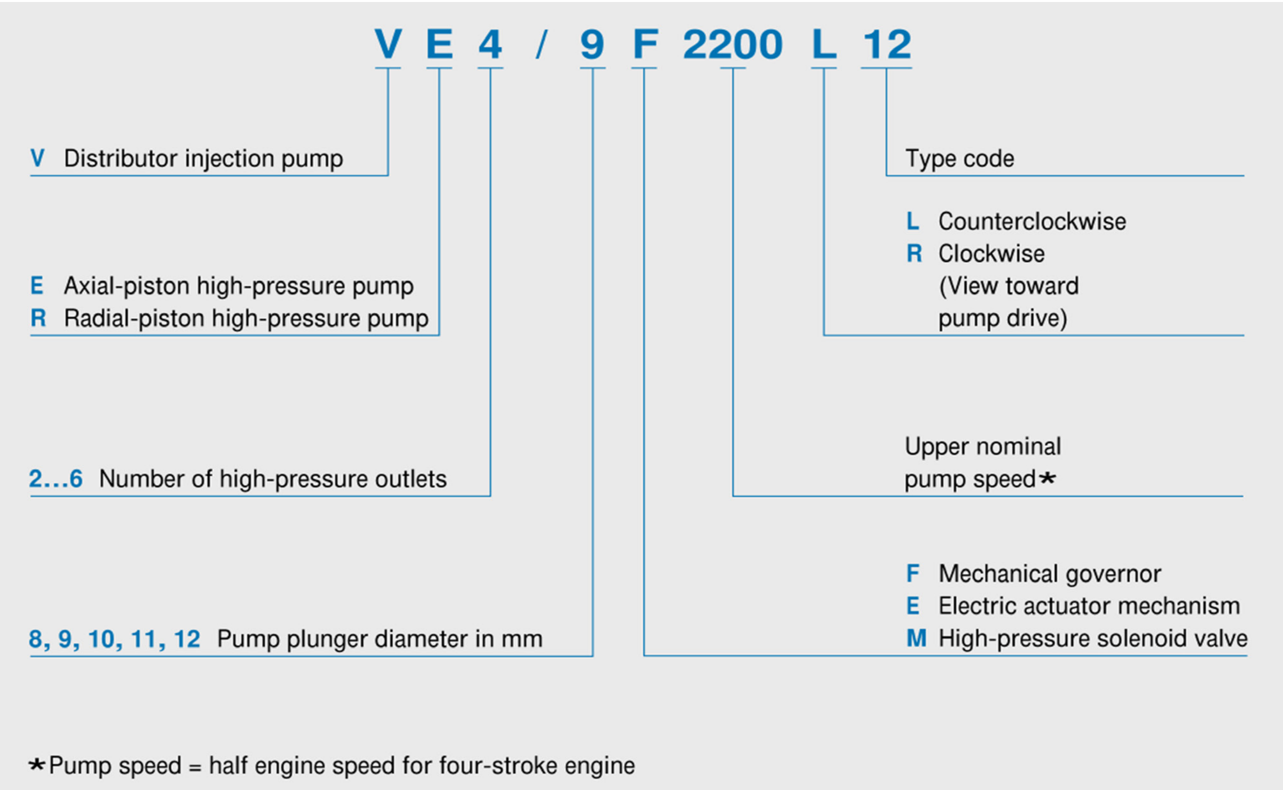


Figure 4: Code for Distributor Injection Pumps (Robert Bosch GmbH, 2003)

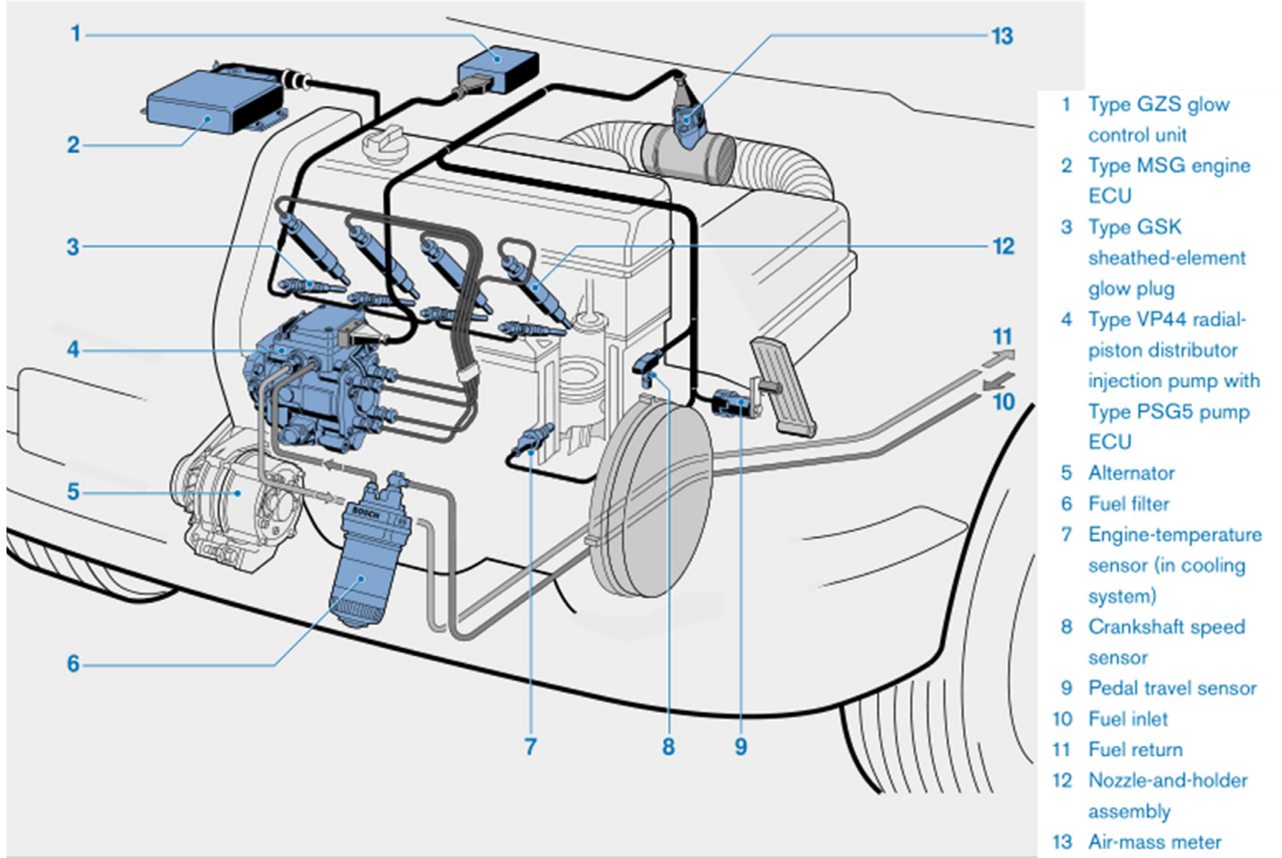


Figure 5: Pump Operational Context (Robert Bosch GmbH, 2003)

The pump works in a series of steps. In the first stage, the pump drive shaft (powered by the engine crankshaft) drives a vane type supply pump which feeds fuel from the fuel tank into the high-pressure stage. The high-pressure pump stage, in this case, an axial plunger which both rotates and reciprocates by virtue of a cam-plate profile, squeezes the fuel creating high pressure which is then fed to the delivery valves via a hydraulic head. These valves carry the fuel through high-pressure lines to the nozzle which empty the fuel into the cylinders. A timing device ensures that the delivery of fuel is adjusted with the demands of the engine. All the controls on the pump are handled by the pump ECU which communicates with the engine ECU. This can be better understood from *Figure 6*.

In addition, a cutaway view of the VP30 pump is shown in *Figure 7,* which highlights the construction of the pump. Various internal parts of the pump can be seen in this view. Some of the important parts of the pump with respect to the functionality are highlighted. The distribution plunger and the cam plate which were mentioned above can be seen here.

A complete in-depth understanding of the construction, working and the control mechanisms of the pump can be found in the Bosch Yellow Jacket Book for the Distributor-Type Diesel Fuel-Injection Pumps (Robert Bosch GmbH, 2003). All the figures in this section were also sourced from Robert Bosch GmbH (2003).

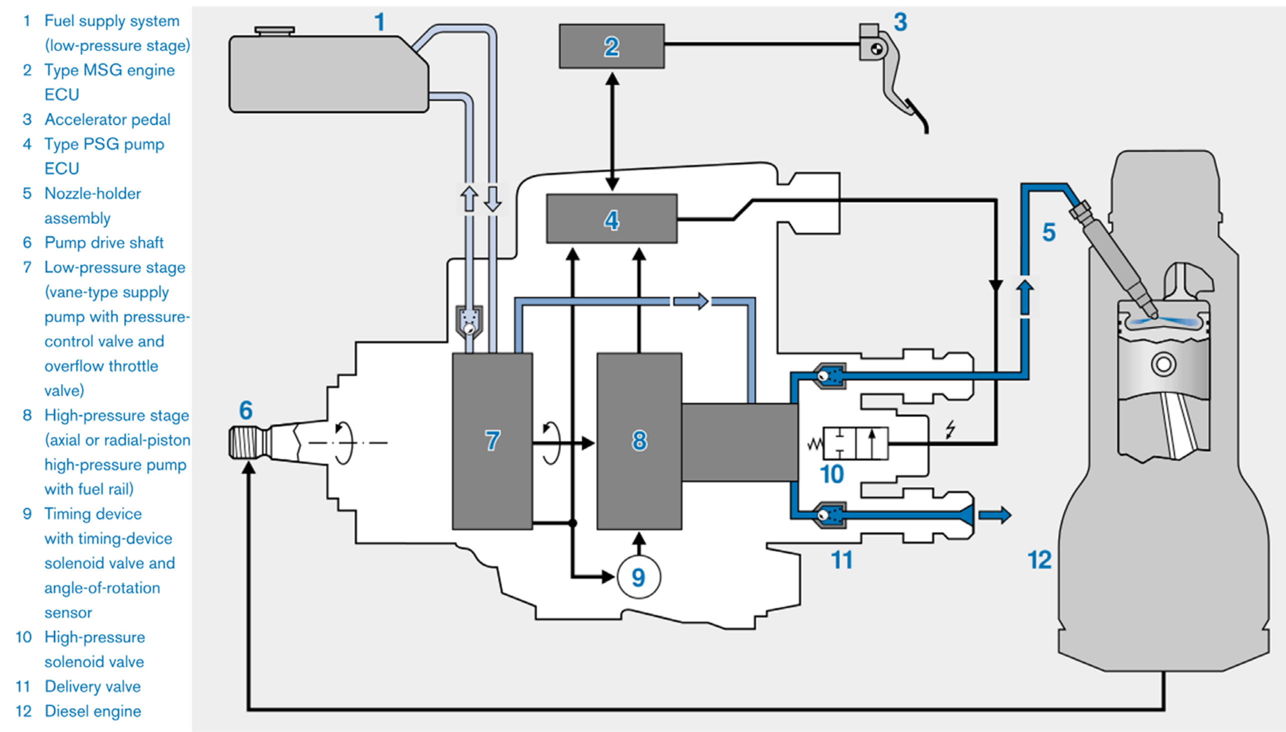


Figure 6: Pump Schematic Diagram (Robert Bosch GmbH, 2003)

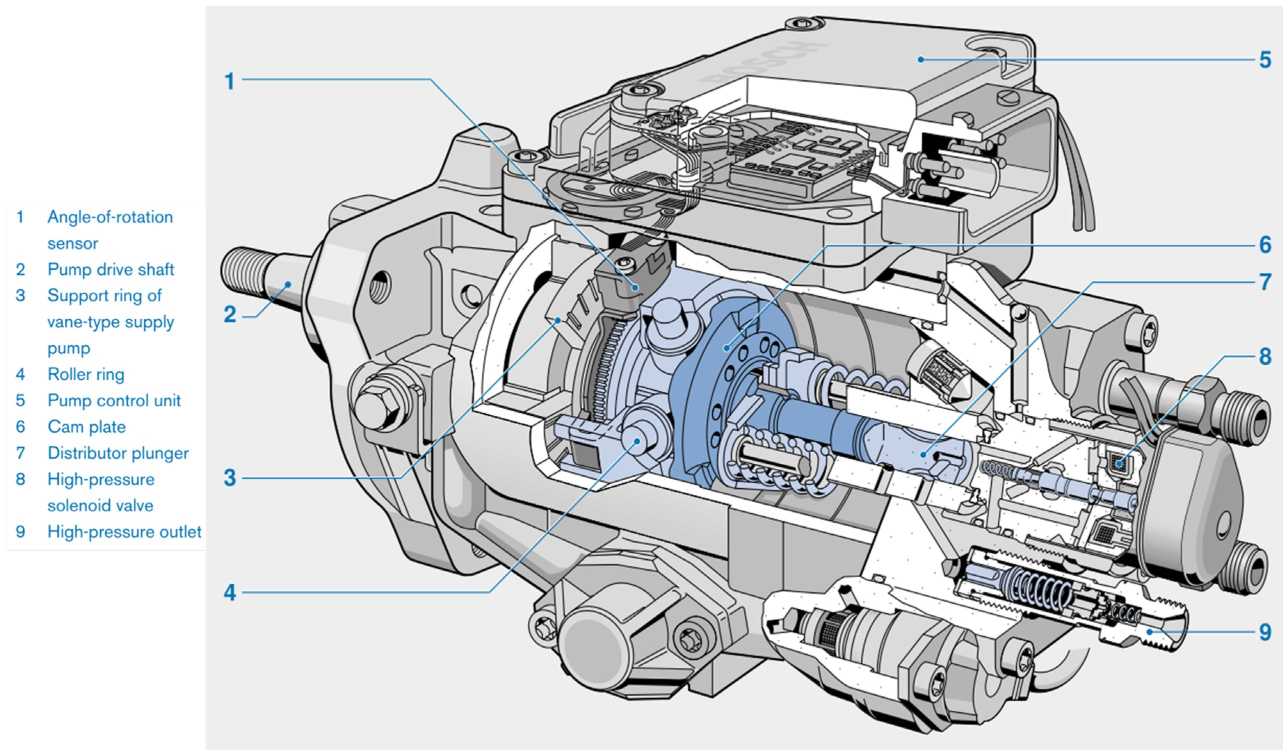


Figure 7: VP30 Pump Cutaway View (Robert Bosch GmbH, 2003)

1.4 Context: 3D Printing Spare Parts for Remanufacturing of the Diesel Pump

With the information about the organisation, the motivation of the AA division to pursue this project and the VP30 pump itself, it was possible to define the context in which this project operated in. The project encompasses a multitude of themes ranging from circular economy strategies such as remanufacturing, the sustainability metrics (environmental and financial) of such a transition, the use of additive manufacturing technologies such as 3D Printing to produce the spare parts and of course, the spare parts themselves.

It is imperative in today's age that organisations move toward the circular economy to protect both the environment as well as their own business interests. Remanufacturing, as previously mentioned is a circular economy strategy to prolong the life of products so that their impact is divided over longer periods of time. With the scale of the sales of the VP30 pump and its expected End of Life approaching (being almost 25 years old), it was extremely important to produce a strategy that can deliver both environmental (prolonging pump life) and financial (high quality inexpensive remanufacturing) bottom lines for Bosch.

With personal mobility moving towards electrification, it might seem counterintuitive to extend the lifespan of a 'diesel' injection pump. However, developing countries (where electricity access is not reliable) still rely on diesel power for mobility especially for cargo transportation and agriculture. Thus, there is some environmental benefit to be gained by extending the product lifetime. On the other hand, newer efficient diesel pumps can be used for this purpose. In that case, the project contributes to the circular economy by allowing these older pumps to be remanufactured into the newer efficient variants if the design permits.

Moreover, the VP30 distributor pump is still used in diesel engines for older commercial and passenger vehicles, especially in developing countries around the world like India. Thus, having these pumps stay operational is of great importance till these systems are phased out by newer systems. This was also important for Bosch to maintain its reputation as a reliable and trustworthy brand with long lasting products.

The VP30 pump by virtue of being a mechanical drive device contains components that might require replacement or repair. In normal operation, the pump is maintenance free due to the fuel acting as a lubricant. However, fuel contamination or pressure loss can lead to component damage. Currently, these spare parts are manufactured using traditional methods and require inventory and storage. The resource cost to maintain these are high. With the pumps having a distributed use profile with some pump units being used more heavily than others, the replacement cycles are also distributed. This made it difficult to gauge the demand for these spare parts and consequently, maintain sufficient inventory. This was confirmed by Mr. Dirk Lummer with data of production quantity from previous years. Bosch used forecasting to predict the demand for these parts but often, these predictions needed a safety buffer to match the actual demand of these parts.

By utilizing new and advanced manufacturing methods that can scale better with the demand projections and allow for just-in-time production, the tooling and inventory costs can be reduced. For spare part production in small volumes, 3D printing is a promising technology that can be used to achieve the desired results without the associated environmental impact of traditional manufacturing. However, this depends on variables like part geometry and material etc (Khosravani & Reinicke, 2020).

Thus Bosch, as part of the EU ReCiPSS project in collaboration with the TU Delft sought to introduce this line of thinking into their diesel pump line. The main desired outcome for Bosch was to produce spare parts for the diesel pump on demand to aid remanufacturing while still reaching a necessary cost and quality base with (hopefully) better sustainability metrics.

The selection of the VP30 pump was the first step towards the incorporation of additive manufacturing for spare part manufacturing to aid product remanufacturing. The VP30 has sales scale and product age to drive the adoption of these newer techniques. If this project is successful, Bosch can incorporate this line of thinking for its other products such as the radial distributor pump (VP44) as well since it shares a lot of common parts. Ultimately, this thinking can proliferate into their entire product stack.

With Bosch's influence in the AA industry, this can ultimately move the entire industry to adopt these techniques, thus accelerating the transition to a more circular automotive industry. This context is visualised in *Figure 8*.

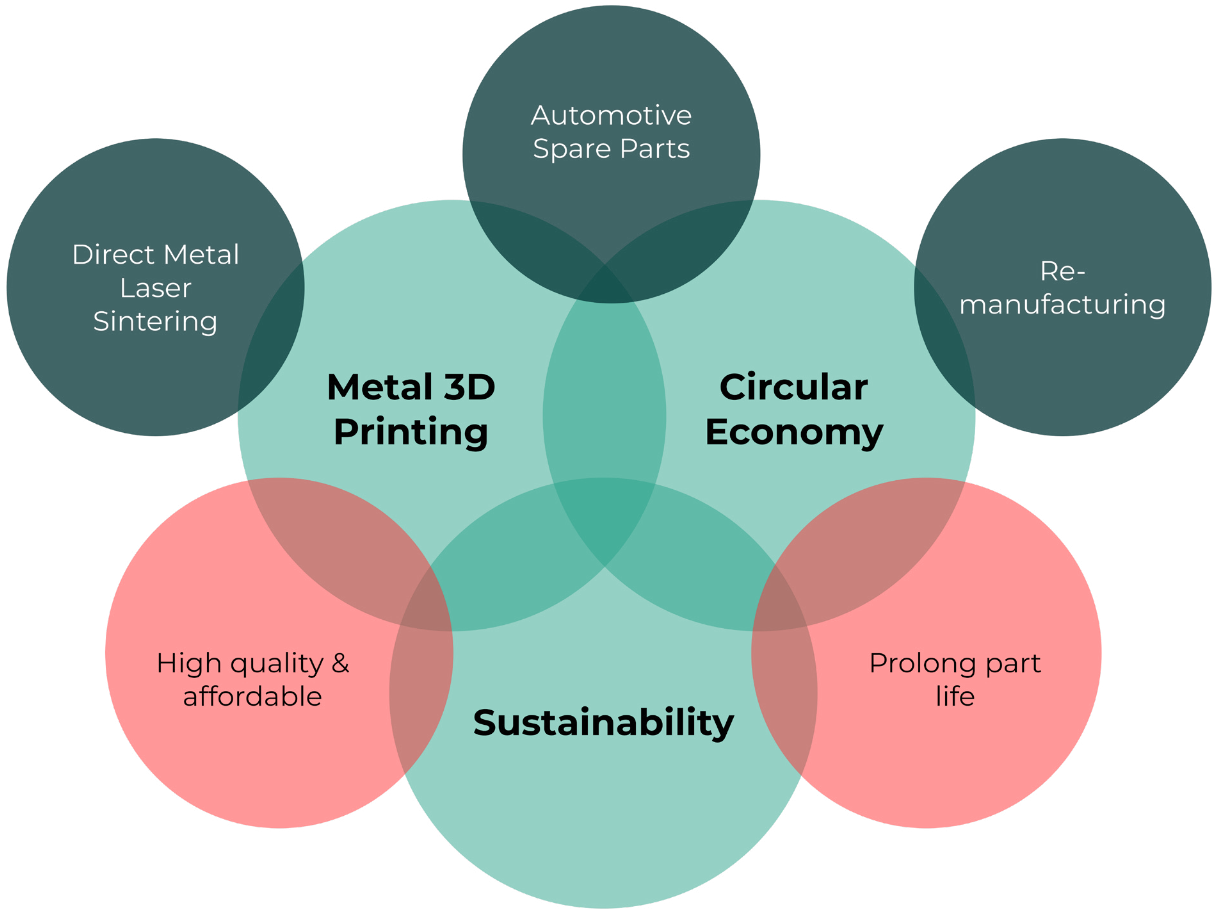


Figure 8: Project Context

1.5 Problem Definition

Combining all the information from the previous sections, a problem definition was arrived at.

The main issue the project addresses is the feasibility and viability of producing spare parts for the diesel injection pump (Bosch VP30) through advanced manufacturing techniques such as 3D printing. The secondary issue that the project addresses is environmental impact as it aims to discover if these advanced manufacturing methods are more environmentally friendly in comparison to traditional manufacturing methods.

In summary, the project aims to answer the following problems:

1. Can 3D printing produce spare parts for the pump at an acceptable cost and quality level compared to the existing manufacturing methods? (Feasibility)
2. Does spare part 3D printing make business sense for the Automotive Aftermarket Division of Bosch to pursue as a remanufacturing strategy? (Viability)
3. Is 3D printing for spare parts more environmentally friendly compared to the existing manufacturing methods? (Sustainability)

The scope of the project is limited to analysing the components of the pump to select parts that are most suitable and necessary to be produced through 3D Printing. This selection is performed using multiple design methods and tools. After the parts are selected, they are designed and prototyped iteratively to be able to reach the desired levels of cost, performance, and environmental impact. The final iterations of these parts and the project itself are then evaluated against the design pillars namely feasibility, viability, and sustainability. Desirability is not evaluated since the case for Bosch AA's desire to pursue this has been clarified already.

The designs are printed to meet the necessary performance requirements. However, the process setup for industrial level production is out of scope of the project. This is because, the printed parts might need post-processing operations such as annealing, grinding etc to meet the required specifications.

The challenges of this project arise in the study of feasibility of advanced manufacturing (especially 3D Printing) to become an economically feasible and environmentally sustainable process to replace traditional manufacturing while ensuring intended production volumes can be produced. With current technology, all the parts of the pump do not have the same value proposition to be produced through additive manufacturing. Additionally, depending on production volumes, current 3D printing technology might be more expensive per part compared to traditional manufacturing. Lastly, given the scale of Bosch, there may also exist organisational barriers toward the implementation of such a remanufacturing strategy.

The limitations of the project stem mostly from the limited duration of the project. The complete redesign of all parts (that are suitable for manufacturing via 3D printing) is not possible due to project time considerations as well as the selection of only priority parts for 3D Printing. Another limitation that might hamper the design-prototyping cycle is the lead time for prototyping since metal 3D printing facilities are not as easily accessible as plastic 3D printing. However, these limitations are likely to be similar to limitations in general business circumstances as well.

Chapter 2: Part Selection

This section of the report deals with the process of selecting some parts of the VP30 pump for further development (design and prototyping) for 3D Printing. A combination of design tools were used to perform this selection. Chief among them is the Hotspot Mapping tool, which in combination with the Disassembly Map allowed for a deep understanding of the product architecture and the impact of each individual component. Desktop research about metal 3D printing along with discussion with experts from Bosch further clarified the selection process. The entire selection process was a continuous endeavour with the hotspot mapping and the expert opinion taking place in parallel, culminating in a selection of two parts of the pump. However, this section describes each method separately for ease of understanding and documentation.

2.1 Disassembly Map

2.1.1 Description

The Disassembly Map was used to understand which priority parts were buried deep in the product architecture and thus, need extra attention in cases of repair and maintenance. According to research from de Fazio, Bakker, Flipsen, & Balkenende (2021), the Disassembly Map is a tool created to facilitate (re)design for disassembly. It allows users to analyse and design products for better service and repairability. Through its visual representation of the product architecture, the tool guides and informs designers about the disassembly process and the location of target components in a product. The tool was created as an outcome of a collaboration between the TU Delft and Philips.

2.1.2 The Value of the Disassembly Map

During the remanufacturing of the VP30 pump, the pump undergoes a complete disassembly to identify worn out and reusable parts. However, there does not exist any literature that maps the product architecture of the pump. For the workers at the factory, there exists a simple step by step guide which informs them of the process to disassemble the pump. To allow designers/workers to understand the fastest disassembly sequence to reach a particular component and inform them of priority parts (i.e., parts with high failure/wear rate, high environmental impact and/or high economic value), there was a need to map out the product architecture in a visual manner. Thus, a Disassembly Map (de Fazio, Bakker, Flipsen, & Balkenende, 2021) of the Bosch VP30 pump was created. This would facilitate a complete understanding of the pump architecture, the integration of the disassembly instructions document, integrate additional data such as part priority and disassembly difficulty in a single document. If change management can be incorporated in this Disassembly Map and if it can be integrated in Bosch's SAP systems, this document can be a good addition to Bosch literature allowing for future work to be conducted on the VP30 pump.

2.1.3 Modifications to the original Disassembly Map

For the VP30 pump, the method adopted to create the map was slightly changed since the priorities for creating the map were not exactly aligned with the original idea. The original Disassembly Map also provided for understanding the time of disassembly, which in the case of the VP30 pump was less relevant due to the moderate volumes and manual remanufacturing. The main aim of the map for the VP30 was to showcase disassembly depth & difficulty and locate target components. The location of target components was done in parallel using the Hotspot Mapping tool which is explained in *Section 2.2*. The VP30 disassembly map was also created by taking into account, the newer version of the Disassembly Map which is still in development (de Fazio, Bolaños Arriola, Dangal, Flipsen, & Balkenende, n.d.). The original version possessed some deficiencies such as the lack of action coding blocks which covered a larger variety of actions, making it unsuitable for the product category of the pump. The version of coding blocks used to define the disassembly map is shown below (see *Figure 9*). The other aspects namely the penalty points, the use of connectors and tools remained the same. The visual structure has also been improved to showcase the depth of disassembly better by incorporating each step as a single action rather than a component being reached.

Single motion disassembly action — Action block shape and color: Hand / Tool

MOST index	Remove	Press/Pull	Tap/Strike	Cut	MOST index
	Hand, Spudger, Lever, Prybar, Plier, etc.	Hand, Spudger, Lever, Prybar, Plier, etc.	Hand, Hammer, etc.	Scissors, Pliers, Knife (up to 80cm cut), etc.	
	No fastener present. Parts are kept in place just by their own weight	Friction fits, Snap fits, Single turn knobs or lid, Buttons, Hinges, Electronic connectors, Adhesives, Zippers, Velcro's, etc.	Connectors requiring a short up-down tapping/striking motion (e.g. nails, washing machine bearings)	Electronic cables, wires, tighteners, surfaces to be cut using scissors/knife, etc.	
1	The part to be removed is light requiring mainly fingers action (indicatively F<5N) and without having to follow a specific controlled removal path	Light press/pull force required (indicatively F<5N), applied mainly using fingers action (also in case a tool is used)	Light tap (not strike), force required (indicatively F<5N), applied mainly using wrist action (also in case a tool is used)	Pliers: light grip force, no cut (e.g. holding in place wire for soldering) Scissors: simple cut requiring light force (e.g. paper or fabric) (No knife, no cutting pliers)	1
3	The weight of the part to be removed is moderate, requiring wrist/hand action (indicatively 5<F<20N) and/or having to follow a specific controlled removal path	Moderate press/pull force required (indicatively 5N<F<20N), applied mainly using wrist action (also in case a tool is used)	Moderate strike force required (indicatively 5N<F<20N), applied mainly using arm action using a hammer (not simple hand tap)	Pliers, Scissors, Knife: Moderate cutting force required (indicatively 5N<F<20N), applied using one hand and requiring one cut action	3
6	The part to be removed is heavy, requiring two hands action (indicatively F>20N) and/or having to follow a specific controlled removal path	High press/pull force required (indicatively F>20N), applied mainly using arm action (also in case a tool is used)	High strike force required (indicatively F>20N), applied mainly using arm action using a hammer (not simple hand tap)	Only Pliers: High cutting force required (indicatively F>20N), applied using one or two hands and requiring up to two cut actions	6

Multiple motion disassembly action — Action block shape and color: Hand / Tool

MOST index	Finger action	Wrist action			Arm action				Power Tool	MOST index
	#Spins	#Turns	#Strokes	#Cranks	#Turns		#Strokes	#Cranks	Std*Screw head diam	
	Fingers, Screw driver	Wrist, Hand screwdriver, Ratchet, T-wrench	Wrench	Wrench, Ratchet	Ratchet	T-Wrench, 2-Hands	Wrench	Wrench, Ratchet	Power screwdriver or wrench	
1	1	-	-	-	-	-	-	-	-	1
3	2	1	1	1	1	-	1	-	<6mm	3
6	3	3	2	3	2	1	-	1	<25mm	6
10	8	5	3	5	4	-	2	2		10
16	16	9	5	8	6	3	3	3		16
24	25	13	8	11	9	6	4	5		24
32	35	17	10	15	12	8	6	6		32
42	47	23	13	20	15	11	8	8		42
54	61	29	17	25	20	15	10	11		54

*Standard screw (length holding threads is 1 to 2 times the head diameter)

Figure 9: Disassemnly Map Action Block Coding

(de Fazio, Bolaños Arriola, Dangal, Flipsen, & Balkenende, n.d.)

