

# Additive



# Manufacturing

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## i) Abstract

The recent advances in additive manufacturing have increased the potential for adoption within sectors such as subsea and similar industries. This report investigates whether this is beneficial through research, case studies, guidelines, and trade-off analyses. Results showed a significant potential, yet these are contingent on specifics and willingness to adapt the thinking process. Instead of focusing on cost, it is more beneficial to examine the design, materials, and method. One of the main advantages of additive manufacturing are the exclusive features made possible for the product. As a result of this report, input parameter matrices defining the printability of a product, in addition to the ideal manufacturing method for a product has been made.

## ii) Acknowledgements

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## v) Abbreviations

AM	Additive Manufacturing
AoM	Approval of Manufacturer
BTF	Buy-to-Fly Ratio
CAD	Computer-Aided Design
CAM	Computer-Aided Machining
CNC	Computer Numeric Control
CSAM	Cold Spray Additive Manufacturing
CT	Computerized Tomography
DED	Direct-Energy Deposition
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
FDM	Fusion Deposition Modelling
FEM	Finite Element Method
FFF	Fused Filament Fabrication
HD	Hopkins and Dickens
MMC	Maximum Material Condition
MRR	Material Removal Rate
NDT	Non-Destructive Testing
NNS	Near Net Shape
PAUT	Phased Array Ultrasonic Testing
PBF	Powder Bed Fusion
SLA	Stereolithography
SLS	Selective Laser Sintering
STL	Standard Triangle Language
TA	Type Approval
UAM	Ultrasonic Additive Manufacturing
UC	Ultrasonic Consolidation
VAT	Vat Photopolymerisation
WAAM	Wire Arc Additive Manufacturing

# 1. Introduction

Additive manufacturing (AM) is a novel group of technologies that allows efficient production of components with complex geometry and functionality. Many industries have adopted the technologies and experienced significant benefits, such as enhanced functionality, lower weight, lower cost, and reduced delivery lead time. While AM earlier was most relevant for polymers, metallic parts can also be produced.

The subsea industry has been conservative in adopting AM technology. Safety offshore is a key concern, and proper qualification of manufacturing methods is required. Offshore components are often exposed to a large number of load cycles which may cause fatigue. Corrosion is also a concern due to the challenging environmental condition. DNV GL and ASTM F42 has developed guidelines for qualification of additively manufactured parts.

The purpose of this report is to contribute to more widespread knowledge and use of AM technology for subsea products. It also aims to explain, compare, and discuss AM processes and its use as a production method, and analyse AM for subsea applications. This report and its appendices follow a drive related to AM and subsea. This drive to find the benefits and challenges of AM for subsea applications. Which was derived to, if AM can be beneficial for subsea use, and in what way a subsea part can be most beneficial for AM. The drive was derived to properly answer it.

AM, commonly known as 3D printing, allows fabrication of parts directly from digital models. Parts fabricated using AM are made by adding material in thin layers. Each of the layers are a cross-section of the part derived from the computer-aided design (CAD) file. When printing, the layers have a finite thickness, making it just an approximation of the CAD part. The thinner the layers, the closer the printed parts are to the CAD model. All AM methods are layer based. The methods differ by the materials that can be used, how quickly the part is printed, how the layers are made, and how the layers are fused together. For the different methods, the parts have different properties. These methods determine the size of the AM printer, the cost of the machine and process, and how much post processing is required. AM have the beneficial ability to manufacture more complex parts that could not be achieved by traditional subtractive manufacturing processes. Several metallic materials may be processed into full dense parts with properties comparable to traditional methods by using AM.

AM can be divided into seven different process categories: material extrusion, material jetting, binder jetting (BJ), sheet lamination, vat photopolymerisation (VAT), powder bed fusion (PBF) and direct-energy deposition (DED). The most used methods in the different processes are fused deposition modelling (FDM) within BJ, stereo-lithographic apparatus (SLA) within VAT and DMLS within PBF.

## 2. Additive manufacturing technologies

Following is a description of manufacturing technologies.

### 2.1. Software

The software processes in relation to 3D printing is shown Fig. 1.



*Figure 1: Software flowchart*

The process starts in a CAD program like Solidworks. This is where a 3D model is designed, and all the features and measurements are specified at this stage of the process. Once the 3D model is completed, it will be saved as an appropriate file for the slicer, often a Standard Triangle Language (STL) file. An STL file is a file containing the surface mesh of the 3D model described with triangles [1].

The STL file will then be loaded into a slicer software. In this software, printing parameters such as layer thickness, infill percentage, print speed and support structure, can be selected. The parameter information is then converted into a file that contains the G-codes for the part. The file containing the G-codes can then be loaded into the 3D printer and will be ready to run the print [2].

### 2.2. Traditional machining

Traditional machining refers to machining with a computer numeric control (CNC) machine, either a lathe, a mill, or a combination of the two. This method of production is subtractive, it removes material to give the part shape. This is unlike the additive methods it will be compared it to. A 7-axis CNC machine is shown in Fig. 2.

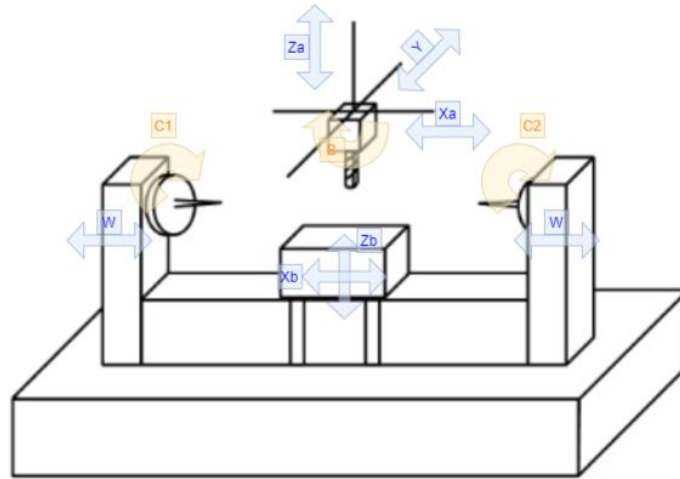


Figure 2: 7-axis CNC machine illustrated by wikicommons

### Cost

To produce with a CNC machine, the actual machine needs to be purchased, a Computer-Aided Machining (CAM) software, a plethora of cutting-tools, chucks, etc. The actual cost will vary greatly between machine types and software needed. An expensive machine could cost more than 400,000 USD, but the average cost is less than 100,000 USD [3].

CAM software providers do not provide a price for their software, they often sell licenses for specific features. Such licenses can cost more than 5,000 USD, where the license can be used on a single computer, so to have several computers running the software at the same time, several licenses are needed. Depending on the company, this cost can easily reach several hundred thousand dollars yearly.

### Maintenance

CNC machines require little maintenance. The operator needs to supply it with oil, refill the coolant, and empty the container for excess material on a regular basis. The coolant tank needs to be cleaned out annually [4].

### Safety

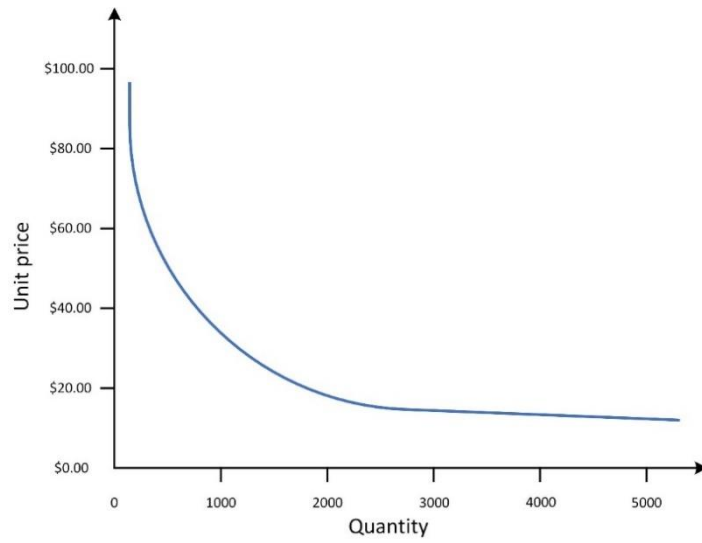
The likelihood of failure depends on several factors: the complexity of the part being machined, the number of units produced, the competence of the operator and programmer, the quality of tools used. Common reasons for failure are, mistakes by the operator or programmer, cutting – tools breaking or a faulty raw part.

The consequences for failure can be severe. It will often result in a broken tool, which needs to be replaced. In a bad case, the machine could be damaged, leading to downtime and service costs. Worst case, personnel could get injured or killed [5].

### Production efficiency

CNC machining is a highly efficient method of mass production. The first unit in a series will always take the longest time to produce, but once it is produced and meets the given requirements,

the rest of the series can be produced in rapid succession. The decrease in unit price is nearly exponential, as seen in Fig. 3 and Tab. 1.



*Figure 3: Unit price vs. quantity graph*

Table 1: Example quote with bulk pricing

Quantity	Unit price	Total price
1	\$311	\$311
2	\$184	\$368
5	\$103	\$515
10	\$75	\$750
25	\$56	\$1,400
50	\$46	\$2,300

Prototyping on the other hand is relatively time consuming. The preparation needed to produce one unit will be same as one hundred units [6].

### **Precision**

A CNC machine's smallest incremental movement is 0.001 mm, theoretically this is the accuracy. In practice, there are a few other factors in place, so reliably machining tolerances of 0.01 mm is more realistic [7].

### **Versatility**

CNC machining is fully capable of machining any material, from wood and plastics to the toughest steel and titanium alloys [8].

## 2.3. Electron beam melting

Following is a description of the various aspects of Electron Beam Melting (EBM), the electron beam variant of the subcategory of AM known as PBF. EBM printers are primarily used within medical industry to produce bones, and for aerospace industry for its ability to produce parts with a complicated geometry. An EBM is shown in Fig. 4 [9].

EBM differ from other PBF technologies in that it uses an electron beam instead of an optic laser to fuse or sinter materials. This leads to limitation in the materials it can print, i.e. the materials must be conductive. Another difference is that the printing chamber is not filled with an inert gas but is instead in a state of vacuum [10] [11].

The process follows a path of first heating the printing chamber to the required temperature, about 40% of the materials melting temperature. Secondly, the printer applies a layer of powder on the construction plate. The electron beam, which is controlled by electromagnetic coils, is pointed towards the cross section that is to make up the current layer of the part. This part of the process is sometimes referred to as, scanning the cross section. When the electrons emitted by the EBM device hits the powder, the kinetic force from the electrons turns into thermal energy which melts the powder together. After one layer of the cross section is completed and the build platform has

moves on layer down, the process of applying a new layer of powder and melting one layer of the cross section is repeated until the product is completed [5] [9] [11].

EBM often produces near net shape due to porosity, and thus require after treatment in the form of CNC machining, shot peening or sandblasting. This process can be reduced by applying a finer layer of powder, which results in a finer layer. This is however more costly, and there is a clear trade-off between material cost and surface post-processing requirement. Because the product needs post-processing, using a thicker layer of powder is more economical [11].

To scale a powder bed printer, the mechanism that ensures fine and even layers need to be scaled as well. However, there are inherent limitations to this, because over a certain point, the mechanisms cannot be ensured to maintain required tolerances. Material contamination is also a problem to consider when using powder bed printers. Oxygen and/or water can compromise the microstructure, properties, and performance of the finished product [10].

By comparing one product produced with different melt scan rates and beam currents, it was concluded that a lower current resulted in faster cooling. This was also the case for lenticular alpha phase size, which was also reduced when using a lower current, which was also true for the width. The material that was used for this comparison was a titanium alloy Ti-6Al-4V [10].

Due to the innate porosity of the printed materials, this is widely used in medical skeletal implants, due to this property being sought after. It is expected that AM PBF produced implants will exceed a revenue of 65 billion USD in 2025 [12].

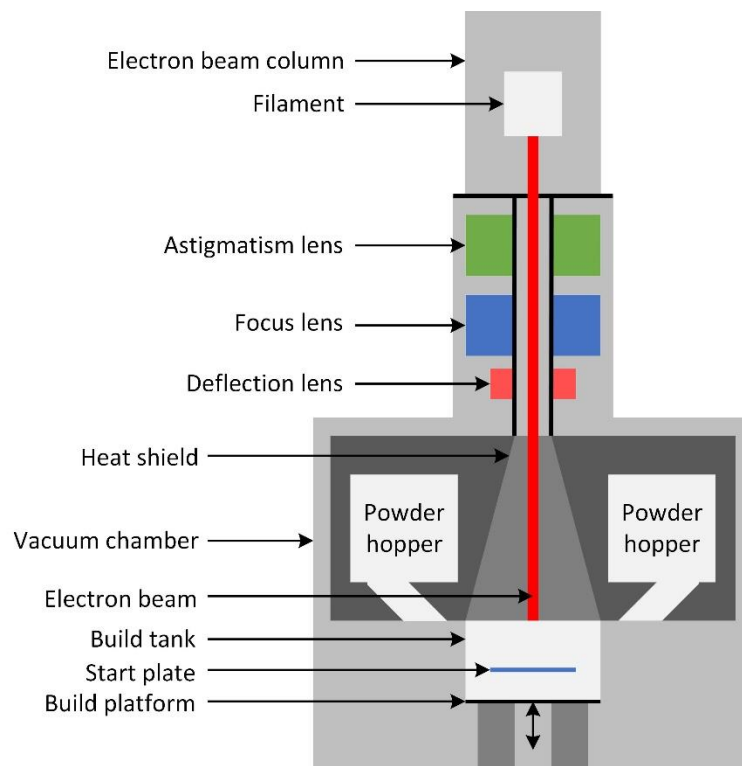


Figure 4: Electron beam process illustration

### Advantages

Advantages of using this method includes that one layer of a cross section is usually 100  $\mu\text{m}$  in thickness, and the finished product have a material density of more than 99%. The mechanical

properties (i.e. yield strength, strain, and micro-stiffness) of finished EBM products are comparable to casting. The electron beam can be directed such that it can melt powder on separate locations, which enables it to produce several parts at once. The electron beam can scan the entire surface of the layers cross section. The process requires less support structures due to lower operating heat compared to other PBF methods. This makes it a faster PBF method, and the unused powder in production can be reused [9] [11].

### **Disadvantages**

EBM is highly limited in the materials available to use in production, due to the conductive property requirements. The printers along with the materials used in production are expensive. The finished products are not as smooth as other PBF methods, and needs a substantial amount of finishing work. EBM printers are quite limited in size, which leads to less options in finished products. Printers come in sizes of 350x350x380 mm where as DMLS are up to 800x400x500 mm. When powder is applied to a finished layer of the product, it results in reheating of the previous layer. This means that the upper layers of the product have undergone fewer heating and reheating processes, which leads to a harder product at the top levels. EBM often produces near net shape due to porosity, and thus require after treatment in the form of CNC machining, shot peening or sandblasting [11].

### **Cost**

The printer cost approximately 250,000 USD or more, making it one of the cheaper printers. The material cost is approximately 150 to 300 USD per kg of powder, making EBM one of the most expensive in terms of material cost.

## **2.4. Ultrasonic additive manufacturing**

Ultrasonic 3D printing is a form of AM that uses ultrasonic welding to manufacture parts. It is usually done in cooperation with a CNC machine since it lays down strips of metal which needs to be machined into the desired part. The machine usually lays down 2-4 layers of material which is then machined into the desired geometry. This is a hybrid manufacturing process. This means that it has the ability to create parts with complex geometries using the AM process, and the ability to manufacture parts with high tolerances using the subtracting manufacturing process. UAM has a lot of different names because many companies have different patents for almost the same processes. However, the most used name is ultrasonic consolidation (UC) and ultrasound additive manufacturing (UAM). Fig. 5 shows the process [13].

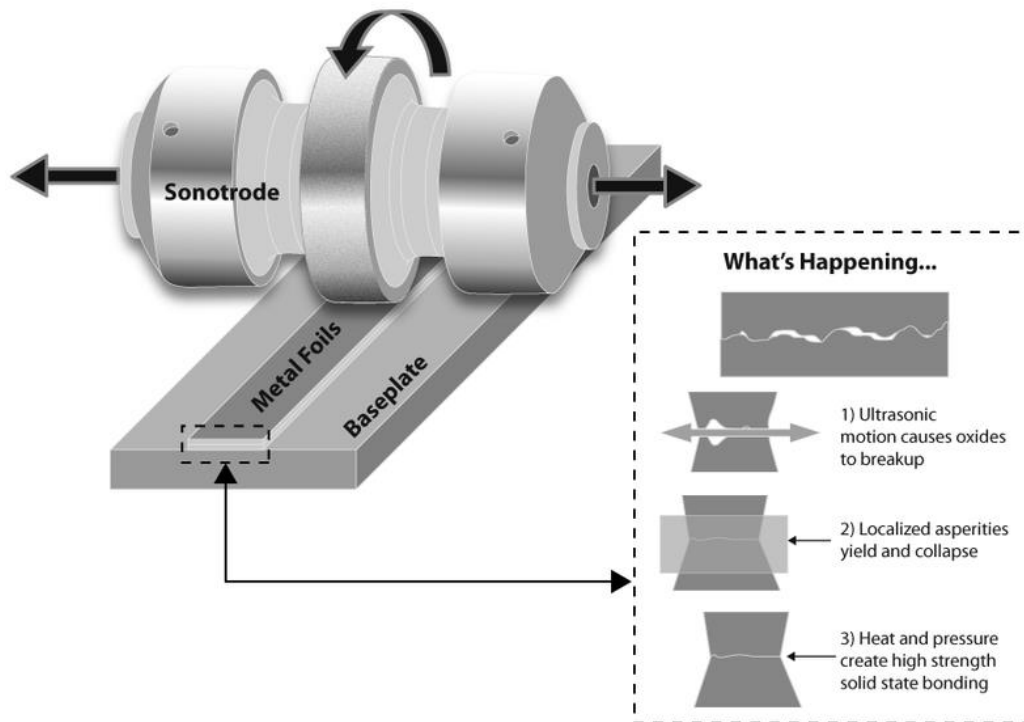


Figure 5: UAM process according to wikicommons

## Cost

The cost of manufacturing a part with UAM is highly dependent on the size and material of the part. The feed material is sheets of different types of metal. This means that the price of the feed material is not too high since producing metal sheets is a common manufacturing process. One thing that may add to the material cost is that the metal sheets must be cut into specific widths and placed on spools by a third-party supplier. Cost information for a large aircraft maintenance shelter (LAMS) baseplate is shown in Tab. 2 [14] [15].

Table 2: Cost of a LAMS UAM part

Line item	Cost
Transport to Holloman Air Force base, New Mexico	1,716.22 USD
Transport to America Makes training Youngstown, Ohio	2,886.98 USD
Material and machine time at OSU	7,000.00 USD
Design time	172.00 USD
Total per unit cost	11,775.20 USD

## Advantages

The main advantages of UAM are smooth surface finish straight from the build plate, because the UAM machine includes an integrated CNC machine. There is no need for a controlled atmosphere since it does not involve melting of the feed material, the highest temperature is 120°C. The material properties of the feed material are intact. This is because the materials are just slightly

heated, meaning that the material does not experience any change in grain size, or have any phase changes occur. It can bind different metals together without creating any brittle alloys. This is because UAM creates a solid-state bond by using pressure and low heat produced by the ultrasonic motion. It is possible to integrate electronics into the part because the temperature is below 120°C and will not damage the electronics. This means that you can print a part with e.g. a temperature sensor, strain gauge or a microprocessor incorporated into the part [14] [15] [16].

### **Disadvantages**

Some of the disadvantages of UAM includes, that it has a higher material waste than other AM processes, this is because the CNC-machining is removing a lot of the material strips that protrude out from the sides. The metal band is also wide, so it must be machined away on narrower parts. It also has an “transient region” where the metal strip that the machine is laying down first touches the metal, this means that the weld in the start will be slightly more variable unlike the rest of the veld where it will be uniform. It has a high manufacturing cost, but this is becoming lower by the year. Some of high price comes from the fact that it requires a technician or two to operate it [13] [14].

## 2.5. Wire arc additive manufacturing

WAAM is a variant of a DED process. WAAM is one of the oldest and simplest variants of AM, first patented in 1920. Currently, WAAM hardware consists of standard, off the shelf, welding equipment with a wire as feedstock. Fig. 6 shows the process. The motion of the printer can be provided by a computer-controlled robot arm on a gantry. The welding process of choice is MIG. It results in easier tool paths and are perfect for materials such as aluminium and steel. When it comes to titanium, the process is afflicted by arc wandering, therefore TIG or PAW are currently used for titanium welding. By using robotic arms, it is possible to print parts up to 12 meters and do the required machine finishing. The arms also monitor the part during the print to assure no defects. A fully finished part can be achieved in one run using this setup [17] [18].

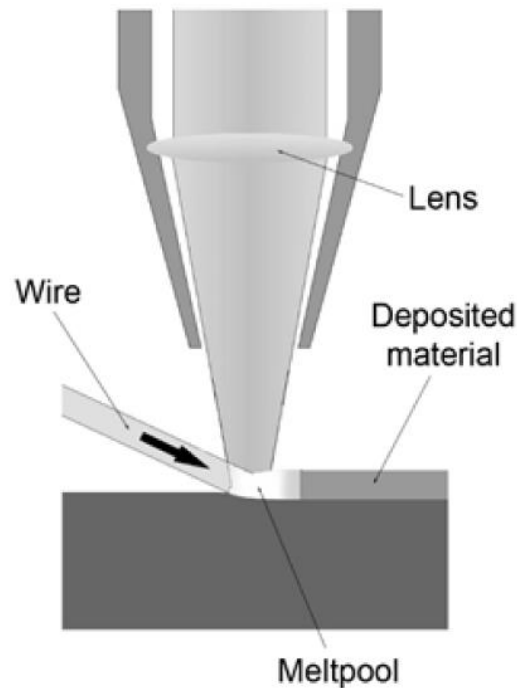


Figure 6: Wire arc according to wikicommons

### Advantages

The positives of using WAAM is that it is cost effective, fast, can print in multiple materials print larger parts than most other AM methods and the material efficiency increases as the part size increases.

### Disadvantages

The negatives are that the method is not fully automated and needs an operator for a successful build, the part must be machine finished and it can only print medium complex parts.

### Cost

The cost of a WAAM printer may vary but starts at about 250,000 USD and upwards. The printer material differs in cost depending on what kind of material shall be used. The price of stainless steel varies with the quantity bought but can cost approximately 20 to 340 USD per spool.

To automate the WAAM process, it is possible to use robotic arms. Cranfield University has built a WAAM printer using robotic arms from Global Robots. The price range of these arms are approximately 10,000 to 18,000 USD [18] [19].

## 2.6. Direct metal laser sintering

Direct metal laser sintering (DMLS) is a variant of the PBF process, where a thin layer of metallic powder is selectively heated to melting temperature by a high-powered laser to fuse it together to a solid part. The surface finish is comparable to that of a casting part. A DMLS is shown in Fig. 7.

The part being printed is exposed to residual stress, the reason being the heat cycling as the laser scans across each layer where previously solidified layer is re-melted and cooled several times at inconsistent levels of heat. The state of stress while heating is tensile and during cooling the stress is compressive [20].

The most common way to reduce residual stress is to post process the parts after printing. Using post-processing increases the production time and may increase the cost. The normal forms of post-processing are heat treatment and hot isostatic pressing, shot-peening have also been successfully used. DMLS printers can print using Stainless Steel 316L or 17-4, Aluminium, Cobalt Chrome, Nickel Alloy 625, and Titanium [21].

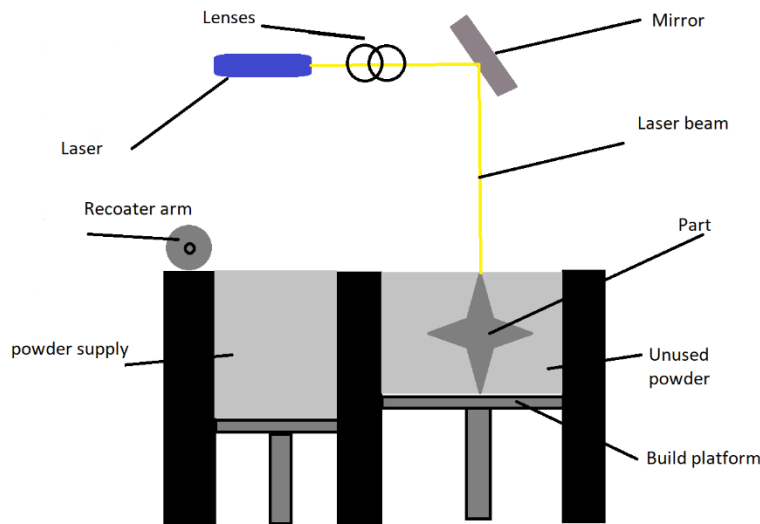


Figure 7: DMLS process illustration

### Advantages

The positives of using DMLS is that it can print in complex geometries, use metals applicable for subsea, the quality can be comparable to a casted part, and the powder can be recycled in another print.

### Disadvantages

The negatives are that the process is somewhat slow, the part can be affected by residual stress, and the print size is limited [20].

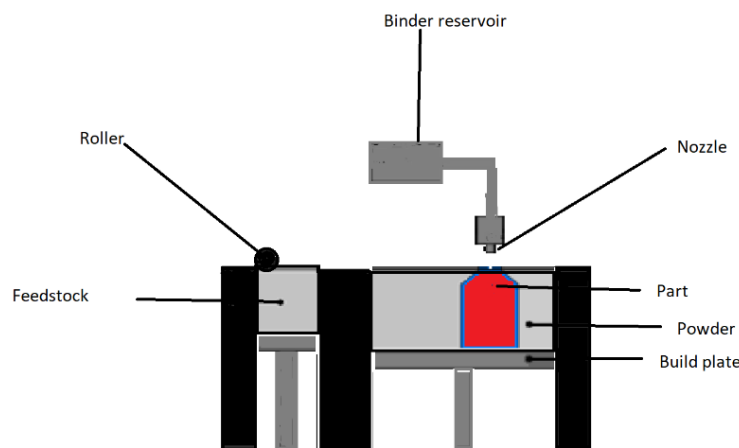
### Cost

The cost of a DMLS printer may vary, but a new complete system from Digital Metal cost approximately 700,000 to 900,000 EUR, see Appendix C3. The cost of the powder varies with the different metals. Stainless steel powder costs approximately 99 to 135 USD/kg, and nickel alloy powder costs approximately 117 to 195 USD/kg, both costs are dependent on quantity [22] [23] [24].

## 2.7. Multi Jet Fusion / Binder Jetting printing

Multi Jet fusion 3D printing is HP's new binder jetting AM method. It is under development now and is currently limited to just polymers, but there are a lot of metals and other materials in development. Therefore, this document will also go through binder jetting as a general process. The way it works is that a layer of powder will be sprayed with a binding agent, this will make the powder stick together forming the part. Fig. 8 shows this process. This is the same process for Multi jet fusion only it will heat the powder up to near sinter temperature and use a detailing agent to make the edges of the part not sinter, only the powder coated with the binder. Then it will repeat the process for each layer until the part is built up and is resting submerged in the powder. Then in BJ the powder and the binder will be left to harden before it is removed and sintered. In MJF the powder is heated to near sintering temperature and the binder will make the powder sinter since it is better at absorbing heat than the powder. After the MJF part is sintered it will be finished and the powder recycled [25] [26].

Currently HP's Jet Fusion 300 and 500 3D printers can print nylon PA12, PA11 and TPU (Thermoplastic polyurethane). Nylon is a great material, but compared to other technologies it currently lacks the material diversity other technologies have [25].



*Figure 8: Illustration of binder jetting*

### **Advantages**

Binder jetting can however print in many different materials, many metals, polymers, ceramics and even sand. The sand printing is used to produce dies for forging metal, this process is called indirect additive manufacturing. BJ is considered one of the cheapest AM processes. Both MJF and BJ does not need support structures to be made since it will be suspended in the powder while it is getting built. This will make the surface of the part smoother since it will not be fused to any support material, this is one of the reasons why MJF gives one of the best surface finishes of the AM processes. The price of the printers is \$50,000 to \$70,000 USD for a MJF printer and starting at \$30,000 USD for a BJ printer. The material cost for MJF is cheap since it is using polymers, for BJ

the feedstock is also powder, but this powder can also be metal, so the material price is the same as for other powder bed additive manufacturing methods [25] [26] [27].

