Additive Manufacturing: Comparative Analysis and Application in Suspension Design

Hanna Tollander and Joel Amb

DIVISION OF INNOVATION | DEPARTMENT OF DESIGN SCIENCES
FACULTY OF ENGINEERING LTH | LUND UNIVERSITY
2023

MASTER THESIS

COMBITECH

ÖHLINS
ADVANCED SUSPENSION TECHNOLOGY

Additive Manufacturing: Comparative Analysis and Application in Suspension Design

Hanna Tollander and Joel Amb

LUND
UNIVERSITY

Additive Manufacturing: Comparative Analysis and Application in Suspension Design

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

Subject: Product Development (MMKM05)
Division: Division of Innovation
Supervisor: Axel Nordin
Examiner: Per Kristav

Abstract

Additive manufacturing (AM), or 3D printing, has emerged as a rapidly growing manufacturing technique with numerous advantages over traditional methods. This thesis project investigates the application of AM in suspension design. The aim is to explore the advantages of AM, investigate suitable product selection processes, and look into the potential for gaining a competitive advantage by leveraging AM effectively.

Through this research, a printable part specifically designed for AM has been developed. The results demonstrate the advantages of AM when the technique is harnessed effectively. Merely switching manufacturing techniques without considering the value-adding aspects of AM is unlikely to yield the desired benefits. However, designing components with AM in mind from the initial stages can unlock numerous advantages.

The findings of this thesis project contribute to understanding how AM can be used to optimize mountain bike suspensions. By evaluating the advantages and disadvantages of the designed parts, valuable insights are provided for Öhlins and the wider biking industry. This knowledge enables informed decision-making for strategic integration of AM in future product development and manufacturing processes.

This research underscores the significance of thoughtful design considerations and effective integration of AM to harness its full potential in enhancing the performance, cost-efficiency, and functionality of mountain bike suspension.

Keywords: additive manufacturing, 3D printing, suspension design, manufacturing advantages, product development

Sammanfattning

Additiv tillverkning (AM), eller 3D-printning, har framträtt som en snabbt växande tillverkningsteknik med flera fördelar jämfört med traditionell tillverkningsteknik. Detta examensarbete undersöker tillämpningen av AM inom design av stötdämparsystem. Målet är att utforska fördelarna med AM, undersöka lämpliga metoder för urval av produkter samt undersöka potentialen att få en konkurrensfördel genom att utnyttja AM på ett effektivt sätt.

I detta projekt tas en printbar produkt, speciellt designad för AM, fram. Projektets resultat visar sedan fördelarna med AM när tekniken används på ett effektivt sätt. Genom att endast byta tillverkningsmetod utan att beakta de värdeskapande delar AM erbjuder, är produkten osannolik att kunna dra nytta av de önskade fördelarna. Om produkten designas med AM i beaktning från ett tidigt stadium kan detta bredda vägen för utnyttjandet av de fördelar som AM erbjuder.

Resultaten av detta examensarbete bidrar till djupare förståelse om hur AM kan utnyttjas för att optimera en stötdämpare för mountainbike. Genom att utvärdera för- och nackdelar med de designade komponenterna förseddes Öhlins, och även den bredare cykelindustrin, med värdefull insikt. Denna kunskap möjliggör för framtida strategiska beslut i hur produktutveckling och tillverkningsprocesser ska tillämpas.

Denna undersökning understryker betydelsen av att göra noggranna designval genom effektiv integration av AM för att fullt utnyttja de fördelar AM kan ge för förbättrad prestanda, kosteffektivitet samt funktionalitet av stötdämparsystem för mountainbikes.

Nyckelord: additiv tillverkning, 3D-printning, stötdämpardesign, tillverkningsfördelar, produktutveckling

Acknowledgments

This master’s degree project was carried out at Öhlins Racing AB in close collaboration with the consultant firm Combitech AB.

We would like to express our deepest gratitude and appreciation to all those who have supported us throughout our journey in completing this master's thesis. Without their guidance, encouragement, and assistance, this work would not have been possible.

A special thanks to our supervisors from both companies as well as supervisors and examiners at the universities:

Öhlins

Pontus Andersson, Rickard Norstedt & Per Falk

Combitech

Tommy Lundqvist & Emil Sundberg

Lund University

Axel Nordin & Per Kristav

Royal Institute of Technology

Mikael Nybacka

Stockholm, May 2023

Hanna Tollander & Joel Amb

Table of contents

List of acronyms and abbreviations

AFT	additive fusion technology
AM	additive manufacturing
BJ	binder jetting
CAD	computer aided design
CP-Ti	commercially pure titanium
DED	direct energy deposition
DfAM	design for additive manufacturing
DMLS	direct metal laser sintering
EBM	electron beam melting
FDM	fused deposition modeling
LENS	laser engineered net shaping
LOM	laminated object manufacturing
MMC	metal matrix composites
PBF	powder bed fusion
PMC	polymer matrix composites
SL	sheet lamination
SLM	selective laser melting
SLS	selective laser sintering
WAAM	wire arc additive manufacturing

1 Introduction

Chapter 1 will give an introduction to the thesis report. It will briefly introduce the two companies, Combitech and Öhlins Racing, as well as the topic of additive manufacturing. It will, amongst other things, also address the purpose and goals of the project, the delimitations set, and a brief outline of the report.

1.1 Background

This master thesis project was conducted in collaboration with the two companies Combitech AB and Öhlins Racing AB. Combitech is a consulting firm with offices in several cities around Scandinavia (Combitech, 2023a). They offer a wide variety of services, with things from for instance IT services and cyber security to product development and supply chain management (Combitech, 2023b). Öhlins Racing is a company with headquarters in Upplands Väsby, with distribution and test centers in Germany, the United States, and Thailand. They develop advanced suspension systems for the automotive, motorcycle and bike industries. (Öhlins, 2023a). Today, the components used in Öhlins's different suspension systems are manufactured with more traditional manufacturing techniques. Öhlins want to gain more knowledge in additive manufacturing (AM), and they are therefore interested in the possibilities of AM for suspension design and manufacturing.

The suspension system is more or less the connection between the body of a vehicle, and the vehicle's wheels when it is in motion. The shock absorber, or damper, is a part of the suspension system and it makes sure that the vehicle can handle bumps, or similar, from the road. It is used to protect the vehicle as well as making the ride more comfortable. (TireRack, n.d.; StudentLesson, 2020a).

AM is a term that refers to the manufacturing techniques where the material is added to build the desired shape, unlike for instance the subtractive manufacturing techniques such as milling or turning where material is removed instead. In AM, the components are first modeled using a computer aided design (CAD) software and then built layer by layer to create the desired geometry. One advantage of AM is the possibility to manufacture more complex parts, and AM is also beneficial when design changes are frequently required. AM is a relatively new manufacturing technology, first demonstrated in the 1980s, and since then the AM technologies have developed rapidly. (Abdulhameed, Al-Ahmari, Ameen, & Hammad Mian, 2019).

1.2 Purpose and research questions

The purpose of this study is to investigate AM as the manufacturing technique for bike suspension design and manufacturing. The questions this report aims to answer are:

- How can Öhlins use AM in their current products?
- What advantages would Öhlins gain from using AM?
- How does Öhlins choose a product that is suitable for AM?
- How will the above questions give Öhlins a competitive advantage?

1.3 Goal

The goal of the thesis project is to optimize either one of Öhlins's products, a part in a product, or a function in a product for mountain bike regarding one or more of the following:

- Combine multiple components
- Optimize function
- Reduce weight
- Lower manufacturing cost
- Ease assembly

The thesis project shall also result in a printable part. The advantages and disadvantages for this design should be documented, and if possible, a prototype should be printed and evaluated.

1.4 Delimitations

Due to the relatively short time period for the project, some delimitations have to be made in order to be able to finish the project on time. These delimitations will be listed below.

- The AM suppliers that will be considered for this project are suppliers with production in Sweden.

- The development of a new product will focus on making use of AM as a manufacturing technique, rather than performing thorough customer research. Therefore, a new product will be based on the same requirements as the current product, but potentially with a few new requirements based on the manufacturing technique.
- This project will mostly focus on examining AM as a manufacturing technique, and designing/adapting products for AM. Therefore, thorough material selection processes will not be made, i.e., the material selection process will be a simplified process.
- When considering the cost, only the part costs will be used in the comparison. In reality, assembly costs for the parts will also have an impact, but this will not be considered here. The ease of assembly will be considered, but as time and not price.
- When investigating products that are potentially suitable for AM, Öhlins’s entire product portfolio will not be looked into, but the products will be limited to the ones proposed by Öhlins at the beginning of the project.

1.5 Outline

The thesis project has been divided into a few different parts. Chapter 2 will describe the general approach for the project, as well as the different methods used for the different parts. Chapter 2 will also cover the work structure of the project. Chapters 3 to 6 will all cover different parts of the project – how they were carried out, and what the results were. Specifically, Chapter 3 will cover the theory and literature, Chapter 4 will cover the choices of product, AM technique, material, and supplier, Chapter 5 will cover the concept development, and Chapter 6 will cover the concept evaluation, concept refinement, and CAD modeling. Chapter 7 will include the discussion and Chapter 8 the conclusions. Finally, the references and appendices will be presented.

2 Method

This chapter will cover all the methods used in the project. It will address the general approach for the project, as well as different methods used for specific parts of the project. This chapter will also cover the way of working, i.e., how the team worked, what the companies could bring into the project work, and what the team did to include the companies in the work to reach the project goal.

2.1 General project approach – The Double Diamond

The general approach for the project was inspired by the Double Diamond model. The double diamond model is a model that aims to help designers go from design problem to delivery. The model consists of four phases: discover, define, develop, and deliver. The first two phases represent the problem space, and the last two phases represent the solution space. (Gearon, 2022; Elmansy, 2021). The upcoming four sections will discuss the four phases of the double diamond respectively, and they will give a deeper description of how the model was applied to this project. An illustration of the double diamond can be seen in Figure 1 below.

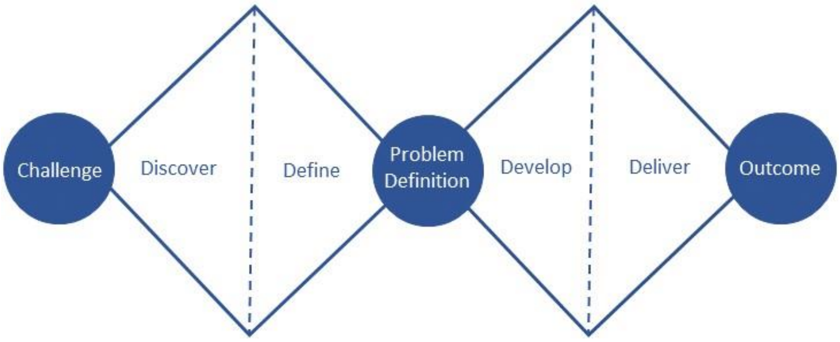


Figure 1 The double diamond approach, inspired by Michael Gearon's model (Gearon, 2022).

2.1.1 Discover

The first phase of the double diamond model is *discover*. This includes research to understand the problem to be solved, but also to understand the potential risks, challenges, and possibilities. There are several different approaches for doing this, and these approaches can include for instance customer research or literature research. (Gearon, 2022).

The research used for this project will be mostly literature research, and therefore, the first phase of the project will be the phase of the literature study. In this case, the literature research is important to be able to better understand the problem that needs to be solved, and to understand the abilities and difficulties of AM. The literature research will include gathering information on AM in general – its advantages and disadvantages compared to traditional manufacturing techniques, and it will also address design for additive manufacturing (DfAM), which is a way of thinking when designing new products to make sure to use the advantages of AM to its full potential (Diegel, Nordin, & Motte, 2019). More background to DfAM will be presented in section 3.1.2. Furthermore, the literature study will include collecting information on some of the specific AM techniques, mostly techniques used for metal parts, but also some other methods. Finally, the literature research will include gathering information about some of the most commonly used traditional manufacturing techniques used by Öhlins today.

2.1.2 Define

The second phase of the double diamond model is *define*. The define phase should result in a clear problem definition. The data gathered in the previous phase should be analyzed to be able to use it, and because of this, it should be possible to state a clear problem definition. (Gearon, 2022; DesignCouncil, n.d.).

In this project, this phase will include choosing a suitable product, AM technique, and material. It will also include the choice of AM supplier. The methods to be able to make the different decisions are further described below.

2.1.2.1 Product choice

When choosing a product, component or concept to continue developing, a tool that is commonly used to determine which product is most suitable is the scoring matrix. In this case, inspiration was taken from the scoring matrix mentioned in Ulrich and Eppinger’s *Product Design and Development* (Ulrich & Eppinger, 2012). Originally, this matrix is used to evaluate concepts, but in this case, it can be adjusted for choosing components suitable for AM. Usually, the matrix has the different concepts, products, or components horizontally and the aspects used for evaluation vertically. Each aspect has a weight which symbolizes its importance. The sum of all weights is equal to 1. When using the matrix, each concept, product, or component is evaluated and scored according to each of the aspects. The scoring is a scale between 1 and 5, and one of the concepts will act as a reference. This concept gets the score 3 in all aspects, and the other concepts are compared, and scored, in relation to this reference. The list below shows how to interpret a specific number in the matrix.

1. Has much lower potential than the reference.
2. Has lower potential than the reference.
3. Has the same potential as the reference.
4. Has better potential than the reference.
5. Has much better potential than the reference.

After each concept has been given a score, this score is multiplied by the weight of the specific aspect, and these weighted scores are summarized for each concept. When each of the concepts has a final score, this number is used to give an indication of which concept that best fulfills the potential improvement aspects. Table 1 below shows an example of a scoring matrix.

Table 1 An example of a scoring matrix inspired by Ulrich and Eppinger's matrix (Ulrich & Eppinger, 2012).

Component / Potential improvement aspects	*Aspect 1*	*Aspect 2*	*Aspect 3*	*Aspect 4*	*Final score*
Weight	0.20	0.35	0.15	0.30	
Component A	3	3	3	3	3.00
Component B	1	2	5	4	2.85
Component C	1	3	3	4	2.90
Component D	2	4	3	3	3.15
Component E	4	5	3	3	3.90
Component F	3	5	5	2	3.70

To establish the importance of each of the different improvements, the weight matrix described in *Produktutveckling - effektiva metoder för konstruktion och design* (Johannesson, Persson, & Pettersson, 2004) can be used. In this matrix, the different aspects are compared against each other, and the sum of the comparison of two aspects should always be equal to 1. If, for instance, criterion A is more important than criterion B, then A compared to B will get a score of 1 while B compared to A will get a score of 0. If two criteria are considered equally important, they will share the total sum of 1, and therefore both will get a score of 0.5. Table 2 below shows an example of this type of matrix.

Table 2 An example of a weight matrix inspired by Johannesson, Persson and Pettersson's matrix (Johannesson, Persson, & Pettersson, 2004).

Criteria	*A*	*B*	*C*	*D*	*E*	*Sum*	*Weight*
A	-	1	1	0	0.5	2.5	0.25
B	0	-	1	0	0	1.0	0.10
C	0	0	-	0.5	0.5	1.0	0.10
D	1	1	0.5	-	1	3.5	0.35
E	0.5	1	0.5	0	-	2.0	0.20
					Total	10.0	1.00

2.1.2.2 Choice of material

Selecting material for a new product is not always the easiest thing to do due to the wide variety of existing materials, and the material requirement the product needs to fulfil. Due to the short time for this project, there will be delimitations in the material selection process. Several materials suitable for AM will be briefly examined already in the literature research, but there will not be a thorough selection process. For instance, if a metal material is chosen, the team will look at suitable materials, and then evaluate them based on price. The exact metal alloy will not be looked into, but the choice will fall on the alloy the supplier offers, and that they think is suitable for the application. Exactly how this process was performed is described in section 4.2.

2.1.2.3 Choice of AM method

The choice of AM method did not follow any particular method. This was instead done by first excluding methods one by one based on limitations, until only a few methods remained. The ones that were excluded first were excluded due to for instance limitations in material, size, cost, or accuracy. When a few methods, that were potentially possible to use, remained, they were evaluated based on accessibility and price. Exactly how this was done is explained in section 4.3.

2.1.2.4 Choice of AM supplier

In this case, there is no specific method to choose the most suitable AM supplier. By successively excluding different options due to methods and materials, a choice can be made. Exactly how the choice was made, and which aspects affected the selection process, will be further explained in section 4.4. The choice of AM supplier was made after both the choice of AM technique and material, since these two factors made it possible to rule out and choose the most suitable supplier.

2.1.3 **Develop**

The third phase of the double diamond model is *develop*. This is the first part of the second diamond, i.e. the solution space. Since the previous phase results in a clear product specification, this phase focuses on trying to find solutions to the stated problem. Here, all different solutions to the problem should be encouraged, to be able to evaluate them all. This can be done in different ways, through for instance sketching, or other ways to visualize the solution. (Gearon, 2022; DesignCouncil, n.d.).

After finishing the second phase, the team will have decided on a product, AM technique, material, and AM supplier. Therefore, this phase will focus on concept development. First, the product requirements need to be specified, and in this project these requirements will be based on the same requirements as the original product, but with a few additional requirements due to the manufacturing technique (AM). After the requirements are specified, a few concepts will be developed based on these requirements.

2.1.4 **Deliver**

The fourth, and final, phase of the double diamond is *deliver*. After finishing the third phase, there will be several different concepts, and here the idea is to start reducing the different concepts to reach a solution. (Gearon, 2022; DesignCouncil, n.d.).

Moving along to the final phase, the team will have a few different concepts to choose from. Therefore, the first part of this phase will include choosing a concept to continue developing, and thereafter refining this concept. There are different methods to evaluate concepts, and the one used in this project will be further described below. After choosing a concept, the CAD software Siemens NX will be used to create a printable 3D model of the concept. The refinement of the concept will be an iterative process, including discussions with Öhlins to make sure to take their input into consideration. This phase will also include test printing.

2.1.4.1 Concept choice

The method for choosing a concept was the same as the method for choosing a product suitable for AM – a concept matrix inspired by the one described in Ulrich and Eppinger’s *Product Design and Development* (Ulrich & Eppinger, 2012), only in this case it was actually used to evaluate concepts.