2.1.4 Method

The method used for creating the Disassembly Map is detailed below. When the process commenced, there were no disassembly instructions available for the VP30 pump from Bosch. Thus, a disassembly was performed based on the exploded view of the pump. The entire process was recorded on video along with audio commentary of the process (see *Appendix 2*). With this initial disassembly, a preliminary disassembly map was created which detailed just the product architecture and the sequence of disassembly. This preliminary map is shown in *Figure 10*. The preliminary map was created since there was no available literature on the pump disassembly process. Two disassembly iterations were required to understand the architecture of the pump and understand the fastest and most efficient disassembly order. Moreover, there was no knowledge of the tools required for disassembly. This iteration provided the exploration needed to understand the disassembly process of the pump. The colours in the preliminary map represent the information gained from the second disassembly iteration. The green blocks indicate that the position of the part in the map mostly followed the correct disassembly order, and the red block indicated the opposite.

After the creation of the preliminary map, the entire pump was reassembled again, and this was recorded on video as well (see *Appendix 2*). Finally, with better knowledge of the architecture of the pump and disassembly steps by virtue of the preliminary map, the final disassembly operation was performed. In this attempt, all the other parameters of the disassembly map such as the tool, the connector, the penalty points, and the action block codes were also monitored and fed into a MIRO board. The entire disassembly operation was video recorded again while the data was being filled into the MIRO and the Hotspot Mapping tool in parallel. The data of the Hotspot Mapping tool is explained in *Section 2.2*. Part clusters were originally identified during the preliminary disassembly stages. Clusters were defined as groups of parts that could be disassembled in the same disassembly action, in line with the Disassembly Map literature. The formation of clusters was also noticed, and special attention was given such that all components within a cluster also had their own disassembly sequences. These clusters were further refined during the final disassembly iteration. At this stage of the process, additional detailed information was received from Bosch regarding the disassembly procedure and instructions. These provided data on the disassembly steps and the special tools required for disassembly. This helped verify the veracity of the map at the time since the instructions in the map aligned with those provide by Bosch. The information regarding the special tools was updated on the MIRO board. The final disassembly map on the MIRO with all the above information is shown in *Figure 11*.

It is important to note that the disassembly map on the MIRO does not indicate the priority parts of the pump or the recommendations to the tool. This data was obtained from the Hotspot Mapping tool (see *Section 2.2*). Moreover, not all parts of the pump (as described in the exploded view) were present in the pump sample and thus, were not considered for this map. Once the data was obtained from the Hotspot Mapping tool, the complete final visual version of the disassembly map was created using Figma. This can be seen in *Section 2.1.5*.

2.1.5 Outcome

The complete disassembly map for the Bosch VP30 pump can be seen in *Figure 12*. The disassembly map contains all the data regarding the parts of the pump, their disassembly sequences, the action blocks associated with each action, information about the tools and connectors and an indication for priority parts and penalty points.

High quality and independently accessible versions of *Figure 10*, *Figure 11* and *Figure 12* can be found in the separate 'List of Figures' document.

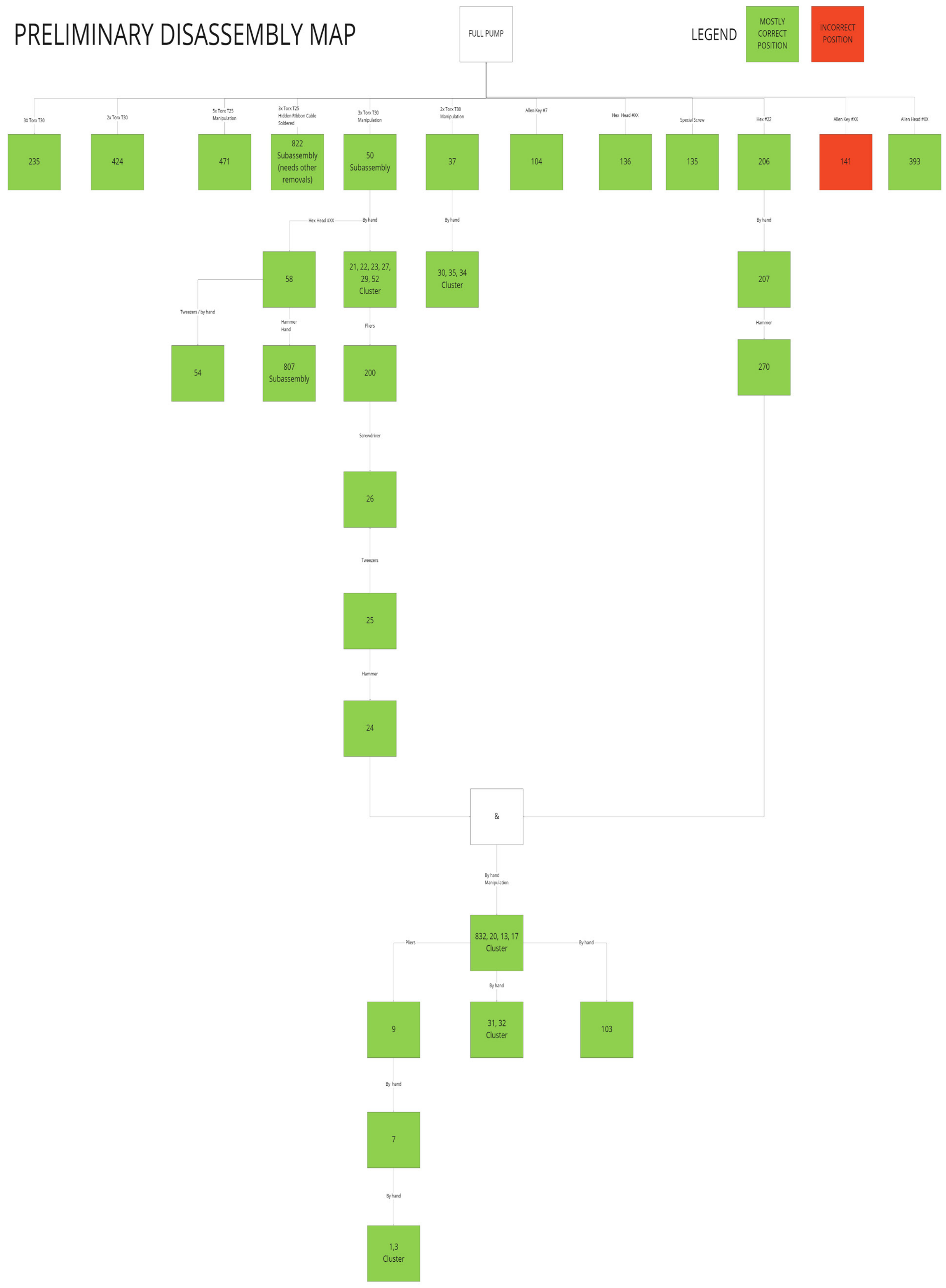


Figure 10: Preliminary Disassemnly Map

Figure 11: Final Disassembly Map on MIRO

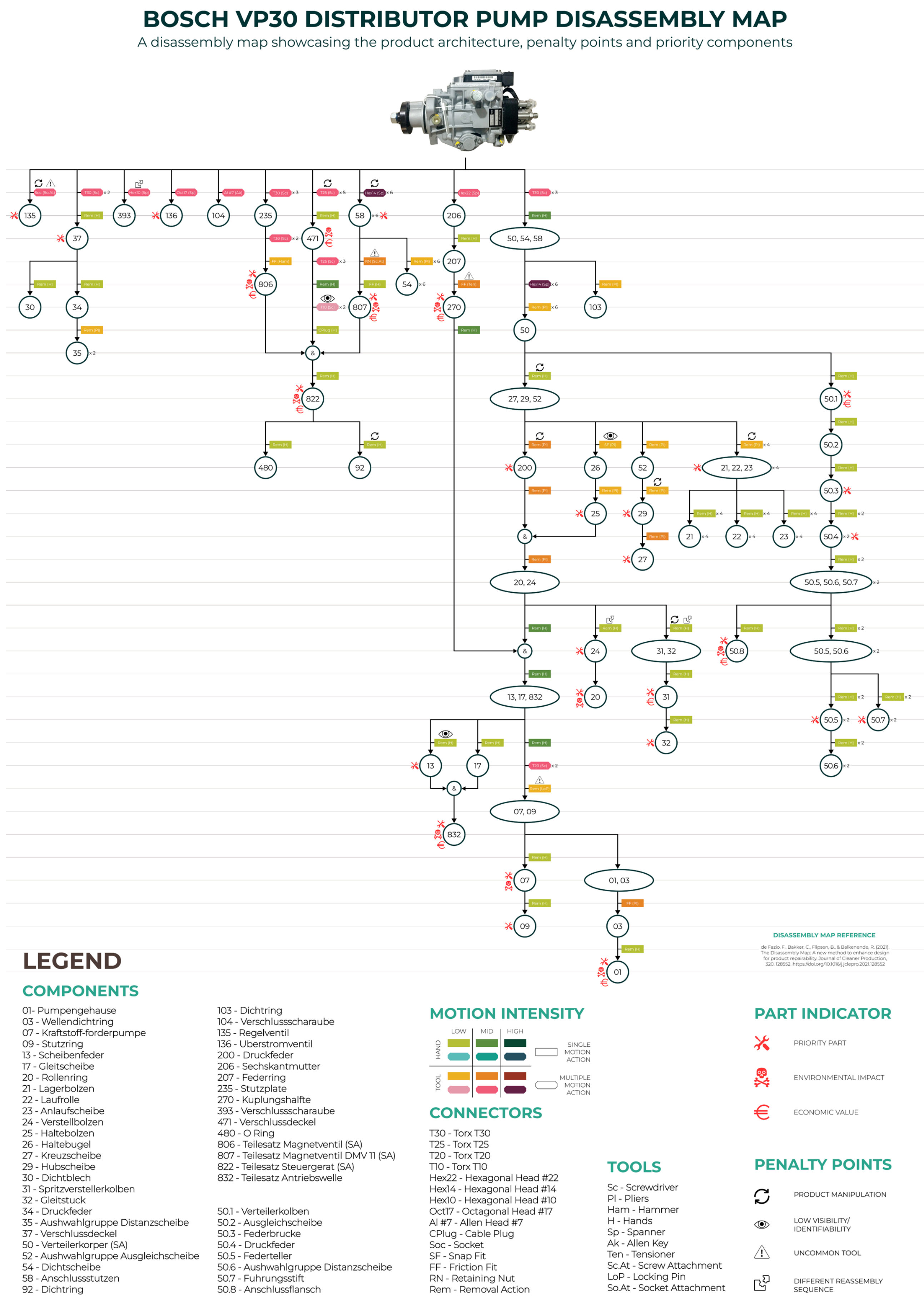


Figure 12: Bosch VP30 Pump Disassembly Map

2.1.6 Observations

An analysis of the final disassembly map showcased a few interesting observations:

- The map had an interesting spread of horizontal and vertical depth. Around half of the components required less than 3 stages to be disassembled. However, the other half followed a very vertical structure with sequential disassembly. Components with high impact (priority parts) as shown from the HotSpot Mapping tool in laid in this vertical structure.

- It was noted that there were many interdependent disassembly sequences as showcased by the '&' character in the map. The formation of clusters was interesting to note as we went deeper into the vertical stack where clusters can be easily separated, and the deepest component can be accessed. Thus, the pump is easy to fully disassemble to its constituent parts once the initial parallel sequences are completed. The clusters in the vertical stack aid in this quick disassembly by removing groups of parts in a single action.

- The motion intensity for most actions in the disassembly (whether hand or tool) were of medium to low intensity. There was only one high intensity motion sequence in the entire product. There was a mix of alternating hand and tool motions which suggest an increased disassembly time (in comparison to only hand motion) due to the constant change between hand motion to tool motion. This changeover time from hand operation to tool operation is codified in Zandin & Schmidt (2020).

- The most common penalty point was that of manipulation since the pump has many faces and edges through which components need to be accessed. The use of special tools provides the penalty points for uncommon tool. The only penalty points for visibility were due to a ribbon cable connector, the shaft key and a retaining bracket which was lost during the disassembly.

- The electronics subassemblies were considered as parts and not disassembled further along with the drive shaft subassembly which is not built to be disassembled.

- Critical components were spread all around the map with a high percentage of priority parts located in the vertical sequential stack as can be seen from the three different indicators. Some high impact parts were also accessible in the early disassembly stages. The priority components selected from the Hotspot Map are visually demarcated with red icons. These parts are explained in the following sections.

2.1.7 Discussion

The Disassembly Map provided a great start to the understanding of the VP30 pump since data on the pump was difficult to obtain. With the completion of the map, there was a better understanding on how the pump was built and assembled. This can be used in the future to develop better access to the target components or used as an educating tool for workers in the remanufacturing facility.

There are a few recommendations that can improve the disassembly map tool further. The coding of the action blocks currently does not encompass the entire gamut of disassembly actions and thus, can be improved further by exploration of more product categories. Specifically, a 'No Action' coding block can be added when an action to remove a preceding component simply reveals the next component in line without needing further action such as hand removal or so. In addition, the vertical grid can be visually modified to showcase the time of disassembly, if necessary, thus giving a visual indication of how much time it takes to reach a target component. This timing data can be obtained from the MOST guidelines (Zandin & Schmidt, 2020).

In the case of the pump, it was found out that the reassembly sequence is not the reverse of the disassembly sequence as is common. In this case, a new penalty point can be introduced to showcase this and allow workers to know where their attention must lie. An attempt at this can be seen in the final outcome in *Figure 12*. Additionally, certain assembly / disassembly sequences are fraught with the danger of losing parts such as opening springs/keys. A provision can be made to showcase this on the disassembly map. This brings to light, the next step in the development of this tool which is the incorporation of a reassembly map which in conjunction with the disassembly map would truly make the repair journey complete.

The limitations of the Disassembly Map are clear from the literature. These include the limited action blocks, the limited product categories modelled and absence of some disassembly actions like de-soldering. However, within the limitations of the tool, the results of the Disassembly Map allowed for a great understanding of the product architecture and the priority parts within the Bosch VP30 pump.

2.2 Hotspot Mapping

2.2.1 Description

The Hotspot Mapping tool was used to identify parts which possess impact in environmental, economic, and functional terms of more than 90th percentile from all the parts of the pump, allowing to select parts which could possibly deliver significant savings through redesign. The Hotspot Mapping tool (Flipsen, Bakker, & de Pauw, 2020) was developed at the TU Delft to facilitate redesign of products while keeping the ease of disassembly and the circular economy in mind. This tool assesses the product architecture and flags components in the product architecture that are critical for disassembly. The criticality of a component depends on its functionality, economic value, and environmental impact as well as the time and the actions required to access it. With this tool, a holistic view of the entire product is obtained with indicators for the critical components. When used in conjunction with the Disassembly Map, the Hotspot Mapping tool provides the raw data and allows us to mark priority components within the Disassembly Map.

2.2.2 The Value of the Hotspot Mapping Tool

The Hotspot Mapping tool allows us to record data about various sections of the disassembly of the pump ranging from action time and difficulty, functional importance, maintenance data as well as material properties. With this vast amount of data, it can pinpoint which components belong to the 80th and 90th percentile of impact. For example, with respect to environmental impact, the tool allows us to see which components possess highest embodied environmental impact and thus, makes the decision to target these parts for certain actions such as repair, reuse, or recovery. Additionally, it allows us to flag priority parts (parts with high maintenance, high failure rate and important for functionality) of the product. Thus, it guides design to make these parts better in multiple ways (better accessibility, better performance, better repair etc). In the context of this project, the Hotspot Map shows us the priority parts which were then considered for further development during the project since there is a possibility for maximum positive change by addressing these parts. The Hotspot Map was used as a selection tool to narrow the scope of parts for further development.

2.2.3 Modifications to the original Hotspot Mapping Tool

The original Hotspot Mapping tool is a spreadsheet-based tool where data can be input in the various fields and the output is shown as either yellow or red flags depending on percentile impact. The same original structure is used for the assessment of the VP30 pump. The 'time to disconnect' field was filled with an estimate of the time since as mentioned previously, the time of disassembly was not the major consideration for this exercise.
For Functional Sensitivity, the field for 'Extra Requirement' was used to divide the functionality aspect into further divisions namely, main assembly functionality level and sub-assembly functionality level. Based on the data from Robert Bosch GmbH (2003), the functionality of these parts was judged. Lastly, it is important to mention that the electronic subassemblies were considered as single parts since they could not be disassembled further reversibly.

2.2.4 Method

The method followed for the Hotspot Mapping tool can be found in the Hotspot Mapping Manual created by Dr. Bas Flipsen (see *Appendix 3*). The creation of the Disassembly Map and the Hotspot Mapping were performed in parallel. The first step was to document the disassembly activity that was performed in both the Disassembly Map and the Hotspot Map spreadsheet. This includes information about the part/subassembly and the activity needed to disassemble it. The documented time for disassembly is an estimate time based on the disassembly activity and thus, not completely accurate data. Secondly, the 'Access Difficulty' data was filled in using the scales as described in the manual. This data included the force required, the accessibility and the precision required for the action. Once the part was disassembled, it was weighed in a precision weighing scale (see *Figure 13*). The material properties of the part were referenced from the detailed Bill of Materials (see *Confidential Appendix 2*) provided by Bosch for the pump. Once the category of material was identified, the Material Properties were documented within the spreadsheet.

Figure 13: Precision Weigh Scale

The Bill of Materials Exploded View (see *Appendix 7*) also provided data about the maintenance requirements. The Bill of Materials categorised parts as A: wear and tear parts; B: spare parts; Z: no spare parts. With this classification, parts marked as A were documented as Level 1 – part wears during use and the other parts as Level 0 – No-to-low maintenance part as per the levels in the Hotspot Map spreadsheet. Since the pump is a high complexity device, it goes without saying that almost all parts contained within are important for functionality. Thus, the functionality data was divided into two parts – the Functionality column and the Extra Requirement column in the spreadsheet. The data was accessed from Robert Bosch GmbH (2003).

Since the pump is divided into various stages/sections as seen in *Figure 6*, the Functionality column documented the level of functionality of the part with respect to the stage that it belonged to. For example, if a part belonged to the high-pressure stage of the pump, it was marked as Level 2 – Main Functionality. Parts such as O-rings, washers, shim rings (though offering important functionality of sealing) were marked as Level 0 – No-to-low functionality since these are cheap, easy to obtain and replace. Parts not part of the main functional stages but still required for functioning were marked as Level 1 – Sub functionality. The extreme complexity of the pump operation thus, necessitated a two-stage functionality check.

In the second stage, i.e., the Extra requirement column, the Level 0 parts from the previous stage were left unfilled. Parts with Level 1 – Sub functionality were further assessed on their functional level within their subassembly. If the part was not important, it was marked Level 0 – Not important. If the part was important, it was marked as Level 1 – Moderate. No part could have the combination of Level 1 – Sub functionality (Functionality column) and Level 2 – Very Important (Extra requirement column). The same logic was applied to parts with Level 2 – Main Functionality. However, in this case, there was no component that could be marked as Level 0 - Not Important in the Extra Requirement column. Thus, the entire data sheet was filled. Notes were added to components where relevant. The flagging system was updated to consider the 'Extra Requirement' column and the results were obtained. These criteria are visualised in *Figure 14* for ease of understanding.

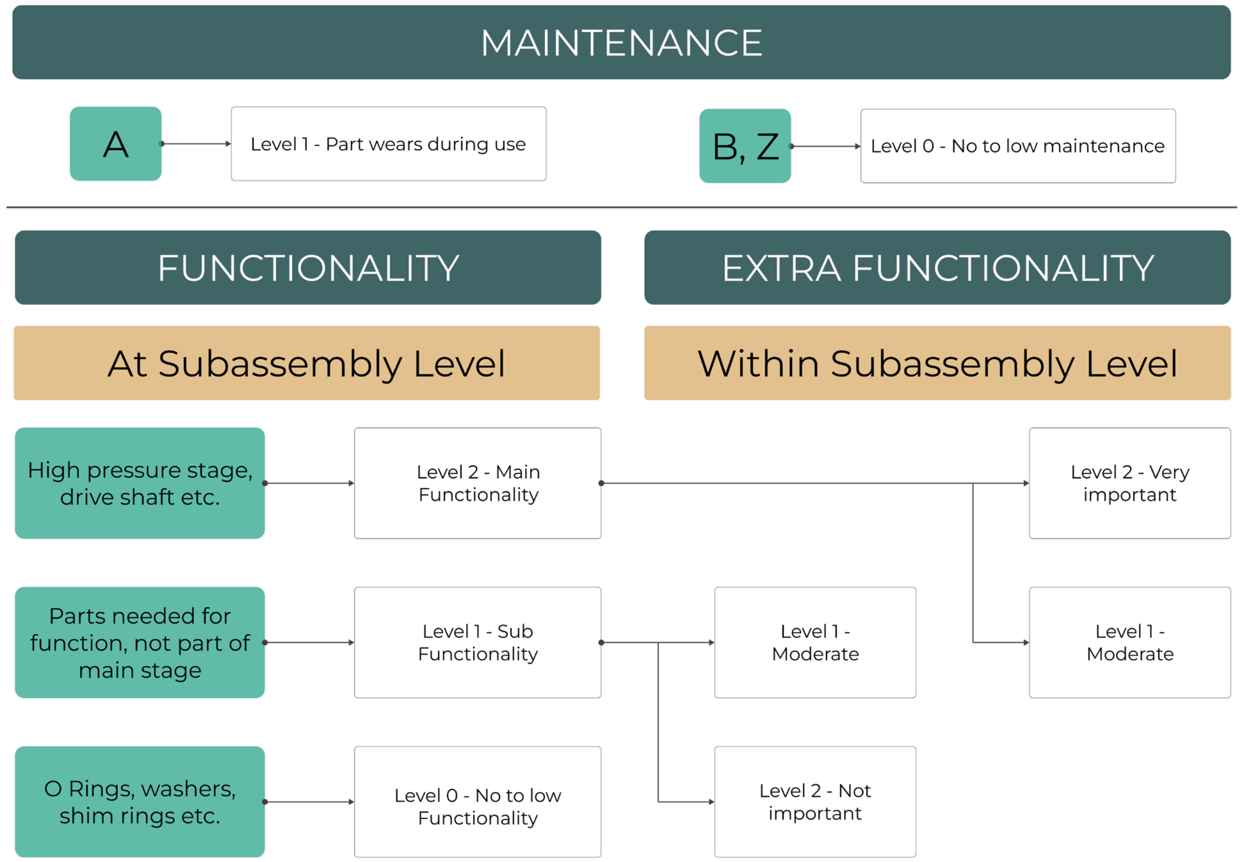


Figure 14: Hotspot Map Input Criteria

2.2.5 Outcome

The outcome of the Hotspot Map tool is the spreadsheet which outputs a flag-based classification of the critical parts of the system. This Excel spreadsheet can be found in *Appendix 4*.

According to the Hotspot Mapping tool, the Bosch VP30 pump possesses the following counts of critical parts under the various categories (see *Table 1*). As mentioned in *Section 2.2.2*, the yellow and red flags indicate a level of impact. Yellow flags indicate that the part falls within the 80th-90th percentile of impact in a particular category, considering all the parts of the pump. On the other hand, the red flag indicates parts that lie in and above the 90th percentile in a category from all the parts of the pump. The category of time has not been considered as discussed previously.

These parts along with the categories they belong to are visualised in *Figure 15*. The parts that were not flagged for any category are not shown. They can be found in *Appendix 4*.

Category	Yellow	Red
Activity	08	02
Priority Part	16	14
Environmental	05	05
Economic	05	05

Table 1: Hotspot Map Output

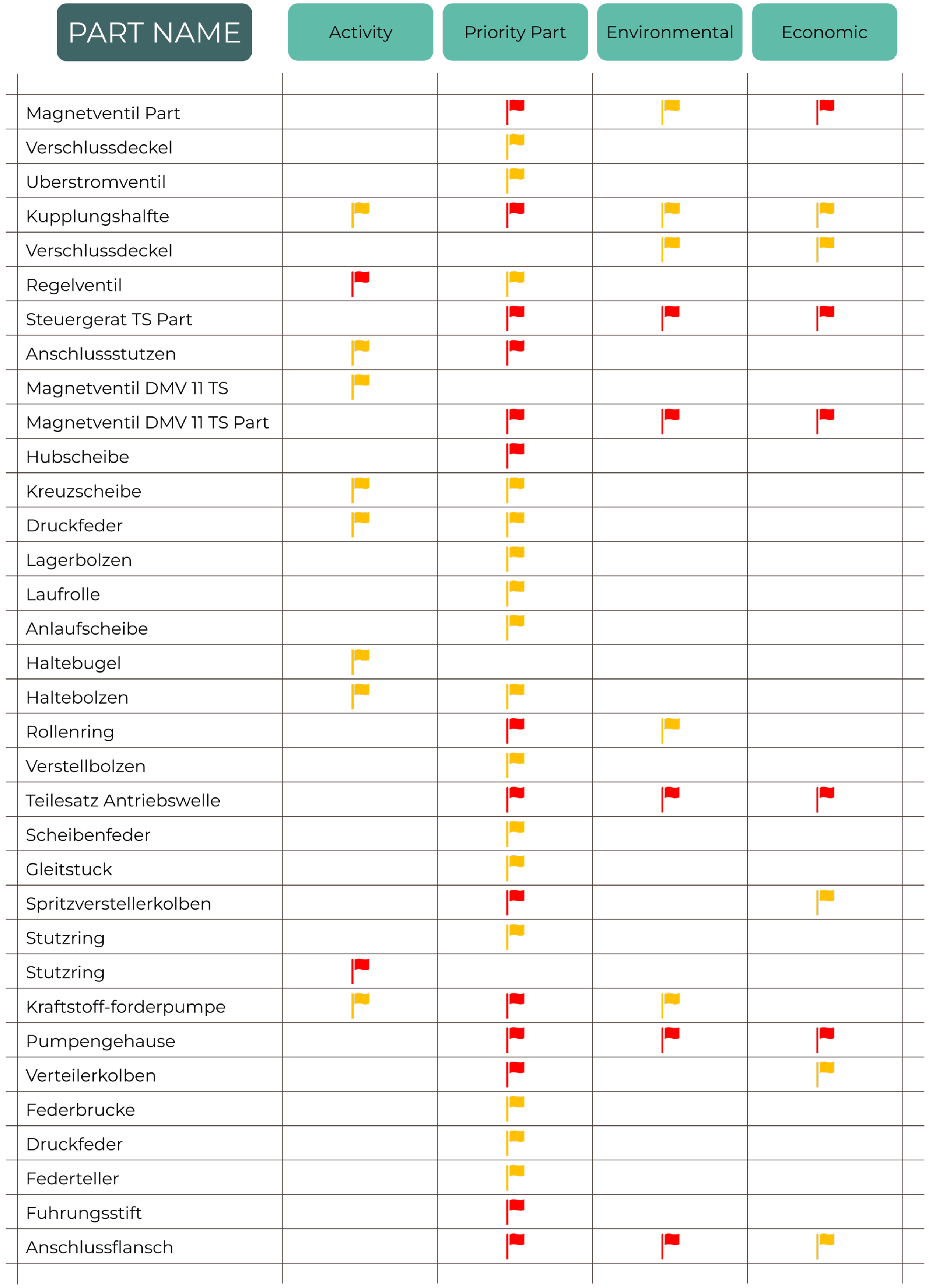


Figure 15: Hotspot Map Results

2.2.6 Observations

An analysis of the Hotspot Map showcased the following observations:

- Since the pump is a high complexity device, there were a lot of priority parts, numbering 30 parts in total.

- The accessibility of most parts was not an issue which is a great sign for repairability with just two red flagged parts.

- As expected, the heavier metal parts were the most environmentally and economically impactful.

- There were four parts which showcased red flags for priority, environmental and economic indicators and these would ordinarily be the first points of attention. However, in this case, they were the pump housing, the electronic components, and the drive shaft, the last of which is not meant to be repairable due to a combination of production method (over-moulding) and a low acceptable level of wear and tear.

- The Coupling Shaft was the most critical part according to the map with flags in four categories.

- Parts flagged on the basis of functionality (30) were greater than the combined count of parts flagged for economic and environmental considerations (20).

2.2.7 Discussion

The Hotspot Map in conjunction with the Disassembly Map provided a great basis for narrowing the number of parts for further consideration. Using the three important indicators of priority, environmental impact and economic value proved to be a good filter to perform the part selection. The total number of parts under consideration was almost cut by half. It also highlighted the most impactful parts within the pump. Some of the results needed a second level of analysis such as those of the Coupling Shaft, but according to the mathematical model of the tool, the results obtained were valid.