### Disadvantages

Currently HP's Jet Fusion 300 and 500 3D printers can print nylon PA12, PA11 and TPU (Thermoplastic polyurethane). Nylon is a great material but compared to other technologies it currently lacks the material diversity other technologies have [25].

### Cost

The price of the printers is 50,000 to 70,000 USD for a MJF printer and starting at 30,000 USD for a BJ printer. The material cost for MJF is cheap since it is using polymers, for BJ the feedstock is also powder, but this powder can also be metal, so the material price is the same as for other powder bed additive manufacturing methods.

## 2.8. Cold spray

Cold spray additive manufacturing (CSAM) is a unique type of AM, recently added to AM's tools. This method uses compressed gas to accelerate powder to a high velocity, this gas being either helium or nitrogen. The powder impacts onto a base of metal called a substrate. This is shown in Fig. 9. The CSAM method relies on particle kinetic energy, unlike most AM methods that relies on thermal energy to bond the feedstock. The bonding is achieved through localized plastic deformation and the mechanical interlocking it causes. While the use of cold spray in AM is a relatively new development, the technology has existed since 1980 as a coating method [28].

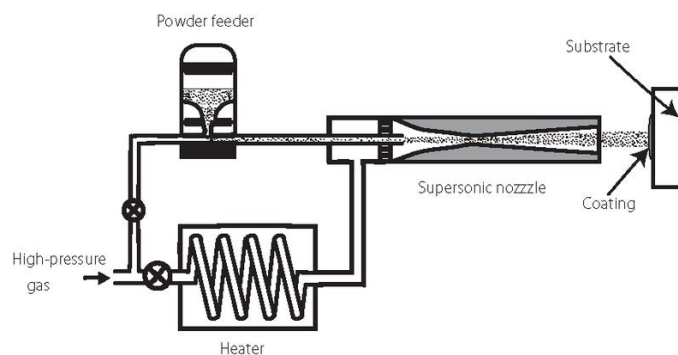


Figure 9: Cold spray according to wikicommons

### Advantages

There are several advantages of this method. The process is a cold process, so the metal avoids defects often seen in laser-based methods. Such as oxidation, residual thermal stress and phase transformation. CSAM does not limit the size of parts being produced. It is a relatively fast method. It is also suitable for repair of existing parts, in contrast to having a new part produced [28].

### Disadvantages

Unfortunately, there are also disadvantages. The dimensional accuracy is low, and the parts will require considerable finishing work like annealing, and machining. The mechanical properties will be weak, as the method produce many structural defects [28].

CSAM is a method well suited for producing NNS workpieces and repairing existing parts, especially with metals like aluminium and copper with high light reflectivity which cause problems for laser-based AM methods [28] [29].

The cost of using CSAM is driven by a few factors. The most notable being powder cost, gas cost, labour cost and electrical cost. The relation between these variables varies based on which gas is used. While He is the more expensive gas, N<sub>2</sub> has a lower deposition efficiency, meaning it expends more powder. With the wasted powder as an added expense, N<sub>2</sub> is the more expensive alternative. Although with a powder recycle rate of 90% or more, N<sub>2</sub> pulls ahead of He in terms of cost [29] [30].

## 2.9. Additive manufacturing materials

Common AM materials frequently consists of powder or wire. In UAM, sheets of metal can be used due to the unique fusing method. For metal powder production the raw material is heat treated, using either torches or water to atomize and form round particles of the material. Not all materials are available in wire or powder form yet, due to the complexity of the reforming process. In addition, not all powders are fit to print using each method, while wire is for DED processes only [17] [21] [31].

Due to the substantial amount of today’s suppliers keeping a selective number of materials available for their production methods, a parts design, method, and material choices come hand in hand. In addition, the Pugh matrix in Appendix D1 shows the methods have differing levels of resolution. The design is dependent on the material, the material is dependent on the method, yet the design should be adapted to the method, shown in Fig. 10.

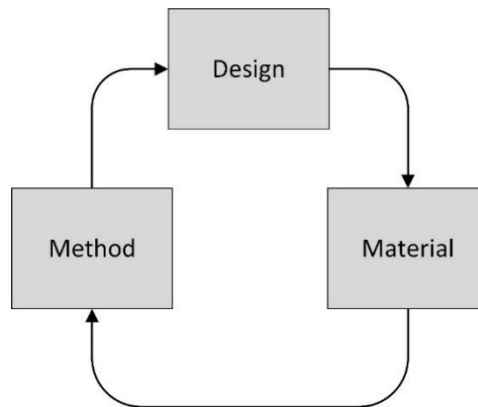


Figure 10: Design choice circle

In the case of post-design choice, most suppliers offer guidance to ensure the part can be printed. In addition, this report includes design guidelines with a matrix to find whether the parts design is viable for printing, in Appendix L1.

An example material for subsea applications is Super Duplex, a relatively sturdy and corrosion resistant material. A provider of this material in both DED, PBF and traditional manufacturing is Sandvik additive. To showcase the relative differences in the material, Tab. 3 and Tab. 4 shows the properties of both varieties of the material, Osprey 2507 (additive) and SAF 2507 (non-additive). In this specific example, in which the supplier has both varieties, the differences in the material are relatively minor [32] [33].

Table 3: Chemical composition of Osprey 2507 (additive) and SAF 2507 (non-additive)

	Fe	Cr	Ni	Mo	Mn	Si	N	Cu	C	P	S
Additive	Bal	25	7	4	1.2	0.8	0.3	0.5	0.03	0.035	0.015
Non-additive	Bal	25	7	4	1.2	0.8	0.3	N/A	0.03	0.025	0.015

Table 4: Mechanical properties of Osprey 2507 (additive) and SAF 2507 (non-additive)

	Additive	Non-additive
Tensile strength	797-956 MPa	800-1,000 MPa
Proof strength (0.2)	≥ 504 MPa	≥ 550 MPa
Elongation (% mm)	≥ 30%	≥ 25%
Hardness (HRC)	29±1	32
Critical Pitting Temp	> 90 °C	72.5 °C

For wires, most data sheets detailing the mechanical properties for welding wires are before production, not demonstrating the material after printing. This means the supplier will need to share their data sheets or extensive testing will have to be done to find the properties and ensure quality, verified in Appendix C2. In contrary, the properties of additive Super Duplex after printing were available, verified in Appendix C4 [34].

For a comprehensive list of suppliers see Appendix G1, the purpose of this list is to give the reader an overview of the suppliers that can be contacted to produce parts additively and some of them will also give a price estimate for the parts.

## 2.10. Additive manufacturing qualification and verification

### Qualification

Due to the rigorous qualification regime for subsea parts, it might be difficult to qualify a part which has been produced additively. The reason for this is that material testing must be done after the part has been produced, this means that an operator will have to use for example ultrasound on a part that has complex geometry. This will be difficult to do compared to material testing for CNC parts, here the test is performed on the material block before it is going to be machined, this will show any defects in the material of the workpiece while it is in a block shape. Furthermore, almost all AM processes involve melting or heating of the material, if the material is a metal this means that it will have to be tested after its final heat treatment. This is because the material can change its material properties when it is exposed to heat over a certain threshold [35].

For most AM processes there will be guidelines provided for that material and that process. In those guidelines there will usually be specified a maximum acceptable flaw size in the part. If these flaws are to be found it is essential that one is able to identify the best nondestructive test (NDT) method for that part since this will decide how small the smallest detectable flaw in the part is. This means that one must choose the NDT method based on the correlations between material, process, part orientation, maximum allowable defect size and the morphology of the part. This means that one cannot test the density of the whole part and verify that it has an acceptable density since the porosity may not be uniformly distributed in the part. One way to test for internal flaws of the AM part is to use phased array ultrasonic testing (PAUT) or computerized tomography (CT) scan. The CT scan can also be used to check the manufactured dimensions of the part compared to the designed dimensions. After the scan/test is done, the designer will have to look at the correlations between the material, process, part orientation, maximum allowable defect size and the

morphology of the part. This is because the defects may be smaller than the maximum allowable size for the part, but the correlations between the material, process, part orientation, flaw position and the morphology of the part may make additional testing required in order to qualify the part [35].

For most AM processes there will be guidelines provided for that material and that process. In those guidelines there will usually be specified a maximum acceptable flaw size in the part. If these flaws are to be found it is essential that one is able to identify the best nondestructive test (NDT) method for that part since this will decide how small the smallest detectable flaw in the part is. This means that one must choose the NDT method based on the correlations between material, process, part orientation, maximum allowable defect size and the morphology of the part. This means that one cannot test the density of the whole part and verify that it has an acceptable density since the porosity may not be uniformly distributed in the part. One way to test for internal flaws of the AM part is to use phased array ultrasonic testing (PAUT) or computerized tomography (CT) scan. The CT scan can also be used to check the manufactured dimensions of the part compared to the designed dimensions. After the scan/test is done, the designer will have to look at the correlations between the material, process, part orientation, maximum allowable defect size and the morphology of the part. This is because the defects may be smaller than the maximum allowable size for the part, but the correlations between the material, process, part orientation, flaw position and the morphology of the part may make additional testing required in order to qualify the part [35]. In short what makes Additive manufactured parts difficult to qualify is the process complexity, where many variables are in play and changing one variable can affect others. The relationships between these variables and how they affect each other are something that needs more research. This is one of the biggest barriers for implementing additive manufacturing for production parts. This is further complicated by the fact that if two identical parts are produced in the same machine, with the same material at the same time the parts are usually not identical they will have a non-uniform distribution of flaws in the parts, difference in surface finish and the density of certain sections of the part may not be identical [35].

There is also a distinct difference between an additive manufacturing process and an additive manufacturing machine. An additive manufacturing machine will produce the part, but this is only one step in the additive manufacturing process. In order to build confidence in the additively produced part it is needed to map out the whole additive manufacturing process. These processes and factors can include feedstock material and manufacturing process, hot isostatic pressing, heat treatment, machining, nondestructive testing/inspection and end-application. A template outlaying this is shown in Fig. 11, if the part owner or producer can make such a document for each additively produced part this would minimize the variability in the production and rise the confidence in the properties for that part. It is also worth noting that there is a lack of data on additively produced parts being used for subsea applications.

All of this makes the qualification of AM parts difficult, most organizations which has implemented AM have developed their own methods for qualification. In the last couple of years, the ASTM F42 committee for additive manufacturing have started to make standards for qualification of AM parts. In the coming years we will see a lot of research and development specific

for AM and qualification of parts, but at this moment we are at the point where each AM part will have to be tested and verified on an individual scale. This makes it extremely costly to get the parts qualified for subsea [35].

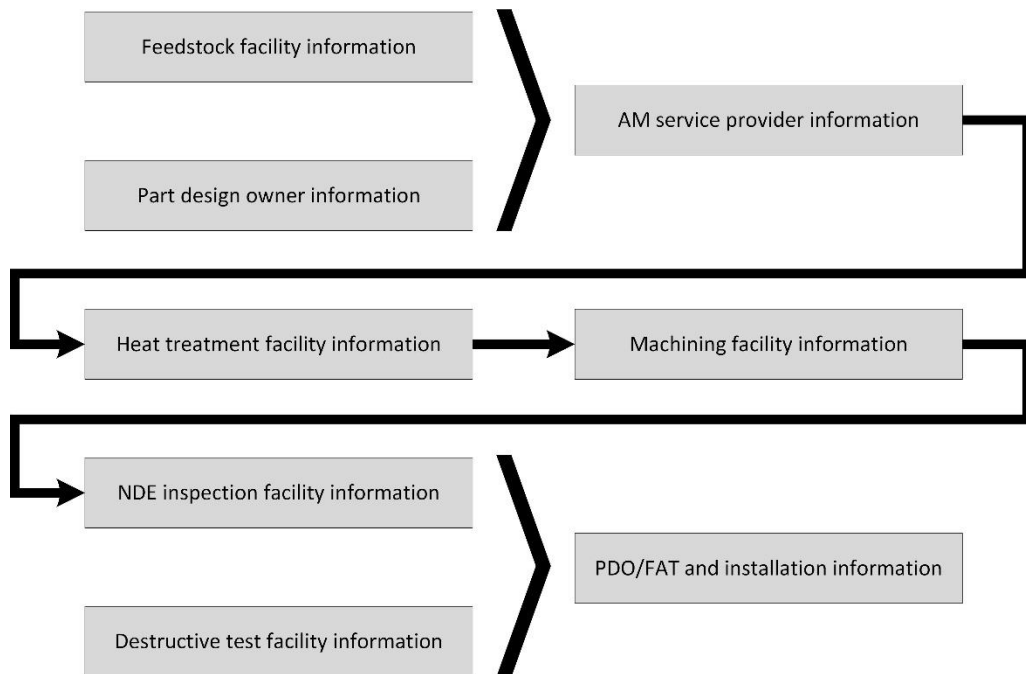


Figure 11: Factory acceptance test

### DNV GL guidelines

In order to keep manufactured products safe and reliable, a standard has been developed by DNV GL in cooperation with TechnipFMC for components and methods used in the subsea industry. A specific guideline has been made for AM components, with its own set of requirements, procedures, and qualifications.

### DNV GL AM guidelines – Step-by-step

The certification needs to go through a process for materials and components for AM [36]:

1. Order a vessel with DNV GL class
2. Order material/product with DNV GL certificate
  - a. Manufacturer should be approved in accordance with DNV GL-CP-0346\*.
3. Request for DNV GL Approval of Manufacturer (AoM) or Type Approval Scheme (TA).
4. Deliver DNV GL AoM/TA.
5. Request for certification of material.
6. Certify material/product.
  - a. Testing should be approved in accordance with DNV GL-CP-0337\*.
  - b. Certification of product should be approved in accordance with DNV GL-CP-0338\*.
7. Deliver material/product with DNV GL or own certificate.

\*The different approval schemes are documented guidelines meant to lay groundworks and ensure thorough and equal review.

DNV GL also has a certification pathway for AM products, with three phases. The procedure qualification phase, the approval phase, and the certification phase, as shown in Fig. 12, with the voluntary procedures shown as well.

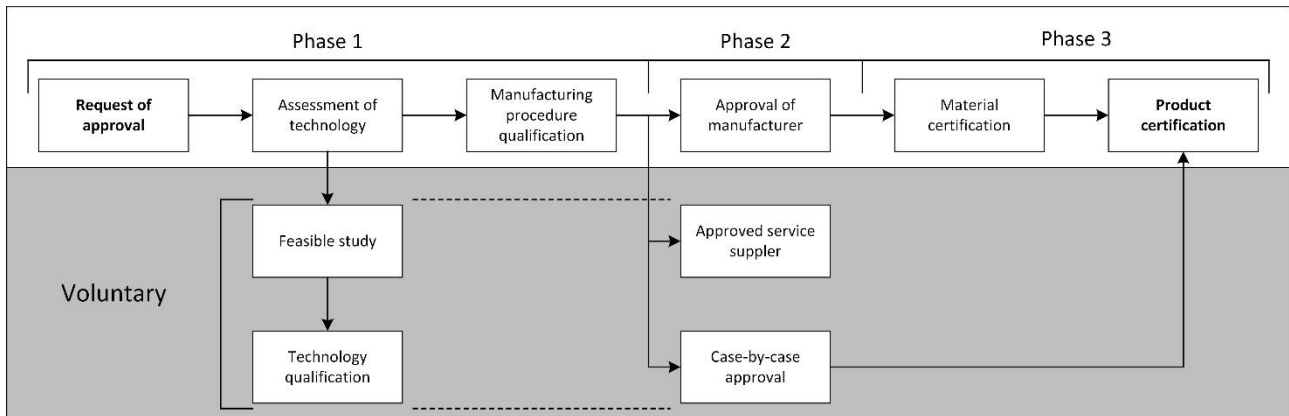


Figure 12: The certification pathway in phases

Following these guidelines makes for a thorough procedure that can be followed for all future AM cases. These guidelines are made specifically for subsea, which demand utter precision and has many contingencies. The gain of using this ensures a part fit for the subsea industry will be made with the required quality assurance.

### Qualification regime

The three main aspects of the qualification regime are the technical requirements, repeatability, and traceability.

### Manufacturing procedure qualification

In order to thoroughly qualify the manufacturing procedure, there are certain steps made between the parties involved:

1. Meetings are set to clarify and make agreements between parties.
2. A scope of all work is determined with the client.
3. Parameters are set defining the products specifications.
4. Qualifying documents involving activities required to meet requirements are prepared.
5. The site is visited, and qualification is witnessed by DNV GL.
6. A final report with all documentation is made by manufacturer.
7. DNV GL evaluates according to their procedures.
8. DNV GL issues a statement of qualification.

## Approval regime

DNV GL states that all parties involved are to follow the rules, and the standards are meant to ensure quality and safety. Tab. 5 shows the areas that need DNV GL approval.

*Table 5: Typical areas for seeking DNV GL approval*

Involvement in AM product life cycle	Process related	Materials/component related	Organisation related
<b>Design</b>	— Design assessment	— Case by case approval — Design approval	— Approval as sub-supplier
<b>Feed-stock</b>	— Manufacturing process approval — Accreditation of equipment — Approval of consumables	— Raw materials inspection/certification — Approval of material safety data sheets — Case by case approval	— Approval as manufacturers — Approval as sub-supplier
<b>Pre-processing</b>	— Verification of design file and cyber security — Verification of build layout with orientation, support structures & test specimens — Integrity of software/firmware	— Review of 3D model for manufacturing	— Cyber security compliance review
<b>3D printing/manufacturing</b>	— Approval of process parameters — Accreditation of AM equipment — Approval of operating procedures	— Approval of manufacturing procedure qualification	— Certification for operators — Approval as manufacturers — Approval as sub-supplier
<b>Post-processing</b>	— Approval of operating procedures.	— Procedure for extraction of test specimens	— Certification for operators — Approval as manufacturers — Approval as sub-supplier
<b>Testing and inspection</b>	— Approval of testing and inspection procedures — Accreditation of testing equipment	— Witness / survey reports	— Approval as sub-supplier
<b>Certification</b>	— Regular, periodical and unscheduled audits	— Inspection reports — Issuance of certificates	— Approval as manufacturers — Approval as service supplier

## DNV GL feedstock testing

Representatives from DNV GL test the material of different products. Test blocks are utilized for most of the tests. These tests are listed as follows: *Visual examination* of the product by a representative of DNV GL, having and sharing the *chemical composition* of the product, knowing and sharing the *density* of both powder and product, *tensile testing* the product with test blocks, *Impact testing* in differing temperatures, *bend testing* the product, *metallographic examination* of the product, corrosion testing, non-destructive testing (NDT) of heat treated product, *hydrogen testing* to find subsea capabilities, *powder recycling tests* to find the amount of salvageable material, *hardness testing* and *surface roughness testing* of product. In addition, powder processes have further mandatory tests, like particle size distribution, particle morphology, flow rate, and angle of repose [37].

## 2.11. AMFG survey

A company named AMFG made a survey in 2019, asking companies around the globe specialising in AM what industries they supply, and which of these industries provides the biggest revenue. As well as what challenges they are facing and how they foresee the AM industry in the future. The most common method of AM among these companies is fused filament fabrication (FFF), with 70% of the companies offering this method of manufacturing. The second and third being SLA and SLS, both being offered by more than 60% of the companies in question. The more relevant AM methods producing parts in metal are all grouped together, this group includes SLM, DMLS, DED and more. Of the companies in this survey, 39% offer metal printing.

65% of the companies offer other services in addition to AM. The most common of these being CNC machining, but other services include vacuum casting, heat treatment, sand casting, laser cutting, dimensional control, metallurgical analysis, 3D modelling, 3D scanning and sheet metal fabrication.

The AM method contributing most to the revenue of the companies is most commonly FFF, with 40% reporting this as the biggest contributor. Metal printing places second, with 23% reporting this as the biggest contributor. Rapid prototyping remains the most profitable process for most of the responders. While small series is a close second. However, small series is expected to become more profitable over the next 24 months.

The oil and gas industry are a less common industry to serve among the responding companies, with around 35% of respondents are within this type of industry. The most common industries are consumer goods and automotive, both of which are served by more than 75% of the companies.

The most common challenge cited by the responding companies is “Lack of 3D printing knowledge”. What is meant by that is parts are not being designed with 3D printing in mind. Parts are still designed towards CNC machining, which is a manufacturing process with different strengths and limitations. As with any new technology, rigid mindsets are considerable challenges to overcome. Especially among designers who have been designing parts with CNC machines in mind for many years. Many companies now aim to guide their clients in how to improve their designs with

AM in mind. And how they can get the most out of the company's services. Another challenge these companies face is deciding the right technology to invest in. With the 3D printing technology developing as quickly as it is, it is difficult to foresee what machine will be profitable. Certification for 3D parts is also a considerable challenge. With many industries having strictly regulated standards for material quality. Many of which vary between industries. This is certainly true for oil and gas as well as aerospace and defence. When asked about their outlook for the next 12 months, these companies are generally positive. Many expect growth and aim to increase their revenue. Some will focus on education, other on developing materials [38].

### 3. Case studies and guidelines

Case studies is a good way for comparing practice and theory. There is a clear necessity for this comparison due to the importance of verifying the various AM processes usage for subsea applications, to confirm their suitability. Without making practical comparisons of various parts that have been produced using traditional methods, like milling, casting or boring, and AM processes, like FDM, PBF or UAM, there will only be statements and theory that differentiate the methods. Even if the AM produced parts prove to be subpar after comparing, they might still prove to be a good enough compromise when comparing lead time, cost, and other factors. The case studies will allow a more objective and practical proof for deciding whether using AM for subsea applications are suitable, with or without acceptable trade-off.

#### 3.1. Planning our approach

Before starting on specific cases, a plan was made for how any given case would be approached. This plan is divided into two phases. The first phase being a reverse engineering phase, where the part and the drawings to gets studied for a thorough understanding of its features and requirements. The second phase being an evaluation of how suitable AM is for producing the part.

## Phase 1: Reverse engineering

Tab. 6 shows the actions taken during the reverse engineering phase.

*Table 6: Reverse engineering*

Course of action	Comment
<p>Inspect the technical drawing. Be familiar with the following:</p> <ul style="list-style-type: none"> <li>• Specific tolerances</li> <li>• Geometrical tolerances</li> <li>• General tolerances</li> <li>• Surface requirements</li> <li>• Material</li> </ul>	<p>The technical drawing will give a clear indication of what properties are important. It will also define the material the part is made from.</p>
<p>Inspect how the part interfaces with other parts. Take note of the part's mechanical functions in an assembly.</p> <ul style="list-style-type: none"> <li>• Its rotating</li> <li>• Its clamping</li> <li>• Its impenetrable</li> </ul>	<p>The functions within an assembly shall be assessed to supplement the understanding derived from the technical drawing.</p>
<p>Assess what forces the parts is subjected to. Run a finite element method (FEM) analysis to identify the parts weak points and evaluate the choice of material.</p>	<p>This should give sufficient understanding of the part's requirements. It will also give useful information like safety factors.</p>
<p>Evaluate the difficulty of producing the part with traditional machining.</p> <ul style="list-style-type: none"> <li>• Necessary tools</li> <li>• Clamp changes</li> <li>• Complex features</li> </ul>	<p>Traditional machining is what AM competes against, so this will give understanding of the competition. This will give insight as to where AM will have the greatest advantage.</p>
<p>Assess the cost of the part. Including lead times.</p>	<p>The price and delivery time of a part is also important from a business point of view.</p>

## Phase 2: Evaluating AM methods

Tab. 7 shows the actions taken during the evaluation of AM methods phase.

*Table 7: Evaluating AM methods*

Course of action	Comment
Asses the different AM methods and decide which is most fitting for the given part.	If it is not obvious which method is the best fit from phase 1, asses the relevant methods and compare.
Asses the benefits of producing the part with AM	How will this improve the part. Where is the potential. Weight?
Asses the challenges of producing the part with AM	Most AM methods will have problems that will need to be solved.
Asses the need for finishing work	This ties into the previous point. A part will often need finishing work as a solution to a problem.
Asses the material choice.	Some materials are better for AM than other. If possible, choose a material suited for AM.
Asses the availability of the raw material used in the AM processes.	This point is connected to the previous point.
Asses the cost of producing the part with AM. Compare the cost to the traditionally produced part.	With this comparison it will be possible to evaluate the viability of producing the part using AM.
Evaluate the possibility of redesigning the part. Then compare the cost and lead time of the new design to the original.	With AM a new way of designing could be beneficial.

In all the case studies the original part is analysed, then the possibility of manufacturing using AM is assessed, prices are compared, and changes are suggested to increase cost-efficiency. This is done following the case study plan from Tab. 6 and Tab. 7.

### 3.2. Bracket

A case study has been made of a sensor bracket. This bracket is designed to mount strain sensors onto a structure. It would be possible to produce this bracket in a plastic material, assuming the Kevlar band fastening the bracket to the structure is not tightened with a force greater than 1000 N. A minor change was made to the part to facilitate a change of material. Producing the bracket in plastic would be beneficial as it would reduce the price to one fourth of the original price, and the lead time down to a few hours. Testing a plastic part would be inexpensive, so doing a physical test is suggested. If plastic is not a viable option, producing the part with DMLS is possible, but expensive. If DMLS is the only option, AM is not recommended.

This case study includes sensitive information from TechnipFMC and will be available in Appendix H1 to this document.

### 3.3. Bracket sensors

A case study has been made of sensors for the sensor bracket. The bracket is used as a mounting device for a displacement sensor. This case was about identifying if a different sensor could be mounted. The motivation behind this was to find a smaller sensor, to reduce the size of the bracket, or open the possibility of a completely new design. However, the requirements for the sensor were that it also had to have a low power consumption and have high resolution.

This case study includes sensitive information from TechnipFMC and will be available in Appendix H2 to this document. A detailed description of the various displacement sensor technologies is also provided in Appendix E1.

### 3.4. Secondary release mechanism block

This case study is a block. This block is designed to hold pipelines onto a structure. A redesign was made to adjust features for an AM design. Cross drilling was removed and sharp corners inside the channels were avoided. Additionally, the part went through several iterations of weight reduction optimisations, eventually resulting in a weight reduction of 75%. Further optimisation to better suit the printing method in accordance with the guideline presented in this report is recommended. Acquiring cost data on this part proved difficult, and so no comparison was made. Considering the amount of finishing work needed with the AM produced part, it can be assumed that the original part will be cheaper. However, the redesigned part will likely have better internal flow and will be considerably lighter.

This case study includes sensitive information from TechnipFMC and will be available in Appendix H3.

### 3.5. Slick joint

This is a case study of a slick joint. This slick joint is a large pipe with end connectors, penetrated by several pressurized channels. This part is too large for most AM methods. A common viable method would be WAAM. Using WAAM to produce a NNS of this part with internal channels. Assuming the channels made with WAAM are sufficient and not disrupting the internal flow. Cost data was unavailable for this part, so no cost comparison could be made. Producing a NNS workpiece and then machining it could seem counterproductive, but with this case the drilling of channels is a challenge and huge time sink while machining. And so, if this part of the machining could be avoided, it could be worth adding another chain to the production link.

This case study includes sensitive information from TechnipFMC and will be available in Appendix H4 to this document.

### 3.6. Conceptual part

This is a case study of a “smart”-component. This component is designed to hold sensors subsea to gather information over a period of time. In the case study the original concept is analysed, then the possibility of manufacturing using AM is assessed. The case study also involved finding suitable components for the internal workings of the part.

Most the parts seen in this case study are less suitable for AM, except for the internal bracket. This bracket can be printed in nylon or any other desirable polymer. The design can be easily adjusted to accommodate different sensors and wiring. Given the limited information given about this case, as it is highly classified, the conclusions reached in Appendix H5 and Appendix H6 are conceptual.

This case study includes sensitive information from TechnipFMC and will be available in Appendix H5 and Appendix H6 to this document.

