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“Additive manufacturing: Part design, optimization and manufacturing processes selection Implementation of a project-based learning education for AM using the case study of a pressure air engine”

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Master of Science Thesis

Examiner: prof. Eric Coatanea
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ABSTRACT

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Additive manufacturing (AM), due to significant advancement from traditional manufacturing and new potentials has attracted significant interest in a diverse set of industries. Considerable advances have been made in the expansion of new and innovative AM processes. However, less attention has been paid to the teaching of these new processes in educational institutions.

While there has been comprehensive research into traditional manufacturing processes and its teaching practices are well established, few adequate additive manufacturing training programs exist to educate students in the field of engineering. To fill this gap in education, this thesis aims to design an AM training course specifically for mechanical engineers using state-of-the-art pedagogical methods.

Since traditional educational methods involved less student participation in the process of learning, one goal of this thesis is to encourage active student participation during the training course. The most critical stages of AM product development will be covered in a case study that students will carry out as part of the course.

This thesis proposes a comprehensive course for AM. A case study forms the prime core of the course content, and a combination of pedagogical methods are employed to enhance the quality of learning.

PREFACE

This master thesis was written with guidance from the research group for the Faculty of Engineering Sciences at the Department of Mechanical Engineering and Industrial Systems (MEI) at the Tampere University of Technology (TUT). This master thesis is the completion of a master's degree in Automation engineering.

The goal of this thesis is to develop a course for additive manufacturing technologies using suitable pedagogical methods.

I would like to thank my supervisor Prof. Eric Coatanea for giving me this opportunity to work in my favorite field, sharing his precious knowledge and pushing me in the right direction. Without his guidance, this thesis would not have been possible.

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Mohammadtaghi Hosseini Cheraghmakani

Tampere, 21.09.2018

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LIST OF SYMBOLS AND ABBREVIATIONS

2D	Two dimentional
3D	Three Dimensional
AHP	Analytic hierarchy process
AM	Additive Manufacturing
BJ	Binder Jetting
CAD	computer-aided design
CNC	Computer Numerical Control
DED	Directed Energy Deposition
DfAM	Design for Additive Manufacturing
DFF	Design for Functionality
DFM	Design for manufacturing
EBF3	Electron Beam Freeform Fabrication
EBM	Electron-Beam
FDM	Fused Filament Fabrication
FEA	Finite element analysis
GD&T	Geometric dimension and tolerancing
LENS	Laser Engineered Net Shaping
LOM	Laminated Object Manufacturing
LS	Laser Sintering
MCDM	Multi criteria decision-making
mLS	metal Laser Sintering
PBF	Power Bed Fusion
pLS	Polymer Laser Sintering

RP	Rapid Prototyping
SLM	Selective laser melting
STL	STereoLithography
VT	Vat Polymerization
WAAM	Wire Arc Additive Manufacturing

1. INTRODUCTION

Additive manufacturing (AM), due to its immense potential to fabricate three-dimensional parts, has generated interest in industrial production. Additive manufacturing is also known as three-dimensional (3D) printing and is mostly used for tooling and rapid prototyping. However, recent research enabled its capability to be used in manufacturing end-products for a more extensive variety of applications. In contrast to conventional manufacturing that subtracts material to obtain a desired shape, additive manufacturing shapes an object by combining layers of material on each other.

New engineering skills and mindset are required to utilize the benefits of manufacturing advances in AM, and engineering training programs should be adjusted accordingly. A technical oriented study program needs to be developed to deliver the knowledge of new technology. However, traditional methods of education have not sufficiently integrated recent engineering principles.

Recently, more universities are including an additive manufacturing course in their programs. One of them is an online course by Colorado University[1], a 17-week course discussing advanced topics regarding AM. However, the delivery mode of this course is a traditional classroom method with more focus on lecturing. Moreover, examination constitutes a significant proportion (75%) of the assessment of the course. The stated objective of another course offered by John Hopkins University[1] is mostly focused on training students on the fundamental principles of AM and the differences between AM processes.

One of the best courses available is provided by the Massachusetts Institute of Technology, known as MIT [1]. The program outline is clear, and the scheduling is well organized. Despite being an intensive five-day program, enough lab sessions are included in the course. This course has less focus on using case studies as content of the course. Also there was no mention of assessment in the course outline.

A set of eight short courses by SME[2], an organization with a crucial focus on manufacturing, entails different aspects related to AM such as design, safety and material sciences. The outline and content of each course are well defined and described in detail, yet there are no means of assessment for the courses.

Most AM courses cover practical aspects of additive manufacturing and are less focused on fundamental principles of design for manufacturing. As an example, one course teaches design for additive manufacturing with no technical background on Computer

Aided Engineering (CAE)[3]. Although it is difficult to include all aspects of manufacturing in one course, it is however crucial to familiarize students with the essential principles of engineering.

Considerable effort has been made on the technical aspects of teaching additive manufacturing, but less attention has been paid to the pedagogical part. Until now, courses have covered a limited range of the teaching and working methods, and traditional lecturing has been the primary choice.[1][2][3][4] This is why additional studies focusing on the pedagogical side of engineering teaching are needed to improve the academic grounding of the subjects taught and the ways of delivering them to students. Also, significant effort should be focused on how students deal with practical problems and how teachers should guide students during a course. In order to point out complex issues in AM and shows the background knowledge in this field, the case study approach had been chosen for this thesis.

This thesis aims to design a comprehensive course for additive manufacturing involving a case study. The most critical stages of engineering design are included, enabling students to understand real-life working practices and acquire hands-on experience through the course.

The proposed novel course employs suitable teaching and working methods using a case study as its core. These methods allow students to independently learn the basic principles of Additive Manufacturing with comprehensive support from teachers. The combination of selected teaching methods will encourage more active participation in group work and help students develop their abilities and skills technical problems.

2. THEORETICAL BACKGROUND

2.1 What Is Additive Manufacturing?

Additive Manufacturing (AM) developed based on Rapid prototyping system in 1987 by 3D systems[5]. Rapid Prototyping is a series of process for development of a product using test ideas. By the help of Rapid Prototyping (RP)[6], it is possible to quickly fabricate a model, using computer-aided design (CAD) to represent before the final release. RP has been widely used in a variety of industries for conventional manufacturing.[7][8]

Unlike the conventional manufacturing, which parts are subtracted from a piece of material, Additive manufacturing uses layer-based approach. The quality of the final part is subjected to the thickness of the layers; thinner layers will result in the closed shape of the final part to the original. All AM Machines use the layer-based approach with small differences which will determine features of each machine such as the accuracy of the final part, material properties, how fast a part can be made, amount of post-processing needed after manufacturing and total price of the machine and process.[9]

2.2 AM process chain

AM Contains few phases from Computer-aided design (CAD) to the final physical part. Small, relatively simple parts may use first steps of the process, in contrast, compound products with more engineering details on it will go through all the stages of AM and require more development via iteration.[9][10]

1. Generation of Computer-Aided Design, Model of Design
2. Conversion of CAD model into AM machine acceptable format
3. Transfer to AM Machine and CAD Model Preparation Machine setup
4. Machine setup
5. Build
6. Post-processing[9][10]

- **Generation of Computer-Aided Design, Model of Design**

Form a concept of visual appearance of the product is the first step in any product development process. It can be in forms of documented information, sketches or 3 dimensional digital models. Like convention manufacturing, the first step in AM chain process is generating a 3D model of the desired part. CAD modelling might be iterative in metal powder bed technology based on feedback from issues may arise during the printing and demand for changes in design process.[11]

CAD model can be generated by a designer via a 3D modelling software, by automation optimisation, 3D scanning of current physical part or mixture of all these options [9].

- **Conversion of CAD Model into AM Machine, Acceptable Format**

Most of available AM technologies uses STereoLithography (STL) file Format. STL format is a simplified format of a CAD model by eliminating some structure data of 3D model and turn it into guesstimate surfaces with series of triangular stitches [9][11].

- **Transfer to AM Machine and CAD Model Preparation**

A CAD file should be imported to STL with a pre-process software such as Cura or Slic3r. After the transferring to the STL file format, the dimensions can be modified. Errors such as faults related to triangles, shells and open edges and contours might happen during the procedure. Some of these errors are critical such as open counters and inverted triangles and can impact the geometries of the parts, however, some are considered are acritical and tolerated such as double triangles and shells.[9]

After the STL file being built, some actions should be done for the printing process. The first step is verification of the part from any error [9]. Usual errors might be related to the triangles characterize surfaces in the part or open edges and contours [11]. The orientation of the part being printed, the scale of the model, the quantity of the parts, layers and support models can be modified in AM system software. In should be noted that STL file manipulation software tool has different features to control the pre-build process [9]. Since at this stage software will slice a part into some layers to be built, it is called 'Slicing'[11].

- **Support Generation**

Since the primary function of the support is to handle the heat and mechanical anchor with a minimum amount of cross-sectional area, careful design in this stage plays an essential role. Ways of generation of support might vary in different AM methods. For example, in powder bed processes, it is possible to either generate support in CAD modelling or the STL software program. However, generating support in STL software offer more control feature to modify the details.[11]

- **Build File Preparation**

After support generation, based on the chosen layer thickness, a slicer software will split the part into layers. Some other essential parameters should be considered at this stage such as beam power, scan speed, rastering path and islands[11].

- **Machine Setup**

The last step before the built process is machine preparation, which has two main tasks: machine hardware setup, and process control. Although manual preparation for hardware setup might be different for every AM systems, the control stage is in some way similar which is observing printing phase checking for any error that might occur.[9], [11]

After choosing a proper location of the part on the plate, these parameters should be defined: build process parameters, material parameters, and Part parameters.[11]

- **Build**

All AM machines have the similar order of processes for building, layering, material deposition and layer cross-section formation. In the condition which there is no error throughout this stage, AM machines follow the repetitive procedure of layering until the part is finished.[9]

- **Post-processing**

To achieve the desired dimension tolerance and excellent quality of the end part, some process should be done to the part. Depending on the AM system that has been used, a different application can be utilised such as Computer Numerical Control(CNC) tools, abrasive finishing, chemical, or thermal treatment.[9], [11]

2.3 Additive Manufacturing Technologies

2.3.1 Material Extrusion

Process Overview:

Material extrusion-based in AM technologies use a well one-dimensional (1D) road of material to fill in a 2D space to shape one layer. The layer-by-layer repetitive process makes the formation of a 3D object. An example of these technologies is Fused Deposition Model patented by Stratasys Inc shown in Fig.1 In this process, a thermoplastic polymer is fed through a nozzle in which the polymer is heated there to its glass transition or melting point. The melted polymer shape into the roads, which then forms the 3D, Object by layers. One of the main characteristics of this process is that it is hugely reliant on features of the paths such as adhesion between them and all its adjacent paths in inner and outer direction[10]. This technology is the most common process and best cost effective regarding the process and post-fabrication.[11][12]

Process Development

Although there have many developments in Fused Filament Fabrication (FDM) technology, there are still issues that must be improved. The primary concern is the strength of the part, which is just 10-65% in the direction normal to the build layers compared to the direction along the filament. This problem places a severe restriction in FDM where parts are exposed to dynamic or multi-direction static loads.[11][10]

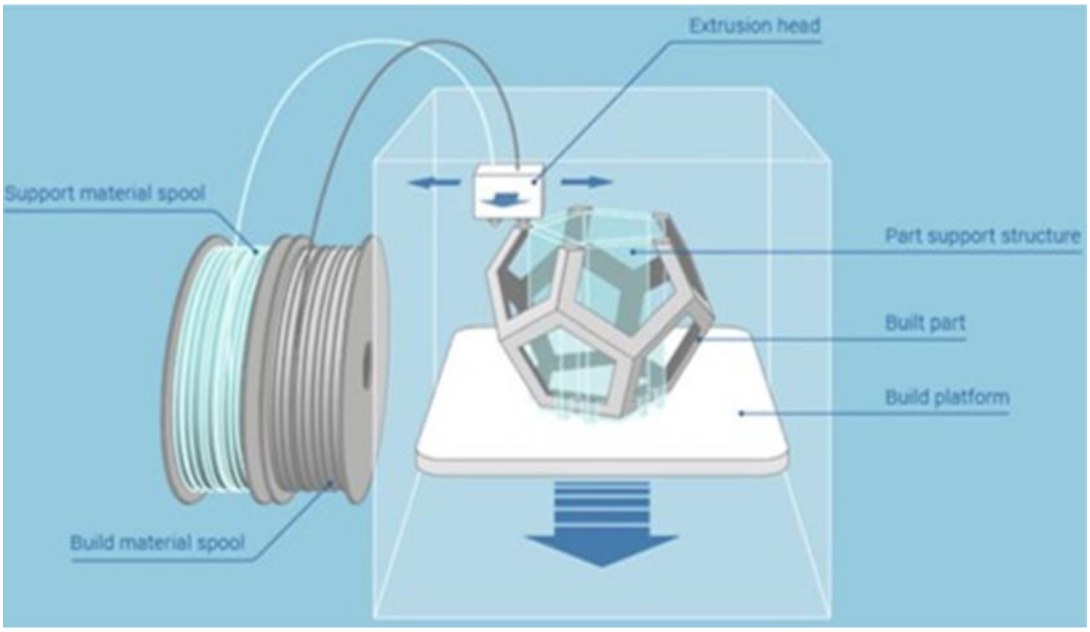


Figure 1.Fused Deposition Model Process[11]

2.3.2 Vat Polymerization

Two main configurations in this technology are SLA and cDLP, which the first one is known as the upright style where the build plate is submerged into a vat of resin. The latter configuration is inverse where the plate is in a vat of resin and the process starts from the bottom of the vat pulls upwards as the build continues. The end part in upright style is entirely submerged in the resin vat while in the inverse style the finished part is out of the resin. One distinct benefit of the inverse configuration is the time related with forming and shaping of each layer is less compared with the upright configuration; therefore, it is more appropriate for the end-user environment. Fig.2 shows two examples of these configurations.[11]

Part accuracy and surface finish are the main advantages of the vat polymerization. Typical dimension accuracy of the modern SL machines is better than 0.002 in./in and surface finish is ringing from submicron Ra to over 100 µm R_a. Due to these feature of Vat Polymerization, vector scan stereolithography is widely used for functional prototypes as the rapid prototyping field.[9]

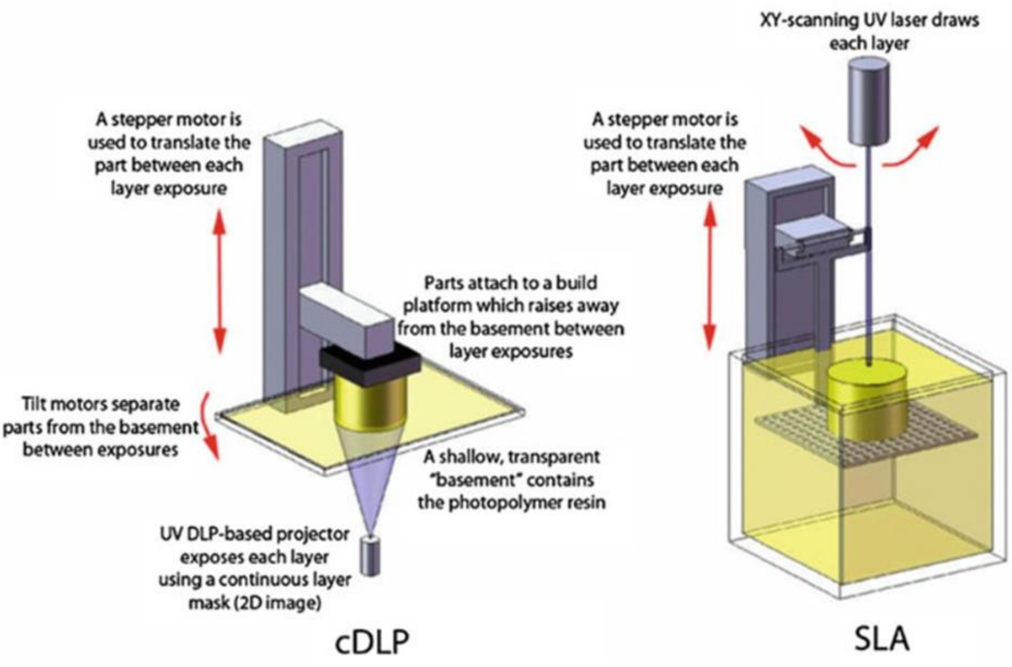


Figure 2.Fused Deposition Model Process[11]

VP technologies are flexible in terms of size scale and different machine configurations. Different configuration such as patters generators and light sources can be used in this technology.[9]

A downside of VP processes is its limited range of material. The commercial material are acrylates and epoxies, which do not have the proper durability and strength for fine quality of the injection. Therefore, many production applications do no use the VP processes.[9]

2.3.3 Material Jetting

An extensive array of single or large nozzles deposit droplets of materials that forms layers on a surface to shape the 3D object in Material Jetting additive manufacturing process. This technology is prototyping because of its material availability, flexibility, office enjoinment and build speed. An example of how Material Jetting machine works is depicted in Fig.3. [11]

Currently, Material jetting is the only technology that offers color turning and voxel level. Materials that can be used in this technology are the plastics such as rubbery elastomer and variety of elastic/elastomer materials mixing in two. Higher scalability in productivity, material flexibility and part dimension are some features compared to Fused Deposition Modeling and the Photopolymerization technologies.[11][13]

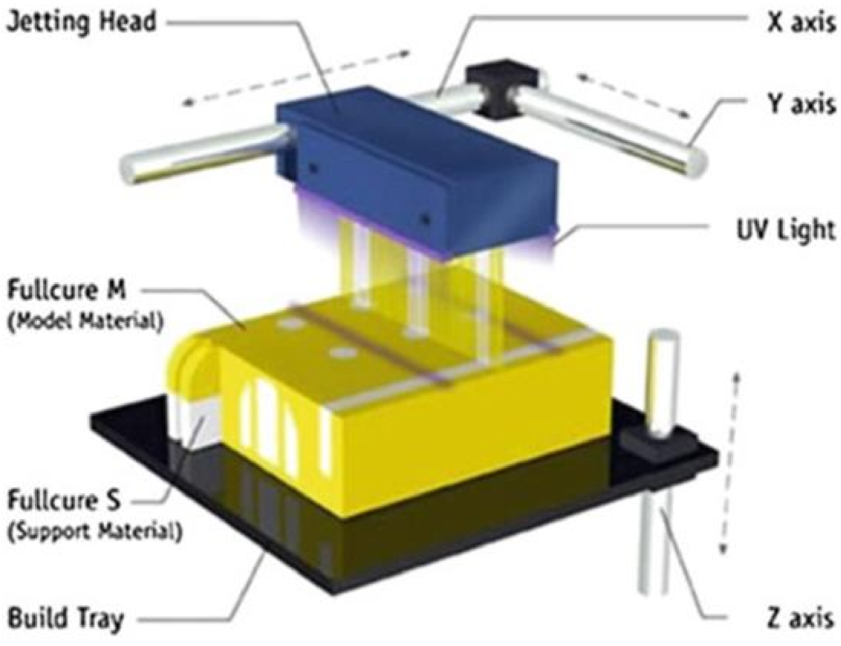


Figure 3.Multi-jet material jetting technology[11]

Ease of building parts in multiple material, scalability, capability of printing colors, high speed and low cost are the main pros of the material jetting processes. Also, the printing machines are lower in price compared to other technologies of AM. By using hundreds or thousands of nozzles, the quick deposition of material over a large area is possible; hence the high speed and scalability can be achieved.[9]

One drawback of this method is the small range of material which is limited to waxes and photopolymers. Another disadvantage is that the part accuracy of large parts is not as good as other processes such as vat photopolymerization and material extrusion. [9]

2.3.4 Sheet lamination

It is one of the two existing technologies which combine subtractive and additive step to produce a 3D part. In this technology sheets of material are bounded then trimmed by CO2 laser to produce desired stacks of layers.[9] Fig.4 depicts the concept of the Laminated Object Manufacturing (LOM)[11]. The additive steps are done by applying pressure, heat or both to bound sheets together by using adhesive using a roller.

Sheet lamination technology is flexible, robust and has wide range of material and can be used in different applications. This process is suitable for ceramic, polymer, paper and different types of metals.[9]

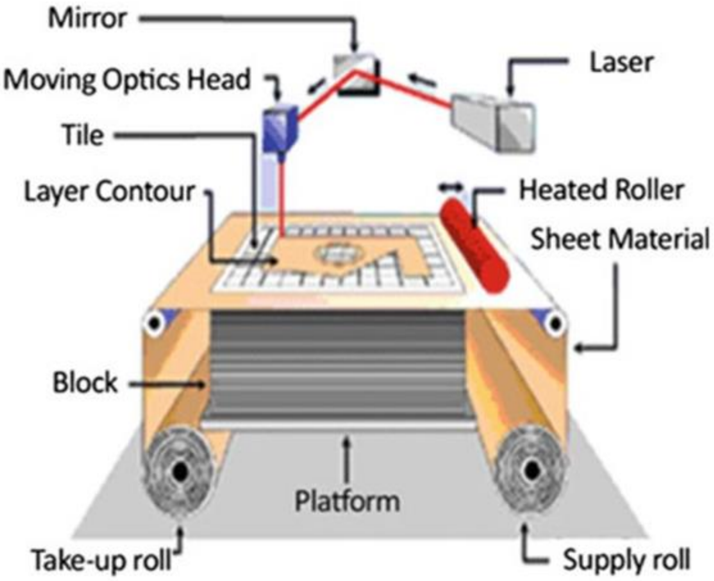


Figure 4.Sheet Lamination[11]

2.3.5 Powder Bed Fusion

The working principle of power bed fusion (PBF) is based on utilizing a thermal source for producing fusion between powder particles, a method for controlling the powder fusion and a tool for adding the layers. The most frequent thermal sources for PBF are lasers, and those technologies that utilize laser are known as Laser Sintering (LS) subsequently LS can be categorized in Polymer Laser Sintering(pLS) and metal Laser Sintering (mLS). [9][14]

This technology has been widely used for direct manufacturing since polymers, ceramics, metals and composites can be utilized as materials. If metal can be welded it is considered as a suitable material for PBF processing, metals such as steels, typically tool steels and stainless, nickel-base alloys, cobalt-chrome, titanium and its alloys, some aluminum alloys. Even precious metals such as gold and silver have been offered to use by PBF. Due to the different set of working principle and solidification the mechanical properties of the parts made by PBF are different compared to other manufacturing processes. Thus, heat treatment is needed to attain standard microstructure.[9][8]

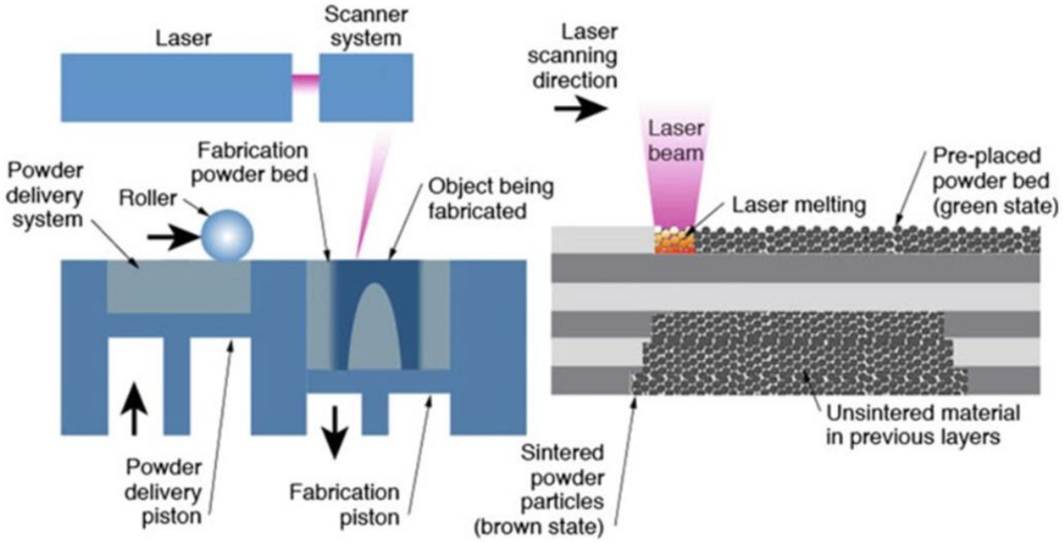


Figure 5.Selective laser melting/sintering technology[11]

Advantages of PBF-L

Using a wide range of CAD software that can generate STL files is the best advantage of the PBF processes. STL software allows to fix, edit and prepare for 3D printing. Support structure design, the orientation of the part and duplication are some of the features of STL file editing software.[5][6]

Fabrication of the unique and complex shapes such as internal lattice structures, shells and internal cooling channels is possible with powder bed fusion. The advantages of producing complex shapes are minimizing the material and strength optimization.[5]

To achieve the desired surface finish some post AM process operations might be required. Heat treatment to enhance properties; peening, polishing and coating for surface finishing. To achieve precise accuracy and support removal CNC machining might be necessary as well.[5]

Limitation of PFL

Process complexity is an issue in PBF like other metal AM methods. Design consideration, process control and form model generation to the finished part is recommended. Other issues such as product consistency, process repeatability, process transportability and material properties should be defined precisely for manufacturing critical parts.[5][15]

Controlling fusion process and each of its features is another important consideration of PBF, elements such as melt pool size, laser power, powder layer thickness and travel velocity of the melt pool. Unfused regions of powder are depicted in Fig.6 which might be result of inadequate parameter selection or process disturbance.[5][15]

Build volume will directly scale the raw material required for powder bed system. The raw material used for actual part and material after the printing which remains as reuse or recycling. Additionally, Directed Energy Deposition (DED) powder feed system has close fusion efficiency, but Wire feed system has approximately 100% efficiency in this term.[5][15]

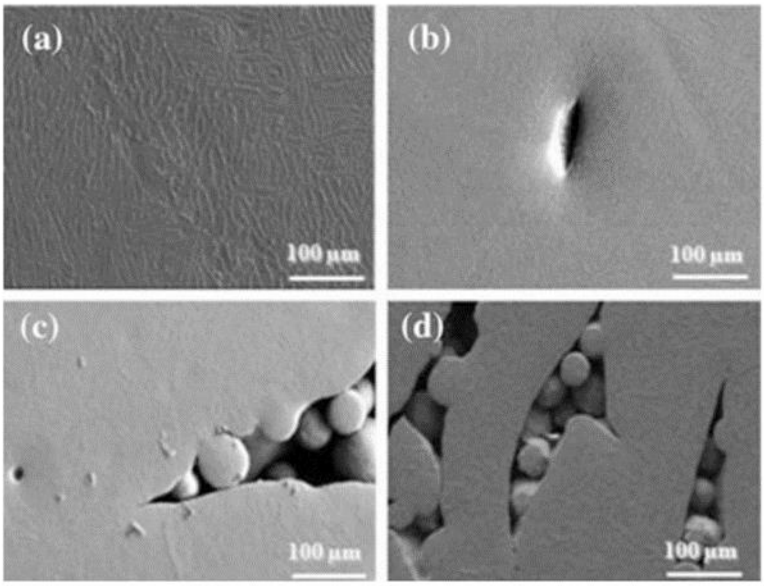


Figure 6.Regions of unfused powder[5]