There are a few recommendations to improve the tool further. The first of which is to increase the breadth of available tools (hammer was missing) and material categories (ceramics were missing). The definition of a priority part is currently limited to a high functionality part that needs maintenance. This definition can be expanded or allowed to be customised as per the product category that the tool is being used to analyse. For example, in the case of the pump since the parts have longer lifetimes, the definition of a priority part can be changed to parts that have a high rate of reuse or scrapping. This would help the remanufacturing operation to reach the part quickly and make the decision.

Another recommendation which is not specifically for the tool, is to make data about electronics subassemblies more accessible and detailed so that the hotspot map is more accurate. For example, data (weight) regarding the solenoid valve assembly only exists at the assembly level. The data of its constituent parts (weight, material etc) is missing from this Hotspot Map.

Lastly, the database used to calculate the values for these various categories can be updated to Granta EduPack 2022 instead of relying on Granta EduPack 2018.

In conclusion, the Hotspot Map tool was pivotal to narrow the part selection for further development and offers a lot of customisations to be applicable for a wide variety of product categories. Together with the Disassembly Map, they offered an in-depth understanding of the product architecture and critical components.

2.3 3D Printing Capability Research

Since most of the parts of the VP30 pump are metallic in nature as well as most of the parts selected as an outcome of the Hotspot Mapping exercise, the focus of our research and further development was on advanced manufacturing technologies for metal. As discussed in the context of the project (*Section 1.4*), 3D Printing specifically, metal 3D Printing is a very interesting technology to explore. With metal additive manufacturing, it is possible to meet the goals of quick and on demand production. This section offers a summary of metal 3D printing processes and the various possibilities therein. Most of the research for this section was possible due to resources made available by industry leading metal 3D printing organizations such as Markforged, Hubs, 3D Systems, Materialise etc. This section offers only a brief overview and is not to be treated as a 3D printing guide.

2.3.1 Metal Additive Manufacturing Technologies

3D Printing, as an additive manufacturing technology is based on the principle of layer-by-layer creation of the final product. However, this can be achieved in various ways. Consequently, metal 3D printing can also be performed in multiple ways. The four most common categories of metal 3D printing are discussed below. Other less common methods can be found in research from 3DPrinting.com (2021).

According to (Markforged, 2021a), metal powder is the backbone of metal 3D printing. Metal powder is the default metal stock and almost all technologies use metal powder as a base. The differences lie in how these technologies choose to bind these powders. These are explained below.

- Metal Bed Powder Fusion (PBF):

This technology relies on machines distributing a thin layer of metal powder and selectively melt/sinter the areas of the product cross-section in a layer-by-layer manner. In the end, the powder can be removed, and the part is what remains. There are two main techniques to melt/sinter the metal powder, Selective Laser Melting (SLM) uses a laser beam to melt the powder and fuse the layers together whereas Electron Beam Melting (EBM) uses an electron beam for the same. The SLM printers are more accurate but slower in comparison to the EBM printers. This category includes DMLS (direct metal laser sintering), SLM (selective laser melting), and EBM (electron beam melting) machines. Although DMLS used to mean only sintering when it was first invented, the advancement in lasers means that today, these lasers are capable of fully melting the metal and thus, most machines today use SLM but the term DMLS is still used to describe it.

- Direct Energy Deposition (DED):

In this method, metal stock (either powder or wire) is fed continuously and fused on the spot by a laser. Thus, the resultant parts are very similar to powder fused products. This method is similar to welding and thus, can also be used to repair parts. There are two primary techniques separated by the feedstock they use. For powder DED, the print head blows powder in accurate quantities out and the laser fuses it to the layer below. With wire DED, the laser melts the metal wire and fuses it to the layer below. Wire DED machines offer greater build volumes and less precision compared to powder DED machines.

- Binder Jetting:

This technique is relatively new and is based on the technology of inkjet printing. The machine distributes a metal powder layer, and the printing head passes a binder which adheres to the cross section of the part. Once the binding process is completed, the build is sintered to melt the binder and fuse all the metal layers together. This technique is similar to SLM but in fact, does not melt the metal.

These machines are much faster than SLM machines and allow for batch production. Thus, they offer the greatest speed for larger volume production runs. However, due to the sintering phase, the products are more porous and thus, possess weaker mechanical properties.

- Bound Powder Extrusion:

This method is one of the few which does not use metal powder as stock. The metal powder is fused with a wax polymer to create a metal filament which is easy to handle. This filament is extruded in a similar process to a plastic FDM 3D printer and a base part is created. There are two post-processing operations that must be performed, namely washing to remove the binder, and sintering to fuse the part. This shrinks the part since the volume occupied by the binder is filled by the metal. This is the currently, the cheapest way to access metal 3D printing.

2.3.2 Materials

Currently, metal 3D printing can be performed with a range of different materials. Although the list is not as exhaustive as those available for traditional manufacturing, the available materials cover a fair range of the spectrum and most applications that metal 3D printing is used for today can be served through these materials. There are primarily two drivers which determine if a material is possible to be 3D printed. These are the demand for the material and the possibility to make it as a powder since most techniques use metal powder. The most common materials available are those which are traditionally hard to work with i.e., need better tooling, expensive machines etc. In these cases, additive manufacturing becomes more valuable than subtractive. Thus, the materials available for 3D printing are as follows:

- Steels: Maraging and Stainless

Steel is the most common metal. It has a low cost and great post-processing options. Commonly, stainless and tool steels are printed. Alloy steels which are commonly used are easier to produce via conventional methods. Maraging steel, which is an extreme high strength steel is also printed.

Grades - Stainless Steels (17-4 PH, 316L, 304, C465); Tool Steels (H13, A2, D2, 1.2709)

- Titanium:

Although Titanium is not a common material, its high cost and excellent properties make it suitable for 3D printing. It is strong, light, corrosion resistant and biocompatible.

Grades: Ti-6Al-4V, TiGr5, TiGr1, TiGr23

- Aluminium

Aluminium is very cheap and easy to produce through conventional means. Thus, it is not a great candidate for 3D printing. However, with components that are cast, there is a benefit to 3D printing since these parts are significantly weaker than common aluminium alloys.

Grades: AlSi10Mg, AlSi7Mg0.6, AlSi12, A6061

- Special Alloys

Exclusive, expensive, and special alloys are a great candidate for 3D printing. Nickel and Cobalt-Chromium alloys are the most common in this segment. They are great for dental and industrial applications, corrosion resistant and strong.

Grades: Nickel (Ni625, In718), Cobalt Chromium (COCrF75, CoCr)

These are the common materials that are available for 3D printing today.

2.3.3 Design Guidelines:

While designing parts for metal 3D printing, it is important to keep in mind certain design guidelines which will ensure that the production and printing phase are easier to achieve. Depending on the type of material and process, a different set of design guidelines apply for each combination. A sizeable but not exhaustive list of guidelines can be found from research by accomplished 3D printing manufacturers such as Markforged and Materialise. These can be found in *Appendix 5*.

2.3.4 Post-Processing

Although metal 3D printing can open a wide range of part designs, post-processing is an important element of printing metal due to the techniques involved in the print stage. The use of binders and powders means that the printed part is not always immediately suited for use. There are a range of post-processing methods some of which are mandatory and some which depend on necessity. A short summary is described here.

Depending on the technique used, washing and sintering are the most common post-print activities that are undertaken to improve part properties. The washing phase is used to get rid of any binding agents. The sintering phase is used to fuse the metal layers and improve the mechanical properties of the printed part. Lastly, heat treatment (commonly annealing) is performed to increase strength, relieve residual stress, and achieve isotropic material properties. Post these processes, other normal processes like traditional manufacturing can also be performed like hardening, coating, electroplating etc. CNC machining is commonly used at this stage to perform fine operations such as grinding, precision boring, threading, etc. These reduce the surface roughness and improve GD&T especially for functional surfaces/interfaces. Surface finishing operations such as sanding, media blasting, polishing etc can be performed to improve surface finish.

Most important to note is that, almost all the time, the direct output of a metal 3D printer cannot be put into use directly and needs some sort of treatment and post processing to be rendered useful. This is a limitation of the additive manufacturing industry and needs technological advancement to ensure parts can be used straight out of the print bed.

2.3.5 Summary and Inferences

With all the information regarding the various methods, materials, post processing and guidelines, it becomes difficult to make a single choice for these. A summary of this information is visualised below in *Figure 16*.

It is important to understand what this information means for the context of this project. Given that most of the parts as an outcome of the Hotspot Map (*Section 2.2*) are either made from steel or aluminium, these are the materials most likely to be used. In the case of the steel parts, the alloy steel parts are likely to be printed with maraging steel since they are available and possess better properties. However, they might offer a challenge to meet the cost target. Other types of tool steels can be prototyped for varying results. Regarding the production method, it would be unwise to limit ourselves to just one method since many factors determine which method is best suited to the parts selected. A different method can be used for the initial prototypes to finalise the design and then, modified to best suit the method that can deliver the necessary properties (mechanical, production volumes etc). For example, we can use Bound Powder Extrusion to quickly and cheaply prototype various designs and then, batch produce them using Binder Jetting. Another consideration is the availability of machines in the vicinity and time. Since we are based in the Netherlands, facilities in the EU are preferred. Preferably, these should be in the BeNeLux area or Germany for fastest lead times and delivery. Purely from a cost perspective, it is most accessible to use a Bound Powder system like that of Markforged. However, Bosch has access to 3D printers which primarily use DMLS/SLM and some with Binder Jetting. Thus, the choice of method depends on the practical constraints of this project and is not an indication of which is the best technique. This is better explained in *Chapter 3* which deals with the design and prototyping actions for the selected parts.

With an understanding of how metal 3D printing works and a list of parts from the Hotspot Map, a few 3D printing criteria have been developed for evaluation for the final selection of the parts. This is explained in the next section (*Section 2.4*).

Technology	Maturity	Cost ($)	Facility Requirements	Part Size	Precision
Powder Bed Fusion	High ●●●	500k - 1M+ $$$	Powder management, ventilation, post-processing equipment (CNC, EDM, HIP, heat treatment)	2mm - 350mm	High ●●●
Binder Jetting	Low ●○○	300k - 2M+ $$$	Powder management, batch sintering solution, post-processing equipment (surface finishing, heat treatment)	1mm - 150mm	High ●●●
Bound Powder Extrusion*	Medium ●●○	150 - 200k $	Basic ventilation (not for metal powder), post-processing depending on use case (CNC, heat treatment, surface finishing)	10mm - 250mm	Medium ●●○

Figure 16: Metal 3D Printing Comparison (Markforged, 2021b)

2.4 Part Proposal

With all the information about 3D printing technologies and an initial selection of parts through the Hotspot Map, the criteria for further selection were defined. The first level of selection was to decide which of the parts as flagged by the Hotspot Map must go for further consideration. The general criteria used to make a preliminary selection and the final selection were the hotspot mapping data along with variables such as the geometry, the difficulty of 3D modelling and most importantly, the value of 3D printing the parts. These are explained in the sections below.

2.4.1 Preliminary Selection Filtering

As can be seen in *Figure 15*, there were many parts which were flagged by the Hotspot Mapping tool. To consider all these parts for the redesign would require extensive time and resources. Thus, a selection process was performed to refine the list further and create a preliminary proposal. During the preliminary selection, the criteria as defined above were used loosely since the proposal had to cut down the selection from around 34 parts to around 10. This was a request from the expert at Bosch, Mr. Dirk Lummer who was later consulted for the final selection.

The first order of refinement was to look at only the 'red flagged' priority parts. Within these red flagged parts, it was evident that the 'Magnetventil', 'Steuergerat' and 'Magnetventil DMV11' were components of electronic/solenoidal nature. Given that the focus was on metal 3D printing for this project, these parts were discarded from the selection. A separate project would be needed to investigate remanufacturing for the electronic components. These red flagged priority components were then checked on their environmental and economic impact. The Fuhrungsstift, being a red flagged part with the least impact was discarded since there were many parts within the preliminary proposal already. Initially, the idea was to limit the preliminary proposal to the red flagged priority parts.

However, in this manner, parts that would be suitable for 3D printing, possess great potential for remanufacturing and have a yellow priority flag would have been missed. Thus, all the yellow priority flagged parts were checked. The 'Uberstromventil' and the 'Regelventil' were discarded due to being control valves which are extremely difficult to be produced by 3D printing today. Most of the other yellow flagged parts fell under the umbrella of fasteners, pins, springs, and shims. These parts are cheap and easy to manufacture traditionally and storing an inventory is not a major issue. A high value for 3D printing does not exist for these parts. These parts were thus discarded from consideration. The only yellow flagged part that was left was the aluminium 'Verschlussdeckel' and thus, added to the preliminary selection.

Lastly, a check was conducted on the parts that were environmentally and economically impactful. The only part which was not a priority part but economically and environmentally impactful was another aluminium 'Verschlussdeckel' and thus, added to the preliminary proposal. To refine the proposal further, the materials of all the selected parts were extracted from the Bill of Materials to check if a similar replacement material for 3D printing was available. Fortunately, all the selected parts had either a similar or better material available for printing. The datasheets of these 3D printing materials were then attached to the proposal.

Thus, an initial filtering of the parts from the output of the Hotspot Map was performed using the above method.

2.4.2 Preliminary Proposal Substantiation

The preliminary refinement of the parts was conducted. The Hotspot Map output 34 selected parts and they were reduced to 12 parts following the preliminary refinement. It was time to perform a substantiation process to make the final preliminary proposal of 3 selected parts to the Bosch expert. This was performed by applying the criteria as mentioned before i.e., geometry, 3D modelling difficulty, and value. These criteria were chosen since they specifically evaluate the 3D printing suitability of these parts. Many other criteria can be chosen to evaluate suitability, but these criteria cover the major concerns with respect to 3D printing. The criteria of print time and cost were deliberately not considered in this early stage to prevent the explorative design phase from becoming too narrow. To keep in sync with the Hotspot Mapping tool, these criteria were also classified by means of flags (red, yellow, and green) for different levels. These criteria levels are visualised in *Figure 17*.

The 12 preliminary parts were then investigated against these criteria and scored. A detailed explanation of the scoring is given in the next section (*Section 2.4.3*) where each individual part is discussed separately. To complete the preliminary selection, these scores were multiplied to create a combined score for selection. By multiplying, the gains of each sub-category are amplified and the worst performers in each category are eliminated. Since there was a part-by-part consideration planned, this helped make the selection process more streamlined. The highest combined score possible was 8 and the lowest score was 0 with the other scores being 1, 2 and 4. The part proposal was to be done on a spectrum with parts ranging in difficulty, material, and geometry. A fair distribution of these characteristics was expected to ensure that the project delivered maximum output value.

	SCORE = 0	SCORE = 1	SCORE = 2
GEOMTERY	· Lots of precision features · Lots of internal features · Has a high aspect ratio · Needs support structures	· Few complex surfaces · Few curves and drafts · Some precision features · Has a medium aspect ratio · Might need support structures	· No precision inserts · Low aspect ratio · Few holes · Very few internal features · Few unsupported features
3D MODELLING DIFFICULTY	· Complex model · Internal features · Precision features · External curved surfaces · Internal curved surfaces · Might need 3D scanning	· Slightly complex model · Internal features · External curved surfaces · Some precision features	· Simple model · Basic features such as bosses, sweeps, rotations, and cuts
VALUE	· Solid or dense infill · Thick walls	· Low functionality · Low wear parts · Medium thickness walls	· High functionality · Wear parts · Hollow/thin-walled parts

Figure 17: Preliminary Selection Scoring Criteria

PART NAME	Priority Part	Environment	Economic	Material Availability	Geometry	3D Model	Value	Score	**Selection**
Verschlussdeckel	yellow			green	green	green	green	8	green
Kupplungshälfte	red	yellow	yellow	green	yellow	green	red	0	red
Verschlussdeckel		yellow	yellow	green	green	green	yellow	4	yellow
Anschlussstutzen	red			green	red	yellow	yellow	0	red
Hubscheibe	red			green	green	yellow	green	4	green
Rollenring	red	yellow		green	yellow	green	yellow	2	yellow
Teilesatz Antriebswelle	red	red	red	green	red	green	red	0	red
Spritzverstellerkolben	red		yellow	green	yellow	green	green	4	yellow
Kraftstoff Förderpumpe	red	yellow		green	yellow	green	yellow	2	yellow
Pumpengehäuse	red	red	red	green	red	red	green	0	red
Verteilerkolben	red		yellow	green	yellow	green	yellow	2	green
Anschlussflansch	red	red	yellow	green	red	yellow	red	0	red

Figure 18: Preliminary Part Selection Proposal

The highest scoring part – the aluminium 'Verschlussdeckel' was the first part to be selected for the proposal to Bosch. From the parts with the score of 4, the 'Hubscheibe' was selected since it was the only part with a different material (Steel) and possessed an interesting geometry. From the parts with the score of 2, the 'Verteilerkolben' was chosen for its simple geometry and different material (Stainless Steel). The parts with the score of 1 or 0 were not selected. Thus, the scores were then normalised to a flag system where green parts indicated proposed parts, yellow indicated other possible options and red indicated a non-choice.

This preliminary proposal (see *Figure 18*) was presented to the expert at Bosch, Mr. Dirk Lummer for part-by-part discussion and final selection. The complete proposal with accompanying notes in spreadsheet format can be found in *Appendix 6*.

2.4.3 Part by Part Discussion

Post the creation of the preliminary proposal, a discussion meeting was held with the expert at Bosch, Mr. Dirk Lummer to finalise the part selection for further development. This section details the reasoning behind the selection or non-selection of each part based on the preliminary proposal and insights from the expert.

1. Verschlussdeckel (Locking Cover):

This part was a selected part (green) in the preliminary proposal due its great performance in all the criteria of geometry, 3D modelling and value. Additionally, it was a yellow flagged priority part which is used in the timing device of the pump. Lastly, KOSH (a subsidiary of Bosch which runs the remanufacturing operations) suggested this part for 3D printing since they had a demand for this part in their operations. Thus, this part was selected for further development.

Figure 19: Locking Cover

2. Kupplungshälfte (Coupling Shaft):

This part was a non-selection (red) in the preliminary proposal. The main reason was the lack of value for 3D printing since this was a solid steel block which could easily be machined through a turning lathe process. The profile also did not have any hollow sections which could add value. Thus, this part was not selected for further development.

Figure 20: Coupling Shaft

3. Verschlussdeckel (Locking Cover):

This part was a possible option (yellow) in the preliminary proposal. The main reason for non-selection was that a similar aluminium cap had already been selected and thus, the value addition to the project would be minimal. Additionally, this part was not a priority part even though it was environmentally and economically impactful. The part with more functional importance was chosen. Thus, this part took the position of the backup aluminium part if difficulties arose with the other part.

Figure 21: Locking Cover

4. Anschlussstutzen (Delivery Valve):

This part was a non-selection (red) in the preliminary proposal. The main reason was the geometry of the part. By virtue of being a delivery valve, there were many internal precision bores. This was unsuitable for 3D printing and would need extra machining in post. The material of the valve was also commonly available C35 steel and thus, jumping to maraging steel would be an overdesign for the valve. Thus, this part was not selected for further development.

Figure 22: Delivery Valve

5. Hubscheibe (Cam Plate):

This part was a selected part (green) in the preliminary proposal. The main reason was that it was a priority part with wear during use. The need for constant replacement adds great value for 3D Printing. Secondly, a moderate geometry coupled with a different material (Maraging Steel) to meet the strength requirements put this part into the upper level of the complexity spectrum. The cam profile and the forged nature of the part were challenges. There would also be a need for post-machining. However, this part offered an opportunity to explore a different aspect of metal 3D printing. Thus, this part was selected for further development.

Figure 23: Cam Plate

6. Rollenring (Roller Ring):

This part was a possible option (yellow) in the preliminary proposal. Similar to the Hubscheibe, this part was a forged high strength steel part with a simple geometry. However, this part needed more support structures for printing due to its geometry. Moreover, the part needed to be very precise since it was the seat of the rollers. Though the geometry and finishing for this part were easier than the Hubschiebe, the current extrusion pressing production method had many merits and thus, this part took the position of backup steel part if difficulties arose in the other part.

Figure 24: Roller Ring

7. Teilsesatz Antriebswelle (Drive Shaft):

This part was a non-selection (red) in the preliminary proposal. The main reason for this was that this part was an assembly of three parts which cannot be currently separated post manufacturing. Moreover, it was a solid shaft and thus, the value proposition for 3D printing was minimal. The locating ring (one of the three components) was an interesting discussion since this part had sourcing difficulties, new tooling was expensive due to the plastic over moulding required and there was medium demand for this part. The locating ring also required a lot of precision. Thus, despite the low value for the shaft, the value proposition for the locating ring was immense. Thus, the decision on this part was deferred till some experiments were conducted to better determine the proposition. For the time being, this part was not selected for further development.

Figure 25: Drive Shaft

8. Spritzverstellerkolben (Timing Device Piston):

This part was a possible option (yellow) in the preliminary proposal. This was a multi-body part with an aluminium cover and a steel ring. The part of interest was the aluminium cover. It had great value and was easy to model. There were some internal bores, but they were manageable. However, the value proposition was based on an estimate of the current production process (turning) since the process data from the supplier was not available due to end of delivery. Additionally, since it was an aluminium part and two parts were previously considered with the same material, the value for the project was minimal. Thus, this part was not selected for further development.

Figure 26: Timing Device Piston

9. Kraftstoff-Förderpumpe (Supply Pump):

This part was a possible option (yellow) in the preliminary proposal. This part was a multi-body part with three bodies (slotted washer, locating ring and vanes). All these bodies have simple geometries and are easy to model. Currently, they are all made from different grades of steel keeping failure in mind. However, for 3D printing, all of them would need to be produced with the same material which could compromise functionality. Moreover, all the parts are solid and the value for 3D printing was minimal. Thus, this part was not selected for further development.

Figure 27: Supply Pump

10. Pumpengehäuse (Pump Housing):

This part was a non-selection (red) in the preliminary proposal. Though this part was a red flagged part in all Hotspot Map criteria, the geometry of the part was very complex with lots of internal surfaces and precision bores. There was great value from 3D printing this part since it was hollow and there was potential for lot of material saving. The material was also easily available. However, within the restrictions of this project, the creation of the 3D model would be extremely time consuming and complex. The non-availability of the 3D model from Bosch was the sole reason for the difficulty of considering this part. Thus, this part was not selected for further development.

Figure 28: Pump Housing

11. Verteilerkolben (Hydraulic Shaft):

This part was a selected part (green) in the preliminary proposal. This was mainly due to its priority part tag, simple geometry, and the opportunity to explore 3D printing a different material (Stainless Steel). The reason that Stainless Steel would need to be used was due to the high chromium content of the current steel used (a like for like replacement). However, the expert viewed the geometry as uninteresting for 3D printing due to its solid nature and mentioned that the part could be easily produced with a turning operation (lathe, CNC lathe). The value proposition was thus reduced. Thus, this part was not selected for further development.

Figure 29: Hydraulic Shaft

12. Anschlussflansch (Hydraulic Head):

This part was a non-selection (red) in the preliminary proposal. The main reason was the poor result in the evaluation criteria for 3D printing suitability. The part was a solid steel block with precision internal bores and was forged for high strength. The not so suitable geometry, difficult modelling and low value proposition made this a difficult choice. Thus, this part was not selected for further development.

Figure 30: Hydraulic Head

Thus, the part-by-part discussion with the expert concluded with the final selection of two parts which is detailed in *Section 2.5*.

2.5 Final Part Selection

The part-by-part discussion of the preliminary proposal for selecting parts for further development is explained in detail in *Section 2.4.3*.

From the initial proposal which proposed three parts (all with different materials, geometries, and complexity), the final selection after the discussion with the expert was limited to two parts. These two parts are separated by different materials. Their geometries ranged on a spectrum from simple to moderate difficulty. Both parts have great value for 3D printing as well as the project since they allowed for experimentation with different materials and geometries.

There were backup parts for both selected parts in case, unforeseen difficulties arose with any of these parts during the design-prototyping phase. An interesting part – the locating ring remains to be investigated in the future and could add further value for the project. The selected parts offered a good mix of complexity and variation for this project, contributing to the understanding of 3D printing and improving remanufacturing of the VP30 pump.

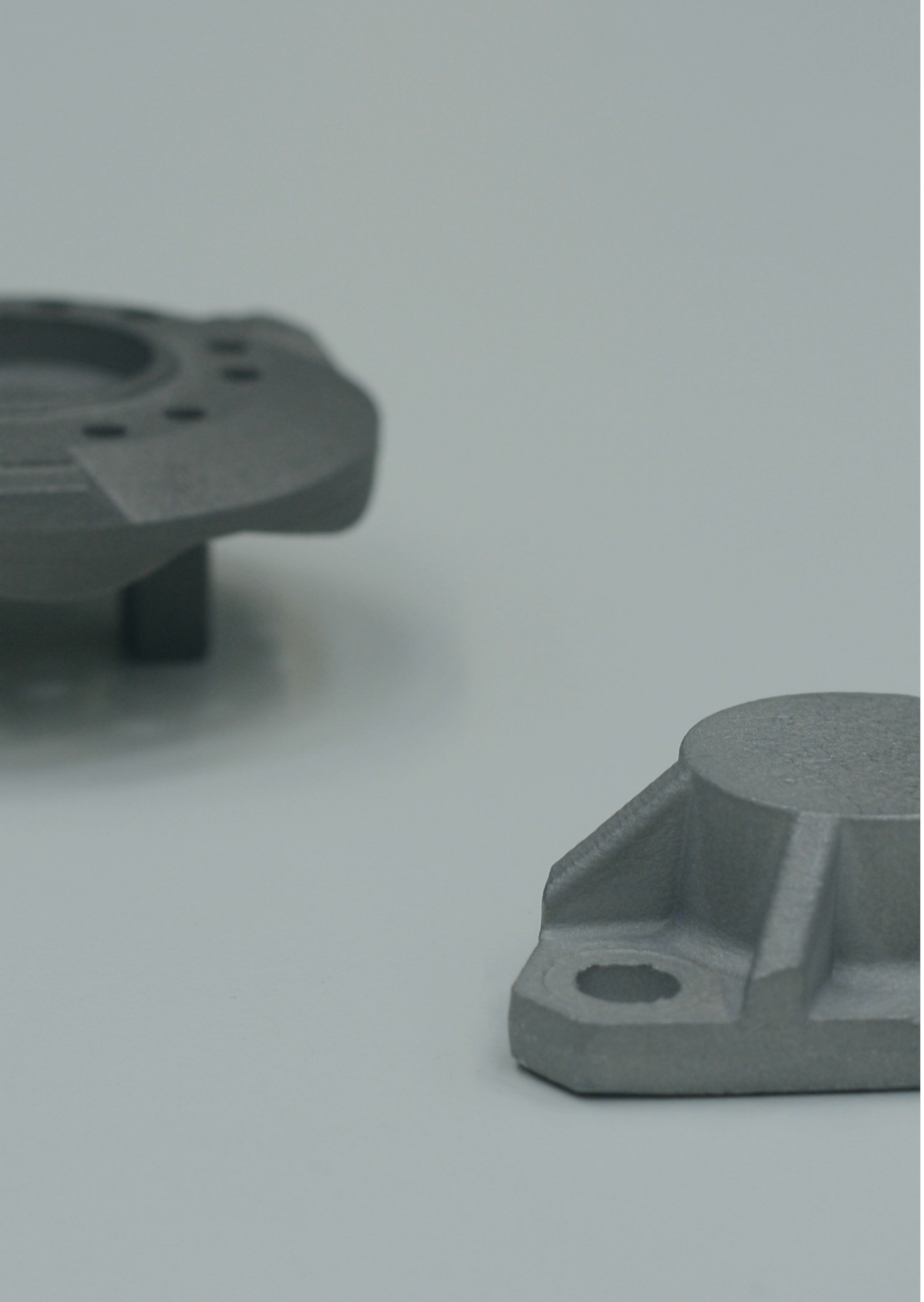
The chosen parts for further development for design-prototyping were:

1. Pos 37 - 1465.530.818 – Verschlussdeckel (see *Figure 19*)
2. Pos 29 - 2466.111.080 – Hubscheibe (see *Figure 23*)

The two backup parts were as follows:

1. Pos 471 - 1465.575.003 – Verschlussdeckel (see *Figure 21*)
2. Pos 20 – 2460.232.088 – Rollenring (see *Figure 24*)

The position numbers and the 10-digit number provide information about the part and its material which can be found in the Bill of Materials Exploded View (see *Appendix 7*).



Chapter 3: Design & Prototyping

This section of the report deals with the process of designing and printing the selected parts of the VP30 pump. The process of 3D modelling, the issues in the process and the solutions within are enumerated. Visits were conducted to two relevant factories, the 3D Competence Centre and Koller + Schwemmer GmbH for this project and the learnings of these visits are described. The quotation process and the process of selection of the 3D printing service provider has also been explained. Moreover, a preliminary analysis of the printed parts was performed which also led to creating a summarised design guideline for DMLS 3D printing. Lastly, a reflection on the utility of the Product Journey Map for the pump was performed.

3.1 Modelling

The initial task for the design and prototyping phase of the project was to create 3D CAD models of the selected parts since 3D CAD models form the basis of all additive manufacturing technologies. This was an especially important part of the project since Bosch did not possess any 3D CAD models of parts of the VP30 pump, primarily because of the old age of the pump. This section details the process of 3D modelling the selected parts, the issues faced in the process, the choices made to make the modelling process easier, some test polymer 3D prints to verify the model and lastly, the 3D models themselves. All the models were created using SolidWorks 2021 on a student license.