### 3.7. Design considerations

As a reaction to the highlighted question of what the benefits and challenges of AM for subsea appliances are, the derived question, if AM can be beneficial for Subsea, was made. To answer this question efficiently, the design considerations in Appendix I1 was made. The document is meant to give the reader some basic guidelines and considerations when designing for additive manufacturing. The excel sheet in Appendix L1 has been made based on the information in this document. The benefit of the excel sheet is that it will highlight the features that will be a problem for additive manufacturing while it still is in the design stage, while it also can be used for existing parts.

## 4. Discussion

### Development cycle

The assignment had a sound basis with a high potential. As the project progressed, the consensus got closer and closer to AM not being the most effective for subsea due to qualification and the way of thinking AM allows and is suited for. Fig. 13 shows the different stages in a development cycle, where the efficiency and opportunity decline the later through the stages AM is considered. For this project, part design and manufacturing analysis were the main areas of focus. The conceptual part was almost within the product architecture stage, but due to a lack of full context it was not fully explored.

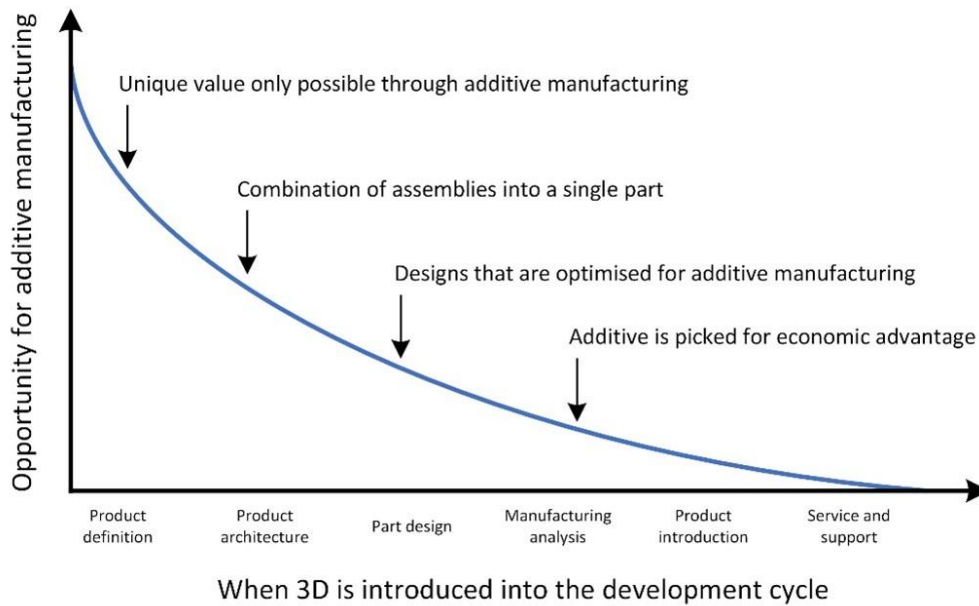


Figure 13: Efficiency through stages of development cycle

### The value of full context

Part of the trouble encountered with analysing the cases in this report is the lack of information regarding detailed functionality and specifics of the intended product, due to confidentiality and discretion. Fig. 14 shows the pathway to continuously improve a part, and the value of having the specifications and design choices under the same individuals.

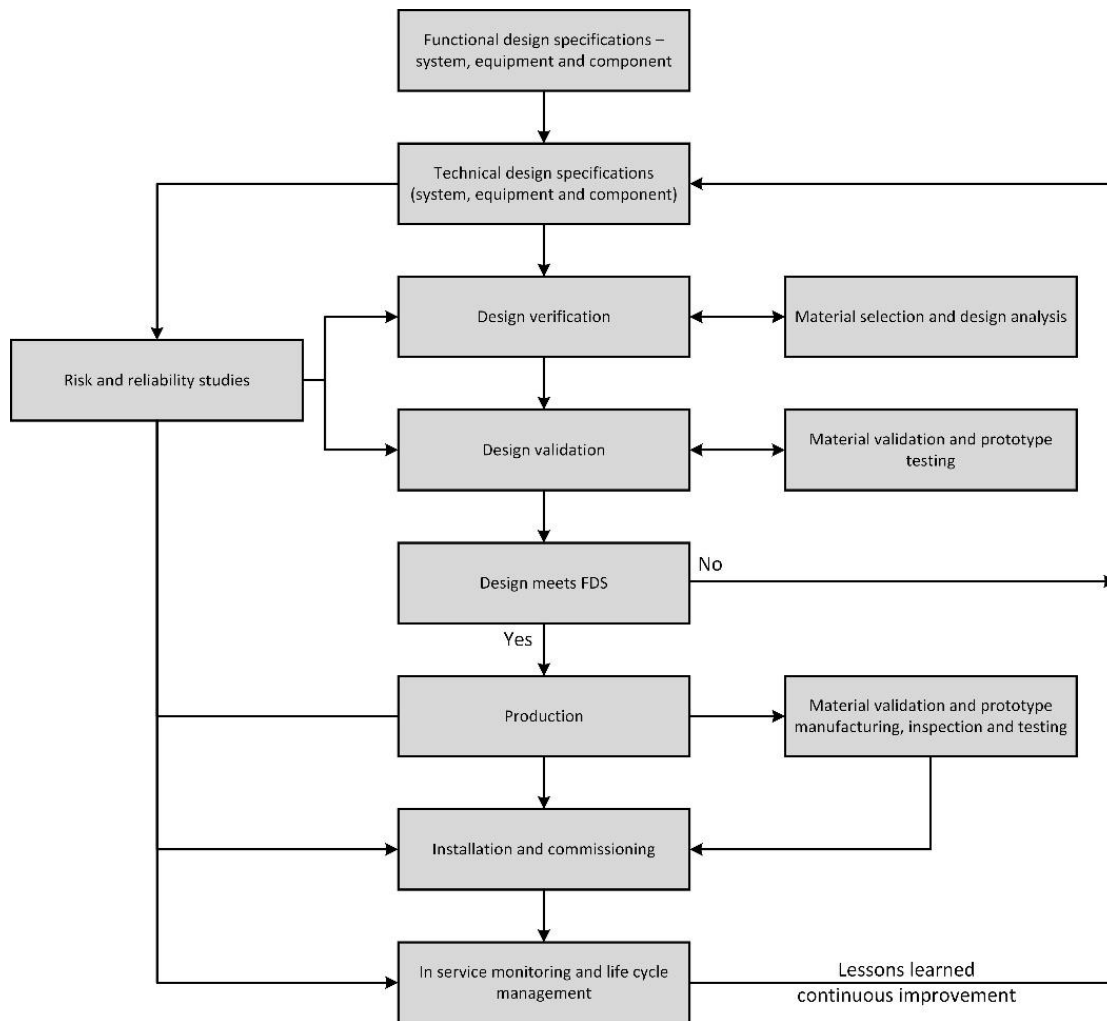


Figure 14: From specification to life cycle of part

## Verification

Due to the rigorous qualification regime for subsea parts, it might be difficult to verify the material properties of an AM part. This makes qualification of AM parts difficult. The reason for this is that material testing must be done after the part has been produced, this means that an operator will have to use for example ultrasound on a part that has complex geometry. This will be difficult to do compared to the material testing for CNC parts, here the test is performed on the material block before it is going to be machined, this will show any defects in the material of the workpiece while it is in a block shape. Furthermore almost all AM processes involve melting or heating of the material, if the material is a metal this means that it will have to be tested after its final heat treatment. This is because the material can change its material properties when it is exposed to heat over a certain threshold.

## **Cost**

A major concern for many industries when considering whether to adopt AM as a production method is the cost or cost effectiveness of the method. However, getting entangled in merely considering the cost of these methods and the products they produce compared to traditional machining can be a mistake. Something that most of the cost formulas answer, is that AM is only cost effective when small quantities are produced, but the strength of AM does not necessarily lie within the cost aspect at all. What AM as a production method primarily does is to provide the producer with options in the design of products regarding geometrical complexity. AM should be considered the method of choice if complexity in geometry is essential to a desired function. This all seems to indicate that comparing traditional machining with AM is somewhat futile, due to that the production methods only have in common the fact that they are production methods, but little else.

## **EBM**

This type of printer is precise and very fast, using powder layers of up to 100 µm and being able to scan the entire cross section with its electron beam makes it not only a fast method, but also means that it enables production of several products at once. The layers can also be reduced to a much smaller thickness but will be at a cost of build time in favour of higher precision. This method has the printer that is most limited in size, and can at a maximum build 46.55 l, or 0.04655 m<sup>3</sup> size products. The finished product will, dependant on the layer thickness of the powder, be near net shape, and will invariably require CNC machining to finish it. One of the two biggest drawbacks of this method is however the problem of porosity caused by the phase shift innate in the process, this is fine in applications where this property is wanted, like for implants used in medicine, but in applications that require durable parts this is not likely a suitable method. The other major drawback is that EBM cannot print using stainless steel, and the materials used in this method is also the most expensive.

## **DMLS**

DMLS is a variation of the PBF process, meaning it uses metal powder as its print material. A high-powered laser is used to selectively heat and melt the metal powder and fuse it together to a solid part. DMLS is a fast and precise printing method, it is able to print using powder layers as thin as 25 µm and print at a rate of 2-8 mm<sup>3</sup> per second. The printers can print several parts at once using stacking. It is also possible to print different parts in the same session. DMLS uses the powder as support elements in the process and when the printing is complete, the remaining powder is simply vacuumed up to be used in future printings, making it very economical. Unfortunately, the printer is not very scalable. It is restricted by the need of a chamber. The largest printer size and volume is 800x400x500 mm or 160 litres.

The biggest drawback using DMLS is the exposure of residual stress, this can cause an elastic compressive strain within the layers. This is due to the cooling and reheating of layer of inconsistent levels of heat. The results of this may be reduced, but not removed, by applying some finishing treatment. The most used form of finishing is heat treatment, shot-peening and hot isostatic pressing.

DMLS is applicable for subsea since it can print in all materials needed, but due to the strain stress, it may not be the best solution.

## **CNC**

CNC machining is the traditional way of manufacturing that the additive methods will have to compete against. The big difference between CNC and AM is that CNC is a subtractive method, it removes material rather than adding it. In terms of precision a CNC machine moves in increments of 1  $\mu\text{m}$ , that said there are other factors affecting how reliable the machine is. Most solid material can be machined using CNC, including wood, polymers, and metals. Prototyping with CNC can be time-consuming, but if it is a large quantity of parts being produced, the cost per unit is reduced significantly. The raw material needed for CNC production is relatively inexpensive. The CAM software on the other hand is very expensive, an expense that scales with a company's production. A CNC machine requires little maintenance, most of which can be performed while the machine is operational. CNC machining can be quite dangerous, with death and injury being a very real possibility. Therefore, strict HMS regulations are necessary.

## **UAM**

UAM is an AM processes in which also utilises a subtractive manufacturing process, making it a hybrid manufacturing process. This means that any organisation which utilises this process (CNC) will be able to take advantage of existing knowledge about subtractive manufacturing already present in the organisation. It also has the advantage of not exposing the metal to high temperatures, so it avoids the problems which occur during melting for instance HAZ, recrystallisation etc. It can also produce parts which contains two different metals without creating fragile alloys.

UAM also has some drawbacks, the biggest of which is the price and availability. This process had only been used in universities or in the research and development of large organisations, until a couple of years ago. This means that the price is higher compared to other manufacturing processes. It also has a higher material waste than other AM methods due to its use of metal strips, which needs to be machined away in between the layers. In summary, it is one of the more interesting AM processes, but it still has a way to go in terms of price and material waste. Some of its features makes it a very interesting way to produce parts, especially since one can imbed electronics into the parts due to the low production heat.

The cost of UAM manufactured parts will also decrease in the coming years. The leading company in UAM production Fabrisonic has in the recent years got funding from NASA and other large organisations. This means that this production method will get more funding and exposure, opening it up to a bigger market.

## **WAAM**

WAAM is an AM process which is based on the principle of welding. This means that a machine, usually a robotic arm with a welding machine attached to it will build the part up from the build plate using the feed wire. The arm will move the welding arc so that it will deposit a line of material in the shape of the part on the building plate, it will then move the welding arc up to the

next layer and build the next layer on top of the last layer. The part that is created is a near net shape (NNS) part. This means that the part it creates will have the basic shape of the part and you will have to machine it into the desired form after it is made in the WAAM machine. This saves material and time since you already have the rough shape of the part. With this process you will be able to build on the existing knowledge that the organisation has on welding and machining. You will also be able to create parts with the same tolerances that the CNC machine you use to finish the part with has. As with all welding processes the mechanical properties of the metal will be altered, but this is something that is known and there are steps that you can take to mitigate it since welding has been used for many years in the industry.

### **Pugh Matrix**

From the conclusion of Appendix D1, WAAM and UAM score highest among the AM processes. The Pugh matrix also includes CNC machining as a method of production. This is the traditional method AM processes compete against. CNC machining does get the highest score in the Pugh matrix, which was to be expected. The summarised score from the Pugh matrix suggests which method is better from a general point of view, although none of the AM methods were expected to beat CNC machining with current technology. WAAM however received a comparable score with CNC in the Pugh matrix. With that said, AM processes will still offer many benefits for niche purposes and should not be disregarded solely based on a Pugh matrix. However, the underlying point to draw from the Pugh matrix is that to draw a conclusion from it may be a faulty method. To merely look at the various processes only considering each other will not do much to enlighten which process will be likely to succeed at a given task. When a product is under development it will therefore more likely be necessary to analyse all the elements that will go into making it. Be this material, design, or the production method itself, because all of this will be intertwined in relation to which production method that can be most suitable.

WAAM score is also worth a special mention. WAAM receives a score comparable to CNC machining, despite requiring CNC machining as a form of post processing. This again underlines the fact that a Pugh matrix does not necessarily tell the complete story.

The Pugh matrix from Appendix D1 gave insight into the different methods, how the methods compared, where they excelled. Besides this, it was used as a basis for the choice matrix in Appendix L2 to determine the preferred method for a chosen part.

## 5. Conclusion

To answer the question of what the benefits and challenges of AM for subsea appliances are, the advantages are related to the solution to complex demands and a possible reduction in lead time, which both will lead to a possible reduction in cost. The challenges are related to specifics. If the chosen method, material, and design of a part are not created in parallel, the full potential of AM will not be taken advantage of. To answer the derived question of how AM can be most beneficial for Subsea, tooling and areas which do not require qualification are the key at the moment. As a result of this report, Appendix L1 for whether a parts design is fit for additive use was made, in addition to Appendix L2 for which additive method is best fit for the production of a part, which can also be used as a guide for future design of parts.

Working with AM is much less restrictive regarding geometry and complexity. In fact, higher complexity is desirable to reduce material usage and build time. This great advantage is being fully utilised in many industries, including aerospace and medicine. For subsea on the other hand, common important features are fine sealing surfaces, tight tolerances and super alloys. All which are features AM does not yet deliver to a satisfactory degree. AM generally has rough surfaces, at the same time, added complexity will often equal to more surface area, leading to greater risk of corrosion, a major concern when working with subsea. This is not to say that AM has no place in the subsea industry, it should be carefully considered where to apply it. Tooling is an often-overlooked part of a products lifecycle, and an area where AM has potential, custom tools can be designed and produced within 24 hours, to make assembly or testing processes more efficient. Adjusting existing parts to get the benefits from AM has proven to be of questionable value. Instead, a design should be made with a production method in mind, like designers have done with CNC for many years. The method limits the possible materials which in turn affects design decisions. All four of these factors: design, method, material and verification must all be considered in unison.

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## 7. Appendices

### Appendix A1. Project management

Following are all planning and management for the project. The group contract, areas of responsibility, project model, the risk analysis, tools used, Gantt chart, problem discussion, delegation, and main user stories for this project.

#### **Group internal contract**

To make the collaboration work appropriately amongst the group, one of the earliest matters the bachelor group settled upon was the group internal contract. This was substantial to unify and define how the workings of the group should operate, in addition to evading potential future conflicts.

# Contract of Operations

## Gruppe 10

- The team members are obligated to attend all group meetings.
- If a team member is unable to attend a meeting, he shall inform the project leader in advance.
- All assigned work shall be submitted before its deadline\*.  
\*All work not finished/submitted should be accounted for and analyzed.
- In case of disagreement, the project leader shall call a vote.
- In the case of a tie, the project leader has the final say.
- Every opinion and idea have the right to be expressed freely.
- All members of the team shall act with respect towards the others.

*Simen A. Hegge*

**Simen A. Hegge**

*Inge Moen*

**Inge Moen**

*Fredrik Lium*

**Fredrik Lium**

*Gustav Kallager*

**Gustav Kallager**

*Halvard Løver*

**Halvard Løver**

### Areas of responsibility

In a project, as considerable as this, it is important to establish the various areas of responsibility. Using earlier projects as examples, it was found how they divided these areas of responsibility, although most other projects included a more physical end product. Taking this into consideration, the main areas that were established to be most important and relevant, were documentation, risk management, requirements lead, test lead, electrical lead, machine lead, CAD lead, sample part lead and project leader. These areas of responsibilities were assigned to always have a person responsible.

**Simen Hegge** Project leader  
Risk manager

**Gustav Kallager** Electrical lead

**Fredrik Lium** Documentation lead

**Halvard Løver** Requirements lead  
Sample part lead

**Inge Moen** Mechanical lead  
Test lead  
CAD lead

## Scrum

In order to move forward in the project, Scrum was chosen as the project model. The project leader was assigned the role of both product owner and scrum master. The reason for this is because the project group is small, and to keep the project leader as the main communications link between the group and internal- and external supervisors.

When picking Scrum, the goal was to have an iterative process, always improving or adding to the project. The work intervals in Scrum consists of sprints, usually lasting a week, or sometimes months at a time. The four phases of a sprint are planning, review, retrospection, and daily meetings. During the start phase of the process, the planning took a larger portion compared to the other parts of the Scrum process. Finding what to do, how to do it, and how to divide the tasks among the group members over time proved to be a difficult, but important task. The review and retrospection parts went by faster. There were certain tasks requiring longer sprints than anticipated, but this led to a more thorough overall progression.

### **Risk analysis for development**

A risk analysis matrix was made in order to avoid future conflicts. It contains different areas that may affect the project. The risk analysis is made to foresee the potential consequences that may happen in the future. By assessing the risks beforehand, they may be avoided and resolved effortlessly if they were to happen. The risk analysis matrix in Tab. 8 shows the risks, the affected areas, the severity, likelihood and impact of the risk, and the recommended handling of the event [39].

In hindsight, the difficulties encountered throughout the project were related to risk 1 and 11, due to Covid-19 restrictions and considerable interest from the client.

Table 8: Risk analysis matrix

#	Risk	Affected areas	Severity	Likelihood	Risk impact	Recommended action
1	Covid-19	Developer's health and project advancement	Medium	High	Medium	Online meetings and working from home
2	Unable to complete task	Project advancement	Medium	Low	Medium	A frequent rundown of task completion, new delegation
3	Over budgeting	Client will lose respect and may reduce support	Medium	Low	Medium	Keep an eye on expenses, come to an agreement with client
4	Injury/fire	Developer's health and project advancement	High	Low	Medium	Manage an HMS plan prior to physical work
5	Hardware/software are failure	Loss of progress	High	Medium	High	Save backups of documents frequently, use school computers if needed
6	Plagiarism	Rejection of work and loss of credibility	High	Low	Medium	Ask for access to use certain sources, otherwise, the document must be rewritten, figures/tables must be remade
7	Internal conflict	Teamwork and project advancement	High	Low	Medium	Conflict resolution, student counselling
8	Loss of equipment	Loss of progress, client may lose respect	High	Low	Medium	Replace lost equipment, contact insurance company
9	Personal circumstance	Personal life, project advancement, group integrity	High	Low	Medium	Take a personal day if needed
10	Breach of contract	Client will lose respect	High	Low	Medium	Preventative measures should have been in place
11	Scope creep	Project will become unmanageable	Medium	Medium	Medium	Evaluate whether the feature is in a requirement or the contract

## **Project tools**

Following is a description of the various tools used for writing, design, and communication between group members.

### **Jira**

Jira is a website utilised for a wide range of cooperative project work. It is initially a product intended to follow software bugs and issues, but it was remade for other types of work. It has a few functions leaning towards iteration and overseeing projects. This is done through functions like showing and allowing to keep track of work processes, issue tracking, road mapping, progress reports, logging, Scrum sheets, backlog, and other functions. With everything considered, this makes for a good match for use in our bachelor project. Particularly since the bachelor group follows an agile Scrum model for the work processes.

### **MS Teams**

Microsoft Teams is a unified communications and collaboration platform. It combines ongoing workplace chat, video conferencing, cloud storage and file collaboration, in addition to application integration. Teams is an upgrade from Microsoft Skype and is ideal for group work such as a bachelors project, especially granting ease of communication between the group and the client.

### **Discord**

Discord is another communications platform. It specialises in voice and video calls while also allowing for file sharing within the group, group updates, and chat and voice channels to for example create meetings-in-meetings.

### **Solidworks**

Solidworks is used for design and analysis of parts and constructed assemblies in the case studies, and is a CAD based program that allows for construction- and technical drawings performed using computer-based software and tools.

### **Gantt**

Gantt charts are used in planning related to project management. It makes for a relatively easy way to show plans and activities in the progress over time. The Gantt chart made to show the progression and planning of the project is shown in Tab. 9. It shows the general progression chart of the entire length of the project. The plan is to work and iterate throughout the project segmented by the end of each sprint (Fridays), and divided to each iteration shown from 1 to 5. Tab. 10 shows the updated Gantt chart [40].

Table 9: Gantt chart V1 (15.02.2021)

	15.01.21	22.01.21	29.01.21	05.02.21	12.02.21	19.02.21	26.02.21	05.03.21	12.03.21	19.03.21
Delegation and specification	1	1			2					
Research	1	1	1	2	2	2	3	3	3	4
Trade-off analysis		1	1	1	1	2				3
Risk analysis			1	1		2				
Cost analysis		1	1	1		2	2		2	
Process analysis		1	1	1		2	2		2	
Case studies							1	1	1	2
Subsea analysis							1	1		
Conclusion				1	1					
Merge of work				1	1			2	2	

	26.03.21	02.04.21	09.04.21	16.02.21	23.04.21	30.04.21	07.05.21	14.05.21	21.05.21	28.05.21
Delegation and specification										
Research	4	4	4	5	5	5	5	5		
Trade-off analysis										
Risk analysis										
Cost analysis										
Process analysis										
Case studies	2		3							
Subsea analysis	2	2		3						
Conclusion	2	2	2		3		4	4		
Merge of work		3	3	3	4	4	5	5	5	

Table 10: Gantt chart V2 (02.04.2021)

	15.01.21	22.01.21	29.01.21	05.02.21	12.02.21	19.02.21	26.02.21	05.03.21	12.03.21	19.03.21
Delegation and specification	1	1			2					3
Research	1	1	1	2	2	2	3	3	3	4
Requirements and test plan				1	1		2	2		
Trade-off analysis		1	1	1	1	2				3
Risk analysis			1	1		2				
Cost analysis		1	1	1			2	2		3
Dummy part							1	1	1	2
Case studies								1	1	1
Sensor trade-off										1
Merge of work				1	1			2	2	

	26.03.21	02.04.21	09.04.21	16.02.21	23.04.21	30.04.21	07.05.21	14.05.21	21.05.21	28.05.21
Delegation and specification										
Research	4	4	4	5	5	5	5	5		
Requirements and test plan	3	3					4	4		
Trade-off analysis				4						
Risk analysis										
Cost analysis	3	3	4	4	4	5	5	5		
Dummy part	2	2	3	3	3	4	4			
Case studies	2	2	3	3	3	4	4	4		
Sensor trade-off	1	2	2	3	3	3				
Merge of work	3	3	3		4	4	5	5	5	

## The problem

Examining the purpose of the assignment is important to determine what the client requires. From this examination, together with the client, the requirements to the project were established. To verify that the requirements were met, a test plan was made. One of the main objectives in this report is a trade-off analysis, meant to find and estimate how the various AM methods compare to each other, and which one of the methods are worth to further examine with a special consideration for subsea applications. In addition to the trade-off analysis, a few parts were provided by the client as case studies. These case studies revolves around whether it is possible to produce these parts using AM, or if the parts could be redesigned in order to accommodate to the AM methods.

Not understanding the problem is a common reason for a project to fail. By misunderstanding the underlying issue your project is supposed to address, much of the work being put in could turn out to be a complete waste of time. To avoid this, it is vital for the participants of the project to have a clear understanding of the actual problem before they work towards a solution.

For theoretical projects, like this one, summarizing the assignment into a single problem can be challenging. The problem that was aimed to be answered was to find the benefits and challenges of AM for subsea appliances. This summarises the assignment, and if a satisfying answer is provided, the project is a success. Keeping this in mind will prevent the students from going astray in their research. The students will continuously be aware of that what they are doing which should be getting them closer to answer the problem.

## The *wicked* problem

Part of what made this project so problematic was the question of what specifically to challenge. What was realised was that it was the task itself. Although it sounds counter-intuitive, having an open-ended problem made the answer more comprehensive. Through the iterations of requirement specification and test planning, the project progression got closer to narrowing down the tasks, although not necessarily the problem. It can be viewed as a wicked problem. Wicked problems are categorised as a dilemma in planning theory which have ten distinct properties [41]:

- 1) There is no definitive formulation of a wicked problem.
- 2) Wicked problems have no stopping rule.
- 3) Solutions to wicked problems are not true or false, only good or bad.
- 4) There is no immediate and ultimate test of a solution to a wicked problem.
- 5) Every solution to a wicked problem is a “one-shot operation”; because there is no opportunity to learn by trial and error, every attempt counts significantly.
- 6) Wicked problems do not have an exhaustively describable set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
- 7) Every wicked problem is essentially unique.
- 8) Every wicked problem can be considered to be a symptom of another problem.
- 9) The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem’s resolution.
- 10) The planner has no right to be wrong.

Having a process of jumping back and forth from problem definition and answer, suits the agile project model of Scrum, where the document is iterated several times, to reformulate, find new angles, and ways to attack the tasks at hand.

In the case of this project, the goals at the start were to find and compare AM methods and specifying AM in relation to a bracket sensor. Finding how the methods compared made for a good introduction but did not sufficiently describe the benefits and challenges with AM in relation to the subsea industry. The goal was moved to making a cost analysis, suggesting improvements for several cases, and making a guideline to make efficient designs for AM. As well as discussing how a subsea part can be designed for AM, should be considered before how AM can be beneficial for a subsea part. In the middle of the project, the goal of making a convincing argument for a potential conversion within the client company was added. In addition, the necessity of an easy to consume report was highlighted towards the end of the project.

### **Partition and delegation**

The project group choice of one person taking on the role as both project leader, scrum master and communications manager, combined with the updated Gantt diagram as a general plan allowed for a rapid and straightforward task handling. Potentially critical decisions were made into internal discussions, while the majority of lesser decisions were managed by the project leader.

In order to efficiently handle and overcome a potentially impossible task, the project was partitioned into subcategories, as shown in Fig. 15. These subcategories were again partitioned into smaller, more manageable tasks that were delegated among the group members, using Jira. Particularly extensive tasks encountered took more time but did not delay the overall progression of the project and was covered within the planned Gantt diagram. When utilizing the agile scrum project plan, several iterations went on in enhancing the subcategories' contents, as shown in Tab. 10.

The time divided over the different processes throughout the project is shown in Appendix K1.

