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Guidelines for increasing application of 3D Metal Printing- a case study at Equinor ASA

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ABSTRACT

The world is evolving towards automation at a rapid rate. With this, there are lot of gaps that need to be filled as we switch from conventional methodology of doing things to the adaptation of newer automated technology. One of those many news aspects is Additive Manufacturing, also known as 3D printing. 3D Printing has changed significantly over the years, from it being used for making prototypes for the designs, to its being used for making actual functional parts. Having the potential to revolutionize the manufacturing industry in many different aspects, it has become very important for every industry to penetrate the technology in their mainstream methodology of doing things.

The aim of this thesis is to takes all of the factors into account and develop suitable guidelines for increasing application of 3D Metal Printing. The project is done in collaboration with Equinor ASA, where in a case study was performed on a standard part provided with them. The methodology of conducting the study focuses on realizing the received part, that is manufactured using conventional technique, to be produced using 3D printing technology. The first part of the thesis consists of a thorough literature survey about the 3D printing technology and its market. The survey is followed by the experimentation phase which involves reverse engineering, redesigning, analysis, simulation, and cost estimation with a comparison study on each. During this course of realization, guidelines with suitable justification are prepared. Furthermore, the challenges and opportunities offered by the additive manufacturing technology are also discussed. This will also provide a direction in order to integrate additive manufacturing technique in the conventional manufacturing technology.

KEYWORDS

Additive Manufacturing, 3D/3DM printing technology, topology optimization, design, guidelines.

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List of abbreviations

3D	3 Dimensional
AM	Additive Manufacturing
3DMP	3D Metal Printing
SMEs	Small and Medium -scale Enterprises
SLS	Selective Laser Sintering
FDM	Fused Deposition Modelling
JIT	Just-In-Time
CAD	Computer Aided Designing
MJF	Multi Jet Fusion
LPBF	Laser Powder Bed Fusion
DPBF	Direct Powder Bed Fusion

EBM	Electron Beam Melting
NPJ	Nano-Particle Jetting
DOD	Drop-On-Demand
LMD	Laser Metal Deposition
EBAM	Electron Beam Additive Manufacturing
WAAM	Wire Arc Additive Manufacturing
UAM	Ultrasonic Additive Manufacturing
LOM	Laminated Object Manufacturing
SLA	Stereolithography
DLP	Digital Light Processing
CDLP	Continuous Digital Light Processing
SMAC	Shielded Metal Arc Welding
GMAC	Gas Metal Arc Welding
3DMW	3D Micro Welding
PAW	Plasma Arc Welding

1 INTRODUCTION

The complexity of manufacturing in the race of developing a newer product or technology has increased exponentially and has made it necessary for the development of those manufacturing processes in the first place. Manufacturing processes, thus, have evolved drastically past few decades to meet these demands. Inclusion of additive manufacturing to the earlier subtractive manufacturing/ metal removing process has opened different doors in the field of manufacturing and one of such technology is 3DMP or the 3D Metal Printing. In simple words, 3DMP is similar to a computer jet printer but unlike forming a 2D digital image on a paper by extruding ink through a nozzle, it oozes out a metal on a print bed corresponding to the design fed to the printer resulting a 3D structure or any desired shape. But having that said, 3D Metal Printing has many other ways to make a product e.g., Powder Bed Fusion, Material Jetting, Binder Jetting, etc.

Since the technology of 3DMP is still very immature and the cost comes at premium, it is very difficult for the small and medium scale enterprises (SMEs) to replace it with conventional manufacturing techniques. Thus, it is of prime importance to prepare guidelines so as to facilitate in switching to the 3D metal printing technology, without or minimal changes in the operation and production level[1]. The guidelines will stand as a gateway to achieve the scope of the additive manufacturing system. It will be a key element for the industrial 4.0 and provides a great opportunity for working alongside with the automation. Additive Manufacturing will enable the transition from mass production to mass customization in a number of existing and rapidly growing sectors such as, aeronautics, automotive, medical, energy, defence, and consumer good[2]. Having seen such a huge potential, the major stakeholders of these sectors are in a race to make new breakthroughs every day. It can also be seen even in the lowest level such as SMEs trying to take a shift from the conventional way of manufacturing because of the advantages it offers in terms of every element. With suitable guidelines, it will be a great boon for all different scales of the enterprises to reach out to adapt changes.

1.1 Background and Overview

Additive manufacturing has been around for around three decades since it was first patented as stereolithography in 1986. There has been a number of newer developments every year within the Additive Manufacturing System to cope up with the competition and to offer better techniques. From using it for prototyping using polymers to printing actual working parts using metals and composite, Additive Manufacturing has become a very big pool of tools and techniques for futuristic and sustainable progress. Making a fully functional part in a small desk has become a reality eliminating all the complex work, big machines, huge workforce, supply chain network, and many other factors which have always been challenging. There have been a number of key events since the development of the first additive manufacturing system to the present-day advancement. The first patent expired in 2014 making it possible for more development and the recent day's progress is evident about how fast the technology has evolved in the recent years. Some of the major events marked in the history since the first notable work until the expiration of the patent has been listed along with the year below[3].

1981–1984: The Early Minds

- In 1981, Dr. Hideo Kodama described the laser beam curing system.
- In 1984, Alain le Méhauté with his two colleagues working on rapid prototyping.

1984–1988: The Invention of Stereolithography

- In 1986, Charles Hull patented for stereolithography
- In 1988, 3D systems produced the SLA-1

1988–1992: An Era of Innovation

- SLS (Selective Laser Sintering) developed in 1988
- FDM (Fused Deposition Modelling) developed by Stratasys in 1992

2014- : Revolution

- Patent expired in 2014

3D printing might be considered as a recent technology, but it can be seen that the Stereolithography, SLS and FDM, were developed in between 1980 and 1995 and all the new-born methods of 3D printing are in one or the other way derivatives of these technologies[3]. Among all of the new systems, 3D metal printing which has revolutionised the metal industry in the recent years has become one of the major elements of the additive manufacturing system. With the maturity of the technology taking place rapidly and the freedom of development which metal printing has offered have become of a great interest to all sorts of industries. However, the technology is still quite immature, and the high cost and other complexities involved has made it quite challenging for 3D metal printing to penetrate as a major production system. Thus, knowing the potential of the metal 3D printing, it is necessary to make suitable guidelines about how it can be replaced or work alongside the mainstream conventional manufacturing system.

In order to achieve this objective, we chose one of the cases of Equinor ASA and made suitable guidelines so as to test its applicability. Equinor ASA is a multinational energy company operating in more than 30 countries. It is primarily engaged in exploration, development and production of oil and gas, as well as wind and solar power[4]. Equinor is expecting to reduce its warehouse size conditioned with the same level of responsiveness and preparedness. The company is envisioning through Just-In-Time (JIT) methodology, a digital warehouse where spare parts compatible with additive techniques to be ordered for their production. Then through Additive Manufacturing, they can get their products delivered promptly. The idea is to produce the part in an onshore printing facility/firm before transporting the component to their platform. The guidelines suitable to fit this objective can be, therefore, generalized so as it fit for all small and big enterprises.

1.2 Scope

The project will highlight the challenges and opportunities that are faced and discovered throughout the course of preparing the guidelines. The main topics that it would cover include additive manufacturing techniques, especially 3D metal printing, and its related subjects. A special focus when establishing the guidelines will be attached to the technical aspect regarding the materials, design, and related printer technologies. The project will start with following four core fields when discussing the possibility of transformation from subtractive to additive manufacturing: Materials, construction methods, production methods and business models related to production capacity planning.

Different design considerations would be tested to assist the metal printing of parts. The designs could be printed on the 3D printers to check for practicality of it in the real-time applications. The approach would also consider the sustainability factors and find ways to develop guidelines that would consider the environmental factors as well.

2 LITERATURE SURVEY

2.1 Additive Manufacturing

There are different methods by which a product can be manufactured, each of them having their own characteristics. The method selected is based on the attributes of the finished product. All the different methods can be classified under the following manufacturing systems:

i. Subtractive Manufacturing
ii. Formative Manufacturing
iii. Additive Manufacturing

The main reason behind this classification is the way the raw materials are handled. As per the name says, subtractive manufacturing is defined as the reduction of a block of material to desired shape and size. The most common examples are milling, turning, grinding, etc[5]. On the other hand, formative manufacturing uses a mould or replica of the desired part with necessary dimensional tolerances. Different combinations of stresses are applied which causes the plastic deformation of the required material corresponding to the mould, for example, injection moulding, die casting, pressing, etc. These methods have been used for centuries and involve an abundance of technology. Additive manufacturing is, however, a recently developed technology, which involves sequential addition of layers of material throughout a 3D envelope which is automatically controlled. It is still in its early stages of development, which was first patented in 1986 as stereolithography by Chuck Hall. Earlier, the materials generally used were polymers but as the time advanced, different metals and composites were able to be printed using various printing technology[6]. Unlike now where it has been used in mainstream manufacturing, additive manufacturing was only used for prototyping in the starting days. Among the number of 3D printers available now, only Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM) techniques were used in the early days [7].

With recent development in the number of different methods to print practically all the commercial materials, the demand for 3D manufacturing is exponentially rising. It has been able to address many challenges faced in conventional manufacturing. Additive manufacturing has given a new room for research and innovation as scaled prototyping has become a possibility and the precision achieved is exceptionally high. Although it has many challenges of its own regarding to various factors, it has been able to show a great potential to overcome in the days to come.

2.1.1 Working

Usually, additive manufacturing is considered as a technique in which the required raw material is fed to the machine and then the printer prints navigating the motorized nozzle, layering material one over the other to form the required shape. It is true but it involves many underlying steps as the required printed part is achieved. The first steps involve making a 3D file from the correctly dimensioned drawing in a Computer Aided Designing (CAD) software. While design, all the necessary changes are made so as to facilitate the manufacturing of the part in the printer. This may include adding suitable supports, changing dimension, selection of the base, etc., based on the requirement. Once all the necessary precautions are taken in order to ensure that the manufacturing is possible without any errors, it is converted into a standard 3D format and is exported to be sliced in a slicing software. Slicing is one of the most important steps as it gives a visual animation of how the part will be manufactured layer by layer. The resulting file is then exported to the 3D printer in a format, such as .stl, .AMF or .3MF[8-10]. However, .stl is the most common standard format of conversion. The file is then sent to the printer and all the necessary parameters such speed, layer width, temperature, etc. are selected. All of these factors give an estimated production time the printer will take to print the required part. Once the part is completed it is suitably extracted from the printer bed and sent to the post processing phase. Figure 1 represents the basic Additive Manufacturing Process [2].

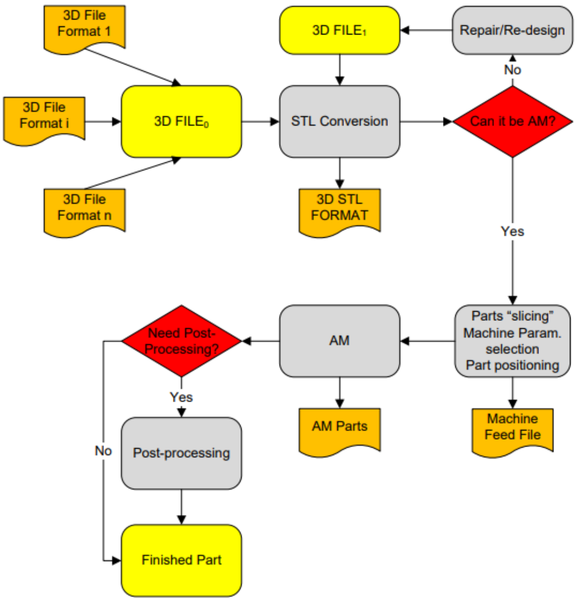


Figure 1 Steps involved in the Additive Manufacturing Process[2]

2.2 Additive Manufacturing Techniques

Additive Manufacturing is a very wide branch involving many different methodologies to print. The techniques vary depending upon many different factors such as power beds, heating source, type of material used and so on. Depending on that, additive manufacturing can be categorized into 7 major different technologies which in turn has sub-categories[11]. This has been discussed below.

i. Powder Bed Fusion
    - Multi Jet Fusion (MJF)
    - Selective Laser Sintering (SLS)
    - Laser Powder Bed Fusion/Direct Metal Laser Sintering (LPBF/DMLS)
    - Electron Beam Melting (EBM)
ii. Material Jetting
    - Material Jetting
    - Nano-Particle Jetting (NPJ)
    - Drop-On-Demand (DOD)
iii. Binder Jetting
iv. Direct Energy Deposition
    - Laser Metal Deposition (LMD)
    - Electron Beam Additive Manufacturing (EBAM)
    - Wire Arc Additive Manufacturing (WAAM)
v. Material Extrusion
    - Fused Deposition Modeling (FDM)
vi. Sheet Lamination
    - Ultrasonic Additive Manufacturing (UAM)
    - Laminated Object Manufacturing (LOM)
vii. Vat Photopolymerization
    - Stereolithography (SLA)
    - Digital Light Processing (DLP)
    - Continuous Digital Light Processing (CDLP)

The major technologies as listed above are further explained to understand their working, advantages, and the shortcomings.

2.2.1 Powder Bed Fusion (PBF)

This is the most common and matured form of metal printing where a powder which is located on a fusion bed is consolidated with the help of a heat source, a laser, or an electronic beam.

The powder, typically 20-120 microns, is of the desired metal, usually with specific properties so as to make it suitable for the process. The heat beam melts the powder into desired geometry. It works on the principle of melting and recoating. The print or the fusion bed is a thick metal plate over which the first layer of metal is melted which bonds with the plate as it cools. The first layer is then recoated with powder and the process of melting and recoating is repeated until the required 3D model is formed. Heat source is programmed manually based upon the desired 3D model. Powder Bed Fusion technique comprises of Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS). The major difference between them being SLM is used to produce a 3D model which is of a single metal whereas DMLS produces 3D models from different metal or metal alloy[12].

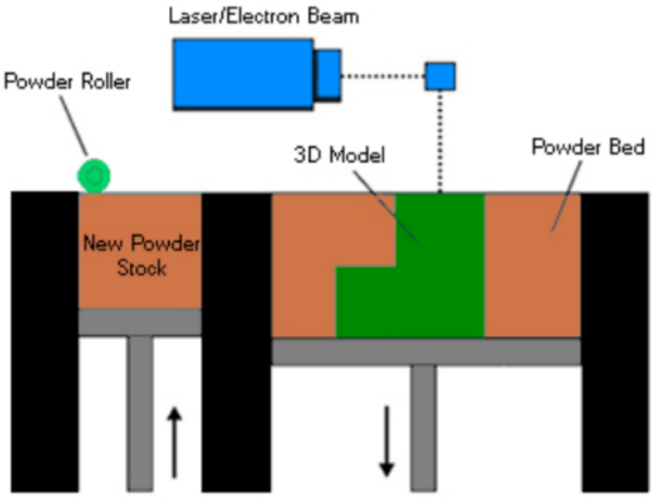


Figure 2 Infographic of Powder Bed Fusion Metal Printing[13]

Advantage of this method of 3D printing is that it can offer a wide range of material to be 3D printed and no support structure needs to be provided as then powder itself provides it a base which the 3D model can be made. Major drawback of this methodology is the fatigue fracture. The primary cause of these fractures is crack growth where small voids and cracks within the part can force stress to divert and pile up in sharp corners and thus exceed the metal’s strenght locally and causes the crack to grow, therefore, more the imperfections are present more the fatigue life of the material is going to suffer. This is the reason the 3D parts formed require additional finishing to reduce the stress concentration areas[14].

2.2.2 Material Jetting (MJ)

Although the material jetting was developed for 3D Printing of resins and polymers, the development of the Nanoparticle Jetting by XJet, in 2016, has given an opportunity to print 3D parts using metal as well as ceramics. Its working is quite similar to an inkjet printer which ink jets out from the nozzle tip on a paper. In this technology, a nozzle jets out metal and forms the cross-section layer by layer on a build tray. The metal is jetted based on either of the two methods i.e., continuous jetting or drop on demand (DOD).

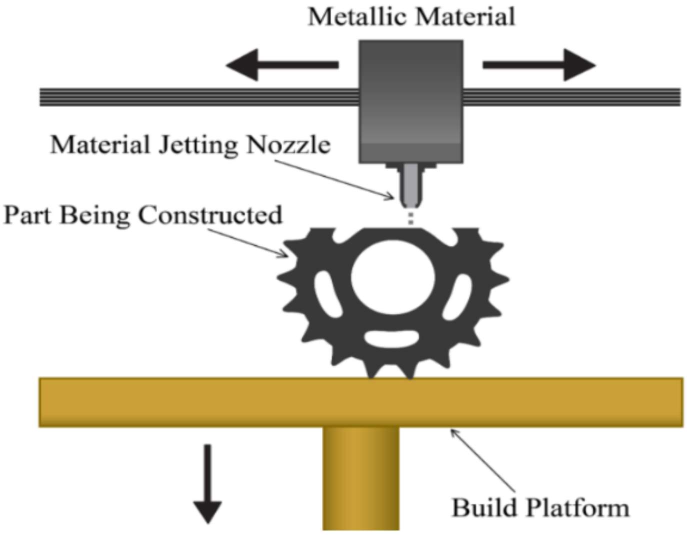


Figure 3 Infographic of Metal Material Jetting[15]

In this technique, metal is not melted but instead present in a liquid form which is sintered after the metal is jetted out of the nozzles, thus give a safety advantage. Similarly, it is the faster process to 3D print a model.

The process allows for a very good surface finish as well as better strength because of the nanoscale jetting. Since it uses a special fluid form instead of the powder form, it is easy to handle and work with. The major drawback is it is still limited to small parts only. The price of making a part using this methodology is very expensive for commercial printing[15].

2.2.3 Binder Jetting (BJ)

The process of Binder Jetting lies between the Powder Bed Fusion and Material Jetting in a sense that it consists of a powder bed and a binder supply which jets from the nozzle on the powder forming an adhesive bond between the powder material. Once the first layer of the powder is completed, a new layer of powder is spread and the earlier layer acts as the bed of the new layer. The process of binding and recoating continues until the complete 3D model forms. The binder is in a liquid form and once the 3D model is completed, the excess powder is cleaned, and an additional layer of binder is applied to improve its mechanical and structural properties because the properties are inferior as compared to the parts made from other methods of 3D printing. The binder is basically an adhesive with suitable properties depending upon the corresponding metal on the powder bed.