2.3.6 Binder Jetting

Combination of the material-jetting and the powder bed fusion working principle form the binder jetting process. As it is shown in the Fig.7, the material in the form of powder is laid on a Z-positioning plat with even thickness across the layer. A single or multiple nozzle move around the platform to glue the powder particles by depositing droplets of binder materials; repetition of this process by formation of layer-by-layer makes the 3D part. The color printing capabilities is possible with multi nozzles. Post processing is required in metal or ceramic applications such as removal of loose powder binder Also to achieve higher strength, heat treatment of the part at sintering temperature to allow solid-state diffusion.[11]

Most of the advantages of the binder jetting process are common with material jetting, although binder jetting can be faster since an insignificant portion of the entire part volume must be distributed through the print head[10]. Combination of the powder material and additives allows for material compositions. Compared to material jetting, slurries with higher solids loadings in binder jetting made it possible for better quality of metallic and ceramic parts[16].[5]

Parts fabricated wit BJ processes are generally having inferior surface finishes and accuracies with parts made with Material jetting. To achieve a proper mechanical properties infiltration is usually needed. [9]

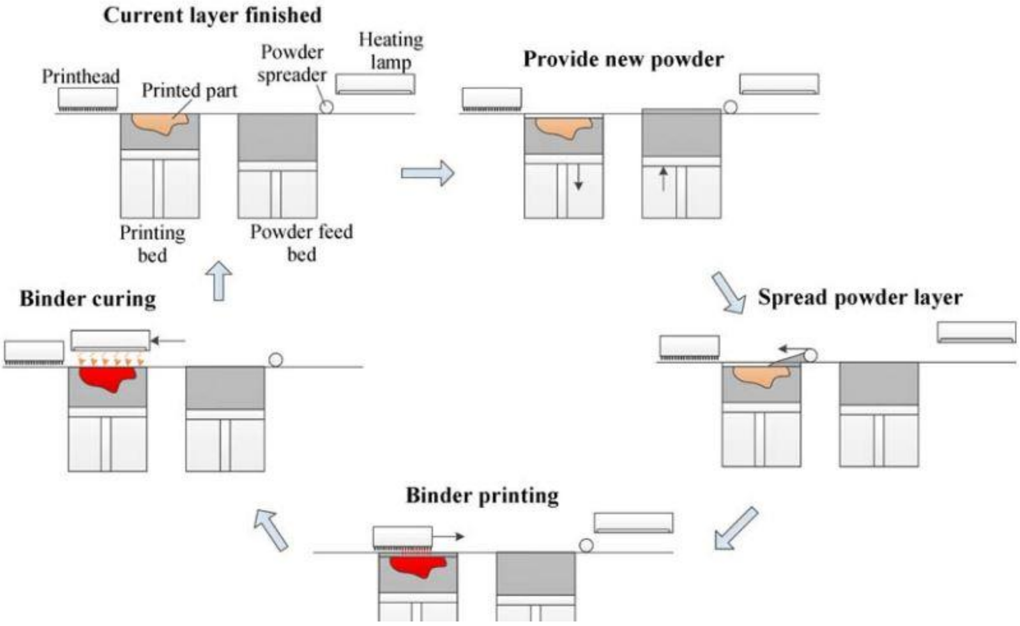


Figure 7. Schematics of Binder Jetting process steps[7]

2.3.7 Directed Energy Deposition

Creation of parts by melting the material while it is being deposited is possible with Directed energy deposition (DED). The basic method is mostly used for metals however it can work for ceramics, polymers and metal matrix composites. The principle of manufacturing with DED is that, a direct energy or hear source in a form of laser or electron deposit the material on a narrow region and melt it at the same time. [9]

Laser Engineered Net Shaping (LENS), the Wire and Arc Additive Manufacturing and the Electron Beam Freeform Fabrication (EBF3) are three forms of this type of additive manufacturing. The difference among these technologies are the forms of materials and energy source. In LENS, powder raw material and a laser beam are utilized in a “tool head where the powder is injected into a spot on a surface where the laser beam focuses its energy onto”[11]. The WAAM process uses the same working principle but with different energy input which is arc struck between the feed wire and the surface. Also, the raw material in this method is in the form of Wire. The combination of LENS and WAAM forms the working principle of EBF3 where the energy source is an electron beam and high vacuumed build environment. High vacuum ensures focusing the operation of the electron beam.[11]

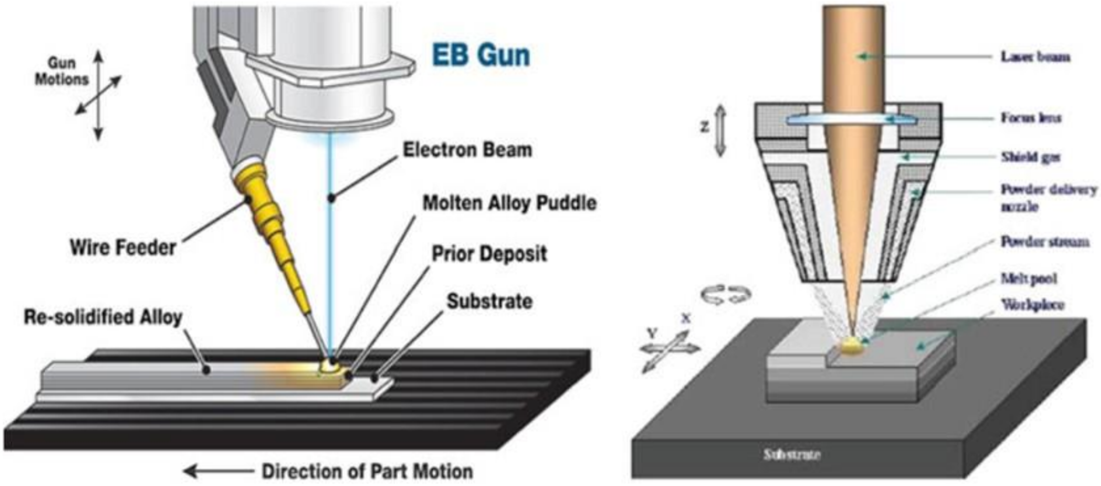


Figure 8.Directed Energy Deposition[11]

The directed energy deposition has a fundamental restriction which is in surface finish and dimensional tolerances of the build part[10]. These methods are mostly used in hybrid manufacturing where the overall process is done by directed energy deposition and achieve the desired surface finish and tolerances by subtractive technologies. Additionally, it is a suitable technology to repair large mechanical components.[11]

2.4 Design for Additive Manufacturing

2.4.1 Overview

The primary definition of Design for manufacturing (DFM) is to eradicate manufacturing complications, lessen manufacturing, assembly, and logistics costs. With all AM technologies competences, it is possible to take advantages for reconsideration in DFM. Several companies such as Siemens, Phonak, Widex, Align Technology and Boeing are now using different methods of AM to produce state-of-the-art products such as hearing aid shells, dental braces and parts for F-17 Fighter jets. One of the most considerable benefits of AM is its uniquely customized based technology that enables industries to utilize low-volume manufacturing.[9]

Usage of AM requires using process principles and machine characteristics efficiently to understand designs and functionality. In Comparison with conventional manufacturing methods such as machining, forging, casting and welding, AM has less restriction regarding geometry realization. With all the benefits of AM being mentioned.AM technologies also have some boundaries. For instance, as shown in Fig.9 fabricating via powder bed fusion a calibration structure with internal conformal cooling channels is unfeasible. The reason behind it is rooted in the nature of the method itself. Added to that, post-processing for parts with large overhang areas might be labor-intensive (Fig.10). Like traditional manufacturing, during design for AM, geometry optimization and geometrical design should be considered carefully.[11]

Although overall consumption with improved manufacturing flexibility is that it will increase attention over design for functionality (DFF) rules, most research in AM have been targeted on current knowledge based on experimental observation, new materials and process development. As a result, guidelines for AM design fail to offer extensive material to launch proper manufacturing production.[11]

The main limitation for application of AM in industries is that most existing AM design guidelines don’t cover all aspect of the manufacturing process; thus, it is hard to adopt new processes, new product designs or new materials. [7][11]

In classic manufacturing for example machining, mechanical and physical properties of the materials, remain almost constant; however, in AM processes particularly AM of metals, these features are reliant on the geometrical designs of the structures. Therefore, the most important part of the design for additive manufacturing (DfAM) is to focus on developing geometrical design. The focus of most present research is either material/process optimisation or structural optimisation and few works that combine both.[11]

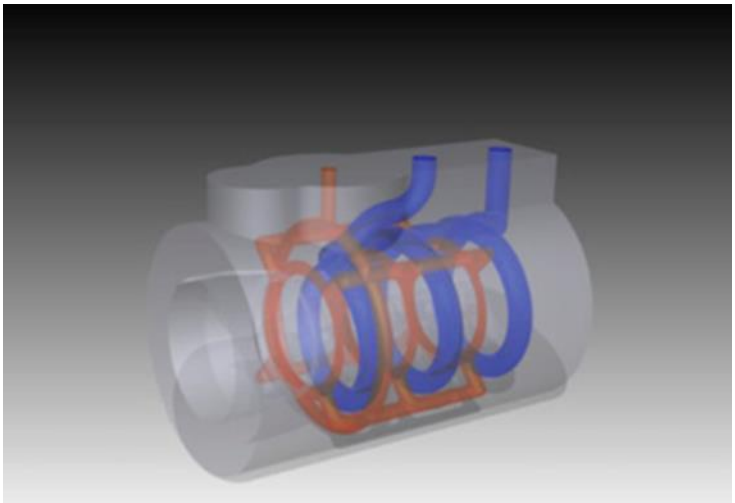


Figure 9.Calibration tool with conformal cooling channel designs[11]

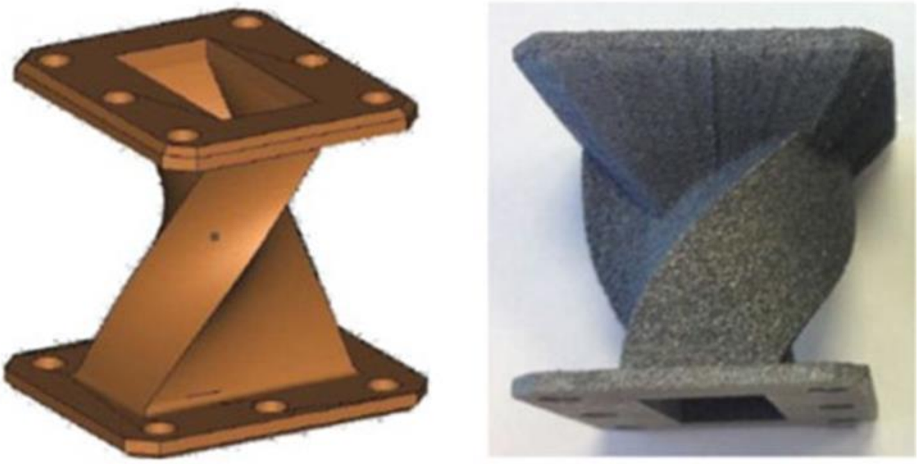


Figure 10.Comparison between CAD and actual part with direct metal laser sintering (DMLS)[11]

2.4.2 Design for manufacturing and Assembly

Reducing cost and complication of the manufacturing are the primary purpose of Design for manufacturing. To achieve this purpose, wide-ranging expertise in manufacturing, assembly processes, material behavior and supplier capabilities are needed. However, applying all the requirements might be problematic and time-consuming. Many methods, practices and tools have been developed by researchers and companies, which can be classified into three main categories:

- Industry practices, focusing on product development
- Collections of AM rules
- University research in DFM[9]

During the 1980s and 1990s, different companies such as Boeing, Pratt & Whitney, and Ford tried to restructure product development into teams of designers, engineers, manufacturing personnel, which each could have a different number of people varying from hundreds to thousands. The main purpose was to ensure better flow of data among groups and better communication. The important incentive of this reorganising was to find problems on early stages in the product development.[9]

The Recognising materials power handbook [17] has offered best example for the second category for Product Design for Manufacture. General samples of practices in product design in different manufacturing processes such as molding, casting, forging, stamping, machining, and assembly. [9]

The most recognised instance in university research is The Boothroyd and Dewhurst toolkit. The general idea was to gather all the necessary information needed to assess manufacturability of designs based on problems and costs estimates.[9]

Key idea of DFM is to train designers to have an overall understanding of limitations demanded by manufacturing processes then how they can lessen constraint violation in their design. Some of these limitations already decreased by AM technologies however, the nature of some tools used in manufacturing, rules and methods should be changed to illustrate the freedom allowed by AM to designers. [9]

Fig.11 exemplify the difference between DFM and DFAM by showing a design concept for transmission cooling air to electronic units in military aircraft. The first design is made by a traditional manufacturing process such as sheet metal forming, stamping, assembly with screws, etc. On the other hand, on the right AM benefits have been used comprehensively reducing number of parts by integrating all of them into one single part to eradicate assembly operations.[9]

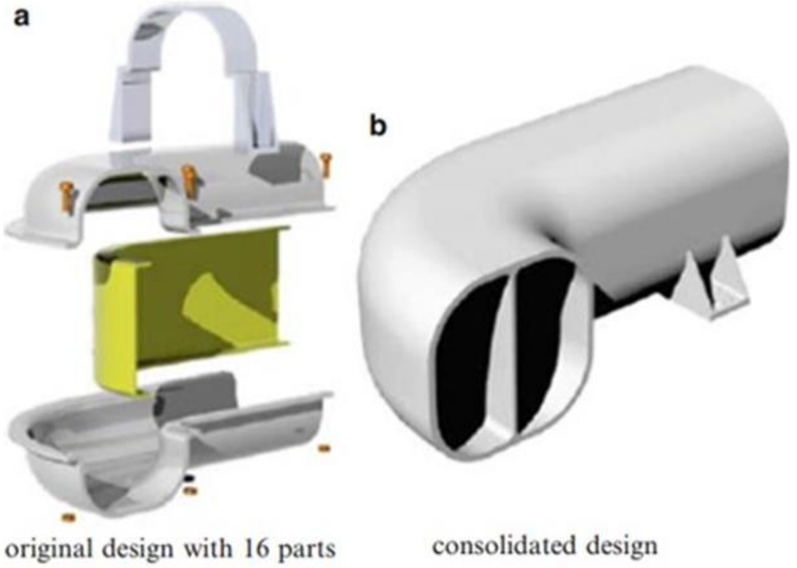


Figure 11.Aircraft duct example[9]

2.4.3 AM Capabilities

layer-based feature of AM provides four exceptional capabilities compared to Conventional manufacturing processes.[9]

- **Shape complexity:** Freedom of building any kind of shape
- **Hierarchical complexity:** Complex shape regarding the scale of the part
- **Functional complexity:** Monitoring the printing process
- **Material complexity:** Combination of materials on layers

- Shape Complexity

In AM, the layer shape does not affect printing the layer. For instance, any points of the part is reachable to fabricate in powder bed fusion (PBF) and vat photopolymerization (VP). Similarly, AM processes do not have limitations of conventional manufacturing regarding part complexity and tool accessibility. Additionally, each part is subjected to a unique machine setup, putting it differently, previous part’s machine setup does not influence the next part printing process. Since tools and fixtures are the same, additional preparation is not needed. Another great benefit of AM regarding shape complexity is automated process planning. In the build section of AM chain process, there is no need for manual work.[9]

- Hierarchical Complexity

In AM, there is the possibility to divide the part into microstructure and define a unique feature for each of them concerning size, cooling rate, composite structure, etc. This exclusive capability is linked with the application of cellular structures to fill specific regions of a geometry which will influence strength, weight and stiffness of the part.[9]

- Functional Complexity

Layer-based manufacturing enables to observe inside the part during the process of printing. Thus, the operational mechanism would be possible in some AM processes by controlling each layer of the part. Also, situ assembly is feasible with this unique capability.[9]

- Material complexity

In AM technologies process of building is a point to point; consequently, it enables to place the material differently at different locations. This concept so-called heterogeneous, are often challenging in manufacturing useful parts. The main obstacle to the usage of this concept in AM is absence of CAD tools that allow designers to define different materials on the different geometry of a part.[9]

2.4.4 General Consideration

Layer-based nature of the AM processes affects the geometrical qualities such as feature resolution, geometrical accuracy a surface finish along build direction, which is Z-axis.

Shown in Fig.12 a, the result of layer-based process on staircase effect is among the other shapes. In addition, the geometrical accuracy Z-direction is affected by shaping characteristics such as deposition profile, shrinkage and layer thickness of the material through the printing process. Furthermore, feature angles will cause less effective bonding length between layers which lead to different mechanical properties of the structure from the desired one.[11]

Another critical factor that influences the geometrical error in powder bed fusion process is shrinkage throughout the melting-solidification procedure which is related to power bed density.[11]

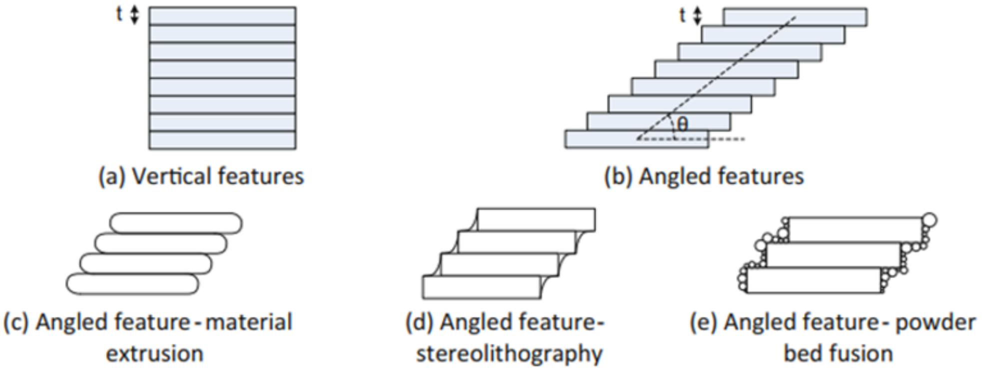


Figure 12.Staircase effect of AM parts[11]

2.4.5 Benchmark

The resolution of a part in AM processes is related with its geometries. Since there is no standard process resolution for all the design, several researches have been done to create standards benchmark to present evaluation of the geometrical qualities of AM systems. However, the achievement was poor so far. Three kinds of benchmark for parts are listed below:

a) Geometric Benchmark: “used to evaluate the geometrical quality of the features generated by a certain machine.”[11]
b) Mechanical benchmark: “used to compare the mechanical properties of features or geometries generated by a certain machine.”[11]
c) Process benchmark: “used to develop the optimum process parameters for features and geometries generated by certain process systems or individual machines.”[11]

The geometric benchmark assesses qualitative or quantitative parameter of a part such as precision, surface finish, accuracy and repeatability. Considering that this category covers most of AM benchmark parts, it is operative for fixed designs to optimize process selection and process parameters. The con of this benchmark is that GD&T information could not be merely generalized. Fig.13 depicts some of the suggested designs for geometric benchmark.

The primary emphasis of Mechanical benchmark parts is evaluating the qualitative mechanical properties of a part under material/process combinations. Testing of AM parts will be assessed by current material characterization standards (e.g. ASTM E8, ASTM B769). Since these standards have been on the utterly confusing approach for AM characteristic. Usually, Mechanical benchmark parts and geometric benchmark combined, utilize as process benchmark.

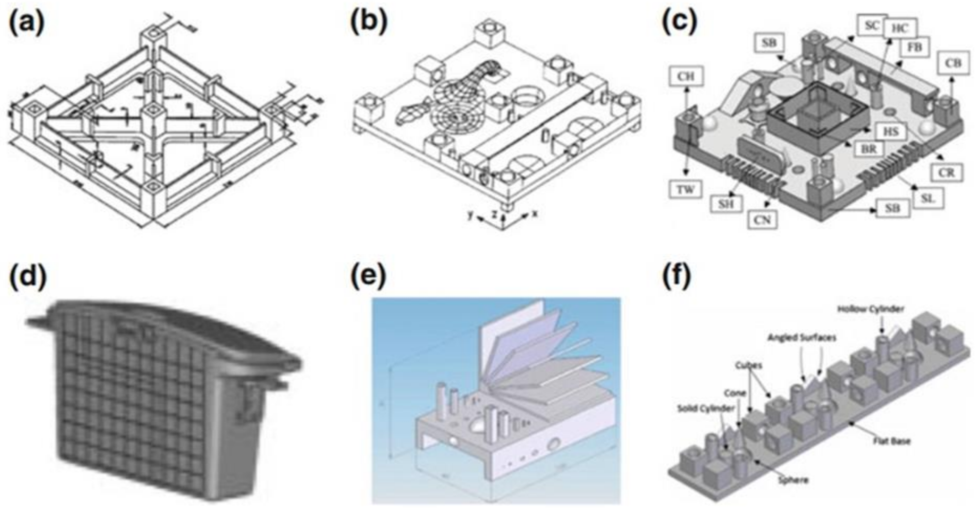


Figure 13.Geometric benchmarks design proposals

A standard benchmark part was introduced by National Institute of Standards and Technology (NIST) providing both geometric and process benchmark [18]

As shown in Fig.14 inclusive set of Geometric Dimensioning and Tolerancing (GD&T) characteristics, AM feature designs such as minimum feature sizes, overhanging features, and extrusion/recession features.[11]

Another issue regarding the DFAM is design for the quality issue. Quality control in AM can be proceed via two ways: in-process measurement and post-process part qualification. Although the criterion for traditional manufacturing has been employed extensively, for AM processes, an adequate closed-loop feedback qualification process does not exist. Most AM systems do not operate with closed-loop control; thus, the quality of the final parts might change significantly. Added to that, post-process measurement for parts with a support structure and freeform geometries can be problematic. Parts are shown in Fig.15 emphasize the need for the method of inspection to establish the quality protocol.

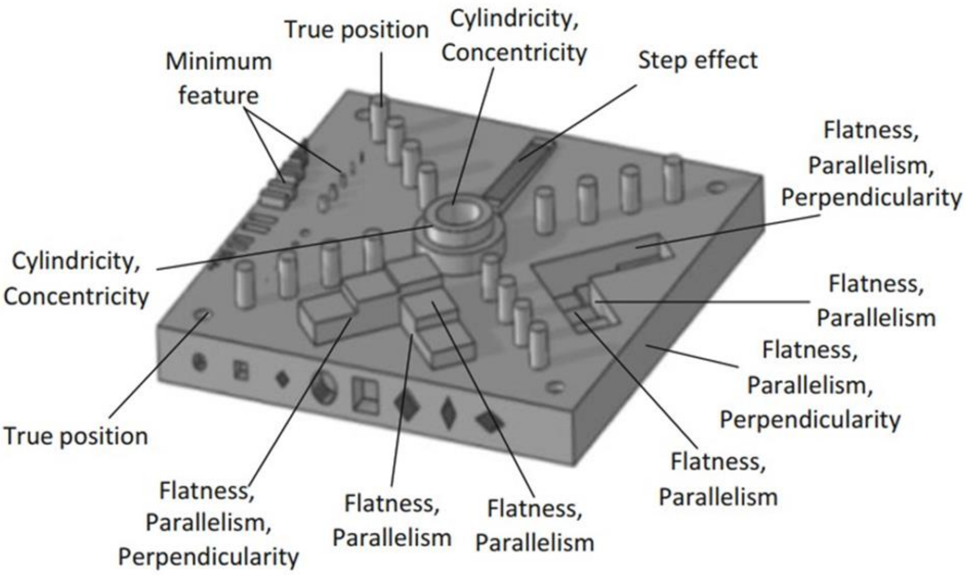


Figure 14.NIST proposed standard benchmark part design[11]

Figure 15.Some freeform AM parts that are difficulty to inspect[11]

2.4.6 Inspiration to 3D Design

Balancing between design complexity and fabrication capability is often a need which should be considered. To gain the benefit of the AM, the focus for designers should be on design itself not working of the manufacturing processes or design tools.[5]

- Elements of Design

For Engineering design, elements take the top-down approach, an iterative, circular and repetitive process of the questions such as what is needed; what is the effective use? The answers then will be used in a design to balance and enhance the requirements.[5]

- Material Selection

Commercial metal stock is available in form of sheet, pipe, channels, angel iron, I-beams, etc. Due to the industrial standards and development over the past century, there is a wide range of valuable knowledge over the mechanical properties and information related to manufacturing.[5]

The best source to look for the information of the AM machines and materials are in the vendors' website. Data sheet of the products and machines are available which include the material properties, nominal chemical composition, design consideration, parameter guidelines and post processing requirements. valuable knowledge over the mechanical properties and information related to manufacturing.[5] Most prevailing types of metal alloys provided by AM machine vendor are listed in the Table.1

Due to the limited range of AM powder metals, recycling the powders is a reasonable option then use them in the prototyping stage of development. Then on the production stages, the material can be upgraded. This feature of AM makes it more sustainable however more study is needed for the supply of metal in additive manufacturing.[5]

One of the advantages of AM processing is repair and adjustment of the parts that have been in service. Cost of replacement of the components that are subject to corrosion, wear, and breakage is a driving factor of renewing them. Examples such as weld cladding the marine shafts, train wheels and jet turbine blades are some common practice in the service life extension field.[5]

AM with its CAD design capability, cleaning and preparation procedures, 3D part scanning, automated decision-making features made renewal and repair of complex parts possible.[5]

- Process selection

Issues such as material, application, part size and service requirements are the most important criteria decision factors in process selection for Additive Manufacturing processes.[5]

Depending on the size of the business, each manufacturing type has its benefit and limitation, for example CNC processing might be the best choice for a small workshop. Businesses should consider all aspect adoption of AM since AM processing has its own cost, skills and learning procedure. Currently available resources such as skills and machines in the workshop or company effect on choosing the proper AM process. For example, a company has already heat treatment furnace or other sorts of post-processing machine, and this will affect the type of device the company might purchase in the future.[5]

Alloy Type	Aluminum	Maraging Steel	Stainless Steel	Titanium	Cobalt Chrome	Nickel Super Alloys	Precious Metals
Aerospace	✓		✓	✓	✓	✓	
Medical			✓	✓	✓		✓
Energy, Oil, Gas			✓				
Automotive	✓		✓	✓			
Marine Envoironmnet			✓	✓		✓	
Machinability	✓		✓	✓		✓	
Weldability	✓		✓			✓	
Corrosion Resistance			✓	✓	✓	✓	
Hight Temperature				✓		✓	
Tools and Molds		✓	✓				
Consumer Products	✓		✓				✓

Table 1.Most common types of metal alloys provided by AM machine vendor

- Solid Freeform Design

AM give us freedom of design without usual constraint such as shapes, dies, molds and tool geometry in conventional design. Although AM has excellent advantages in design complexity, understanding, optimizing, and fabricating complex designs using AM processes might be a frustrating task. Optimizing different design variable, which might rise to hundreds, is not possible without the aid of a computer-based algorithm. Software offer variety of features such as multi-scale modelling. multi-physics and Big Data mapping to develop the design the part and process.[5]**.** Fig.16 is an example of the Solid Freeform Design by AM processes.