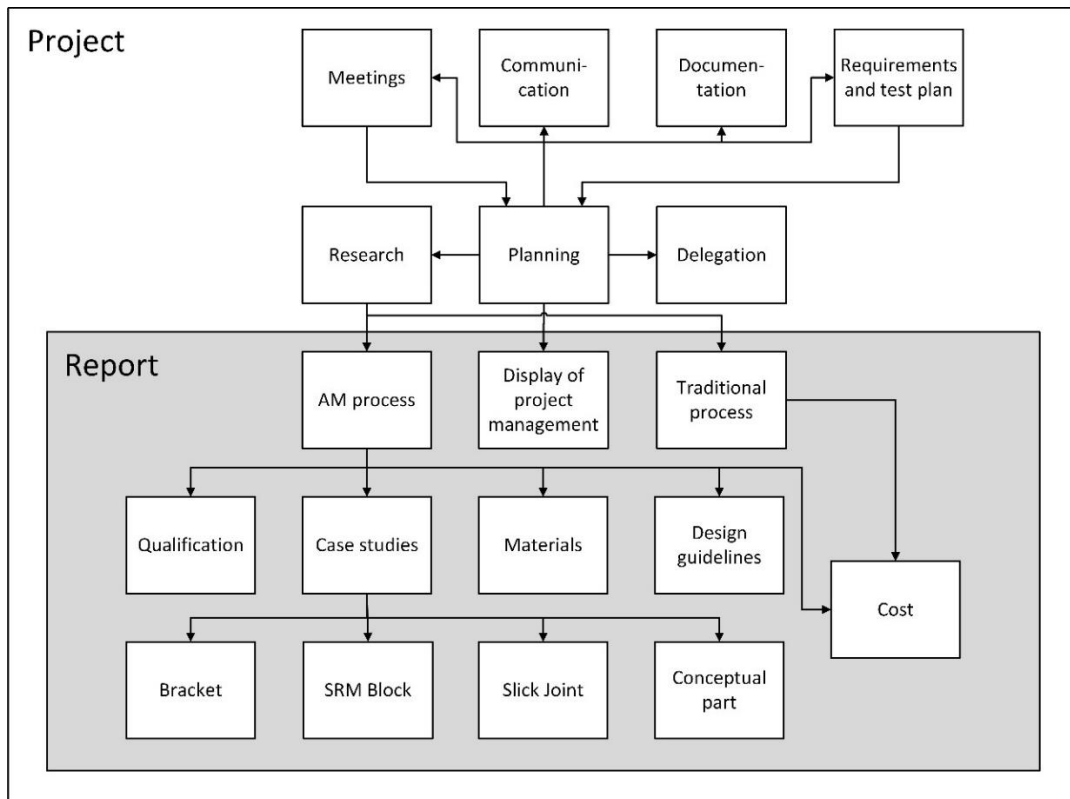


Figure 15: Project procedure partition

## User stories

To get both the bachelor group and a potential reader of this document endorsed in these technologies, there was derived some user stories. User stories are meant to give context and examples of use. These stories are not needed to understand how this report will operate, but rather how it may be utilised. Tab. 11 shows an overview of user stories with their valued criteria and priorities.

*Table 11: User stories*

User story	Acceptance criteria	ABC/priority
As a producer, I want to have as low as possible production time and cost, so that I can produce more products cheaply.	<ol style="list-style-type: none"> <li>1. Reduce lead time</li> <li>2. Cheap materials</li> <li>3. Ensure that AM products are of the same quality as other production methods</li> </ol>	<ol style="list-style-type: none"> <li>1. A</li> <li>2. A</li> <li>3. A</li> </ol>
As a maintenance worker, I want to repair or be able to replace parts easily, so that system downtime is at a minimum and operations can remain continues.	<ol style="list-style-type: none"> <li>1. Receive parts that match specifications</li> <li>2. Fast delivery</li> <li>3. Parts made from the correct materials</li> </ol>	<ol style="list-style-type: none"> <li>1. A</li> <li>2. B</li> <li>3. A</li> </ol>
As a maintenance worker, I need to repair the system in question fast, so that the system can resume operation with minimum downtime, which will ensure a minimum of unnecessary expenses.	<ol style="list-style-type: none"> <li>1. Reduce lead time</li> <li>2. Fast delivery</li> <li>3. Parts that are easy to install</li> </ol>	<ol style="list-style-type: none"> <li>1. A</li> <li>2. B</li> <li>3. B</li> </ol>
As a CEO, I want to increase efficiency and decrease production cost, so that I can ensure good profit margins.	<ol style="list-style-type: none"> <li>1. Cheap materials</li> <li>2. Fast delivery</li> <li>3. Assemble/print parts on site</li> <li>4. No 3<sup>rd</sup> parties</li> </ol>	<ol style="list-style-type: none"> <li>1. A</li> <li>2. B</li> <li>3. C</li> <li>4. A</li> </ol>
As a transporter/storage worker, I want to I want efficient storage, transportation is made easier and storage space is kept to a minimum.	<ol style="list-style-type: none"> <li>1. Parts that require minimal storage space</li> <li>2. Minimum amount of required parts stored</li> <li>3. Easy to transport</li> </ol>	<ol style="list-style-type: none"> <li>1. C</li> <li>2. B</li> <li>3. B</li> </ol>

## What to gain from these stories?

The user stories will help to understand what matters in a process, and what is desired from the customer or client. To derive the user stories a potential scenario was made, where a person was assigned with a role. This led to what that specific person may want to achieve in relation to the assigned role. This further led to what result that achievement would have. The user stories help to pinpoint the people that might be affected by or wanting certain changes. By analysing these user stories, it was derived that price of materials, production time, and AM production methods

absolutely must match or exceed requirement specifications of machined parts. Alternative user stories are provided in Appendix A3, Appendix A4 and Appendix A5.

## Appendix A2. Making a trade-off analysis

A trade-off analysis is a document, but more precisely a method, to compare different concepts, according to parameters set by the manufacturer [42].

There are six stages of a trade-off analysis:

### *Understanding*

The first stage involves research. Not only is there a need to find all the various relevant alternatives from reliable sources, but to compare the alternatives, knowing what they are and can do what is required. This first stage is not as much a part of the trade-off document, but a step in the process of making a trade-off analysis.

### *Listing alternatives*

The second stage is listing the alternatives, their details, their benefits, and drawbacks. This gives a potential reader insight into how the concept is and works.

### *Defining criteria*

The third stage, defining the criteria, is an important part of the analysis. Exactly which areas of the concept is important, and what should be compared. The criteria impact the trade-off findings considerably. Examples can be efficiency or cost.

### *Weighting the criteria*

The fourth stage, weighting the criteria, is a deeper customisation of the comparison. One area of the concept may be worth more than the others.

### *Scoring the metrics*

The fifth stage will be based on tangible facts applicable to the criteria in most areas, but for vaguer and less quantifiable areas, the scoring risks being biased due to human nature. Although, if done by a group of individuals, the scoring for those areas may be more objective.

### *Analysing the output*

Lastly, there is the sum of scorings, where it is seen which methods fares better against each other, and which areas each concept excels or fails at. For stages three to five, a method to display and handle the stages is something called a Pugh matrix, or a decision-matrix method.

## Appendix A3. Alternate user story 1

These are user stories written the way it was thought during the systems engineering class.

### **UserST: Steve the workshop manager**

Steve is an experienced manager working at a well-established company. After many years in the industry, he has become adept at his job and enjoys his daily routine. Today however, he was not looking forward to it.

The last mail Steve had received the day before, was an order for a certain part. He was familiar with it; it was a part they delivered on a semi regular basis. And yet he knew it would cause unrest among his employees.

This part was such a torment to prepare for machining that they would usually always have the setup on one of the assigned mills detachable tables. Unfortunately, the table had recently been used for a different part, and so they had to set it all up from scratch.

On top of this, the part would be made from a horrible material for machining, prone to fracture the milling tool bits, causing delays and not to mention stress for the operator.

Steve enters the workshop, mentally preparing for the endless complaining his employee would barrage at him. On his way over to the mill that would produce the part, he passed the new LPBF 3D printer the company had invested in. This gave Steve an idea, everything about the part that would be troublesome for traditional machining would make no difference if it were printed.

Steve brought the part to his colleague in charge of the printer. After discussing the requirements and possible changes to the part, they decided to print it and do some thorough testing to make sure it meets the requirements. The mill would not be available for another week regardless, so even if it were to fail, the part would still be delivered before the deadline.

The printing was done without any issues, and since the printer can run without a lot of surveillance, they printed a second part to check how consistent the test results were, and to perform destructive testing. And although the printed parts did not perform as well as the machined parts, they were still well within the required performance. The only exception being the finish on a couple of surfaces. Which was expected and easily dealt with.

Steve was relieved that an order which would usually cause several headaches was finished with little to no troubles. Now being more familiar with AM he decided to put some time into reviewing the products he was responsible for, to see if there were others with properties well suited for printing. Which he discovered; there certainly were.

### **What to gain from this story?**

Printing would be easier and less costly for this part and relieve the workers of unneeded tension.

Appendix A4. Alternate user story 2

**UserST: Failure of a critical part**

The large oil platform, out at sea, secluded, is having their day-to-day operations. There are usually clear skies, but today heavy wind and rain is surrounding the platform as far can see. Hopefully, it will not affect the processes. And it does not seem to be more than a hindrance, for now. At 04:00 in the morning, warnings can be heard in the control room, a part is malfunctioning and needs a replacement. A spare part like this is not at the platform. Due to the weather conditions, getting a spare part by delivery will not be available until the storm passes, possibly a week. Every day means millions lost. Not to mention the possibility of other parts failing as the system is vulnerable.

But they bought the latest AM printer. It could be used on-site. It made the part in 1-2 days, ready for use. They have the team in place to change it, making this a fair procedure. Tab. 12 shows the cost of changing a part.

*Table 12: Cost of the various procedures to change a part*

Methods	Cost USD	Time	Goal
Bring in part	Buy and get (5,000) + a week before getting (7*1,000,000)	7 days	Get a good part from a reliable source
Spare part at site	Storage cost X + spare of all parts (> 1,000,000)	1 hour	Fix as quick as possible
Print part	One time price (1,000,000) + Raw metals (1,000)	4-48 hours	Customise and make it on the go

Never were it that easy in the past, to get the parts needed.

**What to gain from this story**

Having access to a printer would ease the general production at a critical location and ensure losses were minimised in this case.

## Appendix A5. Alternate user story 3

### **UserST: WAAM**

A company is going to develop and produced a new part, they have just bought a new WAAM machine and would like to test this out as a manufacturing option.

In the start of the manufacturing process the part will be modelled in a CAD software, after the part has been modelled the part file will be transferred to a software which will turn in to a G-code for the machine which will lay down the wire.

After the part has been approved for manufacturing, it is then sent to the slicer. The slicer is a software which will slice it into an NNS-part (Near net size). This means that the part will be made larger than intended so you will be able to machine the finished part out of the NNS-part.

This manufacturing process allows us to save materials since we just have to machine away a couple percentages of the material. The most amount of time will be spent in a CAD software this allows us to run testes and optimisations on the part before it becomes a physical object.

Some of the drawbacks with this method is that the metal will have voids, oxides, heat effected zone and all other drawbacks of welding since this is the technology this method is built upon. But since most of the time is spent in the CAD software you can run multiple FEM tests on the part and find ways to tweak the model to make a stronger part. To do this the company must produce its own values for the metal used in the part, then they must choose a factor of safety according to the intended use of the part.

The production time can be shortened down by utilising a WAAM hybrid machine where the CNC mill is integrated in the machine.

### **What to gain from this story?**

Time and cost will be better if using WAAM in this case.

## Appendix B1. Requirement specifications and test plan

All the requirements have been developed in cooperation with the client. Different stakeholder views have also been taken into consideration when the requirements were developed. For example, the Norwegian government regarding safety regulations or USN regarding the requirements to the project.

The requirements in this project are not labelled as A, B and C requirements. This was decided in cooperation with the client, and the reason is that a requirement cannot be diverted from, else it is not a requirement. In a previous project in system engineering class at school, A, B and C requirements were used. The advantage of this method is that one can prioritise what requirements must be focused on in case the project runs into problems, and certain requirements must be removed from the project.

The requirements were separated into different categories, customer requirements, case study requirements, physical part requirements, economical requirements and stakeholder requirements. The physical part requirement assumes that a part can be produced. This is uncertain at this point, due to the current situation with Covid-19. The requirements were divided into categories to get a better overview from multiple perspectives. This made sure the bachelor group was able to understand which requirements were needed and stated from the different stakeholders.

In the requirements document, the sentences are built around the word “shall”. The layout of the requirements document consists of the requirements, and a comment to each of them. The comments are used to give the reader more information about the requirements.

As previously stated in chapter 3.1, the problem in the project is: “What are the benefits of AM for subsea appliances?”. If a satisfying answer is given to this question, the task will be successful. This is why the problem statement was used to create the requirements. One example of this is requirement 1.05 shown in Tab. 13, where the original problem statement is taken, and then different requirements are derived from the different viewpoints.

*Table 13: Requirement 1.05 from our requirement document.*

1.05	The report shall evaluate special requirements for subsea parts (including DNV GL guidelines)	In order to make an assessment for suitability for AM produced subsea components
------	---	--

Another requirement based on this statement is 2.02 shown in Tab. 14, where the viewpoint is from an economical and lead time perspective.

*Table 14: Requirement 2.02 form our requirement document*

2.02	The group shall evaluate functionality and reduction in lead time and cost.	In adherence with 1.2, 1.3 and 2.1
------	---	------------------------------------

## Requirement specifications

The requirement specifications were divided into customer-, case study-, physical part-, economical-, and stakeholder requirements.

## Customer requirements

The customer requirements are shown in Tab. 15.

*Table 15a: Customer requirements*

#	Requirement	Comment
1.01	This project shall result in a report.	This document, developed alongside the client, will be used to describe what our report will involve.
1.02	The report shall evaluate and describe different methods for AM of metallic parts.	To thoroughly get an overview and research the AM processes without significant bias.
1.03	The report shall evaluate and describe some of the advantages and disadvantages of the various AM-methods.	To thoroughly get an overview and research the AM processes without significant bias.
1.04	The report shall evaluate special requirements for material of parts.	In order to make an assessment for suitability for AM produced components.
1.05	The report shall evaluate special requirements for subsea parts (including DNV GL guidelines)	In order to make an assessment for suitability for AM produced subsea components
1.06	The report shall include a suppliers list.	Showing who is providing machinery, equipment to get an overview over competition and client.
1.07	The report shall strike a balance between fun from the writer's perspective, and formal, from the reader's perspective.	In order to make a good report, the report needs to be formal and objective. Meanwhile, we as writers during this assignment are encouraged to have fun.  The project report will be published for public consumption, whilst adhering to 1.08 and the university's standard for citations and sources, the university standard is IEEE reference style.

Table 15b: Customer requirements

#	Requirement	Comment
1.08	The report shall ensure that classified information should not be revealed to the public.	Parties are responsible and liable for any consequences, criminally and financially to the confidentiality clause as stated on the signed contract.
1.09	After the project is finished, all files and documents provided by TechnipFMC shall be removed and deleted from the group members computers and such.	In order to comply with the confidentiality clause of the "Standardavtale for bachelorprosjekt".
1.10	Every week a progression meeting is to be held with TechnipFMC, and minutes of meetings of this shall be delivered to TechnipFMC and the internal supervisor.	In order to keep track of progression and to be better able to plan each sprint of the project.
1.11	The report shall evaluate possible solutions for the bracket provided in the assignment and assess whether it can be redesigned and incorporate sensors like strain-gauge sensors.	This is to assess whether a bracket of reduced size and/or different material can be used, that incorporates a considerably smaller sensor.
1.12	The report shall evaluate and showcase the costs of AM.	To find where the economic gains and pitfalls of AM are, in addition to comparing costs with traditional machining.
1.13	The report shall use the knowledge gained to make a matrix aimed at showcasing what components are better manufactured additively.	This is to compress the findings into something tangible which can be used in the industry. A template, guide or input.

## Case study requirements

The case study requirements are shown in Tab. 16.

*Table 16: Case study requirements*

#	Requirement	Comment
2.01	The group shall assess whether 3-5 subsea components are suitable for AM.	To address whether a method is suitable or not in use for subsea applications, comparing AM and CNC will be required.
2.02	The group shall evaluate functionality and reduction in lead time and cost of the case studies.	In adherence with 1.2, 1.3 and 2.1
2.03	The group shall evaluate possible redesign of the case studies for simpler manufacturing in the report.	AM production might enable complete or partial redesign of the case study parts.
2.04	The group shall suggest a method for manufacturing the case studies in the report.	In accordance with the subsea guidelines

## Physical part requirements

The physical part requirements are shown in Tab. 17.

*Table 17: Physical part requirements*

#	Requirement	Comment
3.01	The group shall make a printed part.	The group shall attempt to make a part to verify the validity of the information used.
3.02	Any parts shall adhere to special requirements for subsea parts (including DNV GL guidelines)	TechnipFMC primarily produce and make products used in subsea applications, so adherence to DNV GL.

## Economical requirements

The economical requirements are shown in Tab. 18.

*Table 18: Economical requirements*

#	Requirement	Comment
4.01	The project shall adhere to economical agreements between group and client.	Adherence to "Standardavtale for Bachelorprosjekt 5. Utgifter"
4.02	The group members shall not receive any financial compensation for this project.	The group will not be financially reciprocated for working on this project.
4.03	All expenses for this project shall be covered by TechnipFMC.	Students are not liable for any financial loss nor expenses occurred during the execution of the assignment.

## Stakeholder requirements

The stakeholder requirements are shown in Tab. 19.

Table 19: Stakeholder requirements

#	Requirement	Comment
5.01	The resulting report shall meet the university's standards for publishing, while adhering to 1.6	USN wishes to publish every bachelor's degree, the report should facilitate this whilst also pertaining to 1.09.
5.02	All files created and used during the assignment shall be delivered free of malware.	All project files are to be scanned for computer malware with Malwarebytes before handing in.
5.03	The group shall adhere the government guidelines regarding Covid-19.	Whenever possible keep 1 m distance, else use face mask, and disinfect hands regularly. Work from home if needed.
5.04	Every week a meeting shall be held between the group and the internal supervisor at USN.	The meeting will take place at campus or online if necessary, according to 5.03.

## Test plan

It is important for the requirements to be verifiable, and from this a test plan have been developed. The test plan is separated by each of requirement subclasses, customer requirements, case study requirements, physical part requirements, economical requirements and stakeholder requirements. For each requirement the bachelor group defined the verification method and the verification criteria.

The verification method is the method which realise the given requirement. These are the steps needed to take to make sure a requirement is being met. For our assignment which is mostly theoretical, these methods are quite straightforward.

Verification criteria defines the scope of the test. Once this criterion is met, the requirement is verified, and the test is over. This definition is necessary in order to limit the test. If the scope of the testing is ill-defined, one will not be able to determine when the requirement is met. The test plan document is included in this report in Appendix B1.

## Customer requirements

The test plan for the customer requirements is shown in Tab. 20.

*Table 20a: Customer test plan*

#	Requirement	Verification Method	Verification Criteria
1.01	This project shall result in a report, as approved by client, about AM.	The report is to be checked and evaluated by the university and client.	Client approval of the report based on the criteria defined by the student task.
1.02	The report shall evaluate and describe different methods for AM of metallic parts.	The report is to be checked and evaluated by the university and client.	The report contains an evaluation of the different methods of AM.
1.03	The report shall evaluate and describe some of the advantages and disadvantages of the various AM methods.	The report is to be checked and evaluated by the university and client.	The report contains an evaluation of advantages and disadvantages of AM methods.
1.04	The report shall evaluate special requirements for materials used in AM.	The report is to be checked and evaluated by the university and client.	The report contains an evaluation of the special requirements for materials used in AM.
1.05	The report shall evaluate special requirements for subsea parts (including DNV GL guidelines)	The report is to be checked and evaluated by the university and client.	The report contains an evaluation and comparison between AM produced parts and subsea special requirements.
1.06	The report shall include a list of Norwegian suppliers capable of performing AM on metallic materials.	The report is to be checked and evaluated by the university and client.	The report contains a list of suppliers.
1.07	The report shall strike a balance between fun, from the writer's perspective, and formal, from the reader's perspective.	The report is to be checked and evaluated by the university and client.	The report contains sufficient formal language by the client's standards.

Table 20b: Customer test plan

#	Requirement	Verification Method	Verification Criteria
1.08	The report shall ensure that classified information shall not be revealed to the public.	The report is to be checked and evaluated by the university and client.	Compliance to the contract “Standardavtale for bachelorprosjekt” between all parties that have signed it.
1.09	After the project is finished, all files and documents provided by TechnipFMC shall be removed and deleted from the group members computers and storage hub devices.	All files pertaining to TechnipFMC are to be deleted post-publishing.	Verification mail sent to client with all files pertaining to TechnipFMC and a confirmation that all those files have been deleted by each group member.
1.10	Every week a progression meeting is to be held with TechnipFMC, and minutes of meetings of this shall be delivered to TechnipFMC and the internal supervisor.	Weekly progression meetings will be scheduled, and minutes of meetings will be written.	The minutes of meetings have been delivered to TechnipFMC and the internal supervisor.
1.11	The report shall evaluate possible solutions for the bracket provided in the assignment and assess whether it can be redesigned and incorporate sensors like strain-gauge sensors.	The report is to be checked and evaluated by the university and client.	The report contains an assessment of whether a bracket of reduced size and/or different material can be used, that incorporates a considerably smaller sensor.
1.12	The report shall find and showcase the costs of AM.	The report is to be checked and evaluated by the university and client.	The report contains a cost analysis showcasing the costs of AM versus traditional machining.
1.13	The group shall use the knowledge gained to make a matrix aimed at showcasing what components are better manufactured additively.	The report is to be checked and evaluated by the university and client.	The report contains a matrix showcasing what components are better manufactured additively.

## Case study requirements

The test plan for the case study requirements is shown in Tab. 21.

*Table 21: Case study test plan*

#	Requirement	Verification Method	Verification Criteria
2.01	The group shall assess whether 3-5 case studies are suitable for AM.	The case study is to be checked and evaluated by the university and client.	The report contains an assessment of 3-5 subsea components and their suitability for AM.
2.02	The group shall evaluate functionality and reduction in both lead time and cost of the parts pertaining to the case studies.	The report is to be checked and evaluated by the university and client.	The report contains an evaluation of functionality and reduction in lead time and cost.
2.03	The group shall evaluate possible redesign of the case studies for simpler manufacturing in the report.	The report is to be checked and evaluated by the university and client.	The report contains an evaluation of a possible redesign of a part to achieve a comparable or better result than CNC.
2.04	The group shall suggest a manufacturing process for manufacturing the case studies in the report.	The report is to be checked and evaluated by the university and client.	The report contains a comparison of the various printing methods.

## Physical part requirements

The test plan for the physical part requirements is shown in Tab. 22.

*Table 22: Physical part test plan*

#	Requirement	Verification Method	Verification Criteria
3.01	The group shall print a specific part in plastic, provided by TechnipFMC, and the same part redesigned in order to compare their structural properties.	The report is to be checked and evaluated by the university and client.	The report contains a comparison of a part produced in plastic (Demo part) and its original material.
3.02	All parts shall adhere to special requirements for subsea parts (including DNV GL guidelines)	The case studies are to be checked and evaluated by the university and client.	All parts pertaining to requirement 2.01, 2.02, 2.03, 2.04 and 2.05 has included the special requirements as specified by DNV GL.

## Economical requirements

The test plan for the economical requirements is shown in Tab. 23.

*Table 23: Economical test plan*

#	Requirement	Verification Method	Verification Criteria
4.01	The project shall adhere to economical agreements between group and client.	The project's expenses are to be reviewed by the end of May.	All expenses related to the project are to be covered by TechnipFMC, and the group members are not to receive any payments.
4.02	The group members shall not receive any financial compensation for this project.	The project's expenses are to be reviewed by the end of May.	The group had no financial gain from this project.
4.03	All expenses for this project shall be covered by TechnipFMC.	The project's expenses are to be reviewed by the end of May.	The projects expenses were all covered by TechnipFMC.

## Stakeholder requirements

The test plan for the stakeholder requirements is shown in Tab. 24.

Table 24: Stakeholder test plan

#	Requirement	Verification Method	Verification Criteria
5.01	The resulting report shall meet the university's standards for publishing, whilst adhering to 1.08	The report is to be checked and evaluated by the university and client.	The report does not reveal classified information. The report is written using IEEE reference style.
5.02	The group shall deliver files free of computer malware.	All project files are to be scanned with Malwarebytes for computer malware before it is handed in. The files will be tested on 2 different PCs before submission.	The files sent contain no malware.
5.03	The group shall adhere to "Covid-19 nasjonale tiltak".	Whenever possible keep 1m distance, else use face mask and disinfect hands regularly. Work from home if needed. If a group member is feeling ill and are showing symptoms, he shall be tested.	If there is reason to suspect that a member of the group is infected, he shall be tested. The test shall be completed, and he shall be in quarantine until a result is received.
5.04	A meeting shall be held every week between the group and the internal supervisor at USN.	A minutes of meetings document shall be made for each meeting and delivered to the internal supervisor.	The minutes of meetings have been delivered to the internal supervisor.

## Appendix C1. Email – Written permission from Cranfield University

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### Additive Manufacturing - Research paper question for Bachelor's

4 e-poster

**Simen Aleksander Hegge** <simen.aleksander@gmail.com>  
Til: s.williams@cranfield.ac.uk

5. februar 2021 kl. 06:26

Hi,

I am a student at University of South-Eastern Norway currently having my Bachelor Thesis along with my group. We are, together with our client (the international company TechnipFMC), researching and analyzing Additive Manufacturing and its use in the industry, particularly for Subsea.

The reason I send this email is I found a research report at researchgate . net prepared and uploaded by Filomeno Martina and Stewart Williams called "Wire+arc additive manufacturing vs.traditional machining from solid: A cost comparison".

Within this document it states "*No part of this document may be reproduced or transmitted in any form or by any means, electronic or mechanical, for any purpose, without the express written permission of Cranfield University.*".

I wish to refer to this document in the thesis, do you know who can authorize such a permission?

Regards,  
Simen Aleksander Hegge  
(Machine Engineering Student)

---

**Williams, Stewart** <s.williams@cranfield.ac.uk>  
Til: Simen Aleksander Hegge <simen.aleksander@gmail.com>

8. februar 2021 kl. 00:35

Hi Simen,

Yes I can authorise this – what exactly would you like to use?

Cheers

Stewart

Stewart Williams  
Professor of Welding Science and Engineering  
School of Aerospace, Transport and Manufacturing  
Building 316 (Conway House) North, Ground Floor, Cranfield University, Cranfield, Bedfordshire MK43 0AL  
E: [s.williams@cranfield.ac.uk](mailto:s.williams@cranfield.ac.uk)  
T: +44 (0) 1234 75 4693  
W: [www.cranfield.ac.uk](http://www.cranfield.ac.uk)

---

**Simen Aleksander Hegge** <simen.aleksander@gmail.com>  
Til: "Williams, Stewart" <s.williams@cranfield.ac.uk>

10. februar 2021 kl. 00:41

I wish to refer to:

- Chapter 4.3,
- figure 6 from chapter 5.1 and figure description,
- figure 20 from chapter 5.4, it's figure description along with table 6,
- and chapter 6's conclusion.

Regards,  
Simen Aleksander Hegge  
(Machine Engineering Student)  
[Siteret tekst skjult]

---

**Williams, Stewart** <s.williams@cranfield.ac.uk>  
Til: Simen Aleksander Hegge <simen.aleksander@gmail.com>

10. februar 2021 kl. 13:21

Hi Simen

Yes that is fine.

[Siteret tekst skjult]

## Appendix C2. Email – Mechanical properties of welding wires

13.5.2021

Gmail - Technical information of welding wires



Simen Aleksander Hegge <simen.aleksander@gmail.com>

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### Technical information of welding wires

---

**Brent Saul** <brent.saul@weldwire.net>

3. mai 2021 kl. 14:36

Til: Simen Aleksander Hegge <simen.aleksander@gmail.com>, ap@weldwire.net, ar@weldwire.net, sales@weldwire.net

Hi Simon,

These Mechanicals are before welding.

Brent

Brent Saul V.P.

WELDWIRE CO INC.

103 QUEENS DRIVE

KING OF PRUSSIA, PA 19406

800-523-1266 EXT 104

610-265-3555

LinkedIn

WhatsApp

[WWW.WELDWIRE.NET](http://WWW.WELDWIRE.NET)

[WWW.DURAMAXWELDING.COM](http://WWW.DURAMAXWELDING.COM)

---

**From:** Simen Aleksander Hegge <simen.aleksander@gmail.com>

**Sent:** Monday, May 3, 2021 8:34 AM

**To:** ap@weldwire.net; ar@weldwire.net; sales@weldwire.net

**Subject:** Technical information of welding wires

Hi.