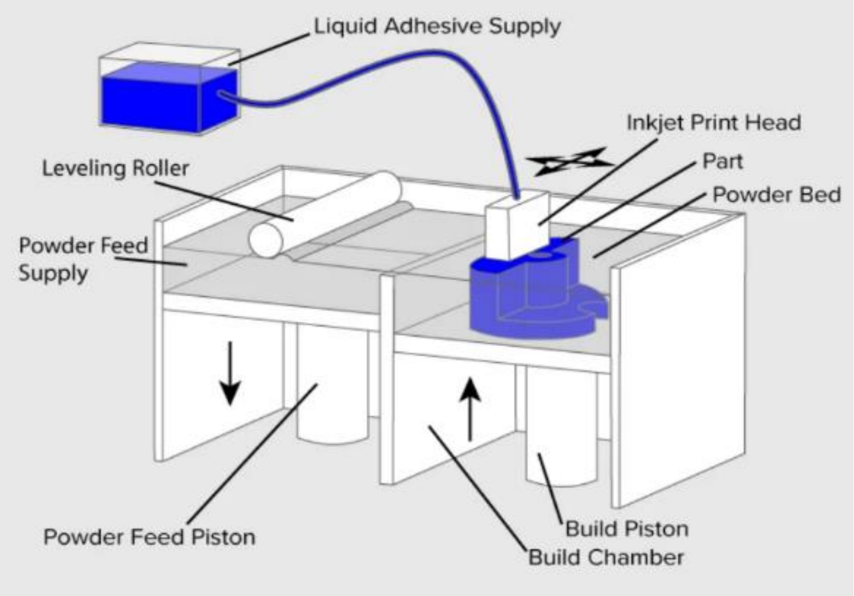


Figure 4 Infographic of binder jetting

This technology is used for printing large parts rather than small ones due to the high degree of porosity but are suitable for fabricating moulds, specially which are multicoloured. There are very little residual stresses but the parts are brittle in nature so chances of fractures are very high if an additional treatment of an extra layer of adhesive is not provided[16].

2.2.4 Direct Energy Deposition (DED)

Direct Energy Deposition(DED) uses gravity or the pressured gas to deposit melted powder metal directly on the build platform to form a desired 3D shape. It consists of a multi axis arm one of which feeds powder metal and the other arm focuses a laser beam of a very high intensity coaxially to the powder arm such that the powder melts as it falls on the built platform or the existing part on which a 3D model is to be built. The process takes place in a conmtrolled environment usually in the presence of an inert surrounding so that no oxidation occurs resulting in good material properties. The arm moves in the vertical direction wher as the bed is allowed for horizontal movement[17].

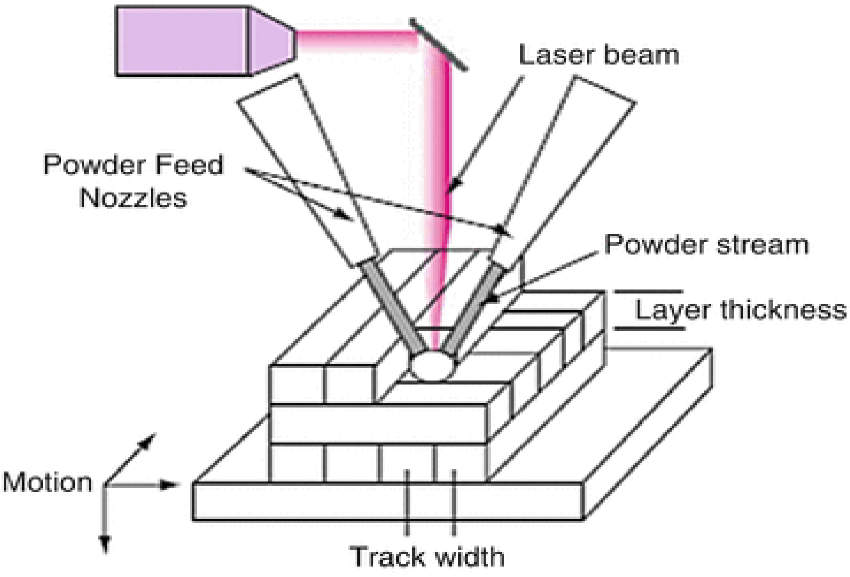


Figure 5 Infographic of Direct Energy Deposition[18]

The ease of use and the freedom to use different kinds of metal makes this process very suitable for repairing existing parts however, the elimination of the support material makes it difficult to print complex geometries[18].

2.2.5 Fused Deposition Modelling (FDM)

Fused Deposition Modeling(FDM), also referred as Fused Filament Fabrication(FFF) makes use of a metal filament which is heated and extruded through the nozzle onto the build platform layer by layer so as to print a part of desired geometry.

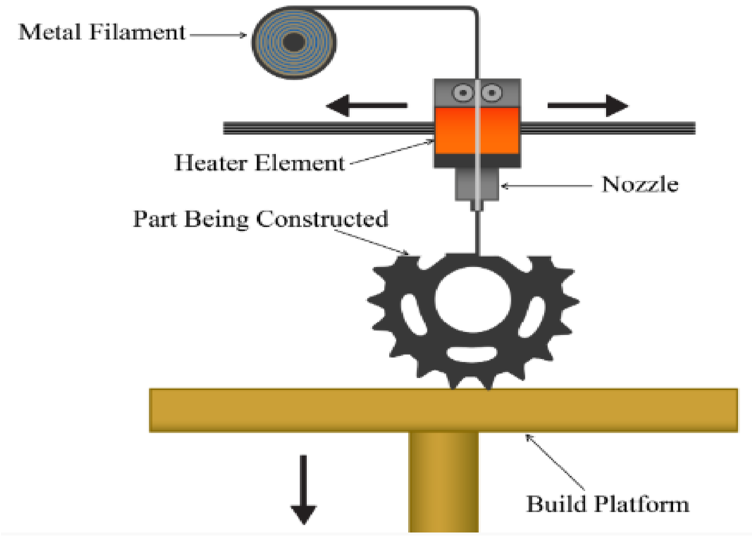


Figure 6 Infographic of Fused Deposition Modelling [19]

The metal passes through a heated element which melts the filament which then oozes out of the nozzle tip. As it comes in contact with the base or the platform, it cools and solidifies. It is similar to a hot glue gun, with the only difference being the thermoplastic adhesive sticks replaced by the metal filament. It has limitations with its application as it cannot accommodate complex geometries. Also the cohesive bond between its vertical layer is very poor making it irresistible tension. The attractive feature of this process is its low price and ease of use[19].

2.2.6 Sheet Lamination (SL)

Sheet Lamination technique uses rollers to feed the thin metal sheets. Another roller heats the sheet and such sheets are layed layer after layer forming an adhesion between the layers. The desired length of the layer when achieved is cut with the help of a layer. This way a 3D part is formed on the platform.

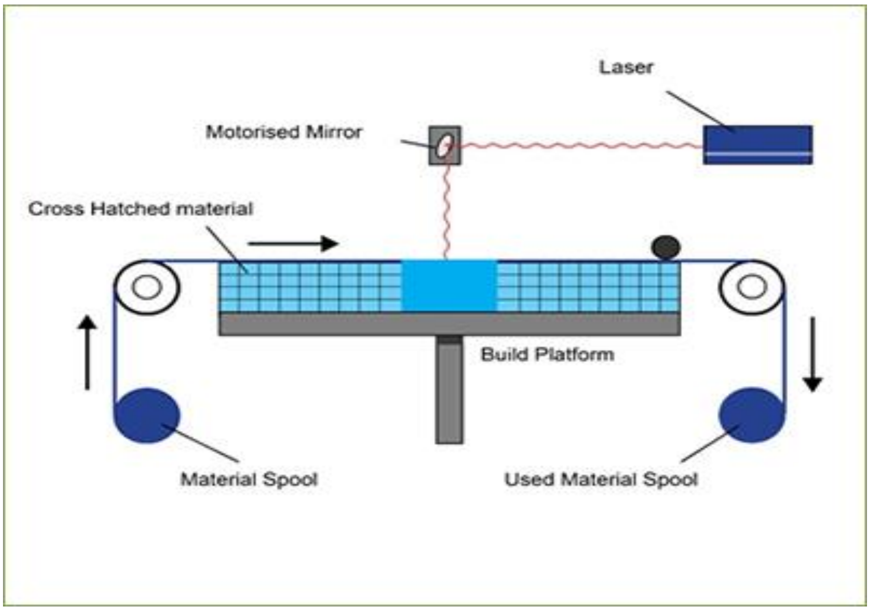


Figure 7 Infographic of Sheet Lamination [20]

This process is quite cheap and can be used to make large models and can work very fast as compared to other 3D modelling methods. But layer on layer of metal sheet placement has a very weak cohesion bond, therefore, the model is poor under tension. Similarly, complex geometry cannot be obtained by this method.

Although there are many different methods of metals 3D printing, only few of them are researched upon for their commercialization. It is very important to choose the most suitable technologies so as to facilitate the maximum productivity along with the superior properties. With that in consideration the below listed are the two technology which have been extensively used by industries for printing of metals[20].

i. Powder Bed Fusion Metal Printing

- i. Electron Beam Melting (EBM)
- ii. Laser Melting (LM)
- iii. Laser Sintering (LS)

ii. Direct Energy Deposition

- i. Laser Metal Deposition (LMD) – Powder-Based and Wire-Feed.
- ii. Arc- Based DED
    - -Shielded Metal Arc Welding (SMAC)
    - -Gas Metal Arc Welding (GMAC)
    - -3D Micro Welding (3DMW)
    - - Plasma Arc Welding (PAW)

2.3 Printing Materials

For the metal printing, the printing materials are divided into two categories. They are

- Pure Metal
- Alloy Powders

The selection of the material is done based on the requirement for the specified application and the printing technology is selected based on the material which best suited for the production. Pure metals are generally used for making jewelleries and other customized products and are very widely used because of their limited properties. For commercial application, alloys and other composites are used for printing materials with required properties. This gives control over the parts that needs to be printed. Materials are used in the powdered form because of easy handling. Also, it offers easy cleaning of the printers after the completion of printing[21]. Some of the advantages of using metal powders over any other forms of metal are listed below.

- The spherical shape of the power helps to ensure the good flow/coating ability and offers a high packing density,
- The size of the particles is usually below 50 µm or 150 µm depending on type of machine and finishing of the surface,
- The particle distribution allows it to be tailored to the desired application and properties,
- Powder offers a controlled chemical composition and gas content.

Table 1 represents some of the common materials used for 3D printing along with their properties.

Table 1 Some Materials and their basic properties

Materials	Properties
Aluminium Alloys	Good mechanical & thermal properties Low density Good electrical conductivity Low hardness
Stainless steel & tool steel	High wear resistance Great hardness Good ductility and weldability
Titanium alloys	High wear resistance Great hardness Good ductility and weldability
Cobalt-Chrome superalloys	Excellent wear & corrosion resistance Great properties at elevated temperatures Very high hardness Biocompatible
Nickel superalloys (Inconel)	Excellent mechanical properties High corrosion resistance Temperature resistant up to 1200°C Used in extreme environments
Precious metals : Pure Metals	Used in jewellery making Not widely available

Based on the list of printing technologies which are mostly used for commercial printing, table 2 shows the printing technique used to print the pure metals.

Table 2 Pure Metals and their respective printing technology

Metals	Printing Technology
Gold	LM (Selective)
Titanium	LS, LM and LMD
Iron	EBM
Niobium	EBM
Copper	LM and EBM

Similarly, the alloy powder also has the respective printing technologies which offers printing the alloy powder better as compared to other technologies. Some of the alloys along with their printing technologies are listed below.

i. **Aluminium-based**: Al-40Ti-10Si, Al-Si-10Mg and Al-15Cu

Printing Technology- Selective Laser Melting(LM)

ii. **Cobalt-based**: Co-29Cr-6Mo, Co-26Cr-6Mo-0.2C

Printing Technology- Selective Laser Melting (LM) for Co-29Cr-6Mo

- Electron Beam Melting (EBM) for Co-26Cr-6Mo-0.2C

iii. **Copper-based**: Cu-30Ni

Printing Technology- Direct Energy Deposition (DED)

iv. **Iron-based**: Stainless Steel, Tool Steel and Alloy Steel

Printing Technology- Selective Laser Melting(LM), Laser Metal Deposition, Electron Beam Melting(EBM)

v. **Nickel-based**: IN625, IN718

Printing Technology- Selective Laser Melting(LM), Laser Metal Deposition, Electron Beam Melting(EBM)

vi. **Titanium-based**: Ti-6Al-4V

Printing Technology- Selective Laser Melting(LM), Laser Metal Deposition,
Electron Bed Melting(EBM), Gas Tungstenm Arc Welding.

2.4 Market Situation

Although additive manufacturing has been for over more than three decades, it is still very immature to penetrate the manufacturing industry with a bigger stake. This is primarily because of the fact that the transition from the subtractive manufacturing comes at a cost and the risks that the decision maker has to take. The technology is still in the research phase for its commercialization and is very slow. It has been able to address some of the issues seen in the conventional manufacturing methodology but still it takes a lot more work to completely switch to additive manufacturing. The industries that have started producing parts using 3D metal printers are using it in parallel with the conventional processes which has helped to avoid some of the foreseen risks.

Looking at the brief history of the 3D manufacturing, it was introduced and patented in 1986 and had been growing ever since at a very slow rate but the growth became significant after 2014 when the patent for the Additive Manufacturing equipment had expired. It has taken an exponential leap and the technology which was limited to prototyping has now been one of the major manufacturing methods. Figure 8 shows the number of additive manufacturing units sold from 2002 to 2018 representing an exponential trend with a big difference in number of the system sold after the year 2014[1, 22].

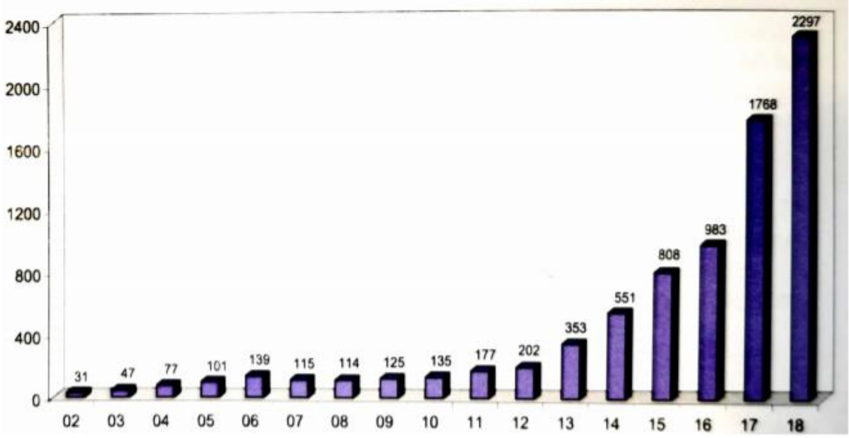


Figure 8 Metal AM systems sold from 2002 until 2018[1]

As per the Wohlers Associates' Report in 2019, "The average annual growth rate of worldwide revenues produced by all products and services by the additive manufacturing technology over the past 30 years is an impressive 26.9%. The average growth over the past four years (2015-2018) is 24.4%." This shows how fast the technology of 3D printing is penetrating the manufacturing industry either replacing or working in union with the conventional manufacturing processes. Sales of different additive manufacturing systems have grown from 1,768 units in 2017 to 2,297 units in 2018, an increase of 29.9% only in one year.

USA leads in the total market share of this technology with almost half of the market accounting to 42.7% with Israel trailing behind with 25.2% of the total market and, Europe and Asia sharing 19.9% and 10% respectively. As per 2018 data, additive manufacturing technology is a massive $9.795 billion industry growing at 33.5% from $7.336 billion in 2017. The growth has been at a rate of 25.9%, 17.4% and 21% in the years 2015, 2016 and 2017 as compared to the previous year. The growth has been increasing as a result of growing competition worldwide for coming up with a better manufacturing technology which could effectively and efficiently replace the conventional technology, for better[23].

Similarly, with the growth in the technology, the demand for the metal used for the purpose is also growing rapidly. In 2018, out of a $1.495 billion market for different materials used for 3D printing, about 17.4% i.e., $260.2 million accounted for metals. This number rose from $183.4 million in 2017 with an increase of 44.6%. The pie chart in figure 8 shows the market share of different materials used in 3D Printing[24].

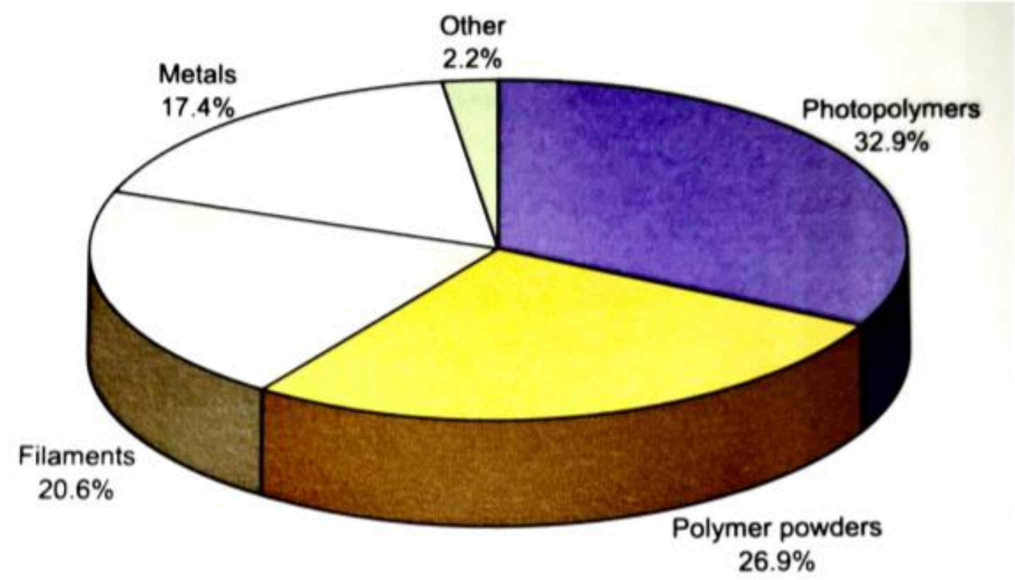


Figure 9 Market share by material type in 2018 [23]

Figure 10 illustrates the sales of metal for additive manufacturing from 2009 until 2018. It can be clearly seen that as the additive manufacturing technology has grown since last one decade in an exponential rate, sales of metal for printing have also grown in the similar fashion.