3.1.1 Locking Cover (Verschlussdeckel)

The Locking Cover is a die-cast aluminium cover used in the timing device of the pump which ensures the flow of fuel is properly metered according to the speed of the shaft. The modelling process consumed 1 complete workday.

The model was created primarily using (cut) extrude, (cut) revolve, and sweep (cut) features. Fillets were applied where necessary and the technical drawing (see *Confidential Appendix 3*) served as the primary document to guide the modelling process. Certain features of the part which existed due to its nature of being a cast part like the seam line were not relevant for 3D printing and thus, ignored for the 3D model. However, dimensional accuracy was still maintained to ensure that the part fit the desired specifications.

Specifically for the locking cover, the following issues were found in the modelling process and the fixes made are described below.

- It was unclear at first, from the drawing, if the 1° draft angle for the holes were inward or outward. Since there was a chamfer on one end, the draft angles were considered to be outward for ease of entry of the bolts.

- The flat plan was mentioned in the technical drawing with no depth information. This was taken as 0.1mm.

- The dimensions of the internal cavity and the accompanying angles did not match with the modelling limitations. Using the dimensions from the drawing would have made the model underdefined. Thus, the start point of the curves were matched to the end point of the previous curve and the change in angle noted. The angle was changed to 6.12° from 6° to meet geometry constraints. (see *Figure 31*)

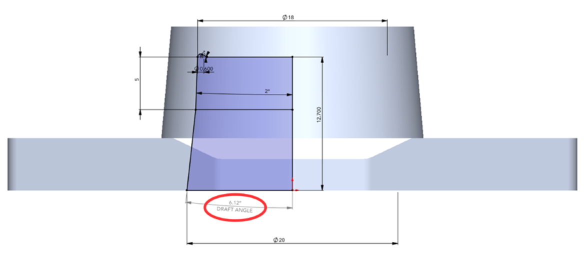


Figure 31: Angle Change

- The sweep cut for the internal scoop would be a zero-thickness geometry if a guide curve of Ø 20 mm was used. Thus, a guide curve of Ø 20.05 mm was used. (see *Figure 32*)

The progression of the 3D modelling process can be seen in *Figure 33*. Polymer 3D prints using PLA were made to check the model for any features that were different from the original part and if the modifications made in the modelling process had a significant impact on the geometry of the part (see *Figure 34*). A visual check and some critical measurements using Vernier Calipers were taken to ascertain that the model was according to specification.

Once this was complete, the model was finalised and saved. The final 3D model can be found in SLDPRT, STL and STEP formats in *Appendix 8*.

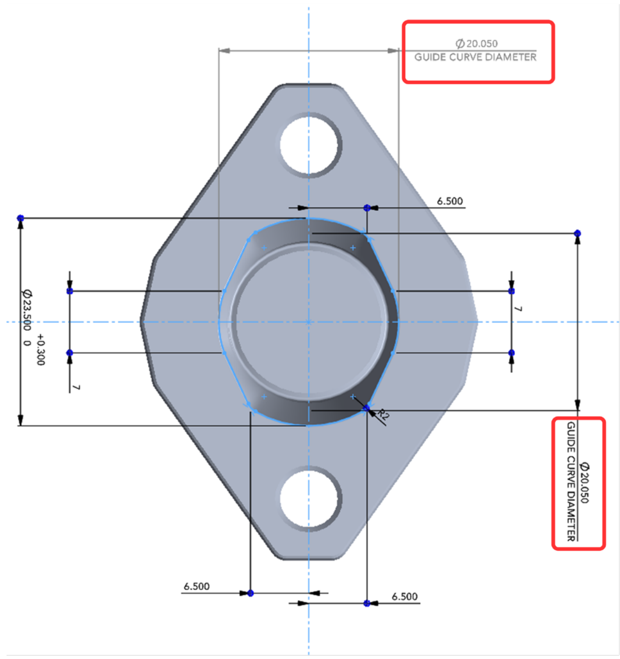


Figure 32: Guide Curve Diameter Change

Figure 34: PLA Test Prints

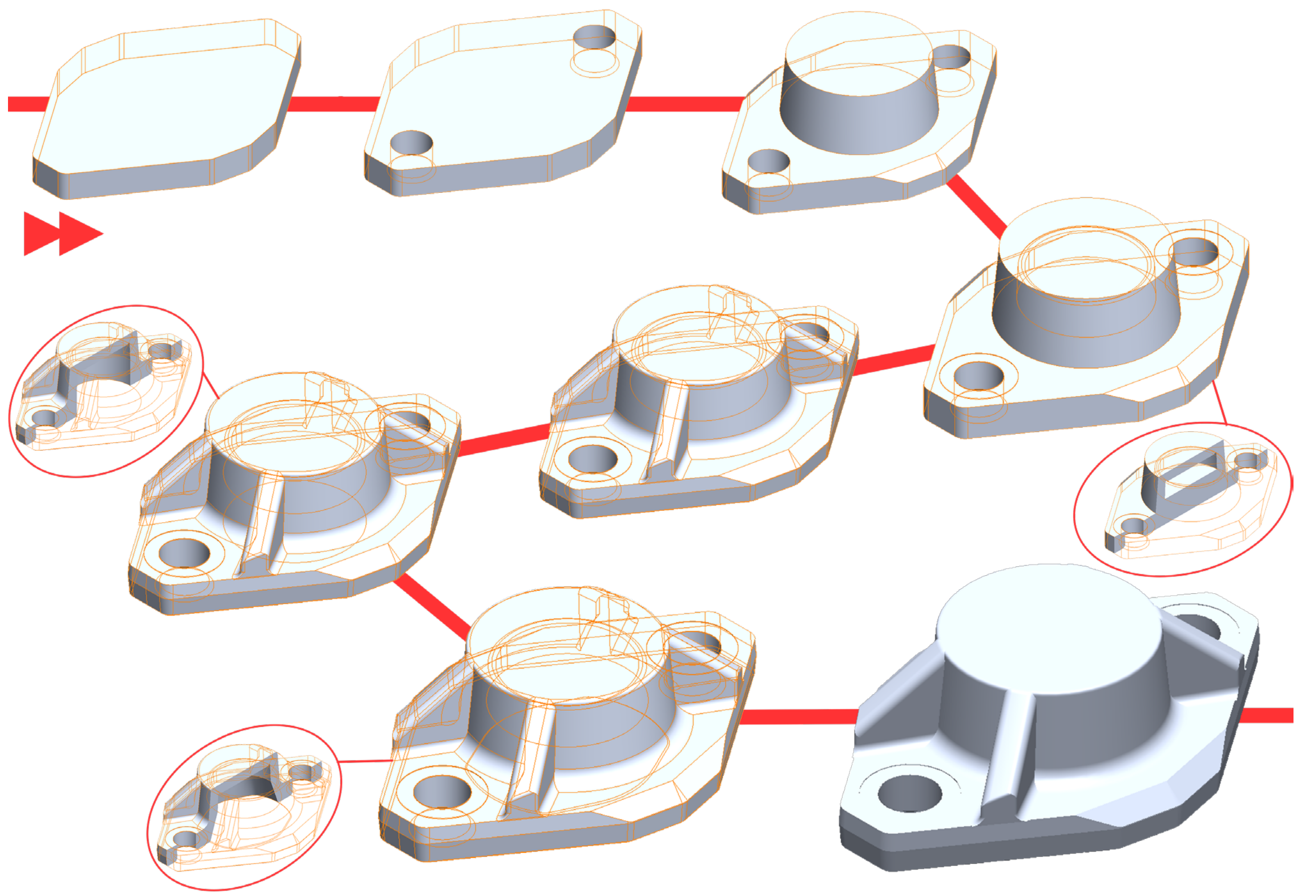


Figure 33: 3D Model Progression

3.1.2 Cam Plate (Hubscheibe)

The Cam Plate is a forged alloy steel part used in the high-pressure chamber of the pump which provides the rotary and reciprocating motion to the shaft which injects the fuel to the various cylinders. The modelling process was tedious as this part is highly complex (due to the cam profile) and precise. The modelling time consumed 7 complete workdays.

The model was created primarily using (cut) extrude, (cut) revolve, sweep (cut) features and circular patterns. Fillets were applied where necessary and the technical drawings (see *Confidential Appendix 4*) served as the primary document to guide the modelling process. Since this part had many variants and many production steps, there were many technical drawings to refer to, which further complicated the process. Not all technical drawings contained the same information and there were instances of inconsistency. In such cases, the deviations to the 'basic drawing' dimension always prevailed. Certain features of the part which existed due to its nature of being a forged part like the clamping jaws were not relevant for 3D printing and thus, did not need to be highly precise in the 3D model. However, dimensional accuracy was still maintained to ensure that the part fit the desired specifications.

Specifically for the cam plate, the following issues were found in the modelling process and the fixes made are described below.

- The straight pin is part of the final part, but it is press fit into the cam plate. Even though, these parts could have been integrated into a 3D model, they were kept separate since they were made of different materials. Only the cam plate was modelled.

- Most dimensions in the drawing had a pre-grind and post-grind dimension attached. Since it was not feasible to make two 3D models for both variants, the final dimension of the part was chosen for the 3D model. Various scaling and slicing software can make changes to the model to attain the desired end result depending on post-processing needs.

- The outer diameter dimension for the jaws was provided with only a symmetry relation in the drawing. This was then measured using Vernier Calipers on the existing part and verified with geometry checks on the 3D model. (see *Figure 35*)

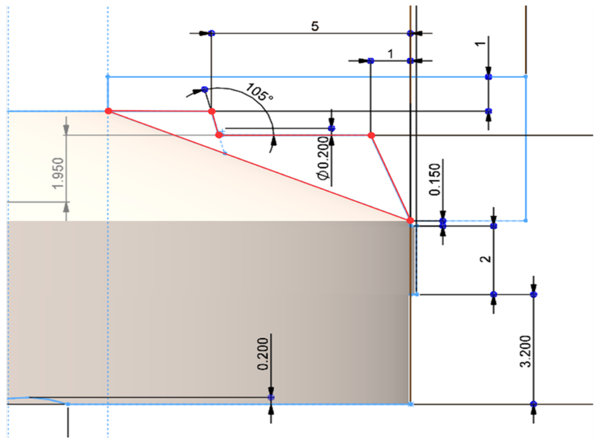


Figure 35: Jaw Dimensions

- The radii dimension for the claws were not possible to model. These were remnants of post-process machining. Thus, it was not included in the 3D model.

- The dimension of the lower curvature was not defined in the drawing for the 6-cam variant. Thus, reference was taken from the 4-cam variant and a tangential relation and distance of 0.2mm was set as per the tolerance range mentioned in the drawing. (see *Figure 35*)

- The cam lift data was provided for 57° in intervals of 5' each. This was too cumbersome to plot. Thus, the cam profile was plotted on intervals of 1° as shown in *Figure 36.* This proved to be quite cumbersome as well.

- Due to limitations of the modelling tool and my skills, the exact profile of the inner recess of the cam profile could not be replicated. Thus, an approximation of the recess was made in the same manner of the existing part. Some machining will be needed to make this recess a perfect match. (see *Figure 37*)

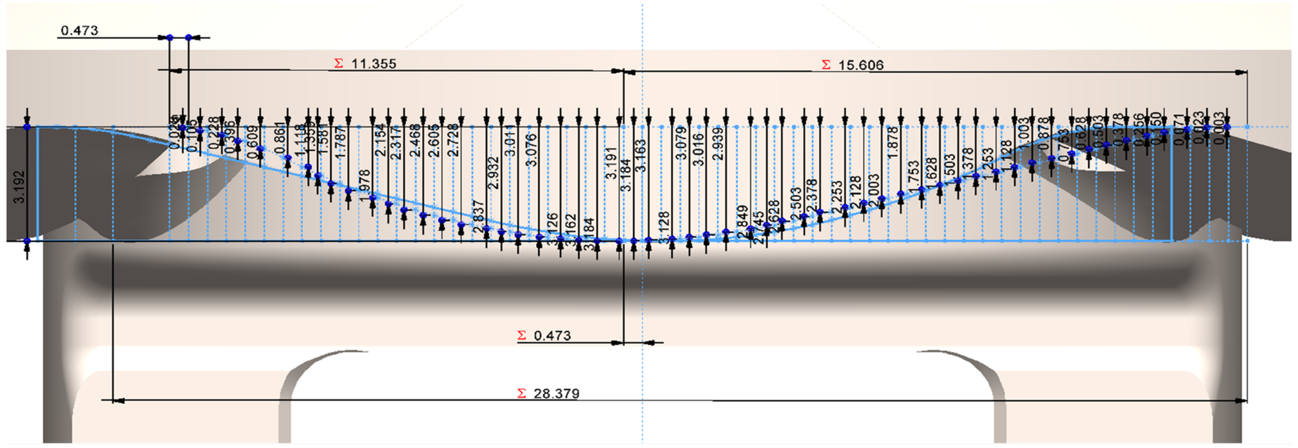


Figure 36: Cam Lift Plot

The progression of the 3D modelling process can be seen in *Figure 38*. Polymer 3D prints using PLA were made to check the model for any features that were different from the original part and if the modifications in the modelling process had a significant impact on the geometry of the part (see *Figure 39*).

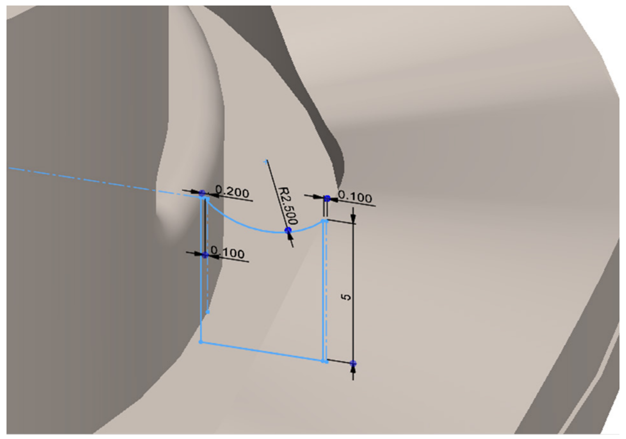


Figure 37: Inner Recess

A visual check and some critical measurements using Vernier Calipers were taken to ascertain that the model was according to specification. It was found that the direction

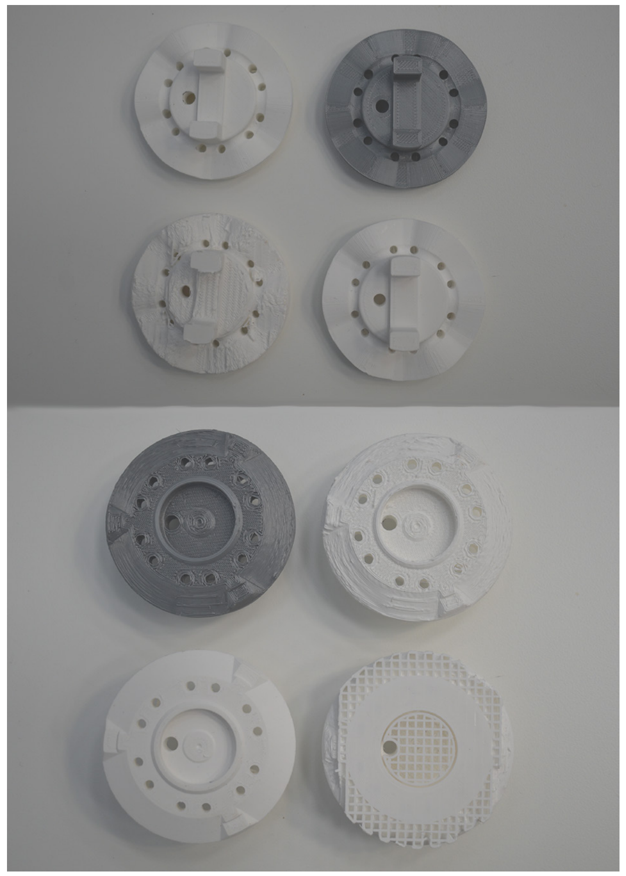


Figure 39: PLA Test Prints

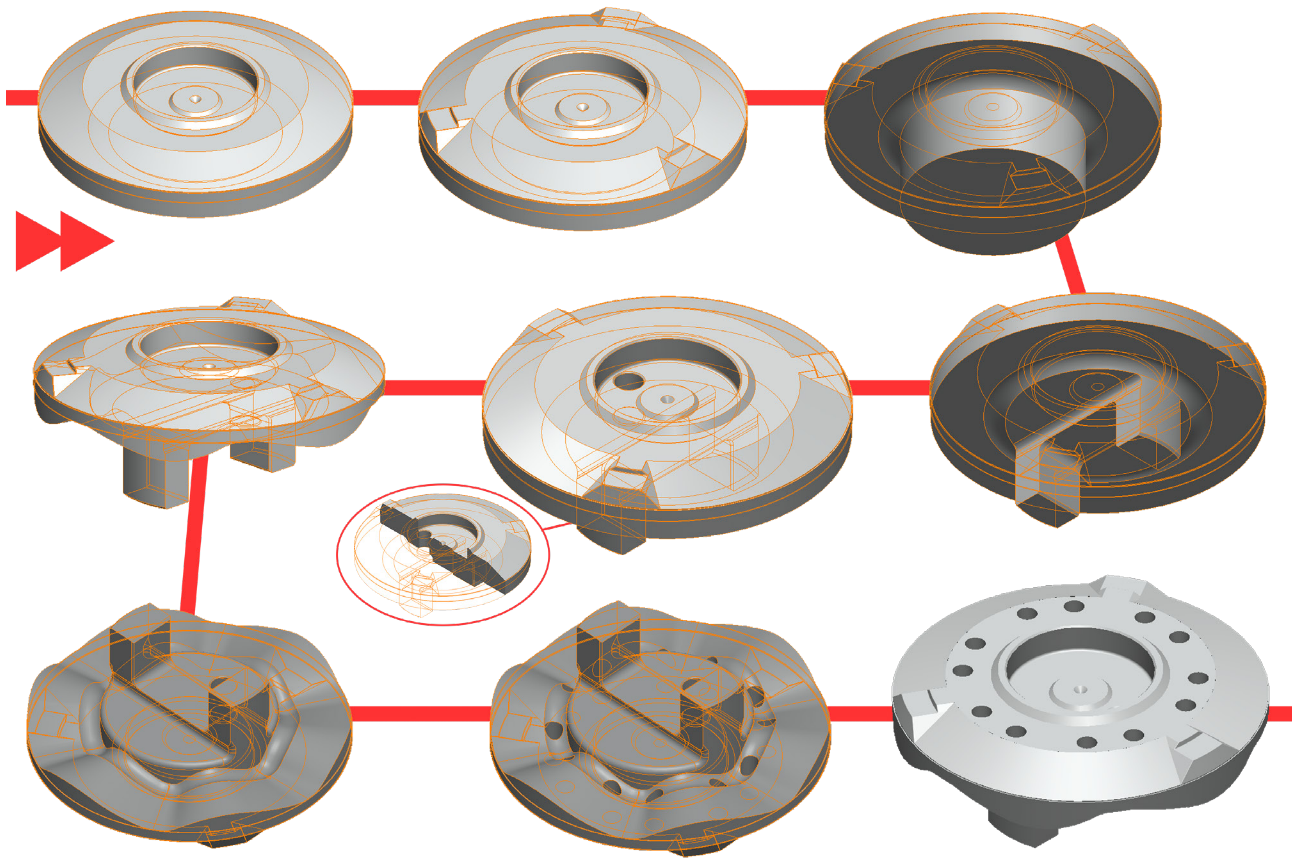


Figure 38: 3D Model Progression

of the cam profile was reversed in relation to the original part. This error was observed only due to performing the polymer print step. This proved that the value of a pre-metal plastic print stage to ensure model correctness. The direction of the cam profile was then reversed in the 3D model, and the model was checked for any other inconsistencies.

Once this was complete, the model was finalised and saved. The final 3D model can be found in SLDPRT, STL and STEP formats in *Appendix 9*.

3.2 Facility Visits

In the quest for the further development of the parts for 3D printing, two facility visits were arranged by Bosch AA. The first was Koller + Schwemmer GmbH (KOSH), a subsidiary organisation of Bosch who performs remanufacturing operations for the VP30 pumps. The second visit was to the 3D Competence Centre where research is carried on how 3D printing can help Bosch's internal product lines and make products and processes better. Both these facilities were in Nürnberg and the trip was sponsored by the ReCiPSS project. These visits allowed me to get better acquainted with the operational aspects of remanufacturing and learn about the metal 3D printing process. This section presents a succinct summary of the learnings obtained from the visits to the two facilities.

3.2.1 Koller + Schwemmer GmbH (Remanufacturing)

1. **Operations:**

- The remanufacturing operations were observed for the VP44 pump, a close cousin of the VP30 pump since the VP30 operations take place at Jihlava, Czechia.
- The disassembled parts are selected for reuse or discarded based on visual inspection. A manual for visual inspection exists for operator training.
- If some parts are difficult to disassemble due to factors such as rust, they are discarded.
- There are separate bespoke fixtures for both assembly and disassembly which make it easier to manipulate and work with the pump.
- The parts selected for reuse are washed in an industrial washing machine for 10 mins. Parts from previous cycles which are already washed, are then used for remanufacturing.
- Only two piles of parts exist: scrap and reuse. Oil contaminated scrap is kept separately. All scrap is sent to scrap partners and further End of Life (EoL) strategies are unclear.
- Some parts of the pump are only available as parts sets such as the shaft and the electronics. Thus, duplicate items in these part sets are discarded which causes unnecessary waste. However, due to low volumes, compliance requirements and customer needs, these sets need to be sold together in one package.
- Once assembled, the pumps are tested on a bespoke test bench for about 2 hrs where a variety of tests are conducted. Primary among them are the 'Überprufung' and the programming of the pump control unit. Only the entire pump is tested and there are no tests for individual parts.
- There are no set rules for reuse and scrap since every incoming pump has a vastly different use and life cycle (depending on fuel quality, environment, hours run etc). Thus, remanufacturing is done on a case-to-case basis through visual inspection.
- An inventory of the necessary spare parts is maintained in case there are not enough reusable parts. These parts consume storage space in the facility. The main supplier of these spare parts is the Karlsruhe facility of Bosch AA.

2. **Part Composition for Remanufacturing:**

- Electronic parts of the pump such as the control unit are never reused due to high reliability requirements.
- Disposables like O rings, seals, washers are always discarded, and fresh ones are used.
- For new builds, the housing, timing device,

O ring set, ribbon cable, pump control unit are always fresh parts.

- Bearings, shaft, supply pump, hydraulic head and cam rings have the potential to be reused.

- Fasteners are a mix of reused and new parts since they are inexpensive. Old fasteners undergo a surface treatment before they can be used again.

3. **3D Printing Adoption:**

- The incorporation of 3D printed parts in this flow is simple as long as the parts are certified to meet the specifications of the original part. A 'First Sample Quality Document' is needed for the same.

- The main concern against 3D printing remains the cost of the parts since conventional suppliers are still active for almost all of the parts even at this stage of the pump's life cycle.

4. **Important Figures**

- Remanufactured pumps have a warranty period of 1 year as against the 2 years for a newly manufactured pump.

- The Cam Plate, though classified as a wear part is often reused. The order demand per year is quite low at around ~20 units.

- The Locking Cover, though not classified as a wear part is often damaged by workers disassembling these pumps from the vehicles and thus, require replacement. The order demand is an average of ~300 parts per year.

These main learnings were useful in understanding the remanufacturing process and the barriers for incorporating 3D printed parts into the remanufacturing workflow. It was also interesting to learn that as far as remanufacturing operations go, there was no discrimination on the basis of the production techniques used. The important point of note was that the parts must be certified to the original design specification, and they can be used. A quote from my guide at Koller + Schwemmer summarised the situation saying, "There will come a time when 3D Printing will be better (cheaper), but it is not at this moment."

3.2.2 3D Competence Centre (Metal 3D Printing)

1. **3D Printing Process:**

- For DMLS, support material is still needed since the lasers are powerful and the supports prevent warpage and allow for better bonding between layers.

- Machines from different vendors can use the same slicer tool with slight modifications.

- The orientation in which to print the part depends on what post-processing is required. It is necessary to look at the whole process chain before deciding the orientation and not only the print process. If certain features are functionally important, the orientation should be such to give those features maximum precision.

- Datum surfaces (mentioned in technical drawings) are important to decide what the print orientation should be.

- There are four main paths for optimising 3D print cycles: Quality, Cost, Speed, Detailing.

- Quality of 3D prints are measured by density, distortion, shrink percentage and impurity percentage. DMLS offers high density and repeatability and thus, is industry choice for metal 3D Printing technology.

- BinderJet technology is promising but needs some time to become a fully mature technology that can meet the precision demands of the automotive industry.

- Metal powder storage and safety is a very important consideration for DMLS. Only vendor recommended powders are used to preserve machine warranty. The quality of powder ultimately impacts the print quality. Humidity is the biggest barrier for powder storage and needs, specialised rooms for storage.

- The 3D Centre offers a professional powder analysis, simulation and design support for all 3D printing engineering needs.

2. **Part Specific Parameters:**

- The selected parts i.e., Cam Plate and Locking Cover can be exactly replicated in the 3D printer without needing accommodations. These printed parts are harder than traditional processes and annealing is necessary.

- For the cam plate which has multiple variants in production, 3D printing can be used to produce the raw part and the different cam profiles can be machined on location as per the requirement.

- The material for the Cam Plate, 16MnCrS5 has been printed before at the 3D Centre but needs extra validation for certified production grade parts.

3. **Organisational Barriers**

- The adoption of 3D printing depends on OEM interest to incorporate this process flow in their organisations. There are strong barriers namely the need for new tools, new processes, and requirement/loss of manpower.

- 3D printing offers the advantage to combine multiple traditional manufacturing processes in one. This saves on tooling, storage, and partnership (supplier, contractor) costs.

- Within Bosch AA, the release procedure is the biggest barrier due to time and effort required to complete the approval.

- The other barriers are related to capacity and the quirks of the organisational structure in which the 3D Competence Centre sits in.

- Bosch AA can provide the assembly and testing facilities for the VP30 parts. A change in the process flow is needed to incorporate the 3D Centre's tooling.

- The lack of process FMEA for 3D printing is one of the biggest barriers in its incorporation into normal process flows within Bosch.

These main learnings were useful in understanding the metal 3D printing process (DMLS) and the barriers the 3D Centre faces in incorporating 3D printing processes within Bosch. It was also interesting to learn the other aspects of DMLS such as the powder storage, safety, and lack of process FMEA.

3.3 Quotation & Order Procedure

With the 3D models ready and knowledge gained from the visits to the remanufacturing and metal 3D printing facilities, the next step was to print the 3D model. Though Bosch was involved with the project, it was important to also understand the commercial operations of third-party 3D printing service providers. Thus, RFQ's (Request for Quotations) were sent to various providers and the best option was chosen to print the 3D models. This section details the quotation and order procedure for printing the two parts.

3.3.1 Gathering Quotations

A request for quotation (RFQ) was sent to various 3D printing providers. The parameters of the quotes were providing just the 3D model and a 'standard' process finish. Some suppliers offered a 'fine' process with smaller layer heights and better tolerances. However, to ensure the quotes were comparable, the 'standard' finish for each supplier was chosen. Post-processing was limited to removal of support structures only. Part certification was not requested to prevent sharing of confidential information and higher cost.

These providers were asked to respond with the cost of printing, the lead time, the scope of service (post-processing) and the print material. A Google search was performed to look for 3D printing service providers. The search was restricted to locations in the EU due to ease of shipment and possibly lower lead times. At the end of the search, 15 service providers were shortlisted based on location and ease of navigating their website. These 15 providers were then contacted for the RFQ's.

All the shortlisted providers advertised the availability of Aluminium AlSi10Mg which was needed to print the Locking Cover. This was an almost like for like replacement for the material used for traditional manufacturing (A413.0). The material for the Cam Plate (16MnCrS5) is an alloy steel and not readily available for 3D printing. Thus, the available materials for printing the Cam Plate were Maraging Steel (MS1) and Stainless Steel (SS316L and C465). These materials have better material properties than the original alloy but are more expensive to produce.

From the 15 providers, 4 of them only served large customers and large order quantities and were not suitable for prototyping. 5 of the providers never responded to the initial RFQ. The remaining 6 providers responded with quotes containing all the necessary information. These quotes are summarised in *Figure 40*.

With these quotations in hand, the negotiation process began to reach the best possible combination of price and lead time.