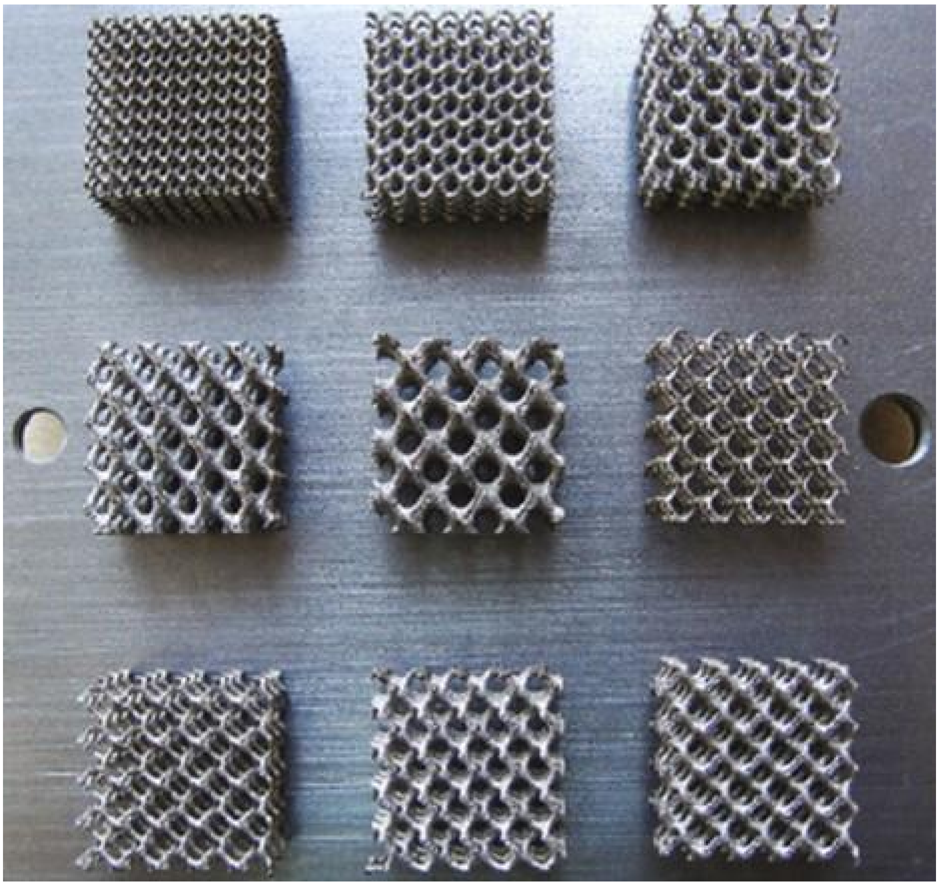


Figure 16.Nine gyroid cellular lattice structures 25*25*15 mm built on a base plate by the Selective Laster Melting (SLM) process using stainless steel[5]

- Design Tool

A complete parametric model-based engineering can contain a CAD model over to Finite Element Analysis (FEA) to CNC machining and inspection. Metal AM can use of traditional CAD/CAM methods and enhance it for AM capabilities.[5]

Some errors such as scaling issues, non-watertight designs, shared edges, inverted normal vectors, gaps and non-volumetric geometry might happen during the translation of the CAD file to STL or during modification of the STL file. Their errors should be solved before the generating the final control file. If one is planning to use an internal structure such as honeycomb, lattice, etc. he/she should consider these features for the application or software they are purchasing.[5]

- Creating AM design

Milwaki[5] described parametric, feature based approach in [5] Which allow dimensions to be defined utilizing variables rather than fixed values. This approach gives the possibility to adjust the model shape by modifying the values of the variables and regenerating the model to its new size and shape.[5]

Additional, functional feature of the manufacturing design can be considered in the AM process. The orientation of a flat surface, powder removal hole for internal AM volumes or adding the layer of material for future abrasive post processing are some examples of the features that can be used in manufacturing by AM.[5]

- Design Freedom Offered by AM

Some examples of design freedoms accessible by AM without conventional processing limitations.[5]

- *Freedom from metal shape* constrains of angles, rods sheets and massive blocks.
- *Freedom from traditional process* shape constraints, such as straight drilled passageway, linear bends, etc.
- *Freedom from some traditional post-processing limitations,* such as tool-reach-access.
- Consolidation or the ability to combine multiple parts into one complex part, which minimize the further assembly, joining process and risk of failure-associated parts.
- Decrease the amount of waste material.

Possibility to design rigid and lightweight components by adding strengthening features where they are required, eliminating unnecessary mass, varying wall thickness, etc.[5]

The design freedoms mentioned above are added features to design, hence the essential requirement and criteria for manufacturing would not change by AM. Moreover, the production and processing requirement should be considered. Designers should keep in my mind that some of the constraints of convention manufacturing are mutual with AM.[5]

- AM Metal Design Constraints

Although AM proposes a wide range of design possibilities, it is not possible to make anything you want without limitations. Depending on the process selected to manufacture the part, constraints such as material and AM processes still exist.[5]

2.4.7 Additional Design Requirements

- Support Structure Design

An essential phase for design and fabrication of AM components is support structure design. Fig.17 depicts parts with its support which are built within a single build volume. In powder bed processes with lasers, supports are typically needed. Also, in DED and hybrid systems, base plates may be used. In electron beam process such as Arcam's EBM process, there is a possibility to eliminate support structure since parts may be consolidated. Designer must consider support structures and part orientation cautiously to avoid shrinkage stress generated during the building process.[5]

- Design of Fixtures, Jigs, and Tooling

Post-processing of AM parts consists of operations such as drilling, machining, EDM welding, etc. Thus, design and fabrication of fixtures, jigs and tooling might be necessary. These manufacturing aids may be used for series of similar parts also being modified for individual components.[5]

For positive positioning during post-processing, fixture and part can be integrated and fabricated together and being removed later. Metal and sometimes high-performance plastic may be used for these parts. Using AM for fixture does not make the manufacturing cheaper, so comparison of cost is a must in this matter.[5]

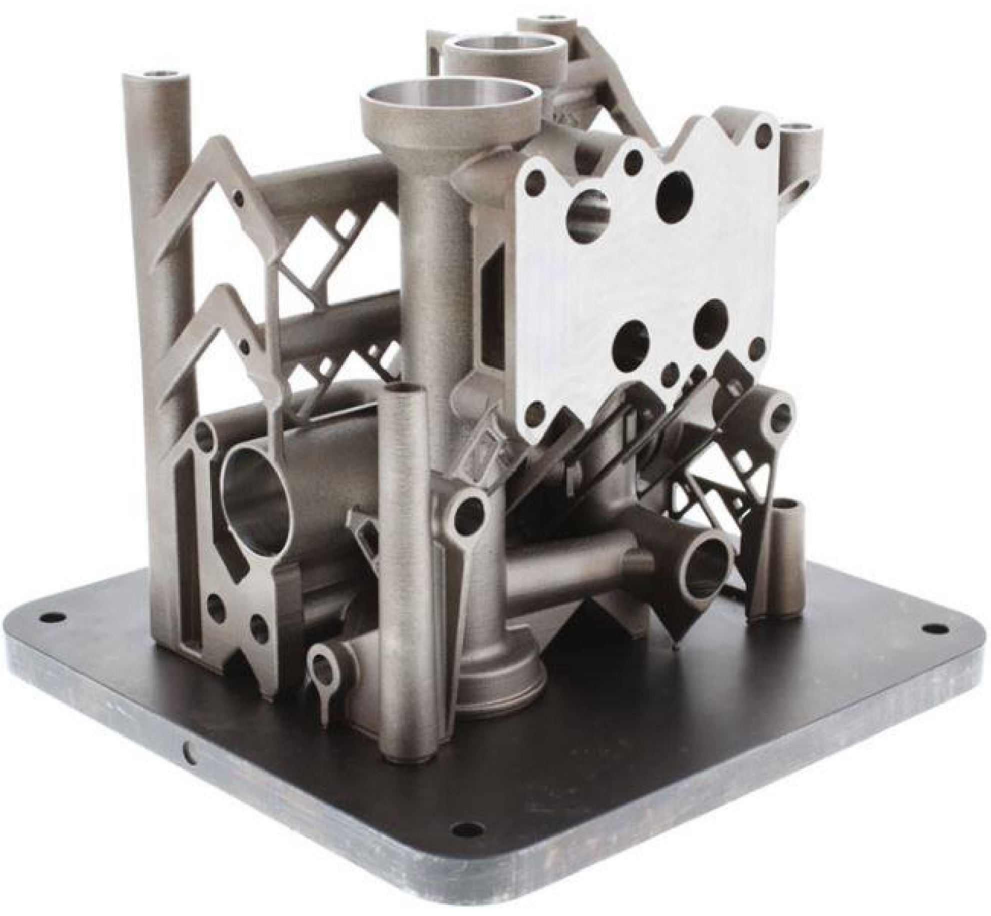


Figure 17. Part and support structure shown within a single build volume[5]

- Hybrid Design

One form of hybrid design is an integration of additive design along with the subtractive form of manufacturing which is called retrofitted AM/SM processing system. Another type is when a current part is changed with additive features to produce the final component. To date, this integration is generally restricted to CNC/DED. As metal parts being manufactured by subtractive means, then additive features form the final shape. Combining AM features with conventional manufacturing can lessen the cost of the production by using simple commercial shapes.[5]

2.4.8 Cost Analysis

Cost approximation, business consideration, and the economics of AM entail attention all along the design and process development cycle. [19] [19]

Some aspect of cost consideration has been identified in Fig.18, typical crossover analysis based on Deloitte break-even analysis approach [20] has been depicted in Fig.19. Tooling and process development require significant pre-investment for conventional production. Thus, the production stream relies on production quantities and sale. On the other hand,

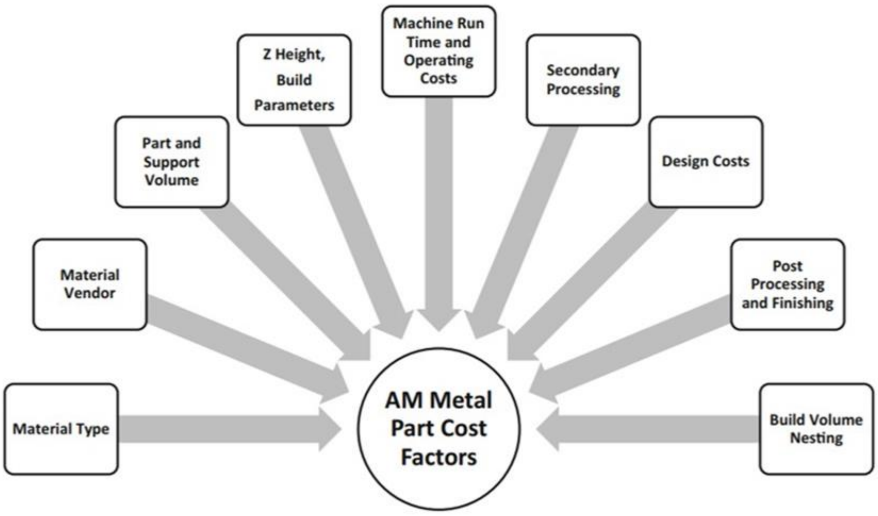


Figure 18.Cost factors consider when designing for AM

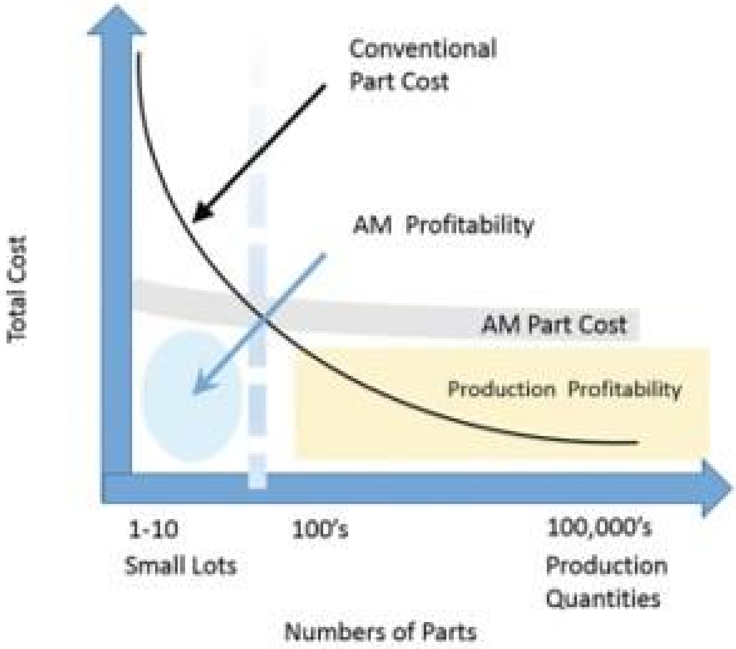


Figure 19. A typical break even analysis based on the Deloitte break even analysis approach[5]

AM reduced these costs and made it possible to manufacture expensive small-scale parts. It should be noted that AM methods total cost which include AM parts, design, material and build are still uncertain. A rule of thumb is that products made by wire methods cost twice as much as the conventional processes and powder products cost two times more than the wire products.[5]

Table 2.Cost consideration for small businesses[5]

Fixed Cost	Recurring Costs	AM Parts Costs
Capital costs	Hardware Maintenance	Part design cost
Initial facility and installation cost	Software Maintenance	Tech and touch labor cost
Amortization		
	Consumables, build plates, etc.	AM metals, inert gas, etc.
	Engineering and facility support	Energy cost
	Training	Post-Processing
		Prototyping, trial and error
		Failed Build

3. CASE STUDY

3.1 Introduction

To examine the process of the mechanical design and difficulties during the process and later moving on to additive manufacturing design, an oscillation air engine has been chosen. A simple engine with few design requirements. The primary focuses on the preliminary stage was to lessen the number of parts for easiness of assembly and consider the cost of manufacturing. Since there are plenty of examples of the same engine for educational purposes, the simplest one was chosen and been reversed engineered (Fig.20). The conventional design process will be presented by the positioning table, and all the final drawings will be shown in the appendix.

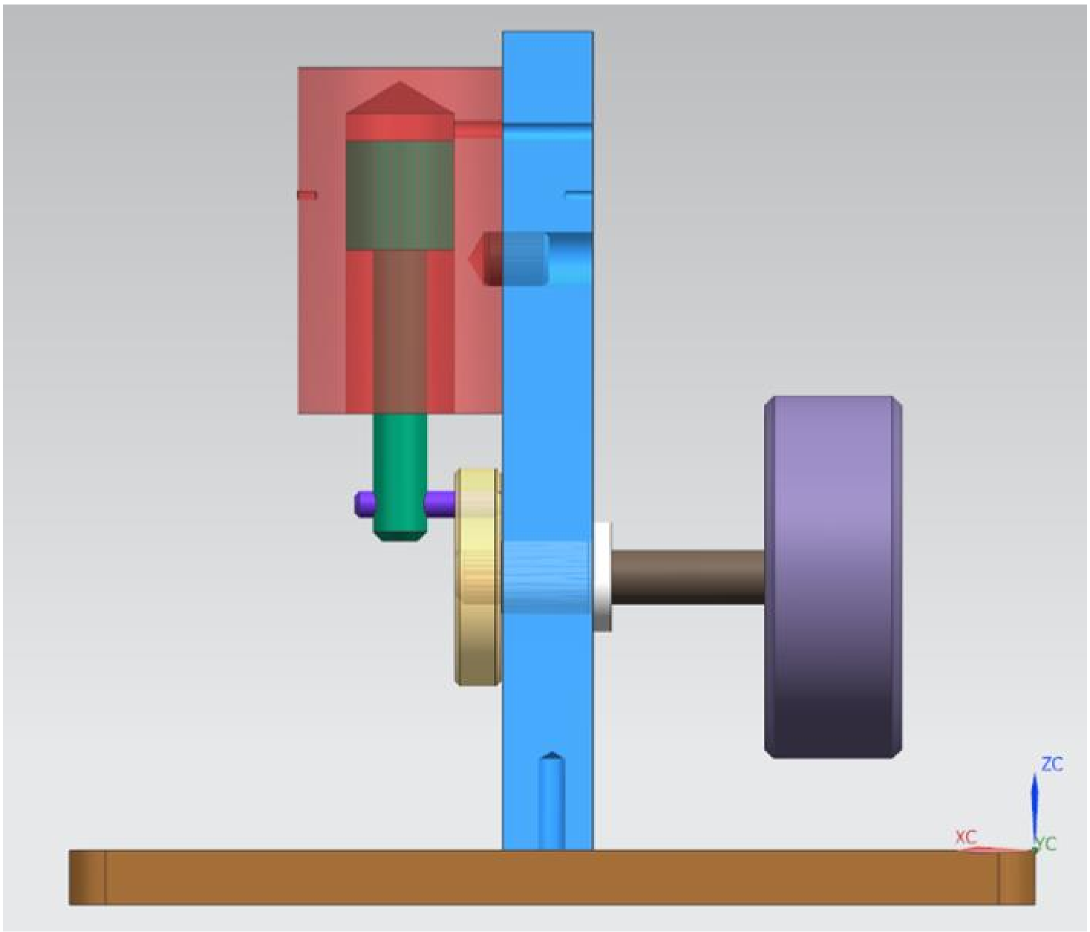


Figure 20. Oscillation air Engine

The report of case study consists of:

- Conventional Design
- Design for Additive Manufacturing

- Functional Surfaces
- Manufacturing options,
- Decision making
- Topology optimization

3.2 Conventional Design

The initial Geometric Dimensioning and Tolerancing was done by the CLIC/QUICK_GPS method.[21] The main reason to choose this method was the simplicity and easiness of steps in this method.

- **Base Plate:**

Material: Steel or Wood

The function of the plate is to support the entire engine so that the engine can function adequately without undesirable vibration. The plate will be mounted on a table or another support with four holes on each corner of the plate. The size of the screws is arbitrary.

To have the Frame of the engine properly mounted on the plate, both top and bottom surfaces of the plate should be parallel to each other. Moreover, flatness tolerance was chosen to control both surfaces. Also, the primary contact area of frame and plate (10x20 mm) should be machined with the roughness of Ra=2.4. [22]

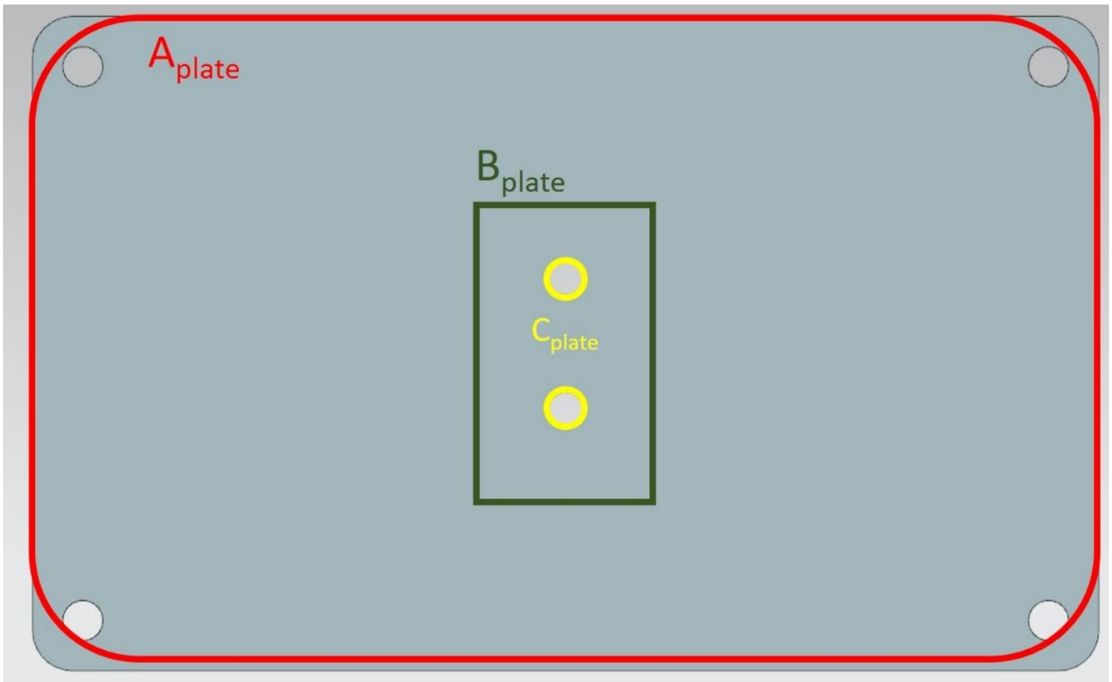


Figure 21.Base Plate functional surfaces

Table 3.Base plate functional and positioning surfaces

Name of the part/ Code	Plate		
Type of Surface	Plan	Plan	Screw
Positioning Surface	A	B	C
Type of interface	Contact	Contact	C Sunck M4
Type of Surface	Plan	Plan	2Plans// sym
Contact Surface / Contact Part	Table or support	D	E

- **Frame:**

Material: Brass or Steel

The frame is the backbone of the engine, and all the other parts mount on the frame. Those areas of the frame which are in contact with other parts should be machined with the roughness of Ra=2.4

Most important features of the frame are the distances of axle bore, adjustment pinhole and through hole for intake air.

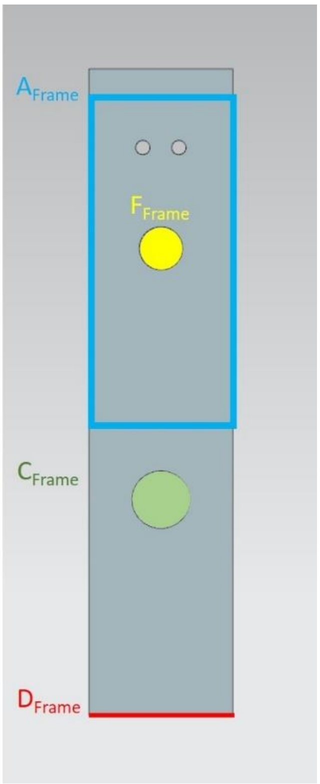


Figure 22. Frame rear functional surfaces

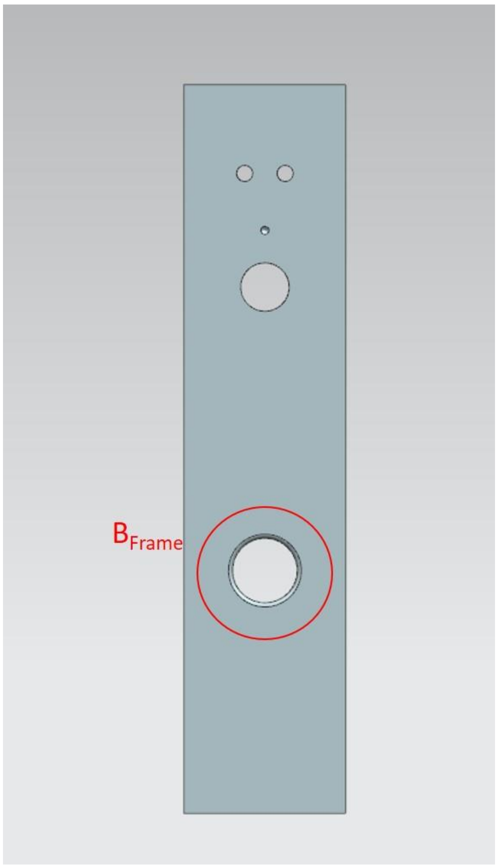


Figure 23. Frame front functional surfaces

Table 4. Frame functional and positioning surfaces

Name of the part/ Code	Frame					
Type of Surface	Plan	Plan	Cylinder	Plan	Screw	Cylinder
Positioning Surface	A	B	C	D	E	F
Type of interface	Contact	Contact	Clearance fit	Contact	Screw	Interference fit (G6/h6)
Type of Surface	Plan	Plan	Cylinder	Plan	2plans/sym	2plans/sym
Contact Surface / Contact Part	A / Cylinder	D /Bearing	B/ Bearing	A/ Base	C/ base	M/ Adj Pin

- **Cylinder:**

Material: Brass

There is just one hole for intake and exhaust in the cylinder. Therefore, the positioning of the intake hole to the pinhole is essential.

The bore of the cylinder should have exceptional quality for a smooth running of the piston; hence, H7/h6 tolerances were chosen.

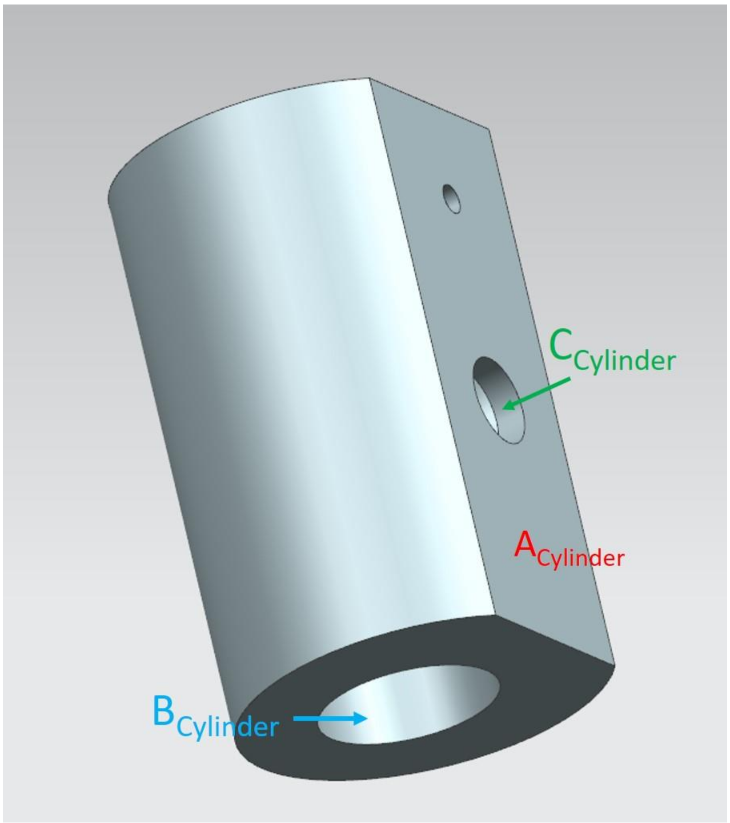


Figure 24. Piston functional surfaces

Table 5. Piston functional and positioning surfaces

Name of the part/ Code	Cylinder		
Type of Surface	Plan	Cylinder	Cylinder
Positioning Surface	A	B	C
Type of interface	Contact	Clearance fit (H7/g6)	Interference fit (P6/h6)
Type of Surface	Plan	2plans/sym	2Plans// sym
Contact Surface / Contact Part	A/ frame	H/Piston-top	M/ Adj Pin

- **Crank:**

Material: Mild Steel Bar

The contact between bearing and Crank will hold the Crank into its position and keep the gap= 0.2 mm

The total runout used for preventing vibration and oscillation.