A few concepts, that would fulfil the product requirements to different extent were developed and evaluated based on criteria that were considered important. The weights of the different criteria were also determined in the same way as when the product was chosen – with the method described in *Produktutveckling - effektiva metoder för konstruktion och design* (Johannesson, Persson, & Pettersson, 2004).

2.2 Work structure

2.2.1 **The project team**

The project team consisted of Hanna Tollander, a student at Lund University (LTH), and Joel Amb, a student at the Royal Institute of Technology (KTH). Before the start of the master thesis project, the team had not met before. The team was put together by Combitech and Öhlins with the idea to bring together knowledge and experience from two different universities and two different companies.

2.2.2 **The companies**

As mentioned in section 1.1, this project was a collaboration between the companies Combitech and Öhlins Racing. Each of the companies provided different types of knowledge and expertise during the project work, and this is further discussed below.

2.2.2.1 Combitech

Since Combitech is a consulting firm, they mostly provided knowledge on the topic of AM to the project, as well as a broad network of people that could potentially be of help during the project work.

2.2.2.2 Öhlins Racing

Since the team worked with Öhlins's products, Öhlins could deliver deep knowledge of the different technologies used today, as well as product-specific information such as product requirements, or cost of current products. They are also the project sponsor and therefore they decide the desired outcome for the project.

2.2.3 **Involvement from the companies**

During the project work, it was always important to take the companies' opinions into account, and in this case Öhlins's opinions and ideas in particular were important since the team worked with their products, and since they are the project sponsor. Therefore, the supervisors at Öhlins were always included in the different decision processes to make sure that no aspects were missed, and that they would be satisfied with the results. Of course, Combitech was also included in the different decisions, and the supervisor at Combitech made sure to provide contact information, or set up meetings, with different people that work with AM at

Combitech. Apart from the regular discussions, activities that were done to include, and get feedback from, both companies are further described below.

2.2.3.1 Product workshop at Öhlins

To make sure the team had enough knowledge about the products, a workshop was held early. At this workshop, a thorough presentation about the products was held to make sure the team would understand the different parts of the products, and their respective functions. Without this knowledge and information, it would be difficult to make accurate decisions about the different products, and which of them that are most suitable for AM.

2.2.3.2 Assembly workshop at Öhlins

After choosing the most suitable product, another workshop was held at Öhlins. This workshop focused on assembly of the chosen product, to get a deeper understanding of the specific product that had been chosen. The idea was to understand the different functions, how the product worked, and why it was designed the way it was. The team also got more information about for instance the different materials it was manufactured of, and how this mattered for the product in question.

2.2.3.3 AM presentation from representative from Combitech

After most of the literature had been gathered, a meeting was held with the AM expert at Combitech. In the meeting, a presentation was held about different techniques, and also some examples of when AM have been used in other applications. This meeting was very helpful since the team could ask important questions about things that had been unclear during the literature study. The team could also ask some questions about AM suppliers in Sweden, which made the process of finding relevant suppliers easier.

2.2.3.4 Technical meetings with supervisors from Öhlins

So called “technical meetings” were held with the supervisors from Öhlins during the concept development and concept refinement phases. The reason for this was to get continuous feedback during the development process, to make sure no important aspects were missed.

3 Discover

Chapter 3 will cover all the theory related to AM – general strengths and weaknesses of AM, as well as specific AM techniques and materials suitable for the application. It will also address the traditional manufacturing techniques that Öhlins uses today, and background on aspects that affect the cost of components manufactured with AM.

3.1 Additive manufacturing

Compared to traditional manufacturing methods, AM is still a relatively new method (as mentioned in section 1.1), and since it became more widely available, it has grown at a rapid pace. To give an incentive to switch from traditional manufacturing techniques towards AM, the method would need to create value of some sort. In this section, different kinds of value creation through additive manufacturing are examined to give a deeper knowledge of how the method could be motivated, but it will also address a few reasons for not choosing AM as manufacturing method.

3.1.1 **Advantages and disadvantages of additive manufacturing**

Producing components with AM, compared to traditional manufacturing techniques, has both its advantages and disadvantages and it is important to have these aspects in mind when looking into different manufacturing techniques. Some of the advantages with AM include part complexity, speed, material and resource efficiency, and efficiency within the supply chain, while some of the disadvantages include high costs, limitations in material, requirements for post processing, and slow build rates. All of these aspects will be further discussed below.

One of the advantages with AM is that **part complexity** does not affect cost. It is easier to manufacture more complex components with AM compared to traditional methods. When using traditional techniques, components might need to be divided into several different parts for manufacturing to be possible. This results in a higher number of parts that need to be assembled which is time-consuming and therefore comes with a higher manufacturing and assembly cost. If using AM instead, it would be possible to manufacture the entire component in one part, and it would also be possible to redesign several traditionally processed components into one single component that is manufactured with AM. This could reduce costs related to manufacturing and assembly times (Gibson, Rosen, Stucker, & Khorasani, 2021). With the possibility to increase the complexity, the part can be optimized in more ways. With the increased complexity, unnecessary material can be removed which decreases the overall weight of the component. With the same philosophy, the function of the part can be optimized without the previous limitation applied through the choice of manufacturing method (Aydin, 2020).

Another advantage with AM is **speed**. If considering only the actual time when processing the material, AM is generally not faster than conventional techniques. However, the actual time when processing the material is not the only time that needs to be considered. Conventional methods usually require a lot more time for machine setup which is why it is necessary to consider the entire process and not only the time when the material is processed. Especially for more complex parts, it can be beneficial to choose AM instead of other manufacturing techniques. If using AM, no machine setup is required to the same extent and the component is manufactured in one part, which reduces setup and assembly times. (Gibson, Rosen, Stucker, & Khorasani, 2021).

A third advantage with AM includes **material and resource efficiency**. Since AM is a process where material is built layer by layer, and where each layer represents a cross section of the component, there is not a lot of material waste. For many different AM processes, the leftover material can be reused for other components later. When producing components with AM, all that is necessary is the actual AM machine. The technique does not require any cutting tools or other resources to produce the components, which makes the process resource efficient. (Satish Prakash, Nancharaih, & Subba Rao, 2018). Although, the AM methods that require post processing, (metal AM processes in particular), may still need some tooling to achieve the desired properties.

Finally, there are also several different ways in which AM can affect the **supply chain**. Since it is possible to increase the complexity of components manufactured with AM (as mentioned above), this results in fewer parts to store and transport, which leads to fewer suppliers and a lower cost for storage and transportation. It is also beneficial from an environmental perspective due to the reduced need for transportation. AM also enables more custom-made components, which also decreases the need for storage. Finally, AM enables shorter development times since testing and modifications can happen more efficiently, resulting in quicker market response. (Rinaldi, Caterino, Manco, Fera, & Macchiaroli, 2021).

Even though AM has quite a few advantages, there are also some drawbacks to the method. First, there are relatively **high costs** related to AM. For some techniques, the investment cost for the machines is considered high, but of course the cost also depends on the specific machine, and the quality of the machine. Also, many of the materials are relatively expensive. (Satish Prakash, Nancharaih, & Subba Rao, 2018). Especially for metal AM, the material cost is relatively high due to the manufacturing cost of the metal powder. Another limitation includes the possible **component size** since the size of the component is limited by the volume of the machine, depending on the AM method chosen. (Vranić, Bogojević, Ćirić Kostić, Croccolo, & Olmi, 2017).

Other drawbacks include the **limitation in materials**, the **requirement for post-processing** and the **slow build rates**. If discussing metals, there are not a lot of different metals suitable for AM. Components manufactured with AM usually also have relatively **poor surface properties**, which result in requirements for post-processing to achieve the desired surface quality. (Unleashed, 2021; Padasak, 2022). Lastly, AM is still not a manufacturing technique that is suitable for manufacturing large series due to the slow build rates compared to traditional methods (Unleashed, 2021).

3.1.2 **Design for additive manufacturing**

To be able to take advantage of the benefits of AM to its full potential, it is important to consider AM as the manufacturing method already during the product development phase and design it for AM from the beginning. This approach can be referred to as DfAM. A complete redesign of a component is the best way to take advantage of the benefits of AM, but it is still possible to either replace the manufacturing technique directly, or to adapt a component to better fit the AM process. (Diegel, Nordin, & Motte, 2019).

The optimal design depends on the specific AM method, as well as the material used, but there are still some general design guidelines to consider when designing for AM. The first guideline is to consider the printing direction, and print the component in a direction that decreases, or preferably eliminates, the need for support material. The need for support material makes the process both slower and more expensive due to more material that is printed and thereafter removed. Because of this, a component that is designed for AM should have features that enable printing with no, or minimal, support material. (Saunders, 2017). Examples of this include replacing overhangs with self-supporting angles when possible. Which angles are self-supporting depends on the specific AM method and the material, but for metal AM, the angle should generally be over 45 degrees in relation to the build plate. (Materialise, n.d.; Saunders, 2017). When designing for AM, it is also important to design to avoid residual stress in the final component. To do this, sharp edges should be filleted to avoid areas of stress concentration. (Saunders, 2017), and the walls should also have an even thickness, and not be thicker than necessary (Diegel, Nordin, & Motte, 2019). Apart from this, it is important to consider possible wall thicknesses and part sizes, since these might differ for different AM techniques and materials.

3.2 Additive manufacturing processes

AM is a term for manufacturing techniques where the material is added to build a component from a 3D (CAD) model. The range of suitable materials will depend on the AM method. The focus here will lie on the AM techniques that are possible to use for manufacturing of metal and/or composite components. In Figure 2, an overview of the categories involving the different metal processes is presented. The main categories identified for metal AM are direct energy deposition (DED), powder bed fusion (PBF), sheet lamination (SL), and binder jetting (BJ). Another addition is the method additive fusion technology (AFT) which is used for composite materials. These categories are further explained in the following sections.

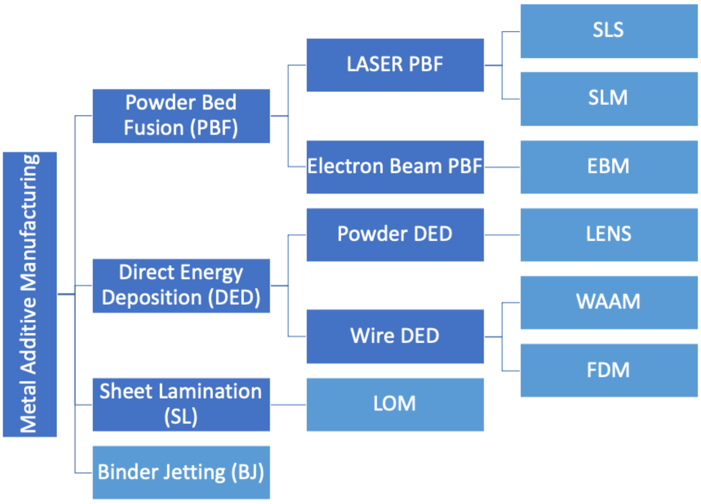


Figure 2 A breakdown of additive manufacturing processes, and their categories.

3.2.1 **Direct energy deposition (DED)**

DED is a category where the material is added to the model through either wire or powder, specifically targeted towards an area. The process is similar to welding, where the material is added through wire.

3.2.1.1 Wire arc additive manufacturing (WAAM)

The wire arc additive manufacturing (WAAM) process was particularly developed for metal additive manufacturing and is based on the same technique that is used for welding. The material is fed as a metal filament in form of wire. This wire is heated through an electric arc to melting temperature and deposited on the model, see Figure 3. WAAM is very material efficient, as the material is directly extruded to the model. (Derekar, 2018). For expensive materials such as titanium or similar this method can greatly reduce the material cost. The method is effective for large prints since the process can take place in a semi-uncontrolled environment similar to welding. One example of the size capacity of WAAM is the walking bridge that was printed by MX3D in Amsterdam (MX3D, n.d.). The yield strength of the printed material is slightly lower than if the product would be wrought (Derekar, 2018) but the difference could be acceptable depending on the requirements set on the product.

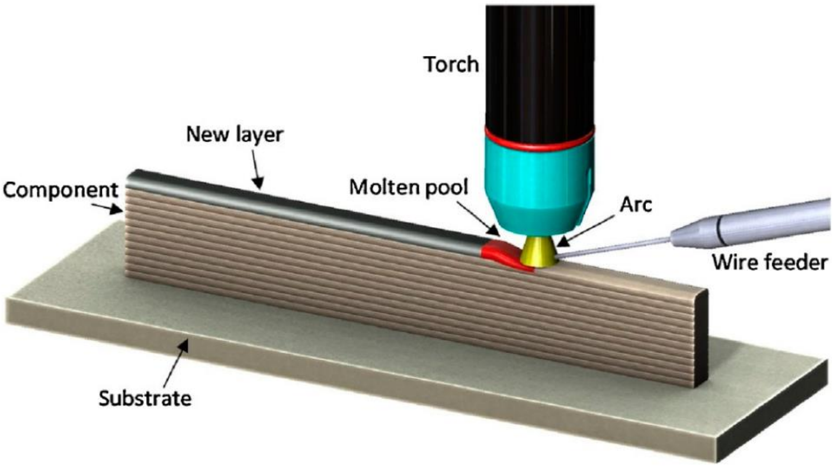


Figure 3 An illustration of WAAM (Jin, et al., 2020).

3.2.1.2 Fused deposition modeling (FDM)

The fused deposition modeling (FDM) technique was initially designed for use with thermoplastic polymers. The printer takes filaments of the material and heats it to just over the specific melting point. The liquefied material is then extruded through the printer head nozzle and builds the model with thin layers through material extrusion. (Satish Prakash, Nancharaih, & Subba Rao, 2018). The technique is generally used with thermoplastics but can be applied to certain metals as well. FDM achieves lower mechanical properties compared to other AM methods (for example selective laser melting (SLM) that will be discussed in the upcoming sections) and is not considered suitable for structural parts (Liu, Wang, Lin, & Zhang, 2020). The benefits achieved by FDM are a lower energy expenditure as well as lower costs due to cheaper filament, machines, and maintenance. Another benefit of FDM is the ease of use. Some limitations of FDM include the printing speed, which is low, as well as a rough surface finish (Cano-Vicent, et al., 2021).

If using this method for metals, it is usually a metal filled polymer filament that is being printed. The metal powder content of this filament is usually around 80 percent, and after printing it, the part is sintered. This makes sure the metal powder is fused together, and that the polymer material is burnt off. (Diegel, Nordin, & Motte, 2019).

3.2.1.3 Laser engineered net shaping (LENS)

The laser engineered net shaping (LENS) technology was developed by Optomec, Inc (Optomec, n.d.) and is an advanced DED process. The process uses metal powder which is distributed through the machine nozzle. The nozzle contains the distribution system as well as a laser, see Figure 4. The metal powder is fed with a constant flow through the nozzle towards the model and is melted with the laser (Izadi, Farzaneh, Mohammed, Gibson, & Rolfe, 2020). Compared to powder bed processes (see section 3.2.2), the metal powder is not distributed to the same extent since the material is only applied towards the area that is printed. This provides the technique with greater control of the material feed, but also results in parts with higher residual stresses due to the lack of unmelted powder around the part. The technology is ideal to use for repairs of existing products since it can work in 3D (Izadi, Farzaneh, Mohammed, Gibson, & Rolfe, 2020).

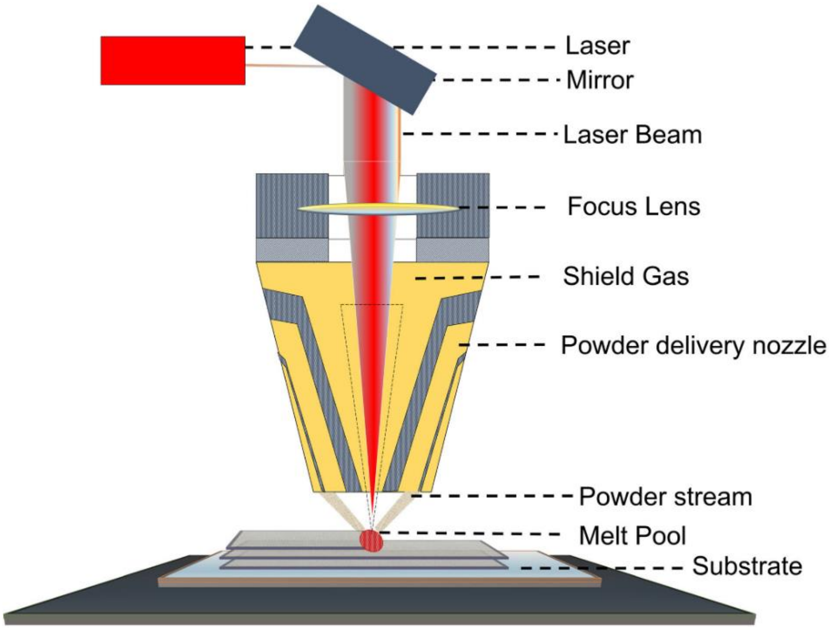


Figure 4 An illustration of LENS (Guddati, Sandeep Kranthi Kiran, Leavy, & Ramakrishna, 2019).

3.2.2 Powder bed fusion processes (PBF)

PBF processes are processes within AM that are based on material in powder form. The components are built layer by layer, and a heat source ((usually a laser beam or an electron beam) heats or melts the powder to create the desired component. An example of this can be seen in Figure 5. The different PBF processes are selective laser sintering (SLS), selective laser melting (SLM), and electron beam melting (EBM). The PBF processes work with metals, polymers, ceramics, and composites, but the different processes are suitable for different materials. (Diegel, Nordin, & Motte, 2019; Singh, et al., 2020). The three PBF processes will be further presented below.