3.3.1 Final Order

From the given quotations, K3D in the Netherlands offered the cheapest quote with a satisfactory delivery time. They also offered the possibility to visit the printing facility to experience the process which would have proven useful for further research. However, a call from the Account Manager at Xometry EU (Germany) introduced the Target Price Order Tool where customers can quote for a target price for their order and Xometry tries to find providers who can reach the mark. With this tool, I was able to quote a target price of €300 incl VAT and Xometry was able to achieve this and promise the fastest lead time from all the vendors. Thus, the final order was confirmed with Xometry EU, and the part was ready to ship in exactly 1 week after the order. The parts arrived in the Netherlands on 13 June, 2022. The 3D printed parts (compared with original parts) are shown in *Figure 41.*

The summary of the parts ordered were as follows:

1. Locking Cover – AlSi10Mg – 1 nos
2. Cam Plate - Maraging Steel 1 – 1 nos

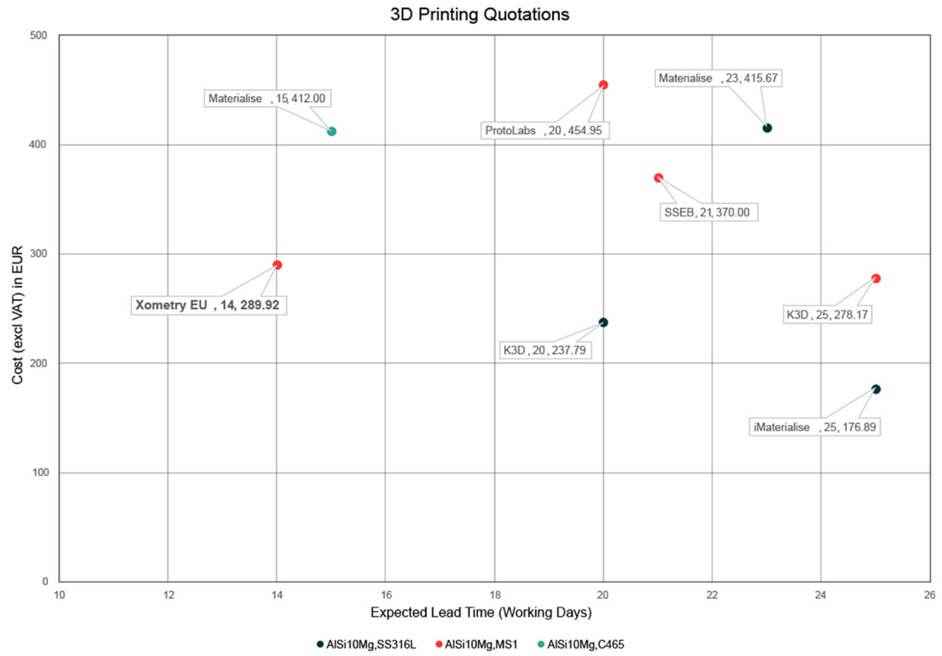


Figure 40: Quotation Summary

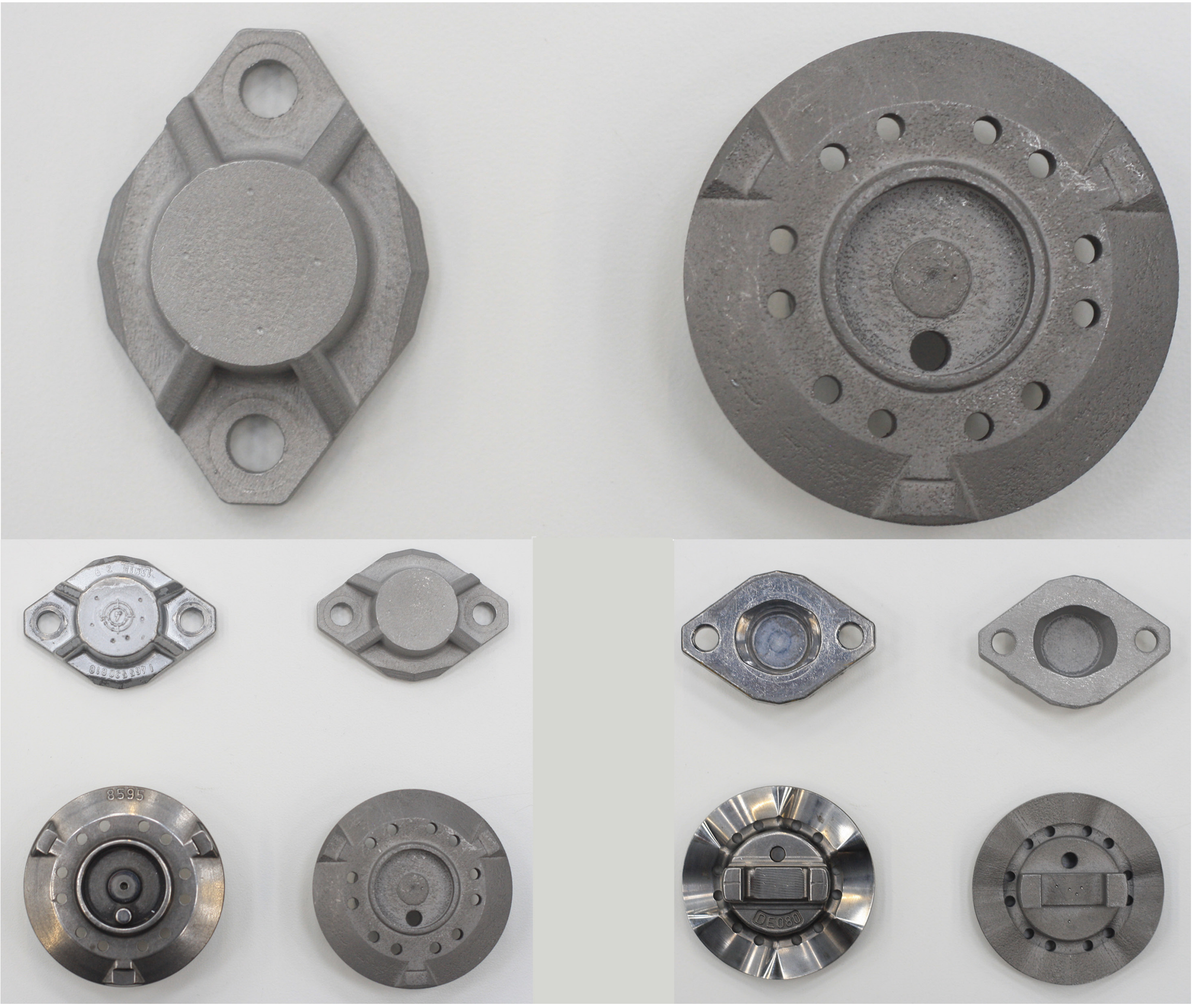


Figure 41: 3D Printed Parts

3.4 3D Print Analysis

The 3D Printed parts are showcased in this section. A preliminary visual analysis of the parts was performed to reflect on the limitations and advantages of the process. It is important to note that small indentations can be seen on the surface of the prints. These are not print defects but rather, the remnants of the hardness testing performed. The hardness testing is explained in *Section 4.2.1*. The main limitation in this process was the lack of iterations in the model-print-analyse cycle of development. This was caused primarily by two reasons: high lead times for prototyping from external vendors combined with the lack of an in-house metal 3D printers and more importantly, the expensive nature of prototyping which limited the number of iterations possible due to budgetary restrictions. Further research can help bridge these limitations and uncover better results in this domain.

3.4.1 Locking Cover

The surface finish was limited to Rz63 and thus, was quite rough. This was not measured however, and the supplier specifications were considered. Grinding is necessary after 3D printing, especially for the lower face as a matter of part functionality. (see *Figure 42*)

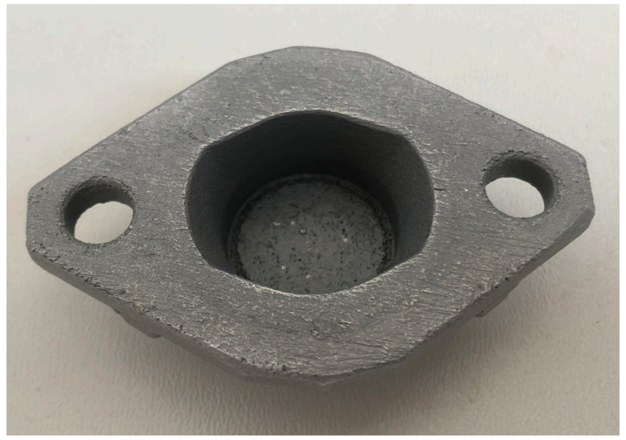


Figure 42: Rough Surface Finish

The layer separation can be visually seen in the ribs while the rest of the part looks homogenous. (see *Figure 43*)

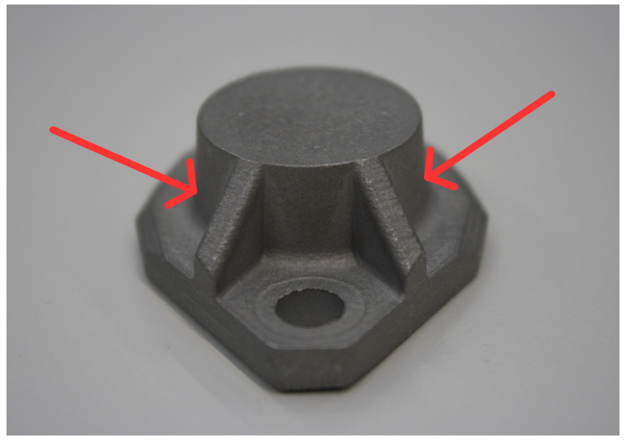


Figure 43: Layer Detailing

The grain direction (powder coater direction) of the metal powder is clearly visible in the horizontal plane. (see *Figure 44*)

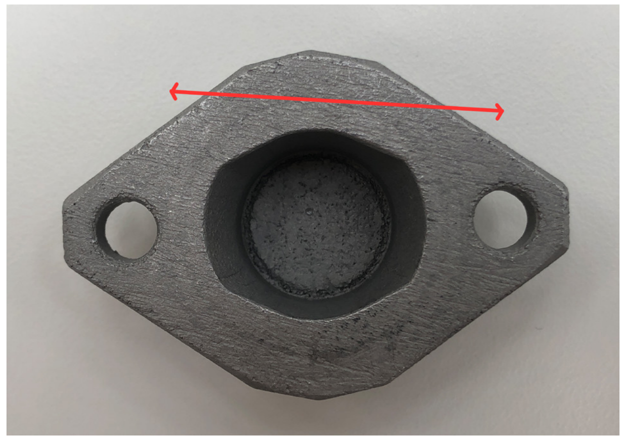


Figure 44: Grain Direction

The outer fillet radii and chamfers are impressively maintained while the inner radii and chamfers are not fully resolved. This could be due to the support structure needed for inner features. (see *Figure 45*)

Overall, with a little post processing such as grinding, the 3D printed part can be made to feel like the traditionally manufactured part, both visually and physically.

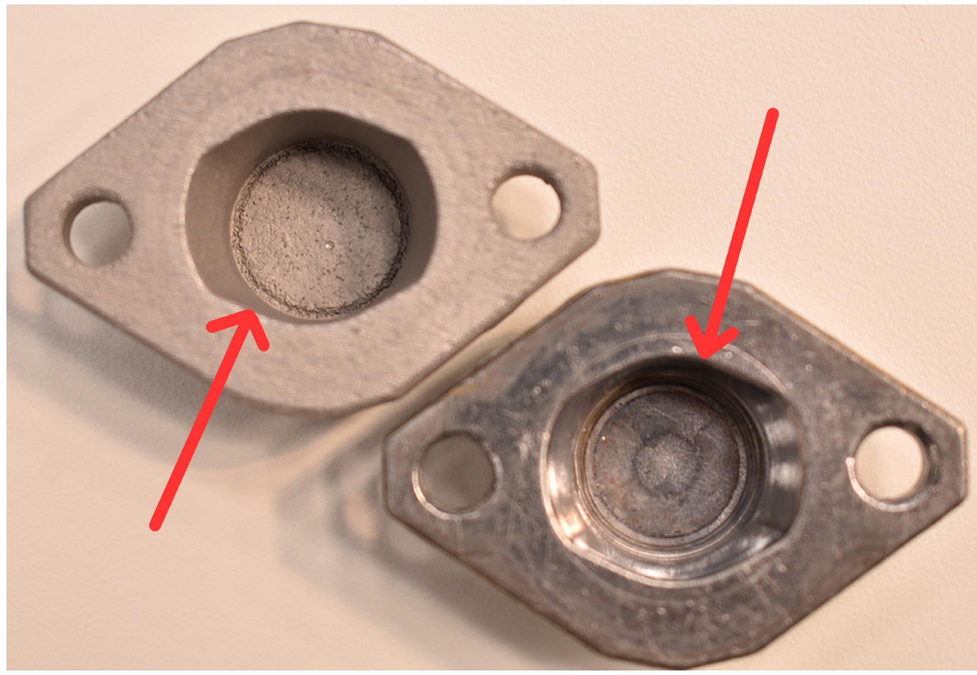


Figure 45: Internal Feature Resolution

3.4.2 Cam Plate

The surface finish is limited to Rz63 and thus, was quite rough. This was not measured however, and the supplier specifications were considered. Grinding is necessary after 3D printing, especially for the cam profile as a matter of part functionality. (see *Figure 46*)

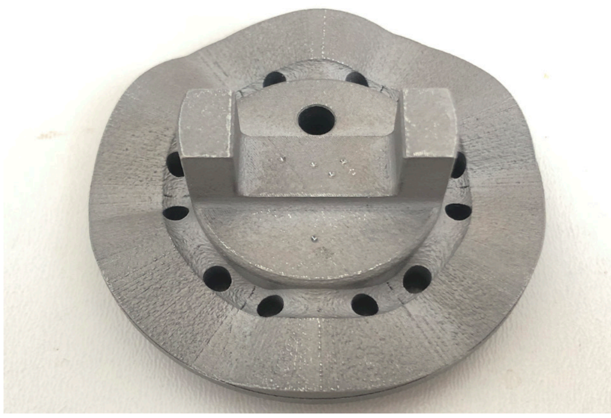


Figure 46: Rough Surface Finish

The resolution of the notch in the top face is poor thereby preventing a solid lock with the injector shaft. This is important for the function of the part. This could be due to a larger print resolution than the feature itself. (see *Figure 47*)

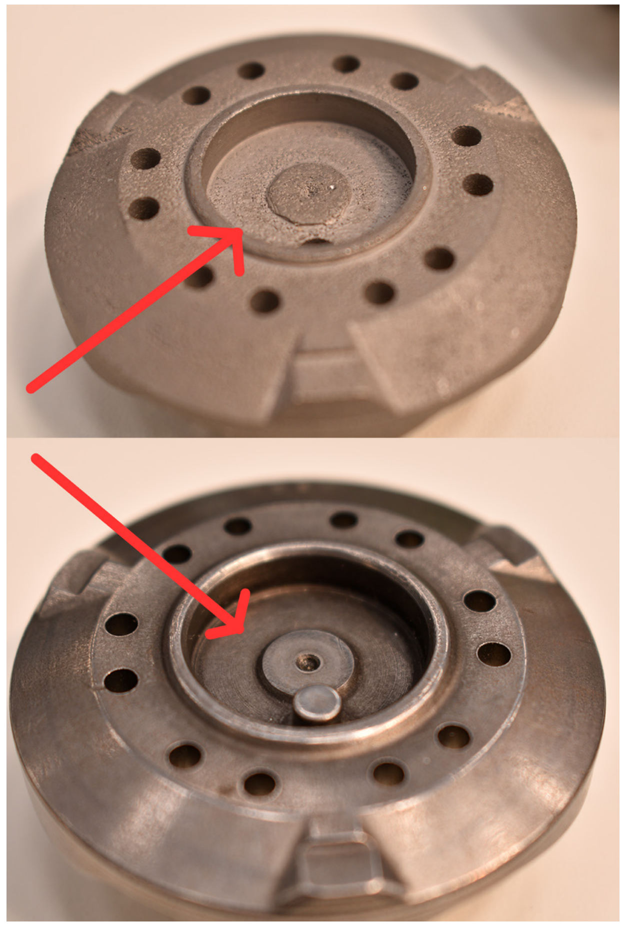


Figure 47: Notch Detailing

The faces of the holes are impressively round and have no draft or bridging which are common 3D printing defects. (see *Figure 48*)

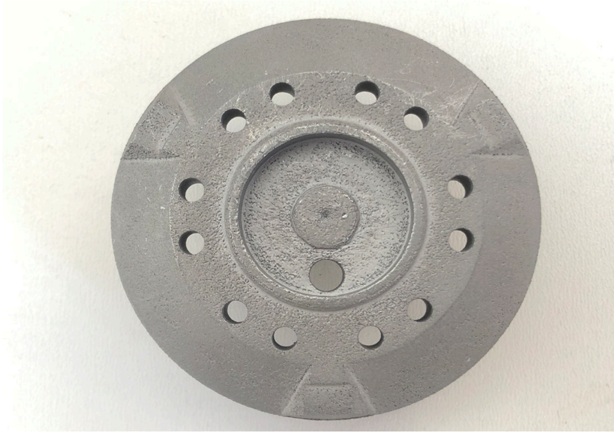


Figure 48: Hole Detailing

The lower half of the part is identical to the conventional part bar some changes due to modelling difficulties and surface finish. (see *Figure 49*)

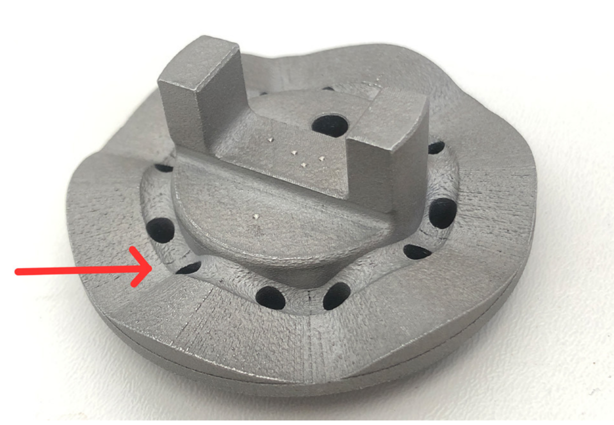


Figure 49: Lower Sweep Details

Overall, with post processing operations of annealing and grinding, the 3D printed part can be made to feel like the traditionally manufactured part, both visually and physically.

3.5 Design Guidelines for Direct Metal Laser Sintering (DMLS)

With the parts designed and printed, the possibilities and limitations of metal 3D printing (DMLS in particular) were clear. This section explains some design guidelines to follow for designing for DMLS. Most of the information on basic guidelines such as layer height, tolerances, surface finish, aspect ratio etc. can be easily found on the internet from various providers such as Proto3000 Inc. (2018). They can also be found in *Appendix 5*. This information is easily accessible. This section aims to bring to light information that is latent and thus, not easily available in such design guides and developed from my personal experiences during this project.

A few guidelines are mentioned below:

- It is important to keep the size of the parts in mind before printing. Most commonly available metal 3D printers can only print sizes around 250x250x250 mm. If the parts to be printed are bigger, a design of connecting mechanisms or to connect them post printing must be thought of.
- Due to the layer-by-layer printing process, details within parts that encompass multiple layers must be carefully designed. Features must have a minimum size of ~0.5mm to be properly resolved in normal printing (layer height of 0.1mm or more). An example of this can be seen in *Figure 45* where the internal curve of the locking cover is not fully detailed.
- With smaller layer heights, slower printing speeds and fine granulated powder, greater levels of detail can be achieved but this needs a compromise between quality, time, and cost.
- Hole sizes up to 6mm are easily managed and do not require support as can be seen from the bores in the Cam Plate. Bigger sized holes require support and thus, may have a rough inner surface. (see *Figure 50*)

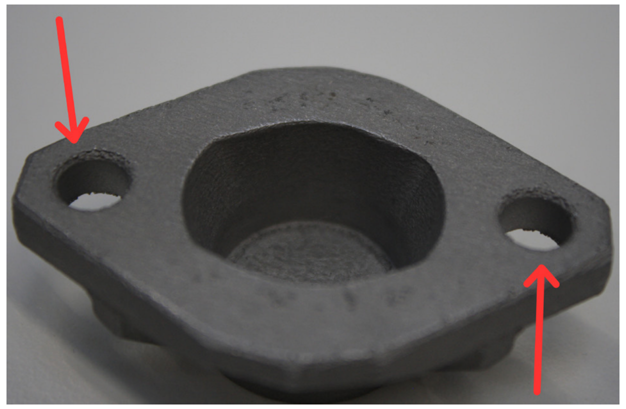


Figure 50: Hole Surface

- DMLS printing requires support structures since the powder does not support the part (partly due to the weight of the metal) and, the laser can cause warpage in the printed areas without sufficient support structures. All overhanging features must be self-supporting if support structures are not desirable. A common rule is to apply supports for overhangs above 30 deg for steel and 45 deg for aluminium.
- Though there is no limit on max wall thickness, the thicker the walls are, the higher the stresses contained within the part which could lead to internal deformations. Thus, a thickness of around 2mm is considered suitable for walls.
- Overhanging features tend to have poor surface quality due to the nature of the print process. This can be seen in *Figure 45* (internal faces of the parts).
- As with any other manufacturing process, it is always advised to not have sharp edges to prevent stress concentration. For 3D printing, it also counts as a factor to ensure better detailing since sharp edges are difficult to print. A minimum radius of 0.5mm is preferred to reach the quality of the showcased 3D printed parts.
- As mentioned in *Section 3.2.2*, the orientation of the print must be decided after looking at the complete process chain of the product and not just the printing process.
- To prevent the effects of bridging, using triangles or rounded corners at the top allows the structure to support itself and reduces the need for support structures. (see *Figure 51*)

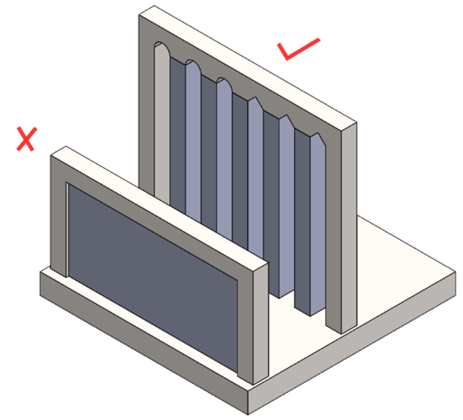


Figure 51: Reduced Support Structures

- Though it may seem quite seamless when looking at the print process, the recoating blade applies force on the part when it travels along the bed. To prevent the part from bending/breaking, it is important to allow the coating blade to have a smooth lead via a single point instead of a face. This can also be a factor in setting the print orientation. In the case of the Locking Cover, this is valid and it is important to orient it slightly tilted along its horizontal axis (see *Figure 52*). This also applies for vertically angled features of the parts facing into the coating blade. For the Cam Plate, the circular profile helps with orientation.
- Support structures are a necessary evil in the process. They are important to maintain good geometry, detail, and strength. However, they use a lot of energy in printing and removal. Minimising supports through good design, as with other 3D printing technologies can prove to be very

beneficial. Unfortunately, images of the part with the support structure could not be obtained.

- Post-printing treatment such as sintering, or annealing is important after DMLS to relieve stress and ensure strength. They also prevent layer delamination, cracks, and warpage.
- Lastly, it is important to consider the separation process (either mechanical or wire EDM) as part of the design and this can allow extra freedom in the possible profiles.

These guidelines were developed from my personal experience during the project and can be amended and improved with further iterations.

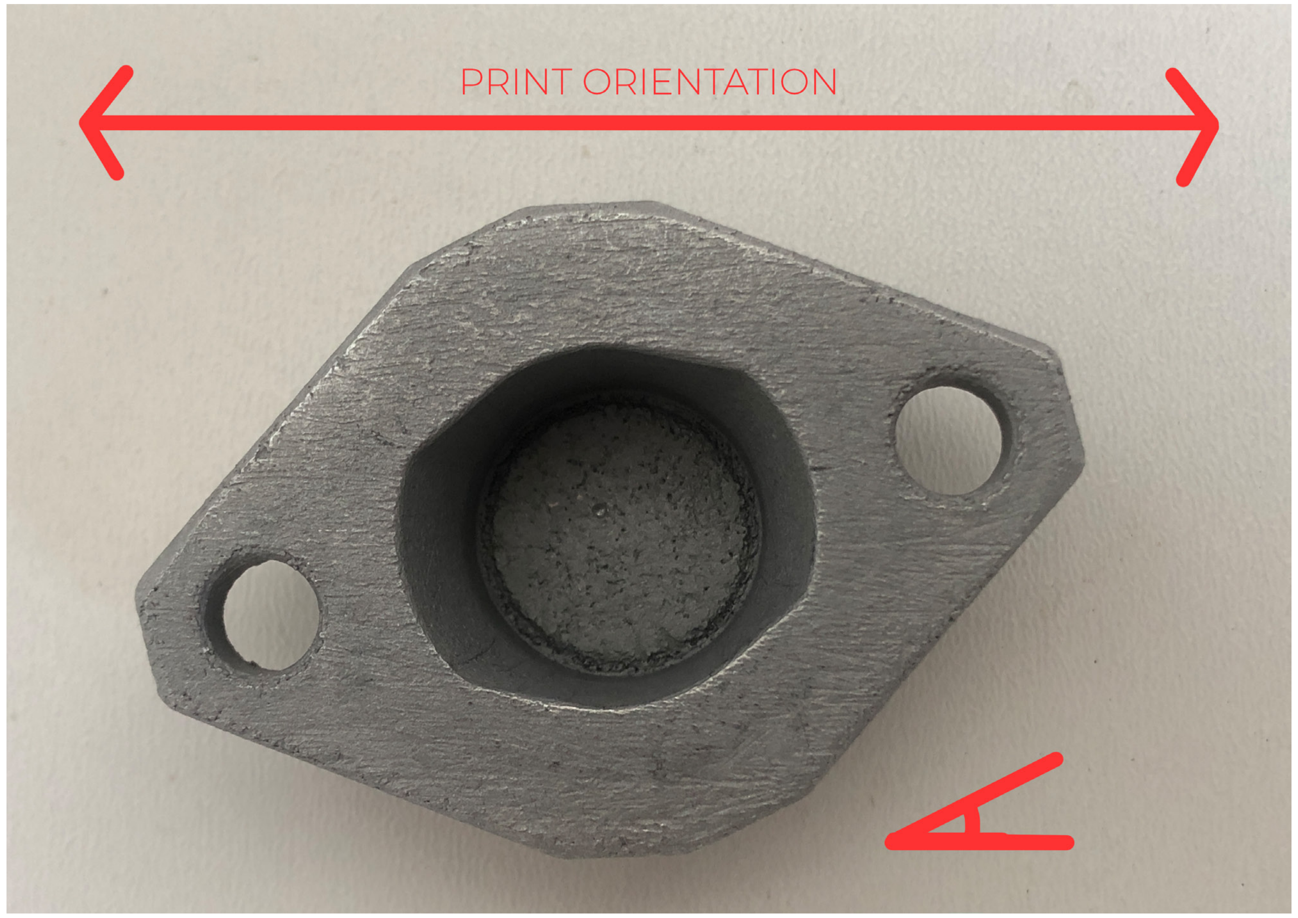


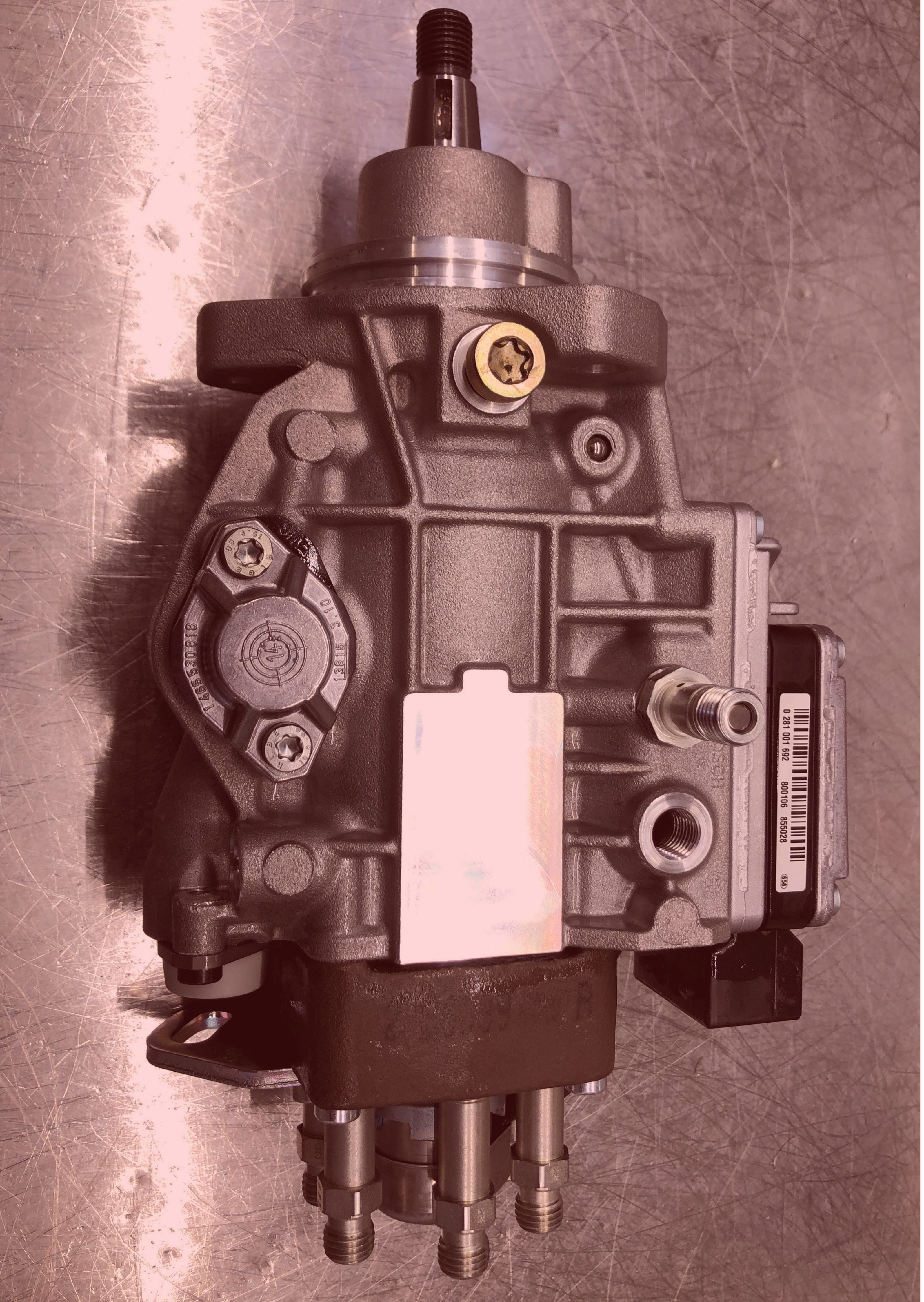
Figure 52: Print Orientation

3.6 Product Journey Map Reflection

The Product Journey Map (PJM) is a tool developed by Kooijman (2022). It provides a visual understanding of how the various sub-assemblies within a product undergo their lifecycles and where opportunities exist to make these cycles more circular. Thus, it serves as both a tool of information as well as a tool for discovery. An attempt was made to incorporate the thinking of the Product Journey Map in this project. A reflection of the possibility of using this tool in the context of a diesel fuel injection pump and its sub-assembly lifecycles was performed. This reflection can be found in *Appendix 10*. The appendix also includes *Figure 53* and *Figure 54*.