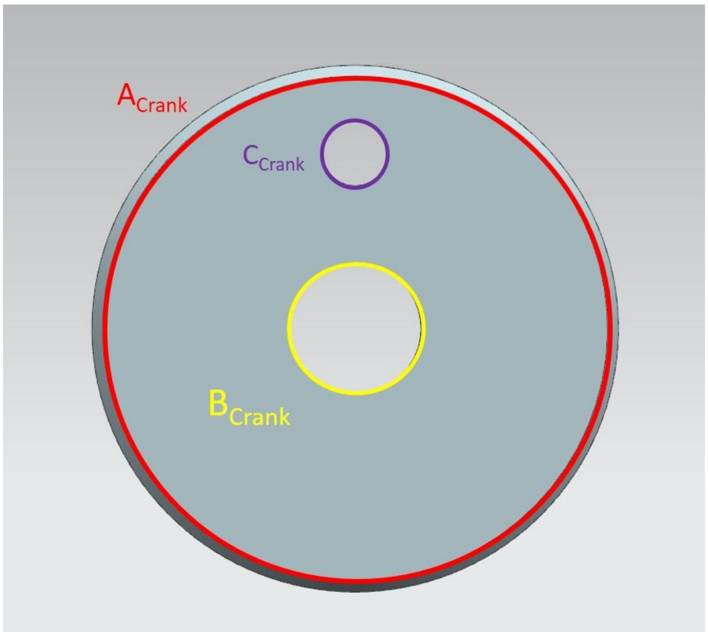


Figure 25.Crank functional surfaces

Table 6. Crank functional and positioning surfaces

Name of the part/ Code	Crank		
Type of Surface	Plan	Cylinder	Cylinder
Positioning Surface	A	B	C
Type of interface	Contact	Clearance fit	Interference fit
Type of Surface	Plan	2plans/sym	2Plans// sym
Contact Surface / Contact Part	A/ frame	K/Axle	L/ Crank Pin

- **Piston:**

Material: Brass

The piston is made of two separate parts assembled by interference fitting. The outer surface of Piston-Top, which is in contact with the bore of the cylinder, should have excellent quality to function smoothly.

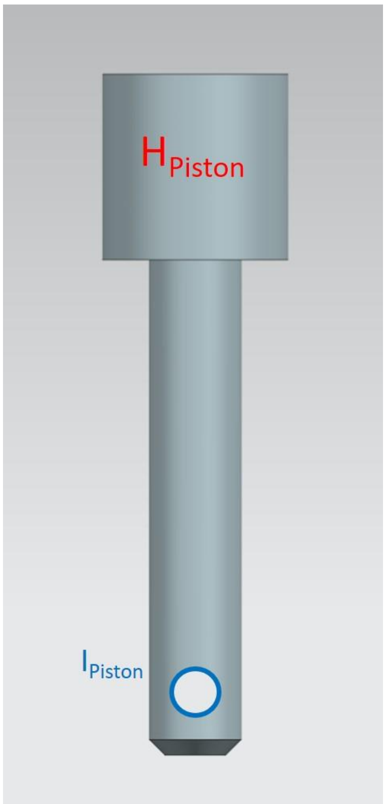


Figure 26.Piston functional surfaces

Table 7. Piston functional and positioning surfaces

Name of the part/ Code	Piston-Top	
Type of Surface	Cylinder	Cylinder
Positioning Surface	H	I
Type of interface	Clearance fit (H7/g6)	Interference fit (H9/h6)
Type of Surface	2plans/sym	2plans/sym
Contact Surface / Contact Part	B/ Cylinder	A/Piston-Link

- **Axle:**

To meet the desired quality and to consider the cost of manufacturing for the axle, it has been decided to use a ready-made stub. Since the roughness and quality of the part are ensured other parts can be modified based on it.

Table 8. Axle Functional and positioning surfaces

Name of the part/ Code	Axle
Type of Surface	Cylinder
Positioning Surface	K
Type of interface	Interference fit (P9/h6) Clearance fit (with Bearing) Interference fit (with Flywheel)
Type of Surface	2plans/sym
Contact Surface / Contact Part	B/Flywheel A/bearing B/Crank

- **Bearing:**

Bearing was selected based on the DIN ISO 4379 F-Form. [22]

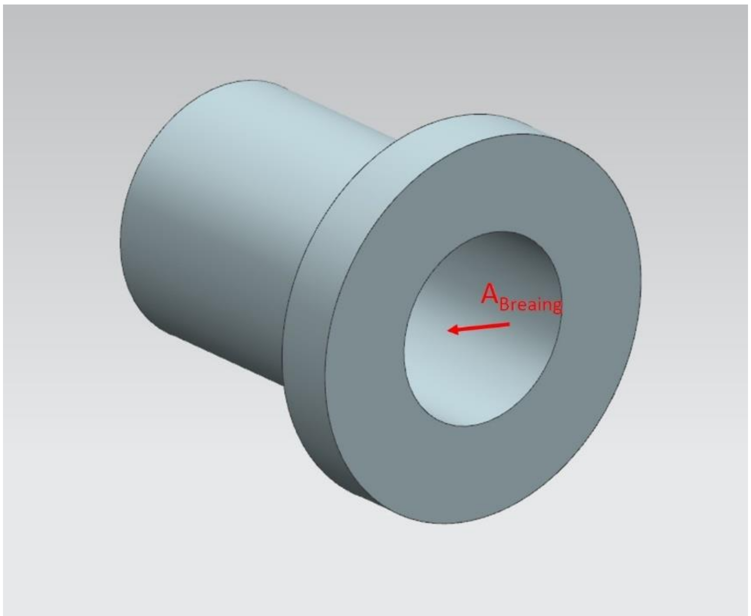


Figure 27.Bearing functional surfaces

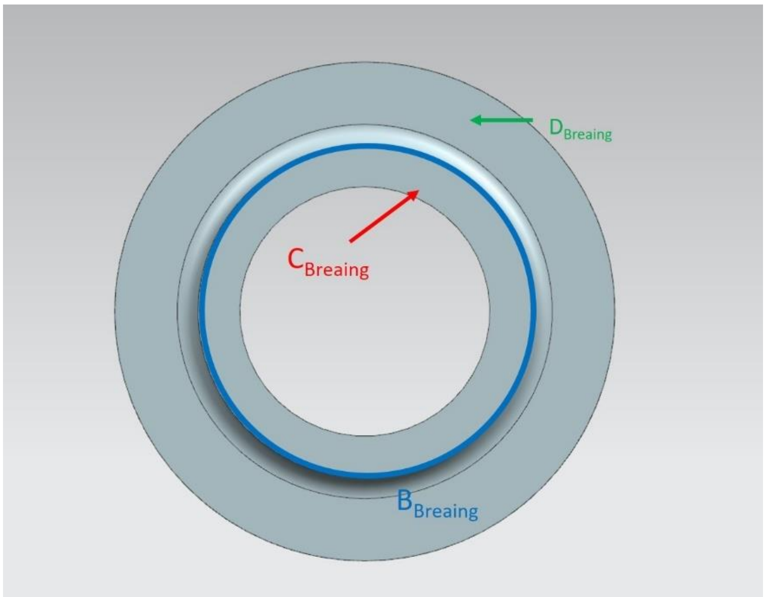


Figure 28. Bearing functional surfaces

Table 9. Bearing functional and positioning surfaces

Name of the part/ Code	Bearing			
Type of Surface	Cylinder	Cylinder	Plan	Plan
Positioning Surface	A	B	C	D
Type of interface	Clearance fir	Clearance fit	Contact	Contact
Type of Surface	2Plans// sym	2plans/sym	Plan	Plan
Contact Surface / Contact Part	K/ Axle	C/frame	A/ Crank	B/frame

- **Flywheel:**

Flywheel store rotational energy and the primary design requirement is total runout and type of fitting.

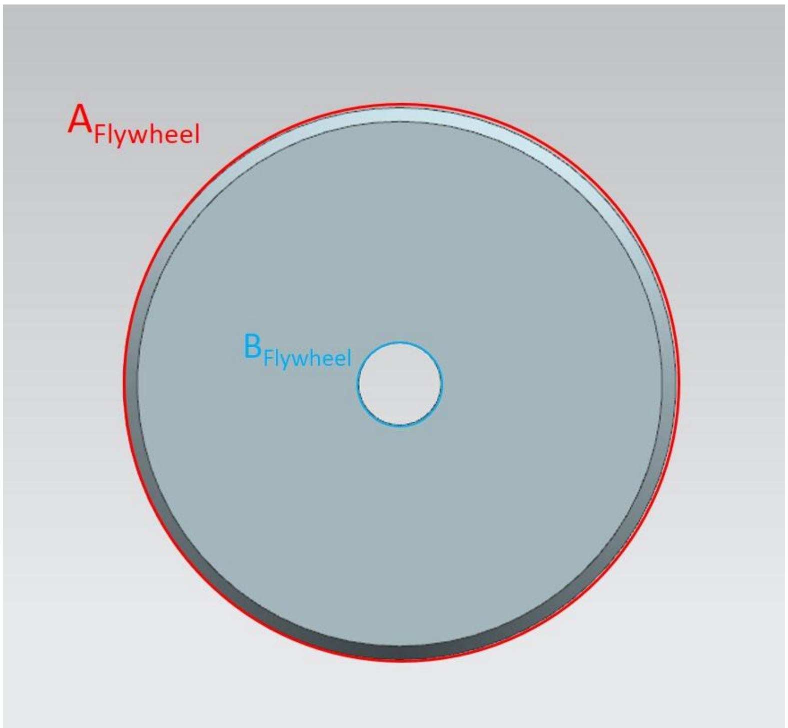


Figure 29.Flywheel functional surfaces

Table 10.Flywheel functional and positioning surfaces

Name of the part/ Code	Flywheel	
Type of Surface	Plan	Cylinder
Positioning Surface	A	B
Type of interface		Interference fit (P9/h6)
Type of Surface	2plans/sym	2plans/sym
Contact Surface / Contact Part		K/Axle

Assembly steps:

1. The Frame will be mounted on the plate with counter sunk screw
2. The Plate and Frame should be mounted and screwed on a base (a thick wooden part)
3. Cylinder will be installed to the frame by pin
4. Complex A
    - Axle should be fitted to the Flywheel hole
    - Bushing will be inserted from the other side of the axle until the end
5. Complex A will be mounted on the Frame inside the Bushing
6. The Crank will be fitted to the axle
7. Piston should be inserted to the cylinder fitting to the crank with the Crank pin

3.3 Design for Additive Manufacturing

- Overview

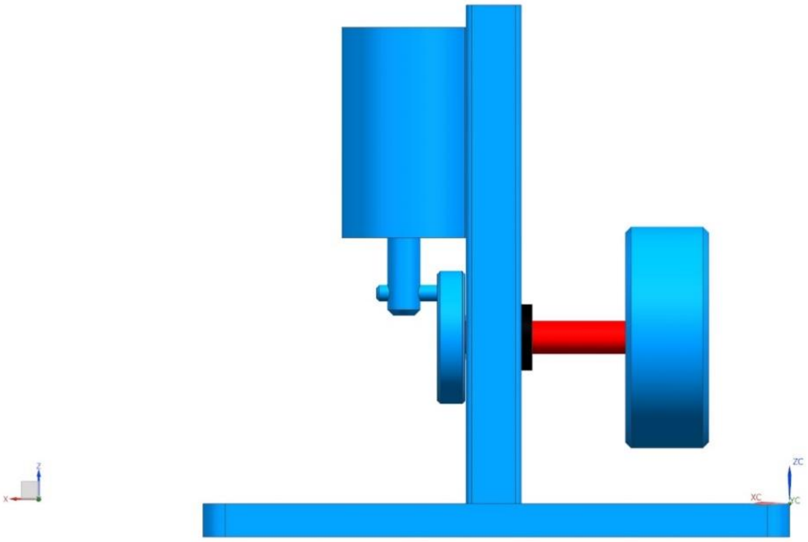


Figure 30. First draft of DfAM of the oscillation engine

It is possible to manufacture all the parts in blue color (Base, Frame, Flywheel, Crank, Crankpin, Piston and Cylinder) with Additive Manufacturing processes. However ready-made Bearing and Axle will be used. Since the finish surface and functionality of these parts are critically important also the price of purchasing them is lower than manufacturing them either with conventional methods or AM.

- Base Plate + Frame

To use the advantages of the AM technologies the Base plate and Frame has been designed to be consolidated. There is no functional need to manufacture them separately, but some changes must be made for AM. The base plate can be manufactured without significant changes since it does not consist of any complex shape. Since the whole part will be printed vertically, the screw bores will be remained as for conventional design.

To avoid the “wrapping” [23] in AM technologies the edges on the Frame should be blended or at least not to be fully sharp.

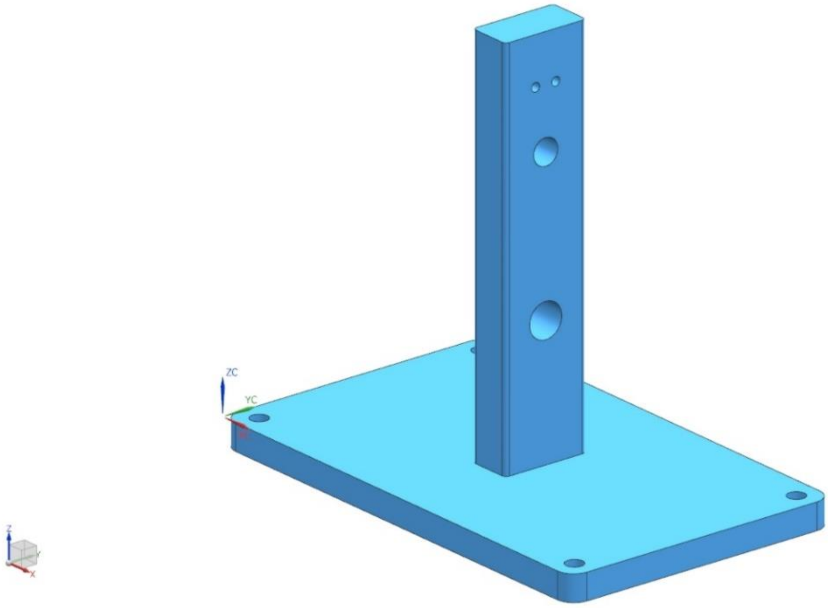


Figure 31.Consolidated Base and Frame

- Cylinder

The Cylinder can be printed with most of the Powder Bed processes, and it should be noted that the most important functionally of the cylinder is the surface quality of the bore. It should meet the criteria that have been defined for it. The main changes for AM are that edges are blended, adjustment bore, and airflow exhaust has been removed. These bores can be drilled after the printing. Post processing is a necessity to use for cylinder bore since none of the AM technologies can provide the finish surface that has been defined for the bore.

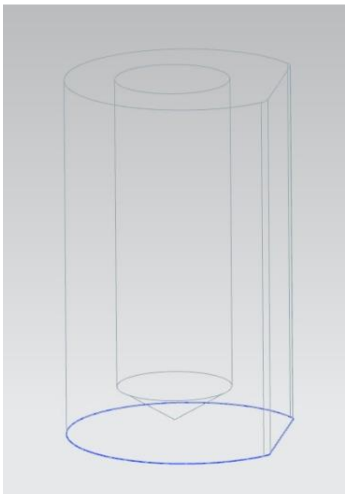


Figure 32. Cylinder orientation for AM

- Piston

Piston crown and connection rod shaft had been consolidated in the piston system. There is no limitation to print the piston as is shown in the Fig.33 however the bore for Crank pin needs support during the process of printing. Since the diameter of the bore is 3mm, the post-processing might be challenging to reach the desired surface finish. Another option for the Crank pin bore is to drill it after the printing but positioning during for the drilling process should be carefully done.

To reach the desired finish surface of the crown, post-processing is needed. It should be noted that removing the supports under the crown and leave it without post-processing does not affect the functionally of the piston.

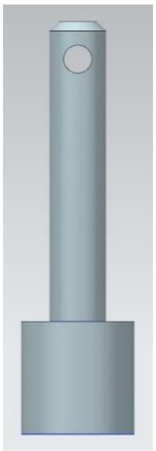


Figure 33.Piston orientation for AM

- Crank

There have been no changes in the Crank. Just one side of the crank has a 0.2 mm tolerance gap with Frame. Therefore, the side that had been made on the top layer will be the used as contact side.

The essential consideration for the parts with bore and holes are the surface quality; thus, further study is needed to gather the required information if the bores should be done in AM or later with drilling. Using the lattice structure is an option; however, the thickness of the part might be problematic to use these kinds of structure.

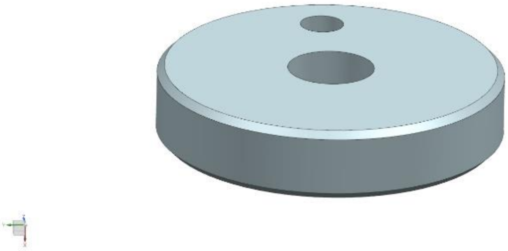


Figure 34. Crank orientation for AM

- Flywheel

Since the axle has been chosen from off the shelve and requires a specific type of tolerance for the bore, post-processing is necessary to meet the fitting requirements.

Lattice structure will not be used in Flywheel since the functionally of it is to store mechanical rotation, and decreasing weight or material will affect its functionality.

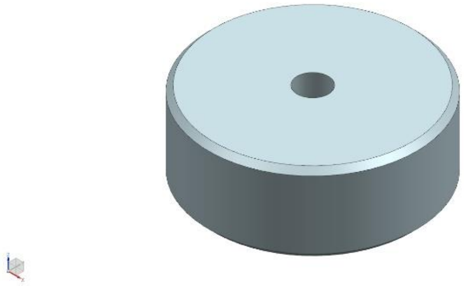


Figure 35.Flywheel orientation for AM

3.4 Functional Surfaces

The purpose of this part is to illustrate the functional surfaces of each parts. Each of these surfaces influence on decision making of manufacturing. Each functional surface has been depicted with its requirements.

- Cylinder

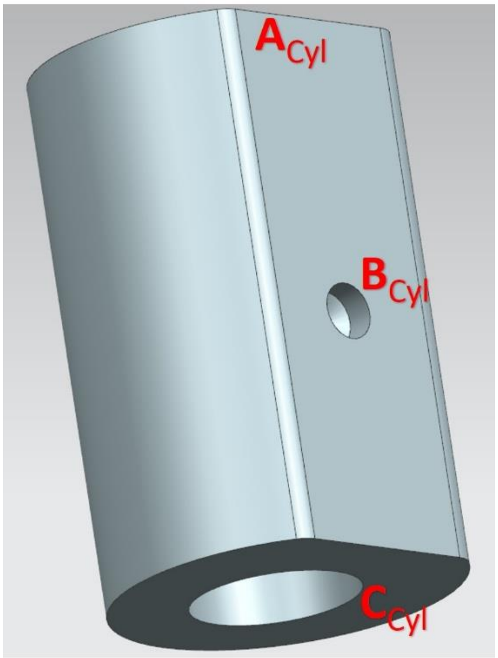


Figure 36.Cylinder functional areas

Functional Surface	Functionality
A_{Cyl}	Cylinder is power unit of the engine, it inverts the pressures air energy into mechanical energy **A_{Cyl}** surface contact with Frame Requirements: Smooth surface for proper mechanical movement, Ra = 2.4 If the surface roughness does not meet the desired value, air will leak from the intake hole and engine would not function. Installation of the cylinder and frame requires an excellent surface. Therefore, the surface **A_{Cyl}** should have the desired finish surface to attach correctly to the frame. The roughness of the surface should not be higher than defined otherwise it will cause air leakage, and the whole engine would not function.
B_{Cyl}	**B_{Cyl}:** contact the Cylinder to the Frame **B_{Cyl} is** Adjustment pin bore Requirements: 1- The dimension tolerance of diameter of the **B_{Cyl}** should be P6
C_{Cyl}	**C_{Cyl}**: Cylinder bore, Piston travels along the bore **C_{Cyl}:** Smooth surface and accurate positioning are required Requirements: 1- The cylindricality should not exceed the value of C_{Cyl} = 0.1 2- The dimension tolerance of diameter of the C_{Cyl} should be H7 Piston and the rod will transfer kinetic energy from the compressed air to mechanical energy. To have a smooth movement, the surface roughness of the piston and inner bore of the cylinder should be according to the calculation.

Table 11. Cylinder functional surfaces and their functionality

- Piston

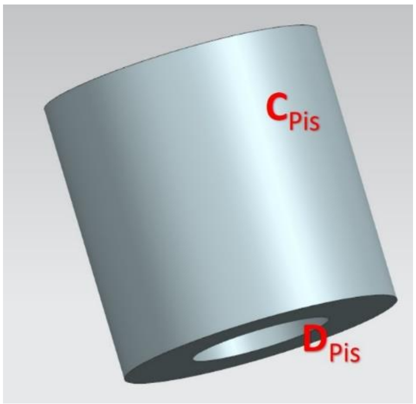


Figure 37.Piston functional areas

Table 12.Piston functional surfaces and tier functionality

Functional Surface	Functionality
C_{Pis}	Piston move along the cylinder bore (**C_{Pis}**) by force of air pressure. **C_{Pis}** Requirements: 1- The cylindricality should not exceed the value of $C_{c\text{-}Pis} = 0.1$ 2- The dimension tolerance of diameter of the C_{Pis} should be <u>g6</u>
D_{Pist}	Connection bore with Rod Interreference fit in **D_{Pist}** to attach the Rod to Piston Requirements: 1- The concentricity should not exceed the value of $D_{c\_Pist} = 0.1$ 2- The dimension tolerance of diameter of the D_{Pist} should be H9

- Piston Rod:

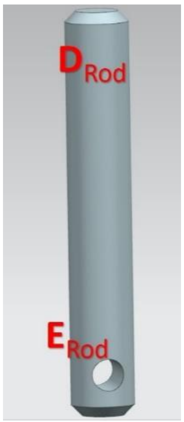


Figure 38.Piston-rod functional areas

Table 13.Piston Rod functional surfaces and their functionality

D_{Rod}	Transfer the vertical movement to Crank via Crank pin Interreference fit in **D_{Pist}** to attach the Rod to Piston Requirements: 1- The Run-out should not exceed the value of $D_{r\_Rod} = 0.1$ 2- The dimension tolerance of diameter of the D_{Rod} should be js9
E_{Rod}	Connection hole with Crank pin **E_{Rod}** connects rod to the Crank Requirements: 1- The Perpendicularity should not exceed the value of $E_{p\_Rod} = 0.2$ 2- The dimension tolerance of diameter of the E_{Rod} should be G7 Mechanical energy will be transferred via pin to Crank. Assembly of these three parts (Piston rod, Crank pin and Crank) require an exceptional quality on the outer surface. Any loose connection will affect the performance of the engine.

- Crank Pin:

Figure 39.Crank pin functional areas

Table 14.Crank functional surfaces and their functionality

Functional Surface	Functionality
$\mathbf{E}_{\mathbf{crn\_pin}}$	Crank pin connects the Piston-Rod to the Crank $\mathbf{E}_{\mathbf{crn\_pin}}$ **:** functional surface of the connection Requirements: 1- The dimension tolerance of diameter of the $\mathbf{E}_{\mathbf{crn\_pin}}$ should be 3mm

- Crank:

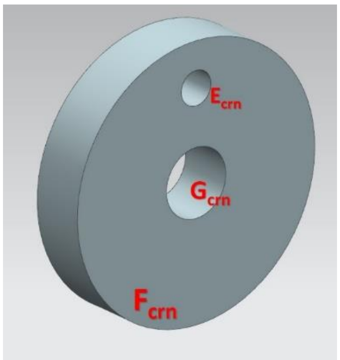


Figure 40.Crank functional areas

Table 15.Crank functional surfaces and their functionality

Functional Surface	Functionality
E_{Crn}	Converts the linear motion of the piston into the rotational motion for the axle. **E_{Crn}** concoction surface between crank and rod Requirements: 1- The positioning should not exceed the value of E_{Crn} = 0.2 2- The dimension tolerance of diameter of the E_{Crn} should be G7 Mechanical energy will be transferred via pin to Crank. Assembly of these three parts (Piston rod, Crank pin and Crank) require a fine quality on the inner surface. Any loose connection will affect the performance of the engine.
G_{Crn}	**G_{Crn}**: Connection bore with Axle Transfer the rotational energy to axle Requirements: 1- The positioning should not exceed the value of **G_{Crn}** = 0.2 2- The dimension tolerance of diameter of the **G_{Crn}** should be G7 Surface for connecting the crank and axle. The same with other assembly surfaces, **G_{Crn}** should meet the required roughness. The engine would not function with clearance tolerance thus post-processing to achieve the needed criteria might be necessary.
F_{Crn}	Gap space between Crank and Frame **F_{Crn}:** Functional and not attached surface Requirements: 1- The surface roughness of the **F_{Crn}** should be N7 The distance between this surface and the frame should not be more than 0.2 mm. Thus, this surface should meet the required roughness. Post-processing for one side of the Crank is mandatory.

- Axle

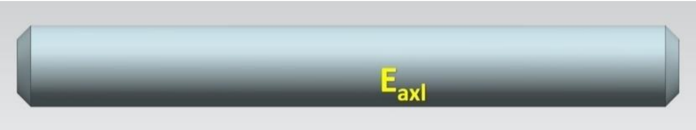


Figure 41.Axle functional area

Table 16.Axle functional surfaces and their functionality

Functional Surface	Functionality
E_{axl}	Transfer the rotational energy to flywheel **E_{axl}**: contact surface of axle, crank and flywheel and transfer Requirements: 1- The surface roughness of the **E_{axl}** should be Ra = 2.4 2- The dimension tolerance of diameter of the **E_{axl}** should be 8mm

- Flywheel:

Figure 42.Flywheel functional area

Table 17.Flywheel functional surfaces and their functionality

Functional Surface	Functionality
G_{fly}	The flywheel stores the rotational energy. **G_{fly}** contacts axle and transfer the rotational energy to the axle. Requirement: 3- The circular run-out of the flywheel should not exceed the value of **G_{fly}** = 0.1 (H) 4- The total mass of flywheel should be in the range of () 5- The surface roughness of the **G_{fly}** should be Ra = 6- The dimension tolerance of diameter of the **G_{fly}** should be P9 Possible consideration to fulfill the requirements: • Run-out can be improved by machining the other surfaces of the flywheel The primary function of the flywheel is to store the rotational energy. Since other surfaces are not in contact with any other parts, finish roughness is not essential however the total run-out should be considered here. Post processing is not needed if vibration and oscillation does not affect the main functionality of the engine.