I am working with company TechnipFMC to find fitting materials for possible additively manufactured products.

The technical information documents of your welding wires, example ER316, show mechanical properties. Are these values indicative of before or after welding?

Regards,

Simon

## Appendix C3. Email – Cost of printer build from Digital Metal

2/15/2021

Gmail - Bachelor assignment for TechnipFMC



Gustav <gustav.kallager@gmail.com>

---

### Bachelor assignment for TechnipFMC

3 messages

---

**Gustav** <gustav.kallager@gmail.com>  
To: info@digitalmetal.tech

Fri, Jan 29, 2021 at 2:25 PM

I am a bachelor student at the University of South-Eastern Norway working on my bachelor assignment for TechnipFMC.

The project revolves around the usage of additive manufacturing and we are comparing the different types of additive manufacturing processes. Is it possible to get a price listing of your printers?

Best regards  
Gustav Kallager

---

**Nilsson Mats** <Mats.Nilsson@digitalmetal.tech>  
To: Gustav <gustav.kallager@gmail.com>  
Cc: Sakratidis Alexander <Alexander.Sakratidis@digitalmetal.tech>

Fri, Jan 29, 2021 at 7:07 PM

Hi Gustav,

The list price of our printer is 495.000€ + ancillary equipment so for a total new set up where you need to invest in everything you need to calculate with about 7-900.000€ dependent on your need.

If you need additional information, please let me know.

**Best regards**

**Mats Nilsson**

Area Sales Manager

Digital Metal AB

SE-263 83 Höganäs | Sweden

Mobile +46 (0)72 242 47 81

mats.nilsson@digitalmetal.tech | <https://digitalmetal.tech/>

[Quoted text hidden]

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E-mail is susceptible to data corruption, interception, unauthorized amendment, tampering and viruses, and we only send and receive e-mails on the basis that we are not liable for any such corruption, interception, amendment, tampering or virus or any consequences thereof.

Höganäs AB  
Registered Office: Höganäs  
Reg. No: 556005-0121

## Appendix C4. Email – Properties of Super Duplex at Sandvik Additive

20.5.2021 Gmail - TechnipFMC- Superduplex

 **Simen Aleksander Hegge** <simen.aleksander@gmail.com>

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**TechnipFMC- Superduplex**  
1 e-post

---

**Nikhil Dixit** <nikhil.dixit@sandvik.com> 18. mai 2021 kl. 11:05  
Til: "simen.aleksander@gmail.com" <simen.aleksander@gmail.com>  
Kopi: Johan Wallin <johan.wallin@sandvik.com>

Hi Simen,  
I hope you are well!

My name is Nikhil Dixit, and I work as an Application Engineer at Sandvik Additive focusing on Superduplex area. I received your email regarding material datasheet of Osprey2507. Yes, the mechanical, corrosion properties shown in the datasheet are the values we obtained after processing the metal powder-Osprey2507 using Additive Manufacturing. Let me know if you have anything in particular and in that case, we can schedule a quick call to discuss further.

Have a nice day ahead!


/Regards,

[Nikhil Dixit](#)  
AM Application Engineer  
Additive Manufacturing Division

Mobile: +46 (0) 70 616 33 49  
Tel: +46 26 26 61 40  
[nikhil.dixit@sandvik.com](mailto:nikhil.dixit@sandvik.com)

Sandvik Manufacturing Solutions AB  
Sandviken, Sweden

<https://www.additive.sandvik>  
<https://www.additive.sandvik/en/super-duplex/>



ADDITIVE BY SANDVIK  
PLAN IT – PRINT IT – PERFECT IT  
READ MORE ABOUT OUR THREE-PHASE PROCESS AT [ADDITIVE.SANDVIK](https://www.additive.sandvik)



## Appendix D1. Pugh matrix for methods

In order to get an estimate of how the methods compare, and where they excel, a trade-off analysis was made. An added benefit to this was the group's enhanced understanding of the methods. To make a proper Pugh matrix, comprehending the concept of a trade-off is important. Appendix A2 clarifies what a trade-off analysis involves.

The Pugh matrix for the various AM production methods is shown in Tab. 25, where cost refers to how much the method itself cost in terms of acquiring new machines or printers. Material cost refers to what the various materials used for that specific method cost in approximation to kg. Size refers to the method's ability to produce products of various sizes, e.g., the size of the chamber or build plate of a printer. Scalable refers to the availability to produce or acquire printers or CNC of bigger or smaller sizes, where, in this case bigger is better. Resolution refers to the methods precision, i.e., least amount of movement for CNC, or the layer thickness of the printers. Efficiency refers to the method's production speed. Versatility refers to the method's ability to use various materials, e.g., EBM is limited to conductive materials. HMS refers to the method's safety and health requirements and other necessary precautions. Durability refers to the method's finished product and that products durability, e.g., porosity of the finished product. Maintenance refers to the method's requirements in relation to maintenance or other work required to keep the machine producing products continuously. Suitability refers to the method's ability to use materials that are directly suitable for subsea applications, e.g., EBM cannot print stainless steel. Finishing requirements refers to the method's requirements after it is done producing the product, e.g., both EBM and WAAM are NNS methods that require some CNC machining to finish. Commercialised refers to the how widespread the method and the ability to gain from using the method.

Table 25: Pugh matrix of the AM processes and machining

Criteria	Weight	EBM	WAAM	UAM	DMLS	Machined	CSAM	BJ/MJF
Cost	1	4	5	2	1	3	3	4
Material cost	5	1	4	3	2	5	3	2
Size	4	1	4	3*	2	5	5	3
Scalable	3	1	5	5	1	5	5	2
Resolution	2	2	1	5	3	5	2	4
Efficiency	4	4	5	1	3	2	5	4
Versatility	3	2	4	5	4	5	4	4
HMS	4	5	4	2	4	2	4	5
Durability	3	2	3	4	3	5	3	3
Maintenance	3	2	4	5	5	4	2	4
Suitability	5	1	5	5	5	5	5	5
Finishing requirements	2	2	3	5	4	5	3	4
Commercialised	1	2	3	2	4	5	3	3
<b>Sum (unweighted)</b>	<b>x</b>	<b>29</b>	<b>50</b>	<b>47</b>	<b>38</b>	<b>56</b>	<b>47</b>	<b>47</b>
<b>Sum (weighted)</b>	<b>x</b>	<b>85</b>	<b>161</b>	<b>145</b>	<b>129</b>	<b>171</b>	<b>154</b>	<b>145</b>

\*This is an adaptable CNC module, meaning that the size of the finished product is arguably more dependent on the size of the CNC machine rather than the UAM module.

From Tab. 25 it is evident that traditional CNC machining is the highest scoring production method, both with and without weighted numbers. CNC machining is a production method that has been developed and specialised over decades and would likely score higher than a relatively new and not as developed technology. However, WAAM scores comparably high with its unweighted score, but interestingly that gap is reduced when comparing the weighted scores between CNC machining and WAAM. The two primary points where the two methods differ in score is relating to resolution and finishing requirements. WAAM produced products are near net shape, and thusly require some machining to complete the product, and resolution and finishing requirements are therefore closely related. When comparing the other methods, UAM along with BJ/MJF also scores relatively high. This is because UAM utilises machining in production, which gives it a high resolution, but it falls short in relation to efficiency. BJ/MJF however scores lower in relation to material cost, but otherwise gets an overall good score. DMLS however scores quite a bit lower, the printer and material cost, along with limited printer size is what limits this method mostly. The method is however quite fast. EBM is the lowest scoring of all the methods compared to machining. This method has the highest material cost, the smallest printer size, the resolution of the finished product is produced to be near net shape, so it requires machining to be completed. What limits this method mostly however is its inability to print using stainless steel.

Apart from UAM, all the various AM methods have problems with the finished product regarding material durability. WAAM, DMLS and EBM all heats the materials to their respective melting points to print metal, this means that a phase shift occurs in the process itself. This leads to increased porosity and cracking. With some EBM application for instance this porosity is wanted, like in implants used in medicine. CSAM does not have this issue with heat, but as the methods mechanical bonding is based on plastic deformation, the bonds get weaker with harder materials, which gives CSAM a lower score in durability. In applications that are to be used in subsea, durable products is a requirement, because the products must be able to withstand substantial pressures.

## Appendix E1. Sensor technologies

One of the case studies in this project is a bracket that uses a displacement sensor, which is used to measure the amount with which an object has been moved. Displacement sensors can be divided into two basic types, contact sensors and non-contact sensors. Contact sensors are sensors that come into physical contact with the measured object, and non-contact sensors are sensors that does not come into physical contact with the measured object.

For linear displacement methods involving contact, there is usually a shaft in direct contact with the monitored object. The displacement of the shaft is then monitored by the sensor. The movement in the shaft are used to measure voltage, resistance, capacitance, or mutual inductance. For angular displacement methods involving physical contact, the rotation of a shaft might directly drive the rotation of the transducer element. Non-contact sensors might involve presence in the vicinity of the measured object, causing fluctuation in air pressure or magnetic field in the sensor, or change the capacitance or inductance.

### Potentiometer sensors

A potentiometer sensor is a contact sensor that consists of a resistance component with a sliding contact, that can be moved over the length of the component. These sensors can be used for both linear and rotary displacements, where the displacement results in a potential difference. The rotary potentiometer consists of a wire-wound track or a conductive film of plastic with a rotatable sliding contact. The angular sensor can be either single turn or allow several turns by having a helical track [43].

Because potentiometer sensors are contact sensors, they are subjected to wear and tear due to its moving parts. The range of the sensor is either limited by the length of the linear or angular length of the sensor, but they are easy to implement and use. Applications for these sensors can be for electronic systems in cars, where they can be used to determine the accelerator pedal position.

As shown in Fig. 16, if the input voltage  $V_s$  is constant, between terminals 1 and 3, then the output voltage  $V_o$ , between terminals 2 and 3, is a fraction of  $V_s$ . This fraction is determined by the resistance ratio between  $R_{2,3}$  and  $R_{1,3}$ , which leads to

$$\frac{V_o}{V_s} = \frac{R_{2,3}}{R_{1,3}}. \quad (1)$$

This means that if there is a constant resistance per unit length across the track, the linear or angular displacement will be directly proportional to the output voltage [43].

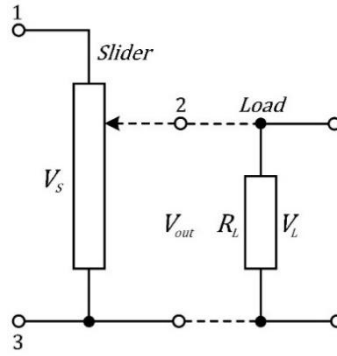


Figure 16: A potentiometer sensor circuit connected to a load

For a potentiometer sensor that allows for several turns, each turn can be referred to as a step. Then if the potentiometer has  $N$  turns, the resolution becomes  $100/N$  for each turn, as a percentage. The resolution of the sensor is therefore dependent upon the diameter of the sensor. Using a potentiometer made of conductive plastic ideally gives infinite resolution, but has a higher temperature coefficient, than a wire wound track, so temperature has a greater effect on accuracy [43].

A potentiometer can only be immune to linearity error if the connected load has an infinite resistance, i.e. the relationship between  $V_s$  and  $V_o$  is only proportional if  $R_L$  is infinite. This means that the effect of the load across the output must be taken into consideration. The effect of a finite load is therefore that it makes the otherwise linear relationship non-linear. The total resistance  $R_{tot}$  is calculated as,

$$R_{tot} = R_p(1 - x) + \frac{R_L x R_p}{R_L + x R_p}, \quad (2)$$

where  $R_L$  is the load resistance,  $R_p$  is the potentiometer resistance and  $x$  is the position of the potentiometer as a fraction between 0 and 1. A potentiometer circuit is a potential divider circuit, as shown in Fig. 17, and the voltage over the load is therefore the fraction of the load resistance and the total resistance of the circuit. The fraction of the load voltage and the source voltage is calculated as

$$\frac{V_L}{V_s} = \frac{x R_L R_p / (R_L + x R_p)}{R_p(1 - x) + x R_L R_p / (R_L + x R_p)}, \quad (3)$$

and is rewritten as [43]

$$\frac{V_L}{V_s} = \frac{x}{(R_p/R_L)x(1 - x) + 1}. \quad (4)$$

The error of a load with a finite resistance is calculated as

$$e_R = x V_s - V_L, \quad (5)$$

by replacing  $V_L$  in (5) with  $V_L$  in (4)

$$e_R = xV_s - \frac{xV_s}{\left(\frac{R_p}{R_L}\right)x(1-x) + 1}, \quad (6)$$

(6) is simplified to [43]

$$e_R = V_s \frac{R_p}{R_L} (x^2 - x^3). \quad (7)$$

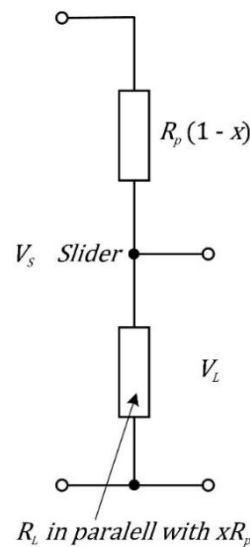


Figure 17: A potentiometer as a potential divider

If the load has an infinite resistance, then  $V_L = xV_s$  as calculated with (5). From (7) it is also clear that if  $R_L \gg R_p$  then  $error \rightarrow 0$ . There might however not be possible to manipulate the load resistance to be of the magnitude that might be desirable, thusly one solution to solve the problem of non-linearity is to use an operational amplifier as a voltage follower. An operational amplifier has an input resistance that is very high and is often assumed to be infinite [43].

### Strain-gauged element

The strain gauged element is a contact sensor, where the electrical resistance strain gauge is a metal wire, metal foil strip or a strip of semiconductor material. The resistance is wafer like and can be applied onto surfaces like a postal stamp is shown in Fig. 18. When exposed to strain, the resistance changes and this change is equal to

$$\Delta R = RG\varepsilon, \quad (8)$$

where  $R$  is the resistance of the strain gauge,  $G$  is the gauge factor and  $\varepsilon$  is the strain affecting the strain gauge. Strain is the ratio between present length/original length, therefore the change in resistance in the strain gauge is a measurement of a change in length [43].

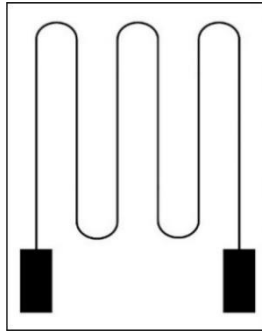


Figure 18: Simplified strain gauge layout

One form of displacement sensor has strain gauge sensors attached to a flexible element in the form of cantilevers, rings, or U-shapes as shown in Fig. 19. When forces are applied, and the flexible element is bent, the electrical strain gauges mounted on the element becomes strained, which gives a change in resistance that can be monitored. The change in resistance measures the change or deformation in the element [43].

Applications for this type of sensor include areas where deformation in a material can occur, this can be as a weight sensor or to measure torque in a motor, and is shown Fig. 19.

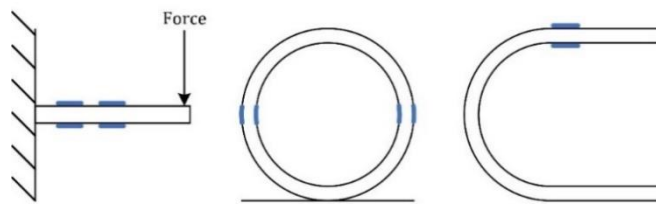


Figure 19: Different uses for the strain gauge (strain gauge portrayed in blue)

### Strain gauge load cell

One way to implement strain gauges is to attach several of them onto a cylindrical tube, shown in Fig. 20. When the cylinder is subjected to a force that compresses it, the strain gauges have a resulting change in resistance which is used to measure the strain, i.e. the applied force. This is a commonly used method of a force-measuring transducer and on the use of resistance strain gauges to monitor the strain produced in some member when stretched, compressed, or bent by the application of force. This arrangement of the strain gauges is referred to as a load cell. Temperature also produces change in resistance, so the signal conditioning circuit must be able to eliminate the effects of the temperature. Load cells that are used to measure bending is typically used to measure smaller forces than those that measure compression [43].

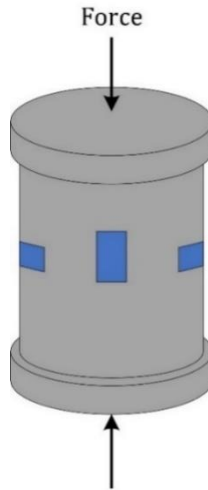


Figure 20: Strain gauge load cell (strain gauge portrayed in blue)

### Differential transformers

The linear variable differential transformer (LVDT), shown in Fig. 21, is a contact sensor that consists of three coils distributed systematically along an insulated tube. The central coil is the primary coil and the other two are identical secondary coils, which are connected in series that have opposing outputs, i.e., zero output. To monitor the displacement, a magnetic core is moved through the central tube. When the core is displaced from its position in either direction, which leads to a greater e.m.f. induced in either of the secondary coils. The e.m.f. in the secondary coil is calculated as

$$e = M \frac{di}{dt}, \quad (9)$$

where  $i$  is the current and  $M$  is the mutual inductance, which is dependant upon the magnetic core and the number of coils. For an input current represented as a sinusoidal signal

$$i = I \sin(\omega t - \phi), \quad (10)$$

to the primary coil, then the e.m.f. for the first secondary becomes

$$v_1 = k_1 \sin(\omega t - \phi), \quad (11)$$

and the e.m.f. of the secondary coil becomes

$$v_2 = k_2 \sin(\omega t - \phi), \quad (12)$$

where  $k$  and  $\phi$  depend on the degree of the coupling between the primary and secondary coils for a specific core position.  $\phi$ , the phase, is the difference between the primary and secondary alternating voltages. The two couplings are in series and their output becomes

$$v_o = v_1 - v_2 = (k_1 - k_2) \sin(\omega t - \phi). \quad (13)$$

When the core is in its central position  $k_1 = k_2$ , and the voltage output is thusly zero. When  $k_1 > k_2$ , the output voltage becomes

$$v_o = (k_2 - k_1) \sin(\omega t - \phi), \quad (14)$$

while if  $k_1 < k_2$ , the voltage output becomes

$$v_o = -(k_1 - k_2) \sin(\omega t - \phi). \quad (15)$$

However, this means that there is a phase shift of  $180^\circ$ , and (15) can thusly be rewritten as [43]

$$v_o = (k_2 - k_1) \sin[\omega t + (\pi - \phi)]. \quad (16)$$

The amplitude of the output from these signals are the same regardless of displacement direction. A phase sensitive demodulator and a low-pass filter is required in order to convert the signal from ac to DC, and gives values that are unique for each displacement [43].

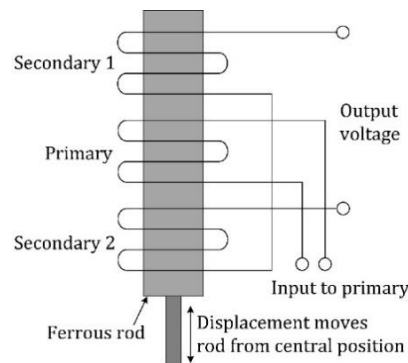


Figure 21: Linear Variable Differential Transformer

A LVDT is an inductive sensor encapsulated in a stainless-steel housing, making it resistant to mechanical, electrical, and magnetic interference. Because it is a non-contact sensor it does not suffer from any mechanical wear and tear, and therefore require little maintenance. Since LVDT is widely used in industries, lots of research has been concluded on it. A LVDT with a metallic glass ribbon has been developed to achieve better performance than controversial devices. A LVDT can be modified and applied for precise measurement in 1D and 2D actuators. In the design process of a LVDT, it is important to reduce the non-linearity of the sensor [44].

### Piezoelectric sensor

A piezoelectric sensor is a contact sensor made of piezoelectric materials, which are comprised of ionic crystals. When a force is applied to these materials, stretching, or compressing them, they generate an electric charge which is proportional to the resulting displacement, and is shown in Fig. 22 a). The stretching or compressing of the sensor charges either side of the sensor, making one of them positively- and the other negatively charged. The charge produced by the sensor results in a voltage output. The charge is calculated as

$$q = kx = SF, \quad (17)$$

where  $q$  is the net charge,  $F$  is the force proportional to the displacement and  $S$  is the charge sensitivity which depends on the material it is made of and the crystal orientation. Both  $k$  and  $S$  are constants [43].

Metal electrodes are placed on either side of the piezoelectric crystal as shown in Fig. 22 b) from, making the calculation of the capacitance of the piezoelectric crystals to

$$C = \frac{\epsilon_0 \epsilon_r A}{t}, \quad (18)$$

where  $\epsilon_0$  is permittivity of free space,  $\epsilon_r$  is the relative permittivity of the material,  $A$  is area and  $t$  is its thickness.

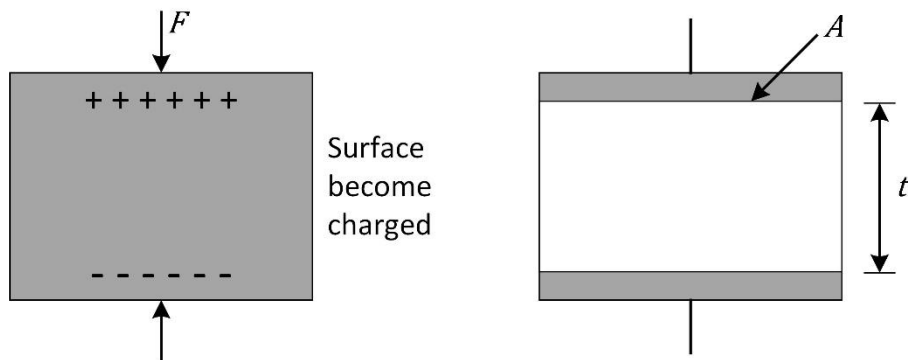


Figure 22: a) piezoelectric material, b) piezoelectric capacitor

The charge from  $q$  (17) is equal to

$$q = Cv, \quad (19)$$

where  $v$  is the potential difference produced across the capacitor, giving

$$v = \frac{St}{\epsilon_0 \epsilon_r A} F. \quad (20)$$

Rewriting  $F/A$  to  $p$  and  $S/\epsilon_0 \epsilon_r$  to  $S_v$ , where  $S_v$  is the voltage sensitivity factor, gives [43]

$$v = S_v t p. \quad (21)$$

These sensors are used to measure pressure, force and acceleration. When pressure is applied to the sensor it becomes charged, but the resistance element the capacitor will discharge over time. This means that the sensor is not suitable for prolonged pressures, and is better suited for measuring changes in pressure that only lasts for a short periods of time. The time it takes for the capacitor to discharge is dependent on the time constant of the circuit. A piezoelectric sensor is therefore suitable for applications that include measuring touch, vibration or shock [43] [45] [46].

## Capacitive element

A capacitive element is a non-contact sensor that consists of two parallel plates, that converts a change in position into an electrical signal. The capacitance of a parallel plate capacitor is given by

$$C = \frac{\epsilon_r \epsilon_0 A}{d}, \quad (22)$$

where  $A$  is the area of overlap of the plates and  $d$  is the distance between them,  $\epsilon_0$  is permittivity of free space and is a constant, whilst  $\epsilon_r$  is the relative permittivity of the dielectric between the plates. From these variables, a capacitive sensor can be used for monitoring linear displacement and will observe one of three events which is the variables from (22). These three is the increase or decrease in the distance between the plates, the change in overlap of the plates, or a change in the permittivity between the plates, which can be caused by the introduction of a dielectric element and is shown in Fig. 23 [43].

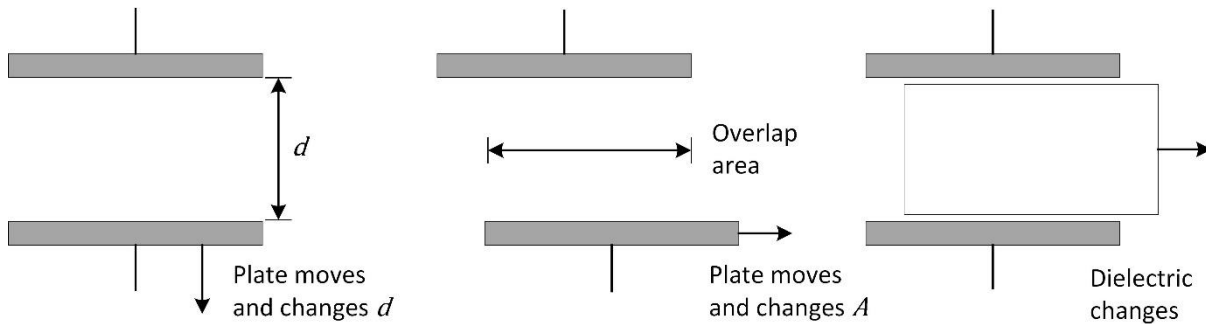


Figure 23: The various events of which the capacitive sensor might detect

The change in the capacitance is calculated by

$$C - \Delta C = \frac{\epsilon_r \epsilon_0 A}{d + x}, \quad (23)$$

which leads to

$$\frac{\Delta C}{C} = -\frac{d}{d + x} - 1 = -\frac{\frac{x}{d}}{1 + \frac{x}{d}}. \quad (24)$$

The relationship between  $x$ , which is displacement, and  $\Delta C$  is however non-linear, but this can be solved by using a push-pull displacement sensor, as shown in Fig. 24 [43] [47].

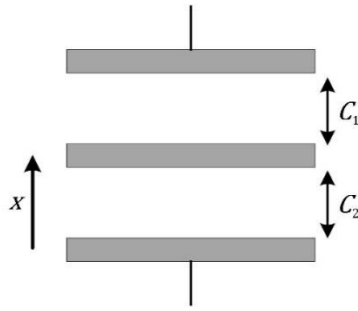


Figure 24: A capacitor push-pull sensor

A push pull sensor is essentially a capacitor with three instead of two plates, where the top and middle plates form one capacitor, and the middle and bottom form a second capacitor. When a displacement occurs, the central plate will move, resulting in for instance in an increase in separation between one of them, whilst decreasing it from the other, this is shown in Fig. 25. Calculating the two capacitances then becomes

$$C_1 = \frac{\epsilon_0 \epsilon_r A}{d + x}, \quad (25)$$

and

$$C_2 = \frac{\epsilon_0 \epsilon_r A}{d - x}. \quad (26)$$

By using an a.c. bridge where  $C_1$  is in one arm and  $C_2$  is in the other, then the displacement  $x$  is proportional to the voltage change [43].

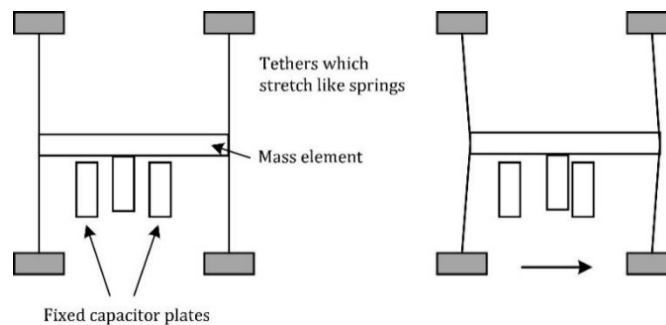


Figure 25: The central capacitor plate moves, decreasing the left-hand capacitor and increasing the right-hand one

These types of sensors can be very accurate, with a resolution in picometers or 0.001% of the full measuring range and a linearity error of 0.01%. Their measuring ranges are however limited to 300  $\mu\text{m}$ . Temperature is consistent around -20 to 80  $^{\circ}\text{C}$  [48] [49].

The applications for which capacitive sensors can be used include proximity, position, displacement, fluid level and acceleration measurements. Advantages of capacitive sensors is that they are non-contact sensors, which means that they require little to no maintenance. They require little power and are relatively small in relation to the distance that it is measuring, and it can be

used to distinguish between different types of materials based upon their relative permittivity. These sensors require the sufficient shielding to not be affected by any other components of the circuit it is a part of, and the circuit need to be designed to meet accuracy specifications and protect the sensor from any effects from the environment [50].