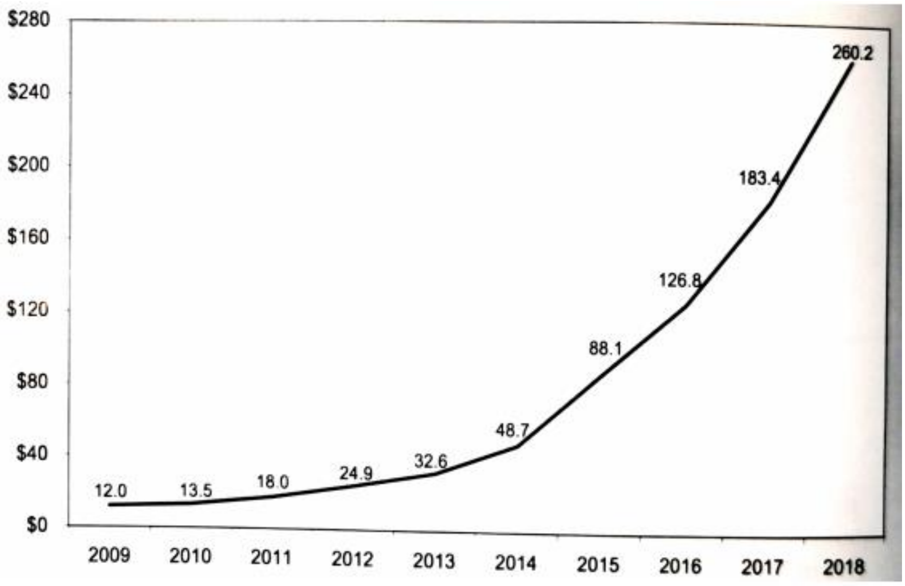


Figure 10 Sales of metal for printing from 2009 to 2018 [23]

Since the industry is growing exponentially, it is really necessary to prepare a business model so as to make the penetration of the technology without hampering the operation of the present manufacturing methodology[22].

3 METHODOLOGY

The project aims to prepare guidelines for the application of Additive Manufacturing and to impart knowledge about different parameters involved in the technology. In order to prepare the guidelines, a case study was prepared in collaboration with Equinor AS. The approach towards the case to find a viable solution would result in suitable guidelines for the Additive Manufacturing. Furthermore, a number of already performed case studies and experiences in additive manufacturing were taken into account to achieve the objective. Each step performed during the course of experiment is considered to be a guideline for applying the additive manufacturing technology.

3.1 Case Study

For the purpose of performing experiment the task was to consider an already existing standard part being used in an assembly, which earlier was manufactured using conventional techniques such as subtractive or formative manufacturing, and prepare it for the producing through additive manufacturing technique. The procedure included a number of steps from the point the part was first received to the point it was prepared for additive manufacturing.

All the experiments were performed at the UiT’s Metal Lab. The tools and the software used during the process are mentioned in each of the steps.

The part received from Equinor, as seen in figure 11, was a housing of an actuating which is an integral part of a larger unit for centering the Turret on Norne FPSO (warehouse buck). It is originally manufactured by IP-Huse on Harøya. The part is delivered according to marine standard, which originates in DNVGL's requirements for mechanical structures. The material is carbon steel and the quality corresponding to S355J2H according to EN 10219-1. During the event of leakage, the housing is filled with pressurized hydraulic oil and the housing is over pressed and deformed.

Figure 11 Original part

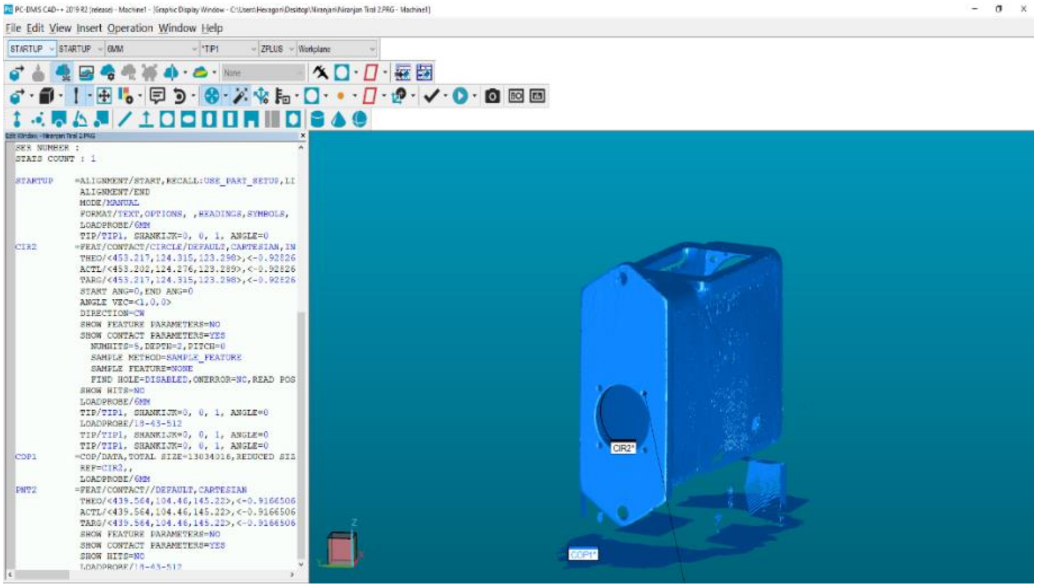
3.1.1 Pre-processing of the part

The main step of preparing the part for additive manufacturing is to redesign it, as the design for the existing parts are often not suitable for 3D printing. Design approach for the conventional manufacturing technique is usually, to make it as easy as possible for production whereas for additive manufacturing, it can as complex as required, taking into account the limitations of the metal printers used. Also, the key is to use as little material as possible. In order to redesign the existing part, the dependent attributes such as holes, flanges, etc has to be structured suitably or else the redesign part would not fit in the original assembly. Therefore, the true dimension of the part has to be known and then redesigned accordingly. Since, the standard CAD drawings of for the parts were not available, the first task was to perform reverse engineering on the part. Reverse Engineering is extraction of information from an existing engineered structure or design[25]. In order to do it, 3D scanning technique was employed. 3D Scanning is process of capturing the visual image and information of the real part with precision instrument. The scanned part can be modified, improved, and converted into CAD files to prepare blueprints for the scanned parts[26]. Since the part received had a lot of irregularities, deformations and a layer of paint which would deviate the true dimension, the paint was removed using tools such as angle grinder, hammer, chisel, metal brushes and sandpapers. It was one of the destructive methods of removing the paints and the non-destructive methods such as chemical treatment can be employed if the information about applied paint is available. The figure 12 illustrated the part after the removal of paint using the specified tools.

Figure 12 Pre-processing step 1

3.1.2 3D Scanning

The paint free part was then shifted to the 3D scan table and oriented the best way possible so that the maximum information about the part can be extracted. It is really important to decide beforehand how it should be oriented as once the 3D scanning process is initiated any movement of the part results in inaccurate results. The scanner used for the purpose was Hexagon Romer Absolute Arm 3D at the UiT's facility. The scanner was supported with PC-DMIS CAD++ 2019 R2 software to visualize the scanned data and feed the necessary instructions to the scanner. The scanned data is shown in the figure 13 in the PC-DMIS CAD++ 2019 R2's environment[27].



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SER NUMBER :
STATS COUNT : 1