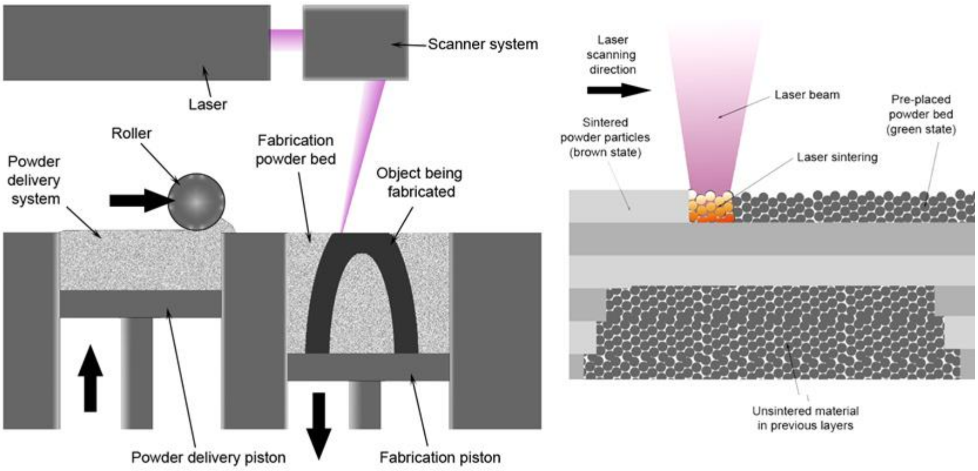


Figure 5 An illustration of PBF (SLM in this specific example) (WikimediaCommons, 2023a).

3.2.2.1 Selective laser sintering (SLS)

SLS is a technology where a powder bed is spread out and a laser is used to sinter the powder particles in certain areas. The sintered powder particles correspond with the desired cross-section of the part. When the powder is sintered, another layer of powder is spread out and the process is repeated until the desired geometry is created. (Abdulhameed, Al-Ahmari, Ameen, & Hammad Mian, 2019). This method is generally used for polymer materials, sometimes with fillers such as glass fibers or carbon fibers. If SLS is used to manufacture polymer parts, support structures are not required. (Diegel, Nordin, & Motte, 2019).

3.2.2.2 Selective laser melting (SLM)

SLM is another PBF technique, but it is mainly used for metals instead of polymers (Diegel, Nordin, & Motte, 2019). The printer distributes a thin layer of metal powder over the printing area. This layer is then treated with the laser to fuse the powder together into a solid metal part. The laser gives the possibility to alter the temperature of the metal rapidly in a very controlled area. The metal is melted with the laser and returns to the solid state without the added energy. (Song, Wen, Yan, Wei, & Shi, 2021). SLM is an AM technique that provides parts of high accuracy, but the method requires the use of support structures, which can sometimes be difficult and time-consuming to remove. (Diegel, Nordin, & Motte, 2019).

3.2.2.3 Electron beam melting (EBM)

EBM is a technique where, just as for the other PBF processes, a thin layer of metal powder is distributed over the work surface. The difference is that instead of a laser, a high-power electron beam is used to melt the powder. The electron beam operates under vacuum. It scans the building area and depending on the material and the powder properties, different preheating temperatures are used. Regarding residual stresses in the component, the level is usually lower for components manufactured with EBM compared to the other PBF techniques (laser-based) due to the higher build temperatures. (Körner, 2016). EBM was commercialized by Arcam AB (Körner, 2016). Arcam AB is a Swedish company founded in 1997, and in 2017 they joined GE Additive (GE Additive, n.d.).

3.2.3 **Sheet lamination (SL)**

SL is, just as the other AM methods, a method where material is added layer by layer. In SL, cut material sheets are stacked and bonded together, and this forms the component. There are several different sheet materials that are possible to use, for instance metals, polymers, ceramics, and even papers. (Gibson, Rosen, Stucker, & Khorasani, 2021).

3.2.3.1 Laminated object manufacturing (LOM)

The laminated object manufacturing (LOM) technology employs the use of metal sheets and layering them to build a model. The sheets are prepared with a coating of a suitable adhesive. The sheet is then rolled out over the building platform and with the use of lasers it is cut to the desired shape for the specific layer. The sheet is then further rolled out to expose more uncut metal and the next layer is cut from the sheet and attached to the model. LOM is a relatively inexpensive process, and it does not require support material to the same extent as other methods. But the accuracy is poor in certain directions, and due to the laser cutting of the metal sheets, the method results in material waste. (Anand Kumar & Prasad, 2021).

3.2.4 **Binder jetting (BJ)**

Binder jetting (BJ) is another powder-based AM technique, but instead of a laser or an electron beam, a liquid binding agent is used to bind the powder particles together. The technique works similarly to the PBF techniques; powder is spread out and the binding agent is applied to the areas that needs to be solidified. These areas represent the cross section of the component. After finishing one layer, new powder is distributed, and the process continues until the component is finished. When it is finished, it needs to be sintered to fuse the powder particles together. Due to the need for sintering, this method is only suitable for relatively small components since the components shrink slightly during the sintering process. (Diegel, Nordin, & Motte, 2019). BJ works for several different types of materials, for instance polymers, ceramics, or metals. Another advantage with the technique is the build rate, which is relatively high since only the binding agent needs to be printed. (Ziaee & Crane, 2019). Figure 6 below shows an illustration of the BJ process.

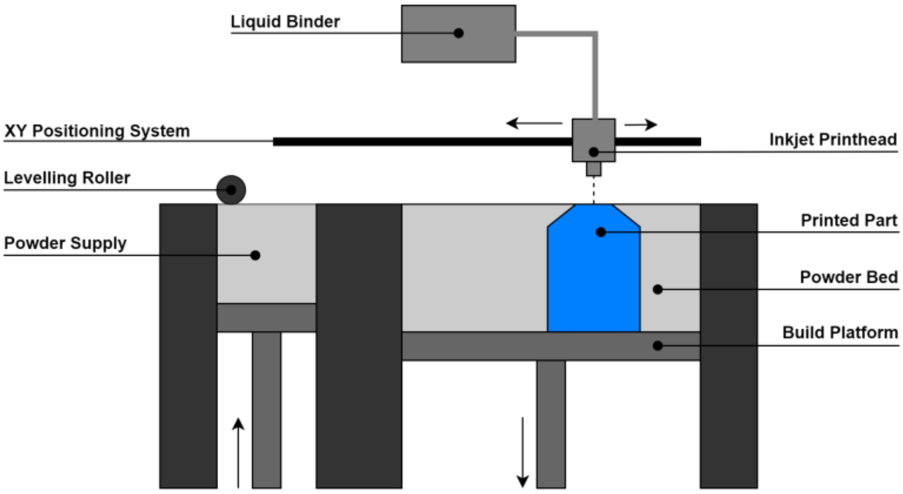


Figure 6 An illustration of BJ (WikimediaCommons, 2023b).

3.2.5 Additive fusion technology (AFT)

AFT was developed by 9T Labs and is a process to print composite materials such as carbon fiber together with thermoplastics to achieve desired properties. The process involves two stages, the first is the printing where the product is extruded with a blend of reinforced plastics. The machine makes use of long fibers in the form of wire to reinforce the plastics. With the part printed, the after treatment starts with a hydraulic press. The part is placed in the fusion machine and is then pressed to remove voids from the print and improve the part properties. If the part was printed in more than one piece, it is during the fusion process the pieces are attached together to form the final component (9T-Labs, 2023a). The method could be compared to FDM in how it works if the fusion process is disregarded.

3.2.6 Comparison overview

Table 3 below shows a comparison between all examined AM techniques.

Table 3 A comparison of all examined manufacturing methods.

Method	*Materials*	*Limitations*	*Strengths*	*Cost*	*Yield rate*
WAAM	Aluminum, Titanium, Steel, Stainless steel, Bainitic steel	Surface roughness	Suitable for large structures	Low	Low
FDM	Stainless Steel, Copper	Printing speed, surface finish	Low energy expenditure	Low	Low
LENS	Aluminum, Titanium, Steel, Cobalt satellite, Copper	Residual stresses in final component	Repairs of existing products	High	High
SLS	Graphite, Short-fiber reinforced composites	Material choice (mostly polymers)	Polymers does not require support	High	High
SLM	Aluminum, Titanium, Stainless steel, Ceramic short-fiber reinforced composites	Support structures	High accuracy	High	High
EBM	Titanium, Cobalt chrome	Needs to take place in vacuum	Lower residual stress due to higher temp.	High	Low
LOM	Sheets of metals, polymers, ceramics, paper	Material waste	Does not require support structures	Low	High
BJ	Stainless steel, Inconel, Copper, Cobalt-chromium	Needs to be sintered	Short print time	Low	High
AFT (9T-Labs, 2023b)	Carbon-fiber and glass-fiber reinforced polymers	Part complexity	Material properties vs weight	Low	Medium
Casting (ClubTechnical, 2018a)	Most metals	Part complexity	Material choice	Low	High
Forging (ClubTechnical, 2018b; Reliance Foundry, n.d.)	Steel, Stainless steel, Aluminum, Brass, Copper	Simple shapes, rough tolerances	Mechanical properties	Low	High
Milling (John, 2022; StudentLesson, 2020b)	Steel, Stainless steel, Aluminum, Brass, Copper	Limitations on design	High accuracy	High	Low
Extrusion	Lead, Aluminum, Magnesium, Copper, Nickel, Titanium	Part complexity	Production rate	Low	Low

3.3 Materials used in additive manufacturing

There are several different materials possible to use for AM, and this subsection will mainly focus on different metal and composite materials.

3.3.1 **Metals**

The metals suitable for AM are steel, aluminum, titanium, nickel, and magnesium (including some of their alloys) (Hajare & Gajbhiye, 2022). These metals are further discussed below.

3.3.1.1 Steel

The most commonly used steels for AM are the austenitic stainless steels, the maraging steels, the precipitation hardenable stainless steels, and the tool steels (Hajare & Gajbhiye, 2022). The austenitic stainless steels are characterized by high corrosion resistance and good mechanical properties (Michler, 2016). They also have very good biocompatibility (Haghdadi, Laleh, Moyle, & Primig, 2021). Austenitic stainless steel is the most commonly used class of steel for AM, and components manufactured of austenitic stainless steel can be used in different ways in many different industries due to the properties mentioned above. (Haghdadi, Laleh, Moyle, & Primig, 2021).

3.3.1.2 Aluminum and its alloys

Aluminum alloys are commonly used due to their light weight and low cost, but still with sufficient mechanical properties for many applications. For AM, two of the alloys that have been most interesting to look into are AlSi10Mg and AlSi12. Advantages with these alloys are low shrinkage and good cast-ability, while disadvantages include both low tensile strength and ductility. (Aboulkhair, et al., 2019).

3.3.1.3 Titanium and its alloys

In several different industries, titanium (and its alloys) is an interesting material due to its high strength, wear resistance, biocompatibility, and corrosion resistance (Tshephe, Akinwamide, Olevsky, & Olubambi, 2022). Titanium is considered a metal that is hard to machine with conventional methods, and expensive both in terms of refining of raw material and manufacturing. Therefore, titanium is mostly used in high-end applications when conventionally processed. Due to the poor machinability and high cost (especially when producing complex geometries), titanium and titanium alloys have become interesting materials to use for AM since AM makes it possible to process materials that are difficult to process in conventional ways. With many of the AM processes discussed in section 3.2, it has been possible to produce near fully dense components with commercially pure titanium (CP-Ti). Depending on the specific AM method used, it is possible to achieve a microstructure that is similar to the microstructure of traditionally cast CP-Ti. (Zhang & Liu, 2022).

3.3.1.4 Nickel and its alloys

Nickel based superalloys are commonly used in AM when producing products that will operate in high temperatures, due to the good high-temperature performance. The nickel-based superalloys also have good corrosion resistance and stability. (Guo, et al., 2023).

3.3.1.5 Magnesium and its alloys

Magnesium is another lightweight metal. Due to this, magnesium has been used for several lightweight applications in for instance the automotive industry. Magnesium is also an interesting material in medical applications such as implants, due to its biocompatibility and stiffness, which is similar to bone. (Jahangir, Mamun, & Sealy, 2018; Karunakaran, Ortgies, Tamayol, Bobaru, & Sealy, 2020). Although these aspects make magnesium an interesting material, magnesium is a reactive metal. It is possible to process it with AM, but the high reactivity makes it difficult. (Karunakaran, Ortgies, Tamayol, Bobaru, & Sealy, 2020).

3.3.2 **Composites**

Composites are materials that are interesting to work with due to their good mechanical properties in combination with their relatively light weight. Both polymer matrix composites (PMC) (fibre-reinforced polymers) and metal matrix composites (MMC) (fibre-reinforced metals) have been used for many applications in several different industries, and several PMCs and MMCs can also be used for AM. (Yakout & Elbestawi, 2017). The PMCs are the composites that are most interesting for this project, and therefore PMCs are further investigated.

3.3.2.1 Polymer matrix composites (PMC)

There are several different fibers to use in PMCs, and commonly used fibers are carbon fibers and glass fibers. Carbon fibers have very good mechanical properties, and also high thermal and electrical conductivity, but it is an expensive type of fiber. Glass fibers have high strength, and good thermal properties and corrosion resistance. Also, the price is lower than for carbon fibers. But, glass fibers have low stiffness, and they are also more sensitive to moisture than carbon fibers. (Sjögren, 2021). Both carbon fibers and glass fibers can be used for AM, although carbon fiber is the most commonly used of the two (Wang, Zhou, Lin, Corker, & Fan, 2020). Components can be manufactured with either short or long (continuous) fibers, but what is important to remember with long fibers is that the components will have anisotropic material behavior, i.e., the material properties will be different in different directions. (Sjögren, 2021).

3.3.2.2 Design guidelines for composites

Compared to designing for metals, designing for fiber-reinforced plastics has its limitations. When using continuous fibers, the fibers take up all the loads (more or less), and therefore it is important to consider the fiber orientation. Something else that is important to consider is the variation in thickness and the corner radii. The reason for considering variation in thickness is that stress concentrations might otherwise occur. Therefore, it is important to make the transitions as smooth as possible and avoid slopes of more than 3 degrees in the transition area. Regarding the radii, it is important to have a sufficient internal radius to avoid cracking of the fibers. The internal radius should be at least 5 mm. (Sjögren, 2021).

3.4 Traditional manufacturing techniques

There are several traditional manufacturing techniques used by Öhlins today, particularly casting, forging, milling, and extrusion. To make more accurate recommendations regarding AM, and which components are most suitable for AM, it is essential to understand the current manufacturing techniques as well. Therefore, casting, forging, milling, and extrusion will be further investigated.

3.4.1 **Casting**

Casting is the process where molten material is poured into a mold. The material then solidifies, which results in a final part with the same shape as the mold. Casting is a process that enables the manufacturing of relatively complex components, but the manufacturing of the mold is simplified by avoiding unnecessarily complex shapes. When designing components for casting, it is important to avoid too sharp corners and to consider section thicknesses and shrinkage of the component. Otherwise, there is a risk of stress concentrations and cavities in the final component. (Mital, Desai, Subramanian, & Mital, 2015). An illustration of the casting process can be seen in Figure 7 below.

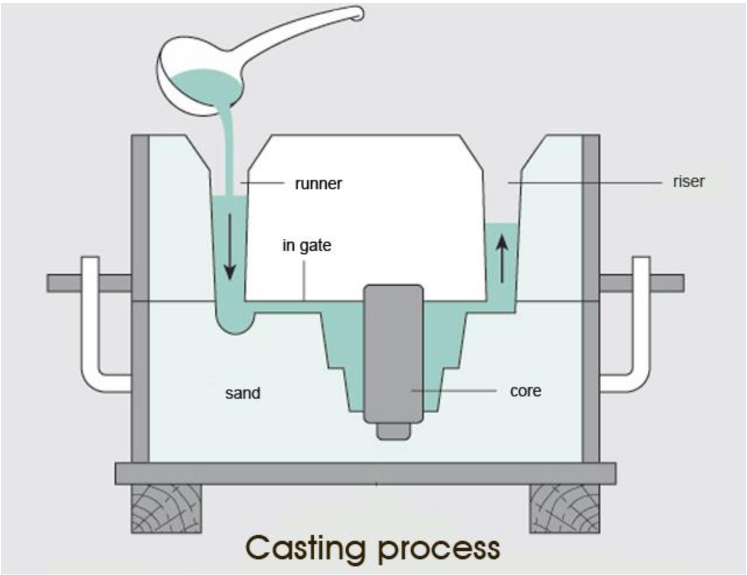


Figure 7 An illustration of the casting process (Chennu, 2017).

3.4.2 **Forging**

Forging is a manufacturing technique that has been used for a long time. It is the process when metal is processed by either hammering or by applying pressure and pressing the material against a die. The process is based on the plastic deformation of the metal, which occurs due to different types of compressing forces. Forging is normally a process that gives good tolerances. It also enables relatively complex component design and relatively large production rates. (Ghassemali, 2022). An illustration of the forging process can be seen in Figure 8 below.

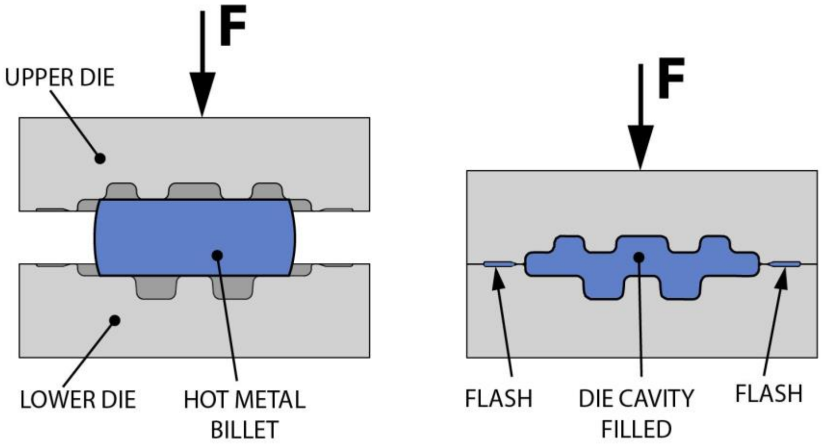


Figure 8 An illustration of the forging process (EngineeringClicks, 2016).