- Frame:

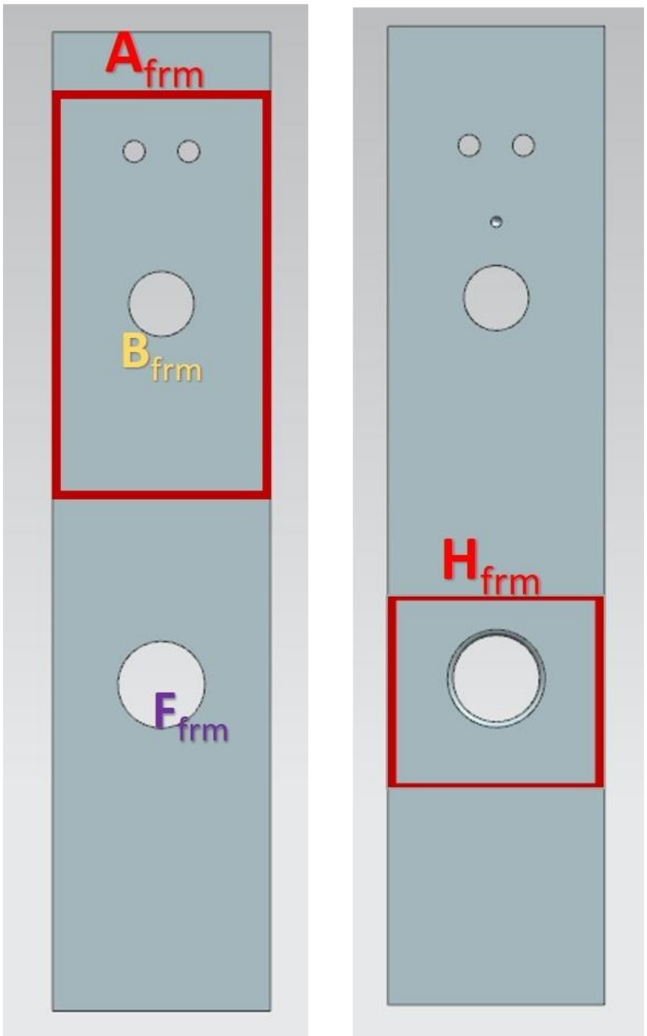


Figure 43.Frame Functional areas

Table 18.Frame functional surfaces and their functionality

Functional Surface	Functionality
A_{Frm}	Frame acts as a stander for cylinder and axle A_{Frm} contact with Cylinder Requirements: 1- The surface roughness of the **A_{Frm}** should be N7 Installation of the cylinder and frame require an excellent surface. Therefore, the surface A1 should have the desired finish surface to assemble appropriately to the cylinder. The roughness of the surface should not be higher than defined otherwise it will cause air leakage, and the engine would not function.
B_{Frm}	**B_{Frm}** connection bore for adjustment pin and Cylinder Requirements: 1- The positioning should not exceed the value of **B_{Frm}** = 0.2 2- The dimension tolerance of diameter of the **B_{Frm}** should be H7 The adjustment bore is designed to fix the cylinder to the frame by adjustment pin. Any misalignment and dispositioning will cause a functional failure.
F_{Frm}	Surface with gap of 0.2 mm with Crank Requirements: 1- The surface roughness of the **F_{Frm}** should be N7 A bearing should be fixed to mount the axle on the frame. All the bearings require a specific surface quality; thus the **F_{Frm}** should meet the desired criteria.
H_{Frm}	**H_{Frm}** the bore which hold the bearing Requirements: 1- The perpendicularity should not exceed the value of **H_{Frm}** = 0.2 2- The dimension tolerance of diameter of the **H_{Frm}** should be H7 Mounting the bearing requires certain surface finish on the frame.

3.5 Manufacturing Options

All the possible manufacturing options have been listed in the table.19. The idea is to represent all the possible means to manufacture one part or consolidate them. DMLS and SLM are identical in terms of process and the only difference is the usage of material in these process.[23]

Table 19.Manufacturing Options

Parts	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9	Option 10	Option 11
Base	Machining	WAAM	Machining+WAAM	DMLS	SLM	EBM	Binder Jetting	Binder jetting	EBM	WAAM	DMLS
Frames	Machining							WAAM	SLM	EBM	Binder Jetting
Flywheel	Machining	WAAM+Off the Shelf	WAAM	DMLS/SLM	EMB	Binder Jetting	DMLS/SLM	EBM	Binder Jetting	WAAM	Machining
Axle	Off the Shelf		Machining	DMLS/SLM	EBM	Binder Jetting				DMLS	Binder Jetting
Crank	Machining	Machining	DMLS/SLM				DMLS	SLM	EBM	Binder Jetting	Binder Jetting
Crank-Pin	Machining		DMLS								Off the shelf
Piston-Crwon	Machining	WAAM	WAAM	DMLS/SLM	EBM	Binder Jetting	DMLS	SLM	EBM	Binder Jetting	Machining
Piston-Rod	Machining	Off the shelf					DMLS	SLM	EBM	Binder Jetting	Off the shelf
Cylinder	Machining	WAAM	DMLS/SLM	EBM	Binder Jetting	Machining	SLM	DMLS	EBM	Binder Jetting	Machining
Adj-Pin	Machining	Off the shelf	DMLS	SLM	EBM	Binder Jetting					Machining

3.5.1 Decision-making

Precision, flexibilities and quality of the products depend on selection the process selection[24]. The productivity of the manufacturing system such as quality, cost and rate is highly dependent on what kind of implementation has been used[25]. However, with a wide range of choices available today, defining the best alternative for a specific production set-up is not an easy task[26]. Multi-criteria decision-making (MCDM) helps to choose the best equipment among other alternatives. [24]

A proper evaluation is a time-consuming and challenging process which requires advanced knowledge. Decision maker needs several factors to be considered and a massive amount of data that should be analyzed [25]. Saaty in the [27] developed an Analytic hierarchy process (AHP) method and described how to determine the relative importance of a set of activities in a decision problem which has multi-criteria[28].

To find the best manufacturing option for three parts (Base, Frame and Flywheel) of the engine the AHP method will be used. Three main criteria for this case study are limited to Time, Cost and Quality. These criteria have been defined for simplicity of the judgment and decision-making. Nonetheless, more measures affect the decision-making process.

It should be noted that the main reason for choosing the Wire Arc Additive Manufacturing (WAAM) as DED process was to simplify the options and availability of WAAM machine in TTY facilities.

The factor of Time in this comparison consist of:[15]

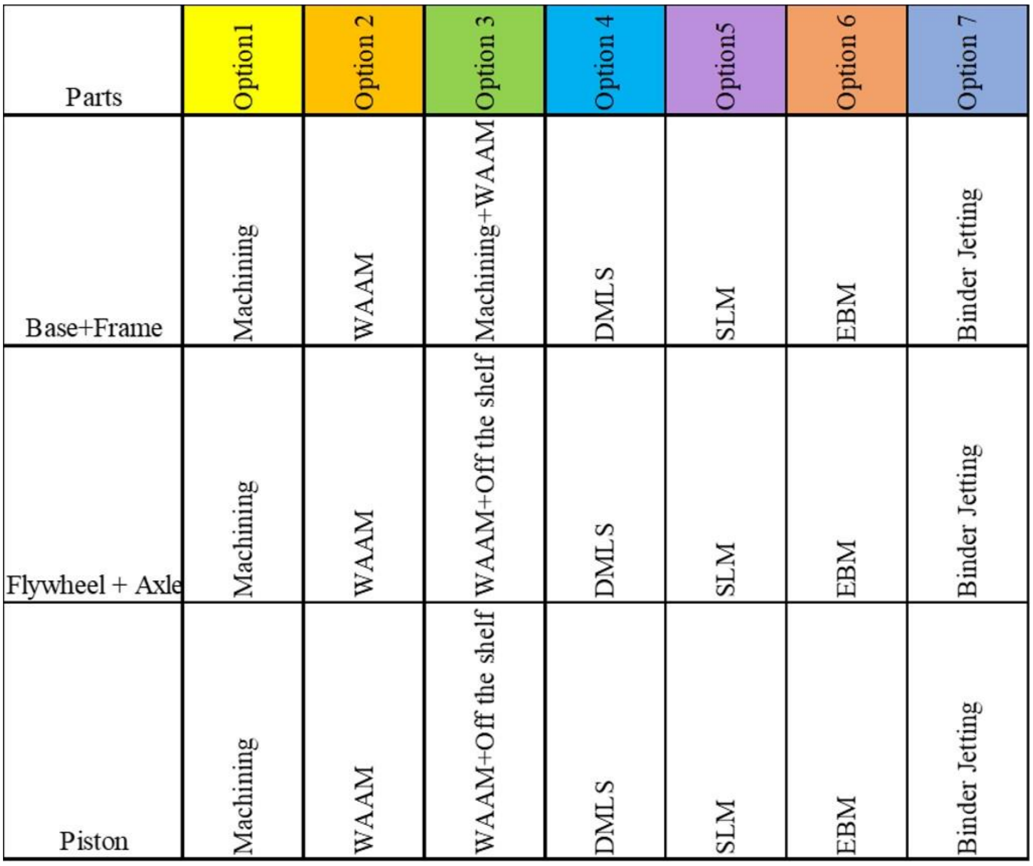
- Model of Design
- Conversion of CAD Model into AM Machine, Acceptable Format
- Support Generation
- Machine Setup
- Build
- Post processing

Quality here is considered the quality after all the post-processing methods. Since additive manufacturing processes are new in comparison with conventional manufacturing methods and there is a wide range of standards for the quality and geometric measurement, the machining methods here has been defined as the reference quality.

The measure of judgment was given based on the [29] and [23]. Since effective measures are relative in a manufacturing process, one might consider one of these criteria more important than others. Hence different result might be achieved with the same method.

In the previous section (3.5 Manufacturing options) all the possible options were presented in the Table.19, however for the sake of simplicity and considering the time of this thesis, just three parts (five parts in conventional design which decided to be consolidated in AM) were measured. Even though the functionality of these parts is different from the others, the same result will be achieved if one continues to do the AHP method for the other parts.

Table 20.Manufacturing options for selected parts



Parts	Option1	Option 2	Option 3	Option 4	Option5	Option 6	Option 7
Base+Frame	Machining	WAAM	Machining+WAAM	DMLS	SLM	EBM	Binder Jetting
Flywheel + Axle	Machining	WAAM	WAAM+Off the shelf	DMLS	SLM	EBM	Binder Jetting
Piston	Machining	WAAM	WAAM+Off the shelf	DMLS	SLM	EBM	Binder Jetting

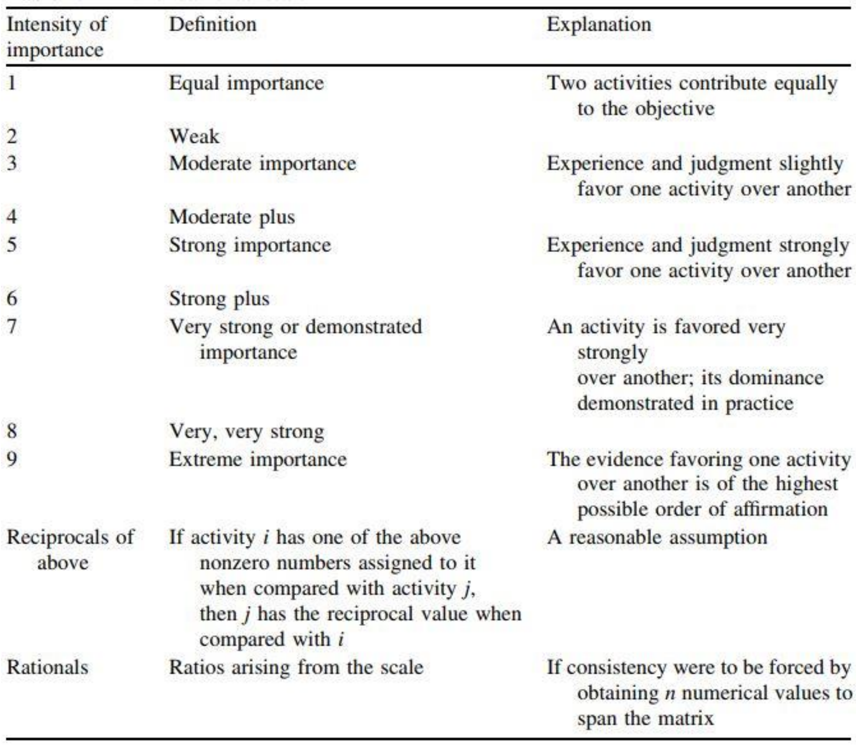
The analytic hierarchy processes

To create generic priorities for an organized decision, we need to follow these steps:

1. State the problem and related the know-how needed.
2. Build the decision hierarchy by the goal on top, then objectives through the mid-range levels to the lowest level.
3. Create set of pairwise comparison matrices. Each element should be compared to the next level element.
4. From the priorities attained from comparisons, weight can be found for the immediate level below. It should be done for each element. For each element below, all the weight values should be added, and overall priority will be obtained. The procedure should be continued until the final priorities of the last element are obtained.

To make a clear comparison, each element should be scaled based on the importance over the other elements with respect to the criterion. Table.21 represents the scales and which number should be used.

Table 21. Saaty-scale for pair comparison[30]



Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Table 22. Pair comparison performance criteria, Main objective: Finding the optimal path for manufacturing specific part with a specific AM-technology

	c1	c2	c3
c1	1	6	4
c2	1/6	1	1/3
c3	1/4	3	1

After the pair comparison is determined, the next stage is to compute the weight of the compared elements. The weights are the eigenvector W of the largest eigenvalue λ_{max} of the comparison matrix A.[30]

$$\boldsymbol{A} * \boldsymbol{\omega} = \lambda_{max} * \boldsymbol{\omega}$$

$\lambda_{max}$is the eigenvalue that belongs to the eigenvector $\boldsymbol{\omega}$, the calculated weights vector, and n is the rank of the matrix, for a consistent matrix $\lambda_{max} = n$ and therefore the consistency index would be zero.

Since matrix A will be inconsistent matrix due to subjective judgment, the eigenvector cannot be calculated analytically. The method here is to normalize the elements in each column then averaging each row to get the eigenvector.[30][31]

1. Normalizing the values in each column of the comparison matrix
   Formula

2. Summing each row of the comparison matrix and normalizing the resulting values by dividing through the number of criteria.

A highly consistent index of A is important for the quality of the weight's results. For accurate approximation the consistency ratio (CR) must be less than 0.1. The consistency ratio is calculated by consistency index (CI) of the comparison matrix A over the consistency index that has been randomly generated (RI). As long as the CR is less than 0.1 the process will continue to the end to achieve the best result.

$$CR = \frac{CI}{RI} < 0.1$$

The rest of pairwise comparison can be found in Saaty [30]and with this short instruction, the pairwise comparison of our case study will be presented.

In the next section the criteria, their weighs results and CR check will be presented. After that the alternative method of manufacturing for each part will be presented as prior step.

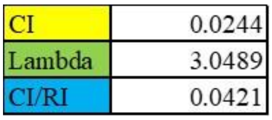
3.5.2 Analytic hierarchy process result

- ***Base + Frame:***

Criteria	Time	Cost	Quality	Weights
Time	1	1/4	1/7	0.08
Cost		1	1/3	0.265
Qulity			1	0.656

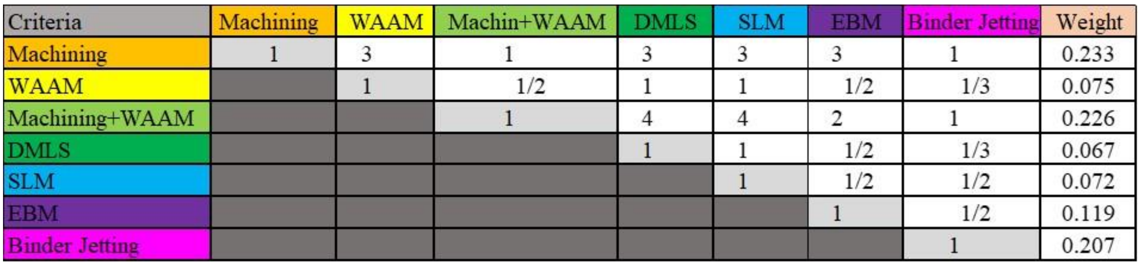
Figure 44. Base + Frame Pair comparison performance criteria

As it is shown in the Fig20. The Time of the manufacturing has the highest importance for Base + Frame. The quality comes second because tolerances of the bores and surface quality of the Frame is highly important for smooth movement of the piston.



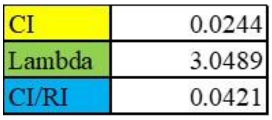
CI	0.0244
Lambda	3.0489
CI/RI	0.0421

Figure 45.Base + Frame Pair comparison consistency check for all the criteria



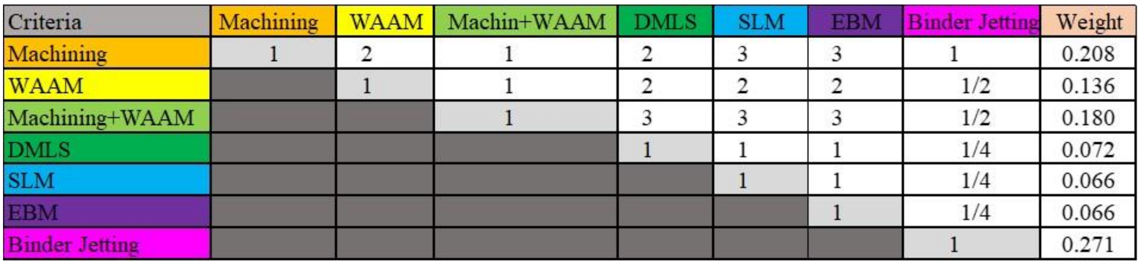
Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	3	1	3	3	3	1	0.233
WAAM		1	1/2	1	1	1/2	1/3	0.075
Machining+WAAM			1	4	4	2	1	0.226
DMLS				1	1	1/2	1/3	0.067
SLM					1	1/2	1/2	0.072
EBM						1	1/2	0.119
Binder Jetting							1	0.207

Figure 46.Base + Frame Pair comparison of Time criterion for AM options



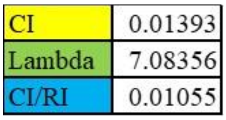
CI	0.0244
Lambda	3.0489
CI/RI	0.0421

Figure 47. Base + Frame Consistency check for Time Criterion



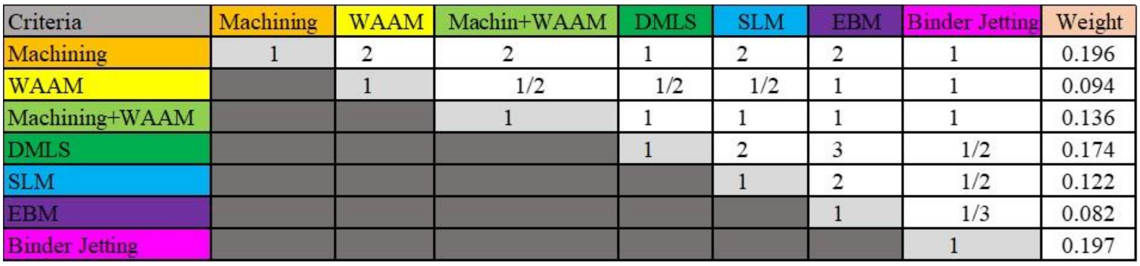
Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	2	1	2	3	3	1	0.208
WAAM		1	1	2	2	2	1/2	0.136
Machining+WAAM			1	3	3	3	1/2	0.180
DMLS				1	1	1	1/4	0.072
SLM					1	1	1/4	0.066
EBM						1	1/4	0.066
Binder Jetting							1	0.271

Figure 48.Base + Frame Pair comparison of Cost criterion for AM options



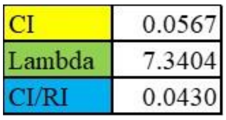
CI	0.01393
Lambda	7.08356
CI/RI	0.01055

Figure 49. Base + Frame Consistency check for Cost Criterion



Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	2	2	1	2	2	1	0.196
WAAM		1	1/2	1/2	1/2	1	1	0.094
Machining+WAAM			1	1	1	1	1	0.136
DMLS				1	2	3	1/2	0.174
SLM					1	2	1/2	0.122
EBM						1	1/3	0.082
Binder Jetting							1	0.197

Figure 50.Base + Frame Pair comparison of Quality criterion for AM options



CI	0.0567
Lambda	7.3404
CI/RI	0.0430

Figure 51.Base + Frame Consistency check for Quality Criterion

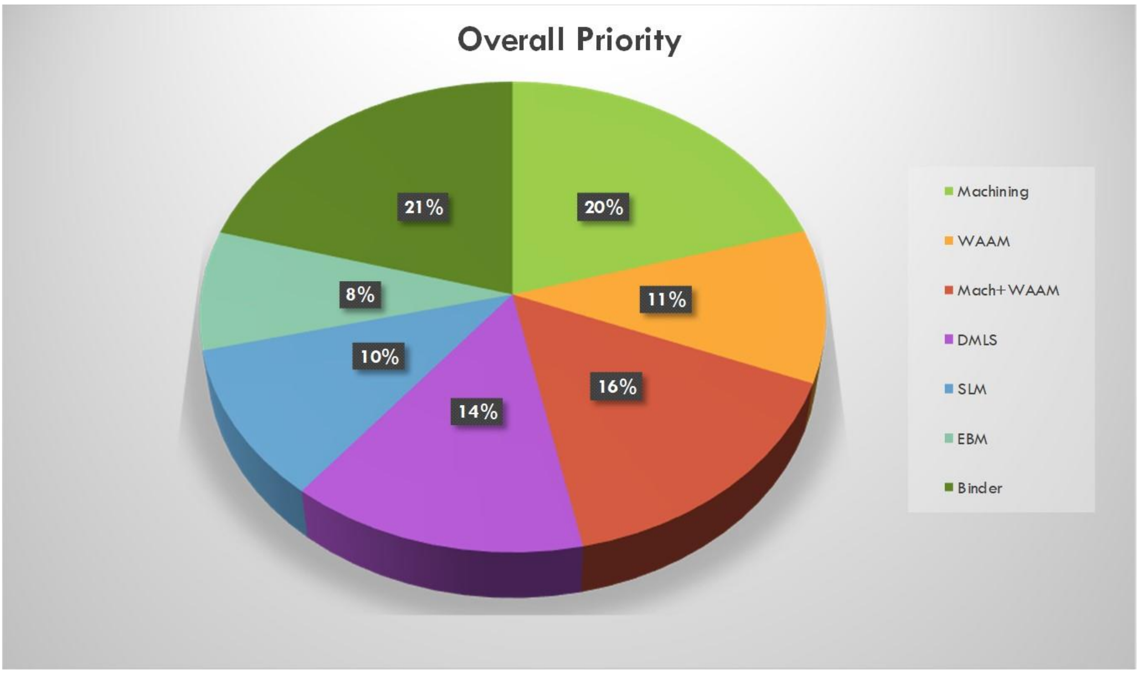


Figure 52. Base + Frame overall prioritization

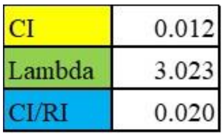
As it is indicated in the Fig.52 The binder technologies were the best option after pairwise comparison with a slight difference with Machining. One reason is that Binder Jetting is the closest option to machining regarding Cost[23]. The Base + Frame does not have design complication, therefore; the quality of the Binder can be competitive with Machining with simple parts.

- **Flywheel + Axle:**

Criteria	Time	Cost	Quality	Weights
Time	1	1/4	1/6	0.093
Cost		1	1	0.423
Qulity			1	0.484

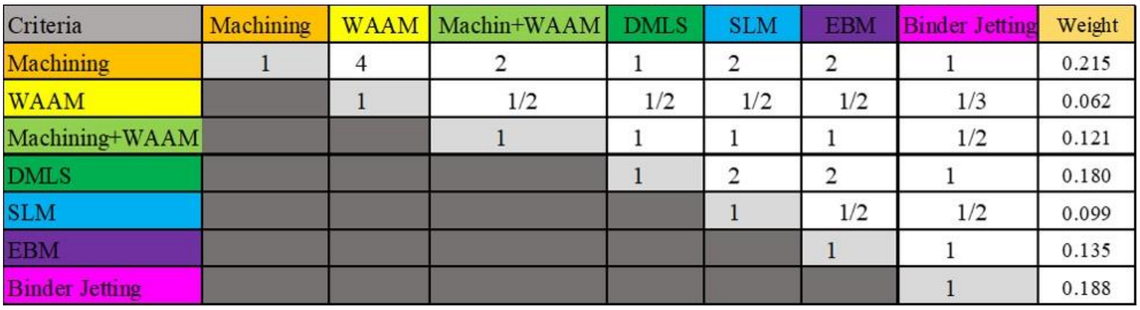
Figure 53. Flywheel + Axle Pair comparison performance criteria

Like the Base + Frame part, Time is the most important factor for the Flywheel + Axle. It should be noted that in some cases, time and cost are considered as a combine criterion.