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             ALIGNMENT/END
             MODE/MANUAL
             FORMAT/TEXT,OPTIONS, ,HEADINGS,SYMBOLS,
             LOADPROBE/6MM
             TIP/TIP1, SHANKIJK=0, 0, 1, ANGLE=0
CIR2        =FEAT/CONTACT/CIRCLE/DEFAULT,CARTESIAN,IN
             THEO/<453.217,124.315,123.298>,<-0.92826
             ACTL/<453.202,124.276,123.289>,<-0.92826
             TARG/<453.217,124.315,123.298>,<-0.92826
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             ANGLE VEC=<1,0,0>
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             SHOW CONTACT PARAMETERS=YES
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               SAMPLE FEATURE=NONE
               FIND HOLE=DISABLED,ONERROR=NO,READ POS
             SHOW HITS=NO
             LOADPROBE/6MM
             TIP/TIP1, SHANKIJK=0, 0, 1, ANGLE=0
             LOADPROBE/18-43-512
             TIP/TIP1, SHANKIJK=0, 0, 1, ANGLE=0
             TIP/TIP1, SHANKIJK=0, 0, 1, ANGLE=0
COP1        =COP/DATA,TOTAL SIZE=13034016,REDUCED SIZ
             REF=CIR2,,
             LOADPROBE/6MM
PNT2        =FEAT/CONTACT//DEFAULT,CARTESIAN
             THEO/<439.564,104.46,145.22>,<-0.9166506
             ACTL/<439.564,104.46,145.22>,<-0.9166506
             TARG/<439.564,104.46,145.22>,<-0.9166506
             SHOW FEATURE PARAMETERS=NO
             SHOW CONTACT PARAMETERS=YES
             SHOW HITS=NO
             LOADPROBE/18-43-512
```

Figure 13 3D scanning using Hexagon Romer Absolute Arm in PC-DMIS CAD++ 2019 R2

3.1.3 Processing of the scanned data

The scanned data with all the required information was then transferred to Geo Magic Design X. This software is used for reverse engineering which makes 3D scanned data easy to handle, modify and further extract more information from it. It is used to transform the raw scanned data into required CAD models. As seen in the figure 14, the coloured patches can be formed from the scanned data and each of them can be worked independently in order to filter the scanned data.

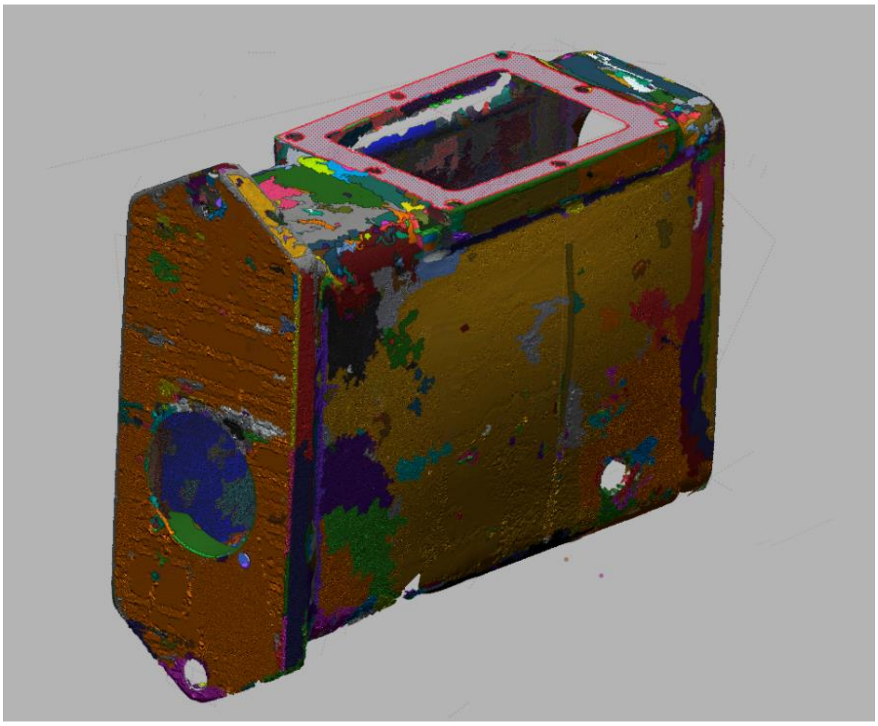


Figure 14 Processing the Scanned Data in Geo Magic Design X

The coloured patches are called as regions and local planes can be made in each of the area. All the unnecessary scanned data can be removed using it and the file can be transferred to any of the CAD software directly to generate required drawings from it. The scanned data as seen in the above figure 14 was processed in the Geo Magic design X and the improved scanned model is shown in the figure 15. The different colour scheme in this figure indicates the deviation in the data after processing as compared to the scanned data. It ranges from blue to red indicating the negative and the positive change, with green colour indicating the mean[28].

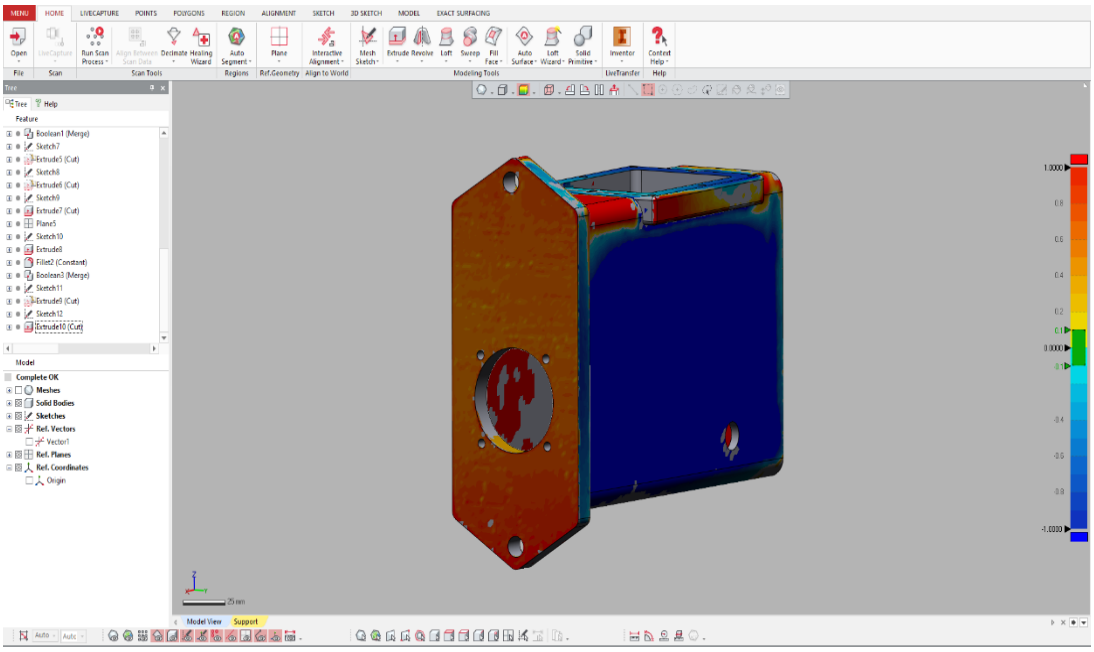


Figure 15 Improved scanned data in Magic Design X environment

3.1.4 Drawing Extraction

Upon the completion of processing the scanned data, the resulting model was exported to Autodesk Inventor for further improving it and extracting the drawing with dimensions from it. The purpose of exporting it to a CAD software is to make the changes within the model with greater freedom. Figure 16 illustrates the completed revere engineered model after repeated trials, analyses, and modifications in Autodesk Inventor.

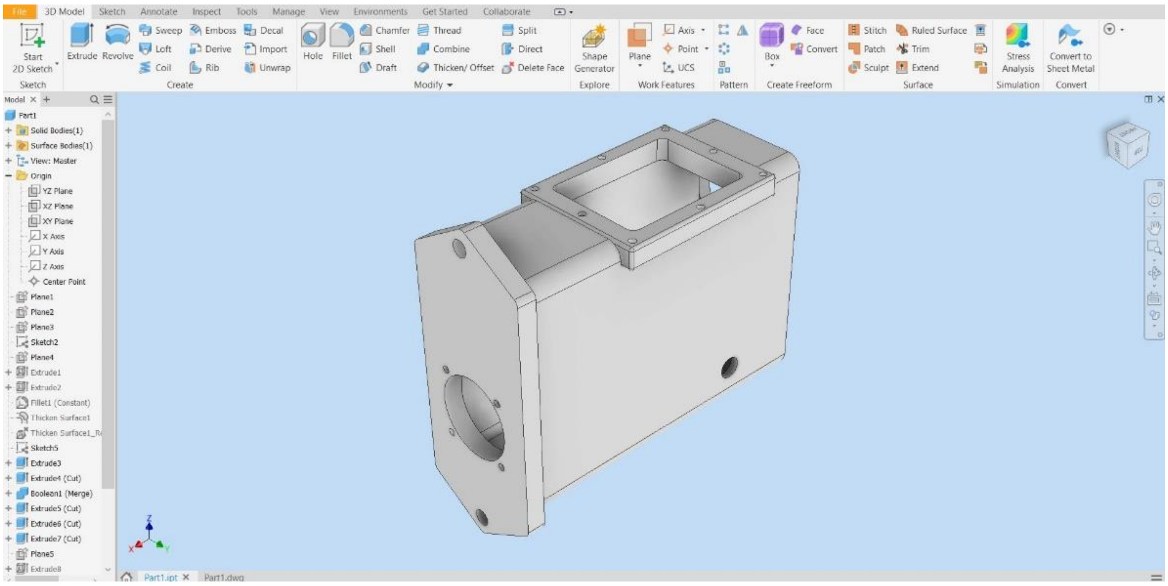


Figure 16 Complete model in Autodesk Inventor Environment

This was then converted into CAD drawing with all necessary dimensions shown in it. The figures 17 and 18 are the final drawings in two different views. Since the reverse engineering was performed in a deformed part, the dimensions were subjected to some tolerances.

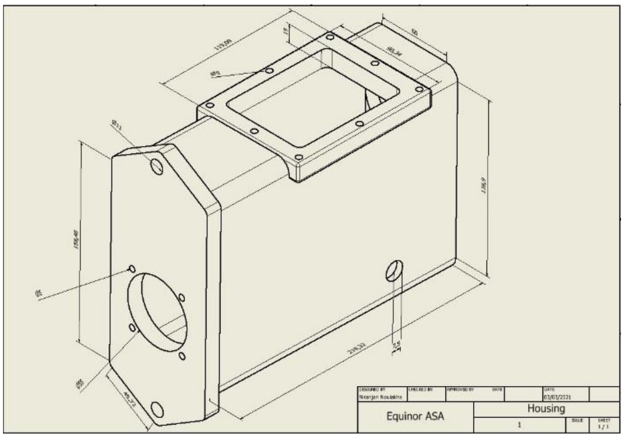


Figure 18 Front View with dimensions

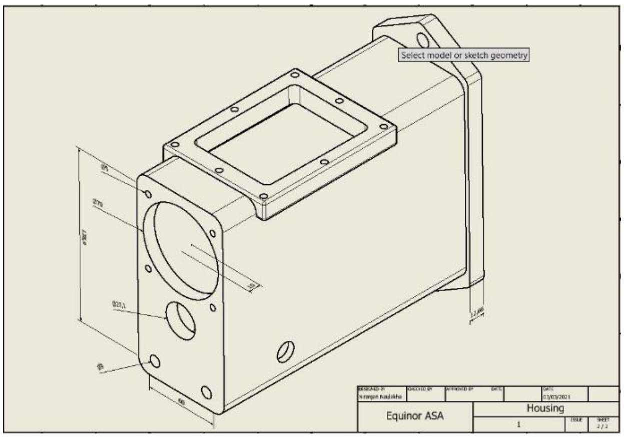


Figure 17 Back View with dimensions

The model, as seen in the drawings is rectangular in structure. Also, the centre part is completely hollow. Therefore, 3D printing this as it is, would be very costly. Similarly, the support material required during the 3D printing would be a lot making it unsuitable for printing. Similarly, it would require an equal amount of time and effort for post processing and the removal of the supports once the printing is completed. Hence, it was really important to redesign the part which would function the same way as well as became suitable for realizing it with additive manufacturing. The design approaches are explained in detail in the next chapter.

4 DESIGNING AND PROOF OF CONCEPT

4.1 Iterative Process of Technical Design

The part received from Equinor upon which the Reverse Engineering was performed, was not only considered in order to realize it for additive manufacturing but also to redesign it in a way such that the reasons that caused it to fail could also be resolved. A total of 67 such parts are used in the total in order to centre the turret on the Norne FPSO. Each of the part has a life cycle of 3 years and the failure occurred during an event of leakage. The problem is that the part is filled with the pressurized hydraulic oil during leakage in the actuating valve which cause the housing to be over pressed and deformed. Therefore, during the design approach it had to be taken into account so that it could be overcome as well.

Thus, the objective of redesigning process has been to

- Overcome the failure
- Make the part suitable for additive manufacturing
- Analyse and compare between the old and the new design.

The redesign approach was divided into steps and each step led to some improvement or an idea of do’s and don’ts for the additive manufacturing design approach[29]. Moreover, no previous design approaches were adapted with an aim to come up with a new approach if possible. Therefore, the redesigning was initiated by simply trying to make changes that can be applied just by the visual inspection of the part and its drawings[30].

The approaches were followed with constraints as follows:

- No changes in the functionality of the part.
- Holes or other features had to remain in same location and orientation so as not to affect the other part of the turret assembly.
- Any changes with the features had to be suitably adjusted with justification.
- Basic design standards were followed.

4.2 Execution of redesigning

4.2.1 Design 1

The first redesign approach was very basic as seen in figure 19, and the only aim was to remove any extra material that was present. The only location in the part where some extra material was noticed was the front face of the housing near the holes. The triangular shape initially present in it was due to the fact that the conventional approach for production is to make a part as quickly and easily as possible so making curves present near the holes in the front face requires an additional time and precision to achieve[31]. However, for 3D printing, this is not an issue if proper codes of command are fed to the printer. Similarly, no changes in any of the features were made during this design approach.

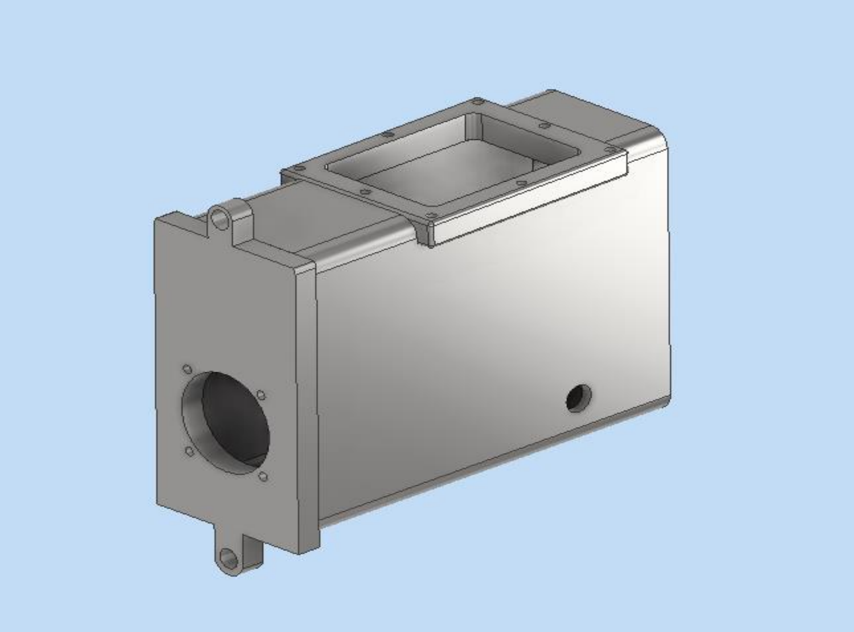


Figure 19 Redesign approach 1

Figure 19 had some improvement than the original design, but it was not enough for it to be realized for the additive manufacturing. The pros and cons for the given design approach are mentioned below.

<u>Pros</u>

- The design had, although a very little, but reduction in weight due to removal of material.
- The part functionality and the assembly dependency were not altered.

Cons

- The failures were not overcome and during the event of leakage, the same problems with the part would occur.
- This could not be 3D printed because it would have a lot of overhangs as the internal structure is hollow and it would require an extensive amount of support material during the printing of the part.
- Additionally, the removal of the supports after the printing and the post processing would have been completed would be very difficult.
- The overall printing would be extensively expensive. The price perspective for the 3D printing has be discussed in the later chapters.

4.2.2 Design 2

The points considered to improve were the cons as mentioned in the design approach 1 and the approach was to work with them to come up with an improved design resolving the problems as much as possible. Therefore, the design achieved after several trials and errors is illustrated in the figure 20.

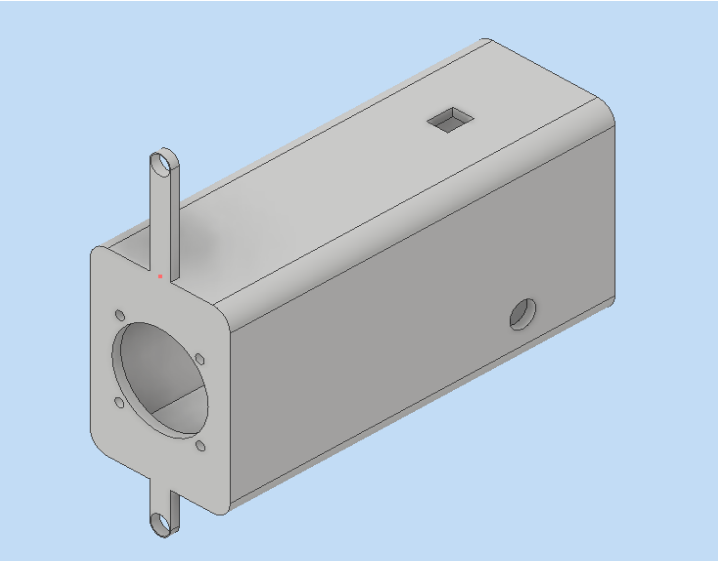


Figure 20 Redesign approach 1

As seen in the above figure, the volume of the part was reduced. This was done in order to prevent the failure of the part during leakage. The location for leakage was at the contact point between the hinged wheel arrangement and the actuating valve which had the pressurized oil represented by Contact C in figure 20. This contact point was present inside the housing and the only way to prevent the leaked oil from filling inside the housing was by situating the contact point outside it. Thus, as seen a small slot was made at the top face and the contact would have been outside the housing. The length of the slot had to be decided based on the rotation of the wheel if applied. This would result in the leaked oil from filling inside the housing and preventing it from deforming due to the pressure which was initially built. Also, the rectangular opening as seen in figure 19 was removed as it was present in the original design in order to adjust the contact point. Since the contact point was outside the housing in this new design, this opening was not required and therefore, could be excluded from the design.

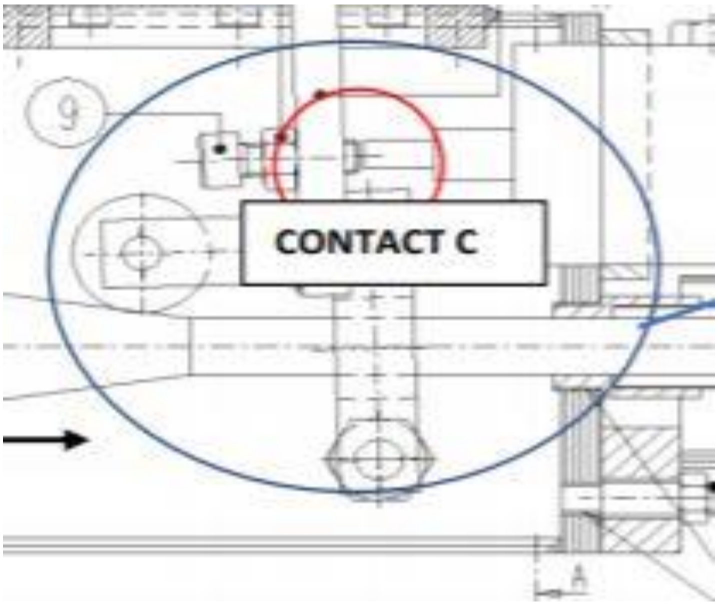


Figure 21 Illustration of the contact point

These changes made the design compact and practically more realizable for additive manufacturing. The pros and cons for this design are discussed below.

<u>Pros</u>

- The failure due to leakage could be overcome by this design.
- The volume reduced and thus, would result in reduction in weight and use of the material.
- The design had not major changes with the part functionality and could be adjusted easily in the assembly with minor arrangements.
- The design would reduce material, both built and the support, as well as cost due to reduction in the time if 3D printed.

Cons

- The shape was still rectangular, and the support material required would still be high during printing.
- The changes made for the contact point has to be properly adjusted resulting in the same functionality.
- A cover has to be made for inclosing the contact C in order to prevent it from external environment as the arrangement is present offshore.
- The post processing work would be difficult for this part as well.
- The printing of the part would be lower compared to initial design approach but still very high.
- Since the contact C is situated outside the housing, an additional holding support for the actuating vale has to be made separately and fixed precisely so that it does not affect the other aspects of the assembly.

Although this new design resolved the issues as seen in the design 1, it gave rise a number of problems as well. Moreover, the design was still not fit for 3D printing looking as its structure as it could still be made using conventional methods of manufacturing in a CNC machine with some special arrangements. Therefore, to make a design suitable for 3D printing along with tackling all the problems seen in above cases, different literatures discussing the design approaches for additive manufacturing were explored and the part was tried to be fit inside the boundaries of the designs which were explained in it. A lot of considerations have to be made while validating a part fit for additive manufacturing. One of the key things to consider is to optimize the part topologically. Topology Optimization was first introduced in 1988 by Bendsøe and Kikuchi and it has been one of the major breakthroughs for designing when adopting additive manufacturing[32].

5 TOPOLOGY OPTIMIZATION

In simple terms, topology optimization means achieving an improved design for a structure by optimally distributing the material based on loads, density and all the other factors to be considered within a domain of the design[33]. When we consider the conventional methods, such as subtractive and formative manufacturing techniques, they have lot constrains for manufacturing that has to be taken into account in order to ensure that the design is feasible such as, for machining the tool access, the removal of the part from a mould during casting, etc.

Due to these constraints, optimizing the topology becomes very difficult to realize and a decision has to made between optimality or the attaining the manufacturing of the part easily. Therefore, whenever topology optimization is considered for these conventional methods either the constrains are suitably adjusted or it is performed around the unconstraint parameters[34].

On the other hand, in additive manufacturing a part is built by subsequent addition of layer of material one over the other. This limits most of the constraints as the end product is obtained upon the completion of the process. Also, parts with a very high degree of complexity can be obtained which was in most cases not entertained by the former technologies. All of these give an opportunity to design a part with freedom resulting in an optimal final part production. Therefore, employing topology optimization becomes realizable and in turn benefits in the end result[35].

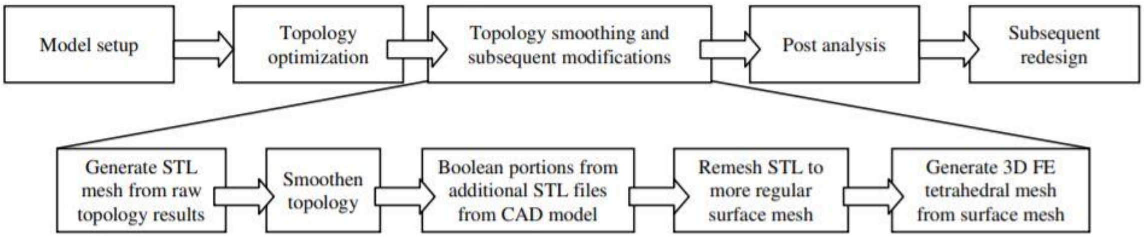


Figure 22 Steps in topology optimization for additive manufacturing[34]

In the illustration shown in figure 22, the flow of work for topology optimization is represented along with a sub flowchart which shows the stages for modification in geometry during the process. Figure 23 shows an example for optimizing the topology of a part.

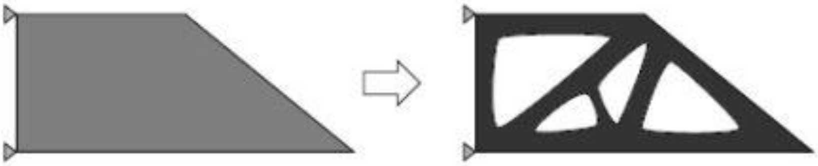


Figure 23 Illustration of topology optimization

The figure shows how the overall geometry and functionality of a part can be maintained but the structural geometry can be optimized based on the requirement. Similarly, overall geometry of the part can also be changed in some cases with main focus on maintaining the functionality aspect. This procedure was then employed for the redesign purpose in order to come up with a design having optimal structure suitable for realizing it for the additive manufacturing[36].

5.1.1 Design 3

As the improvement in design progressed, each trial and error resulted in a direction for coming up with a design which would take all the pros into account and eliminate the shortcomings with the best possible solution. After an insight about the topology optimization, the approach towards optimally designing each of the basic structures within the parts was followed. For this, the design 1 for the part was considered to the broken into sub-parts and each fragment was separately designed and finally consolidation of the redesigned fragments would result in a new design. The sub-parts were chosen based on the features in the part. Since each of the dependent feature had to be suitably adjusted, the face that contained any features such as holes, flanges, etc. were considered as a sub part[37].

The first sub-part considered was the front face for the part. The main features of this face i.e., the holes were fixed in their position, the loads on the parts were simulated and the design of the front face was finally optimized such that the part functioned the same way. The figure 24 represents the transformation and the new design for the front face can be seen.

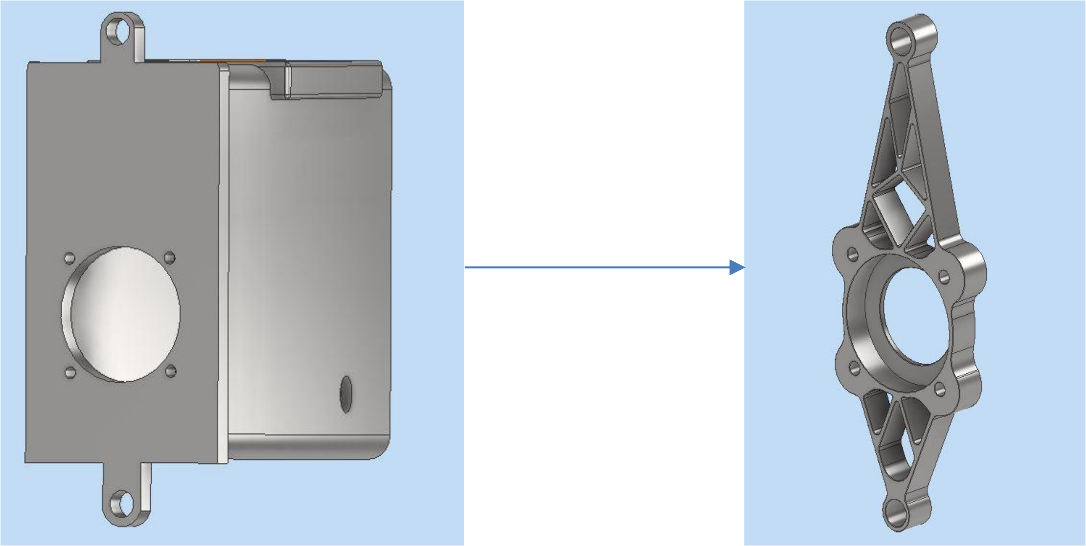


Figure 24 Topology Optimization of the front face

The same approach was applied for the back face of the part. The back face was also similar to the front face consisting of many holes. But, in this case location of the holes were changed such that it did not affect other assembly parts. As seen in the figure 25, the position of the two holes is interchanged. This was done to make the contact point C from figure 21. Under the housing rather an over it as suggested in design 2. This is because, during the leakage, the oil would fall directly on the housing top and any penetration of the oil through the slots, or any other holes would eventually fill the unit with oil and the earlier seen failure could arise again. Therefore, situating it below would restrict all any entry of oil inside the housing and the problem of deformation is completely eliminated[38].