### Eddy current proximity sensors

An eddy current sensor is a non-contact sensor that use the eddy current phenomenon to measure distance. It is used to for measurements against electrically conductive, non-ferromagnetic materials. The sensor applies high frequency current to the coil in the sensor head to produce a high-frequency magnetic field. If a magnetic measurement object is in proximity of the sensor head, the eddy current is induced into it. This results in a change of impedance of the coil in the sensor head. The eddy current sensor measure distance based on the change in oscillation caused by the eddy current [51].

An alternating magnetic field is produced if the coil in the sensor is supplied with an alternating current. If there is a magnetic object close to the alternating magnetic field, the eddy currents are induced in it. The eddy currents produce a magnetic field that distorts the magnetic field responsible for their production. This results in changes in the impedance of the coil and the amplitude of the alternating current. This can be used to trigger a switch at a pre-set level. This kind of sensor is used for detection of non-magnetic but conductive materials. The basic form of an eddy current sensor is shown in Fig. 26. The advantage of this type of sensor is that it is relatively cheap, small size, high reliability and can have high sensitivity to small displacements [43].

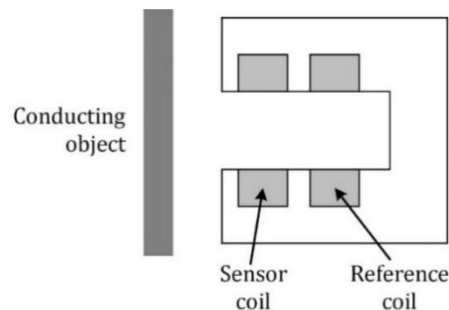


Figure 26: Basic illustration of an eddy current sensor

### Hall effect sensor

The Hall effect sensor is a non-contact sensor and are available in analogue and digital output.

Hall effect sensors use the principle of converting magnetically encoded information into electrical signals. When electric current flows through a material, the electrons in the current moves in a straight line, creating a magnetic field as it charges. If the electrically charged material is placed between the poles of a permanent magnet, the electrons will instead move in a curved path when they move through the material. This is a result of the materials magnetic field reacting with the magnetic field of the permanent magnet. The deflected electrons are move to one side of the material, making it negatively charged and the opposing side positively charged, see Fig. 27. This produces an electric field in the material. The charge separation continues until the forces from the

electric field balance out the forces of the magnetic field. This results in a transverse potential difference  $V$  given by

$$V = K_H \frac{BI}{t}, \quad (27)$$

where  $K_H$  is a constant (Hall Coefficient),  $B$  is the magnetic flux density,  $I$  is the current through the plate and  $t$  is the thickness of the plate. If a constant current is applied to a particular sensor, the Hall voltage is a measure of the magnetic flux density [43].

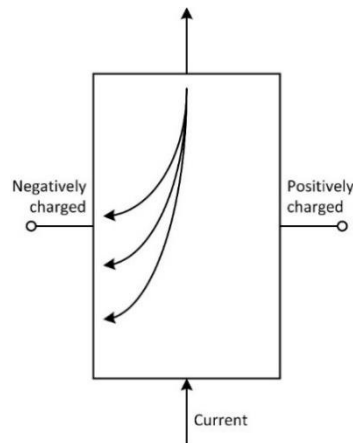


Figure 27: Potential difference in the plate caused by deflection of electrons

There are two different types of Hall effect sensors, linear and threshold. Linear is where the output varies in a linear manner with the magnetic flux density, and threshold is where the output has a sharp drop at a particular magnetic flux density, as shown in Fig. 28 [43].

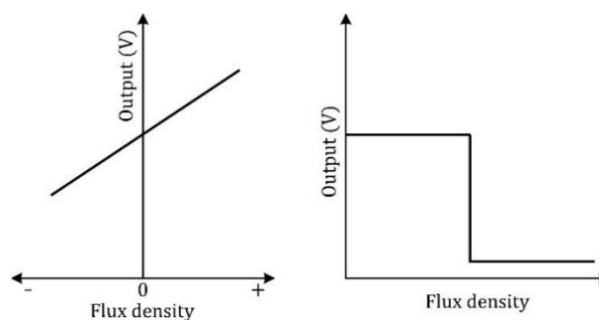


Figure 28: Hall effect output, linear and threshold

Hall effect sensors are activated in the presence of a magnetic field. The sensor is able to sense the distance of an object through the differing strengths in the magnetic field. A Hall effect sensor can be used to measure displacement, position, and proximity if the measured object has a permanent magnet fitted to it [52].

This kind of sensor has a lot of applications. They are often used in automotive systems to sense position, distance, and speed. The most notably field these sensors are used in is anti-locking systems (ABS), and to assist the ignition timings in a combustion engine. Hall effect sensors can also be used in smartphones to detect flip covers. When the flip cover is closed, the magnet in the cover

is brought towards the hall effect sensor in the phone. The sensor then detects the magnetic field and turns the screen off [52].

Appendix G1. Supplier list

Supplier	Contact information	Comment
Tronrud engineering	Address: Flyplassveien 21 3514 Hønefoss, Norway Phone: +47 32 16 18 20 Mail: mail@tronrud.no	A Norwegian firm, known for producing parts additively by using DMLS machines
Sandvik	Address: Sandvik Machining Solutions AB Package station 5322 811 81 Sandviken, Sweden Phone: +46 26 26 00 00	A Swedish firm, have been a supplier for CNC tools for many years, started with AM a couple of years back.
3dhubs	<a href="https://www.3dhubs.com/">https://www.3dhubs.com/</a>  Phone+44 20 3966 9208 Mail: saleseu@3dhubs.com.	An American/European firm that list suppliers of AM as well as gives you a price estimate. Are being used by some big companies such as Audi and ABB. IP protection is ensured for parts sent to them.
3dmetprint	<a href="https://www.3dmetprint.com/">https://www.3dmetprint.com/</a>  Mail: erling.svensson@3dmetprint.com Phone: +46 76 128 55 38 Address: Box 602 (Stallgatan 2) SE-343 24 Älmhult, Sweden	A Swedish 3D printing firm, can take total responsibility for the targeted object, that is both the 3D-printing and finishing / machining of the 3D-printed piece.
Qimtek	<a href="https://www.qimtek.se/suppliers/search">https://www.qimtek.se/suppliers/search</a>  Address: Svärdvägen 9182 33 Danderyd Phone: 0651-300 800 Mail: support@qimtek.se	A Swedish supplier

## Appendix I1. Design considerations for additive manufacturing

The purpose of this appendix is to give the reader some basic guidelines and consideration when designing for additive manufacturing. This document will consist of a general guide for additive manufacturing, design concepts and an excel sheet in Appendix L1 has been made based on the information in this document.

### General workflow for additive design

The first step is to create a 3D model in a CAD software or obtain it otherwise, then it will be sent to the slicer where it will be sliced into slices starting from the bottom and working its way up the model until it reaches the top. The model will now be a 2.5D part this means that there are several 2D lines stacked on top of one another. The 2D lines of each slice represents the toolpaths for the printer on that layer, after it is done with that layer it will move the Z-axis up the predefined layer height and start on the next layer building on top of the last. This is the reason for calling it a 2.5D operation because it will just move a maximum of 2 axes at the same time [86].

After it has been in the slicer a g-code will be generated based on the inputs, the g-code will contain positional information about the model for each layer as well as the position of the support material and other slicer generated settings for example heat, material flow, build plate temperature, etc.. After the g-code has been generated for the part, the next step will be to send it to the printer and wait for it to be produced. After the print is finished you can either start using your part, but most part will need some post-machining or other aftertreatments of the part.

### Design in CAD software and Slicer

First of all a slicer is a software that takes the 3D model and turns it into a 2.5D model. This means that the model will be sliced into layers with a specified thickness and then the software will stack them on top of one another until the layers will resemble the 3D model.

After this is done the slicer software will have many options for the operator to tune the g-code for the optimal production of the parts, it will also include a lot of options for the design of the part too. It is in the slicer the support structure is generated and modified. There are a lot of options for the different structures and forms of the support structure, one of the more interesting is the trees option. This option will build “trees” with branches from the build plate that will support overhangs, holes, etc. the benefit of this is that the operator will be able to avoid having support material ruining the surface under the feature that needs support. You can also decide the density, strength and shape of the support material. It can also be printed in another material so that the support material can be removed chemically [87].

For some processes, the slicer will be used to choose what kind of build plate adhesion the part should have. There are a lot of option but in fused deposition machining (FDM) printing and other processes that involve a part being built up from a build plate. The most common of them are, *Brim*, which adds a single layer around the base of the model to prevent the part from warping. *Raft*, which adds a thick grid with a roof between the model and the build plate. This can be used when the bottom surface of a model is not completely flat or has little adhesion to the build plate for example a long thin cylinder. *Skirt*, which is a couple of lines printed around the model on the first layer, but it is not in contact with the model. This is mostly used as an additional check for bed leveling before the print begins, this mean that the building plate must be flush and parallel to the

X- and Y- plane coming out from the machine's origin. If not the print may be printed in the air or the first layer will be squeezed out and lose its intended shape and size.

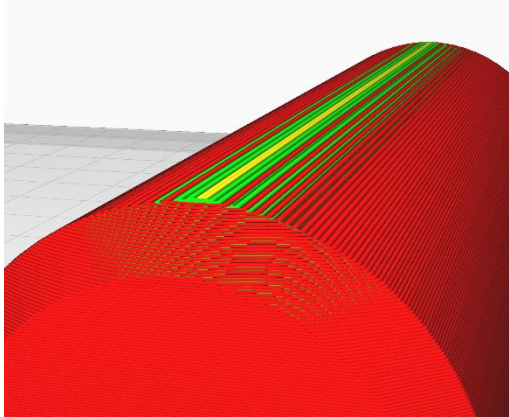
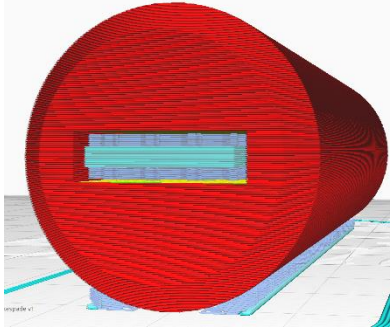
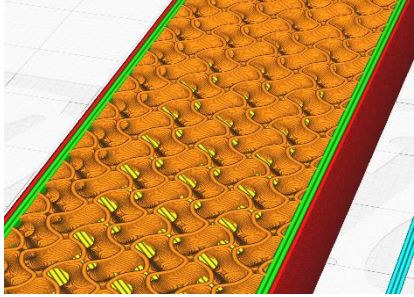
The next design step will be to decide if the part will be solid or have internal geometry often called infill. If infill is chosen there will be some choices that the operator will have to choose, for example the density, pattern, grid thickness, shell thickness, etc.. There are also options for specifying places that need extra strength and have a tougher or denser infill structure. Although to gain the most from the internal geometry it will have to be created in a CAD/simulation software and added to the part before sending it to the slicer. This method will ensure that the part will have the optimum internal geometry based on the forces it is modelled to experience.

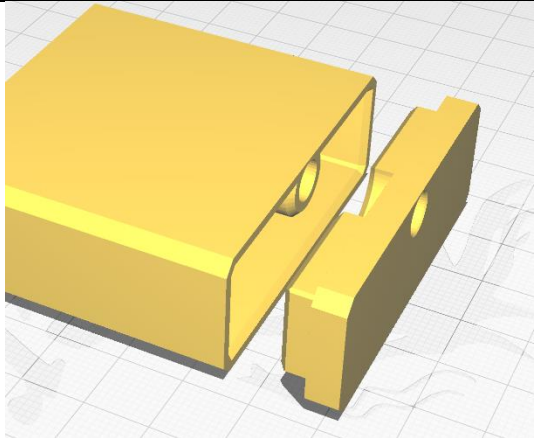
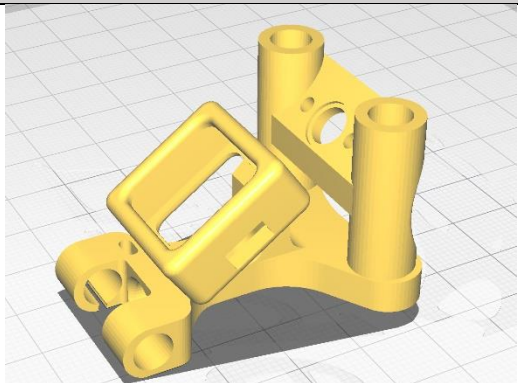
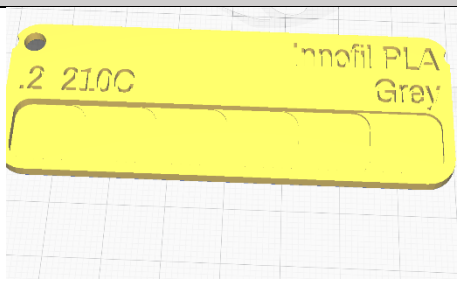
The slicer is also what decides the resolution of the part in the Z-axis (vertical), since it is here you choose the layer height, the lower the layer height the finer the details in the Z-axis will be.

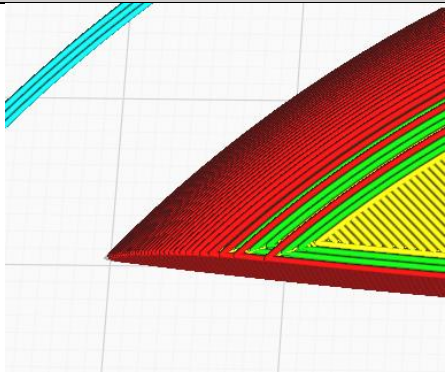
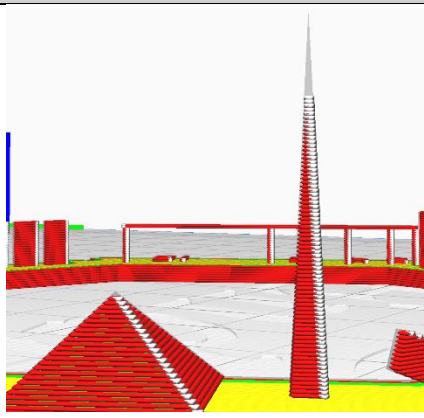
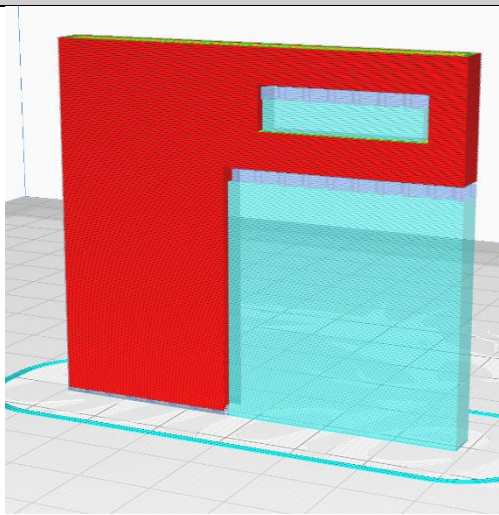
### **General design considerations**

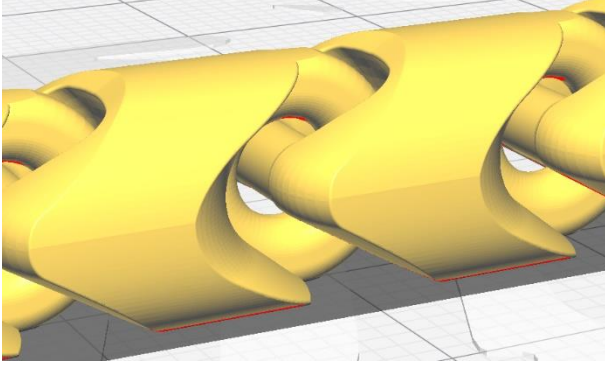
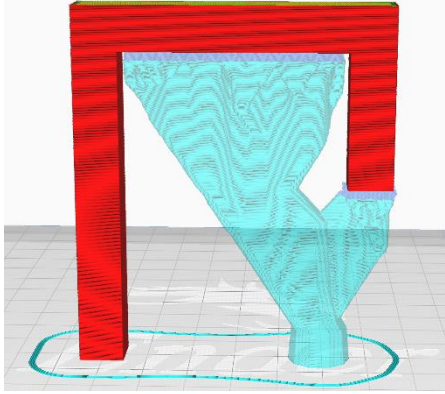
In this chapter some general design considerations for AM will be presented. They will be generalised to suit a wide range of additive production processes. The guidelines presented, which is shown in Tab. 60, in this paper will be based on multiple previous guidelines for design of additive manufactured parts [88] [89] [90] [91] [92].

Table 60: The design considerations

Principle	Description
<p data-bbox="201 282 432 315">Orientation of part</p> 	<p data-bbox="839 327 1390 521">When designing a part that will be produced additively the designer should be aware what orientation the different shapes will be printed best in, but sometimes there is no optimal way [88] [93] [94] [95].</p> <p data-bbox="839 533 1374 891">When choosing the orientation of the part the designer should also be aware that the orientation of the part will influence the surface finish of the part. If a cylinder is printed laying flat the layer lines will be very noticeable along the top and bottom of the part. But if it is printed standing up the surface of the cylinder will be much smoother [93] [96] [97] [98] [99].</p> <p data-bbox="839 902 1390 1178">The designer should also be aware of the anisotropic properties of AM parts when designing and choosing the orientation of the part. This property comes from the way AM parts are made, layer by layer. This means that the part will usually have less strength in the vertical axis it was printed in [93] [96].</p>
<p data-bbox="201 1189 547 1223">Removal of support material</p> 	<p data-bbox="839 1234 1390 1552">The surface finish of the parts that have been in contact with the support structures will be reduced. It will also add time and cost to the post processing of the part. Knowing how the machine and the material behaves when printing at different angles will let you reduce the amount of support structures [90] [98] [99] [93] [95].</p>
<p data-bbox="201 1576 467 1610">Hollow parts and infill</p> 	<p data-bbox="839 1619 1382 1850">If the intended use of the part allows it, it is possible to make the part hollow in the slicer and add an infill pattern. There are a lot of different infill patterns, some will give the part more strength in one direction while others serve a more cosmetic role.</p> <p data-bbox="839 1861 1382 2018">The infill pattern can also be generated from a finite element analysis results, giving the part more strength in an area that is subjected to a known force [93] [94] [100].</p>

Manufacturing features	
	<p>Although AM gives the designer a lot of freedom, the designer should be aware that a fair number of AM parts are prototypes and may be mass produced with another method. This means that the designer should consider the manufacturability of the produced part in comparison to the manufacturing process if the part is a prototype [93] [94] [101].</p>
Interlocking features	
	<p>Most additive production processes have a finite building volume, this means that some parts may be too big to be printed in one piece. The designer can then divide the part into sections and incorporate interlocking features between them, dovetails, splints, weldments, etc.. The designer should try to minimise the amount of support material generated in the interlocking features, since they will reduce the surface quality of the interlocking features [94] [90].</p>
Reduction of parts in an assembly	
	<p>The designer may choose to design the assembly as one part instead of multiple or combine two parts into one. This can also help solve some of the problems with threaded holes or other features that require exact tolerances, for example a part that needed to be mounted to the assembly can be designed as part of the assembly. This means that you no longer need to mount that part since it is already an integrated part of the assembly [93] [90] [94].</p>
Part ID marks	
	<p>If a company is producing a large number of different parts in the same printer, the designer has the ability to produce them with ID marks straight from the printer. For example, if a company is producing two almost identical parts, but one has an 29mm hole and another a 30mm hole, it can be difficult to distinguish them from each other. Therefore an ID marking will make part identification easier [94].</p>

Avoid sharp edges	
	<p>This is because sharp edges will be subjected to the inertia of the mass that is being redirected when the printer lays down material. In other words, the printer will overshoot its intended stopping point making a designed sharp edge rounded.</p> <p>This applies to all methods that must move something with a mass in order to move the position. Most laser AM technologies do not have this problem since they are using mirrors to control the position of the laser beam [90]. They do however have some of the same problems since to laser beam spot is circular.</p>
Round inner edges	
	<p>This will make the removal of dispersive support material such as powders easier [90].</p>
Mane pointy features blunter	
	<p>Pointy features should be blunted according to their orientation. Horizontal points should be blunted parallel to the build plate, and vertical points should be blunted orthogonal to the building plate.</p> <p>Thin features like points will usually brake. Having points is not a problem, but having extremely pointy features (&lt; 2 mm) can be a problem [90].</p>
Design short overhangs	
	<p>This makes sure that the part will not use more support structures than needed. Support material will ruin the surface finish, therefore it should be kept to a minimum. It also makes sure that the material will not slope down in the case of printing unsupported features [90].</p>

<p>Print in place</p> 	<p>The nature of AM will allow the designer to design parts that are manufactured connected to one another. One example of this will be that one can print chain links already connected to each other straight from the build plate. This will allow the designer to design parts that previously would not be possible.</p>
<p>Low island position</p> 	<p>An island is a part of a printed part that is being built above the starting point of the main part. This means that the island will be entirely supported by support material until it reaches a higher layer which brings the island in contact with the main part. The problem with low island positions is that they will have a significant impact on the build time of the part, because the printer will have to make all the support structure for the island [90].</p>

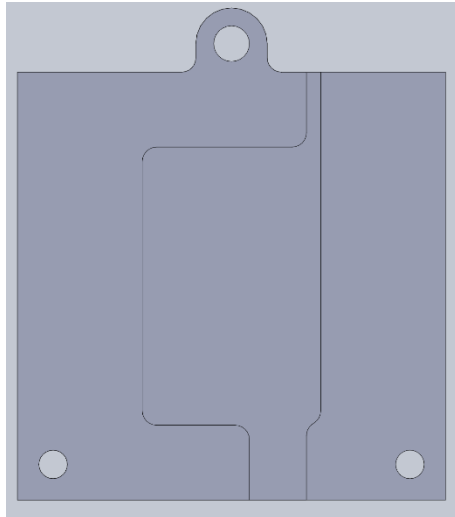
## Design concept

### Incorporating electronic components in 3D prints

Another option which AM enables designers to do is to incorporate electronic components inside the 3D printed part. This can only be done in certain AM processes. This will open a lot of doors for electromechanical design. There are a lot of emerging technologies in this field, such as the ability to print flexible electronic parts and the ability to print the electronics directly into the print. This requires special machines and are mostly used in the medical field. The method discussed here are going to be a lot simpler, we are going to use a fused deposition machining (FDM) printer to imbed an electronic part inside of the 3D printed part [102].

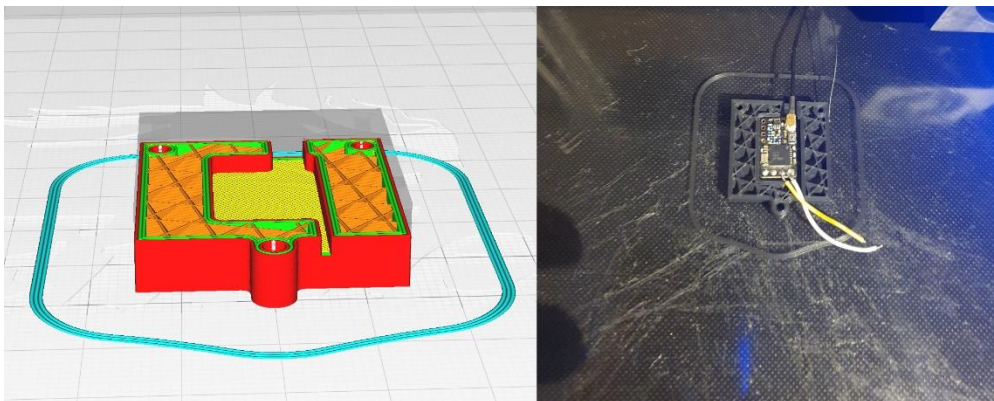
In this chapter a case will be presented, and we will follow its journey from idea to functional part. The object is to embed a TBS crossfire nano receiver inside its antenna mount. The reason for this is to protect it from impacts during take-off and landing, since its intended use is as a control and telemetry link for a drone. It will also help with the noise in the signal since you get to mount the receiver away from other electrical components and carbon fibre structures.

The first step is to design the model in a CAD software and make the internal space for the electronics we are going to imbed shown in Fig. 64.



*Figure 64: The place in the middle of the part is where the electronics will go.*

After the CAD model is created it will be sent to the slicer. In the slicer one will see how the part will be sliced into layers. Then one needs to identify what layer the roof over the electronics will be printed at. This information will be available in the slicer software, after the roof layer is identified the G-code will have to be modified. The modification will simply stop the print at that layer and wait for the input from an operator before moving on, this allows the electrical part to be put inside the print before it starts laying down the next layer. After this is done one should follow the machine closely the first layer to make sure that it will not collide with the electrical part. When the print is ready one will have an antenna and some wires sticking out of the antenna mount and the TBS crossfire nano will be imbedded into it. Then all that is needed to do is to solder the wires to the flight controller and then mount it with two M2 screws into the fuselage, as shown in Fig. 65 and the finished part in Fig. 66.



*Figure 65: On the right the model in the slicer showing the layer the printer will stop at and on the left the TBS crossfire nano RX on the build plate.*

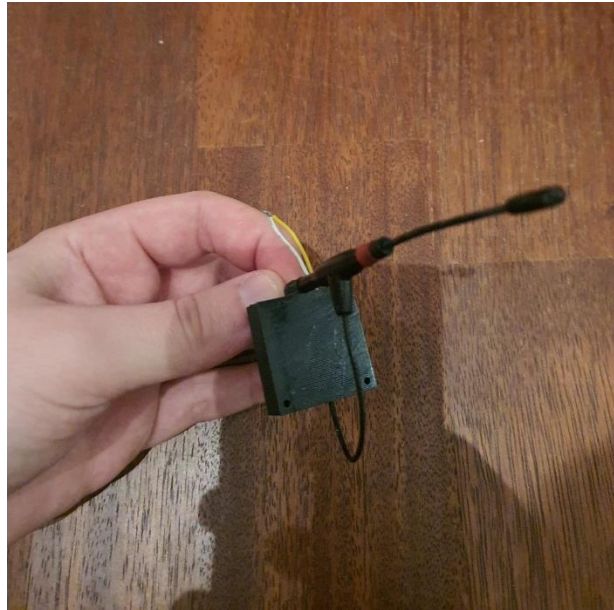


Figure 66: The final part ready for soldering and mounting.

### Identifying the complexity of a part

A way to show some of the thoughts that a designer must consider when designing parts that will be produced additively is the concept of taking the complexity out of the part. Here it will be demonstrated with a triangle. In Fig. 67 you will see that it is a solid triangle, this will take almost 10 hours to print as well as using 57g of material. The part is not very complex either, this is not an effective design for a part that will be produced additively.

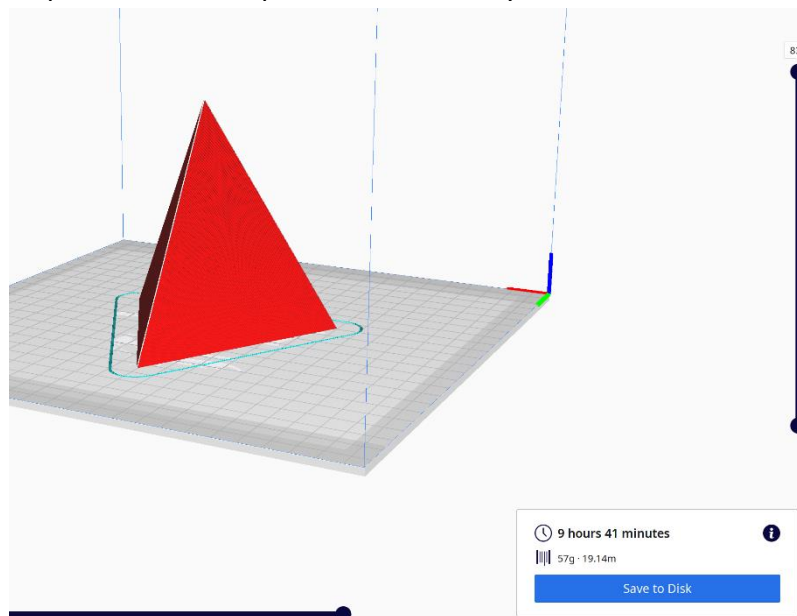


Figure 67: The first step, the material mass is 57 g and print time is 9 hours 41 minutes

In Fig. 68 you can see that we have removed a lot of mass and volume from the triangle while still maintaining most of its strength. The print time has gone down with more than 30% and the material it will use have been cut in half to 25g. This part is substantially more complex than the one

shown in Fig. 67. Producing it with a CNC mill will require it to have multiple repositioning's in the clamp. This part is starting to make sense to produce additively, but it can still be optimized more.