3.4.3 Milling

Milling is a subtractive manufacturing technique where a rotating cutter is used to remove material. The workpiece is fixed, and the cutter moves over the surface, removing material and creating new surfaces. (Carvill, 1994). Some things that are important to consider are to design components in a way that makes it possible to use standard cutter shapes and sizes (Mital, Desai, Subramanian, & Mital, 2015). Examples of this are sharp corners or sharp internal edges which would require the rotating cutter to be a smaller dimension and not feasible with the milling method. Milling is considered a top-down approach since the method removes material until the desired shape is reached. (HUBS, n.d.). Figure 9 below shows some different milling processes.

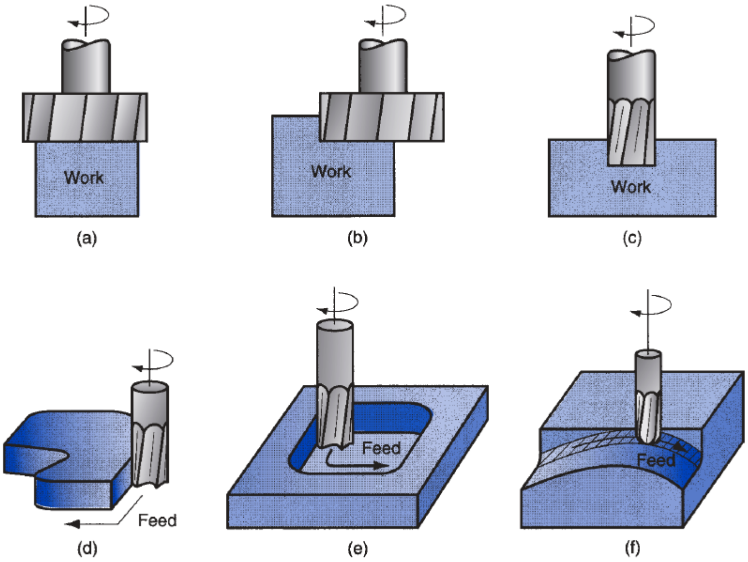


Figure 9 An illustration of some different milling processes (Arian Metal, n.d.).

3.4.4 **Extrusion**

Extrusion is a manufacturing technique where the material is pressed through a die, resulting in a component with a fixed cross-section (Maier & Calafut, 1998). Extrusion is a manufacturing technique that is possible to use for both plastics and metals, but with different materials, the technique differs slightly. An extruder used for plastic materials has a screw in the middle. At the back, the plastic feedstock is added and thereafter heated to its melting temperature. The screw operates inside the extruder and moves the molten material forward and through the die. As molten material is pushed through the die, new material is added at the back, making plastic extrusion a continuous process. (Maier & Calafut, 1998). Metal extrusion works similarly, but with the difference that instead, a metal billet is added to a container, and under a force, the metal is pushed through the die (Sun, Wang, Qian, & Wang Fu, 2022). Figure 10 below shows an illustration of metal extrusion, and Figure 11 shows an illustration of plastic extrusion.

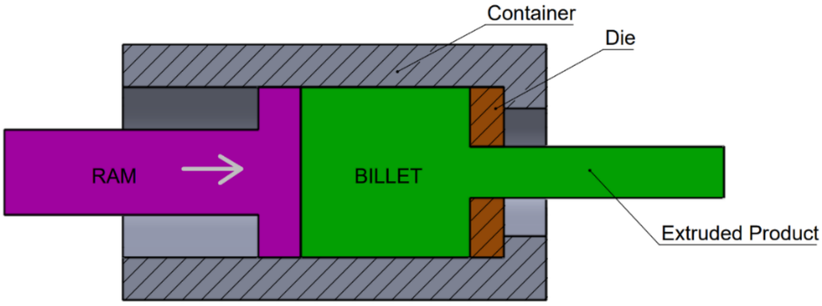


Figure 10 An illustration of the metal extrusion process (SM Lease, n.d.).

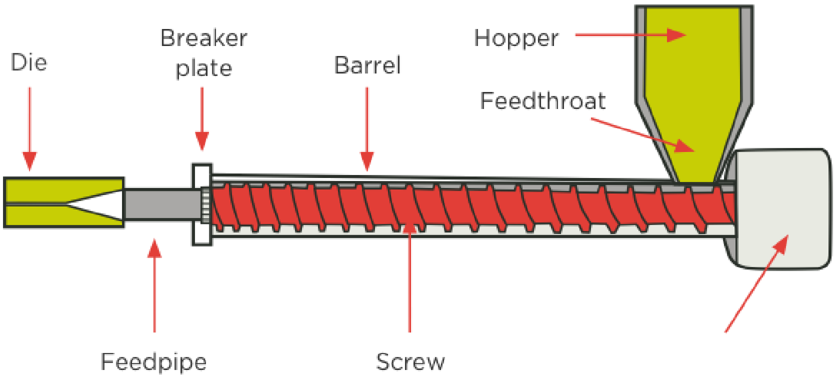


Figure 11 An illustration of the plastic extrusion process (Worksafe, n.d.).

3.5 Aspects that affect the cost

There are several different aspects that influence the cost of parts manufactured with AM, and due to this, it is difficult to make exact cost calculations. Although, it is still possible to approximate the costs.

One of the things that affect the cost includes the investment cost of the machine, and another is the manufacturing time of the parts, since this directly influence the part cost. Also, the cost of the material influences the part cost. (Diegel, Nordin, & Motte, 2019). Something else that affects the cost, that might not be as obvious is the number of parts that can fit on the build plate in each print.

The investment cost of the machine can differ a lot depending on type of machine, size of the machine, and which materials that are being used. Because of this, it is difficult to make approximations for this cost. Different companies make this approximation over different time periods, and the cost per part would be reduced if the printer is used more efficiently. Therefore, larger companies with many customers could offer a lower price than smaller companies that do not have enough customers to keep the printers going all hours of the day.

The manufacturing time of the parts include print time and time for pre- and post-processing. A lot of the time related to post-processing is affected by the design of the part, which is why DfAM, described in section 3.1.2, is important to consider. An example of this is the removal of support material. There are also some aspects that are not affected by the design of the part, and examples of this are the recoater time, which is the time it takes to spread a new layer of powder, and cleaning of the machine (Diegel, Nordin, & Motte, 2019).

Also, the type of material affects the part cost. Different raw materials have different costs (Diegel, Nordin, & Motte, 2019), but also different material forms have different costs. For the processes using a metal powder for instance, the powder cost depends on the specific atomization technology used to produce the powder (Moghimian, et al., 2021).

4 Define

This phase included the choice of product, AM method, material, and AM supplier. Using the information gathered in the literature study, it was possible to look at the problem and develop a method to approach it.

4.1 Choice of product

The following section will explain the product selection process. This process includes both a decision matrix and a weight matrix to determine the weights in the decision matrix.

4.1.1 **Product descriptions**

The different products to evaluate were provided by Öhlins, since they believed that they might be interesting to further investigate for AM. Short descriptions of the different products are presented below.

4.1.1.1 Crown RXF34

Figure 12 below shows Öhlins's entire RXF34 front fork. The crown is the part at the top, that connects the two rods. It is a structural part of the suspension and provides stability as well as stiffness to the front fork.

Figure 12 An image of Öhlins's RXF34 front fork (Öhlins, 2023b).

4.1.1.2 Crown RXF34 Carbon

The Crown RXF34 Carbon is a product identical to the Crown RXF34 in all aspects except the material. This crown is instead made of a carbon reinforced plastic.

4.1.1.3 Check valve TTX18

The check valve in a suspension system acts as a flow regulator, allowing controlled movement of fluid or gas between suspension components. Its primary role is to optimize the performance and dynamics of the suspension, contributing to improved handling, comfort, and overall vehicle stability.

4.1.1.4 Cylinder head TTX22

The cylinder head in a damper serves as a critical structural and sealing component. It separates the compression and rebound chambers, and facilitates the controlled flow of fluid within the damper. It contributes to the overall performance and functionality of the damper by ensuring proper damping characteristics, fluid containment, and attachment points for additional components. In Figure 13, Öhlins cylinder head called TTX22 can be seen.

Figure 13 An image of Öhlins's TTX22 cylinder head (Öhlins, 2023c).

4.1.1.5 TXC Valve

This check valve is very similar to the TTX18 check valve but is operating with air instead of fluids.

4.1.1.6 Check valve OTX14

This check valve is similar to the TXC check valve. The product OTX14 is used in the front fork compared to the TTX18 which is located in the damper for the rear suspension.

4.1.1.7 Remote lever unit

The suspension can be changed with a simple lever located on top of the front fork or rear damper. For competitive use this is not an option since the location of the lever is unreachable at speed and would require the rider to stop to change the setting. This is solved with a control on the handlebar which controls these same settings. This handlebar controller is what is called a remote lever unit.

4.1.1.8 Volume spacers

A volume spacer is an insert added to the air spring assembly of a suspension system to modify the amount of air within the system. It increases the progression of the suspension, providing more support and control to riders. The use of volume spacers allows for fine-tuning of the suspension's performance based on individual preferences and varying riding conditions. This volume spacer is located inside the front fork when in the configuration of an air suspension.

4.1.1.9 Arc form lowers

The arc is a structural part for the front fork. The part gives stability and rigidity between the two cylinders when put under pressure. Figure 14 shows the arc form lower, which is the part between the two rods.

Figure 14 An image of Öhlins's arc form lower for the RXF34 front fork (Öhlins, 2023b).

4.1.2 Decision matrix

Öhlins provided nine potential products that could be chosen to develop for manufacturing with AM. To create the most value with the change of manufacturing method, the product with the highest potential value increase should be chosen. The evaluation of potential is made with a scoring matrix, inspired by the scoring matrix mentioned in Ulrich and Eppinger's *Product Design and Development* (Ulrich & Eppinger, 2012). The scoring matrix is constructed with all products on one axis and with potential improvements on the other. One product is established as a baseline product to compare the other against. The scoring is set to be on a scale of 1-5 where 1 is low potential and 5 is high potential. The baseline product is set to a value of 3 in all aspects. Table 4 below shows the scoring matrix.

Table 4 The scoring matrix used to choose product.

Product / Potential improvement aspects	***Weight reduction***	***Lead time variant***	***Supply chain***	***Production cost***	***Assembly***	***Volume reduction***	***Improved function***	***Final score***
Weight	0.2381	0.0476	0.0238	0.2143	0.1429	0.0952	0.2381	
Crown RXF34	3	3	3	3	3	3	3	3
Crown RXF34 Carbon	2	4	5	5	3	3	3	3.2857
Check valve TTX18	1	3	3	2	3	2	3	2.2143
Cylinder head TTX22	2	3	3	4	3	5	3	3.1666
Check valve OTX14	1	3	3	1	3	1	3	1.9048
TXC valve	1	4	4	2	3	1	3	2.1905
Remote lever unit	3	4	5	5	5	2	3	3.7144
Volume spacer	2	2	1	1	3	2	3	2.1429
Arc form lower	2	3	3	2	1	2	3	2.1666

The potential improvement aspects on the vertical axis were determined by the team, together with representatives from Öhlins, and are based on aspects that create value when manufacturing with AM. Aspects that create value were presented further in section 3.1. What is meant by each specific aspect in this context, and how the team chose to define them, is further explained below.

4.1.2.1 Weight reduction

This aspect means the potential to *reduce the weight* of a product through increasing complexity. One example of this is topology optimization, where the complexity of a product is significantly increased but with less material. With less material, the weight is decreased for the product. In the context of this comparison, the potential is determined by the previous optimization of the weight as well as the size of the product. With a bigger more chunky product, the potential benefits are increased since more mass can be removed.

4.1.2.2 Lead time variant

The aspect *lead time for variants* is based on the time from which a product receives a design change such as new dimensions, and until this new product is in the hands of a customer or designer, depending on if the product is a prototype or a final product.

4.1.2.3 Supply chain

Supply chain includes all the aspects related to the transportation and storage of components or products. If a product is manufactured in Taiwan, assembled in Sweden, and sold in North America, it has to move around the world in order to be delivered to the end customer. If the production would be moved to the same physical location as the assembly plant, the transportation of the product could be optimized and will lead to a better supply chain.

4.1.2.4 Production cost

Production cost includes the cost measured as economical resources used to produce the product.

4.1.2.5 Assembly

Assembly includes aspects such as time or complexity to assemble the components. In this comparison, the assembly was evaluated based on the number of components that needs to be assembled and how complex the assembly is. If the number of parts could be reduced and the time for assembly could be shortened the assembly would be considered improved.

4.1.2.6 Volume reduction

For some of the products, the physical size of a component could be a hinder to what is possible. If this compromised part could be either smaller to better fit or shaped differently by increasing the complexity it would be an improvement of the volume.

4.1.2.7 Improved function

If the function of the component can be enhanced or implemented through the switch to AM, the function would be considered improved.

4.1.3 **Weight matrix**

The value created from different aspects is different for all companies depending on their values and goals. To include Öhlins's values and goals in the product choice, the potential improvements weights were established in a meeting where Öhlins were present and could make their views clear. Table 5 below shows the weight matrix for this project.

Table 5 The weight matrix used to establish the relative importance of the improvement aspects.

Criteria	*Weight reduction*	*Lead time variant*	*Supply chain*	*Production cost*	*Assembly*	*Volume reduction*	*Improved function*	*Sum*	*Weight*
Weight reduction	-	1	1	0.5	1	1	0.5	5	0.2381
Lead time variant	0	-	0.5	0	0	0.5	0	1	0.0476
Supply chain	0	0.5	-	0	0	0	0	0.5	0.0238
Production cost	0.5	1	1	-	0.5	1	0.5	4.5	0.2143
Assembly	0	1	1	0.5	-	0.5	0	3	0.1429
Volume reduction	0	0.5	1	0	0.5	-	0	2	0.0952
Improved function	0.5	1	1	0.5	1	1	-	5	0.2381
							Total	21	1.00

4.1.4 The chosen product

As can be seen in Table 4 above, the product that got the highest score was the remote lever unit. This is a type of controller that is attached to the handlebar of the bicycle, see more in section 4.1.1.7. The remote is a product consisting of relatively many parts, and with several fastening elements to attach the different parts. These aspects made the remote interesting to investigate. It is already a relatively small product, which could mean that large weight reductions and volume reductions might be difficult to accomplish, but decreasing the number of parts would be beneficial from both a production perspective and an assembly perspective. This would also positively affect the supply chain. An example of a remote lever unit can be seen in Figure 15 below. This product is from another brand, but it can still be used to get a visual understanding of the chosen product.

Figure 15 An example of a remote lever unit - although not Öhlins's product but a remote from the company DT Swiss (DT Swiss, n.d.)

4.2 Choice of material

In Öhlins's original product, most of the larger components are made of aluminum, and some of the smaller components that are subjected to greater loads are manufactured in stainless steel. The original remote is manufactured mainly in aluminum because of its properties and relatively low cost.

The composite materials, and techniques for printing continuous fibers would be interesting to look into further, but with limited time and the wear the final product has to withstand, this is ruled out for this project. The composite has plastics as the surface material which would not handle the small details with the same precision as metal.

The team decided to proceed with two different materials, aluminum and titanium. The aluminum was chosen mostly due to the lower cost, and since the original parts are made of aluminum it felt like a suitable choice. Titanium was chosen due to its better properties compared to aluminum, but where the weight is still low. Since one of the advantages with AM includes integrating several parts, and creating more complex parts, the team had an idea that the different parts in a new product would potentially be larger than the parts in the original product. Since the team did not want to increase the weight in the new product, titanium was a suitable choice.

To get the best possible comparison between the manufacturing techniques, the most favored business case is considered, where the AM part material cost should be as low as possible while still having good properties. For this case the aluminum alloy is chosen but with a bit of a changed compound. The chosen aluminum is called AlSi10Mg and is an aluminum alloy suitable for the additive manufacturing process. With the small details in the final design and the requirements for the product this alloy can fulfill this whilst minimizing the price. Since it is an alloy suitable for AM, it is also an alloy that most suppliers offer. Therefore, this material was a safe choice.

4.3 Choice of AM method

From the literature review, nine AM methods that are mature enough to be used for manufacturing today were presented. These methods are:

- WAAM
- FDM
- LENS
- SLS
- SLM
- EBM
- LOM
- BJ
- AFT

With the product established, the appropriate method can be established for that specific product. The first step is to exclude the methods that cannot fulfill the requirements of material, dimensions, and other method-specific limitations.

As presented in section 4.2, the chosen material for the product is AlSi10Mg which is an aluminum alloy suitable for AM. With this choice, some methods such as SLS, LOM, and AFT could be ruled out since they use other materials as their main building block. WAAM is more suitable for large structures and does not provide fine enough detail for a product such as the remote lever unit which has relatively small details. FDM, SLM, EBM, LENS and BJ might be suitable alternatives, but both FDM and BJ require sintering, and therefore they will shrink slightly. Due to the accuracy required for the remote, these methods were excluded for this project. Also, EBM is excluded since it mostly uses other aluminum alloys.

With the above argument, the two viable solutions are LENS and SLM. The two methods deliver high accuracy for small details in the desired material. LENS is in the category DED and SLM in PBF. The methods have different characteristics and do have their place. SLM is the most widely adopted method and delivers very detailed models. With the powder bed, many parts can be printed at once which lowers the manual set-up time as well as printing time. LENS on the other hand is made to print in 3D and can be used for printing very complex geometries. The print method can only print a few parts simultaneously which drives up the cost for larger quantities. In this case the mass production of parts will be evaluated and will give the SLM method an advantage.

Because of the reasons mentioned above, SLM was chosen as the printing method since it reaches all the requirements and is best suited for the evaluated application.

4.4 Choice of AM supplier

When choosing an appropriate AM supplier, the first thing that was done was to look at the market to see what was available. As previously mentioned, this project was delimited to the Swedish market, and therefore, only this market was investigated. In the beginning, it was difficult to find the relevant suppliers since many suppliers only offer plastic AM. Therefore, the team had a meeting with the person responsible for AM at Combitech. This person provided the team with several different suppliers, and also some “key words” to make it easier for the team to find other relevant suppliers. Focus lied on suppliers that could print in metal or composite materials. The most relevant suppliers are listed below:

- Lasertech
- Sandvik
- Amexci

Lasertech offers 3D printed metal parts with their machine, which uses the method direct metal laser sintering (DMLS). DMLS is very similar to SLM but since the machine manufacturer is different, they chose a different name for the method since SLM is trademarked by the company SLM Solutions (JUSTIA Trademarks, n.d.). Lasertech offers metal printing in a range of metals including aluminum, Inconel, titanium, stainless steel and maraging steel (Lasertech, n.d.). This makes Lasertech a contender since they offer the chosen material and the chosen method.