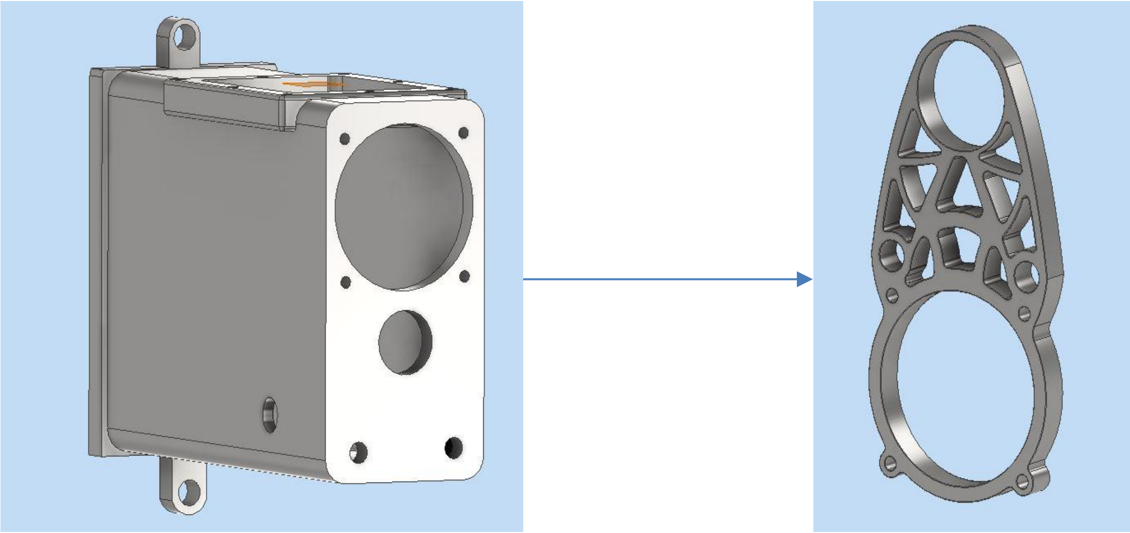


Figure 25 Topology Optimization of the back face

After the major changes on the two face, the only part remaining was the hollow rectangular area which is almost empty and only consists of the shaft and the hinged mechanism. The diameter of only shaft was 32mm. Therefore, if the roller mechanism can be adjusted, the center body can be a 35 mm inner diameter hollow tube with a wall thickness of 8-10 mm. The dimension of the hollow tube could be chosen such that standard size of it is available and can be separately order as printing it would not be feasible from the cost perspective. The final optimized parts can be seen in the figure 26, and the figure 27 represents the final design after parts consolidation.

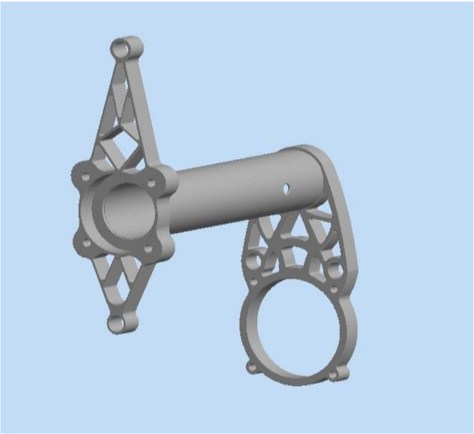


Figure 27 Final Design

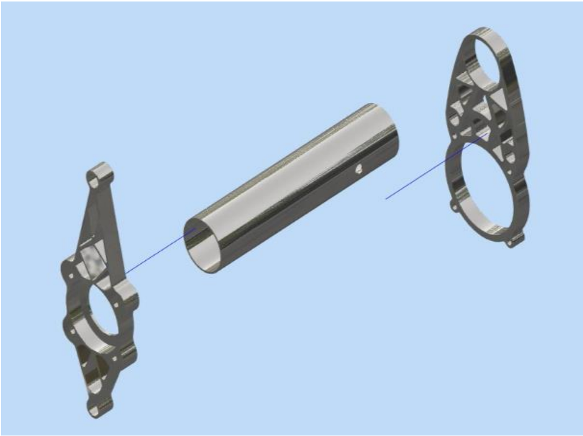


Figure 26 Optimized subparts before consolidation

This new design had all the features present in the original design. For making it to a final end part, front and the back face as seen in figure 26 and 27 would be 3D printed and the center tube of a standard size based on our design dimensions can be purchased from an external supplier. Then the necessary post processing works such as making holes, slots, threads, etc. can be done in a CNC machine and all the sub-parts can be welded as one[39]. All the necessary arrangements for the roller mechanism are made same as it was in the previous design, therefore, it can be assembled exactly in the same manner with slight adjustments. The pros and cons for this design are discussed below.

Pros

- The design had all the advantages as present in the above designs.
- Only the front and the back faces has to be printed, hence, the cost and time for the printing is greatly reduced.
- Using the center tube of standard dimension saves a lot of time than producing it. Also, it is easily available as well.
- The weight of the part is greatly reduced because of the optimized designed.
- The failure of the part due to leakage is completely eliminated.
- The design can be realized for 3D printing as manually printing such part can be very difficult and time consuming.

Cons

- The design had to be analyzed a number of times before as during the actual printing any deviations can cause it to fail.
- There is a high risk of the roller mechanism not to function as it functioned in the original design.
- Reverse Engineering was performed on any already damaged part, therefore, the dimension as compared to an original part.
- Additive Manufacturing is still a very expensive technology and realizing this for actual production can cost a lot.

- The new design might not fit in the actual assembly line, as not enough information about the surrounding assembly was available and they are considered based on speculations.

Similarly, there can be many other pro and cons upon actual printing of the part. However, they can be adjusted based on requirements. The designs look printable, but they have to withstand the same stresses as the previous design. Therefore, a thorough stress analysis was performed on both the original and the new design and the results were compared. The material used for the purpose was carbon steel, the load and the pressure values were taken from when the part underwent failure. The analysis was performed in Autodesk Inventor. The analysis results are discussed in the next section.

6 ANALYSIS AND COMPARATIVE STUDY

It was noted from the previous experience that the original designed failed when the pressured hydraulic fluid leaked inside the housing causing it to deform. The pressure value was found to be 65 bars at that instance. Thus, the analysis was performed for this value of pressure and designed. Although the failure was resolved by isolating the contact point C from inside the housing and placing it outside, the new design was analyzed for the values that cause the initial design to fail. Since, no design for any other parts were available to analyze the design for the entire system, bearing loads along the direction where the shaft reciprocated was applied and a bearing moment around the point where the hinged wheel mechanism rotated back and forth due to the movement of the shaft was applied.

<u>Assumptions:</u>

- Material: Steel, Carbon
- Pin & Fixed Constraints
- Mesh Values:
  - Average Element Size: 0.05
  - Grading Factor: 1.50
  - Maximum Turn Angle: 20 degrees

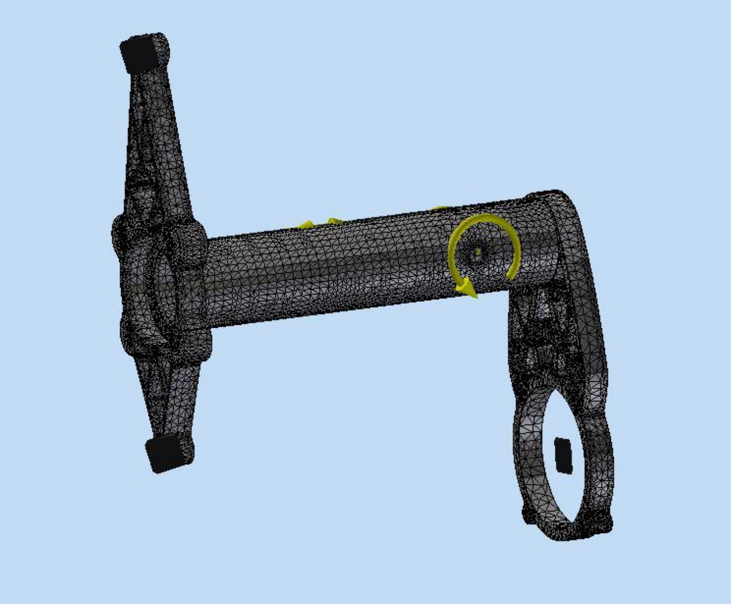


Figure 28 Mesh View with inputs

Bearing Loads

The diameter of the shaft was 32mm. Taking this value for calculating the area, the maximum force that could be applied would be when the shaft and the wall of the center tube for the new design are in contact during failure. However, in the new design the tube greater than 32 mm. If the corresponding load for this value can be endured by the new design, it would not fail for the diameter of the tube greater than 32 mm.

Radius(r) = 32mm = 0.032 m

Area(A)= $\pi r^2 = 3.14 \times (0.032)^2 = 3.21 \times 10^{-3}\ m^2$

Maximum Pressure in the system(P) = 65 bar = 6.5×10^6 Pascals

Therefore, Bending Load (F) =P x A = $6.5 \times 10^6 \times 3.21 \times 10^{-3}$ = **20899.84** N

Bearing Moment

As mentioned earlier, the bearing moment was applied around the point where the hinged wheel mechanism rotated back and forth due to the movement of the shaft. The value for this was also chosen during the failure condition i.e., when it is under the load(F) of 20899.84 N. Since moment is the Force applied across the perpendicular distance, the distance can be considered as the distance from the center of the roller mechanism to the surface of the tube. Since both of them are concentric, the distance can be taken as the inner radius i.e., 16mm.

Load(F) = 20899.84 N

Perpendicular distance (d) = 16mm

Bearing Moment (M) = F x d = 20899.84 x 16 = **334384** Nmm

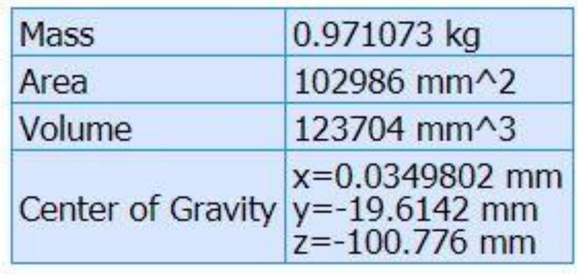
These values were applied to both the designs to inspect their reaction under the following instance

The loads and the moment can be seen the figure 28, marked in yellow.

6.1 Analysis Result

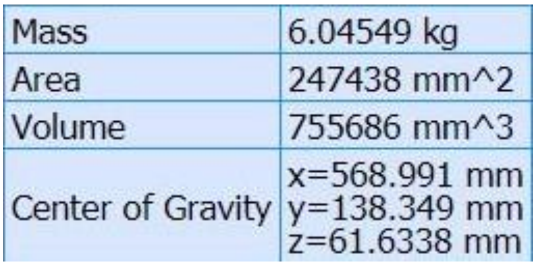
6.1.1 Physical Attributes

Table 3 Physical Attributes for New Design



Mass	0.971073 kg
Area	102986 mm^2
Volume	123704 mm^3
Center of Gravity	x=0.0349802 mm y=-19.6142 mm z=-100.776 mm

Table 4 Physical Attributes for Old Design



Mass	6.04549 kg
Area	247438 mm^2
Volume	755686 mm^3
Center of Gravity	x=568.991 mm y=138.349 mm z=61.6338 mm

Note: Physical values could be different from Physical values used by FEA reported below.

The results for the given set of data are shown in the above tables 3 and 4. From it is clear that the mass of the new design is greatly reduced, almost 1/6th the original mass. However, the hollow tube can add up some extra mass to the design resulting to a mass to around 2 kg in total which is still 1/3rd of the original. This reduction in mass is one of the key elements of switching from conventional methods to the additive manufacturing methods[39]. This results in saving a lot of material, in turn saving a lot of money. Similarly, the other results are superior in terms of number.

6.1.2 Static Analysis

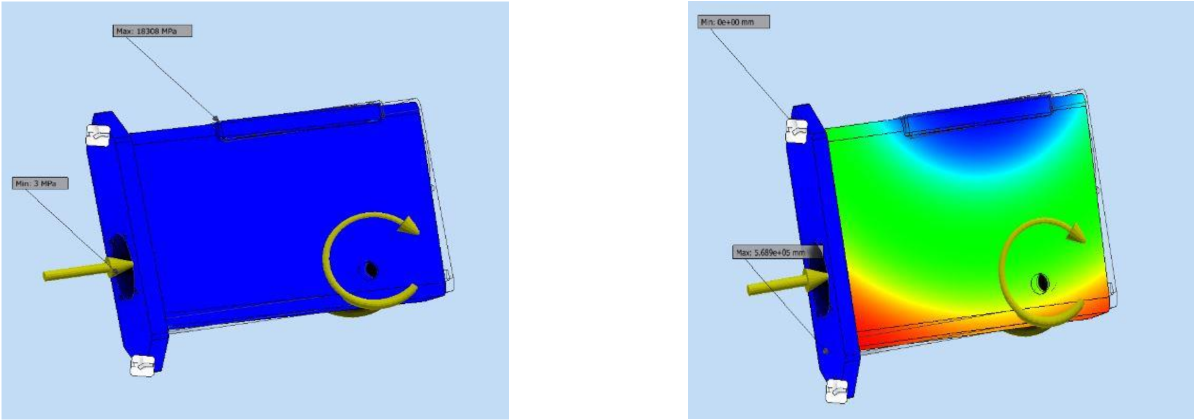
The stress induced, displacement and the safety factors under load was analyzed for both old and the new design under same condition.

6.1.2.1 Original Design

The results in the table 5 and the figure29 represents the maximum and minimum values of each parameters under the specified conditions and values of loads and moments. The color scheme ranges from red to blue corresponding to the maximum and the minimum in each of

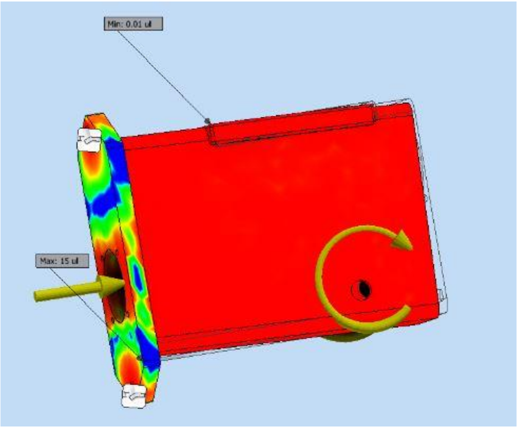
Table 5 Analysis Value for original design

Name	Minimum	Maximum
Volume	755686 mm^3	
Mass	6.04549 kg	
Von Mises Stress	3.46688 MPa	18308.3 MPa
1st Principal Stress	-4214.2 MPa	17487.4 MPa
3rd Principal Stress	-16421.3 MPa	3774.64 MPa
Displacement	0 mm	568895 mm
Safety Factor	0.013655 ul	15 ul



i. Von Misses Stress

ii. Displacement



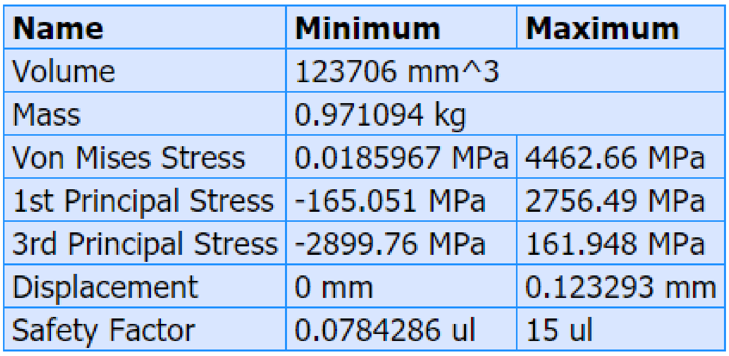
iii. Safety Factor

Figure 29 Analysis results for the original design the regions. It is evident from the analysis that the stresses are within the limits but the other factors parameters i.e., the displacement and the safety factory exceed it and is the reasons for part failure during the leakage. The safety factor which refers to the strength of a part under applied load[40], eventually shows the main reason for the bulging of the part . These values were considered during redesigning with an aim to overcome them.

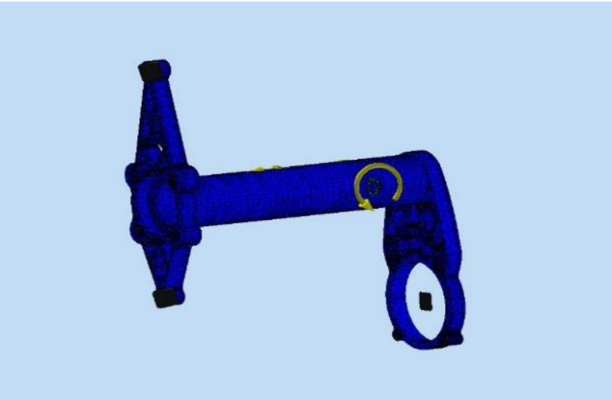
6.1.2.2 Proposed Design

The redesigned part would eventually be of no use if it cannot withstand the specified conditions, even it is optimized topologically and made suitable for metal 3D printing. For the proposed design, the regions where the failure was most likely to occur was focused although the reason for the failure i.e., the leakage would not occur in it. The table 6 and the figure 30 illustrates the results for the proposed design.

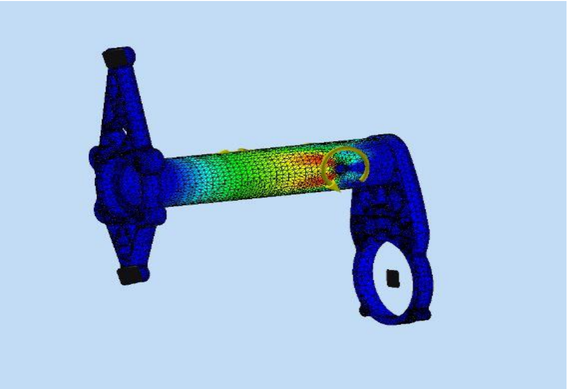
Table 6 Analysis Value for proposed design



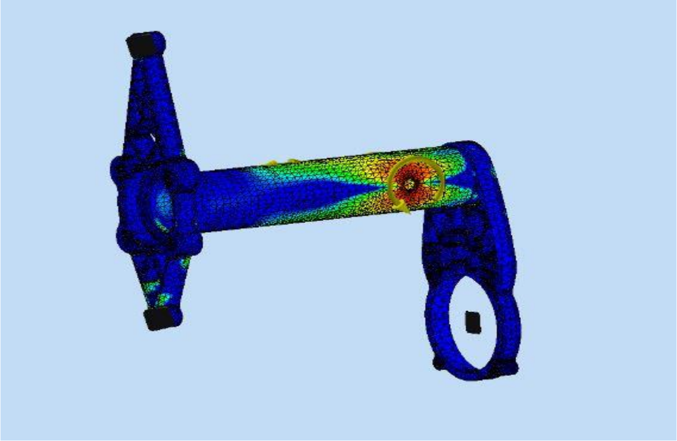
Name	**Minimum**	**Maximum**
Volume	123706 mm^3	
Mass	0.971094 kg	
Von Mises Stress	0.0185967 MPa	4462.66 MPa
1st Principal Stress	-165.051 MPa	2756.49 MPa
3rd Principal Stress	-2899.76 MPa	161.948 MPa
Displacement	0 mm	0.123293 mm
Safety Factor	0.0784286 ul	15 ul



i. Von Misses



ii. Displacement



iii. Safety Factor

Figure 30 Analysis results for the purposed design

It can be clear seen from the color scheme that most of the reguion is covered in blue, indicating that under the same condition that caused the older design to fail could be endured by this new design. Some region near the point where moment was applied has varition of color, but the analysis is performed under the assumption that there is a contact between the shaft and the inner housings het filled with the pressurized fluid, but in practical application if it would not happed due to the proper adjustments. Hence, these region would be taken care in real application and the design would not fail for the applied load condtions.

Therefore, a conclusion can be drawn from this repeated trial and error to achieve a new design that not only additive manufcaturing can be considered as an alternative manufacturing process but the freedom of design that it offers can resolve many causes of faliure and introduce different special features and properties to an existing part as well[41].

7 COST ANALYSIS

There is a substantial amount of costs associated with application of additive manufacturing. The process sounds very simple theoretically, where in the material and design is fed into the 3D printer and a required final output is obtained but in fact, there are a number of tasks one after the other which makes it complex and in addition each of these steps comes at a premium cost[42]. All these factors make additive manufacturing very much limited to prototyping and the commercial production using this technology is still very low compared to the other manufacturing techniques. However, the rapid progress and the thrive to bring down the cost for each factor have been a boon[43]. The machine which can metal print a precise functional part still ranges in millions of dollars.

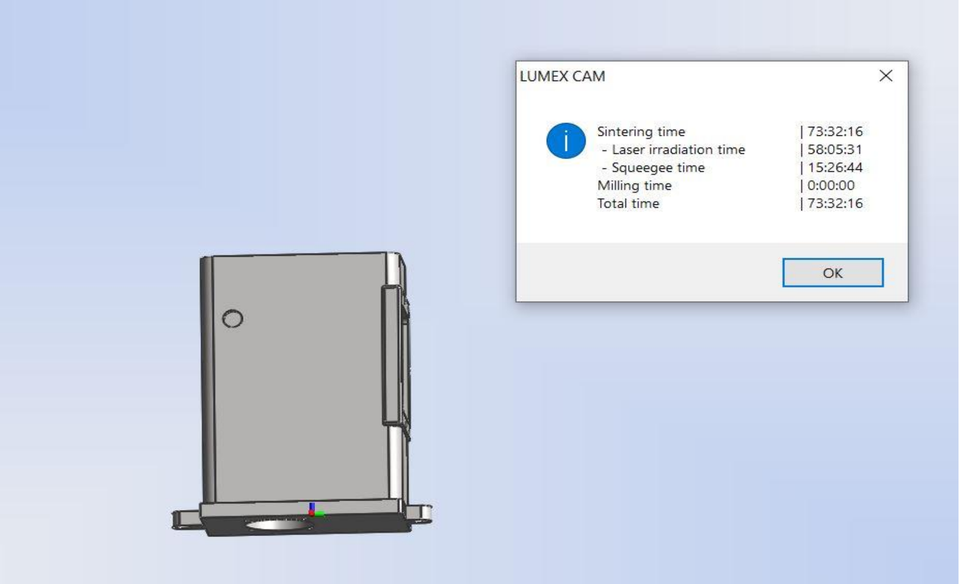
This chapter shows a cost comparison between the old and the proposed design wherein, the cost of technology is not taken into account. The printer considered for this purpose was the Matsuuara LUMEX Avance –60 Hybrid metal 3D printer at the metal lab in UiT Narvik's facility, the material is Stainless Steel 17-4 PH, and all the standard costs were provided by the Department of Industrial Engineering at UiT Narvik. Since this cost estimation was prepared as a research, no profit or surplus charges were included. Both the designs were simulated in LUMEX CAM to find out an estimate printing time in order to prepare a detailed cost analysis.

The basic cost structure is shown in the table 7 below.

Table 7 Standard Costs at UiT's facility

Title	Cost
Material Cost (Stainless Steel 17-4 PH)	1991 NOK/kg
Machine Hourly Rate	598 NOK/hr
Manual Labor(Operator Cost)	900 NOK/hr
Advanced Parameters (Servicing, Base Plate, Part Programming, etc.)	Estimation based on parameters
Additional Profit (25 %)	Not Applicable

The cost was first calculated for the original design without any changes made to it. Although this was not a feasible design for 3D printing as it would require a huge amount of material for the support, it was simulated in order to find out the improvement in costs that it would bring by redesigning.


LUMEX CAM

Sintering time	| 73:32:16
- Laser irradiation time	| 58:05:31
- Squeegee time	| 15:26:44
Milling time	| 0:00:00
Total time	| 73:32:16

Figure 31 Simulation in LUMEX CAM for the original design

As seen in the figure 31, cost estimation is prepared based on the total printing time as approximately 75 hrs. In practical the total time can be twice because of the extensive use of support it would require. However, only the simulated time is used for the calculation purpose.

i. Material Cost

Since the total weight of the part was around 6 kgs, it would require approximately 12 kgs of powder in order to fill up the powder bed. But some powder can be recovered after the printing is completed, therefore, considering 10kgs as material used.

Material Usage = 10 kg

Cost = 1991 x 10 = **19910** NOK

ii. Printing Cost

Time to print as per software = approx. 75 hrs.

Calculated Cost = 75 * 598 = **44850** NOK

iii. Manual Labor Cost (Considering only one operator)

Time may vary between 50 to 100 hrs. depending upon a lot of handling required during the printing of the part. Taking the least time i.e., 50hrs for the purpose of calculation.

Cost = 50 x 900 = **45000** NOK

iv. Advanced Parameters

1. Time to preparation and start printing = 9hrs

Cost = 9 x 598= **5382** NOK

2. Base Plate(preferably c45 steel) = **2000** NOK

3. Time for Part removal from the machine and clean up = 8hrs

Cost= 8 x 900= **7200** NOK

4. Part Removal from the base plate = 1 hr = **900** NOK

5. Servicing of 2 hours each every 9 to 10 hours. 75 hrs. of printing mean 7 services of 2 hrs. each = 14hrs

Cost = 14 x 900 = **12600** NOK

6. Part Programming = 5 hrs.

Cost = 5 x 900 = **4500** NOK

7. Time for Machining = 8 hrs.

Cost = 9 x 900 = **8100** NOK

8. Setup for Machining (1hrs) = 9**00** NOK

9. Post Processing (3 hrs.) = 3 x 900 = **2700** NOK

Total advanced parameter costs = 5382 + 2000 + 7200 + 900 + 12600 + 4500 + 8100 + 900 + 2700 = 44282 NOK

Cost for producing the part

Cost = Material Cost + Printing Cost + Manual Labor Cost + Advanced Parameters

= 19910 + 44850 + 45000 + 44282

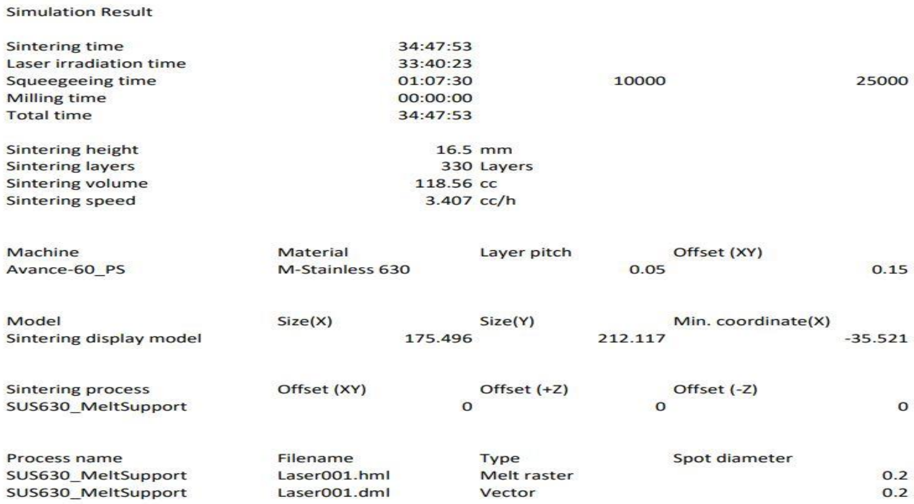
= **154042** NOK

These calculations are made based past experiences on printing different parts. Since no parts as big as the one taken into consideration is printed before, the actual cost might vary slightly from the calculated cost.

Furthermore, the design needs to be optimized because the design is not suitable for 3D printing. The hollow structure present internally will be filled with support material if printed as it is. Therefore, the removal of which during post processing can be very difficult and in worst cases not possible in some unreachable areas. This will lead to extensive rise in the use of material and the total cost for printing might be high.

In a similar manner price were calculated for the redesign part as well. All of costs in this case reduced to a great extent because of the small size and comparatively futuristic design. As mentioned in the former chapters that only the front and the back faces would be printed so the cost is calculated based on procuring the center tube from a supplier and its cost has been adjusted accordingly. Also, both the faces that is to be printed can be made at the same time because of its small size, therefore it would save a lot of time and cost as well.

The cost calculation for the purposed design is discussed below.