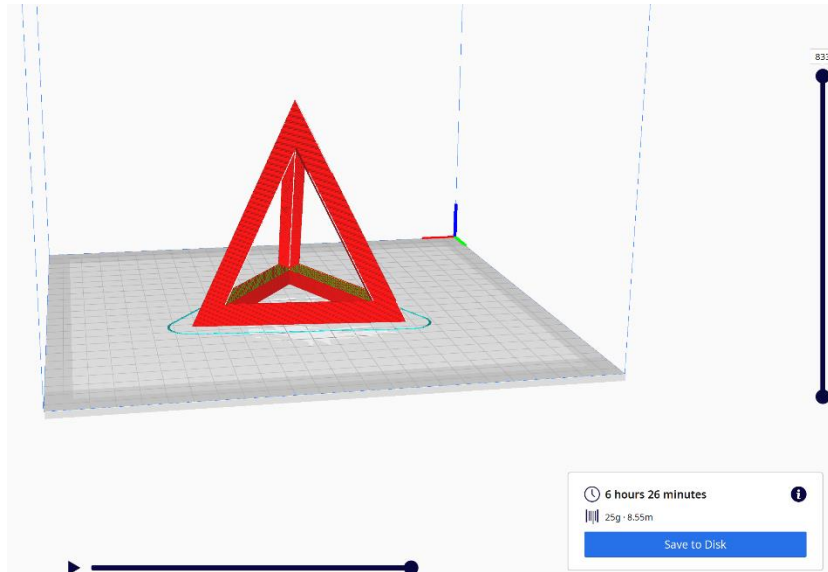


Figure 68: The second step, the material mass is 25 g and print time is 6 hours and 26 minutes.

In Fig. 69 you will see some radical changes to the design. Here the complexity is drawn out of the part. This means that we have identified the specific areas that contain the complexity in the part and taken them out for additive manufacturing. This leaves us with the parts that have the least amount of complexity, in this model it will be the sides of the triangle. The designer should then try to look for a common stock material shape to fill in the parts that are not complex enough for additive manufacturing. For example, steel rods or square tubes. Here in Fig. 69 we can see that the print time is just 30 minutes or about 5% of the original time, but the biggest change is that the amount of material needed for the part is now just 1g or less than 2% of the original part.

Another benefit of this design method is that material testing and qualification will just have to be done on the parts that are produced additively, since the stock material is usually already qualified or have documented properties. And since the parts in Fig. 69 are so small compared to Fig. 67 and Fig. 68 the cost of production of an extra set of parts shown in Fig. 70 for destructive testing will be achievable.

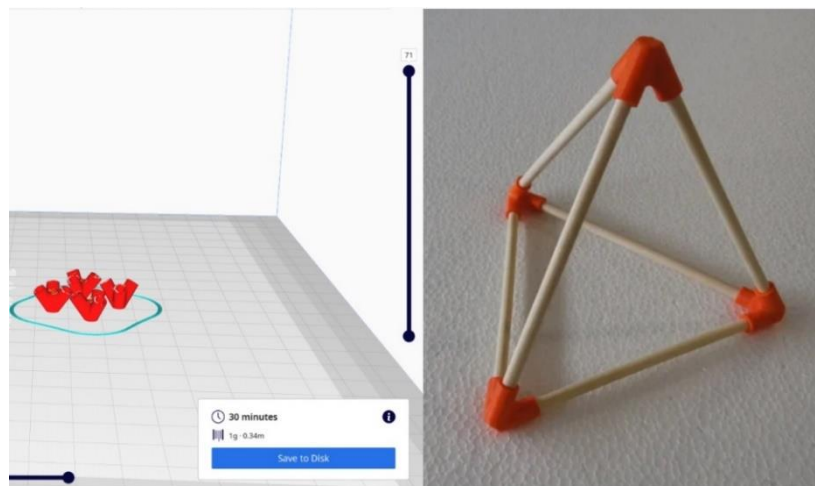


Figure 69: The last step, here the material mass is 1 g and the print time is 30 minutes

Qty	Unit Price	Total Price
1	€178.09	€178.09
2	€104.62	€209.24
5	€58.19	€290.95
10	€41.67	€416.70
25	€31.11	€777.75
50	€26.77	€1,338.50
100	€24.06	€2,406.00
200	€21.04	€4,208.00
300	€19.58	€5,874.00
400	€18.63	€7,452.00
500	€17.93	€8,965.00

Figure 70: The bulk price of production of the third step

### Threads and mating surfaces

Threads and mating surfaces are something that 3D printers struggle with because they usually have some geometric requirements associated with them. To solve this problem the designer will have to design parts that are combined instead of having mating surfaces, as this will make the geometric tolerance between them irrelevant. For threads, the designer should try to incorporate other forms of mounting or fixtures, dove tails and other solutions should be considered.

### 3D printed tools: A viable option of implementing AM in subsea

One aspect of additive manufacturing one should be aware of is the manufacturing of tools or to help in assembly, installation, testing or prototyping. This can give the subsea sector value today. If one can make an installation process which previously needed five people into a one- or two-person job with the use of a plastic part costing 100 NOK or produced on a printer costing 5000 NOK, this could prove to be extremely profitable. In an example case a sensor will be fitted to a large metal structure in duplex offshore. This process usually takes 5 people to complete since the metal structure is so large that it is difficult for one person to mount it with the intended straps. Those 4 other people will just aid in the process of installing the sensor, this means that they can be used for better tasks. The first step should be to see if someone is doing a purely static job such as holding the sensor bracket or the straps. Then the next step should be to see if something can be designed that can do that job adequately. Duplex is a magnetic alloy so the same concept from the chapter about integrating electronical components in 3D printed parts can be used for magnets or just design holes and glue the magnets in place. If the material is non-magnetic the use of glue might be considered. If this enables this to be a one- or two-person job in the same or shorter time, this one installation will have paid for the part and the machine many times over. This would also allow the field operator to make his own tools, fixtures and jigs. Making him able to faster, safer and better perform his job.

Another job which can be done with a 3D printer is to make costume fixtures for CNC clamps, this will make the production of complex CNC parts easier, this can either be done in plastics or metals. The need for high precision in the fixtures in a CNC machine may require the part to be machined after production to ensure that it has the exact geometry. This will however speed up the process substantially compared to sourcing it from a third party that will produce it conventionally. Another workshop utilization for additive manufacturing is in the making of costume grips for orienting or transferring a part that is in assembly. The grips and fixtures can be made in plastic if the part that it will contact is a soft metal and one needs to make sure that it is not damaged in the clamps. This can make the job of the manufacturer faster, cut down the lead time and price for tools and tooling.

## Appendix J1. Cost analysis

The two main cost models for AM are Hopkins and Dickens (HD), and Ruffo. HD estimates the average cost for one part, by assuming that the system produces only a single type of part for an entire year, that it builds at its maximum volume, and that the system is operational for 90% of the time. This includes man-hours, material, and machine expenditures. The cost of power consumption and facility rental were so negligible that they were not included in the results. The average cost of a part is calculated by dividing the total cost by the number of parts produced for one year. The various costs are divided into machine-, labour- and material cost. The methods that were utilised to calculate this were stereolithography, FDM and SLS, and would produce a lever and a cover. What HD found was that the major expenditure for SLS was material, whilst for SLA and FDM it was machine cost. SLS was found to be the cheapest. All formulas and information in this part is from [103].

### Machine cost per part

To find the machine cost, it was assumed that the machine would be replaced after some time, thereby an estimate of machine cost per part is calculated as

$$C_{pp} = \left( \frac{M_C + A_C}{t} \right) + \left( \frac{M_M}{P_V} \right), \quad (31)$$

where  $C_{pp}$  is expenditure of machine per part.  $M_C$  is the cost to buy a new machine.  $A_C$  is the cost of any ancillary equipment.  $t$  is time in years.  $M_M$  is maintenance cost of the machine per year.  $P_V$  is the machines yearly production volume [104].

### Ruffo's methods

Ruffo is an activity-based cost model. Each activity is related to a cost. Ruffo produced the same lever as HD, using SLS. Determining the cost of an AM part, using SLS is calculated as

$$C = P_m M + P_i T, \quad (32)$$

where  $C$  is the total cost of the build.  $P_m$  is the cost of the raw material.  $M$  is mass.  $T$  is total build time in hours.  $P_i$  is the indirect cost rate per hour [€], which can be for instance the cost of production labour/machine hour, machine costs, production overhead or administrative overhead. Additionally, it was assumed that the machine worked 100 hours per week for 50 weeks per year, i.e. 57% utilisation. A diagram for the cost of an AM build can be seen in Fig. 71, here it is clearly shown what can be meant by direct- and indirect cost [104].

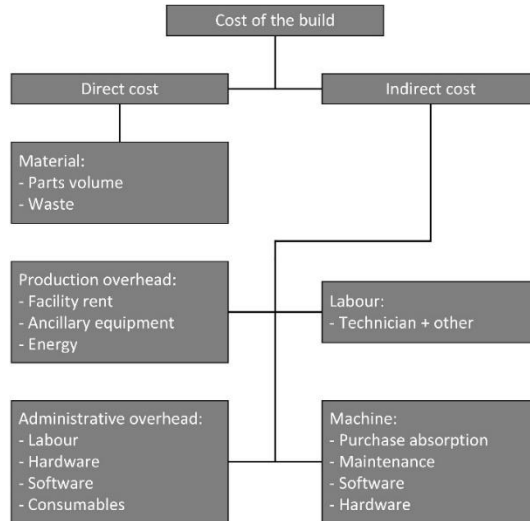


Figure 71: AM build cost

Commonly the cost of production is assuming a scenario where only type of part is produced at any given time, where the cost per part is calculated to be the total cost divided by the number of parts. However, when using AM there is the possibility to utilise the entire build platform, which means that many different parts can be stacked up where it is possible. Ruffo compared three different methodologies for determining cost of building different types of parts simultaneously, the first of them are calculates in the various parts volume as

$$C_{p_i} = \frac{V_{p_i}}{V_B} C_B, \quad (33)$$

where  $C_{p_i}$  is cost of part  $i$ .  $V_{p_i}$  is volume of part  $i$ .  $V_B$  is volume of the total build.  $i$  is an index going from one to the number of parts in the build.  $C_B$  is calculated as

$$C_B = \sum \frac{P_i}{W_t} (t_{xy} + t_z + t_{HC}) + \frac{C_D}{m_u} m_B, \quad (34)$$

where  $m_B$  is the mass of the planned production proportional to the object volumes, and  $W_t$  is the time to manufacturing the entire build.  $m_u$  is the mass of each individual part or unit on the build plate.  $C_D$ , is direct cost, as seen in Fig. 71.  $t_{xy}$  is the time to laser-scan the section and its border to sinter powder.  $t_z$  is the time to add layers of powder.  $t_{HC}$  time to heat the bed before scanning and to cool down after scanning and adding layers of powder. I.e.  $t_{xy}$ ,  $t_z$  and  $t_{HC}$  is the total time spent on the build. However, (34) can also be calculated with (33) [104].

Calculating the cost of a single part, the third method is used, and is calculated as

$$C_{p_i} = \frac{\gamma_i C_B}{n_i}, \quad (35)$$

where

$$\gamma_i = \frac{C_{p_i}^* n_i}{\sum_j (C_{p_j}^* n_j)}, \quad (36)$$

where  $\gamma$  is the part and  $i$  is the part index being calculated.  $n_i$  is the number of parts with index  $i$ .  $j$  is the index of all produced parts.  $C_{p_i}^*$  is the cost of a single part  $i$ , calculated in either (32) or (34) [104].

Calculating the cost of a mass-produced part as

$$C_{p_i} = \frac{\gamma_i^\infty C_B}{n_i}, \quad (37)$$

where

$$\gamma_i^\infty = \frac{C_{p_i}^\infty n_i}{\sum_j (C_{p_j}^\infty n_j)}, \quad (38)$$

where  $\gamma_i^\infty$  is instead of a single part, it is a high number of parts.  $C_{p_i}^\infty$  is a number approaching infinity, i.e. a high number of produced parts  $i$  [104].

It has however been found that method three was superior to the other two methods. This was because the other two methods resulting in an estimate that reduced the cost of larger parts, to the detriment of smaller parts. The third method was therefore identified as the method that most accurately estimating the per part cost [104].

### Allen's method

In certain industries, like the aerospace industry, costly high performing materials are necessary to use. These materials can be costly to not just to purchase, but also to machine into parts. The cost for producing NNS calculated as

$$C_s = (V\rho C_f)(V - v)\rho C_m, \quad (39)$$

where  $C_s$  is the cost of producing a NNS using machining.  $V$  is the volume of original billet and  $v$  is the volume of the component part, but note that  $(V - v)$  is the BTF.  $\rho$  is the density of titanium.  $C_f$  is the cost of ring rolled forged material.  $C_m$  is the cost of machining. The cost of producing NNS using AM is calculated as

$$C_a = v\rho C_d, \quad (40)$$

where  $C_a$  is the cost of producing a NNS using AM.  $v$  is the volume of component part.  $\rho$  is the density of titanium.  $C_d$  is the specific cost of deposited titanium [104].

Using (39) and (40), it was found that with a BTF of 8.33%, AM was more cost effective than machining, because these methods can have a BTF even lower than 8.33%. The conclusion is that AM can be preferable in relation to producing parts with high material cost, high BTF, have complex geometry, needs much machining, and are slow to produce with machining [104].

## Supply chains

Examining costs of machines and material might leave a few stones unturned. Many of the advantages, or possible disadvantages, might not be apparent in the previous methods. This is in relation to inventory and supply chains, i.e., logistics. In many different production chains, there are lots of time wasted in relation to transportation, storage time, and other time-consuming events that are not directly related to production and return on investments [104].

Another aspect of AM, that is also not apparent in any cost formulas, is its ability to produce products that are many times more complex than machining. This is due to machining being for instance its inability to change direction when drilling. AM simply does not have this limitation, because it simply does not print the holes, but rather the material around [104].

In the future, AM might even build entire builds by itself, and might therefore eliminate the need for any supply chains, or at least limit them. This method therefore means to understand the important aspect of the process from raw material extraction and all the way to its final state as a finished product. This is calculated for AM as

$$C_{AM} = (MI_{R,AM} + MI_{M,AM}) + (P_{E,AM} + P_{R,AM} + P_{M,AM}) + (FGI_{E,AM} + FGI_{R,AM} + FGI_{M,AM}) + WT_{AM} + RT_{AM} + T_{AM}, \quad (41)$$

where  $C_{AM}$  is the cost of producing an additive manufactured product.  $MI$  is the cost of material inventory for refining raw materials ( $R$ ) and for manufacturing ( $M$ ) for AM ( $AM$ ).  $P$  is the cost of the process of material extraction ( $E$ ), refining raw materials ( $R$ ), and manufacturing ( $M$ ), including administrative costs, machine costs, and other relevant costs for AM ( $AM$ ).  $FGI$  is the cost of finished goods inventory, for material extraction ( $E$ ), refining raw materials ( $R$ ), and manufacturing ( $M$ ) for additive manufacturing ( $AM$ ).  $WT_{AM}$  is the cost of wholesale trade for AM ( $AM$ ).  $RT_{AM}$  is the cost of retail trade for AM ( $AM$ ).  $T_{AM}$  is the transportation cost throughout the supply chain for an additive manufactured Product ( $AM$ ). A comparison for traditional production methods is calculated as

$$C_T = (MI_{R,T} + MI_{I,T} + MI_{A,T}) + (P_{E,T} + P_{R,T} + P_{I,T} + P_{A,T}) + (FGI_{E,T} + FGI_{R,T} + FGI_{I,T} + FGI_{A,T}) + WT_{Trad} + RT_T + T_T, \quad (42)$$

where  $C_T$  is the cost of producing a product using traditional processes. The variables are the same for (42) as they are in (41), but with a consideration for traditional processes like CNC machining [104].

Where the cost of AM process cost is well understood, the other aspects of cost are less so. Examining this might be worthwhile, because some of the areas where AM might be most cost effective might be in relation to shortening supply chains, reducing lead time, and being less dependent on delivery of multiple parts to assemble the finished product. Especially the latter point, where AM might be utilised to assembling an entire product and might not need several parts to make a whole. This will also have further repercussions, where cost of transportation, assembly, and staff will be reduced. Another aspect is that the infrastructure network will have less chance of bottlenecks [104].

In order to understand the benefits of using AM there is a need to capture and analyse the products full life cycle.

### The total advantage of additive manufacturing

When producing a product, resources, land, time, and labour is expended. Product with short life cycle also demands more resources, land, time, and labour. When a product reaches the end of its life cycle, and is no longer useful, resources might also be required for disposal. Utilising AM might enhance products, enable more abilities, or even extend their respective life cycles [104].

The total advantage is measured in the difference between the usage of land, labour, production time, utilisation, and disposal combined with the utility given by the product, compared to that of machining. This advantage is calculated as

$$TA_L = (L_{AM,P} + L_{AM,U} + L_{AM,D}) - (L_{T,P} + L_{T,U} + L_{T,D}) \quad (43)$$

$$TA_{LB} = (LB_{AM,P} + LB_{AM,U} + LB_{AM,D}) - (LB_{T,P} + LB_{T,U} + LB_{T,D}) \quad (44)$$

$$TA_T = (T_{AM,P} + T_{AM,U} + T_{AM,D}) - (T_{T,P} + T_{T,U} + T_{T,D}) \quad (45)$$

$$TA_U = U(P_{AM}) - U(P_T) \quad (46)$$

where  $TA_L$  is the total advantage of AM compared to traditional methods for Land ( $L$ ), labour ( $LB$ ), time ( $T$ ), and utility of the product ( $U$ ).  $L$  is the land or natural resources needed using AM processes ( $AM$ ) or traditional methods ( $T$ ) for production ( $P$ ), utilisation ( $U$ ), and disposal ( $D$ ) of the product.  $LB$  is the labour hours per hour needed using AM processes ( $AM$ ) or traditional methods ( $T$ ) for production ( $P$ ), utilisation ( $U$ ), and disposal ( $D$ ) of the product.  $T$  is the time needed using AM processes ( $AM$ ) or traditional methods ( $T$ ) for production ( $P$ ), utilisation ( $U$ ), and disposal ( $D$ ) of the product.  $U(P_{AM})$  is the utility of a product manufactured using AM processes, including the utility gained from increased abilities, enhancements, and useful life.  $U(P_T)$  is the utility of a product manufactured using traditional processes, including the utility gained from increased abilities, enhancements, and useful life [104].

However, production also entails material extraction, refining, manufacturing and transportation, among other factors. One of the flaws in this method is that it falls short of being able to capture all aspects of the factors that need to be compared in order to state that  $TA_L$  is actually total. Another factor is that various variables are measured in different units, like land, labour, and time, making them difficult to compare [104].

### Cost comparison overview

To explicitly display the differences of the cost models, the graph in Fig. 72 was made.

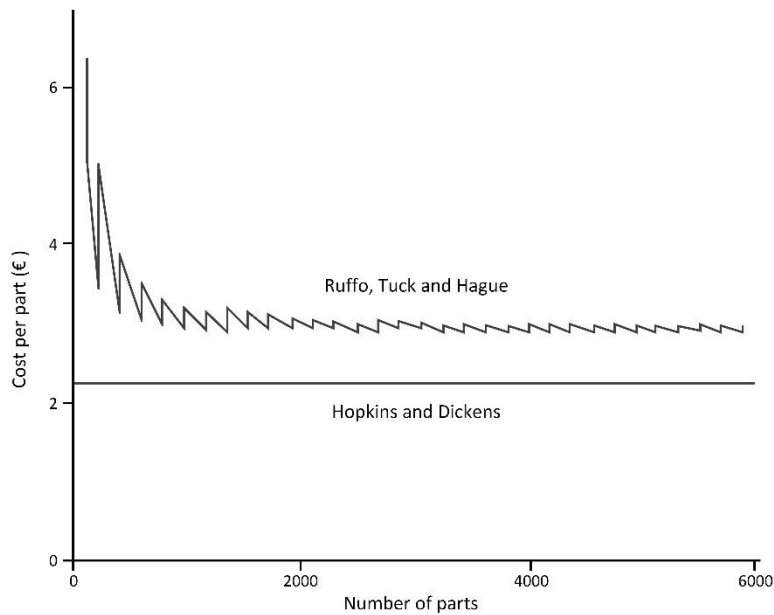


Figure 72: Hopkins and Dickens vs. Ruffo, Tuck and Hague

Calculating the differences will demand in-depth calculations with many variables. It is a subject which deserves a separate research paper. In addition, most graphs in this context will be taken from a specific point of view and cannot be interpreted as absolute in such a brief summary of cost comparisons. Tab. 61, shows a comparison of printer prices, with broad ranges in relation to price. Having these costs gives insight to the overall cost for the process and lifetime costs of the system/technology. Although, if there is interest of finding the price of one print, this information table is not directly relevant [104].

Table 61: Printer technologies price comparison

Technology	ISO/ASTM Definition	3D Printer Price Range
Material Jetting	Droplets of feedstock materials are selectively deposited	\$20k to \$600k
Binder Jetting	A liquid bonding agent is selectively deposited to join powder materials	\$5k to \$1,8m
Material Extrusion	Material is selectively dispensed through a nozzle or orifice	\$0.5k to \$400k
SLA (vat photopolymerisation)	Liquid photopolymer in a vat is selectively cured by light-activated polymerization	\$3k to \$800k
Powder Bed Fusion	Thermal energy selectively fuses regions of a powder bed	\$20k to \$2,0m
Directed Energy Deposition	Focused thermal energy is used to fuse materials by melting as they are being deposited	\$200k to \$5,0m
Sheet Lamination	Sheets of material are bonded to form an object	\$9k to \$37k

Although specifics will be more relevant, having an overview over the different AM Technologies will make it easier to get acquainted with them in relation to each other. Shown in Fig. 73 is a non-specific graph to place the different technologies in comparison to each other, showing the advantages with each technology, also in relation to price. There is no clear comparable “superior” method to be determined from this graph, as it all depends what traits are sought after for the parts intended to be produced [105].

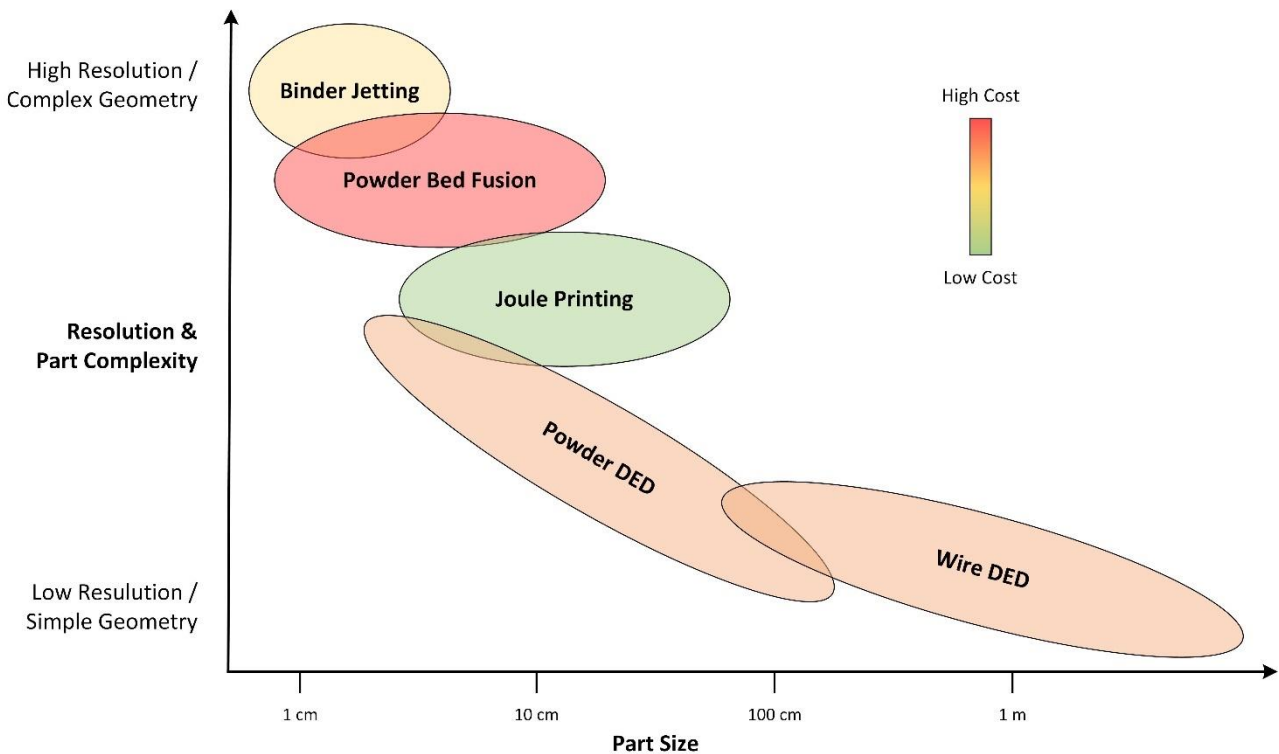


Figure 73: Comparison of additive manufacturing technologies in metal

Finding price comparisons in general for printing technologies like this is not an effortless task, the most reliable source would be earlier research papers, which again would make estimates within certain parameters based on their collection of sources and tests. But in this cost comparison, there has been collected other research paper graphs to compare, show and at the very least get and give an overview into whether or not these technologies have advantages, between each other and versus a standard machined part, and in which areas they excel.

Fig. 74 shows an example part applicable for showcasing BTF, where the same amount of material is used and compared between machining and WAAM. The example part were 10 kg, 20 kg, and 30 kg respectively. The key point illustrated here is that the relating to factor (BTF) of material waste of the product and what degree of material waste makes the different processes superior [106].

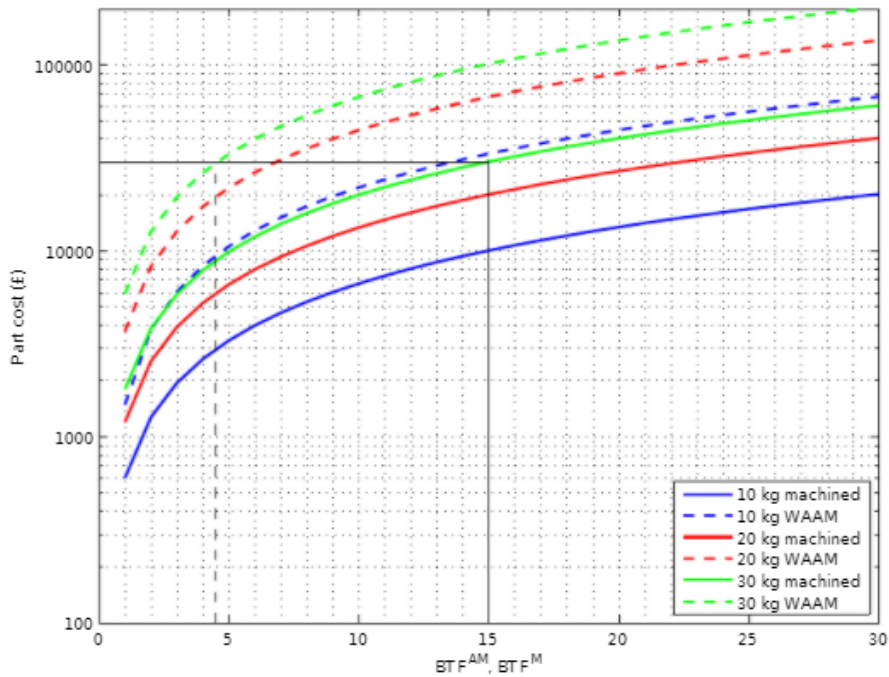


Figure 74: WAAM vs. machined part, function of BTF

The graph from Fig. 74 shows a WAAM printed part compared to a part Machined from solid. At first glance the graph shows that the WAAM part will cost more to make, although, with closer inspection the X-axis is a function of the BTF value. BTF is the raw material weight divided by the end product weight. A higher BTF value means higher waste and more post-processing applicable for the part. In this setting, WAAM will be more profitable to use when the machined part has a BTF = 15, and the WAAM part has a BTF < 4.5. Fig. 69 shows, a machined part that would have a BTF of 45, while a WAAM made part would have BTF of 2.9, resulting in a cost reduction of 65%. WAAM uses the same principle as most AM methods, adding instead of removing, which generally saves material usage and waste.