3.7 Conclusion

Thus, the develop section of the project constituted the creation of the 3D models of the selected parts. These models were created from existing technical drawings and some modifications were made to the design to ensure 3D printing suitability without majorly changing the part design. With these 3D models, a quotation process was undertaken, and multiple quotes were received. The quote with the best combination of cost and lead time was chosen. Moreover, facility visits to the remanufacturing operation site and the 3D Competence Centre led to a better understanding of the entire process and the challenges in incorporating 3D printing into the organisation process flows. The printed parts were then analysed for their suitability and the need for post-processing was made clear. Most importantly, the development process led to the creation of design guidelines for DMLS 3D printing which can prove useful for designers investigating metal 3D printing.



Chapter 4: Testing & Evaluation

This section of the report deals with the testing and evaluation of the 3D printed designs of the selected parts of the VP30 pump. This section focusses on evaluation by means of four pillars of design namely desirability, feasibility, viability and importantly, sustainability. Testing was done primarily for mechanical performance and evaluating the feasibility of the product. The viability was tested by evaluating the costs of the product and the organisational barriers in place preventing the change. Sustainability was evaluated by conducting an LCA which compares traditional manufacturing to metal 3D printing. Desirability, as a pillar was not highly focussed on since there are no direct end users involved in this project. However, all pillars are considered in this section.

4.1 Desirability

The first pillar of evaluation was desirability. Ideally, this is done by evaluating if the product/service/system is desirable to its end users in terms of values and needs. However, in the context of the VP30 pump, the end users are not involved in the chain of the product as it stops with the maintenance/repair shops. The end user is not aware if the product being used is either 3D printed or traditionally manufactured. There is a good argument for the end user to not be able to tell the difference among these as their experience with the product must always remain unchanged to maintain the quality impression that Bosch wishes.

Thus, desirability was evaluated at a stakeholder level with two primary stakeholders. First, Bosch AA itself which is the primary supplier and user of these spare parts. Secondly, remanufacturing shops such as Koller + Schwemmer GmbH. This evaluation was done based on interviews with employees of both organisations and has been an underlying theme throughout the entire report.

The case for Bosch AA's desirability for 3D printing has already been made in *Section 1.2*. This desirability is strategic in nature and allows for Bosch AA to build a more resilient and stronger business model and supply chain. This is especially relevant when suppliers for legacy parts such as those of the VP30 pump do not exist anymore for reasons such as bankruptcy, business pivot, lack of tooling etc. Moreover, since production for these parts has moved to India, it was difficult to find suppliers that were willing to produce the low volumes needed since the demand often did not exceed the minimum order quantity of these suppliers. Bosch AA operates under a thumb rule of having at least three sourcing possibilities for each part they offer. With CNC machining able to meet ultra-low volume demands (~10 units) and traditional manufacturing meeting the high-volume demands (>1000 units), Bosch envisions that 3D printing can fill the gap for middle volume parts.

For repair shops like KOSH, desirability exists in the form of flexibility wherein multiple suppliers can be sourced for the parts as per demand or even better, they can become a supplier of the parts themselves. However, for this, they would need the appropriate processes to be already put in place which is discussed in *Section 4.3*.

Thus, desirability hinges on the other pillars of design to become relevant and thus, was not the primary focus of evaluation in this report. However, it can be concluded that if the other conditions are met, the 3D printing of spare parts would be a desirable outcome for the stakeholders.

4.2 Feasibility

The second pillar of evaluation was feasibility. This concerns if the product in question can perform the desired function to the desired level. Since we were evaluating spare parts, the feasibility was evaluated by checking if these printed parts can replace the traditionally manufactured parts directly in operation. This testing was conducted on two levels: mechanical testing and test bench running. These are detailed below.

4.2.1 Mechanical Testing

The testing of mechanical properties of the 3D printed part was key to understand its efficacy as a suitable replacement for the traditionally manufactured part. Unfortunately, due to constraints of time and resources, the 'dog bone' samples of both the materials (conventional and 3D printed) required for tensile testing were unable to be created. This prevented us from conducting a tensile test to determine the yield strength of the parts.

However, since that is more the realm of material science, it was acceptable to skip this evaluation. The choice of materials for the 3D printed parts namely AlSi10Mg and Steel 1.2709 (MS1) either met or exceeded the performance of the respective materials used in traditional manufacturing. This can be verified through the datasheets of the materials used (see *Appendix 11*). Thus, it was important to conduct an evaluation more on the part level. This was performed by conducting a hardness test and a weight test.

Weight Test:

The parts, both conventional and 3D printed were weighed with an accuracy of 0.01 mg to determine significant changes in density. The weighing setup is shown in *Figure 55*. The weights of the parts are mentioned below in *Table 02*.

Figure 55: Weight Test Setup

Part Description	Weight (g)
Conventional Locking Cover	21.5026
3D Printed Locking Cover	22.2907
Conventional Cam Plate	125.7170
3D Printed Cam Plate	128.6983

Table 02: Weight Test Results

The weight of the parts were similar and hint at similar densities. The differences in weights could mainly arise from the slight changes in geometry detailed in the modelling process (see *Section 3.1*) and the lack of finishing up to the required tolerance and specifications. However, these differences would not have a significant impact on the performance of the pump. A slight reprogramming of the pump ECU would be needed to account for their weight changes. However, this step is already part of the test bench procedure and thus, not a barrier. Thus, from a weight perspective, these parts can be used as replacement parts in the VP30 pump.

Hardness Testing:

One of the critical properties of components which depends on the production processes is the hardness of the component. This test was conducted to compare the hardness of a finished traditionally manufactured part against a 3D printed part straight out of the printer (after removal of support structures). Under normal circumstances, the 3D printed part undergoes annealing and then hardening again to reach a desired hardness level. However, this test aimed to show the level of hardness that can be achieved directly and thus, the potential of 3D printing to produce hard parts.

The test was conducted at the 3mE Faculty of the TU Delft under the supervision of Mr. Tom Riemslag. The test followed was the Rockwell Hardness test. This test is suitable as it is non-destructive and easy to conduct. It is also accepted worldwide. The Cam Plate was tested with the HRC hardness scale which uses a spheroconical diamond indenter whereas the softer Locking Cover was tested with the HRB scale which uses a 1/16-inch ball indenter with a lower test load. The test setup is shown in *Figure 56*. The results of the hardness testing can be seen in *Table 03*.

From the results, we can conclude that the conventional manufacturing of the cam plate results in much higher hardness than the 3D printed variant. This can be explained by the fact that the conventional Cam Plate was case hardened as per design specification, and thus has higher hardness. The raw 3D print was not hard enough to be used directly as a replacement and must undergo treatment (annealing and case hardening) before it can be used as a replacement part.

On the other hand, the 3D printed Locking Cover was much harder than the diecast Locking Cover. This is because casting generally results in a softer material. Moreover, the Locking Cover has a function to withstand pressure (up to 8 bar) and thus, a ductile soft nature is preferred. The hardness of the 3D printed locking cover does make it more resistant to impact but also more brittle. The efficacy of the 3D printed Locking Cover needs to be tested on the test bench to check if it can withstand the necessary operating conditions.

As a conclusion, 3D printed aluminium parts are generally much harder than their cast alternatives. For the case of alloy steel, such a conclusion cannot be reached without measuring the hardness of the forged part before it was case hardened. However, it is important that the parts be within the required specification and thus, some post-processing treatment would be needed to serve as a replacement part.

Figure 56:Hardness Testing Setup

Cam Plate		
Sr No	Conventional (HRC)	3D Printed (HRC)
1	61.6	38.3
2	63.3	39.1
3	61.1	36.8
4	62.4	34.9
Locking Cover		
Sr No	Conventional (HRB)	3D Printed (HRB)
1	47.4	75.6
2	45.2	78.1
3	46.1	77.8
4	47.8	76.5

Table 03: Hardness Testing Results

4.2.2 Test Bench Running

The second test of feasibility was testing the 3D printed parts in the pump under real world/stress test conditions. This was possible through the bespoke testing bench for the VP30 pumps located at the KOSH facility in Nürnberg. Unfortunately, only the locking cover was possible to be tested on the test bench. The cam plate required additional documentation such as a first sample quality document, which was not possible to obtain in the time frame of the project. The locking cover was tested on the test bench for the two main tests i.e., ‘Überprufung’ and the programming of the pump control unit which outputs results on the level of flow of fuel to the nozzles under various conditions.

The test bench was a bespoke Bosch-made bench with the code EPS944. The test bench, the VP30 pump mounted on the bench and, the control computer are shown in *Figure 57*, *Figure 58* and *Figure 59* respectively.

Figure 59: Control Computer

Figure 57: Test Bench

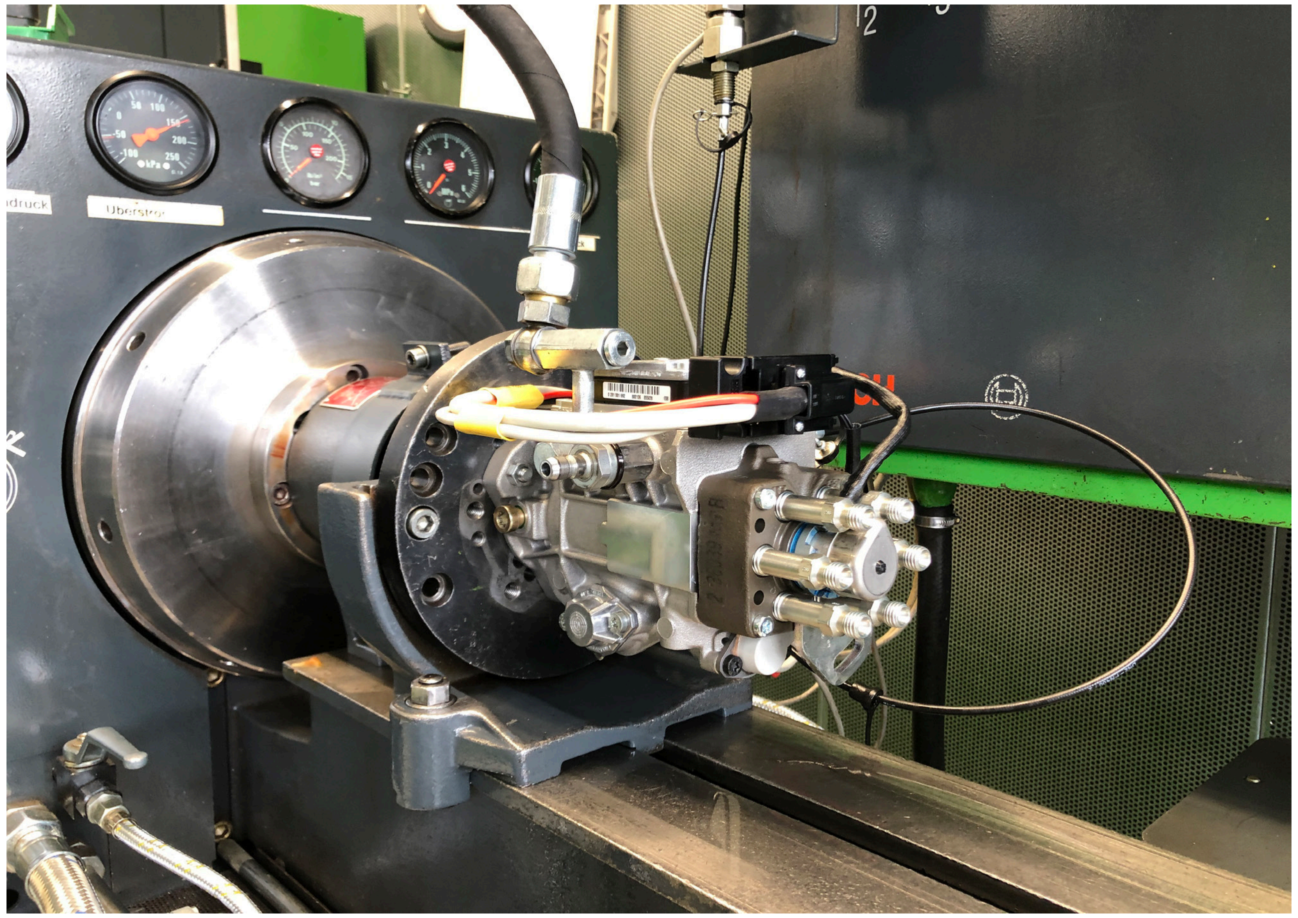


Figure 58: VP30 Pump Mounted on Test Bench

Firstly, the pump was mounted to the shaft via the chuck. Next, a ‘delta phi’ measurement was conducted to ensure that the travel of the ‘Verteilerkolben’ does not exceed the set amount. This is to ensure the fuel delivery is metered to the cylinders properly. Lastly, the fuel lines were connected both for the inputs and the outputs. This setup can be seen in *Figure 60*.

The complete test consists of three main programs namely the ‘Uberprufung’, ‘Pumpenabgleich’ and the ‘FB-Blockierung’. The ‘Überprufung’ is generally performed for remanufactured pumps. For completely new pumps, a ‘Prufung’ is performed. The second program adjusts and verifies the pump working based on the results of the previous test. Lastly, the FB-Blockierung tests a variation of the pump with a particular stage being blocked. Each test run through four phases – measurement, transient, positioning and waiting, for 6 iterations (each at different rotational speeds). These speeds range from 100 rpm to 1375 rpm. The duration of these tests ranged from 90 to 150 mins in total.

Before the test was conducted, the test operator inspected the 3D printed Locking Cover. The need for a smooth surface on the Locking Cover was mentioned to ensure that it remained tight and leak free during operation. He also noted that the rough chamfers on the inner side of the locking cover could pose a sealing problem.

Initially, the tests were conducted on a VP30 pump with a conventionally manufactured locking cover to set the baseline and program the pump control unit for the desired behaviour. This test was successful. The conventional Locking Cover was then replaced with the 3D printed Locking Cover and the tests were conducted again. The primary observation was to ensure that the Locking Cover kept the fuel sealed and that fuel did not leak out.

Figure 60: Full Test Bench Setup

Despite the hardness of the Locking Cover being higher than the conventional part, the 3D printed Locking Cover passed all the tests without problems. No fuel leakage was observed, and the structural integrity of the part was intact. This can also be seen in *Figure 61*. Thus, the 3D printed Locking Cover proved to be a like-for-like replacement for the conventional part without needing any post-processing. The complete test result output and testing videos can be found in *Appendix 12*.

With this result, it was confirmed that using the Locking Cover straight out of the 3D printing bed (without post processing) was feasible. The test operator clarified that long term field testing would still be needed to ensure the functionality would be met, but the test bench results were promising. The operator also conducted a visual inspection of the 3D printed Cam Plate and noted the rough surface of the cam profile. He reiterated that improving the surface finish on both the Cam Plate and the Locking Cover would be needed for maximum efficiency in operation.

Thus, the feasibility evaluation concluded with weight, hardness tests and test bench running. The weights of the 3D printed parts were similar to the conventional parts, allowing for replacing with a slight programming update. The hardness tests showed that the 3D printed Locking Cover was considerably harder than the die cast cover. Since the Cam Plate was case-hardened, the hardness testing did not provide additional information apart from clarifying that the 3D printed Cam Plate also needed to be hardened to meet the performance criteria. Lastly, the test bench runs proved that the Locking Cover can be readily used as a replacement spare part without post-processing, thus highlighting the potential of metal 3D printing. Unfortunately, the cam plate could not be tested on the test bench without certification. The Locking Cover proved to be feasible for immediate use whereas the Cam Plate requires further investigation to make the case for feasibility.

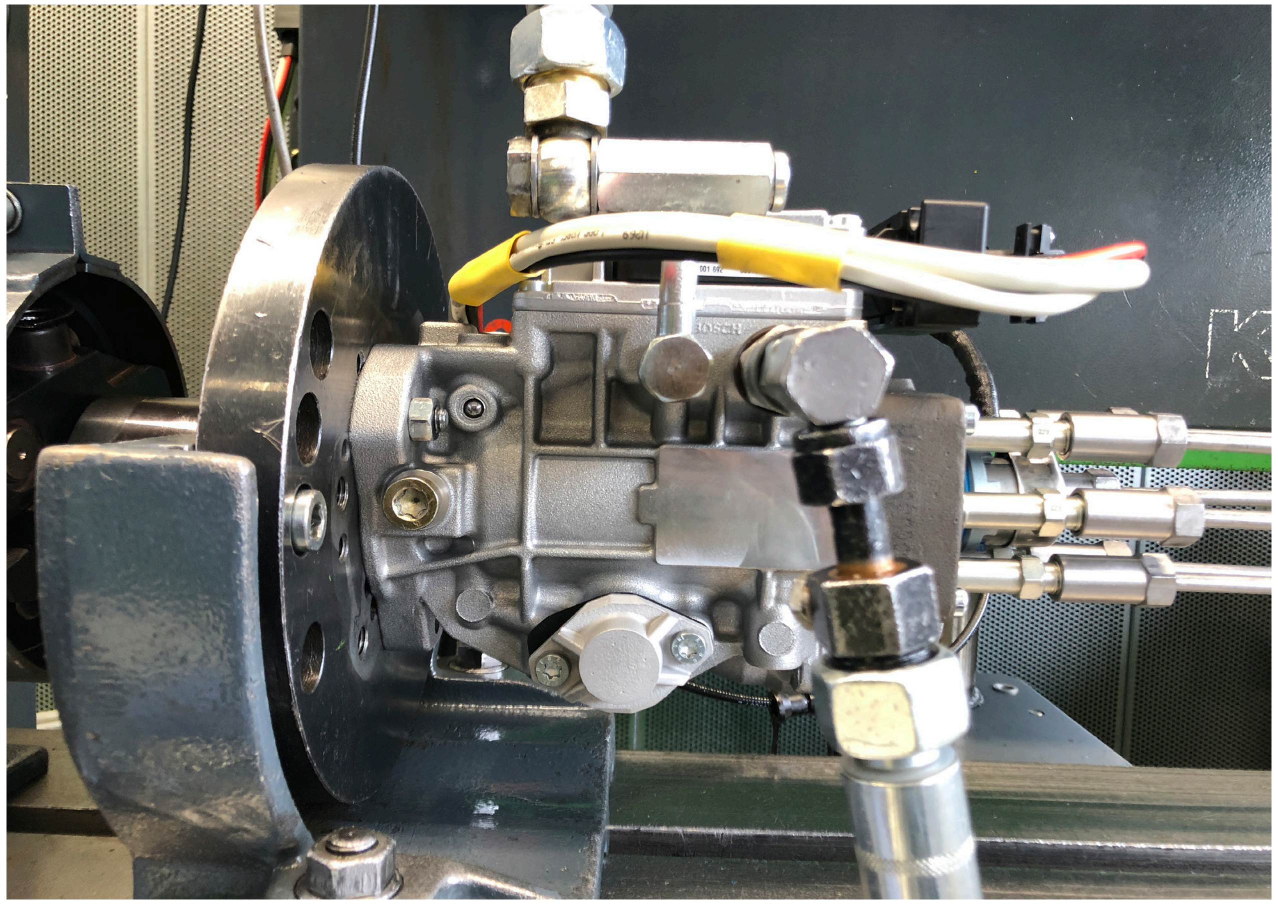


Figure 61: Post-testing Inspection

4.3 Viability

The third pillar of evaluation was viability. This evaluated if the product and organisation can survive in the long term by the proposed 3D printing implementation. The viability evaluation was performed on two levels, firstly the cost of implementation of 3D printing over traditional manufacturing on a part basis. Secondly, the organisational barriers in place to prevent a transition to incorporating 3D printing in the process flow. These are detailed below.

4.3.1 Cost

The information in this section is confidential and not available for public release. This information can be found in the *Confidential Appendix 1*. This includes *Figure 62* and *Figure 63*.

4.3.2 Organisational Barriers

The second manner of evaluating viability was by understanding what organisational barriers existed in the acceptance of 3D printing as a spare part production technique. This section does not evaluate all the organisational barriers but rather, throws light on the three main barriers. This analysis was performed by means of interviews with employees from Bosch AA, namely Mr. Christian Schindler, Mr. Dirk Lummer and employees at the 3D Competence Centre. The three main barriers currently in existence within Bosch are the automotive industry release procedure, the 3D print capacity, and the organisational structure of the 3D Centre. These are described in detail below.

- The Automotive Industry Release Process:

This is by far, the biggest and most significant barrier to overcome in the process to implement 3D printing. Alongside the medical devices and aerospace industries, the automotive industry is known to have notoriously high standards for components to be certified. This is primarily for regulation compliance and has its basis in safety. The process of FMEA (Failure Mode Effect Analysis) which is an engineering activity performed to ensure the safety of the designed components is performed on many levels, some of which include the design, function, and the manufacturing process. For every change in any of these areas, the FMEA must be completely redone to add extra measures, tests, and inspections to assure the quality of the product. Most importantly for OEM suppliers like Bosch is that they must convince their customers (auto giants like VW and BMW) that such a change is necessary and enumerate the benefits of such a change for them. Some of these manufacturers work using change windows where such changes can only be made at specific times of the year which adds an extra later of complexity. The release procedure also involves the entire value chain which means that suppliers of raw materials and sub-contractors must also be included in the FMEA by means of activities such as certifying the supplier (in this case, for the metal powder used to 3D print) or a machine shop where the final grinding might take place. Thus, there is a need for a lot of resources (time and money) and co-ordination between various teams in the organisation (such as design, production, sales, purchase, quality control). This requires a prioritization of resources within the organisation making change a long and tedious process. Additionally, in the industry today, more factors such as environmental sustainability and human rights conditions are also being considered for such changes. As mentioned in *Section 4.3.1*, the costs of 3D printed parts are considerably higher than traditional manufacturing and thus, there need to be other significant reasons for investing the time and resources to make this change and get them certified to meet the standards of the industry. Thus, this remains the biggest barrier for 3D Printing to cross for acceptance. However, the employees at the 3D Centre were quite confident that it was possible to overcome this, but they pointed out that the second barrier (described next) could be a reason for delay.

- Organisational Structure of the 3D Competence Centre:

Within Bosch, the 3D Competence Centre is responsible for researching and developing techniques and opportunities for 3D printing to be introduced into Bosch's process flows for various products. Given the subsidiary nature of the 3D Centre within Bosch, there is a lack of a strong business case for the 3D Centre to function as an independent business. Once the 3D Centre is accorded equal importance in the organisation, backed by a solid business case where cross-subsidisation {a profitable entity (business unit/product) helps cover the costs of a unprofitable entity; for eg: the high prices of few first class airplane tickets helps reduce the cost for many economy class tickets} would not be necessary, the chances of incorporating 3D printing would become better.

- Capacity:

The last but most easily solved barrier is that of capacity. At the scale at which Bosch operates, there is need for a lot more capacity than exists currently within the 3D Centre. Currently, they only have 5 3D printers of various sizes which can print around 4 different materials. This can be easily solved through contract manufacturing if the necessary certification as mentioned above are obtained. To be useful for the entire organisation, 3D technology must develop faster, and more research needs to be conducted to increase capability, not only locally but globally. This increase demands a large investment in terms of money and resources. Bosch is a technology leader in the industry and if any organisation has the resources to make it successful, Bosch would be high on that list. Thus, this barrier is the easiest to overcome.

Another barrier that exists in the adoption of 3D printing for spare parts is the knowledge life cycle of legacy parts such as those of the VP30 pump. Since these parts are old and the demand for these products are higher in developing countries like India than in Europe, the production of these parts has shifted over the years from Europe to India. With a change in production location comes the need for new facilities, new training, and new processes. From conversations with Bosch employees and in the process of acquiring information about the parts, it was found that most of the knowledge about older parts was latent within employees and not specifically documented. When such a production shift happens, this tacit knowledge is often lost, and investments (both in time and money) are needed to develop this knowledge again. Modern processes and data flows are computerised, making this transition easier. However, for legacy parts such as the VP30 pump, this is still a barrier that needs to be resolved.

Thus, a complex web of interconnected barriers, mainly the automotive release procedure, a lack of capacity and organisational structure together combine to create a position where investment and patience is necessary to produce the desired results.

4.4 Sustainability

The last level of evaluation was on an important but often neglected parameter, sustainability. Given the reality of climate change and the need for circular economies, it is important to always evaluate every change on sustainability metrics as well. This was performed by conducting a fast-track Life Cycle Assessment (LCA) comparing the two different methods of spare part production – conventional manufacturing vs 3D printing. This is explained in various sections below. The techniques used in this analysis are obtained from VentureWell (2022).

4.4.1 Scope

The first step of conducting the LCA was to define the scope of the assessment. The scope defines the main reason behind conducting the LCA. For this study, the scope was defined as a 'fast track LCA to compare the environmental impact of production by two different processes for a range of units produced'. This would help us better understand when (no of units produced) a particular production technique was more environmentally friendly.

4.4.2 Boundaries

To keep the LCA manageable and workable, it was important to set the boundaries of the study. This defines the region of comparison based on the scope for which the LCA is being conducted. To do this, we plotted a system map. This is shown in *Figure 64*. This system map tries to include all the possible elements of the system which can be compared. These range in both time and space as mentioned in VentureWell (2022). Since we are mainly comparing only the different manufacturing processes and the inventory data for all the finishing processes was difficult to obtain, a system boundary was created. This system boundary is represented by the 'teal' cells.

In clearer terms, the system boundary only included the raw material extraction, processing and manufacturing of the parts and the tools needed to manufacture these parts (dies, moulds etc). Transportation at all levels was excluded. Since the different techniques intend to produce the same parts, the use phase of the parts will have the same impact and thus were excluded from the analysis. It is possible that the use phase possesses the highest environmental impact. However, that merits a different analysis. Lastly, the End of Life (EoL) scenarios of the parts were unclear due to lack of information from the suppliers. Thus, they were excluded from the analysis. The impact of the machines required for traditional manufacturing and 3D printing were also not included.

4.4.3 Functional Unit

The choice of a functional unit is important to ensure that the LCA represents a fair comparison. A poor functional unit can output completely incorrect results and thus, lead to an incorrect conclusion. Since the comparison was purely on the manufacturing process and the system boundaries were fixed, the functional unit for this study was defined as 'environmental impact per part produced'. This was measured in kg CO2 eq for a range of 1 unit to 50,000 units for various scenarios. This range comparison was a special feature of this LCA since it allowed us to pinpoint at what manufacturing volume, the scale of sustainability tilted from one process to the other.