```
Simulation Result

Sintering time                          34:47:53
Laser irradiation time                  33:40:23
Squeegeeing time                        01:07:30            10000                25000
Milling time                            00:00:00
Total time                              34:47:53

Sintering height                            16.5 mm
Sintering layers                             330 Layers
Sintering volume                          118.56 cc
Sintering speed                            3.407 cc/h


Machine                Material               Layer pitch           Offset (XY)
Avance-60_PS           M-Stainless 630                         0.05                   0.15


Model                  Size(X)                Size(Y)               Min. coordinate(X)
Sintering display model               175.496               212.117                -35.521

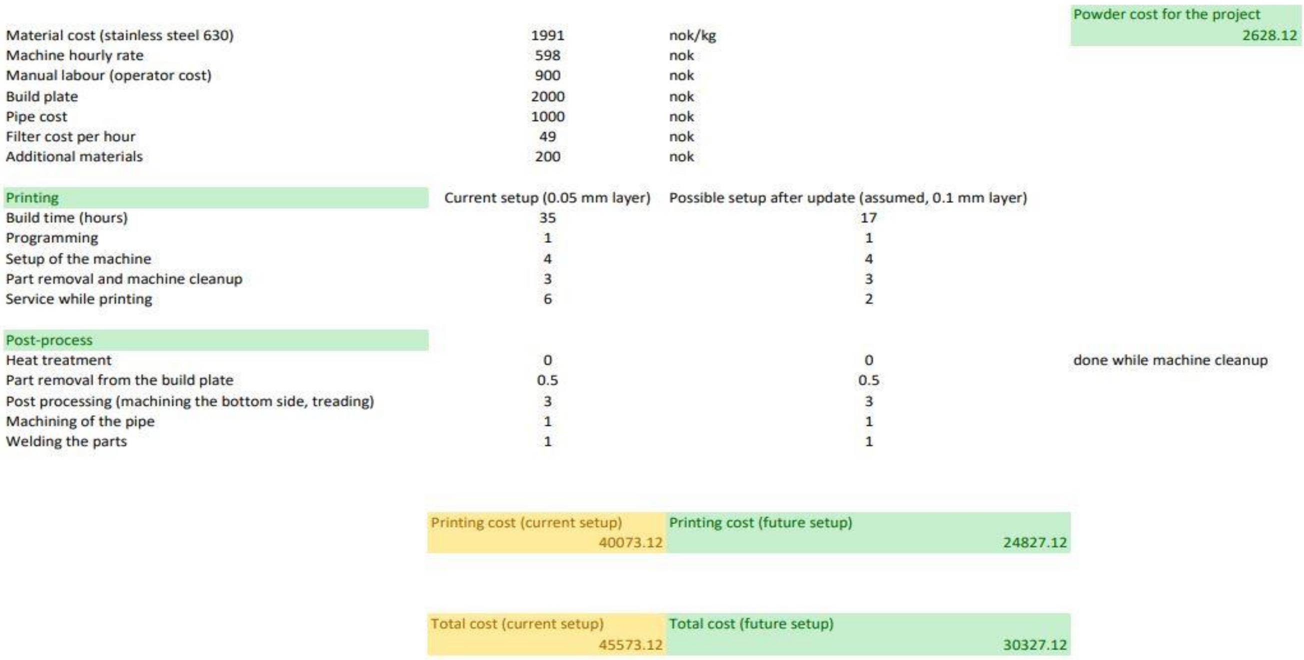

Sintering process      Offset (XY)            Offset (+Z)           Offset (-Z)
SUS630_MeltSupport                          0                     0                      0