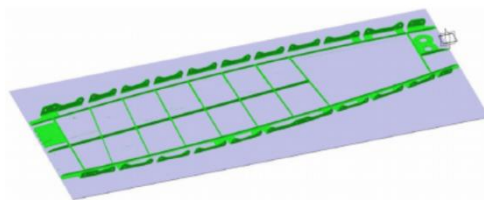


Figure 75: 15 kg aluminium wing rig model

Other sections of the same report looked at graphs related to capacity deposition, deposition rate, material removal rate (MRR), and other factors. The conclusion of the research paper was that the example parts analysed were cheaper to produce by WAAM, potentially reducing between 7% to 69% in overall cost, when comparing the BTF of WAAM to other printing methods BTF.

Another research, made by the US department of Commerce compared the cost differences for different AM processes, while comparing to a traditional machined, and a die-casted part. A key point made, is the difference in production cost between a Laser-Sintered part, and a Die-Cast part. Die-cast parts are made using moulds, whereas Laser Sintering extrudes and builds. In this scenario,

the Buy-To-Fly ratio will be relatively lower for both processes, with less material waste than for example machining.

The authors did a rundown of the costs of the process for an average part made, shown in Tab. 62. The part in question being landing gear assembly for a P180 Avant II. The costs for the Die-cast mould are what makes the price so steep for the Die-cast part. The /N in the chart is for the number of parts made with one specific Die-Cast, reducing the overall cost over efficient and repeated use. Such a comparison shows that the benefit of using SLS lays in the ability to print a specific part relatively cheap.

Table 62: Production costs compared between High-pressure Die-Cast and SLS

	High-pressure Die-Cast Part (€)	SLS(€)
Material cost per part	2.59	25.81
Pre-processing cost per part	-	8.00
Processing cost per part*	$0.36 + 21,000/N$	472.50
Post-processing cost per part	17.90	20.00
Assembly	0.54	-
<b>Total</b>	<b><math>21.29 + 21,000/N</math></b>	<b>526.31</b>

\*Includes the mould for Die-Casting

Using the chart from Tab. 62, N being the production volume variable, the graph shown in Fig. 76 is a visual representation. You can evidently see the implication that SLS will be more cost efficient relative with Die-casting if the Production Volume < 42.

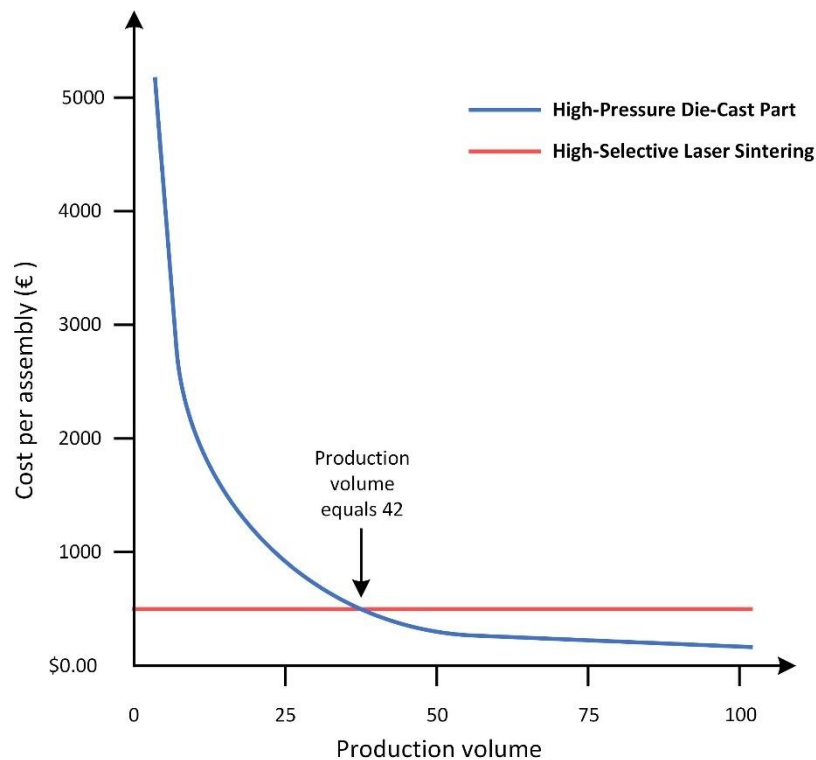


Figure 76: Breakeven point for high-pressure Die-Casting and Selective Laser Sintering

Fig. 77 compares the pricing of AM processes producing a part out of Titanium, and how the cost in average is distributed among the sub-functions of the process. As in Fig. 67, Joule printing is listed as the lowest cost, although, this may be bias to promote the Joule system [107].

As an example, the graph from Fig. 71 shows Binder Jetting has the highest material cost, Laser Powder Bed has the highest printing cost, and Wire has the highest post processing costs, all relative to cost of finished product.

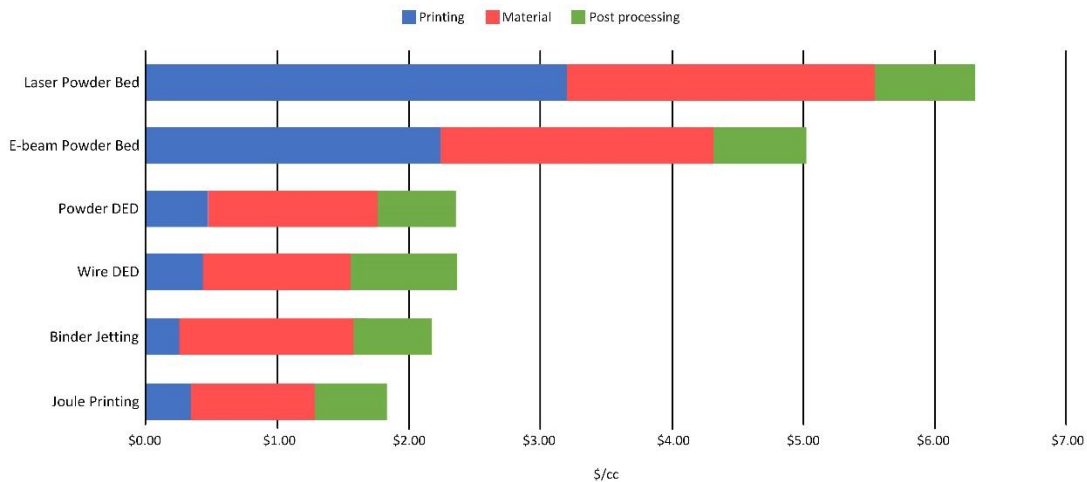


Figure 77: Additive manufacturing costs for titanium – Dollars (USD) per cubic centimetre

The costs of the different printing methods divided into sub-tasks is shown in Tab. 63. These numbers account for the climate in 2019, and as these technology costs has shown a decline in price the last 10 years, it is estimated the prices will drop lower as well [108].

Table 63: Printer technologies price comparison per unit

	Laser Powder Bed	Electron beam Powder Bed	Powder DED	Wire DED	Binder Jetting	Joule printing
Annual operating cost (\$/year)	\$300k to \$500k	\$300k to \$400k	\$150k to \$200k	\$300k to \$500k	\$150k to \$250k	\$300k to \$500k
Print speed (cubic centimetre/hour)	25 to 50	50 to 100	100 to 300	500 to 1,000	100 to 1,000	500 to 1,000
Annual printer utilisation (hours/year)	3,000 to 4,000	2,000 to 4,000	1,000 to 2,000	1,000 to 2,000	1,000 to 3,000	1,000 to 3,000
Per-unit printing cost (\$/cubic centimetre)	\$2.50 to \$4.00	\$1.33 to \$3.00	\$0.33 to \$1.50	\$0.25 to \$0.60	\$0.08 to \$1.50	\$0.17 to \$0.60

Appendix K1. Time distributions

To show each person's involvement in the different processes, the distribution of time over areas of the project are shown below in Fig. 78, Fig. 79, Fig. 80, Fig. 81, and Fig. 82.

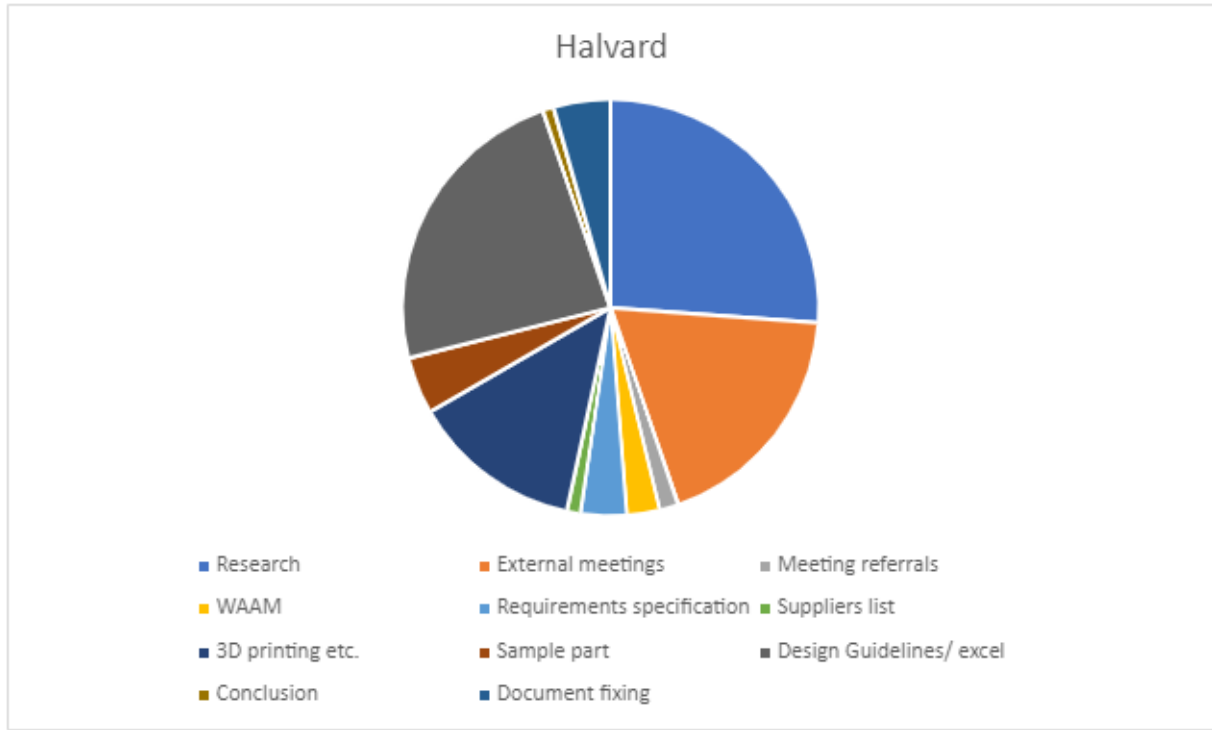


Figure 78: Halvard distribution of time

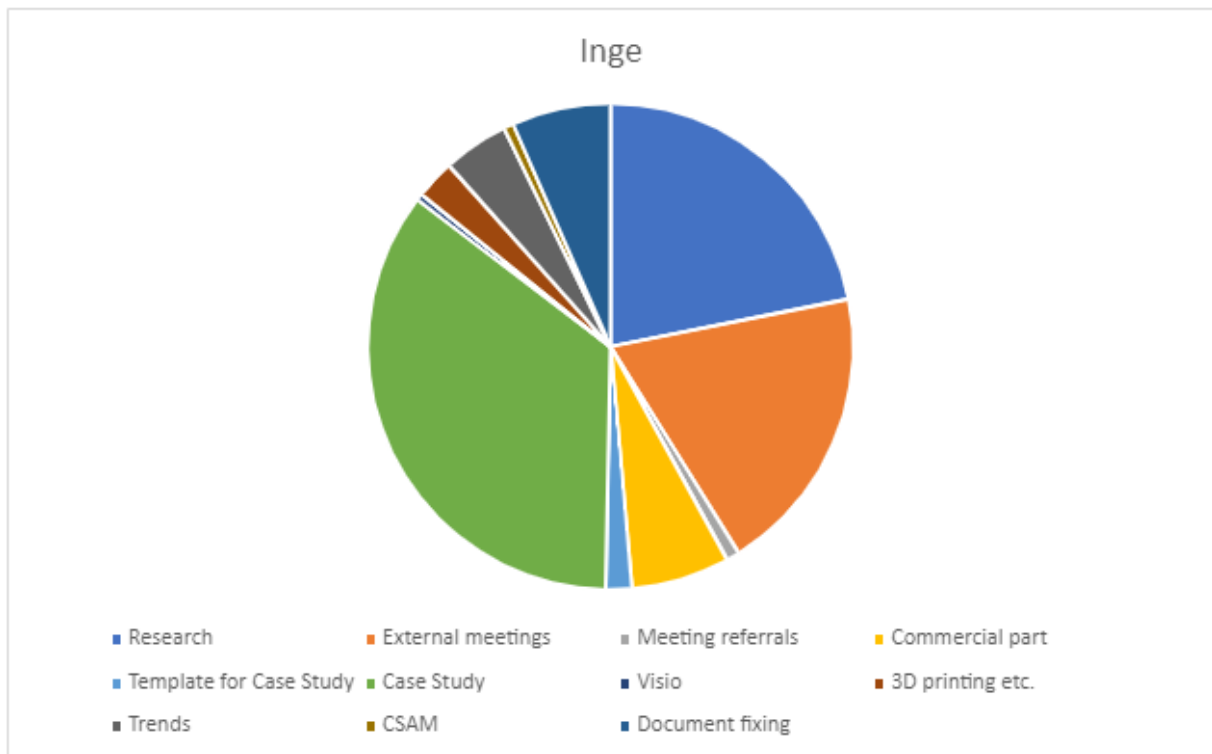


Figure 79: Inge distribution of time

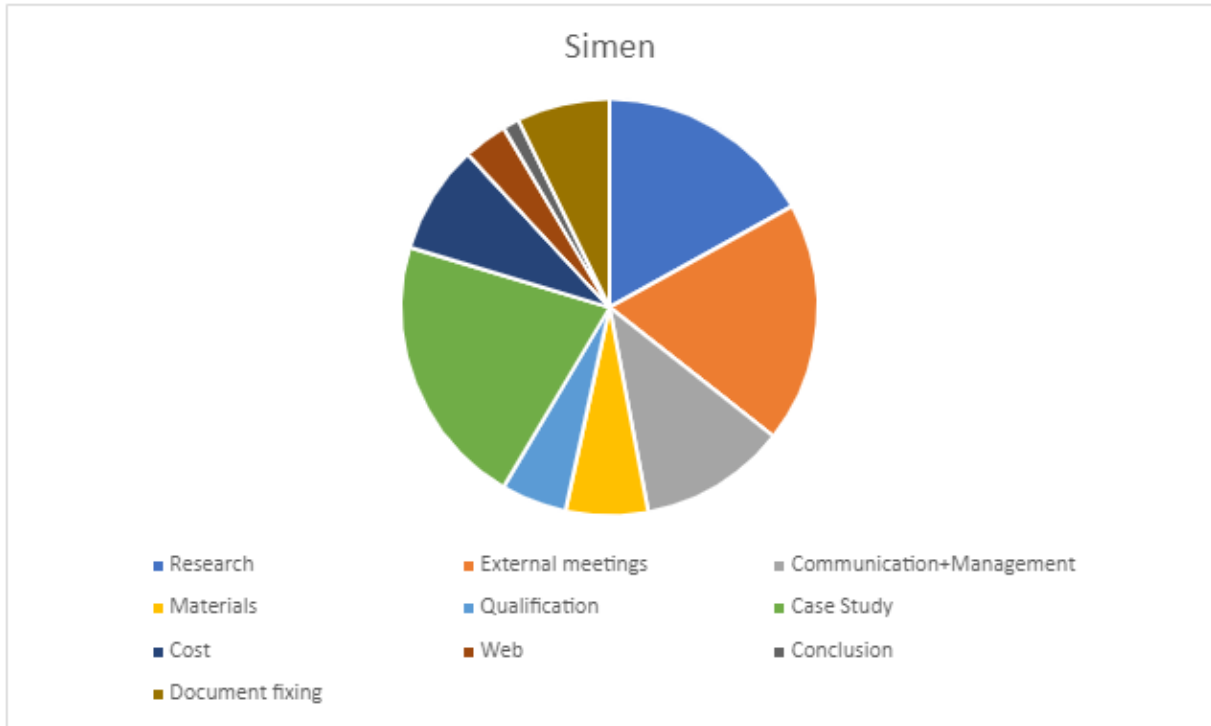


Figure 80: Simen distribution of time

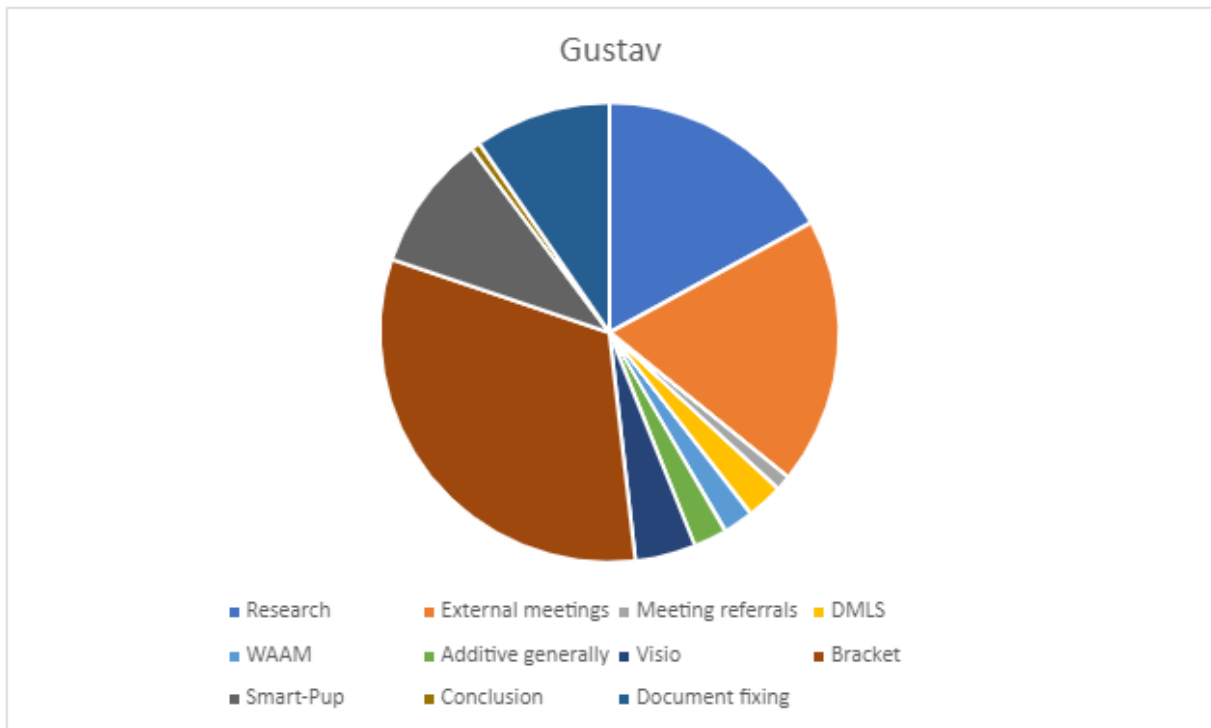


Figure 81: Gustav distribution of time

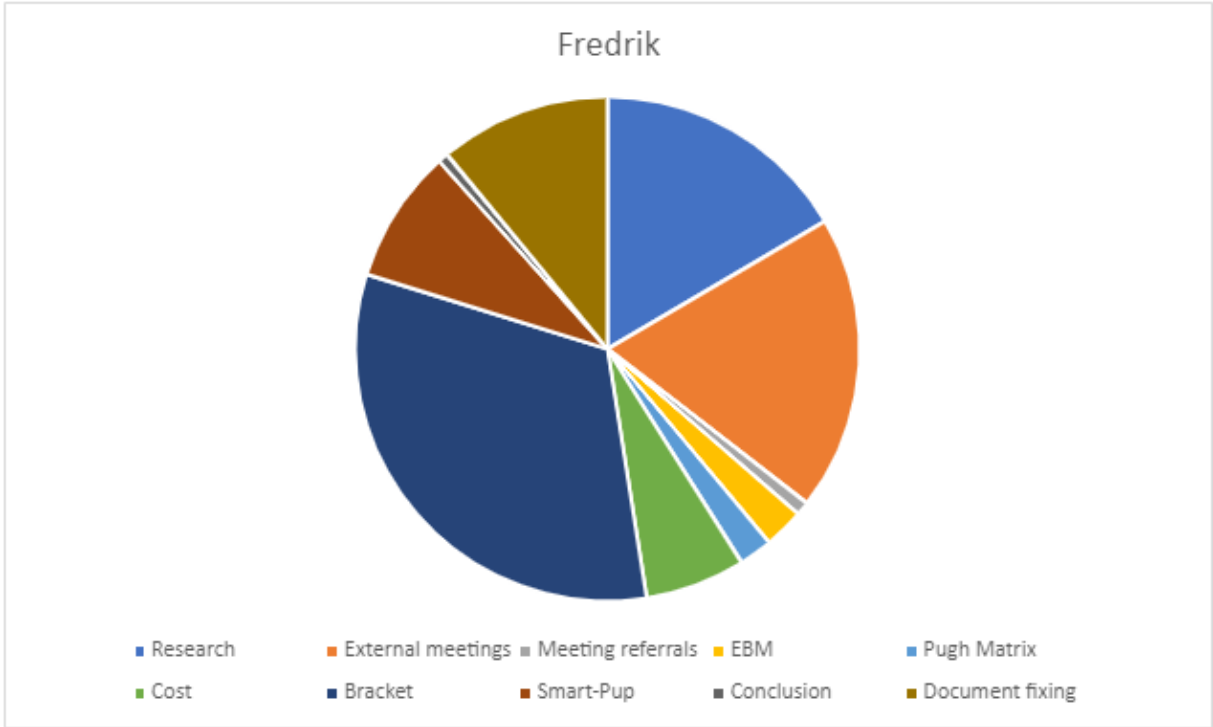


Figure 82: Fredrik distribution of time

Appendix L1. Design scoring

On this page information about the part will be added. You can put a 1 or a 0 in each of the white cells, a 1 is a yes to the statement and a 0 is no. For each of the category's you will only choose one statement, if it contains more than you will choose the statement with the highest weight.

Table 64: matrix for additive manufacturing part ability

Part complexity	Functionality of the part	Support material removal	Features that need support	Weight:	Sum:
Complex parts are suitable for AM	AM parts are usually vulnerable to cycles	Support material will ruin the surface finish of the part where it connects	Parts can be built without support material within certain limitations		
The part is round, square or has a shape that is completely 2D	The part is expected to endure for more than 1000 cycles with large forces acting on it	The volume of the part is smaller than the volume of the support needed to create the part	The part have features that are long and parallel to the build plate	0	5
The part is 2D and can be made in a mill or lathe without repositioning it in the clamp	The part is subjected to large forces, large movements or must endure 100-1000 cycles	The part contain narrow areas that need support material and it may be difficult to remove it from the part	The part have features that are short and parallel to the build plate	0	4
The part can only be made after repositioning it in the clamp on a CNC or lathe	The part will be subjected to moderate forces, will be in movement or are expected to last 10-100 cycles	The part contains internal channels or hollow sections and do not have any opening for support material removal	The part has overhanging features that have a slope that supports it	0	3
The parts surface is complex and would require multiple repositioning in a mill or lathe	The part sees a low or constant force acting on it and it will not experience more than 10 cycles	The part contains support material that can be removed easily	The parts have features that have a minimum of 45° support	0	2
The part is too complex for it to be made in a CNC or lathe, or it contains internal channels	The part will have surfaces that serves no specific purpose and it will not see cycles	The part does not require support material to be produced	The part can be oriented on the build plate so it will not have any overhanging features	0	1
Thin part Features	Amount of post-processing needed	Tolerances of the part	Warping	Weight	Sum:
Thin features can distort and will usually break	The more post-processing needed before the part is finished the higher the price will be	If the part contains mating surfaces they should be adjusted for the deviation from design in the final part	Parts with a large first layer can make the part warp, because of the heat difference in the part		
The part contains features that are thinner than 2mm	The part needs lots of machining and other processes before it can be used	The part is designed without considering the deviation of the final part	The part has a large-sized first layer	0	5
The part contains features that are 2-3mm thin	The part needs mating surfaces to be machined before use	The part is designed with considering the deviation of the final part	The part has a medium-sized first layer	0	3
The part contains features that are thicker than 3mm	The part just needs to be removed from the build plate and minimal support structure removal	The hole and length tolerances in the part are not important or is fully understood	The part has small-sized first layer	0	1

Strongly consider a different manufacturing process

Consider a different manufacturing process

33-40: Needs redesign  
24-32: Consider redesign  
16-23: Moderate likelihood of success  
8-15: Higher likelihood of success

<b>Total:</b>	<b>0</b>
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Appendix L2. Method scoring

On this page additional information about your part will be added. You can put a 1 or a 0 in each of the white cells, a 1 is a yes to the statement and a 0 is no. You do not need to fill out all of the categories only the ones you are interested in.

Table 65: matrix for additive manufacturing part process

Resolution How fine are the smallest details on your part	Part size How large is the part intended to be in X, Y and Z.	Material diversity What kind of materials do you intend to use to produce your part, this will affect your freedom of material choice.	Machine build speed How fast can the machine deposit material, this will affect build time	Weight:
The part should be so close to designed that it does not need additional machining be done	0 The part is over 1 meter in any axis	0 A wide range of materials including metals, polymers, composites and ceramics	0 The machine lays down more than 9 kg/hour	0 5
The part will need features such as mating surfaces to be machined and the non-machined surfaces need to deviate less than 1mm from design	0 The part is 1-0.5 meter in any axis	0 A wide range of metals and polymers	0 The machine lays down 9-3 kg/hour	0 4
Sections of the part will be machined after production, but the surface of the non-machined surfaces will need to have less than 3mm deviation from design	0 The part 50-20cm	0 A wide range of metals	0 The machine lays down 3-1 kg/hour	0 3
The part is intended to mostly be machined after production	0 The part is smaller than 20cm	0 A smaller selection of metal material available	0 The machine lays down less than 1 kg/hour	0 2
The whole part is intended to be machined after production and is created as a rough Near net shape part	0 The part is small and is intended to be multiple identical parts in one print	0 A small selection of material available or just plastics	0	0 1
<b>Machine cost</b> buy. This will affect the price of the part if it is sourced from a third party supplier	<b>Material/feedstock cost</b> How much does the material/feedstock cost to produce, not the material price. This will also affect the price of the part	<b>Tolerances</b> How geometrically similar do the part produced need to be to det designed part	<b>Geometric freedom</b> How much design freedom is needed to produce the part	<b>Weight</b>
Less than \$500,000	0 Cheap	0 Most geometrically similar to designed	0 Most design freedom	0 5
\$1,000,000-\$500,000	0 Medium	0 Less geometrically similar to designed	0 More design freedom than CNC	0 3
More than \$1,000,000	0 Expensive	0 Least geometrically similar to designed	0 Same or less design freedom as CNC	0 1
EBM	WAAM	UAM	DMLS	
total:	total:	total:	total:	0
MF/BJ	Cold spray			
total:	total:			