4.4.4 Inventory

All the data inventory for this LCA was obtained from Granta Edupack 2020, which is one of the most advanced databases in the world. For data related to 3D printing environmental impacts, there was no standard database. Thus, research from Baumers, Tuck, Wildman, Ashcroft, & Hague (2010, 2011); Faludi, Baumers, Maskery, & Hague (2016); Kellens et al., (2017, 2011); van Sice & Faludi (2021) were used. Some data for the inventory such as the weight of the tools (dies and moulds) were not available and thus were estimated. Thus, the uncertainty for them was

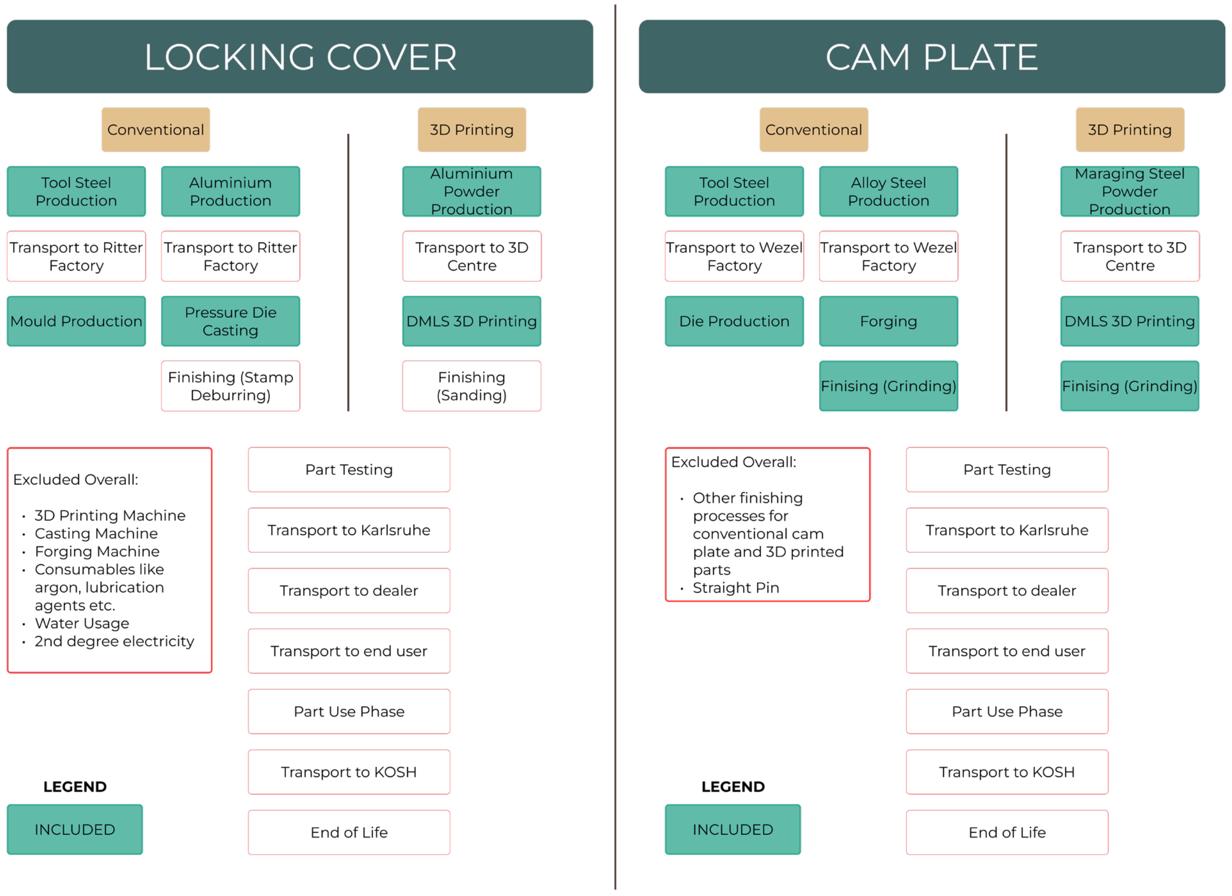


Figure 64: System Boundaries

judged at 50% and multiple scenarios have been made for these cases.

For data about 3D printing impacts for various unit quantities between single part and full plate quantity, the data points for a single part build and a full plate build were linearly extrapolated to calculate the impact for individual unit quantities (see *Figure 65* for the Locking Cover). The uncertainty for these values was set at 50%. The full plate builds for the Locking Cover consisted of 20 units and 16 units for the Cam Plate. Beyond the full plate quantity for each part, all quantities were assumed to have the impact of the full build plate to prevent confusion and for ease of calculation. Since only units in the 1-2-5 series were plotted on the graph, the graph would oscillate wildly between the plotted points and thus, not present a clear scenario. Moreover, these differences would not be very noticeable on a logarithmic scale. Lastly, for intermediate unit numbers, there are multiple ways to print the parts. For eg, the impact of printing 21 units of the Locking Cover need not be the impact of printing 20 units and then 1 unit. It could also be the impact of printing 11 units and then 10 units, which would offer a different result. To prevent this confusion, all quantities beyond the full plate quantity are considered to have the same impact as the full plate build. The values for 3D printing impact of Maraging Steel were not available and were substituted for values of SS316L with 50% uncertainty. The complete LCA spreadsheet with data, notes, uncertainty, and scenarios is available in *Appendix 13*.

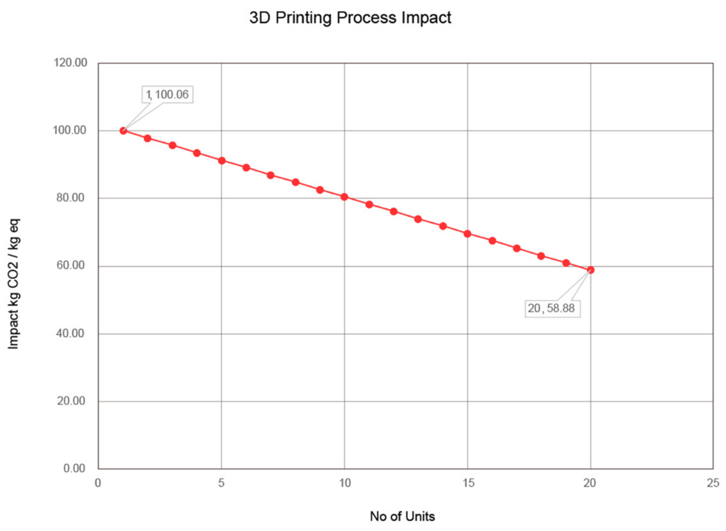


Figure 65: Linear Interpolation between single part and full bed impacts (Locking Cover)

4.4.5 Scenarios, Sensitivity and Results

To ensure that the LCA results were fair, comparable, and real, multiple scenarios were evaluated with different parameters to critically evaluate the two competing manufacturing methods. These scenarios mainly outlined the various possibilities in the design of the tool (casting/machining), the weight of the tool and the impact of different 3D printing arrangements (single part or full build). For this, a bed size of 245mm X 245mm was considered as per the standard machines used at Bosch 3D Centre and a layout was made on how many parts would fit in a full build. For the Locking Cover, 20 parts could fit in one build whereas for the Cam Plate, it reduced to 16 parts. Thus, within these scenarios, there were mini scenarios where the impact of 3D printing reduced as the number of parts increased to account for the usage of the full build plate. Thus, given the uncertainty and the sensitivity analysis, infinite scenarios could be created for analysis. However, the results of a few important scenarios are shown here for both the Locking Cover and the Cam Plate.

Locking Cover

Scenario 1: Aluminium die casting, 50kg tool steel required for die, die is cast and 5kg is machined for precision; 3D printing does not include impact of ancillaries

Scenario 2: Aluminium die casting, 75kg tool steel required for die, die is machined and 30kg is machined for precision; 3D printing does not include impact of ancillaries

Scenario 3: Aluminium die casting, 75kg tool steel required for die, die is machined and 30kg is machined for precision; 3D printing includes impact of ancillaries

Scenario 4: Aluminium die casting, 150kg tool steel required for die, die is machined and 60kg is machined for precision; 3D printing includes impact of ancillaries

Cam Plate

Scenario 1: Alloy steel forging, 100kg tool steel required for die, die is cast and 10kg is machined for precision; 3D printing does not include impact of ancillaries

Scenario 2: Alloy steel forging, 125kg tool steel required for die, die is machined and 35kg is machined for precision; 3D printing does not include impact of ancillaries

Scenario 3: Alloy steel forging, 200kg tool steel required for die, die is machined and 70kg is machined for precision; 3D printing does not include impact of ancillaries