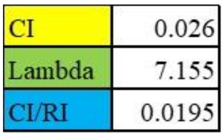
CI	0.012
Lambda	3.023
CI/RI	0.020

Figure 54.Flywheel + Axle Pair comparison consistency check for all the criteria



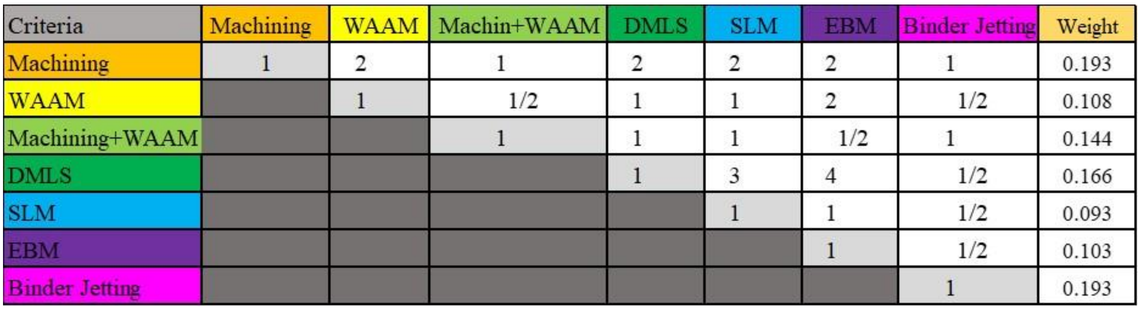
Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	4	2	1	2	2	1	0.215
WAAM		1	1/2	1/2	1/2	1/2	1/3	0.062
Machining+WAAM			1	1	1	1	1/2	0.121
DMLS				1	2	2	1	0.180
SLM					1	1/2	1/2	0.099
EBM						1	1	0.135
Binder Jetting							1	0.188

Figure 55. Flywheel + Axle Pair comparison of Time criterion for AM options



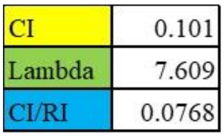
CI	0.026
Lambda	7.155
CI/RI	0.0195

Figure 56. Flywheel + Axle Consistency check for Time Criterion



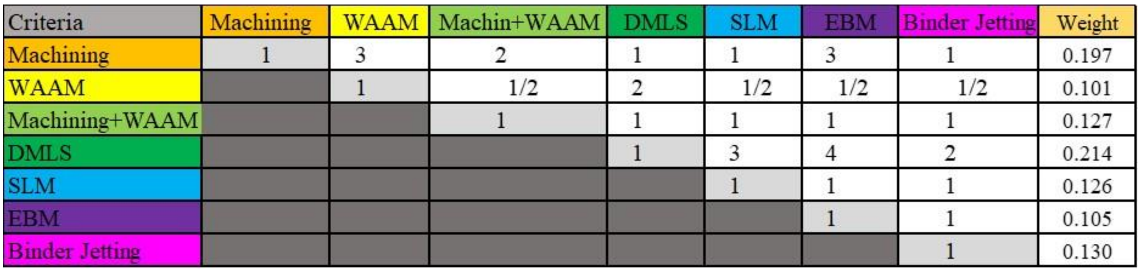
Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	2	1	2	2	2	1	0.193
WAAM		1	1/2	1	1	2	1/2	0.108
Machining+WAAM			1	1	1	1/2	1	0.144
DMLS				1	3	4	1/2	0.166
SLM					1	1	1/2	0.093
EBM						1	1/2	0.103
Binder Jetting							1	0.193

Figure 57. Flywheel + Axle Pair comparison of Cost criterion for AM options



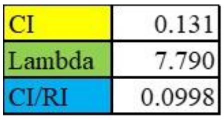
CI	0.101
Lambda	7.609
CI/RI	0.0768

Figure 58Figure 30. Flywheel + Axle Consistency check for Cost Criterion



Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	3	2	1	1	3	1	0.197
WAAM		1	1/2	2	1/2	1/2	1/2	0.101
Machining+WAAM			1	1	1	1	1	0.127
DMLS				1	3	4	2	0.214
SLM					1	1	1	0.126
EBM						1	1	0.105
Binder Jetting							1	0.130

Figure 59.Flywheel + Axle Pair comparison of Quality criterion for AM options



CI	0.131
Lambda	7.790
CI/RI	0.0998

Figure 60.Figure 30. Flywheel + Axle Consistency check for Quality Criterion

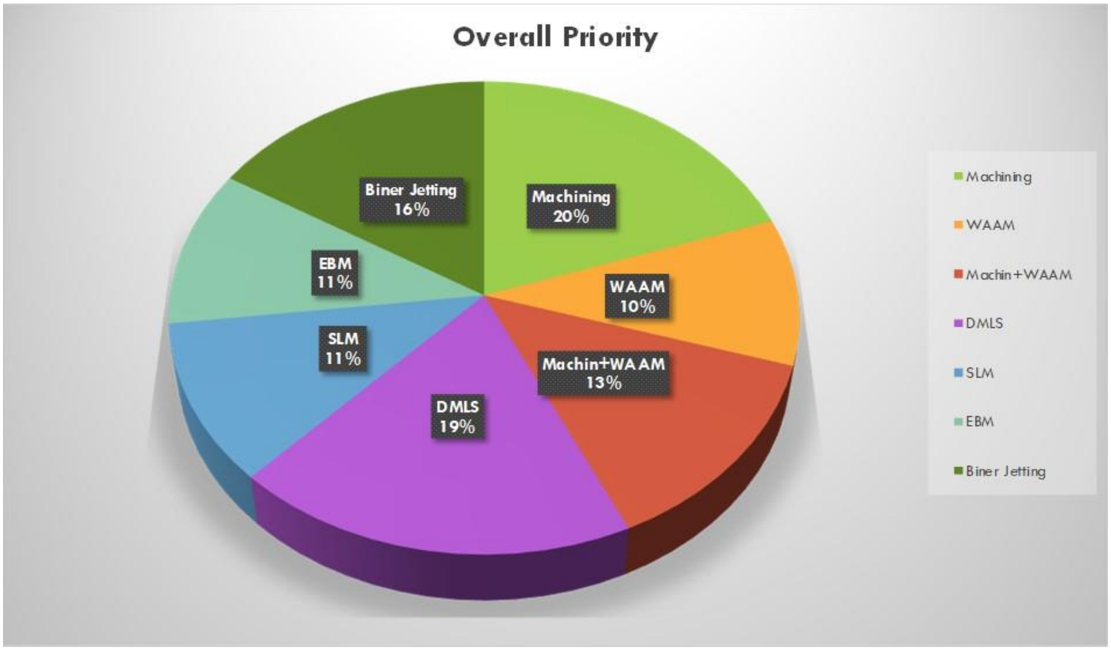


Figure 61.Flywheel + Axle overall prioritization

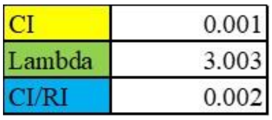
As it is shown in the Fig.61 the best method to manufacture the Flywheel + Axle is the machining. AM with all its capabilities could not win over the traditional manufacturing, the reason for that is that Machining works perfectly fine with these kinds of shapes. The shape of the part is simple, easy to manufacture and demand less workload compared to AM technologies.

The significant outcome of this specific pairwise comparison is that even though AM technologies have a variety of advantageous but still conventional manufacturing has its benefits. In this example, it can be analyzed that features of the parts, design complexity, criteria for a verified part are dominant criteria for selecting the best technology for manufacturing.

- ***Piston:***

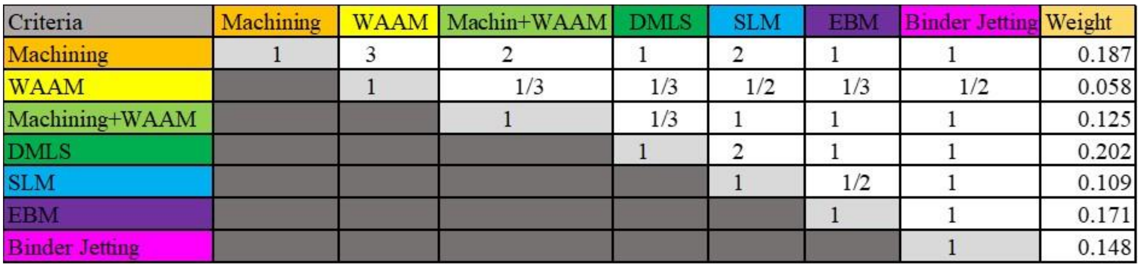
Criteria	Time	Cost	Quality	Weights
Time	1	1/4	1/7	0.082
Cost		1	1/2	0.315
Qulity			1	0.602

Figure 62.Piston Pair comparison performance criteria



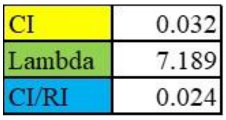
CI	0.001
Lambda	3.003
CI/RI	0.002

Figure 63. Piston Pair comparison consistency check for all the criteria



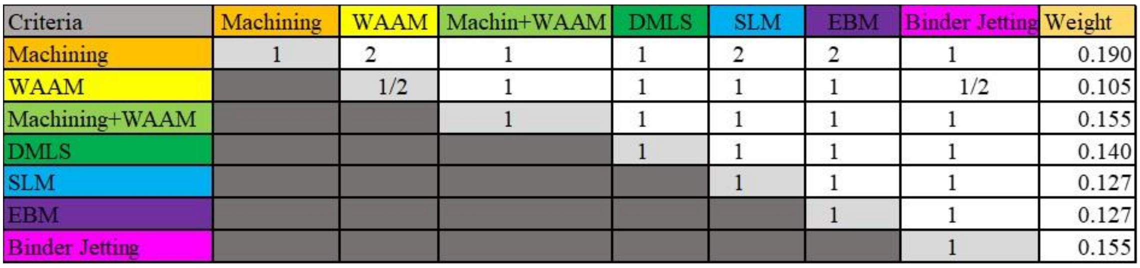
Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	3	2	1	2	1	1	0.187
WAAM		1	1/3	1/3	1/2	1/3	1/2	0.058
Machining+WAAM			1	1/3	1	1	1	0.125
DMLS				1	2	1	1	0.202
SLM					1	1/2	1	0.109
EBM						1	1	0.171
Binder Jetting							1	0.148

Figure 64.Piston Pair comparison of Time criterion for AM options



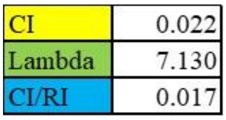
CI	0.032
Lambda	7.189
CI/RI	0.024

Figure 65. Piston Consistency check for Time Criterion



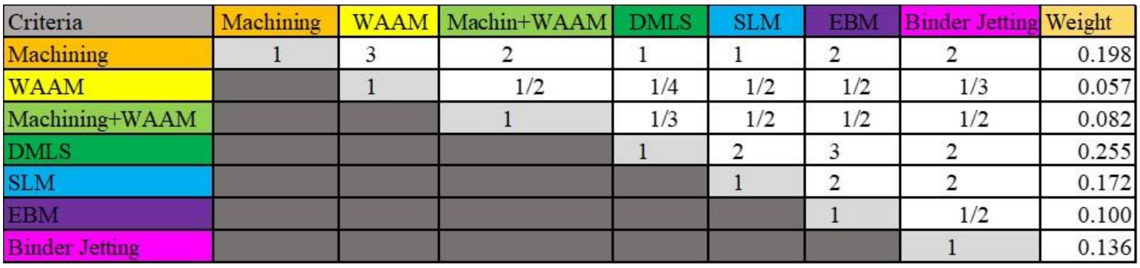
Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	2	1	1	2	2	1	0.190
WAAM		1/2	1	1	1	1	1/2	0.105
Machining+WAAM			1	1	1	1	1	0.155
DMLS				1	1	1	1	0.140
SLM					1	1	1	0.127
EBM						1	1	0.127
Binder Jetting							1	0.155

Figure 66. Piston Pair comparison of Cost criterion for AM options



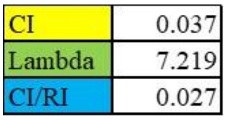
CI	0.022
Lambda	7.130
CI/RI	0.017

Figure 67. Piston Consistency check for Cost Criterion



Criteria	Machining	WAAM	Machin+WAAM	DMLS	SLM	EBM	Binder Jetting	Weight
Machining	1	3	2	1	1	2	2	0.198
WAAM		1	1/2	1/4	1/2	1/2	1/3	0.057
Machining+WAAM			1	1/3	1/2	1/2	1/2	0.082
DMLS				1	2	3	2	0.255
SLM					1	2	2	0.172
EBM						1	1/2	0.100
Binder Jetting							1	0.136

Figure 68. Piston Pair comparison of Quality criterion for AM options



CI	0.037
Lambda	7.219
CI/RI	0.027

Figure 69. Piston Consistency check for Quality Criterion

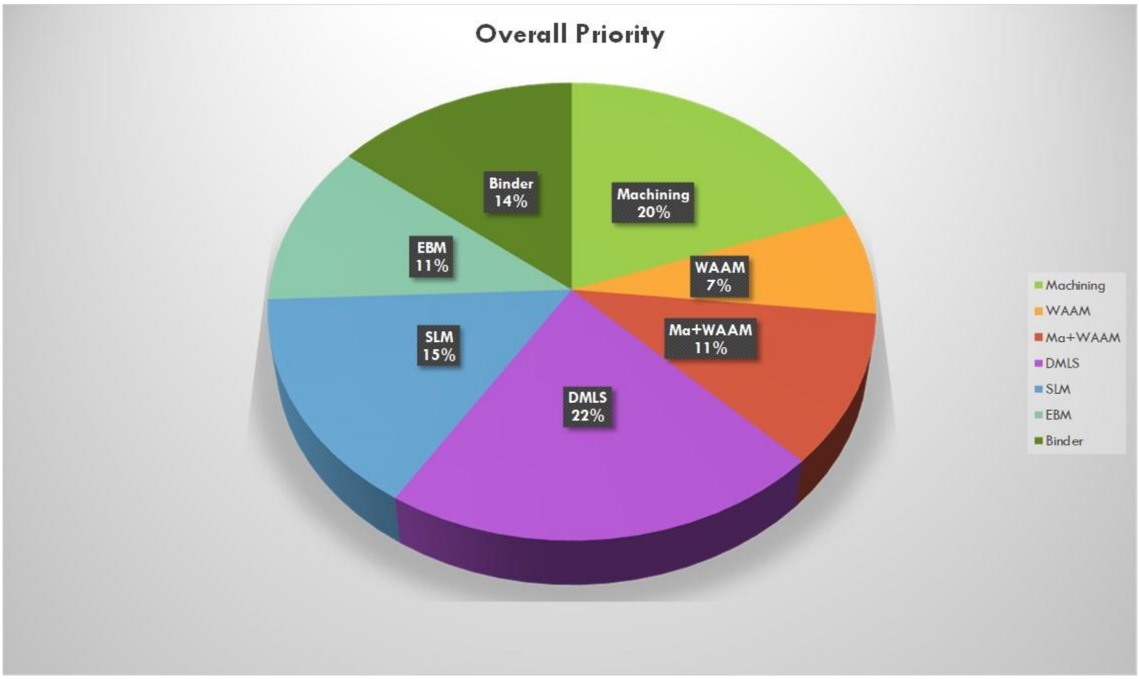


Figure 70. Overall Priority

As it is represented the in Fig.70 the DMLS method was the selected technology to manufacture the Piston. DMLS is the fastest AM compared to other technologies that have been considered for this part[23]. It should be noted that Machining is a secondary option for this part and could be the first option depends on how one defines the importance of the criteria of a part.

3.6 Topology Optimization

3.6.1 Introduction

Topology Optimization has been widely used for different linear structure [32] [33]to minimize the objective function by obtaining material distribution. Therefore, the design domain will be divided into finite elements to achieve the primary purpose.[32]

Topology Optimization is the most effective way of reducing the weight of a structure [34].AM with its unique ability made it possible to manufacture component with a freeform solid shape. Therefore, it can benefit from the result of the topology optimization of parts.

As it was described in the functional surfaces part, just two parts of the engine will be used in topology optimization simulation. Since it has been decided to consolidate the Base plate and Frame, it would be an excellent exercise to get the initial idea of how topology optimisation works and how the result can be used for the redesign phase.

The first step for simulation is to define the parameters which impact the functionality of the parts, such as fixtures, supports, pressure, torque and contact sides of the parts. All the topology optimization was done by ANSYS AIM 19.

As the parameters are presented in the table.22, the pressures for boundary condition are defined based on the mass of the parts assembled on the bores. It should be noted that there is no option to define the exact size of the mesh in Ansys AIM 19; therefore the selection was limited to the grading from Low to High.

Table 23. Topology Optimization initial parameters

	Parts	
	Frame	Base
Boundary conditions	Fixed support: Bottom face Axle Bore: Pressure, 37500 Pa Adjustment Pin: 17000 Pa Intake, exhaust holes: 1600 Pa	Fixed support: 4 screw holes Pressure on top face of base: 1.5E+ 07 Pa
Contact Faces	Front and Rear Shown in Fig.71	Top face Shown in Fig.72
Material	Steel: Density: 7850 Kg m'-3 Tensile yield strength, S_{yt}: 2,5E+08 Pa Young's mosulus, E: 2E+11 Pa Poisson's Ratio, v: 0,3 Bulk modulus, K: 1,6667E+11 Pa Shear modulus, G: 7,6923E+10 Pa	Steel: *Same Mechanical properties as Frame*
Mesh	Mesh Resolution: 7th degree High Size function method: adaptive Growth rate: 1.2 Adaptive resolution: 2 Collision avoidance: stair stepping Shape adjustment: 0,24 aggressive	Resolution: 8th Degree High Growth rate: 1.1 Adaptive resolution:2 Collision avoidance: stair stepping Shape adjustment: 0,24 aggressive
Threshold	Density threshold: 0,125 Maximum Removal: 50%	Density threshold: 0,125 Maximum Removal: 50%

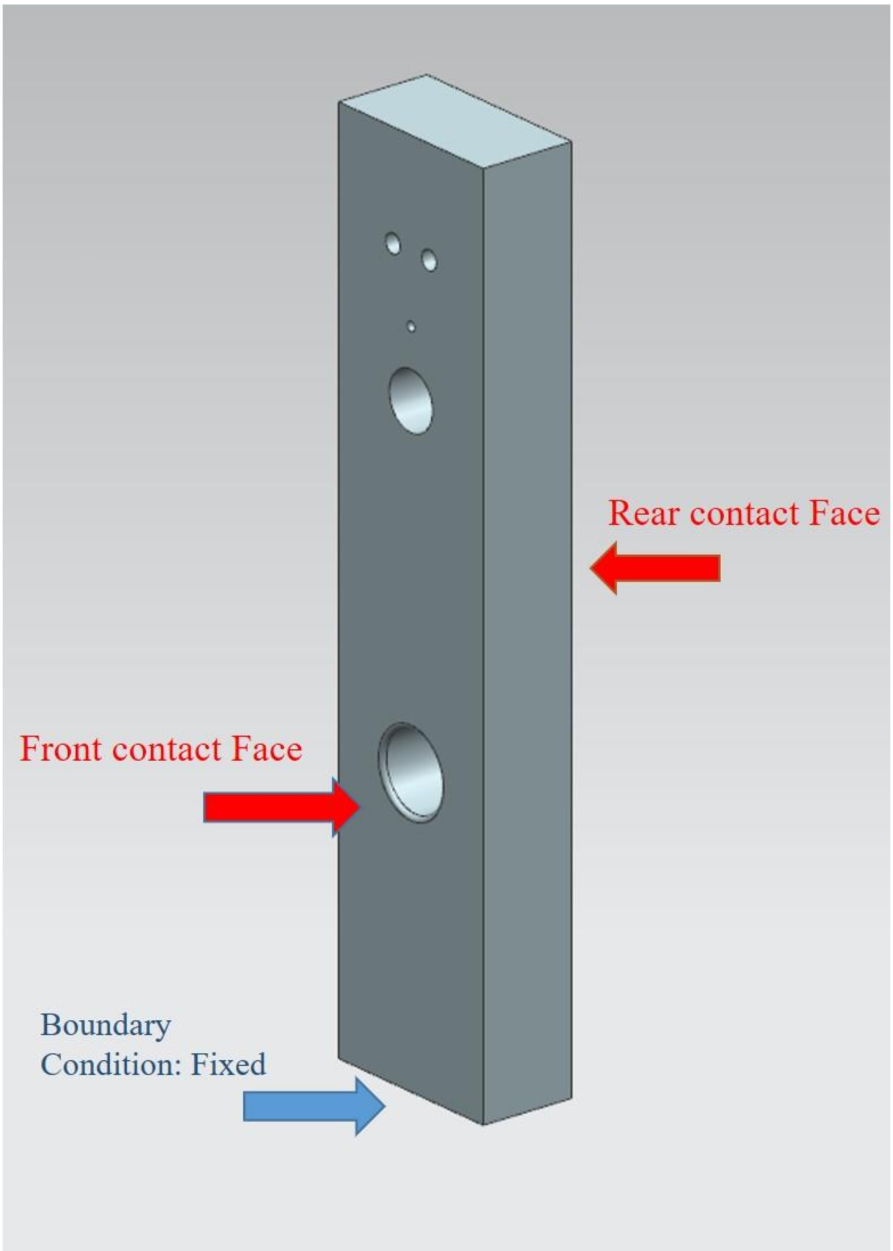


Figure 71. Frame Boundary Condition

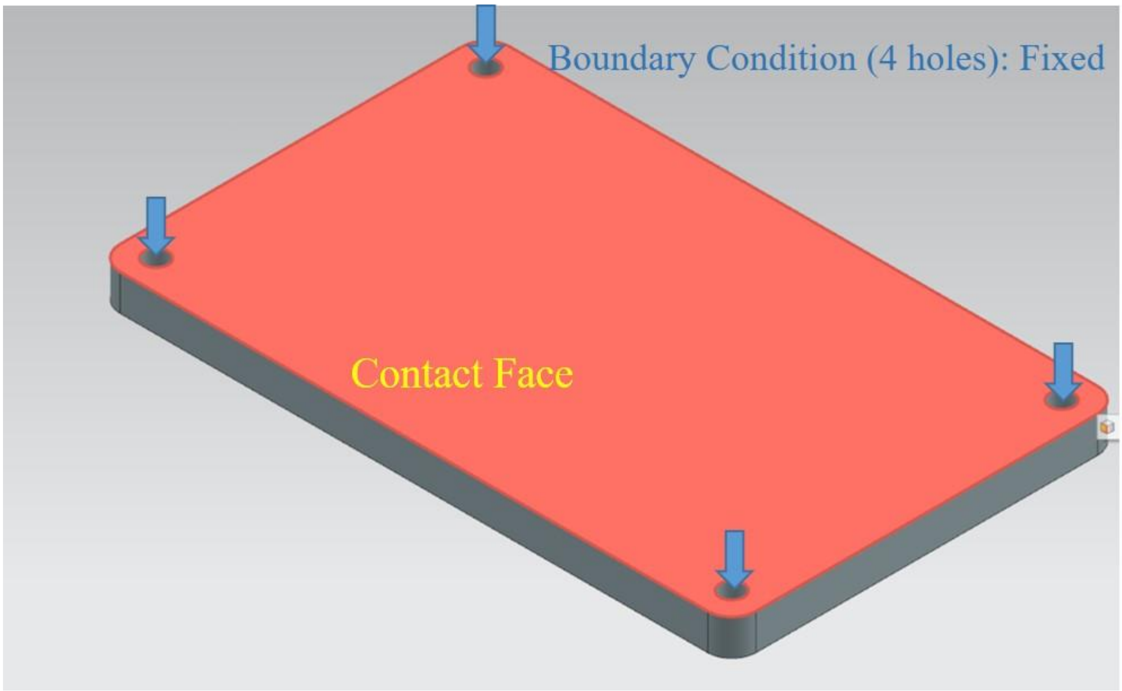


Figure 72. Base Boundary Condition

Table 24.Topology Optimization output parameters

	Parts	
	Frame	Base
Mass	Original Mass: 0,13333 kg Reduced Mass: 0,092773 kg Mass after Topology Optimization: 0,040555 kg	Original Mass: 0,32151 kg Reduced Mass: 0,2338 kg Final Mass after Topology Optimization: 0,087707 kg
Area	Original volume: 1,6984E-05 m^3 Volume after Topology Optimization: 5,1663E-06 m^3	Original volume: 4,0956E-05 m^3 Volume after Topology Optimization: 1,1173E-05 m^3

3.6.2 Topology Optimization result

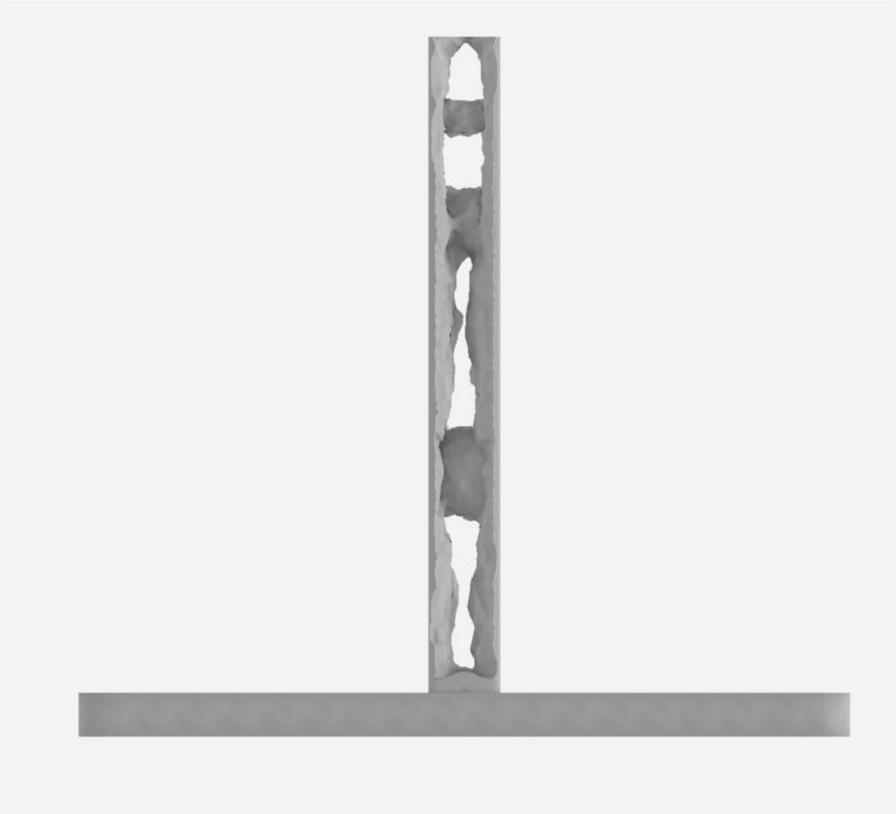


Figure 73. Optimized Base + Frame

As it presented in the Fig.73 the middle part of the frame was partly removed. Due to the constraint parameters defined for the axle bore, intake and cylinder pin bores have shells around them. Although, the simulation was done by different parameters to check significant differences in optimized shape, similar result obtained by the simulation. The main difference was the diameter of the bores which have been considered in the redesign step.

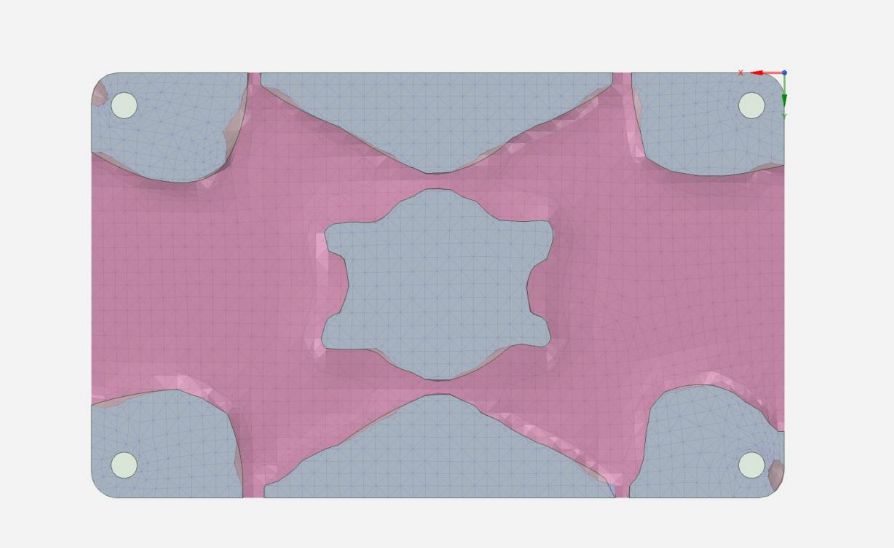


Figure 74. Optimized Base (bottom view)

As it is shown in the Fig.74 the middle part of the base which frame is located on it and corners has not been removed. It shows that material is needed for the fixture and boundary constraint.

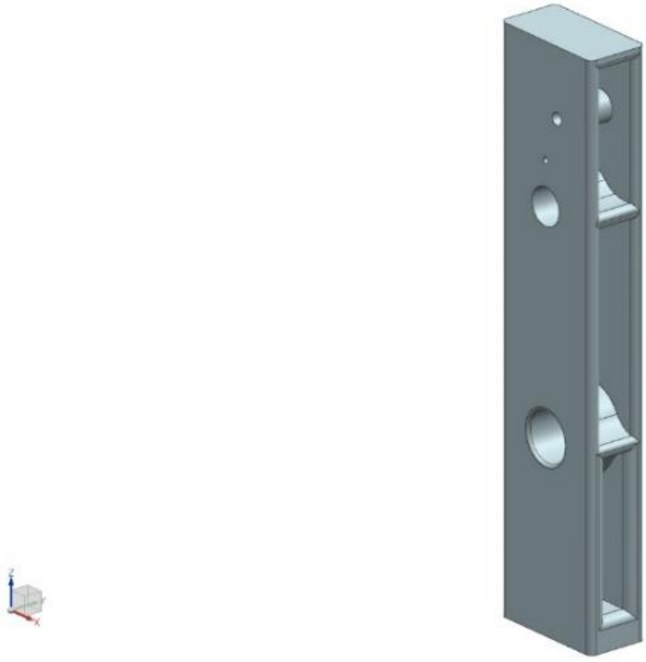


Figure 75. Redesigned Frame after Topology Optimization (Trimetric View)

After topology optimization result, all the manufacturing criteria and printing limitation have been considered for redesign the part. In the final iteration, just the main part has been redesigned. It means that the supports will be designed by the AM software based on the selected AM method to manufacture the parts. It should be noted that AM commercial software has different methods for designing the support; therefore, the final design might change due to the software requirements.