Sandvik offers a wide range of services, and AM is one of them. They offer both a range of metal powders but also the printing as a service. The materials they offer are tool steels, stainless steels, cemented carbide, nickel-based alloys, and titanium alloys (Sandvik, n.d.). Since this does not match the chosen material, Sandvik is ruled out as a manufacturer.

Amexci offers 3D printed parts as a manufacturer. They offer printing in a range of metals such as aluminum, Inconel, titanium, stainless steel and maraging steel (Amexci, n.d.). With the method SLM and the material aluminum chosen, Amexci is a good contender for the choice of manufacturer. Furthermore, the company is partly owned by SAAB which is also the owner of Combitech. This gives an extra incentive for Combitech to recommend Amexci, with the close collaboration and contacts they have within the company.

With both Amexci and Lasertech as viable manufacturers, the team chose to continue with Amexci. This choice was based on the close relations between Combitech and Amexci, and the access this would provide. They also offer a wider range of machines which was positive when it came to their possible guidance and expertise.

5 Develop

The third phase of the project was the start of the product development. After finishing the previous phase, the problem was clearly stated, and it was possible to start working on a solution. The development phase included specifying the product requirements, and generating concepts that could potentially fulfil these requirements. To fully design the product for AM it was determined that the mechanism needed to change. All the concepts presented in this chapter are focused on the redesign of this mechanism.

5.1 Product requirements

It was stated early that a new product, designed for AM, should fulfil the same requirements as the current product. These requirements, as well as a few others that were specified due to the manufacturing technique (AM), are listed below. The product requirements are divided into two categories – the *requirements* and the *desirables*. The requirements are the properties that the new product must fulfil, while the desirables are desired but not required. The requirements are the same as for Öhlins's original product, while the desirables are mostly based on properties that should be able to be achieved with the new manufacturing technique.

Requirements

- A new product shall have the same attachment to the bike as the previous version.
- Two wires shall be attached, one to the front fork and one to the rear damper.
- There shall be three modes through adjustment of the wire length.
- The controller shall be able to be adjusted while riding.
- The controller shall be able to be adjusted with one finger.
- The controller shall not slip during rides on bumpy roads.
- The controller shall hold for wires preloaded with up to 45 N.
- The wires shall be adjusted 8 mm for a new mode.

Desirables

- The product should have a tactile feeling when switching mode.
- The product should have fewer components than the previous version.
- The design should look 3D printed.
- The weight of the product should be less than 51 g.

5.2 Concept generation

The concept generation was performed in a few different steps. First, a few basic concepts were developed, where the focus was on the mechanisms, and not as much on the design. It was important to develop a product that worked and would fulfil the requirements specified in the previous subsection, and therefore, this was the approach. The result of these concepts can be seen in Figure 16, Figure 17, and Figure 18 below, and the following subsections will further describe the concepts.

5.2.1 First concept – Ball plunger

The idea of the first concept is to use a number of ball plungers to lock the product in the different modes. A ball plunger consists of a spring and a ball, and depending on the amount of applied pressure, the ball can move with the spring. This concept uses three ball plungers, and therefore, five small holes are needed to lock the rotation. The first mode uses the first three holes, the second mode uses the three holes in the middle, and the third mode uses the last three holes. The image to the top left in Figure 16 will also include the handle, but this handle is not included in the figure. The idea is that when the handle is pushed, this part will rotate in one direction, which will make the ball plungers stick in a new mode. To change back, the handle is instead pulled, which makes the part rotate in the opposite direction.

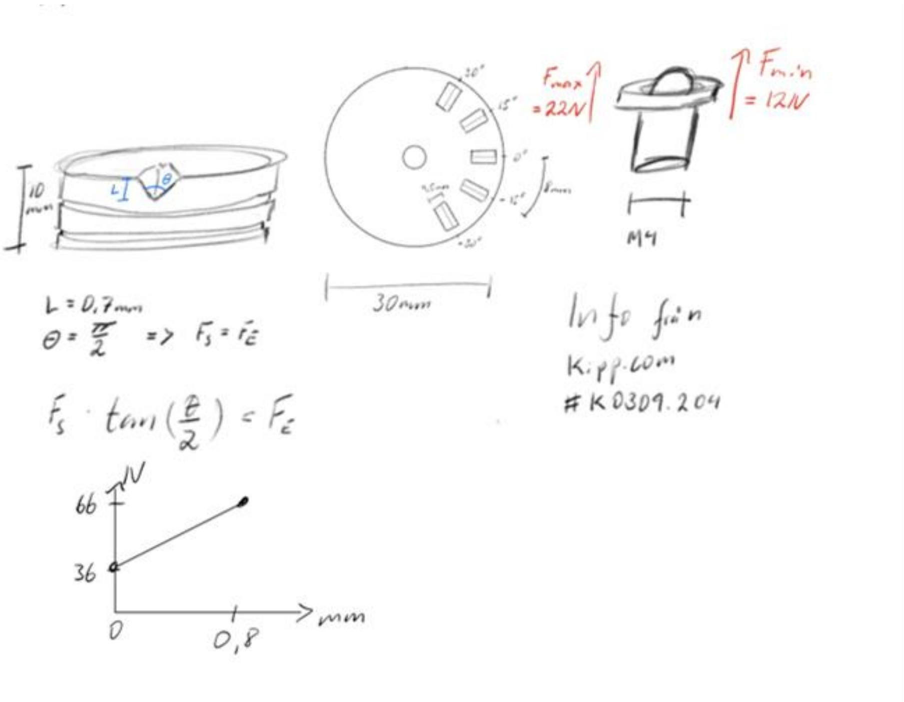


Figure 16 Illustration of the first concept, which will be referred to as "ball plunger".

5.2.2 **Second concept – Bowl**

The idea of the second concept is that a metal arc is attached to an axis with a threaded hole inside, see the image at the bottom in Figure 17. This part can rotate in relation to the larger part in the center. The handle will be part of this larger part, but to simplify the sketch, the handle is not included here. Something else that is not included is the attachment for the wires, which will also be on this part. The grooves will be used to guide the wires. When the two parts rotate in relation to each other, the idea is that the handle on the larger part will be able to move between the three modes on the metal arc. For this mechanism to work, a sliding bearing (second image from the bottom) is needed between the two parts. The two parts also need to be able to move slightly in relation to each other in the vertical direction, hence the need for a spring. The second image from the top in the figure symbolizes the attachment to the bike. There is some room for modifications, but the interface to the bike will remain the same as for the existing product since this part acts as an attachment for more products than just the remote. Lastly, the first image from the top is some type of screw that holds everything in place, and makes sure that the two main parts can move in relation to each other in the way that is intended.

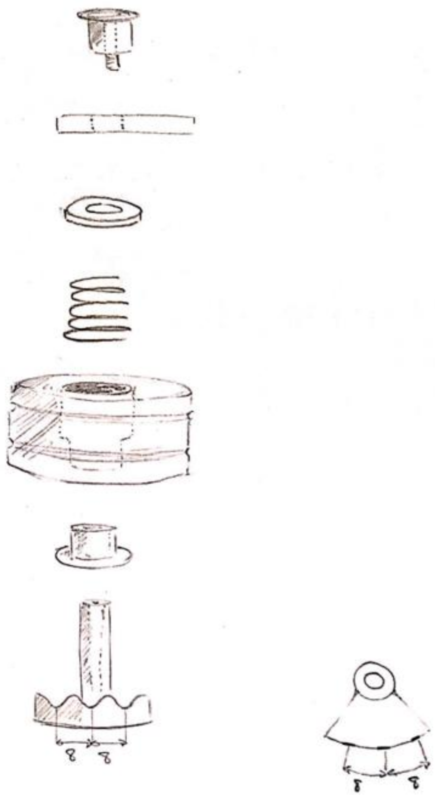


Figure 17 Illustration of the second concept, which will be referred to as "bowl".

5.2.3 **Third concept – Track**

The third concept was inspired by the push-push mechanism in a ball point pen, but with three modes instead of just two. In Figure 18, the part that attaches the remote to the bicycle is not included, but just as for the previous concept, the interface needs to remain the same, but some modifications can be done to this part. Also, the image to the top-left in the figure is similar to the one in the previous concept in the way that it will include both the handle and the attachment for the wires (but this is not included in the image), and that the grooves are used to guide the wires. The difference here is that this part has a small track inside, that is used to guide a pin. This pin can be seen in the image to the top-right in the figure. This part consists of a plate with an axis which makes sure that the two parts can rotate in relation to each other. On the plate, the pin is also attached, and this pin will follow the track that is on the inside of the other part. The track is designed in a way that makes the pin stick in the different modes each time the handle is pushed, and the track also has a small step that prevents the pin from going backwards. The first draft of a track design is what is displayed in the bottom image in Figure 18. Since the two parts need to be able to move slightly in relation to each other vertically, a spring is needed.

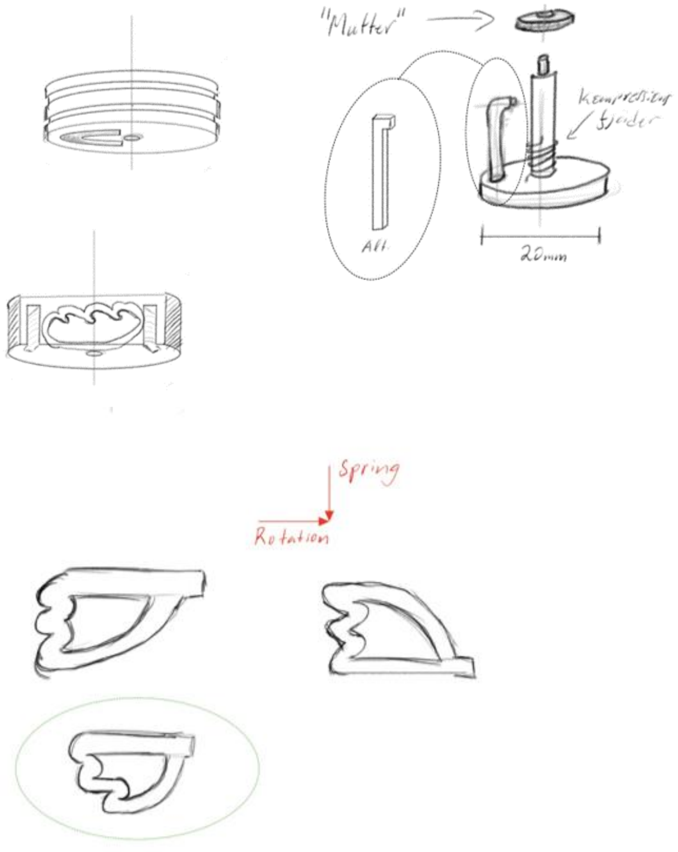


Figure 18 Illustration of the third concept, which will be referred to as "track".

6 Deliver

In the fourth phase of the project, the concepts were evaluated. The concept that would fulfil the requirements in the best way was chosen for further development. How this choice was made will be further described in this chapter. Also, the continued development process will be further described. This process was iterative, and included sketching, CAD modeling, and test printing.

6.1 Concept evaluation

To be able to choose the most suitable concept, the different alternatives have to be evaluated to see which concept that best fulfills the product requirements specified in section 5.1. The method for evaluating the concepts was the same as the method for choosing a suitable product, i.e., the scoring matrix described in Ulrich and Eppinger's *Product Design and Development* (Ulrich & Eppinger, 2012). Also, the method for determining the weights were the same as for the product choice, i.e., the weight matrix described in *Produktutveckling - effektiva metoder för konstruktion och design* (Johannesson, Persson, & Pettersson, 2004). Table 6 below shows the concept scoring matrix, and Table 7 shows the weight matrix that was used to determine the weights.

Table 6 The concept scoring matrix used to evaluate the different concepts.

Criteria / Concept	***Number of parts***	***Reliability***	***Complexity***	***Ease of use***	***Wear***	***Outstanding parts***	***Sum***
Weight	0.167	0.300	0.033	0.233	0.233	0.033	1.000
Reference (original)	3	3	3	3	3	3	18
Reference weighted	0.50	0.90	0.10	0.70	0.70	0.10	3.00
Ball plunger	5	4	3	3	2	4	21
Ball plunger weighted	0.84	1.2	0.10	0.70	0.47	0.13	3.44
Bowl	5	4	4	3	2	3	21
Bowl weighted	0.84	1.2	0.13	0.70	0.47	0.10	3.44
Track	5	4	1	5	2	5	22
Track weighted	0.84	1.2	0.03	1.12	0.47	0.17	3.83

Table 7 The weight matrix used to determine the different weights.

Criteria	***Number of parts***	***Reliability***	***Complexity***	***Ease of use***	***Wear***	***Outstanding parts***	***Sum***	***Final weight***
Number of parts	-	0	1	0	0.5	1	2.5	0.167
Reliability	1	-	1	1	0.5	1	4.5	0.300
Complexity	0	0	-	0	0	0.5	0.5	0.033
Ease of use	1	0	1	-	0.5	1	3.5	0.233
Wear	0.5	0.5	1	0.5	-	1	3.5	0.233
Outstanding parts	0	0	0.5	0	0	-	0.5	0.033
						Total	15.0	1.000

In the scoring matrix in Table 6, the original product was used as a reference to compare the new concepts against. The different criteria used to evaluate the concepts are clarified below, and are based on the team's perception of them at the time of evaluation.

6.1.1.1 Number of parts

This criterion compared the number of parts for the new concept in relation to the reference product, which in this case was the original product. A higher score means that the number of parts is less than for the reference, and a lower score means that the number of parts is higher than for the reference.

6.1.1.2 Reliability

This criterion considered the risk of the product changing modes without moving the handle. A higher score than the reference means that the new concept is less likely to change modes without moving the handle than the reference product.

6.1.1.3 Complexity

AM can deal with high complexity of parts. In this criterion, complexity is not based on the part complexity, but on the mechanism complexity. For instance, the number of moving parts and how they need to move in relation to each other for the product to be usable. A more complex product in total has more points where it can fail.

6.1.1.4 Ease of use

This criterion considered how easy the different concepts were to use. The product is supposed to be used while riding, and because of this, it is easier to push the handle between the different modes, than to push the handle in one direction and then pull it back. A higher score than the reference means that the concept is easier to use.

6.1.1.5 Wear

If a part has many surfaces that rub against each other, there is a substantial risk of wear in the product, and therefore also a risk of failure in the longer lifespan. For this criterion, a higher score means that the concept is less susceptible to wear.

6.1.1.6 Outstanding parts

This criterion is based on the number of purchased (not printed) parts that are necessary for the concept to work as intended. Examples of these kinds of parts are screws or springs. The number of parts is an estimate of what is believed to be necessary at the point of evaluation.

6.2 The chosen concept

Based on the results from Table 6, the track concept received the highest score. This was mainly due to the potential to minimize the outstanding parts with the integration into the printed design. With the track integrated in the handle, it showed great potential to make the push-push mechanism work. It is one of the more complex concepts, and it needs to be developed further from its first concept form. There are two moving parts that need to be able to move in relation to each other. All moving parts make the integration harder since it needs to be considered in all steps to not obstruct or impair the movement. Even though the concept is the more complex it was chosen since the potential was greater than the others. The mechanism has been shown to work for other applications and is considered a good enough proof of concept that this is also possible to develop.

6.3 Concept refinement

The concept refinement was performed in several different steps. It was an iterative process, and the design changed several times during this process as the team noticed things that needed to be changed for the mechanism to work properly. Also, unnecessary material was removed in several places as the design changed, but designing to avoid support material was still considered.

The moving pin, seen at the top right corner in Figure 18, was moved to be incorporated on top of the handle. This design choice was made to make all the moving parts as internal as possible. With one less part moving on the outside, the risk for failure during use decreased, which made the concept more reliable. The pin was placed inside the base. This meant that the base would need take on a larger volume, but the pin becomes more protected. Therefore, this is considered worth it for the final product. The compression spring is also moved inside the base to further support the pin. The spring is incorporated into the design to bring a second force, except the rotation induced by the pre-loaded wires, which is a part of the original concept.

Originally, the idea for the track was to place it inside the handle, oriented along the radius. This was changed to be able to orient the compression spring horizontally towards the base instead of vertically, as originally intended. This was to reduce the overall volume of the base and make the base more streamlined. With the track located flat on the top of the handle it needed to be redesigned to lay flat and move along the radius. With limited space the width of the track was determined to be 2 mm which would be wide enough to handle the forces and still fit inside the set space. Strength calculations were made on the pin to determine the minimum width. This width was then verified in the simulations presented in

Section 6.5.3. The track design was made to incorporate the three different steps with a change of wire length of 8 mm. As can be seen in Figure 19, there is one longer section of the track which switches between the fully open position of the suspension, to the fully closed one. On the return, the pin will settle in the middle section where the suspension is stiffer. From the figure seen perspective, the forces applied are inwards from the compression spring and downwards from the wire tension. To hinder the pin from going backwards from the open position (at the bottom) a raised bottom is incorporated in the track. To enable this functionality a wave washer is added to the pin attachment which leaves the pin to move vertically to go over the heel on the return.

Figure 19 An image of the final track design.

Meetings were held with the supervisors at Öhlins regularly to get feedback on the design, and to make sure they were on board with the work. They also provided the team with valuable tips and ideas for the continued work.

6.4 CAD models

6.4.1 The redesigned original product

For comparison purposes, the original product was adapted for AM. The reason for doing this was to see if it was possible to take advantage of any of the properties that add value for AM even if the product was not designed for AM from the beginning.

After the product had been adapted for AM, it had not changed too much compared to the original. This was because the original product consisted of many different parts that each fulfilled a specific purpose. For instance, several of the parts needed to be able to move in relation to each other, and some of the parts had specific materials that needed to be kept for different reasons. Because of this, it was difficult to integrate the different parts into fewer parts, and therefore focus lied on weight reduction, and to redesign to avoid support material. Regarding the weight, it was possible to remove some of the material from for instance the handles, and in other places where the extra material had no impact. Material was also added to a few places to change overhang angles and therefore avoid support material.