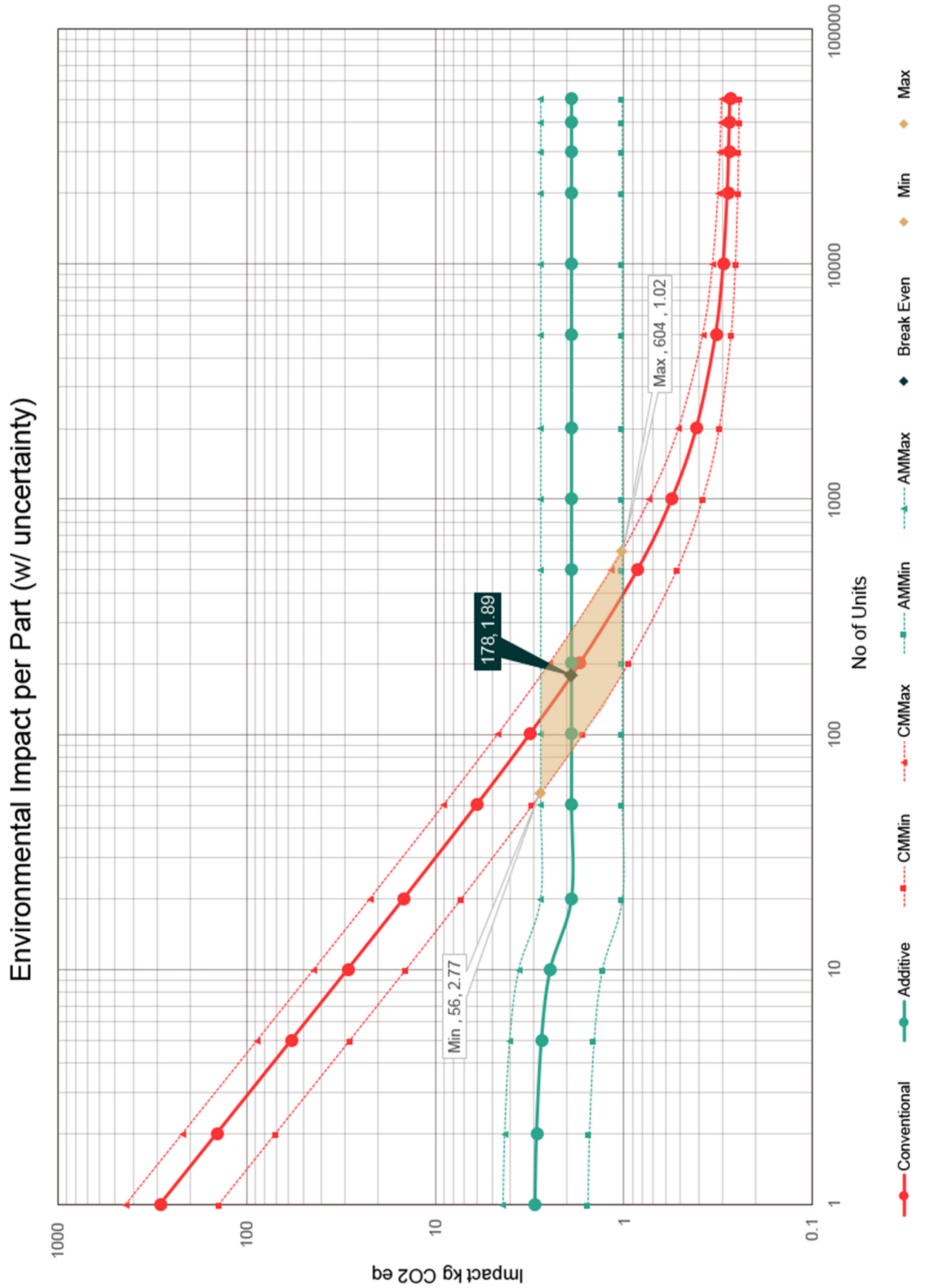


Figure 66: Locking Cover - Scenario 1

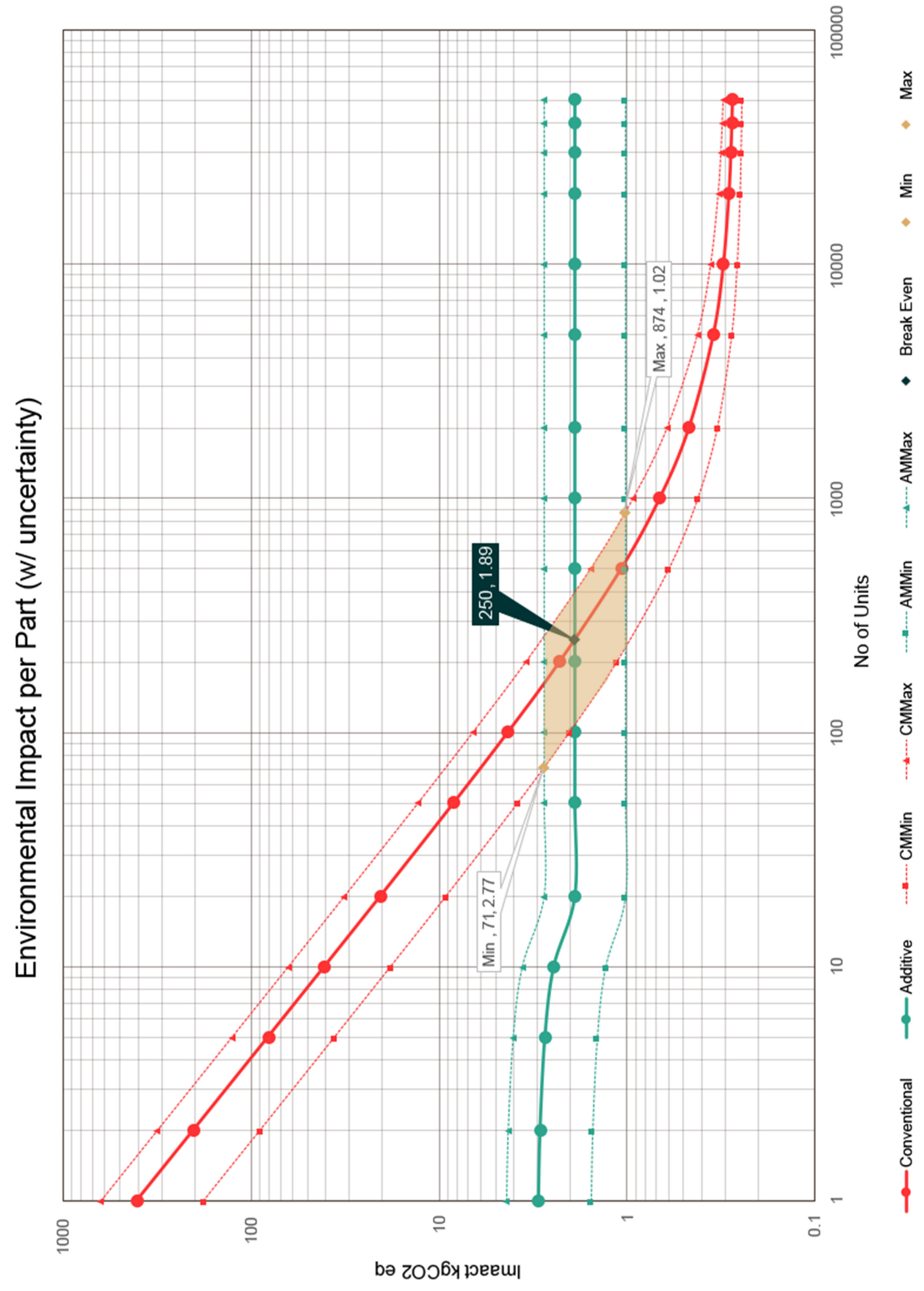


Figure 67: Locking Cover - Scenario 2

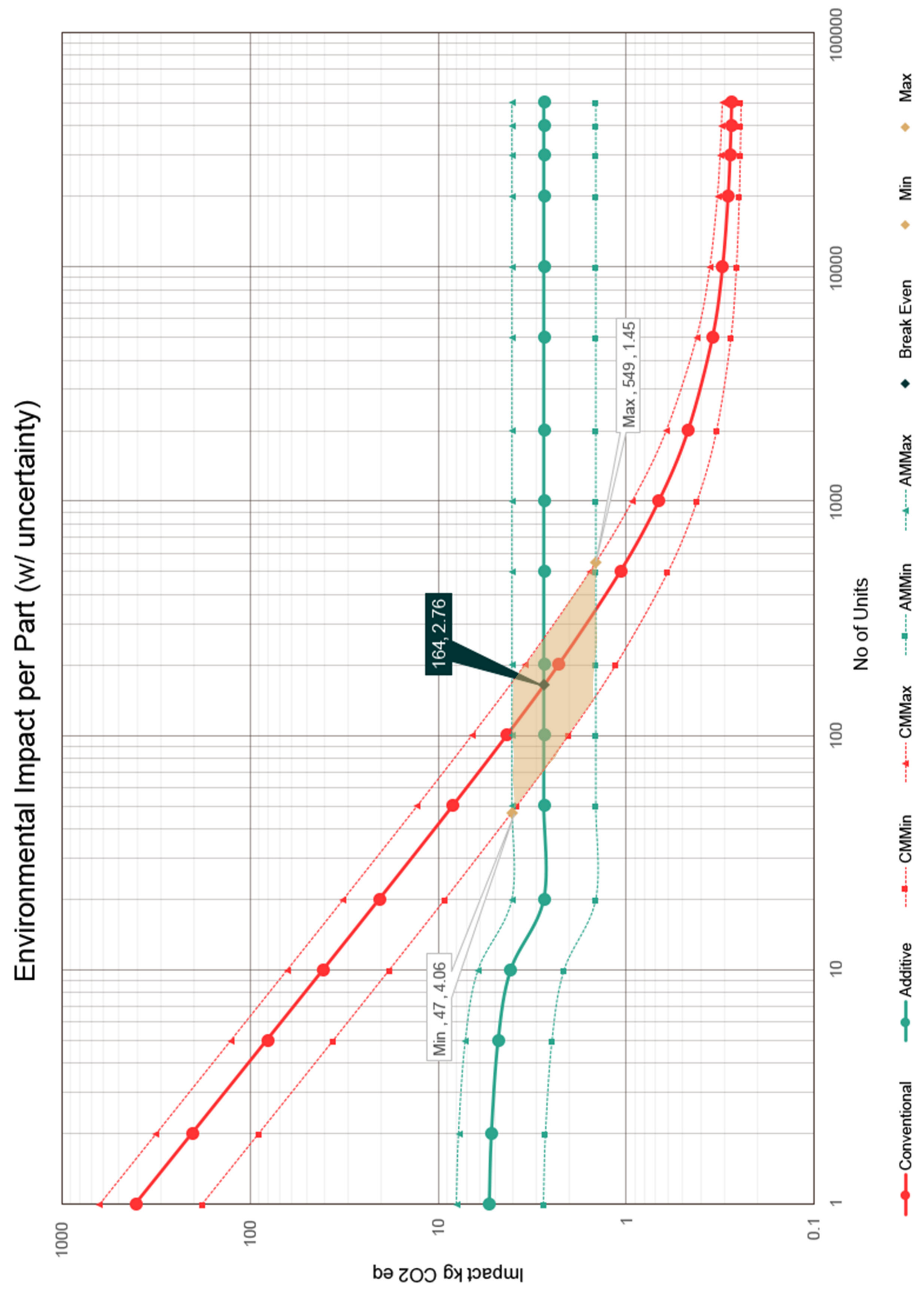


Figure 68: Locking Cover - Scenario 3

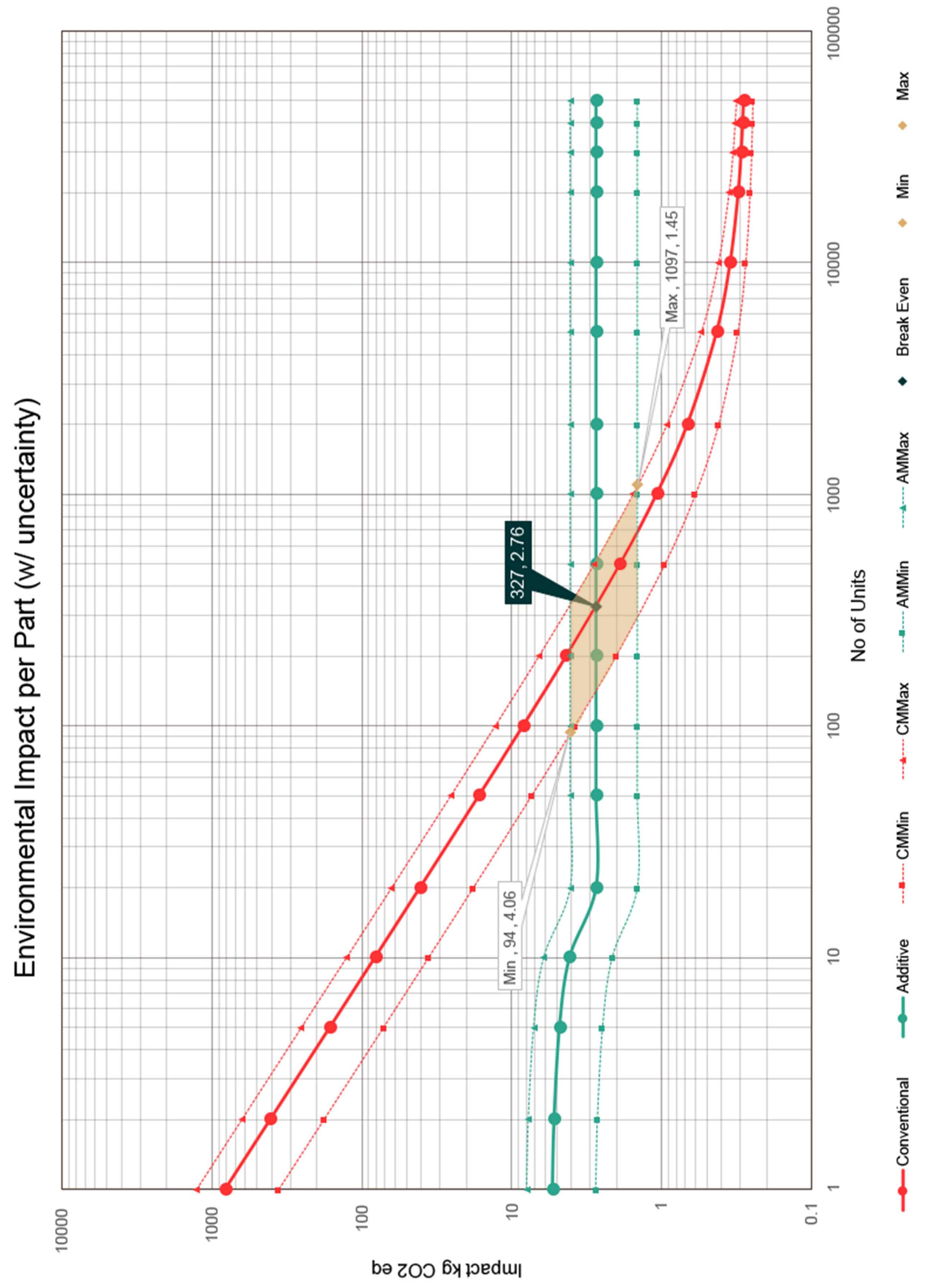


Figure 69: Locking Cover - Scenario 4

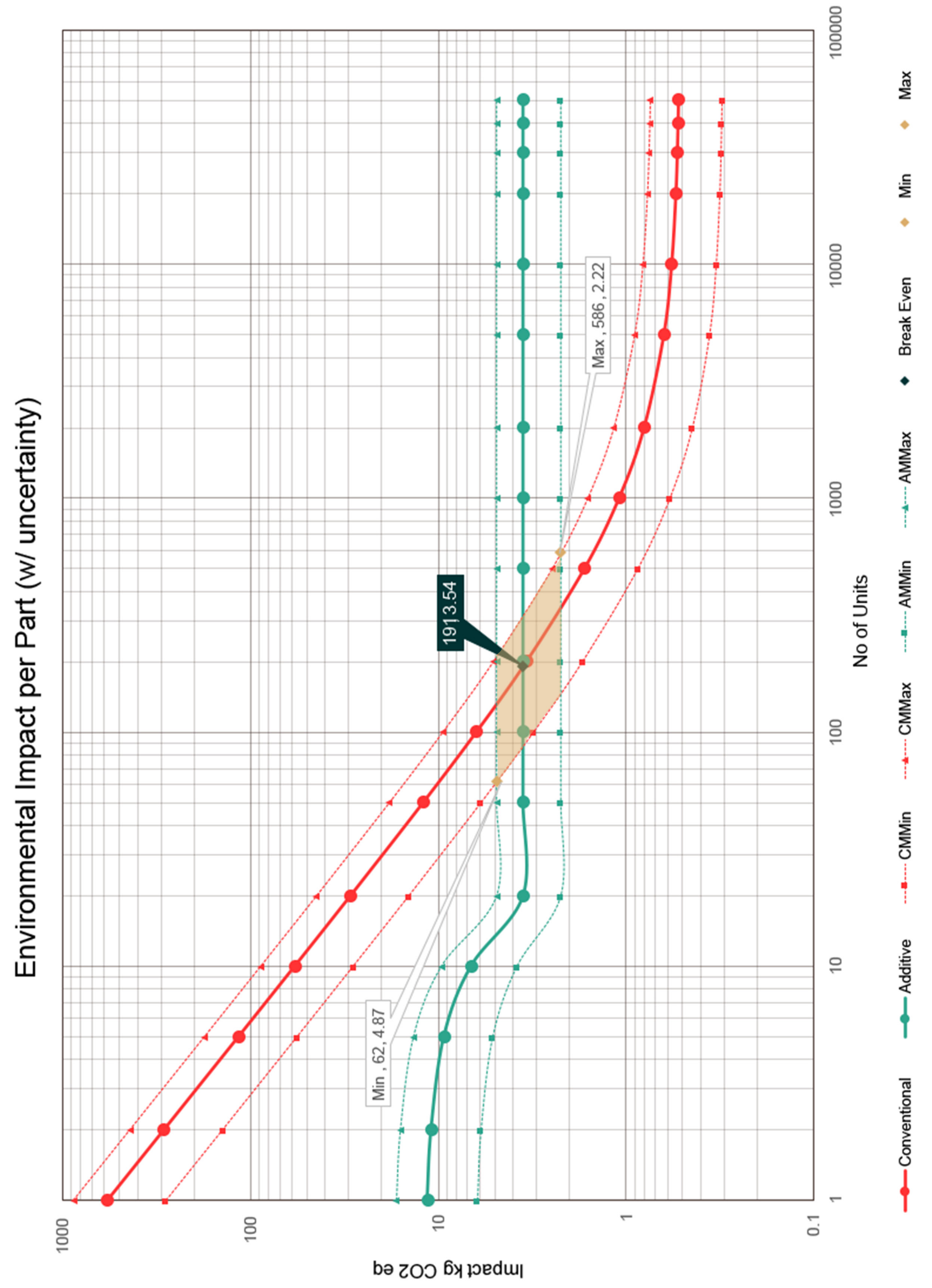


Figure 70: Cam Plate - Scenario 1

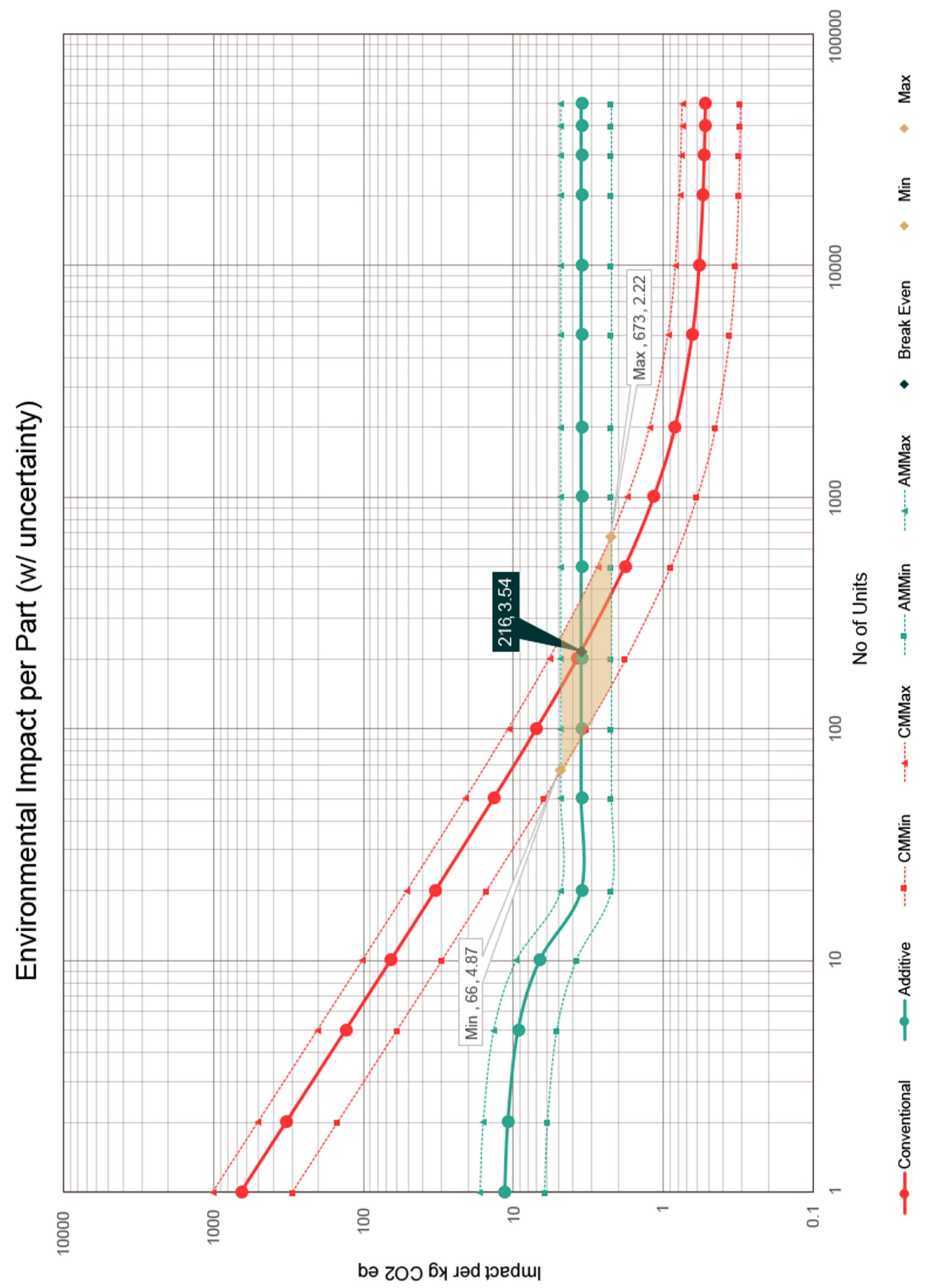


Figure 71: Cam Plate - Scenario 2

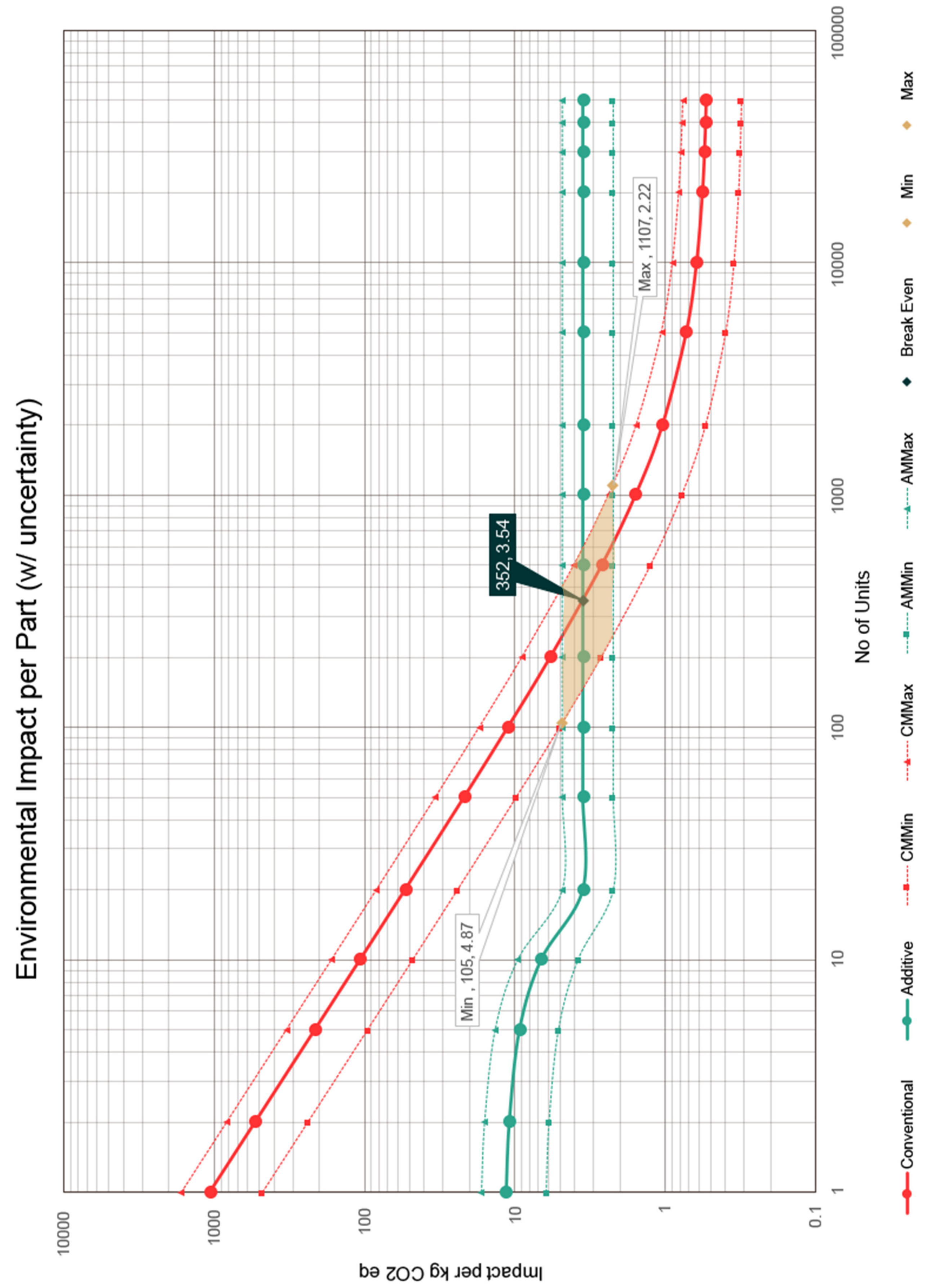


Figure 72: Cam Plate - Scenario 3

4.4.6 Interpretation

The summary of the results can be seen in *Table 04*. From the various scenarios analysed in the LCA, it was clear that there was always a point where the impacts per part produced was lower for conventional manufacturing than for 3D printing. These ranges, depending on the scenario was from 47-1097 units for the Locking Cover and from 62-1107 units for the Cam Plate. Within the scenarios, the influence of the weight of the tools required for the process (moulds, dies) was the control factor for the break-even point.

Given that the order demand per year for the Locking Cover is ~330 units and ~200 units for the Cam Plate, it would be more environmentally sustainable to produce these by 3D printing instead of traditional manufacturing. The average break-even point does not cross 500 units for any of the envisioned scenarios, which is a very low volume of production. These values are based on the average line. If the minimum and maximum lines are considered, the break-even point shifts but never to less than 40 units and never to more than 1200 units. Given the volumes generally used in traditional manufacturing, 1200 units is a small quantity and does not represent a huge win for 3D printing. However, this does make the case for medium level production as originally envisaged by Bosch.

This LCA also fails to consider that the life of the tools needed for traditional manufacturing are long and they can be used again next year. This reduces the impact per part produced in the later years. Moreover, the chosen parts are small with a maximum size of 55 x 55 x 22.5 mm. Thus, a large quantity of these parts (even up to 50,000) can be produced in one cycle and stored without a need for large spaces. This makes the case for 3D printing the part weaker since the environmental impact per part in that case would be considerably lower. Moreover, it also helps prevent other issues such as those related with metal powder handling for every print job. However, part storage needs to take into account corrosion, and this requires VCI (Volatile Corrosion Inhibitor) bags which possess environmental impact of their own.

Following the matrix as defined in van Sice & Faludi (2021), which defines the cases in which 3D printing can be useful, the only potential use case for 3D printing to be more sustainable in this scenario is when the demand volumes are low, and the tooling impacts can be avoided.

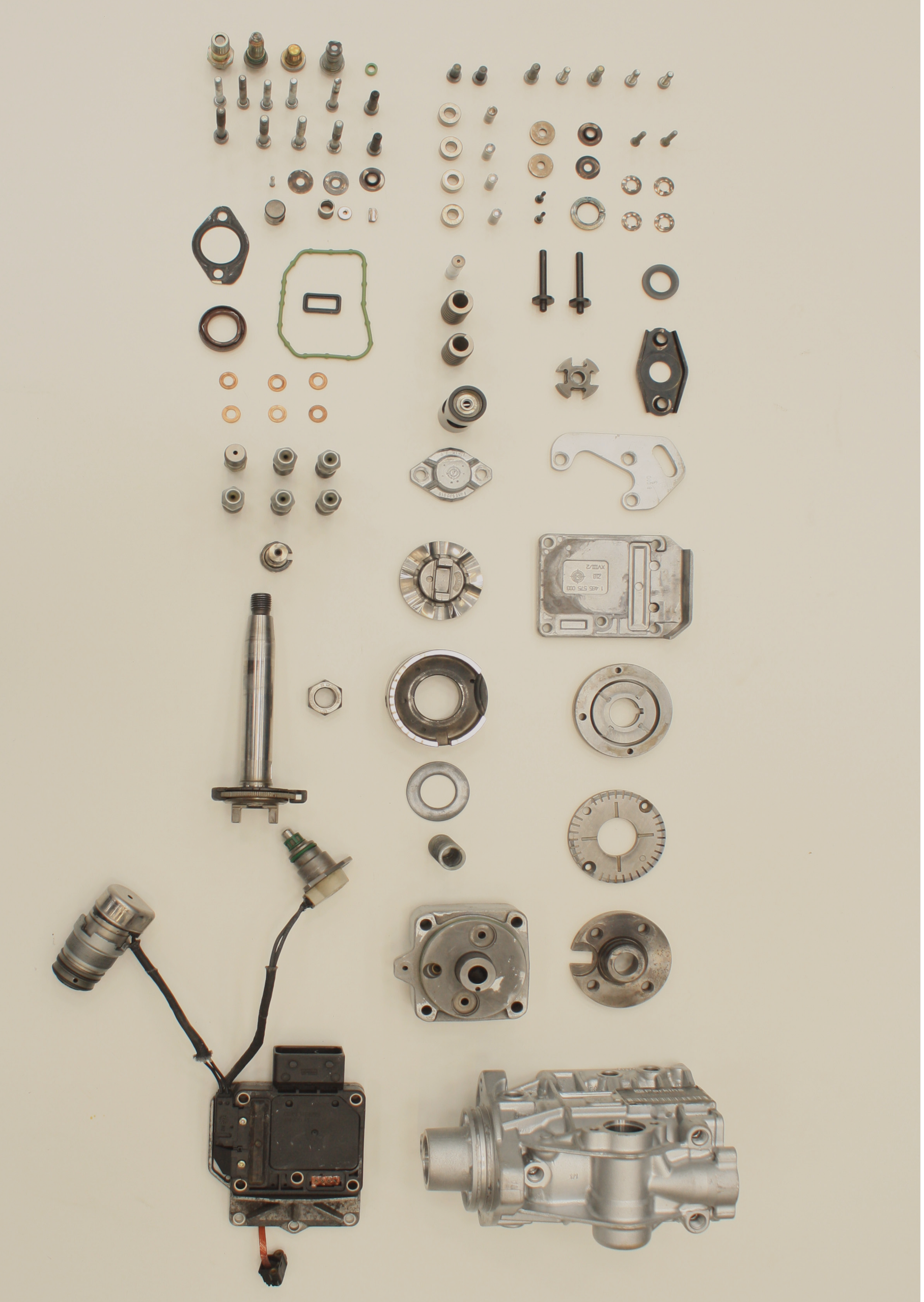
Thus, the LCA underscores the need for other conditions such as requirement of low volumes or lack of tooling for traditional manufacturing for 3D printing to be a more sustainable alternative. The LCA can be made more accurate with accurate data on the tools needed for traditional manufacturing. Moreover, this LCA only considers the production of raw parts. With the addition of other post-processing and finishing processes, the case for 3D printing to be more sustainable could be better or worse since traditional manufacturing also has post-processing involved and different conclusions may be reached.

Part	Scenario	Avg Break Even Units	Break Even Unit Range
Locking Cover	1	178	56 - 604
	2	250	71 - 874
	3	164	47 - 549
	4	327	94 - 1097
Cam Plate	1	191	62 - 586
	2	216	66 - 673
	3	352	105 - 1107

Table 04: Life Cycle Assessment Scenario Summary

4.5 Conclusion

Thus, the evaluation of the outcomes on the four pillars of design leads to the conclusion that though 3D printing spare parts is desirable, it would need the support of other pillars to be concrete. While it is feasible to 3D print the parts, some post-processing is needed to ensure they can serve as a replacement. With respect to viability, the high cost and the automotive release procedure serve as barriers. The costs need to reduce below conventional manufacturing costs to act as a trigger for changing the production process. Other scenarios such as low volume production and lack of suppliers are currently the main means of making 3D printing viable. Lastly, with regard to sustainability, low volumes favour 3D printing but a deeper analysis into tool life and post-processing processes needs to be conducted to truly make the case for 3D printing being more sustainable.



Chapter 5: Project Evaluation

This section details the conclusions of the project, especially by means of a future 3D print investigation flowchart. It also details the limitations and future potential of this research. Lastly, a personal reflection on the process, the project and learnings can be found.

5.1 Conclusions

The goal of this Master graduation project conducted under the aegis of the EU ReCiPSS project was to investigate the possibility to utilise 3D printing to manufacture spare parts for the remanufacturing process of a fuel injection pump, specifically the Bosch VP30. With the help of literature review and expert interviews, the context of the operation of the pump and the need for such an investigation was clarified. The problem definition posed three specific areas concerning the feasibility, viability, and sustainability of 3D printing metal spare parts.

Using newly developed (at the TU Delft) design for sustainability tools such as the Disassembly Map and the Hotspot Mapping tool, two parts of the pump were chosen by virtue of their environmental, economic, and functional impact to further investigate for 3D printing. The modelling and printing process for these parts followed. The modelling process was time intensive, and the 3D print iteration process was limited by budgetary and lead time constraints. However, 3D printed parts were produced and analysed. This process resulted in the creation of design guidelines for DMLS.

The process was then evaluated on the three pillars mentioned in the problem definition. The printed parts have the potential to meet the necessary technical specifications needed to serve as replacement parts. They require some post processing treatment such as annealing and case hardening for the same. The Locking Cover was able to be used directly from the print bed as a replacement part. With respect to cost, the 3D printed parts were quite expensive in relation to conventionally manufactured parts and thus, not viable in isolation. A combination of other factors would be needed to make a viable business case for 3D printing. Moreover, organisational barriers in the automotive industry, mainly the release procedure would make this integration more difficult without the allure of cost savings. Lastly, analysing the sustainability led to interesting outcomes. They showcase that producing low volumes (between ~100-1000 units) is more sustainable by 3D printing than conventional manufacturing. However, this analysis is limited to the primary part production and for a period of 1 year. Thus, the sustainability metrics of 3D printing being better than conventional manufacturing depends on the total demand for the parts over a longer period and if there exists a need for conventional tooling.

Thus, the entire investigation led to the development of a 3D print investigation flowchart which helps potential designers, engineers and management decide if such an investigation of their case is worthwhile. This flowchart can be found in *Figure 73* and a high-resolution version in *Appendix 14*. With this flowchart, the decision of pursuing such an investigation of using metal 3D printing for producing existing spare part designs with minor design changes can be made for products similar to the VP30 pump with in-house or familiar DMLS 3D printing suppliers. The flowchart was developed by considering the various criteria that were used throughout this project during the part selection, design, and evaluation phase. These include questions related to the part such as material, size, 3D modelling and surface finish. In addition, viability criteria such as production volumes, supplier availability, tooling, and process flow; feasibility criteria such as the need for post processing and certification and lastly, sustainability criteria regarding production volumes and post-processing were also considered. This flowchart is not meant as a decision-making tool but rather a guiding tool to help the decision of making such an investigation for a similar spare part. This flowchart does not grant an objective score for decision making but rather nudges the user to think about the possibilities and make a subjective decision, leading to a possible detailed investigation.

Though it may seem that the current investigation for the 3D printing of spare parts for a fuel injection pump does not meet the criteria set forth in the four design pillars, that is but a reflection of the time we are in today, the year 2022. Technology related to 3D printing mainly the lasers, metal powder production, materials, and newer metal printing techniques such as Fused Filament Fabrication (FFF) and Binder Jetting are being researched. These will lead to improvement in efficiency, reduction in costs, greater acceptance for 3D printing as a manufacturing technology, more material possibilities and thus, improve its performance in the viability and sustainability evaluations. Feasibility is already at a high level and needs the push of a greater choice of materials and lesser post-processing to be more widely accepted. With high level research and the backing of global leaders like 3D Systems, Desktop Metal, Markforged, Stratasys etc and the combination with Industry 4.0, 3D printing acceptance is expected to increase in the future. The expectation is that by the year 2030, the status quo will be greatly improved necessitating a renewed investigation in this subject.

The recommendation of this project to Bosch, as the client organisation is to conduct further research using the developed flowchart for other product lines and even other sub-divisions of the company. The case for the VP30 pump might not be crystal clear due to the old age, low volumes, and availability of suppliers. However, there might exist other Bosch products with a different scenario more suited for 3D printing. These investigations might lead to potential savings and bolster at least two, if not all three bottom lines for Bosch.

Within the scope set in the project brief, the achieved results add valuable knowledge to the research area and provide a basis for further investigation. Newer opportunities such as complex designs, need for resilient and simplified supply chains, on demand manufacturing capacity etc. can be fulfilled by 3D printing. Thus, the limitations and future research possibilities are detailed in the following section.

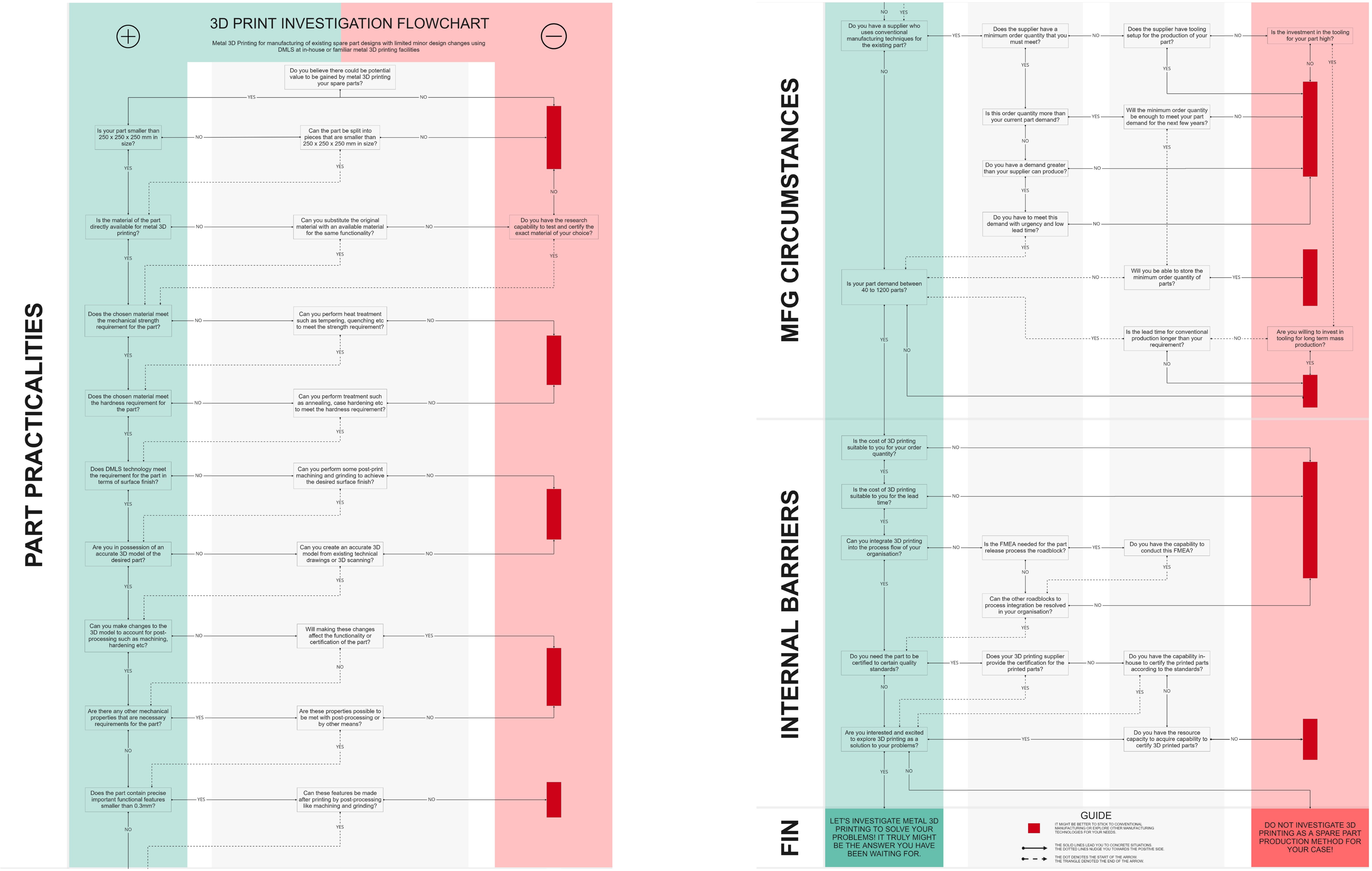


Figure 73: 3D Print Investigation Flowchart

5.2 Limitations & Future Research

The limitations of this project present themselves in various forms and need to be understood while taking the conclusions of the project into consideration.

1. The result of this investigation is only valid for the specific VP30 fuel injection pump and does not include other fuel injection pumps such as the VP44 which share some parts. This research can be thus expanded by investigating other products in the product line or other sectors altogether such as engine blocks and so on.

2. The data used in the Hotspot Map comes from Granta EduPack 2018. This might skew the conclusions slightly since the data is not up to date. Updated data can be used to get the most accurate understanding of the situation.

3. The selection process involved interviews with one expert only. To make the selection process more robust, multiple stakeholders from different functions such as purchasing, quality control should also be invited.

4. The 3D models created in SolidWorks have some inherent inaccuracies due to modelling software constraints or lack of information in the technical drawing. This can be solved with more time and better exchange of information.

5. The 3D print process was conducted at an external facility. This prevented the opportunity to get a close look at the entire process and investigate possibilities for improvement. Future research can focus on investigating the print process for possibilities for improvement.

6. The lack of iterations of the model - print - analyse cycle was due to budgetary and time constraints. By performing more iterations with different materials and different 3D print technologies, the best possible solution can be found and lead to the development of stronger design guidelines.

7. The feasibility tests were conducted on one printed sample. These tests must be conducted on multiple samples and certified to achieve standardisation. Moreover, a tensile test for strength was not conducted and this can be performed as well.

8. Additional organisational barriers by conducting workshops with employees from various functions can be explored. This should include the post-processing and certification processes as well.

9. The LCA is based on some assumptions covered with uncertainty values. These assumptions must be verified and a full LCA from cradle to grave must be conducted to understand the accurate scenario.

These limitations open opportunities to refine this research and deliver better outcomes.

5.3 Personal Reflection

Reflecting is a critical activity in the field of design and allows us to improve as designers. This section contains a short reflection on the design process, the results, and my learnings during this project.

The design process followed during this project was the typical double diamond process. Once literature was reviewed to set a problem definition, there was not a need for much divergence for user context. This can be quite atypical for a design problem. However, since the project dealt more with feasibility and viability and did not have end users directly associated with it, this can be understood. I was very satisfied with the problem definition which covered two main design pillars and added a very important third one: sustainability. My first foray into the design of circular systems was set.

The convergence section in the first diamond led to the use of design methods and tools to select the two parts for further development. This was a phase of the process I found myself highly interested in and where I was able to discover the value of design methods in decision making. Here, I also discovered a new interest in developing design methodology and was able to provide some recommendations for the existing methods. If I get the opportunity in the future, I would like to research and develop some more methods particularly in the realm of circular design. This phase vindicated my choice of having Prof. Conny Bakker as my project supervisor given her expertise in design methodology.

The ‘develop’ phase of the project allowed me to explore physical prototyping and design of the parts. The excitement of exploring new 3D printing technologies combined with solid modelling fundamentals allowed me to delve into the nitty-gritty of the process. For an individual who had not 3D printed a single part before, this exploration laid bare not only a fascination for the technology but also an interest to learn more about it. The visit to the 3D Competence Centre added a sense of reality to this exploration and allowed me to achieve one of my learning aims for this project. I would have preferred to be able to visit the 3D Competence Centre earlier in the project timeline since it would have saved me some valuable research time. However, practical difficulties ensured that only a later visit was possible. Moreover, time and budgetary restrictions only allowed for one design-prototype-analyse iteration, cutting short the expected learnings. This is something I hoped to do more of and realise better, more accurate results.

However, the process followed, and the conclusions reached thereafter, gave me a sense of satisfaction. It also allowed me to have a foot inside the door and provided the opportunity for further learning if needed. Performing the evaluation section allowed me to critically analyse the outcomes of my development work. This is another section I enjoyed working on, particularly the cost and LCA analysis. I have always considered myself as a business oriented individual, by virtue of my upbringing. Choosing IPD over SPD was one of the most difficult choices in my career and thus, an opportunity to work on SPD themed sections in my IPD graduation project was not something I was going to give up easily. The analysis of cost and organizational barriers is something that I am proud of and delighted to have conducted.

More importantly, it was the conduct of the LCA that I was most delighted by. The process of conducting the LCA (with not fully accurate data however) exercised my critical thinking ability and allowed me to dream up multiple scenarios. The guidance by Prof. Jeremy Faludi, my graduation supervisor in this regard was immense and I am grateful for that as it helped me achieve my second learning aim for this project. At the end, I was left with the curiosity to find the LCA inventory data myself and this brought out the environmental scientist in me. Maybe an in-depth study in Industrial Ecology is due soon.

Lastly, since this was an individually managed project, I would also like to reflect on my planning. Completing a MSc graduation project in 100 days was not easy and the planning had to be immaculate. A sudden illness and only 4 working days in the week did offer challenges, but I am happy that I was able to overcome the challenges and deliver the project on time by adjusting the planning to the demands at the time (focussing on report writing over LCA during the mid-term) and prioritising tasks. These learnings allow for new confidence in my work flexibility and adaptability.

It would be remiss of me to not acknowledge the immense support provided by Mr. Dirk Lummer from Bosch, who supported me by answering all my questions and more importantly, being my sparring partner throughout the duration of the project.

Though the conclusions of these evaluations made clear the nascency of 3D printing for this use case, the wonders of technology and the need for serious change to save our environment are not lost on me. In fact, the combination is stronger than ever, and I am motivated to do my best (either in research or industry, either alone or together) to help the world become a better place.

Therein, lies my final educational lesson as a designer: do not let the idealism and optimism in you die and believe in humanity.

FIN.

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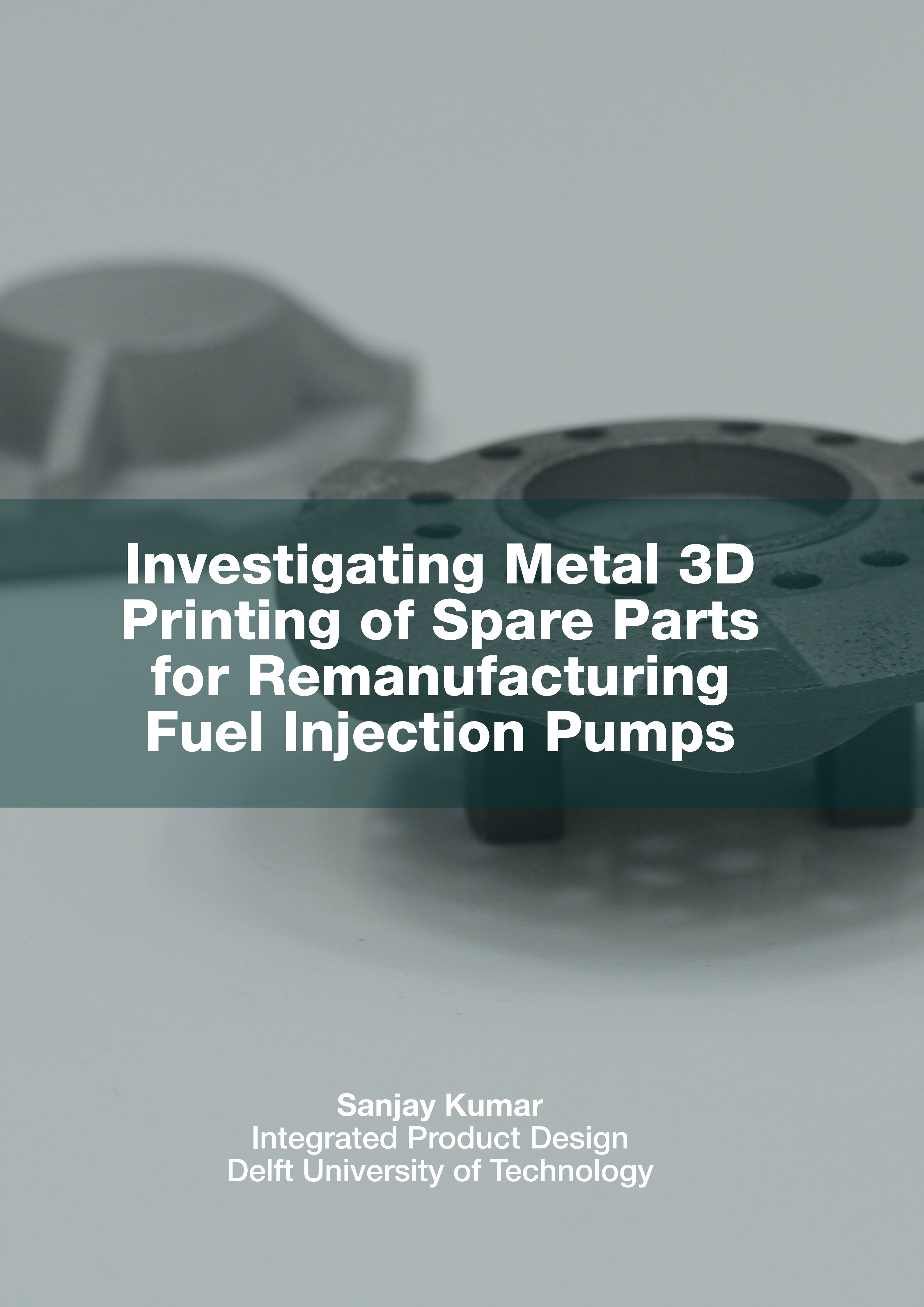

Investigating Metal 3D Printing of Spare Parts for Remanufacturing Fuel Injection Pumps

Sanjay Kumar
Integrated Product Design
Delft University of Technology