Process name           Filename               Type                  Spot diameter
SUS630_MeltSupport     Laser001.hml           Melt raster                                0.2
SUS630_MeltSupport     Laser001.dml           Vector                                     0.2
```

Figure 32 Simulation result for the purposed part in LUMEX CAM

Figure 32 represents the total time simulated for printing the front face and the back face. The total time is approximately 35 hours. The current setup at UiT Narvik facility is set at a layer pitch of 0.05mm. The machine is in queue for update and the layer pitch is assumed to increase to 0.1. Therefore, the time for printing would drop down by half i.e., approximately 17 hours. Therefore, the cost calculation is made based on both the layer pitch is tabulated as seen in the table 8.

Table 8 Cost estimation for the proposed design



			Powder cost for the project
Material cost (stainless steel 630)	1991	nok/kg	2628.12
Machine hourly rate	598	nok	
Manual labour (operator cost)	900	nok	
Build plate	2000	nok	
Pipe cost	1000	nok	
Filter cost per hour	49	nok	
Additional materials	200	nok	
Printing	Current setup (0.05 mm layer)	Possible setup after update (assumed, 0.1 mm layer)	
Build time (hours)	35	17	
Programming	1	1	
Setup of the machine	4	4	
Part removal and machine cleanup	3	3	
Service while printing	6	2	
Post-process			
Heat treatment	0	0	done while machine cleanup
Part removal from the build plate	0.5	0.5	
Post processing (machining the bottom side, treading)	3	3	
Machining of the pipe	1	1	
Welding the parts	1	1	
	Printing cost (current setup)	Printing cost (future setup)	
	40073.12	24827.12	
	Total cost (current setup)	Total cost (future setup)	
	45573.12	30327.12	

The yellow highlighted region represents the cost for producing the completed part, along with welding the center tube and performing all the necessary processing for the current setup. Upon updating, the price would drop down to the one shown in the green highlight.

Comparing the cost for the two design, we can see that the cost has been significantly dropped to 1/3rd of the earlier mentioned cost for original design in the current setup and 1/5th of the earlier mentioned cost after updating the setup at the UiT's facility. This gives an idea about what redesigning a part can offer. This reduction in price gives a room for realizing the penetration of the additive manufacturing technology in the mainstream manufacturing.

8 Discussion

The overview of additive manufacturing along with its core fields was discussed in the first chapters, then the methodology and experimentation in the second followed by an entire redesigning and cost estimation for this project. The main objective of this project was to prepare guidelines for additive manufacturing as it has been growing at a pace but still very hard to work in parallel with the subtractive or formative manufacturing techniques. Although a huge amount of research and development has been made in this, it is still a great challenge to imagine the practicality of additive manufacturing to the fullest. However, the opportunities involved are of greater interest and the new revolution it shall bring to the manufacturing industry is huge. Some of the basic challenges and opportunities associated are discussed below.

8.1.1 Challenges

The main aim of this study is to identify the major challenges, and to create the suitable guidelines in adopting the technology of metal 3D printing in their manufacturing process which has been very rare due to various reasons. The return that it can provide in a long run is so huge that it has become very vital to suitably include the technology without hampering their ongoing process and the progress. The first and the foremost challenge with the inclusion of 3D metal printing is the cost of the technology which is in many cases very tough to cope with. Although the technology has been growing very rapidly for over more than three decades, it is still very immature when it comes to actually using the technology for manufacturing, especially for mass production and still limited to prototyping only or very limited applications. Even if it is not about achieving mass production, the requirement for post-processing the 3D printed product adds on the additional cost to already expensive technology. Similarly, the expertise required for running this high maintenance and complex technology comes at a price that is again very difficult for the industries to bear. Moreover, industries usually look for easy to handle and easy to process methodology such that it does not hamper or affect any other processes. 3DMP, still being in its immature state, is expected to go through a lot of changes with time, which makes it difficult to cope up with these changes in order to remain in the competition. On the other hand, the manufacturing of desired parts by 3D printing is very slow, which in some cases can correspond to days or even weeks, depending upon the complexity of the design. All these factors make it very difficult to include the 3DMP technology even though it has so much to offer. The technology is very unpredictable when it comes to maintaining certain attributes usually associated with quality and repeatability. Furthermore, the industries need to educate their stakeholders in each stage about the technology for assuring that the products maintain the required quality, which demands a lot of effort and very often the stakeholders are very skeptical about the changes. Another challenge that can be seen is that the 3D metal printing technology is growing application by application only. Printing a 3D structure of metal requires a very complex pre-processing task of designing the required product with all the correct dimensions and necessary tolerances. Along with that, it also requires different controlled parameters and environment, which determines the actual fate of the output. To sum up, it requires highly skilled, both pre-and post- processing tasks to print the desired metal product[44]. The information about the technology in different industries as well as in academia is very limited. Therefore, it is very important to make sure that the information about the 3D manufacturing of metal is of high quality and more importantly correct. The price associated with procuring the metal printers and the equally important raw material added by the limited availability of the expertise and the information about the technology has made it hard for it to penetrate the manufacturing industries to replace the existing methods. These are some of the most common challenges faced for the implication of 3D metal printing and tend to increase as their practicality is explored.

8.1.2 Opportunities

It is evident that whenever there are challenges for a certain thing, there are even more opportunities associated with the same thing. In the case of 3D metal printing also, there is a number of opportunities it offers to bring a very impactful revolution in the field of manufacturing. Since the technology is still very mature it opens a number of door for research and developing the technology to make it suitable for the manufacturing industries[45]. The most effective way to achieve it would be to bring the cost of the 3D printers as down as possible. This will give an opportunity not only to afford the technology, but also help in providing greater independence with using the technology. Since the technology is in its early stage, any breakthrough will help the responsible make a big name in the market. When it comes to sparsely populated areas, the technological advantage that metal 3D printers can offer is huge. The regions which are very far from the main market but are completely dependent on every single product, for example, spare parts of the machines, nuts, bolts, etc. Having a metal 3D printer would allow the enterprises to print such parts on their own which would be very beneficial and save a lot of time. The availability of 3D printers allows making a very similar prototype for any complex design, which would help to avoid making big investments but explore the possibilities, capabilities, and test for the efficiency in the prototypes themselves. Another boon it has to offer would be that it will allow the end-users as the generator of the technical solutions themselves and providing them an opportunity to develop new technology. The inclusion of 3D metal printers would help in logistical optimization. This can be seen as that the 3D printers would eliminate a section of logistics saving both cost and time and making it easy for the other sections of the logistics to be optimized. Some small but high-end product supplying enterprises can benefit even from the high cost of both the printers and the materials used for 3D metal printers in a way that the cost comes secondary when compared to the luxury for some customers[46]. They are ready to pay for the fulfilment of their desired products. Metal 3D printers have also made their mark in the medical industry aiding in making implants as well as frameworks for the implants much easier as well as incorporating complexity that is required. 3D printers also allow much clean environment as compared to conventional manufacturing processes as it has very limited use of coolants or lubricants[47]. This also makes it environmentally friendly. Similarly, as compared to subtractive manufacturing the wastage of the raw material is very limited. The 3D manufacturing technology is very safe as compared to the conventional ones due to the very limited human-to-machine interaction. Since the technology is very expensive, there is always a room for bringing down the cost which can be seen as the biggest opportunity for all the different industries competing in the race of making a name in the 3DMP industry.

8.1.3 Guidelines

The entire task of redesigning and a thorough survey of the core fields gave an opportunity to explore the technology and the underlying aspects very closely. The development in this field can change the face of how the manufacturing industry operates, especially in the competition of manufacturing very high-quality products but the mass in production is not a concern. The advantages of the technology are a lot in general, but the course of redesigning the part resulted in some specific ones which are as follows:

i. **Reduction in material**:

As documented in the results for the project, the mass of the part realized for 3D printing reduced to 1/3rd of the original part. This means with the same amount of material required for manufacturing one part using conventional manufacturing process results in three parts using additive manufacturing. This equation might not be validated for all kinds of part but in most cases, there is a considerable amount of material that is saved because the manufacturing is very smart and do not have a lot of constraints to obstruct. Unlike in subtractive and formative, which has to deal with big chunks of materials in most cases, for additive manufacturing, a small change in each layer can be made. This small change adds up resulting in a very complex yet superior results. A very common term referred to as buy-to-fly ratio, especially used in the aerospace industry, is defined as the ratio of the amount of material initially present or fed to the machine to the weight of the final part. The ratio very close to 1, meaning no material or very little material is wasted during the additive manufacturing process. To sum up, the technique offers a lot of room for a reduction in material usage.

ii. **Topology Optimization**:

Optimizing the design offers to produce very smart yet equally strong and functional parts which is another very important aspect of 3D printing. Additive manufacturing is not only a technology but a procedure where 50% of the work is basically designing of the parts and the remaining is the actual production. The design determines whether the part is suitable for manufacturing or not. Along with the smart structures, it can also produce advanced geometries which otherwise cannot be made easily.

iii. **Part consolidation and inventory management**:

Maintaining an inventory is a very difficult and expensive task in the industry. A big portion of the budget has to be spent on it. Additive Manufacturing can eliminate or greatly reduce this issue. Firstly, it can produce a part with very few assemblies reducing the maintenance of complex inventories with various parts and secondly, setting up a 3D printer along with an advanced predictive maintenance technique can help to eliminate the section of inventory completely but producing the part expected to fail right before the estimated end of the life cycle of the part.

iv. **Tooling**:

In comparison to the existing techniques, additive manufacturing eliminates the need for tooling completely which is a very sensitive as well as time-consuming process. Also, it can help to produced parts with different materials at the same time requiring some adjustments.

Furthermore, the task of making the guidelines can be divided into several sections as the case study was performed. Throughout the course of the case study, right from the designing phase to the cost analysis resulted in several footnotes that can be realized to create a set of guidelines in during each stage. However, there are a lot of 3D printers in the market today whose underlying principle is similar, but the working is different from each other, the guidelines were made such that it would address the overall additive manufacturing technology.

The guidelines are thus made taking all of these into account and divided based on the following stages.