The decision on how manufacture the Base + Frame was to print it vertically with binder jetting, Since the Base will act as a support for the frame and manufacture it horizontally makes it by far more complicated and requires several supports for the frames' front and back face.

Based on the topology optimization results, the part should be hollow in areas where there is no pressure, such as areas between the bottom of the frame and axle bore (area A and B, Fig.76) The primary reason why the circular shape of the bore was changed and continued to the sides, were the support structure. During the manufacturing process, supports are needed for the axle bore shell, and reaching the complete circular shape might be challenging. In addition, to lessen the difficulties of shaping a fine circle, and to make sure that there is enough space for the support structure. For the same reason, the bore shell for adjustment-pin bore were continued to the sides. Here, the base for the support structure would be on top of the axle-bore shell.

The bores' diameters were chosen the same as the results however a few changes were made to manufacture the part. The axle and cylinder's pin bore were extended to the edges of the frame, this has been done because later in the support generation step, there will be vacant areas for supports.

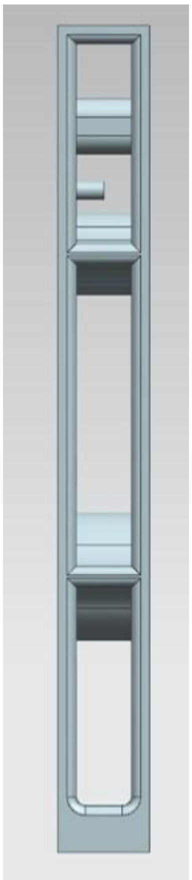


Figure 76.Redesigned Frame after Topology Optimization (Side View)

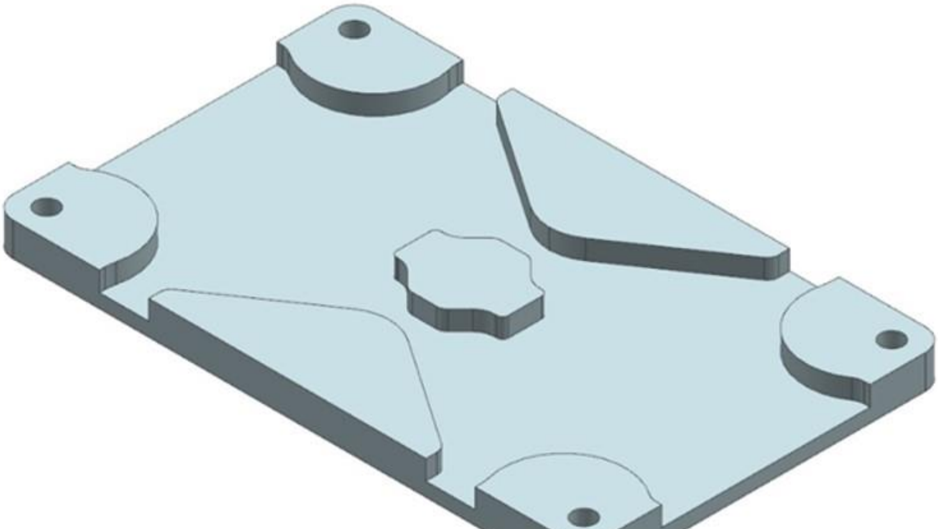


Figure 77.Redesigned Base after Topology Optimization

The rear shape of the base was redesign and formed based on the topology optimization. As it can bee seen in the Fig.77 that the middles parts and corners designed with minor changes to the dimention.

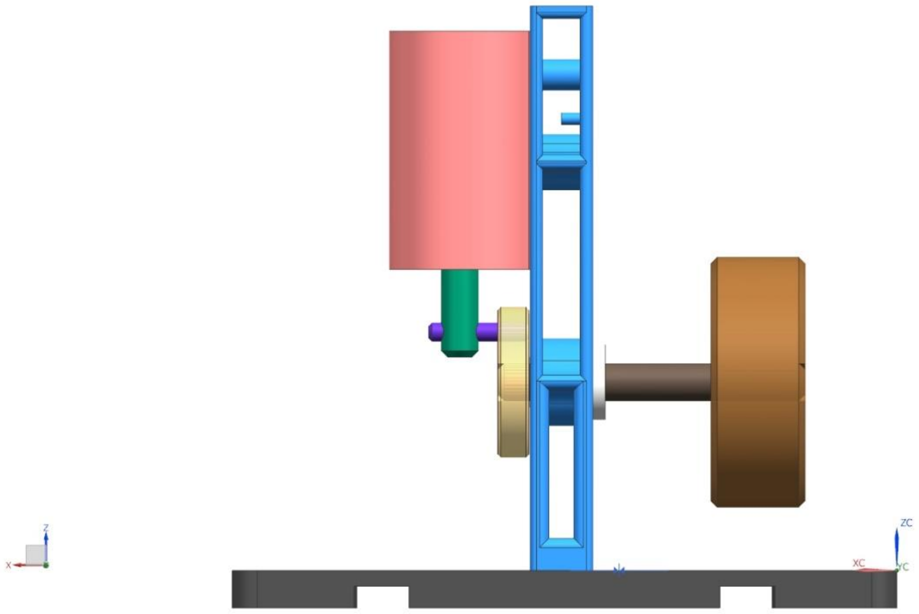


Figure 78. Engine side view

4. PEDAGOGY

4.1 Planning a Course

The start points of planning a course is definition of the learning outcomes for the students. The relatives of the course with other courses and excising knowledge of the students should be taken into consideration. To achieve high-quality learning, the learning outcomes, teaching style and evaluation method should be accompanying each other. The level of understanding needed from the students should be the based on planned outcome. To observe how well the outcome have been accomplished, the assessment should be aligned with teaching. Teaching is often seen as a mechanical transfer of knowledge; thus, teaching is not often aligned. [35] [36][37]

Further to course planning, the emphasis of used teaching and working methods are determined based on the number of hours set in the curriculum. Considering learning is obtained over the student's independent thought, reserving time for independent studying is essential.[37][38]

4.2 Teaching Style

The style of teaching has strong effect on quality of learning and student's motivation. Teaching style is the way of the teacher states himself/herself during the time of teaching while the techniques used by the teacher are called teaching methods. Teaching style should not be ignored while assessing the teaching methods. Teachers have different attitude and it will affect the teaching. [39][40]

In the studies focused on university teaching, the main aims are to establish the conceptual understanding of the students and transfer the knowledge to them. The emphasis on the first aim is students and their development, while used strategies is under the observation.[41]

Table.25 represent two different teaching approaches: content-based and learning-based. Learning is considered as quantitative growth of knowledge in content-based teaching approach. The teacher controls the flow of knowledge being taught to students. The content-based is also called teacher-focused.[42]

On the other hand, the learning-based teaching approach primary focus is to promote the students' learning. It involves the notion of learning as the transformation and progress of the student's know-how.

Table 25. Learning-Based vs Content-based teaching approaches[37]

LEARNING-BASED	**CONTENT-BASED**
1 TEACHING PROCESS	
1.1 Planning teaching • Student needs, earlier knowledge and expectations form the premises of planning. • Students are asked to participate in planning, where possible. • Plans are not too detailed. 1.2 Teaching practices • Knowledge is built in co-operation with the students. • Teaching focuses on broad comprehensive subjects. • The teacher understands that students have various ways of learning. • Stimulating teaching methods are used to enable learning. 1.3 Assessment practices • The depth of the students' understanding is examined through assessment. • Versatile assessment methods are utilized for assessment	1.1 Planning teaching • The teacher's own points of interest form the basis of planning. • The teacher creates a detailed schedule with • no room for flexibility. The teacher also plans the course content independently. 1.2 Teaching practices • Teaching follows the plan strictly. • The teacher transmits the information to the students. • Teaching is largely focused on facts and details. • The teacher chooses a teaching method that he/she is the most comfortable with. 1.3 Assessment practices • Utilizes traditional assessment methods that are familiar to the teacher
2 LEARNING ENVOIRONMENT	
2.1 The role of the teacher • Students are encouraged to be critical and active. • The relationship between the teacher and the students • is equal and informal. Both parties are expected to learn. • The teacher has a positive attitude towards teaching. 2.2 The role of the student • Students are seen as individuals and active participants, who are able to process information and solve problems independently. • Students bear the responsibility for their learning. 2.3 Interaction • Knowledge is built co-operatively.	2.1 The role of the teacher • The relationship between the teacher and the students is more distant. • Students learn from the teacher. The teacher is an expert, who points to the factual content that needs to be learned. • The teacher does not often feel that the teaching is meaningful. 2.2 The role of the student • Students are thought of as listeners and receivers of information. • The individuality of students is not taken into consideration. • The teacher is responsible for the students' learning. 2.3 Interaction

• The interaction between the teacher and the students and between various students is thought to improve the learning results. • Interactive elements are used to enable learning despite the group size. 2.4 Atmosphere • A pleasant and safe atmosphere supports learning. • The atmosphere is created together with the students	• Interaction is not thought to promote learning. • The teacher lacks the tools or is afraid to use interactive teaching methods. • Interaction is not favored in larger groups. 2.4 Atmosphere • The teacher tries to create a good atmosphere through good teaching or humor.
3 Conceptions and learning	
• Learning involves realizing, applying, developing ideas, critical thinking and deep understanding. Learning is a process, during which the students construct their own notions about the phenomenon	• Learning involves remembering or memorizing correct answers and solutions. • The correct answers can be found by reading the course literature
4 Pedagogical development	
4.1 Developing the teaching • The teacher is motivated to develop himself/herself as a teacher. • The development of the teaching improves the learning outcomes of the students. 4.2 Pedagogical understanding • The teacher understands his/her pedagogical skills and has processed his/her teaching	4.1 Developing the teaching • To a large extent, the teacher is not interested in developing his/her teaching. • The motivation comes in the form of a better status or pay. 4.2 Pedagogical understanding • The teacher does not assess his/her teaching practices and is not conscious of his/her skills as a teach

4.3 Workload

Used teaching and assessing methods, teaching experiences and familiarity with the used methods are factors that affect the workload from the teacher's perspective. On the student's perspective, factors such as skills, prior knowledge, motivation, time they reserve for studying and quality of teaching are influential. [43]

Based on different research [43]it is suggested to assign more time of workload on independent learning. One reason behind it is that students feel more stressed of repetition of knowledge by heavy focus on contact teaching. Moreover, students are more likely to focus on memorizing if the large amount of teaching is contact-based.[37]

4.4 Working Methods

To achieve a higher quality of learning actions such as working methods are required. Various working methods chosen by teachers have both qualitative and quantitative effect on the students' studies. It is recommended to choose several methods in a single course hence the students from different perspectives comprehend a deep approach to learning.[37][44]

Learning outcomes and what the students are supposed to learn define the selections of the working methods.[45] Accomplishing different type of outcomes entails a diverse level of information processing. Teaching and studying should be organized in a way that students process information actively[46].

Five methods of working are summarized to use them in the course:

4.4.1 Independent studies

The primary objective of the independent studying is to make them act independently, to achieve the objective of the course by doing preliminary work, exercises, assignments given during contact teaching.[43]

Adequate guidance is always necessary even in the independent studying, because appropriate supervision guarantee that students understand the goal of their studying and what is expected from them.[37]

The teacher only supports the students and main responsibility is on students. Teacher support consist of:

- Advice on the materials
- Motivate students
- Help students through discussion groups or peer reading
- Instruction on how to:
    I. Write an essay
    II. Solve the questions
    III. Pick the most important part of the text

Workload

Based on the comparison in[47], independent studying has less workload than content teaching. The key influential factor is flexibility of the independent studying since students have freedom to choose their own schedule.[37]

Teacher's workload is related to these subjects:

- planning and implementation of guidance
- assessment of the outcomes

Strengths and challenges

The independent learning is flexible for students for assigning time of learning and place of studying therefore they learn responsibility. This method entails analyzing the learned information by students which will lead to learning well.[37]

Although not having certain time assigned for the independent learning might be challenging for the students, good instructions and different millstone can support students to handle this issue. One shortcoming of this type of studying is, getting enough support and guidance by teacher during the assignments. It is important that students understand the importance of the assignment they are given and learning on their own.[37]

4.4.2 Contact teaching

All sort of situation where a teacher is present and mentors the students consider as contact teaching. It can be lecture, exercises or guided laboratory assignment. Additional independent studying should be added to support the actual learning process.[43]

Workload

Contact teaching as a conventional lecture has less burden on students since it only contains of actual contact teaching and studying information presented in the lectures. However, planning for the teaching takes much more time of the teacher. After planning, preparation for the lecture, lecture or other teaching situation itself and recovering after these situations should be considered.[37]

Strengths and challenges

One pros of this style of teaching is the possibility of directing the student's attention by emphasizing on the most important part of the course. Since teacher is directing the process of learning his/her enthusiast about the subject can be advantageous. [37]

Since student's have different education experiences and heterogeneous life, the level of knowledge is not similar. Student's level can be found out by pretest by teacher. Small amount of interaction in conventional contact teaching is its major flaw. Thus, it is important to keep the students focused and interested during the interaction. Also support the interaction with different discussions and analyzing those discussions.[37]

In addition, students should process, analyze, familiarize and implement the information themselves to have a deep learning.[37]

4.4.3 Group Work

Work done in a group without teacher assistance to obtain the group goals is considered as group work. Based on studies it has been shown that it is an efficient studying an assist active role for the students.[37][45]

Planning includes:

- Setting the goals, schedules, working methods and material
- Guidance: "reporting, guidance situations and methods, communication, operation in problem situations"[37]
- Assessment

Workload

Workload in group work consist of actual work in the groups and independent work for the group such as meetings, individual contribution to the assignment. Based on[43] research, since mutual understanding between group members takes time, students feel more taxed than doing the assignment on their own.[37]

Strength and challenges

The idea of performing the assignment by all members and dependency on each other is one of the group work strength.[48]

Sharing ideas and communication are led by interaction between the group members, thus the group’s efficiency is dependent on it.[45]

Group work may escalate learning and performance of each members of the group due to synergy among group members.[37]

One of the challenges is free riding in group work, which means some members are not willing to work actively to gain the objectives of the group. Consequently, the workload will be divided unequally among other members.[37]

In addition, forming a group and assigning rules of each members might be challenging for the students.[45]

4.4.4 Workplace Studying

Training and spending time at the workplace that is associated to the student’s educations is called workplace studying. Students have the chance to exercise their knowledge and other skills in real work environment.[43]

Workload

Although the workplace studying might be stressful for the students at the beginning, it is usually practical and useful for them. Thus, the students may feel less taxed. The teacher workload in this method is quite small, which can be consider as one of its advantageous.[37]

Strength and challenges

The key benefit of workplace studying is the possibility of applying the knowledge and theories that students have learned during the previous courses. Environment of workplace inspire the students to commit to studying. Moreover, it helps them to gain professional skills and development of their professional identity.[37]

Support and intensive guidance at this level is helpful for students to cope with the new and sometimes strange situation. On the other hand, it is expected from the students to be ready to take responsibility and perform according to expectations.[37]

4.4.5 Personal Guidance

Private communication between the student and teacher is called personal guidance. The teacher's aim is to promote the student's study and knowledge.[37]

Workload

The student's workload consists of training for the guidance situation, the actual guidance situation itself and actions needed after that.[37]

Strengths and challenges

With personal guidance, teacher can respond to student's problems one the studying skills level and giving them verbal feedback. Added to that teacher can act as an important motivator for the student if the co-operation between them works well.[37]

If the course is, poorly resourced, personal guidance might be challenging for the teacher's point of view. In addition, personal chemistry and trust between students and teacher are effective to achieve the goal of studying.[37]

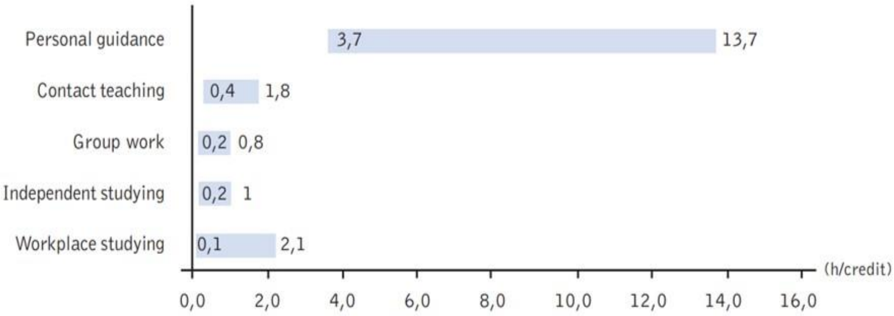
4.4.6 Summary of working methods

To achieve certain learning outcomes, it is recommended to select the working method based on the set goals[49]. Clear and reasonable objectives of learning support the students' commitment. Regular and continuous studying can be supported by guidance to reach those goals.[37]

Contact teaching is usually validated as high cost among teaching methods. Nevertheless, other working methods can be chosen which students are more active and lead to higher quality of learning.[37]

Table.26 depicts an example of summary of workload for different working methods.

Table 26.Teachers' workloads for the various working methods (h/credit)



4.5 TEACHING METHODS

The way of performing teaching is represented by teaching methods.[50] In this section several teaching methods which are most suitable for the course will be presented. Teaching methods should be chosen after the initial set of goals for learning outcomes. Based on each learning outcome, the most appropriate teaching method can be chosen.[37]

Success and failure of the course does not depend on teaching method itself, other factors such as study environment and choosing suitable method for outcome have great influence on it.[37]

4.5.1 Independent work (Easy)

Students independently working on their assignment which may consist of reading, calculation, etc. The time of the assignment might vary from minutes to hours.[37]

Strength and challenges

The breaks in the teaching by independent work is of od its strength, students have time to do their assignment based on their knowledge and ideas. In addition, it makes them to be active while others are doing their assignments in silence.[37]

Exercises (Average)

Exercises can be in form of independent work or in group to do a practical task. One model proposed by [51] is TARTAR (T= Theory, A=Action and R=Reflection). Students using different sort of material such as lectures or models (Theory) to think how they can implement their knowledge on the exercise (Action). Then analyzing of what have been learned after the exercises (Reflection) and what new subjects have been learned during the exercise (Theory).[37]

Giving the students freedom and time during the action phase helps them to develop their knowledge.

Strengths and challenges

The key advantages of exercise as a method of teaching is that it deepens the learning process by connecting theoretical information with action. On the other hand, creating the exercise instruction made by teacher might be challenging. Hence, the instruction should be well directed so the students understand what they have been asked.[37]

4.5.2 Supplementary reading (Very easy)

In this method extra material related to the subjects of the course is given to students. By doing so students have the possibility to deepen their knowledge individually.[37]

Strength and challenges

One benefit of supplementary reading is the possibility of making the students interested in and give them a wider perspective in the subject at hand. It should be noted that choosing the proper material is significantly important to achieve the objectives.[37]

4.5.3 Learning diary (Demanding)

learning diary is a method which students can write about their experiences during the course events such as lectures, exercises and assessment of their own activities. Teacher may find helpful notes on diaries for example which parts where hard for students to understand.[37]

Strength and challenges

Deep approach will be achieved by analyzing the taught subject to students. They will go through what they have learned and the gaps in their knowledge that should be filled. Added to that, teacher will be aware of student’s opinion about the course, so they can develop it.[37]

One challenge in this method is to keep the students motivated to write the diaries during the course not only at the end of it. Students may also feel the diary is pointless so good instruction at the beginning and proper guidance in between is necessary to achieve the objective of the task.[37]

4.5.4 Group work

Small groups are created to achieve the common goal based on the given assignment and a schedule. Teacher is mainly responsible for preparation the assignment and observation the progress among the groups and assessment of the result.[37]

Strength and challenges

Different skills can be acquired by group work such as group work skills, learning from others and how to explain and present their opinions. It will also help students to adapt a deep approach learning since they solve problems in a group.[37]

As any other group task, appropriate guidance and support from the instructor whom is teacher here is needed to promote the operation.[37]

4.5.5 Presentations (lecturing) (Easy)

The most common method in presentation by the teacher. The teacher prepares a presentation related to the subject of studies and teach the information while students are passively catching it. Teacher can activate the students by his/her style of lecturing and encourage their participation. Students either learn the subjects independently or in co-operation with others.[37]

Strength and challenges

One benefit of this method of teaching is that, the freedom for teachers to organize the information based on his/her whishes regarding the target group. Since It can be planned accurately beforehand it is economic and quick way of passing the information to the students.[37]

The emphasis on the teacher's role in this method can be challenging. Students can often make the students passive listener .Also, there is no guarantee that students will learn the lectures organized for them.[52]

Because students might forget the information provided in the lecture, teacher should guide them using note-taking techniques.[37]

4.5.6 Pretest (Very Easy)

This method supports the orientation of the students and happens before the actual course. Pretest can be utilized to get student's background information, motives, areas of interest and other basis data for planning a course. It helps the teacher to link the existing knowledge and what has been gained during the course.[37]

Strengths and challenges

One of the strength of this method is students are forced to learn basic information of the actual course. It also makes it possible for the teacher to adjust the content of the course based on the knowledge of the target group.[37]

Usage of the gathered information is hard, and it should not be over-emphasized since there is not much time to change the implementation of the course.[37]

4.5.7 Problem-based learning (PBL) (Demanding)

In this method, the problem is the basis of the learning. It aims to teach students the working life problems, challenge them by working together, and attain learning. PBL objectives are developing student's problem solving and communication skills.[52]

Strengths and challenges

Since problems do not have straight answers and there is no ready-made questions for them, students are responsible to search for the information then analyses it by themselves. It will lead them to the world of open knowledge and make them familiar with the real-life problem-solving situations.

Assessment of the learning outcome and following the process might be challenging in PBL. Thus, certain attitude is needed from both the students and teacher to reach the goal of the learning.

4.5.8 Case teaching (Demanding)

Students in groups or independently are given a case that they have to make assumptions based on it. The case can be in form of models, application, questions, etc.[45]

Strengths and challenges

One of the strength of this method is testing of previously leaned subjects. In addition, students will learn application of the knowledge and practical problem solving.[45]

The primary requirement to achieve the best outcomes of case teaching are cautious preparation and skilled teacher.

4.5.9 Project work (Demanding)

Relating the theoretical knowledge and real-world actions as a form of teaching is project work. Students in forms of individuals or groups are given projects or they have the freedom to choose their own. Possible roles can be chosen among them to achieve the objective of the learning.[37]

Strengths and challenges

The connection between information and actual operation is one of the strength of this method. Students can experience each step of the process from the planning to implementation and reporting.[40]

The success of this method relies on the teacher guidance and his/her monitoring during the teaching period.[40]

4.5.10 Learning by doing (Demanding)

In this method, students learn by practicing the subjects. It includes laboratory, workshops, workplace training or fixed exercise. The objective of this method is to make the experimental work familiar for the students.[37]

Strengths and challenges

The strength of this method is that it provides neutral studying environment and direct action and process the learning by practical activities.[40]

Since the complex environment of the operation might overwhelm the students, orientation and guidance are needed.in addition, careful consideration is necessary regarding scheduling the teaching session.[40]

4.5.11 Web-based learning (Average)

E-learning utilizes information and communication technologies supporting teaching and studying on the internet.[53] Web-based learning environment may contain all the necessary application of teaching such as instructions, assignments, etc.[38]

Strengths and challenges

The main benefit of this method is its flexibility regarding of time and place.

4.6 Course Planning

4.6.1 Course Description

In this course, students will learn the significance of additive manufacturing (3D printing) and its prominent role in future product development and innovation. Students will gain a wide range of knowledge of additive manufacturing technologies, devices, materials and applications. They will go through the product design with a project (thesis case study), experience the possibilities and limitations of Design for Additive Manufacturing. Also, they get familiar with process chain, post-processing and software issues of AM. Students will gain hands-on experience of operations and fundamental safety principle organized by TUTLab and MEI training workshop.

4.6.2 Who is this course for?

This course is meant for mechanical students whom willing to learn more about additive manufacturing and 3D printing technologies. It is tailored for who seek to understand technical aspects behind the AM technologies. The course addresses the full spectrum of Additive manufacturing technologies with a project focused on metals used in AM.

4.6.3 Learning Outcomes:

- Recognize the benefit of using Additive manufacturing
- Acquire the necessary vocabulary of additive manufacturing equipment, materials and applications.
- Learn the wide-ranging knowledge of the AM processes, devices, capabilities and material used in AM
- Learn the process chain in Additive manufacturing
- Apprehend the terminology of additive manufacturing technologies
- Understand the operatiing principles for each Additive manufacturing technology
- Identify the use of additive manufacturing in product lifecycle
- Acquire the necessary skill for manufacturing product
- Develop a cutting-edge perspective on Design for Additive manufacturing
- Acquire the future market, business opportunities and economics of additive manifesting

- Learn the underlying physical principles of each additive manufacturing technology
- Understand rang of software tools for AM
- Opportunity to design, engineer and fabricate an actual multi-component object using AM (Case study)
- Understand the impact of AM in mass customization
- Gain hands-on experience in manufacturing operation with WAAM robot
- Understand basic principle of safety
- Acquire the general understanding of the post-processing techniques used in AM[54]

4.7 Week Implementation

4.7.1 Week 1

Table 27. Week 1 implementation

Topic	Introduction and Course implementation
Learning Outcome	- Course General Information, Passing requirement - Project description (Cast study and Presentation) - Learning Diary explanation - Goals of the course
Content	- Lecture Note - Recorded video of the lecture - Self-paced additional notes (Prerequisites)
Mode of Study	- Contact Teaching: 1.5 h - Independent work: 4 h - Pretest: 0.5 h
Duration	- 6 h

Supplementary material for Prerequisites:

- Manufacturing principles
- General GD&T

Pretest

- Students' general background and interest

Learning Diary (Through the entire course)

- Estimated time: (10 h)

Description:

The primary goal of this session is to make students familiar with the general course objectives. The supplementary material will be provided for those who are not entirely familiar with the prerequisites of the course.

In this session, no technical knowledge will pass on to the students. Since the most economical method to communicate with students is lecturing, this method has been chosen for the first week of course. Since most facilities provide recording applications for lecture rooms, the author decided to record all the course sessions. By doing so, those students who are not able to physically attend the sessions will have access to the content of the course.

The independent work depends on the students' background. The minimum time to learn the basics of the topic have been considered for four hours, which might differ for each student.

A pretest exercise is defined to get a general overview of students participating in the course. By collecting the general background of the students, the students’ experiences through Learning Diary and result of the project work, teacher/teachers can perceive the overall success of the course and if the outcomes have been achieved during the course.[55][37]

4.7.2 Week 2

Table 28.Week 2 implementation

Topic	AM Definition and basic principles
Learning Outcome	- What is additive manufacturing? - Additive manufacturing term (Fabrication, Layer based) - Distinction between AM and CNC Machining - Historical Developments - Application - Business and Commerce -Social and global Trend
Content	- Lecture Note - Recorded video of the lecture - Self-paced additional notes
Mode of Study	- Contact Teaching: 1.5 h - Independent work: 1 h - Literature Review: 3 h - Supplementary reading
Duration	- 5.5 h

Literature review over the AM application:

Since there are plenty of opportunities for Additive technologies in the market, it has been decided that students look up for those and write a summary in a form Literature Review. Therefore, they will learn what is the need in the market and explore the interesting are of research themselves.