6.4.1.1 Cost of the redesigned original

If this product was to be manufactured with AM, not all the parts would be suitable to print. In this case, three parts would be suitable to print since many of the other parts are standard components, and it would probably be more expensive to use AM. The three parts that would be suitable to print will be referred to as Part 1, Part 2, and Part 3.

After discussions with Amexci, they could provide the team with rough cost estimations for the parts suitable for 3D printing, if these parts were to be printed. In the cost estimations, the chosen material is aluminum (AlSi10Mg), and the cost is the cost per part to print an entire plate. The cost includes both the cost for material, machine setup, machine time, and post-processing.

The cost of Part 1 increased with 54,9 % compared to the original.

The cost of Part 2 increased with 35,9 % compared to the original.

The cost of Part 3 increased with 37,6 % compared to the original.

For the entire product, this meant an increase in cost of 15,1 %.

In these calculations, only the actual part cost has been considered, and not the cost for assembly. Since the number of parts have not changed, the assembly cost is considered the same for both variants.

6.4.2 **The new design**

As previously discussed, the final concept is the result of many concept iterations, with three main parts: the base, the handle, and the pin. With a new design for the remote, the mechanism was changed towards one that can be printed more efficiently.

6.4.2.1 Design process

The product development process started with constructing a new attachment point with specifications derived from the original design. The project team then proceeded to construct the outer bounds of the new design by creating "boxes" where the details can be modeled upon. The previous features that needed to be carried over to the new design were replicated. After that, the team modeled the new mechanism with focus on the main features. They also identified the details that needed to be modeled for the mechanism to work and constructed those. It was ensured that the model, to the best ability, was designed properly for AM by following the guidelines presented in section 3.1.2. For instance, self-supporting angles were used in all the places where it was possible, to avoid support material. There were still a few places where support material was necessary, but the product was designed to minimize it. For instance, some round holes were replaced with droplet shaped holes. Also, unnecessary volume was removed from the model to reduce material, building time, and weight of the final product. Material was mostly removed in places of the model where the surfaces were not used for the mechanism, but where the removed material would not make the product too weak. Simulations (see section 6.5) were performed to verify the concept, and to make sure the removed material would not affect the function of the product. To be able to remove even more material, topology optimizations could be done here, as a next step. Finally, the team designed the visual parts of the model. By following this process, the team was able to create a new product that would meet the required specifications while also being aesthetically pleasing and efficient in its use of material and manufacturing time.

6.4.2.2 The final concept

Just as for the redesigned original product, the new design consisted of three parts that should be printed - the base, the handle, and the pin. An image of the entire assembly, as well as images for the separate parts that will be printed can be seen in Figure 20, Figure 21, Figure 22, and Figure 23 below.

Figure 20 An image of the entire final concept.

Figure 21 An image of the Handle part in the final concept.

Figure 22 An image of the Base part in the final concept.

Figure 23 An image of the Pin part in the final concept.

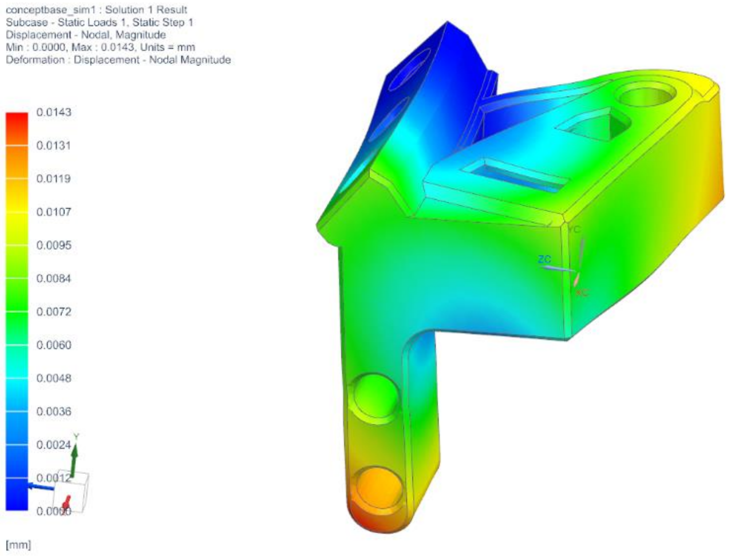
6.5 Simulations

To verify the design of the new product, simulations were made to check the strength of the product under load. The parts were evaluated separately, with each test being the scenario where it would be under the highest possible loads. To be able to construct these scenarios, the maximum force applied by a thumb was researched. The result of this was that 100 N would be a good estimate of a maximum applied force on the control handle (Lo, Chiu, Tu, Liu, & Yu, 2019). All simulations were conducted inside Siemens Simcenter 3D with Simcenter Nastran chosen as the simulation solver. The simulations were made for displacement, stress, and reaction force where the stress was calculated using the von Mises stress calculation. The stress results are then used to calculate the safety factor for the part where the minimum threshold was set to 1.5. The separate scenarios and respective results are presented below.

6.5.1 **Base**

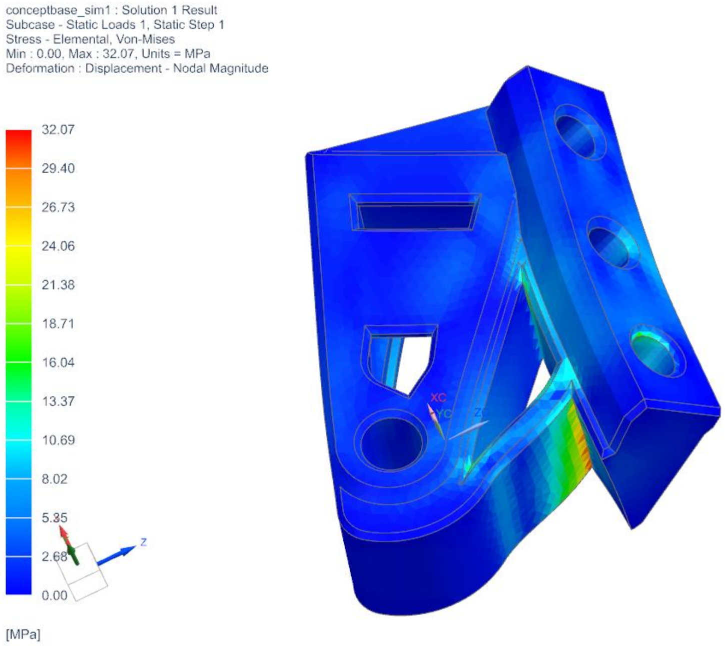
To set up a realistic scenario where the maximum load is applied on the base part, forces are applied at four different target points. In the holder for the wire casing a force of 45 N is applied, divided evenly over the two holders. The force is based on the maximum tension applied from the dampers which would in reality be less since most of the force is transferred into the attachment point of the wires. Another force is applied inside the hole attaching the handle to the base. This force is set to 100 N, which was the maximum applied thumb force if it would be fully applied at this location. Once again this would not happen in reality, since this force is divided over more than this area. The same force is applied inside the track of the mechanism where the pin will be attached. The entire part is anchored in the hole positioned the furthest away from the center of mass since this would be the worst-case scenario.

From the above scenario the simulation is solved and the results are shown in Figure 24, Figure 25, and Figure 26 below. The maximum displacement for the part is 0.014 mm which is well inside the tolerances for the product. The maximum stress is 32.07 MPa, and the material (AlSi10Mg) has a yield strength of above 310 MPa which results in a safety factor of 9.67 (Pan, et al., 2022). The reaction force that occurs in the attachment point is 6.31 N which would not appear to compromise the part. With these results, the base part is considered sturdy enough to be able to handle the forces with margin.



conceptbase_sim1 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Displacement - Nodal, Magnitude
Min : 0.0000, Max : 0.0143, Units = mm
Deformation : Displacement - Nodal Magnitude

Figure 24 Displacement for the Base part, with all loads applied.



conceptbase_sim1 : Solution 1 Result
Subcase - Static Loads 1, Static Step 1
Stress - Elemental, Von-Mises
Min : 0.00, Max : 32.07, Units = MPa
Deformation : Displacement - Nodal Magnitude

Figure 25 Stress for the Base part, with all loads applied.

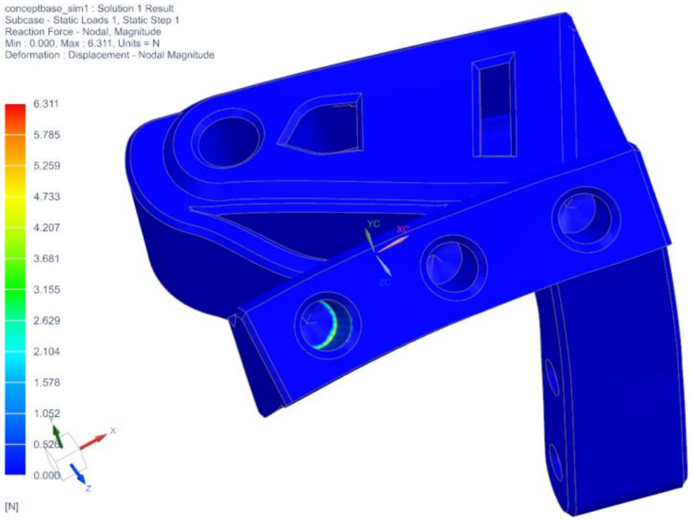


Figure 26 Reaction force for the Base part, with all loads applied.

6.5.2 Handle

The handle is the part that is exposed directly from the forces from the user which in this scenario is the main force. As mentioned in the previous section, the force is set to 100 N. The other force applied is from the wires at their attachment point, and this force is set to 45 N. The center cylinder is locked in all directions except rotation to replicate the attachment screw. The other attachment point which would stop the rotation is inside the track where the maximum force applied to the handle would result in three different scenarios due to the three different modes.

All three scenarios were simulated with very similar results for the displacement and stress with the reaction force placed differently. The simulations for the handle part are presented in Figure 27, Figure 28, and Figure 29 below. The maximum displacement from the applied forces is 0.75 mm at the edge of the handle which is considered alright. The maximum stress on the part results in 161.83 MPa which compared to the yield strength gives a safety factor of 1.92. The maximum reaction force is 15.82 N, 18.40 N and 22.03 N for the different scenarios where the innermost edge results in the highest force. The result for the handle verifies that it is built sturdy enough to handle the forces with margin.

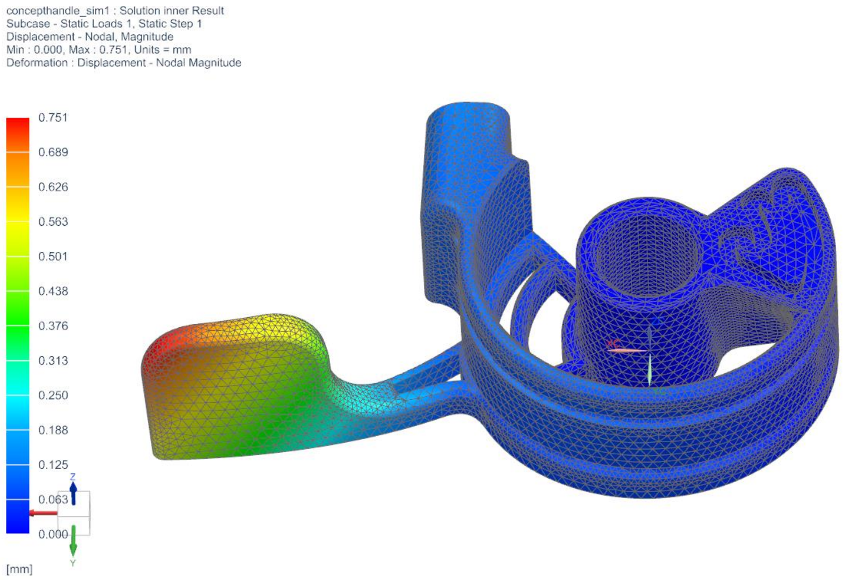


Figure 27 Displacement for the Handle part, with all loads applied.

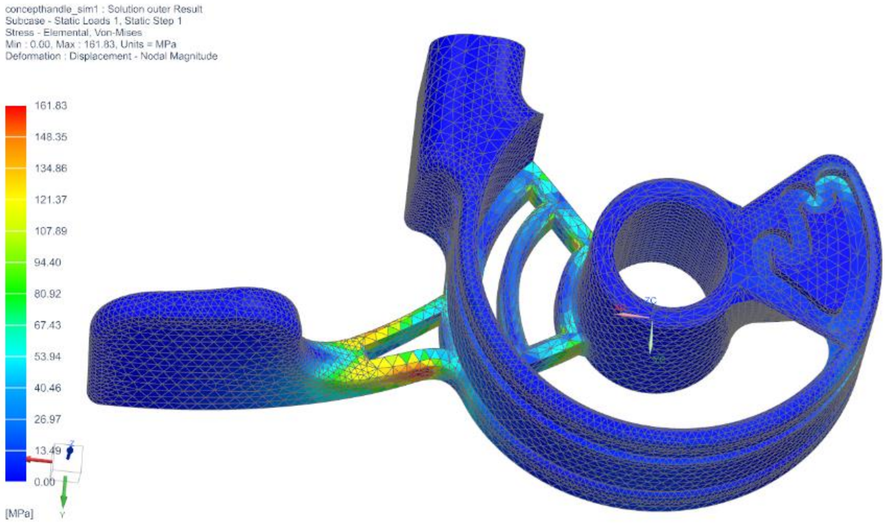


Figure 28 Stress for the Handle part, with all loads applied.

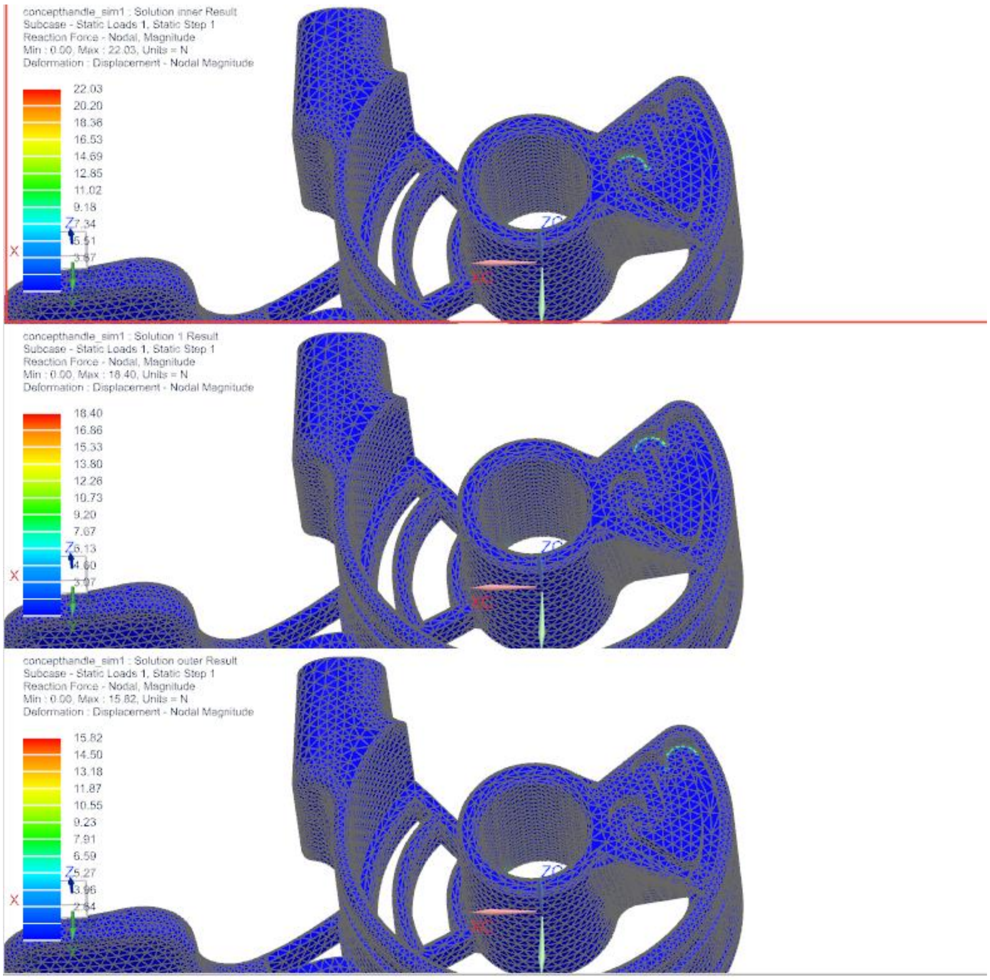


Figure 29 Reaction force for the Handle part, with all loads applied for the three different scenarios.

6.5.3 **Pin**

For the pin scenario, the middle cylinder was fixed to reflect the rail in the base blocking the pin from moving when reaching the edges of the track. Forces were then applied towards the lower cylinder where the track intersects the pin. These forces were set to 53 N to reflect the reaction force previously simulated in the base simulation seen in section 6.5.1.

The simulations can be seen in Figure 30, Figure 31, and Figure 32 below. The displacement with the force applied was 0.0044 mm. This is very low and will not be an issue. The stress on the part reached a maximum of 98.70 MPa. This gives the part a safety factor of 3.14 which is above the thresh hold. The reaction force in the middle cylinder reached 1.57 N which the part should handle with ease. The results deem the part sturdy enough to handle the loads it will be exposed for.