i. Design Phase

As discussed in the project, what design accounts for additive manufacturing, it can be clearly stated that this technology is most about the designing of what needs to print than performing the actual printing of the part . For example, after the reverse engineering process was completed and the drawings were obtained, the task of design optimization was conducted. The optimization of the part topologically is demanding in order to realize 3D printing, but it is a very complex task that makes designing to be overlooked and therefore, not to incorporate the technology in the mainstream manufacturing. Also, the task of redesigning can be very time-consuming and expensive. The time and cost along with the complexity as a barrier open the door for coming up with smart technology that can itself perform the optimization. The technology can be software that does a thorough analysis of the part under consideration and gives the best possible solution or a number of different options for the part to be redesigned. Some of the available software like Autodesk Nastran, GENESIS, etc are available for the purpose but still require a lot of human effort for the result[48].

Similarly, a dimensionally correct drawing is of must in order to progress with the redesigning because unlike in the conventional techniques where making adjustments after the process starts is easy to conduct, additive manufacturing is not yet developed to that extent in order to make such adjustments. Although, there are possibilities of manually rectifying it, but it diverts the goal of attaining automated manufacturing. A viable solution of it can be to incorporate 3D scanning which makes sure both before and after the 3D printing that the end product is dimensionally correct.

3D printing is not only about feeding the material and design to the machine and getting the end result but performing it in a way that the resulting part is innovative in its own manner. The initiation of the project was to simply 3D print the received part but upon exploring the depth of technology, it was proved to be wrong, and the entire re-designing process was performed. This has to be the key for incorporating the technology will all above pointed out inclusions.

ii. Structural Analysis

After an optimal design is obtained, it is required that it addresses its functional attributes as well as should be able to adjust suitably in its assembly environment. A smart design with good performance should be the main object of the end product in most cases. The usage of the 3D printing technology can be widely seen in the aerospace and health industry which are very sensitive in terms of the final output, therefore, the designed part is required to go through a series of tests both before and after the printing is done. For this purpose, there is advanced software such as ETABS, ANSYS, etc for standard applications as well as basic ones like Autodesk Inventor which is used in the case study[49]. Other tailored software based on requirements can also be developed which are very application-oriented and result in better output. The comparison results clearly show in the study that the design improvement can result a number of issues that were earlier seen with the part. Such assessment helps the industries to come up with more futuristic, sustainable as well as innovative end results.

iii. Cost Analysis

The cost of the final product is the main point of interest if the commercialization of additive manufacturing technology is to be imagined. Additive manufacturing has not been able to replace the conventional technology because the cost associated with it are very high in comparison. For example, let us consider a traditional way of manufacturing such as injection moulding for production and compare it with additive manufacturing. In the case of injection moulding, a very high initial cost is accounted for creating an injection mould but once it is created and set up, the machine can churn out piece after piece in rapid succession. Thus, the trends as seen the figure 33 represented as traditional referring to conventional manufacturing is obtained. As the volume increases, the cost becomes dominated only by the material cost over time, therefore, the unit cost decreases over time. On the other hand, if we plot the price of a 3D printed part as a function of the number of parts created, the trend would be similar to the one illustrated in the figure 33. The price will be dominated by the initial machine cost and the line will only marginally trend downwards as we print more parts because of the insane amount of time it takes to print a single part. In order to scale up the manufacturing, additional machines are required which again increases the cost. This turns the traditional economies of scale on their head. Therefore, it is only beneficial for the 3D printing part which falls behind the breakeven point represented by the shaded region in the graph. This case is usually in case of rapid prototyping hence, we do not see extensive use of additive manufacturing for commercial manufacturing .

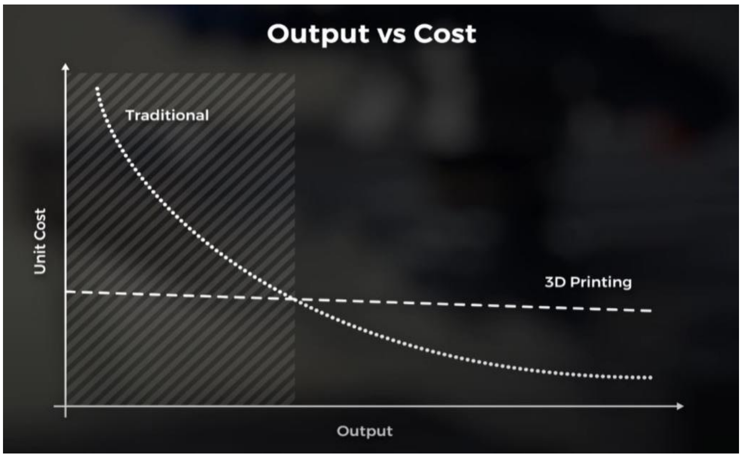


Figure 33 Illustration of Unit Cost vs Output trend

The application of 3D printing can be increased if we can lower down the raw material cost by making the supply more efficient as well as reduce the cost of 3D printers as a whole. This will lower the line of the 3D printing as seen in figure 34 and open room for more parts to be printed by using the 3D printers. The rapid development of this technology in the past few years and the increase in the demand for additive manufacturing has given a hope that the trend can be lowered over time.

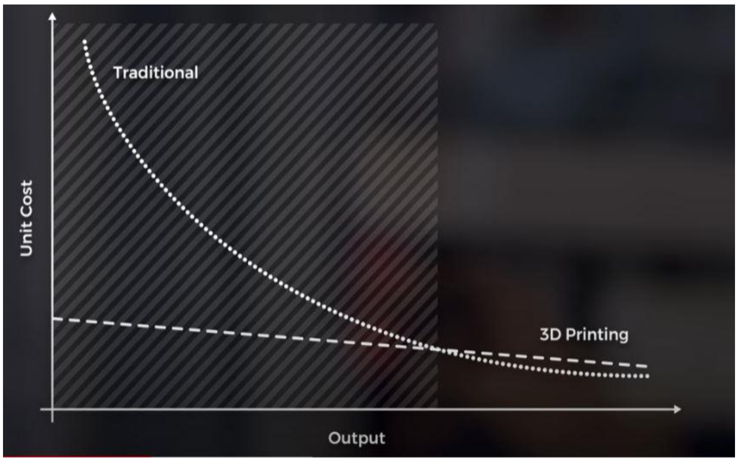


Figure 34 Illustration for increasing the application

Furthermore, it is really important to realize the benefits that can be achieved by manufacturing parts using 3D printing rather than only taking the cost factor into account. The usage of rapid prototyping over the years has given us an opportunity to explore its potential and make major advancements in it.

9 CONCLUSION

The manufacturing industry is facing intense competition in the global market, therefore, in order to compete effectively, the manufacturing industries need to work on reducing time for reaching their product to the market as well as a cost without compromising in the quality of the product[50]. To achieve these objectives, 3DMP technology can play a very important role because of the wide range of products that can be manufactured in the same printer. Not only that, but it is also capable of producing products with different metals in the same manufacturing process. All the challenges that arise in the field of 3DMP can be overcome by introducing the technology in academics as detailed as possible, giving an opportunity to explore more about the technology. The present time Covid-19 crisis has also made us realize the importance of having a mobile and in-house production backup. The supply chain disruption caused in various events as such, makes it necessary in order to make changes with the existing manufacturing methodology. 3D printing, being a very versatile technology, can stand out as a tool to address this issue.

The guidelines discussed should provide a starting point in order to bring 3D metal printers into practise. The project was started without having any prior experience with this technology, therefore, a lot of things were done which would not add any value to the finished part if 3D printed. The guidelines will help anyone without any prior experience with 3D printing technology, to save a lot of time as well as money by not wasting them in unnecessary activities. Similarly, the guidelines does not address to any specific 3D printers but the entire printing technology as a whole. Thus, it can be followed for every existing 3D printing technology. Also, the guidelines can be considered to create guidelines for any specific 3d printers as well. The basic workflow explained throughout the experimentation phase can be further standardized in order to make a workflow chart for applying additive manufacturing technology.

It has been really important to create awareness about the additive manufacturing technology because of so many underlying attributes that can bring a boon to the manufacturing industry. In order to do so, research and development centres should be funded by the private as well as governmental institutions in collaboration with the different industries, so that the opportunities that arise can be looked into more closely. In contrast, the existing advancement in the technology can be exploited by collaboration, installing a 3D printer, and using it for manufacturing achievable parts. This helps to cut down the high investment cost to be faced by an individual enterprise. Different enterprises should educate their customer about the technology as much as possible. 3DMP can bring a drastic change in the manufacturing industry and solve different manufacturing as well as logistical problems existing currently[51]. With the advancement in science and technology as well as the intense competition aiming to attain sustainability, it necessary for every size of an enterprise to experiment with newer technology. Therefore, 3DMP technology can be seen as a strong medium in order to revolutionize the field of the manufacturing industry.

9.1 FUTURE SCOPE

There are lot of assumptions and speculations made during each stage of the case study. Therefore, a study with more concrete data and justifications should be conducted. As mentioned, there are many different types of 3D metal printers available in the market today. Thus, guidelines more specific for each of the metal printers can be made along with the application and other related parameters in focus. Further, the future scope for both the case as well as the project is huge and is mentioned below.

i. **With respect to the case**:

a) Exploration for further Improvement in the proposed design
b) Analysis with more concrete data
c) Upon the completion of verification and validation of the proposed design, printing the part physically and testing can be conducted.
d) Finally, the printed part can be tested in the actual facility.

ii. With respect to the project:

a) Explore more possibilities and limitations of the additive manufacturing technology.
b) Redesign more parts following the guidelines to further improve them
c) Design a dedicated warehouse which consists elements of Industry 4.0.

Furthermore, this thesis work can be considered as a reference to make more detailed guidelines and improve the practicality of the additive manufacturing technology

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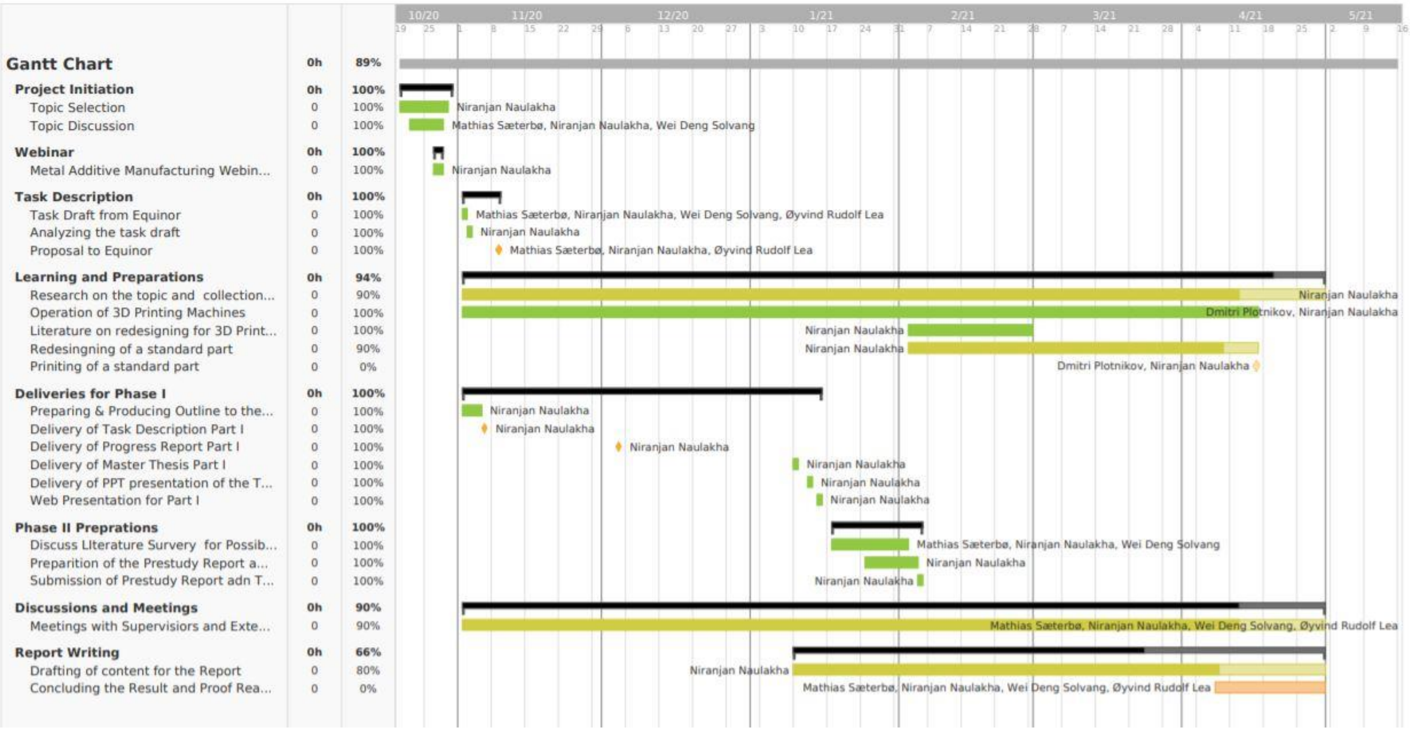
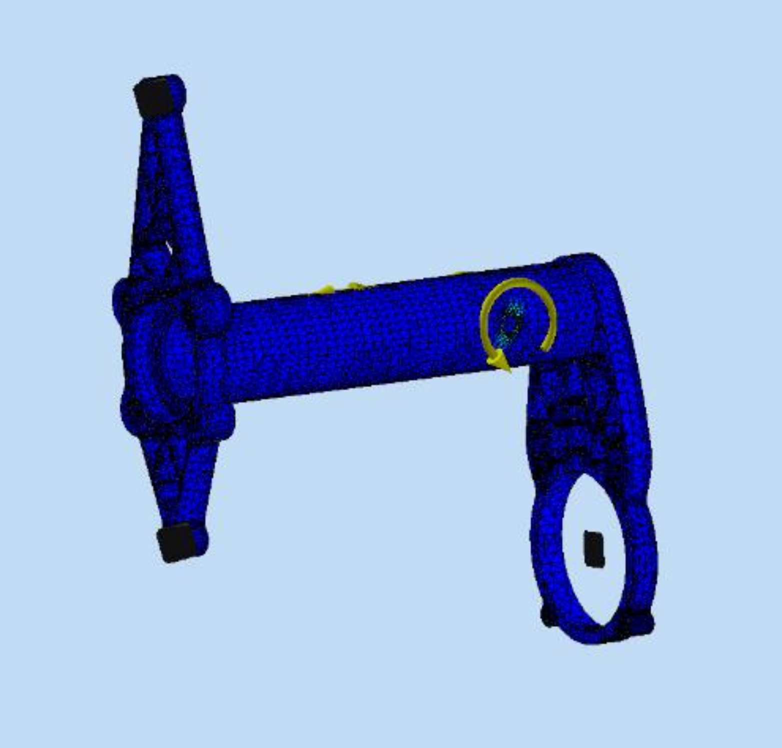
Appendix

i. Gantt Chart

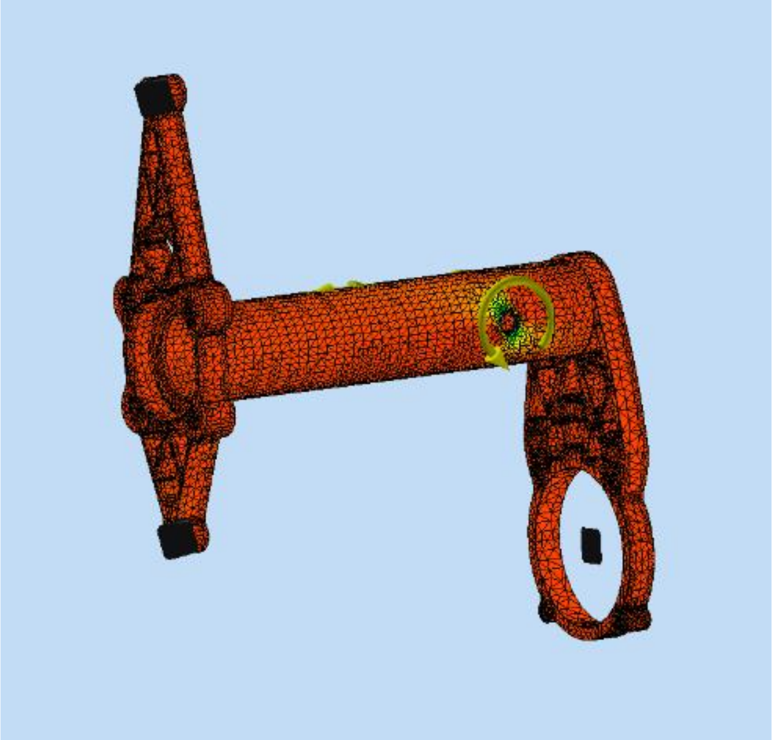


Gantt Chart	**0h**	**89%**
Project Initiation	**0h**	**100%**
Topic Selection	0	100%
Topic Discussion	0	100%
Webinar	**0h**	**100%**
Metal Additive Manufacturing Webin...	0	100%
Task Description	**0h**	**100%**
Task Draft from Equinor	0	100%
Analyzing the task draft	0	100%
Proposal to Equinor	0	100%
Learning and Preparations	**0h**	**94%**
Research on the topic and collection...	0	90%
Operation of 3D Printing Machines	0	100%
Literature on redesigning for 3D Print...	0	100%
Redesingning of a standard part	0	90%
Priniting of a standard part	0	0%
Deliveries for Phase I	**0h**	**100%**
Preparing & Producing Outline to the...	0	100%
Delivery of Task Description Part I	0	100%
Delivery of Progress Report Part I	0	100%
Delivery of Master Thesis Part I	0	100%
Delivery of PPT presentation of the T...	0	100%
Web Presentation for Part I	0	100%
Phase II Preprations	**0h**	**100%**
Discuss LIterature Survery for Possib...	0	100%
Preparition of the Prestudy Report a...	0	100%
Submission of Prestudy Report adn T...	0	100%
Discussions and Meetings	**0h**	**90%**
Meetings with Supervisiors and Exte...	0	90%
Report Writing	**0h**	**66%**
Drafting of content for the Report	0	80%
Concluding the Result and Proof Rea...	0	0%

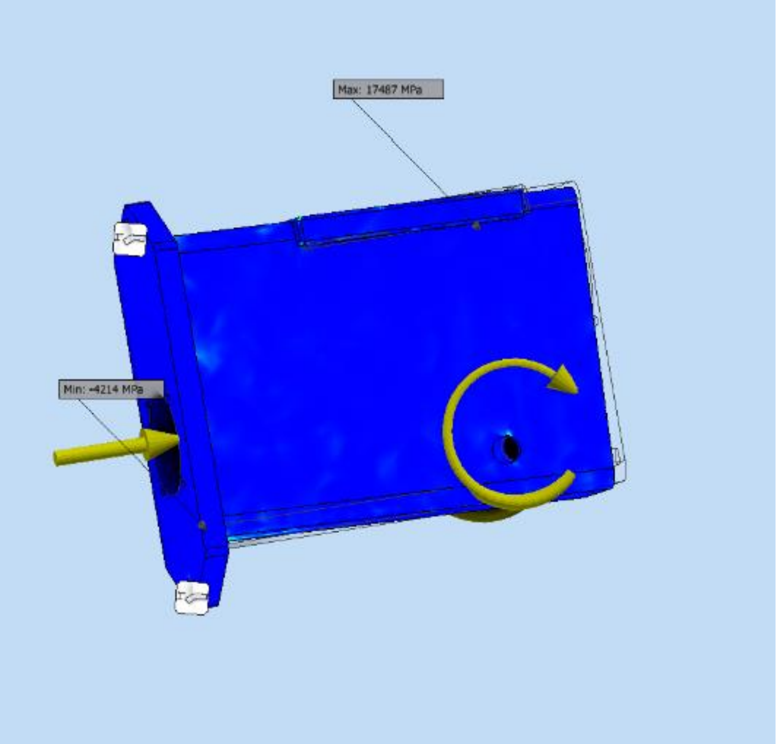
ii. 1st Principle Stress Analysis Result for the proposed design:



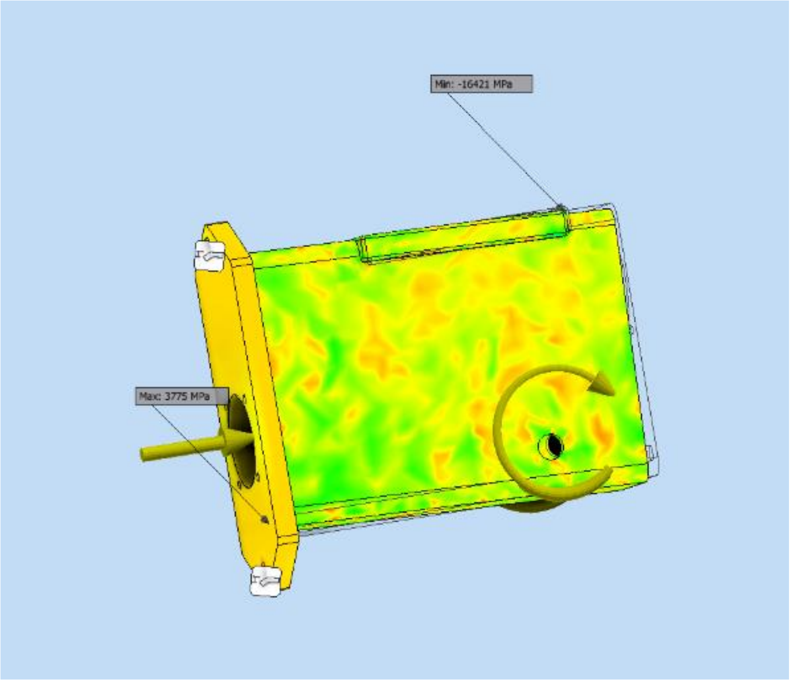
iii. 3rd Principle stress Analysis Result for the proposed design



iv. 1st Principle Stress Analysis Result for the origional design



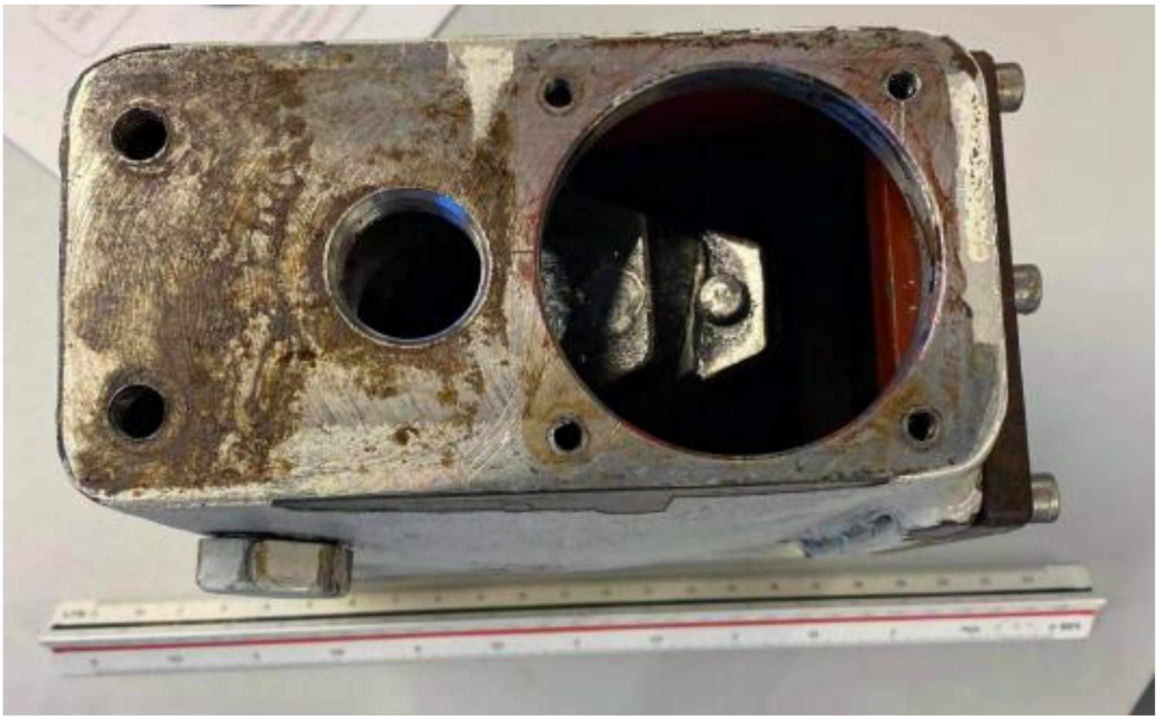
v. 3rd Principle stress Analysis Result for the original design



vi. Received part in different views

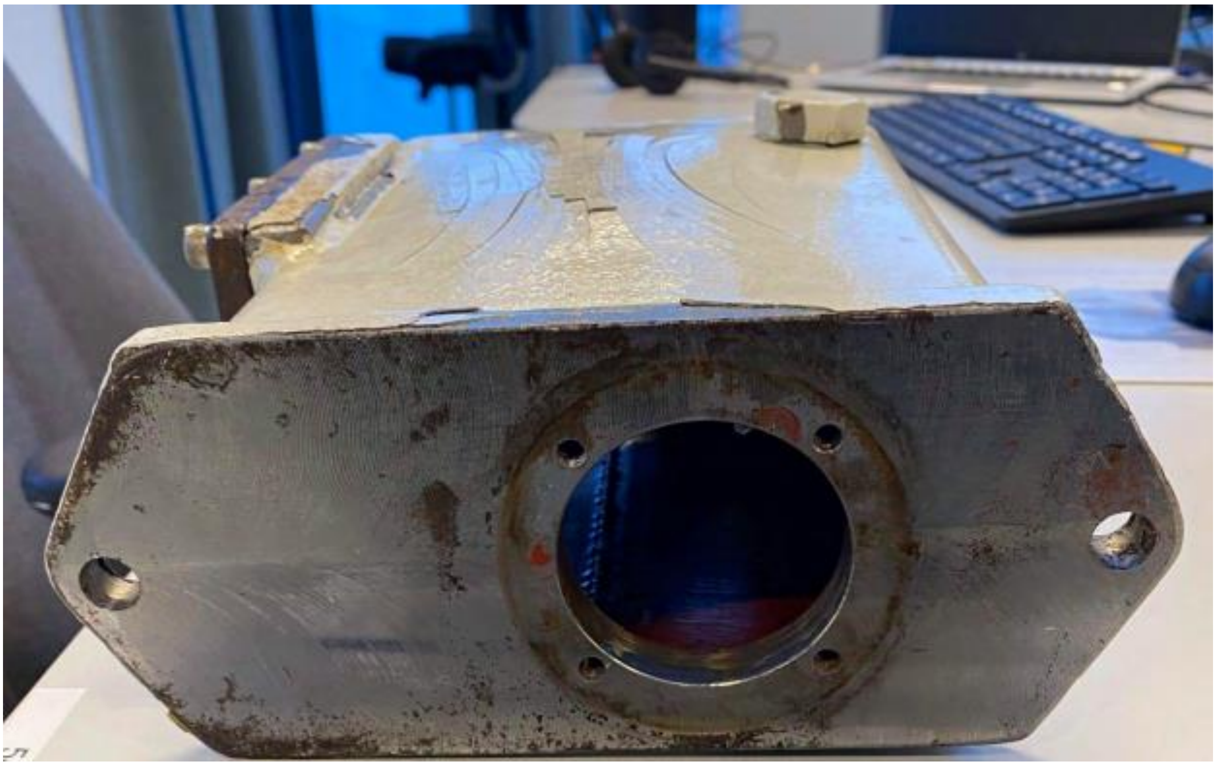
a)

b)

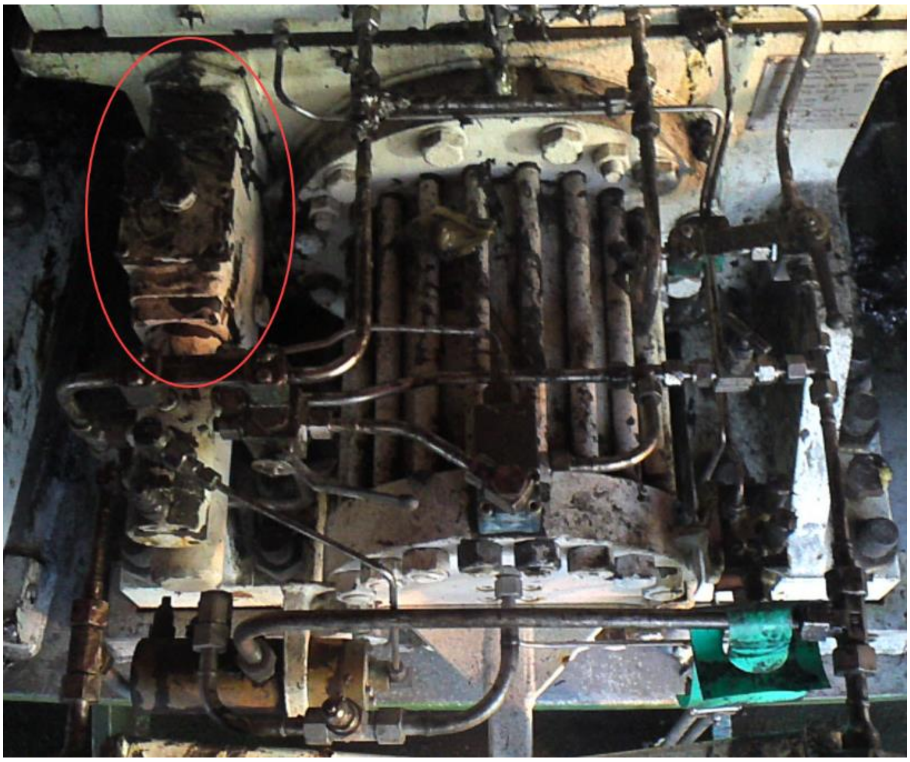


c)

d)

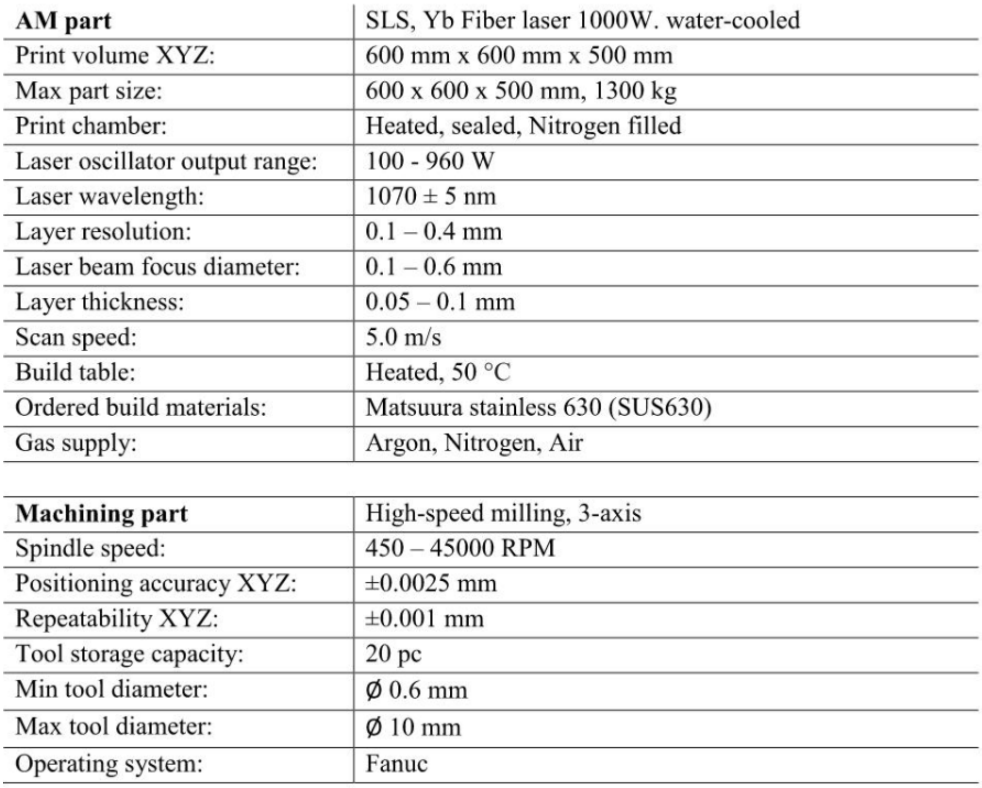


vii. Part shown in the actual assembly indicated by the red oval



viii. 3D printer at UiT's facility: Matsuuara LUMEX Avance – 60 Hybrid

ix. Technical specifications of the printer



AM part	SLS, Yb Fiber laser 1000W. water-cooled
Print volume XYZ:	600 mm x 600 mm x 500 mm
Max part size:	600 x 600 x 500 mm, 1300 kg
Print chamber:	Heated, sealed, Nitrogen filled
Laser oscillator output range:	100 - 960 W
Laser wavelength:	1070 ± 5 nm
Layer resolution:	0.1 – 0.4 mm
Laser beam focus diameter:	0.1 – 0.6 mm
Layer thickness:	0.05 – 0.1 mm
Scan speed:	5.0 m/s
Build table:	Heated, 50 °C
Ordered build materials:	Matsuura stainless 630 (SUS630)
Gas supply:	Argon, Nitrogen, Air

Machining part	High-speed milling, 3-axis
Spindle speed:	450 – 45000 RPM
Positioning accuracy XYZ:	±0.0025 mm
Repeatability XYZ:	±0.001 mm
Tool storage capacity:	20 pc
Min tool diameter:	Ø 0.6 mm
Max tool diameter:	Ø 10 mm
Operating system:	Fanuc