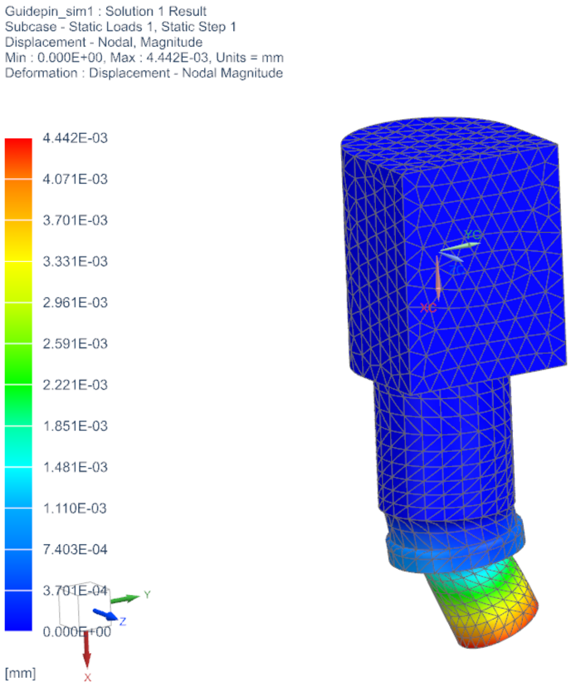


Figure 30 Displacement for the Pin part, with all loads applied.

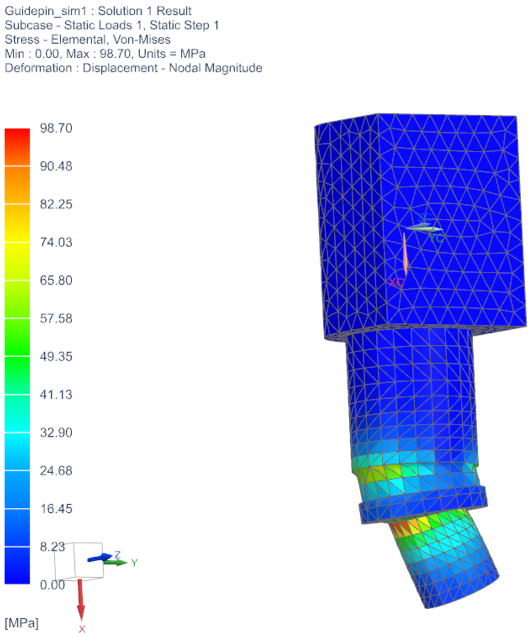


Figure 31 Stress for the Pin part, with all loads applied.

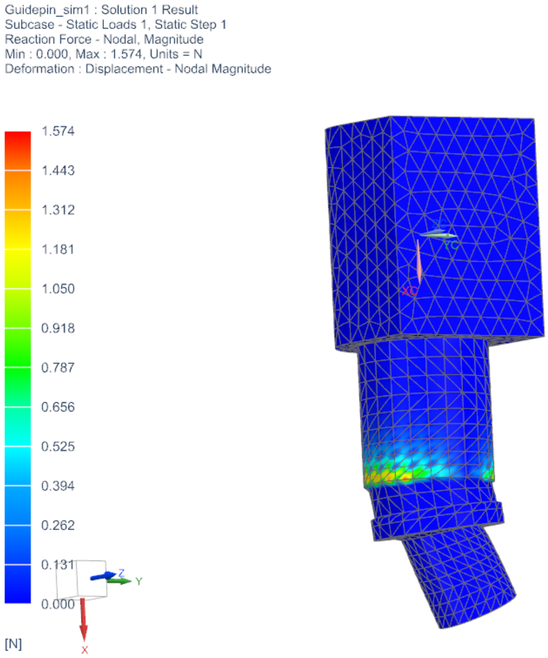


Figure 32 Reaction force for the Pin part, with all loads applied.

6.6 Test prints

Test prints were performed to verify the concept before it was sent for print at Amexci. Since the printer used for the test print was a plastic printer, it would not be possible to test and verify the material, but the idea was that it would still be possible to test the mechanism to see if there was anything that needed to be adjusted before sending the files to Amexci. When the product was assembled, it was realized that some of the parts were not possible to assemble due to the material. For instance, a lock washer would be used to ensure that all components would stay in place, but this lock washer was not possible to use for the plastic parts without damaging the plastic. Figure 33 shows the product, printed in plastic.

Figure 33 A picture of the part printed in plastic.

6.7 Results of the new design

After discussions with Amexci, the team received cost estimates for the different parts if they were to be manufactured in aluminum (AlSi10Mg). Since this is a new product, the comparison of the different part costs for the new product towards the original is miss guiding because of the lesser number of parts. The more accurate comparison would be for the entire assembly. If the parts where to be compared directly to the old ones for the new product, it would lead to a price increase of 50,4% of the base part as well as a 213,9% increase for the handle.

Through combining multiple components as well as changing the mechanism for the product, the number of parts used was reduced by 25%, including screws and handle attachment. This reduction in the number of parts is reflected in the total price for the product. With all parts included there was a price increase of only 1.85%.

The footprint of the assembly is larger than the original in order to make space for the new mechanism. The larger footprint contributes to a mass increase of 38,5% with the remote base being the biggest contributor to the increase.

7 Discussion

This chapter will reflect on the work that was carried out. It will, amongst other things, address the research questions, the new concept, some future work, and some comments about the general project approach.

7.1 The research questions

This section will answer the research questions stated in section 1.2 of this report. The research questions are somewhat connected to each other. The following sections will describe the questions more thoroughly.

7.1.1 **How can Öhlins use AM in their current products?**

This project has shown one way in which it is possible to use AM in Öhlins's current products. The first step is to determine which product from Öhlins's product portfolio that is most suitable. After doing this, it is possible to look into the different requirement for the product, and then determine which AM methods that are most suitable. Although it is possible for Öhlins to use AM, it important to remember that it is always more difficult to go from traditional techniques to AM, than the other way around, and still gain the same value. This is shown in the results, where the newly designed part came out with less parts and a more optimized design, and where the original product that was redesigned for AM became more expensive when manufacturing it with AM than with traditional methods.

7.1.2 **What advantages would Öhlins gain from using AM?**

There are many advantages Öhlins can gain from using AM, if they use the technique properly. Advantages with the techniques were discussed in section 3.1.1. Since Öhlins have several products that are relatively complex, both regarding the complexity of the actual parts (parts with different channels for instance), and regarding the assemblies (products consisting of many different parts), some of Öhlins's products are today both difficult and time consuming to produce. Both aspects are related to high manufacturing costs. If developing new products, that are designed for AM, Öhlins will be able to take advantage of aspects such as manufacturing of more complex parts (since many parts are complex already), and integrating many parts into fewer parts. For parts that are already complex, the manufacturing might be easier, and if integrating many parts into fewer, the assembly time would be reduced, which could potentially result in lower part cost. With this being said, there are a number of Öhlins's products that are still better suited for the traditional methods. One example of this would be the front fork casing. This part is the main structural part of the front fork and too big and simple to draw any of the more substantial benefits of AM from.

7.1.3 How does Öhlins choose a product that is suitable for AM?

There are several ways to choose a product that is suitable for AM. In this project, a scoring matrix was used, and in this matrix the different products were evaluated based on a few criteria that create value when using AM.

There are of course other methods that have not been examined for this project, that could also be used to choose the most suitable product, but this report has presented one option. As in all selection processes, it is important to evaluate based on aspects that are desirable and that create value for the chosen application, and to get as reliable results as possible the products should be evaluated based on as many aspects as possible.

In this project, the products that were evaluated were products that Öhlins had looked into before, and that they thought might be suitable to look into further. This means that a selection of the products had already been made. The product that was chosen for this project was the product that was considered the most suitable product out of the selected products, and not the most suitable product of all Öhlins's products. The approach used in this project can still be a suitable approach, but to get the most reliable results, all products from Öhlins product portfolio needs to be evaluated.

7.1.4 How will the above questions give Öhlins a competitive advantage?

With the answers to the above questions, Öhlins will have a lot of knowledge about the technique. In this case, the knowledge can give Öhlins better prerequisites to use the knowledge properly. As mentioned several times in this report, AM is an expensive technique, and a relatively slow technique, and having the knowledge of how to use it, will give Öhlins an advantage.

Öhlins's current products are mainly manufactured with traditional techniques, and they are also designed for these techniques. Since many of their products consist of assemblies with several parts, it can be difficult to just change the manufacturing technique for some of these parts, since all the parts still need to work together. But, if an entire product was instead designed for using AM, and the components that are easy to process traditionally are changed to traditional techniques afterwards, AM might be a good solution for Öhlins. Many of Öhlins's products are complex, and since manufacturing complex parts is one of the main advantages of AM, Öhlins can probably gain a lot if using AM properly. With the competitive applications the products are used in, price is not as important as function and with the possibility to create these complex parts, but optimized based on weight and functionality, the advantage could be found.

7.2 The new concept

The new concept, designed for AM, consisted of three parts that should be printed - the base, the handle, and the pin. All of these parts were designed with AM design guidelines in mind, to minimize the amount of material, and to use self-supporting angles to avoid support material and therefore also minimize the post-processing.

Evaluating the three parts, both the base and the handle are relatively complex parts, which would make them suitable for AM. The pin, on the other hand, does not have a very complex shape, and therefore it would probably be more efficient to manufacture this in a more traditional way, since AM is a technique that is both slow and expensive.

7.2.1 **Advantages and disadvantages of the new concept**

The new concept, designed for AM, is still only a concept, and not a finished product. Therefore, there are still a lot of things that can be looked into to make sure to take advantage of all the aspects that add value with AM.

The first advantage of the new concept, compared to the original product, is the number of parts. The number of parts was reduced by 25%. Fewer parts add value both from an assembly perspective, and from a supply chain perspective. Regarding the assembly, fewer parts will make the assembly easier, and also shorter, which directly affects the cost of the product. From a supply chain perspective, fewer parts in the assembly means fewer unique parts to store and transport. This also affect the cost of the component. With the resulting 1.85% price increase of the manufacturing cost, further development can lead to a price decrease of the final product which adds to this perspective as well.

Regarding disadvantages, there are also a few that needs to be addressed. The first disadvantage is the size of the product. The new concept is substantially larger than the original product. The reason for this was to make sure that the track on the top would work properly, and would not be too small or have too sharp corners. Another reason is the integration of the compression spring in the base since the spring needs volume to not be obstructed.

Another disadvantage is the risk for wear in the track. The chosen mechanism is a mechanism that is subjected to wear, and this places requirements on the material. The material evaluation in this project has not been made thoroughly enough to be able to determine if aluminum would work in the long run. With the unique design, wear testing cannot be accomplished without the finished product being put to the test with longer exposure.

Looking back at the cost estimates, it can be seen that the new concept, printed in aluminum is still relatively expensive. One of the main reasons for this is that the handle part was designed to be printed "laying flat" on the build plate, which resulted in fewer part being printed in each print. This increases the cost per part since this variable heavily affects the final price. Another aspect affecting the print time is how thick each layer is. In this case, the thickness was set to 60 μm but it could also be changed to 30 μm or 90 μm in the same machine. A thicker layer would reduce the print time. A drawback of a thicker layer is the loss of details, and a rougher surface. For this product the thickness was set based on the post processing needed after the print. With the thicker layer, further processing would be needed to remove the visible layers on the outside of the part.

7.2.2 **Future work**

Since this master thesis project was performed during a limited time period, it would not be possible to deliver a product that would be ready for the market. The product that was delivered is a prototype, and it will need to be further developed and evaluated to reach its full potential. Some ideas for future work and further development will therefore be presented below.

7.2.2.1 Testing and evaluation of physical prototype

The initial idea was that time would allow for some testing and evaluation of the physical model. Although, as the project moved forward, it was realized that some activities took longer than anticipated, and also that the lead times when ordering a prototype was longer than anticipated. Because of this, the physical prototype was not delivered before the end of the project, and therefore there was no time for evaluation of the physical product. With more time, this is the next thing that would have been done, to verify the mechanism.

7.2.2.2 Printed springs

In this project, the springs used in the prototype were purchased from an external supplier, and assembled in a traditional way. With more time, it would be possible to perform more thorough analyzes on printed springs, to be able to better predict both the material properties and the mechanical properties in the spring. By using a 3D printed spring instead, it would be possible to integrate it into another part which would reduce both the number of parts, and the assembly time.

7.2.2.3 More thorough material evaluation

As mentioned already in Chapter 1, one of the delimitations was to focus on the manufacturing technique, rather than performing thorough material selection processes, and evaluations. Since the new product is based on a groove that guides a small pin, there is a risk for wear for both the groove and the pin. This means that the choice of material may have a large impact on how well the product actually works, and because of this, more thorough material analyzes should be done.

7.2.2.4 Weatherproofing

Since the new product that has been developed has an open track on the top, there is a risk that this track will collect water if it rains. Without thorough testing, it is difficult to know how this water would affect the function. With more time, it could therefore be worth it to test the product to see if this is a problem, and thereafter make sure to find a solution that would hinder water to be collected in the track. One idea could be to add small channels to let the water out, but there could also be other suitable solutions.

7.2.2.5 Topology optimization

With more time, topology optimization of the part with the handle is something that might be interesting to look into. A lot of unnecessary material has already been removed from this part, but with the help of for instance Ansys, or other software that can do the topology optimization, the part could be truly optimized regarding weight.

7.3 The general project approach

The purpose of the thesis project was to investigate AM as a manufacturing technique for Öhlins’s products. Öhlins wanted to gain more knowledge in AM. This included how they can use the technology for their current products, what advantages they would gain, how they should choose a product suitable for AM, and how all of the above would give them a competitive advantage. The goal of the project was to use an appropriate method to choose a product suitable for AM.

This product should then be optimized for AM, a printable part should be developed, and the advantages and disadvantages of this product should be documented.

The general project approach was inspired by the double diamond model, and this turned out to be a suitable approach. There were four clear phases, and it was clearly defined what each phase should include, and what needed to be ready to continue to the next phase. This made it easy to perform the different tasks in the correct order, and to make sure to finish all the tasks on time.

The first phase of the project, *discover*, was the phase of the literature study. The literature study was necessary to be able to gather enough information, and get enough knowledge, in the area. Without this knowledge, it would not be possible to provide Öhlins with reliable information about how the manufacturing technique can be used for their products, and it would also not be possible to develop a new product, designed to be manufactured with AM.

The second phase, *define*, included everything that was needed to be able to clearly specify the problem. In this case, Öhlins wanted to know which of their products that was most suitable for AM, and therefore, some type of method to determine this was needed. The products were evaluated based on the value of different aspects that can be achieved by using AM. After finding the most suitable product to continue working with, also specific manufacturing method, material, and supplier needed to be determined before moving on to the next phase.

In the third phase, *develop*, the development of a new product that would solve the specified problem was initiated. This phase was slightly shorter than the other phases, since it only included specifying the product requirements, and generate concepts. In this project, only three concepts were generated. To be able to come up with the best possible solution, this is probably not enough, but due to the short time and many tasks that needed to be fulfilled in this project, it was decided that three concepts would still fulfill the purpose of showing an example of how to go from traditional manufacturing to AM.

The fourth phase, *deliver*, included evaluation of the different concepts, to thereafter choose the most suitable concept. After the most suitable concept had been decided, it was refined to make sure to take advantage of the aspects that create value with AM. The entire fourth phase was very iterative, and the concept was changed several times before it was ready.

7.3.1 **Potential project improvements**

As previously mentioned, clear tasks and a clear time plan made the work move forward smoothly, but even though the project was thoroughly planned, there are always some unexpected things that appear that have not been considered. One of these things included the print direction. During the CAD work, both the current product adapted for AM, and the new product, designed for AM, were designed to be printed in one specific direction, this direction being "laying flat" on the build plate. In this direction, material was both added and removed to avoid support material. This was done by for instance changing overhang angles, or making bottom surfaces flat. After finishing these parts, a meeting was held with the representative from Amexci, who pointed out that the direction that the parts had been designed for would use more of the area on the build plate per part, resulting in more expensive manufacturing per part. Instead, the representative from Amexci suggested that the parts should be printed standing up, since this would reduce the footprint and make way for more parts to be manufactured in each print. With more parts for each batch the price could be reduced, and the manual labor minimized.

Something else that came up after the discussion with the representative from Amexci was the print direction of the parts with threaded holes. As previously mentioned, the interface between the product and the bicycle remained unchanged, and this meant that three threaded holes were necessary. It is possible to print the threads directly, but this comes with requirements for print direction. Because of this, it was decided that all the holes that needed to be threaded would be completely filled during the print, to thereafter be post-processed to make them threaded and to achieve the desired properties. This would result in more post-processing work, but it would enable a more precise print as well as more accurate threads. This also made it possible to both fit more parts on the build plate in each print, as well as print the part in a direction that would minimize the amount of support material.

8 Conclusions

Something that was realized early during the project, was that it is very difficult to take advantage of all the aspects that add value when manufacturing with AM, if the product is not designed for AM from the beginning. AM has a lot of advantages, but it is an expensive manufacturing technique. Therefore, it generally never works to manufacture products designed for traditional techniques with AM, and still gain the same value. The largest benefit from AM is the design freedom that comes with the increased complexity limitation. The manufacturing technique is applicable on products that could make use of this increased complexity. For simpler parts, the traditional manufacturing techniques are still superior in both speed and cost.

Öhlins have products that make use of simple shapes as well as very complex ones. The suspension systems are, by volume, largely made out of simple shapes such as cylinders but with very complex mechanisms to achieve the superior performance. The entire system is not suitable for additive manufacturing because of these simple volumes. With a combination of the traditional methods and additive manufacturing, a superior product can be put forward with more efficient mechanisms that have the potential to be lighter, cheaper and have more functionality. By implementing additive manufacturing, batches of variants for different bikes could be more common. The rear damper has size limitations based on the frame it should be attached to. Standardizing these dampers to fit many bikes is difficult and will result in the limited space not being utilized to its full potential. With the rapid supply chain of additive manufacturing, lead time reduction opens up the possibility for these dampers to be optimized for more bikes, resulting in more favorable advantages.

References

9T-Labs. (2023a). *Additive fusion solution*. Retrieved Feb 14, 2023, from https://www.9tlabs.com/solutions/additive-fusion-solution

9T-Labs. (2023b). *Carbon composite material*. Retrieved Feb 20, 2023, from https://www.9tlabs.com/technology/material

Abdulhameed, O., Al-Ahmari, A., Ameen, W., & Hammad Mian, S. (2019). Additive manufacturing: Challenges, trends, and applications. *Advanced in Mechanical Engineering*.

Aboulkhair, N. T., Simonelli, M., Parry, L., Ashcroft, I., Tuck, C., & Hague, R. (2019). 3D printing of Aluminium alloys: Additive Manufacturing of Aluminium alloys using selective laser melting. *Progress in Materials Science*. doi:10.1016/j.pmatsci.2019.100578

Amexci. (n.d.). *Transform your digital file into a physical part*. Retrieved May 14, 2023, from https://amexci.com/print-a-part/

Anand Kumar, S., & Prasad, R. (2021). Basic principles of additive manufacturing: different additive manufacturing technologies. In *Additive Manufacturing* (pp. 17-35). Elsevier Ltd. doi:10.1016/B978-0-12-822056-6.00012-6

Arian Metal. (n.d.). *Milling*. Retrieved Mar 8, 2023, from http://arianmetal.ir/index.php/en/products/10-milling

Aydin, Ü. (2020, Mar 3). *80% WEIGHT SAVINGS AND 5 MORE ADVANTAGES WHY ADDITIVE MANUFACTURING BOOSTS HYDRAULIC SYSTEMS*. Retrieved Feb 14, 2023, from https://news.pminnovationblog.com/blog/80-weight-savings-and-5-more-advantages-why-additive-manufacturing-boosts-hydraulic-systems

Cano-Vicent, A., Tambuwala, M. M., Sarif Hassan, S., Barh, D., Aljabali, A., Birkett, M., . . . Serrano-Aroca, A. (2021). Fused deposition modelling: Current status, methodology, applications and future prospects. *Additive Manufacturing*. doi:10.1016/j.addma.2021.102378

Carvill, J. (1994). Manufacturing Technology. In *Mechanical Engineer's Data Handbook* (pp. 172-217). Elsevier Ltd. . doi:10.1016/C2009-0-24207-3

Chennu, V. R. (2017, Jan 3). *Casting Process: Advantages and Limitations*. Retrieved Mar 8, 2023, from https://mechanicalengineering.blog/casting-process-advantages-and-limitations/

ClubTechnical. (2018a, Aug 21). *What is Casting? Advantages, Limitations, Defects, Types*. Retrieved Feb 20, 2023, from https://clubtechnical.com/casting

ClubTechnical. (2018b, Aug 23). *Forging | Types, Defects, Advantages, Disadvantages, Applications*. Retrieved Feb 20, 2023, from https://clubtechnical.com/forging

Combitech. (2023a). *Om oss*. Retrieved Feb 1, 2023, from https://www.combitech.se/om-oss/

Combitech. (2023b). *Alla våra tjänster*. Retrieved Feb 1, 2023, from https://www.combitech.se/tjanster/alla-vara-tjanster/

Derekar, K. S. (2018). A review of wire arc additive manufacturing and advances in wire arc additive manufacturing of aluminium. *Materials Science and Technology*, 895-916. doi:10.1080/02670836.2018.1455012

DesignCouncil. (n.d.). *The Double Diamond*. Retrieved Apr 25, 2023, from https://www.designcouncil.org.uk/our-work/skills-learning/the-double-diamond/

Diegel, O., Nordin, A., & Motte, D. (2019). *A Practical Guide to Design for Aditive Manufacturing.* Springer.

DT Swiss. (n.d.). *TWO-IN-ONE REMOTE LEVER*. Retrieved May 17, 2023, from https://www.dtswiss.com/en/suspension/remote-levers/two-in-one-remote-lever

Elmansy, R. (2021, Sep 2). *The Double Diamond Design Thinking Process and How to Use it*. Retrieved from https://www.designorate.com/the-double-diamond-design-thinking-process-and-how-to-use-it/

EngineeringClicks. (2016, Nov 4). *Metal Forging*. Retrieved from https://www.engineeringclicks.com/metal-forging/

GE Additive. (n.d.). *About GE Additive*. Retrieved Feb 3, 2023, from https://www.ge.com/additive/who-we-are

Gearon, M. (2022, Nov 17). *4 phases of the Double Diamond Model*. Retrieved Mar 3, 2023, from https://mgearon.com/ux/double-diamond-model/

Ghassemali, E. (2022). Forging of Metallic Parts and Structures. *Encyclopedia of Materials: Metals and Alloys*, 129-143. doi:10.1016/B978-0-12-819726-4.00148-4

Gibson, I., Rosen, D., Stucker, B., & Khorasani, M. (2021). *Additive Manufacturing Technologies* (3rd ed.). Springer. Retrieved from https://link.springer.com/content/pdf/10.1007/978-3-030-56127-7.pdf

Guddati, S., Sandeep Kranthi Kiran, A., Leavy, M., & Ramakrishna, S. (2019). Recent advancements in additive manufacturing technologies for porous material applications. *The International Journal of Advanced Manufacturing Technology*, 193–215. doi:10.1007/s00170-019-04116-z

Guo, C., Li, G., Li, S., Hu, X., Lu, H., Li, X., . . . Zhu, Q. (2023). Additive manufacturing of Ni-based superalloys: Residual stress, mechanisms of crack formation and strategies for crack inhibition. *Nano Materials Science*, 53-77. doi:10.1016/j.nanoms.2022.08.001

Haghdadi, N., Laleh, M., Moyle, M., & Primig, S. (2021). Additive manufacturing of steels: a review of achievements and challenges. *Journal of Materials Science*, 64-107. doi:10.1007/s10853-020-05109-0

Hajare, D. M., & Gajbhiye, T. S. (2022). Additive manufacturing (3D printing): Recent progress on advancement of materials and challenges. *Materials Today: Proceedings*, 736-743. doi:10.1016/j.matpr.2022.02.391

HUBS. (n.d.). *How to design parts for CNC machining*. Retrieved Mar 15, 2023, from https://www.hubs.com/knowledge-base/how-design-parts-cnc-machining/

Izadi, M., Farzaneh, A., Mohammed, M., Gibson, I., & Rolfe, B. (2020). A review of laser engineered net shaping (LENS) build and process parameters of metallic parts. *Rapid Prototyping Journal*, 1059–1078. doi:10.1108/RPJ-04-2018-0088

Jahangir, M. N., Mamun, M. A., & Sealy, M. P. (2018). A Review of Additive Manufacturing of Magnesium Alloys. *AIP Conference Proceedings*. doi:10.1063/1.5044305

Jin, W., Zhang, C., Jin, S., Tian, Y., Wellmann, D., & Liu, W. (2020). Wire Arc Additive Manufacturing of Stainless Steels: A Review. *Applied Sciences, 10*(5), 1563. doi:10.3390/app10051563

Johannesson, H., Persson, J.-G., & Pettersson, D. (2004). *Produktutveckling - effektiva metoder för konstruktion och design.* Stockholm: Liber.

John. (2022, Nov 19). *Best Metals for CNC Machining-Selection Guide*. Retrieved Feb 20, 2023, from https://mellowpine.com/cnc/best-metals-for-cnc-machining/

JUSTIA Trademarks. (n.d.). *SLM - Trademark Details*. Retrieved May 14, 2023, from https://trademarks.justia.com/855/07/slm-85507057.html

Karunakaran, R., Ortgies, S., Tamayol, A., Bobaru, F., & Sealy, M. P. (2020). Additive manufacturing of magnesium alloy. *Bioactive Materials*, 44-54. doi:10.1016/j.bioactmat.2019.12.004

Körner, C. (2016). Additive manufacturing of metallic components by selective electron beam melting — a review. *International Materials Reviews*, 361-377. doi:10.1080/09506608.2016.1176289

Lasertech. (n.d.). *3D-printing - i metall och plast*. Retrieved May 14, 2023, from https://lasertech.se/se/vara-tjanster/3d-printing

Liu, B., Wang, Y., Lin, Z., & Zhang, T. (2020). Creating metal parts by Fused Deposition Modeling and Sintering. *Materials Letters*, 127152. doi:10.1016/j.matlet.2019.127252

Lo, V. E.-W., Chiu, Y.-C., Tu, H.-H., Liu, C.-W., & Yu, C.-Y. (2019). A Pilot Study of Five Types of Maximum Hand Strength among Manufacturing Industry Workers in Taiwan. *International Journal of Environmental Research and Public Health*. doi:10.3390/ijerph16234742

Maier, C., & Calafut, T. (1998). Extrusion. In *Polypropylene* (pp. 205-221). William Andrew Inc. Retrieved from https://www.sciencedirect.com/book/9781884207587/polypropylene

Materialise. (n.d.). *Design for Additive Manufacturing*. Retrieved Mar 16, 2023, from https://www.materialise.com/en/academy/industrial/design-am

Michler, T. (2016). Austenitic Stainless Steels. In *Materials Science and Materials Engineering.* Elsevier Inc. doi:10.1016/B978-0-12-803581-8.02509-1

Mital, A., Desai, A., Subramanian, A., & Mital, A. (2015). Selection of Manufacturing Processes and Design Considerations. In *Product Development* (2nd ed., pp. 133-158). Elsevier Inc. doi:10.1016/C2013-0-14339-5

Moghimian, P., Poirié, T., Habibnejad-Korayem, M., Arreguin Zavala, J., Kroeger, J., Marion, F., & Larouche, F. (2021). Metal powders in additive manufacturing: A review on reusability and recyclability of common titanium, nickel and aluminum alloys. *Additive Manufacturing*. doi:10.1016/j.addma.2021.102017

MX3D. (n.d.). *MX3D Bridge*. Retrieved Feb 1, 2023, from https://www.smartbridgeamsterdam.com/

Optomec. (n.d.). *LENS Directed Energy Deposition (DED) 3D Printed Metal Technology*. Retrieved Feb 2, 2023, from https://optomec.com/3d-printed-metals/lens-technology/

Padasak, Z. (2022, Oct 5). *Top 10 Advantages and Disadvantages of Using Additive Manufacturing*. Retrieved Feb 23, 2023, from https://www.alphaprecisionpm.com/blog/top-10-advantages-and-disadvantages-of-using-additive-manufacturing

Pan, W., Ye, Z., Zhang, Y., Liu, Y., Liang, B., & Zhai, Z. (2022). Research on Microstructure and Properties of AlSi10Mg Fabricated by Selective Laser Melting. *Materials*. doi:10.3390/ma15072528

Reliance Foundry. (n.d.). *Smithy Secrets: An Intro to Forging Methods*. Retrieved Feb 20, 2023, from https://www.reliance-foundry.com/blog/forging

Rinaldi, M., Caterino, M., Manco, P., Fera, M., & Macchiaroli, R. (2021). The impact of Additive Manufacturing on Supply Chain design: a simulation study. *Procedia Computer Science,* 446-455. doi:10.1016/j.procs.2021.01.261

Sandvik. (n.d.). *Additive Manufacturing Services*. Retrieved May 14, 2023, from https://www.additive.sandvik/en/products-services-am/additive-manufacturing-services/

Satish Prakash, K., Nancharaih, T., & Subba Rao, V. (2018, Mar 24). Additive Manufacturing Techniques in Manufacturing - An Overview. *Materials Today: Proceedings*, pp. 3873-3882.

Saunders, M. (2017). *Design for metal AM - a beginner's guide.* Retrieved Mar 16, 2023, from https://www.renishaw.com/en/design-for-metal-am-a-beginners-guide--43333

Singh, R., Gupta, A., Tripathi, O., Srivastava, S., Singh, B., Awasthi, A., . . . Saxena, K. (2020). Powder bed fusion process in additive manufacturing: An overview. *Materials Today: Proceedings,* 3058-3070. doi:10.1016/j.matpr.2020.02.635

Sjögren, A. (2021). Lecture notes from the course Composite Materials Design (MMKN41). Lunds Tekniska Högskola.

SM Lease. (n.d.). *What is Metal Extrusion, types, and Manufacturing Process*. Retrieved Mar 9, 2023, from https://www.smlease.com/entries/manufacturing/what-are-different-types-of-metal-extrusion-process/

Song, B., Wen, S., Yan, C., Wei, Q., & Shi, Y. (2021). Introduction and basic principles. In *Selective Laser Melting for Metal and Metal Matrix Composites* (pp. 1-16). Huazhong: Elsevier Ltd. doi:10.1016/B978-0-08-103005-9.00001-8

StudentLesson. (2020a, Nov 8). *Understanding the working of shock absorber*. Retrieved Apr 12, 2023, from https://studentlesson.com/shock-absorber-definition-functions-components-types-working/

StudentLesson. (2020b, May 21). *Everything you need to know about milling machine*. Retrieved Feb 20, 2023, from https://studentlesson.com/milling-machine/?utm_content=cmp-true

Sun, C., Wang, M., Qian, L., & Wang Fu, M. (2022). Extrusion Forming of Metallic Parts and Structures. *Encyclopedia of Materials: Metals and Alloys*, 144-159. doi:10.1016/B978-0-12-819726-4.00140-X

TireRack. (n.d.). *Shock Absorber & Suspension Tech 101*. Retrieved Apr 12, 2023, from https://www.tirerack.com/upgrade-garage/shock-absorber-suspension-tech-101

Tshephe, T. S., Akinwamide, S. O., Olevsky, E., & Olubambi, P. A. (2022). Additive manufacturing of titanium-based alloys- A review of methods, properties, challenges, and prospects. *Heliyon*. doi:10.1016/j.heliyon.2022.e09041

Ulrich, K. T., & Eppinger, S. D. (2012). *Product Design and Development* (Swedish ed.). New York: McGraw-Hill Education.

Unleashed. (2021, May 20). *12 Benefits of Additive Manufacturing and 5 Disadvantages*. Retrieved Feb 23, 2023, from https://www.unleashedsoftware.com/blog/12-benefits-of-additive-manufacturing-and-5-disadvantages

Vranić, A., Bogojević, N., Ćirić Kostić, S., Croccolo, D., & Olmi, G. (2017). Advantages and Drawbacks of Additive Manufacturing. *Research & Development in Heavy Machinery*. Retrieved from https://scidar.kg.ac.rs/bitstream/123456789/14223/1/14_2017_IMK14_23_EN57_Vranic.pdf

Wang, Y., Zhou, Y., Lin, L., Corker, J., & Fan, M. (2020). Overview of 3D additive manufacturing (AM) and corresponding AM composites. *Composites Part A: Applied Science and Manufacturing*. doi:10.1016/j.compositesa.2020.106114

WikimediaCommons. (2023a). *Selective laser melting system*. Retrieved from https://commons.wikimedia.org/wiki/File:Selective_laser_melting_system_schematic.jpg

WikimediaCommons. (2023b). *Binder Jetting*. Retrieved May 11, 2023, from https://commons.wikimedia.org/wiki/File:BinderJetting.svg

Worksafe. (n.d.). *Plastics extrusion presses*. Retrieved Mar 9, 2023, from https://www.worksafe.govt.nz/topic-and-industry/machinery/working-safely-with-plastic-production-machinery/plastics-extrusion-presses/

Yakout, M., & Elbestawi, M. A. (2017). Additive Manufacturing of Composite Materials: An Overview. *6th International Conference on Virtual Machining Process Technology (VMPT).* Montréal. Retrieved from https://www.researchgate.net/publication/316688880_Additive_Manufacturing_of_Composite_Materials_An_Overview

Zhang, T., & Liu, C. T. (2022). Design of titanium alloys by additive manufacturing: A critical review. *Advanced Powder Materials*. doi:10.1016/j.apmate.2021.11.001

Ziaee, M., & Crane, N. B. (2019). Binder jetting: A review of process, materials, and methods. *Additive Manufacturing*, 781-801. doi:10.1016/j.addma.2019.05.031

Öhlins. (2023a). *We are Öhlins*. Retrieved Feb 1, 2023, from https://www.ohlins.com/about/this-is-ohlins/#af-we-are-ohlins

Öhlins. (2023b). *Öhlins RXF34 m.2 29" Air Suspension Fork*. Retrieved May 11, 2023, from https://www.ohlins.com/product/rxf34-m-2/

Öhlins. (2023c). *Öhlins TTX22M (Metric) Rear Shock*. Retrieved May 11, 2023, from https://www.ohlins.com/product/ttx-22-m-custom-series-metric/

Appendix A Work distribution and time plan

A.1 Work distribution

The two team members contributed to this project to equal extent, although some of the specific activities were not divided equally. Table 8 below shows the work distribution in percent for the different activities for each of the team members.

Table 8 Work distribution for the project.

Task	*Task time distribution*	*Joel*	*Hanna*
Report writing	35%	40%	60%
Administration	5%	40%	60%
Information gathering	25%	50%	50%
Concept development	10%	50%	50%
Concept refinement	10%	60%	40%
CAD	10%	60%	40%
Simulations	5%	90%	10%

A.2 Time plan

Table 9 below shows the original time plan, and all the ingoing activities that were planned. Table 10 shows the actual time plan.

Table 9 The table shows the initial project time plan, and the ingoing activities.

Project phase	***Milestone***	***Tollgate***	***Deadline***
Project planning	Project plan ready		2023-01-25
		Project plan presented to Öhlins	2023-01-25
Literature review	Relevant information gathered and documented		2023-03-10
		Enough information to initiate next phase and relevant product chosen	2023-03-17
Product optimization	Documentation summarized and product sent for print		2023-04-28
		Documents approved by Öhlins. Product delivered from manufacturing.	2023-05-19
Physical model evaluation	Test conducted, documented and sent to Öhlins		2023-05-26
		Evaluation approved by Öhlins	2023-06-02
Documentation	Report sent to university supervisor and presentation held at university		2023-06-02
		Report approved by all supervisors and presentation held	2023-06-09

Table 10 The table shows the actual project time plan, and all the ingoing activities.

Project phase	***Milestone***	***Tollgate***	***Deadline***
Project planning	Project plan ready.		2023-01-25
		Project plan presented to Öhlins.	2023-01-25
Literature review	Relevant information gathered and documented.		2023-03-03
		Enough information to initiate next phase and relevant product chosen.	2023-03-10
Concept development	Concepts developed, evaluated, and chosen.		2023-03-31
		Concept approved by Öhlins.	2023-03-31
Product optimization	Documentation summarized.		2023-05-05
	Product sent for print.		2023-05-26
		Documents approved by Öhlins.	2023-05-26
		Product delivered from manufacturing.	2023-06-xx
Documentation	Report sent to university supervisor.		2023-05-12
	Presentation held at university.		2023-06-02
		Report approved by all supervisors and presentation held.	2023-06-xx