Project work:

To accomplish the primary outcomes of the course, students will be given project work, which the primary form of the material will be extracted from the case study of this thesis. Students will be asked to go through all the steps of the design. Based on the steps of the project, supplementary material will be given to them to support the learning objective. However, the purpose is that students figure out the critical objective of the case study by

Problem-based learning (PBL) method. Although it might be challenging for students in the early stage of the project, they will have proper support from teachers. The main reasons for choosing this method additionally with other methods is to lessen the burden of the teachers also to activate the students and get them more involved in the learning process.[56]

At the end of the course, students should present the conventional design process, Design for Additive Manufacturing, Process Selection and justification of each phase. Since not all the Additive technologies available in universities, printing the final design is not required.

Description:

Presentation (Lecturing) was chosen for this session to summarize all the necessary information related to the subject. The lecture is just a guideline to describe the fundamental principles; hence students can follow with supplementary material provided for them. For instance, an explanation of Additive manufacturing in medical and construction fields is time-consuming, and not all the target students would be interested in those fields.

Evaluation:

The work that students will return at this session is the Literature Review, and the assessment will be based on how much they covered the AM applications. They must include all the major applications in the market with a short description of the material and type of AM machines. Also, students should mention the opportunities for AM in the industry and research perspective in the future.

4.7.3 Week 3

Table 29.Week 3 implementation

Topic	AM Technologies (Seminar)
Learning Outcome	- Difference between Additive Manufacturing processes - Terminology of AM processes - Type of machines in AM - Material used for each process -Application of each process
Content	- Text Book - Articles
Mode of Study	- Seminar: 1.5 h - Group Work 4 h
Duration	- 5.5 h

Description:

Students in the form of groups will provide a seminar for one AM method selected for them and should be presented for other students. As a result, students have to analyse the subject and figure out the most critical processes of the AM process. Instead of handing them over the ready-made material, students learn based on whatever is more suitable for them. After each presentation by one group, other students should write a short review and describe what went well and what could be better in the presentation.

For those groups who cannot participate in the class, there is a possibility to provide a video of their presentation. In this case, other groups have access to watch and peer review on it

Evaluation:

The evaluation criteria are:

- The content of the Seminar, all aspect of the technology should be included.
- The Presentation excellence and how successful they were to deliver the knowledge
- Creativity will be a plus

4.7.4 Week 4

Table 30.Week 4 implementation

Topic	AM Process Chain and Process selection
Learning Outcome	- Process Chain: • Introduction • Steps of Additive manufacturing (CAD, Conversion to STL, transfer to machine …) • File Format • Software issues for additive manufacturing • STL file manipulation and problems with STL files • Variation of steps in different AM processes • Monitoring of Process Quality • In-Process Part Quality Monitoring • Inspection • Maintenance and Equipment - Process Selection: • Guideline for Process Selection • Decision theory • Approaches to Selection • Challenges of Selection • Production planning and control
Content	- Exercise - Self-paced additional notes
Mode of Study	- Exercise: 1.5 h
Duration	- 1.5 h

Description:

The session should be held in Exercise format because students are asked to practice the subjects are thought to them. Students will be given a comprehensive assignment in the class and teachers will help them during the process (Personal guidance).

Evaluation:

During the exercise session, students will be asked to complete one assignment. Students must complete the assignment to pass the exercise.

4.7.5 Week 5

Table 31.Week 5 implementation

Topic	AM Software
Learning Outcome	- Commercial software in the market - Additional software to assist AM
Content	- Exercise - Recorded video of the Exercise - Self-paced additional notes
Mode of Study	- Exercise: 1.5 h - Independent work: 2 h
Duration	- 3.5 h

Description:

Like the previous session, Exercise format was chosen for this week. Students learn Additive manufacturing software, challenges and a basic guideline for the chosen software. Since it is not possible to cover all commercial software in one session, complementary software manual will be provided for students.

4.7.6 Week 6

Table 32.Week 6 implementation

Topic	Design for Additive Manufacturing (PBL)
Learning Outcome	- Design for Additive Manufacturing and Assembly - Material Consideration - Support Structure Design - Design for Lightweight Structures - AM Unique Capabilities - Core DFAM Concepts and Objectives - Exploring Design Freedoms - CAD Tools for AM - Synthesis Methods (optimization)
Content	- Self-paced additional notes - Supplementary Reading
Mode of Study	- Literature Review: 4 h - PBL: 5 h
Duration	- 9 h

Description:

As it was planned at the beginning of the course to get the students more involved in the learning procedure, Problem-based Learning was chosen for DfAM subject. This part of AM is so diverse that cannot be covered in one and half hour. To give the freedom and time to students, they can go through the additional references and learn on their own. Therefore, no contact teaching is needed, and guidance teaching is possible for the next sessions. One of the advantages of the PBL is that there is no limit for students to learn the subject.

4.7.7 Week 7

Table 33.Week 7 implementation

Topic	Post-Processing
Learning Outcome	- Conventional post-processing methods - Post-processing methods in AM - Support Material Removal - Surface Texture Improvements - Accuracy Improvements - Aesthetic Improvements - Non-Thermal Techniques - Thermal Techniques - Standards and Certification
Content	- Self-paced additional notes - Independent work
Mode of Study	- PBL (Independent Work): 6 h - Supplementary Reading
Duration	- 6 h

Description:

Like the Week 6, Problem-based learning was chosen for this week.

4.7.8 Week8

Table 34.Week 8 implementation

Topic	Laboratory tour
Learning Outcome	- Common AM Methods - Personal Protective Equipment - Mechanical Hazards - Thermal Hazard - Postprocessing Safety - Material Handling - Cleanup and Disposal - Understanding Safety Data Sheets
Content	- Workshop - Safety Data Sheet - Self-paced additional notes - Learning by doing
Mode of Study	- Learning by doing: 1.5 h - Independent work: 0.5 h
Duration	- 2 h

Description:

In this session, students will have a thorough tour in TUTLab in TTY facility. Professional engineers will provide the content of the tour in the Lab. The focus of the tour will be on how to use the machines in the facility and safety issues.

Evaluation:

Students will be asked to include a summary of the Lab tour in their Learning Diary. The assessment criteria are the sequence of the event that happened on tour and what they have learned. The author decided to ask the students to mention in their learning diary that what could be better and what is their opinion of making the tour more useful for them.

4.7.9 Week 9

Table 35.Week 9 implementation

Topic	Project Mid-Presentation
Learning Outcome	- Brief presentation (mid presentation) of project work - Difficulties of project - General feedback over the student's project
Content	- Personal Guidance
Mode of Study	- Personal Guidance: 1.5 h - Group work: 2 h
Duration	- 3.5 h

Description:

Students will present their project work in groups and teachers will give them brief feedback on how they can improve their work. The main aim of this session is that students wrap up their project and present it to the other groups. In this stage of the course, there wouldn't be any grading, just supervising them on how to proceed with the rest of the assignment.

4.7.10 Week 10

Table 36.Week 10 implementation

Topic	Workshop
Learning Outcome	- DED AM Methods - Personal Protective Equipment - Basic Principle of the operation - Thermal Hazard - Material Handling - Cleanup and Disposal - Understanding Safety Data Sheets
Content	- Workshop - Safety Data Sheet - Self-paced additional notes
Mode of Study	- Workshop 1 h -Independent work: 1 h
Duration	- 2 h

Description:

To familiarize the students with the heavy lab machinery and safety principle of the facility, it has been decided to have a tour in a workshop. A short introduction will be given to students that what kind of machines are available and how they can run them based on the manuals. Like the previous workshop tour, the focus of the tour will be on how to use the machines in the facility and what should be considered as safety issues.

Evaluation:

Students will be asked to include a short summary of the workshop in their Learning Diary, also couple of questions regarding the safety issues. The assessment criteria are how many questions they have answered right.

4.7.11 Week 11

Table 37.Week 11 implementation

Topic	Project Presentation
Learning Outcome	- Presentation of the project work
Content	- Personal Guidance
Mode of Study	- Personal Guidance: 1.5 - Group Work: 4 h
Duration	- 5.5 h

Description:

In the last session of this course, students should present their project works and justification of their result. Each stage of the design should be elaborated by figures, also role of group members should be mentioned during the project work. The main aim of this session that they learn how to justify their decision.

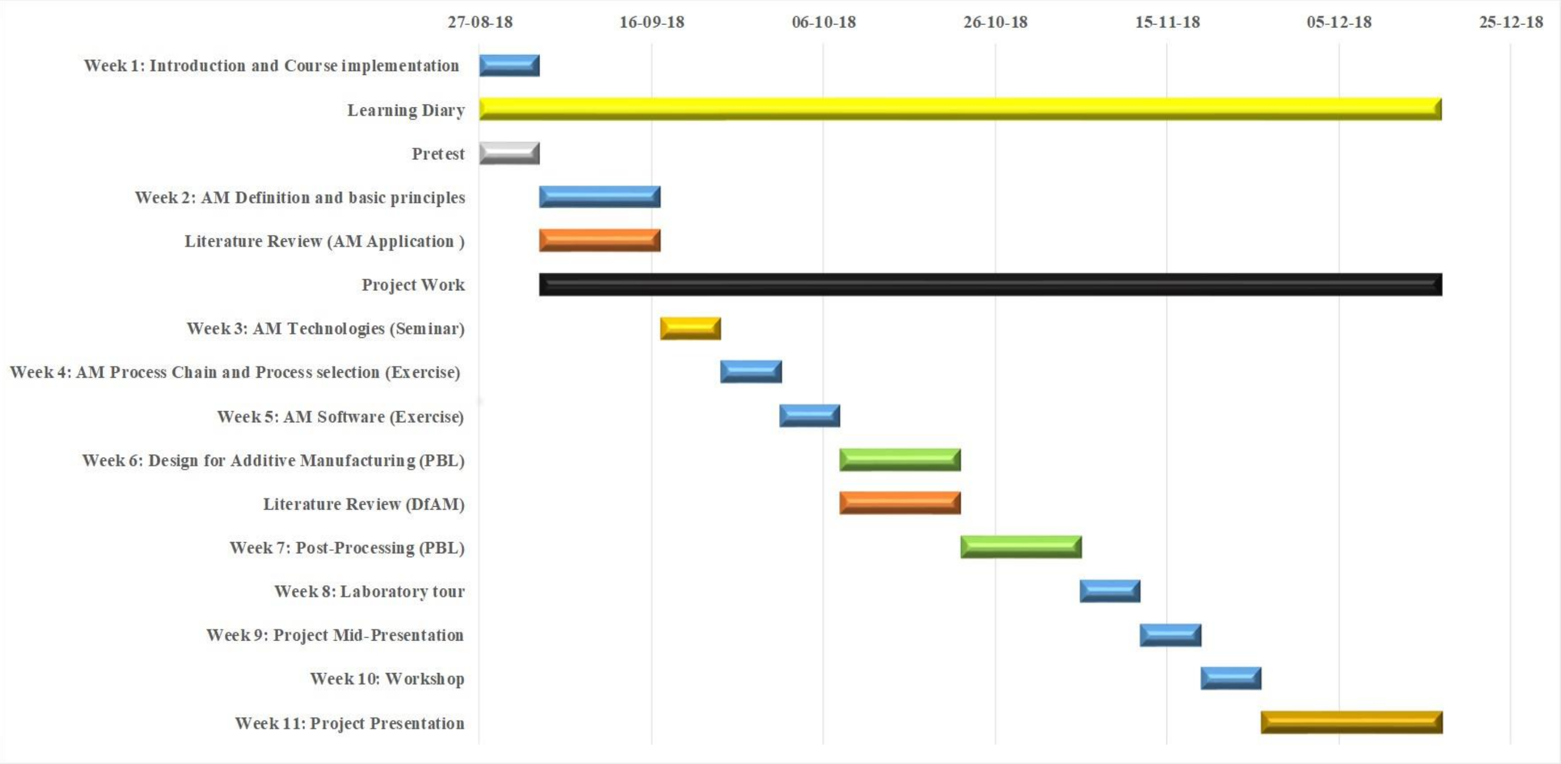


Figure 79. Course Schedule Gantt chart

5. CONCLUSIONS

Overview of the study

The primary goal of the study was to implement a comprehensive additive manufacturing course with hands-on experiences for universities students'. One major focus of this thesis was to use suitable teaching methods to develop student's manufacturing know-how effectively. Additive manufacturing is gaining interest in production; therefore, a new educational program is needed to embrace its great features.

The design process for case study started from the design development stage and continued as iteration for refinement. It should be noted that it was one of the most time-consuming parts of the thesis; therefore, it has been decided to include through content out of this part of the course. Since not all the stages of design development can be covered in the course, supplementary and web-based methods were the solution for the early weeks of the course.

On the next phase, a considerable amount of time has been put on DfAM to get the desired results. Various type of part consolidation and free-form design were considered for oscillation engine's parts. Finally, the selected design options were verified by the thesis supervisor.

In the decision-making phase, Analytic Hierarchy Process (AHP) method was used to choose the best additive manufacturing technologies for selected parts. However, giving importance to each criterion is relative, each of them was evaluated thoroughly to get a realistic result.

In the Pedagogy part, all the methods which can be used in the course were reviewed. It should be noted that a combination of different working and teaching methods were suggested in the course planning section. Utilizing these methods require skilled teachers who can adapt to these methods.

The course planning is a draft of what should be done on each week of the studies for students. In this section, the primary focus is on how the information should be delivered to students. Added to that, supplementary studies play a vital role, since not all the essential content of the course can be covered in the sessions.

Limitation of the work

As for all research and problem-solving projects, the definition of the problem and background research took a significant share of the assigned time compared to other sections. In this thesis, finding a suitable case study which all the desired aspects of the conventional and additive manufacturing design could be included did not proceed as expected. The author expected to add more feature of AM in the case study, but the nature of the case study limited him.

Although, a case study with more parts would have been more comprehensive to cover all aspects of the additive manufacturing specially DfAM section, more time needed for research and design process.

As it was planned at the beginning of the research, course scheduling should entail all the necessary information for a technical course. Since the time of the thesis was limited, the author decided to include essential information the of course planning and leave the precise details for further research.

Having access to software for DfAM and topology optimization was another issue during the thesis. Although all the design procedure had been done by Siemens NX, there are other commercial software which are tailored for this specific purpose. Software which can do topology optimization and modify the shape and support for building parts in 3D printers.

Discussion

Through the design process, the author developed his geometric dimension and tolerancing knowledge which is a valuable asset for further research in this field. The practical know-how of the design process was valuable for further research. To proceed with the decision-making process, the author had to research into most common AM technologies, their feature, advantageous and limitations to define their importance in the pairwise comparison.

Future Work

Based on the findings of this thesis, the author suggests that further research in course planning would be beneficial. Also, research on how each teaching method affects the process of learning in the engineering field. The nature of the thesis limited the author to have an assessment of the course planning and get feedback from students and professionals, thus study over selected individuals on a small scale might be beneficial.

Suggestion

Comparison between different courses shown that not a specific method or selection of methods work for every student in higher education, hence iterative assessment over the quality of the course is a must. The author proposal is to have an ongoing feedback system which students can review each session of the course. In that case, teachers would have a general knowledge of course productivity and enable them to monitor the learning process and have the possibility for agile modification of the course content or the ways of interacting with students.

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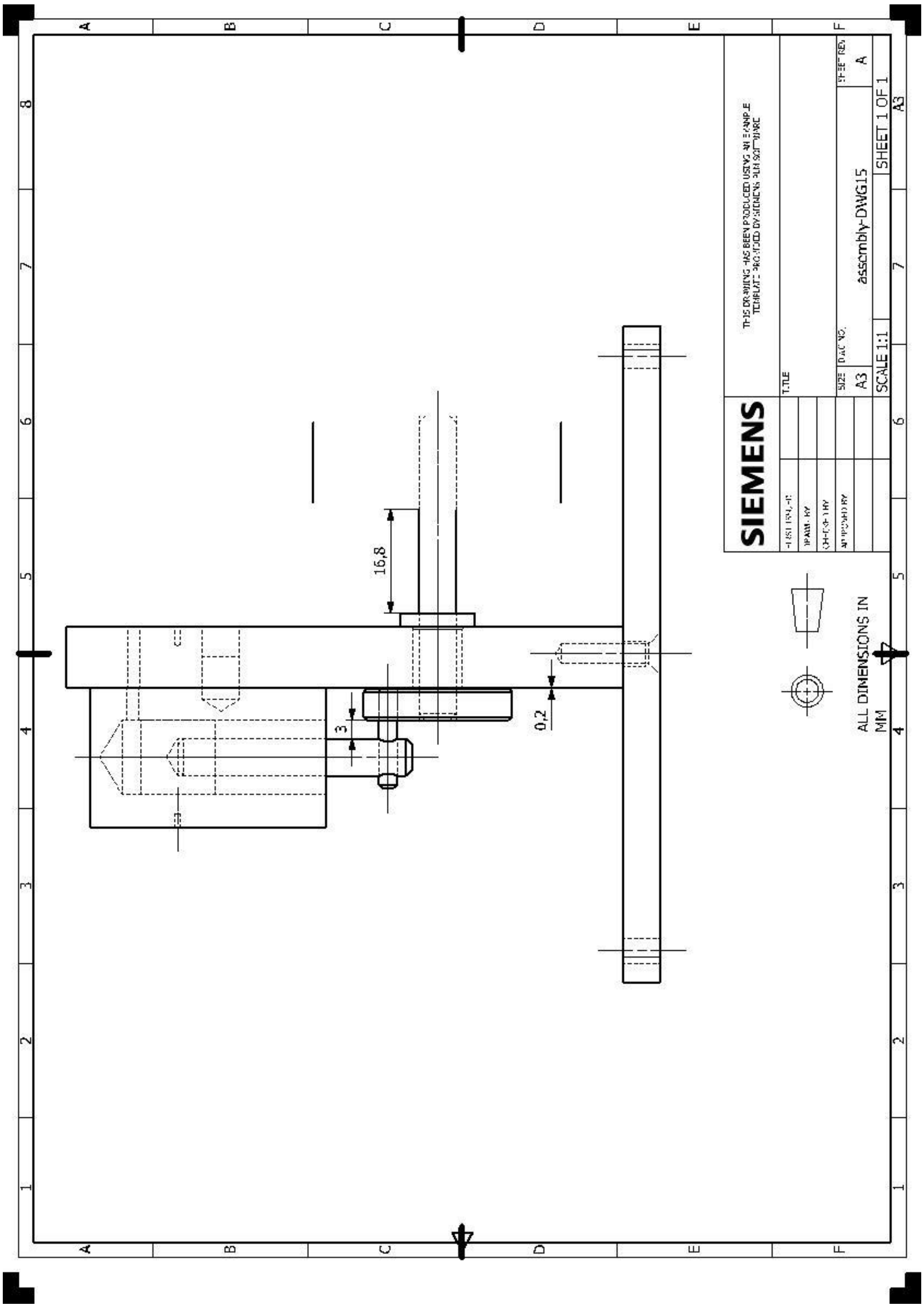
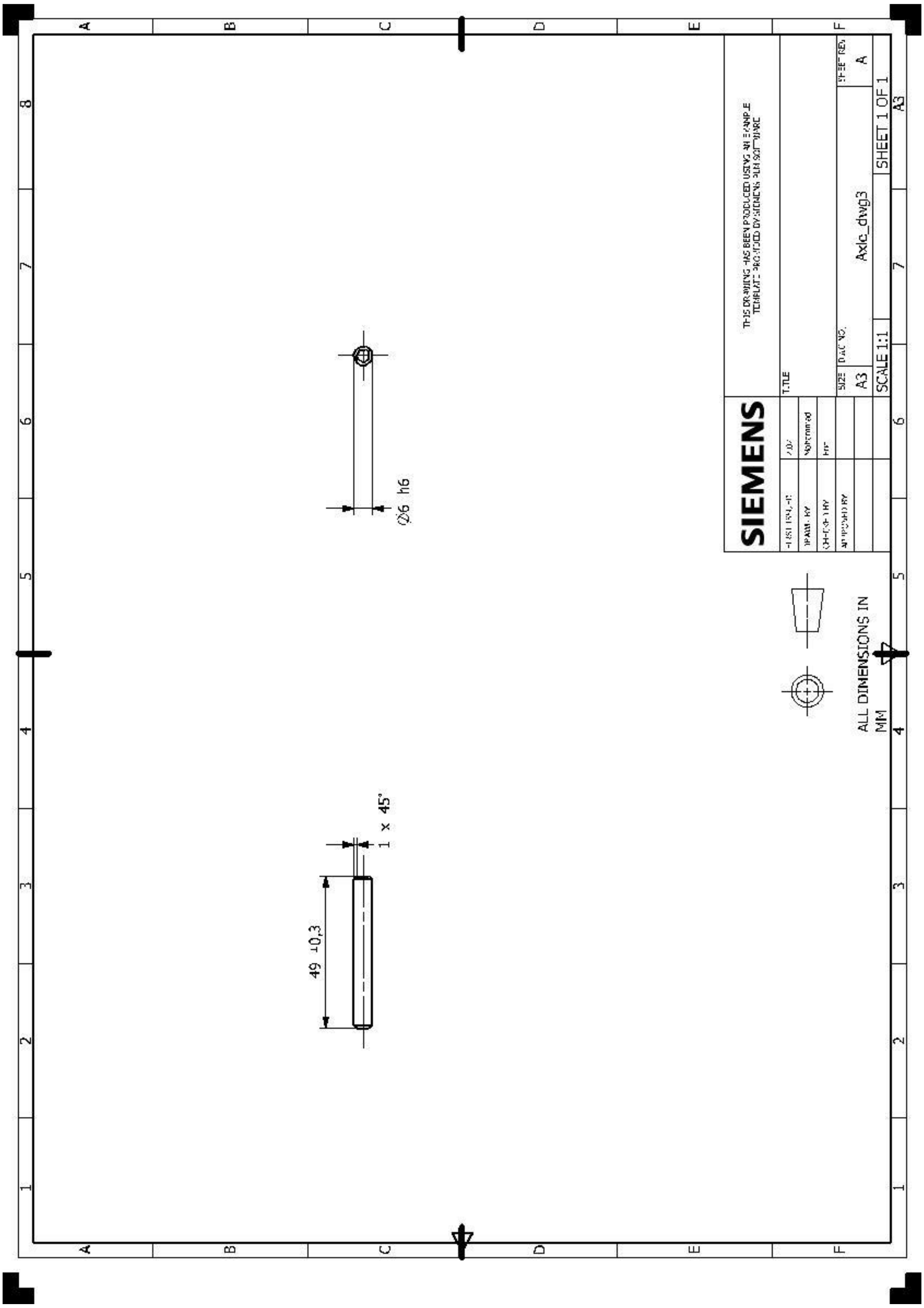
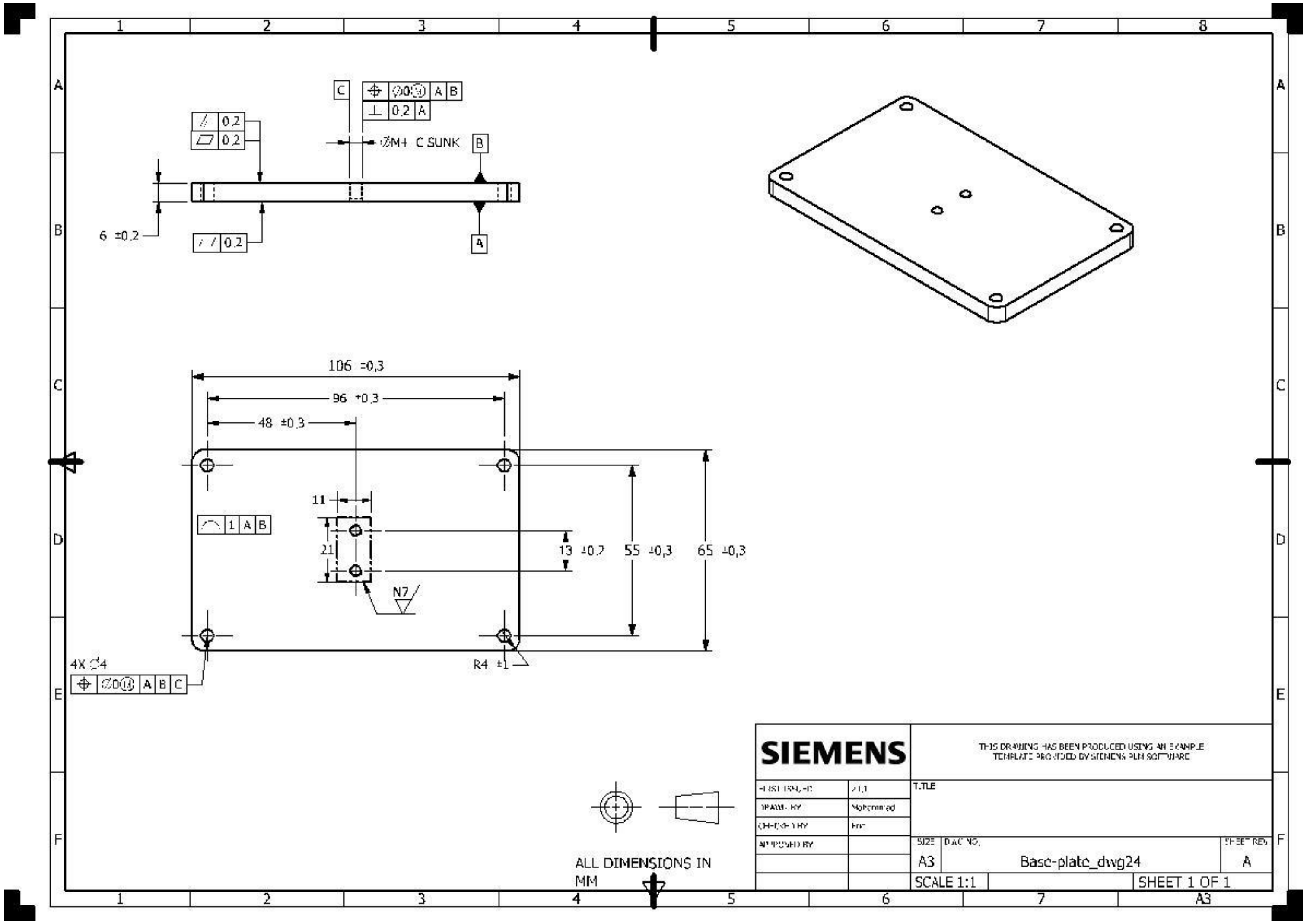
APPENDIX A: CASE STUDY DRAWINGS




49 ±0,3
1 x 45°
Ø6 h6
ALL DIMENSIONS IN MM
SIEMENS
FIRST USED ON
DRAWN BY
CHECKED BY
APPROVED BY
Mohammad
TITLE
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
SIZE
A3
DWG NO.
Axle_dwg3
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3
A
B
C
D
E
F
1
2
3
4
5
6
7
8


0.2
0.2
C
⌀0.1 A B
⊥ 0.2 A
⌀M4 C SUNK
B
6 ±0.2
// 0.2
A
106 ±0,3
96 ±0.3
48 ±0.3
11
21
1 A B
13 ±0.2
55 ±0,3
65 ±0,3
N7
4X ⌀4
⌀0.1 A B C
R4 ±1
ALL DIMENSIONS IN MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
DRAWN BY
Mohammad
CHECKED BY
APPROVED BY
TITLE
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DWG NO.
Base-plate_dwg24
SHEET REV
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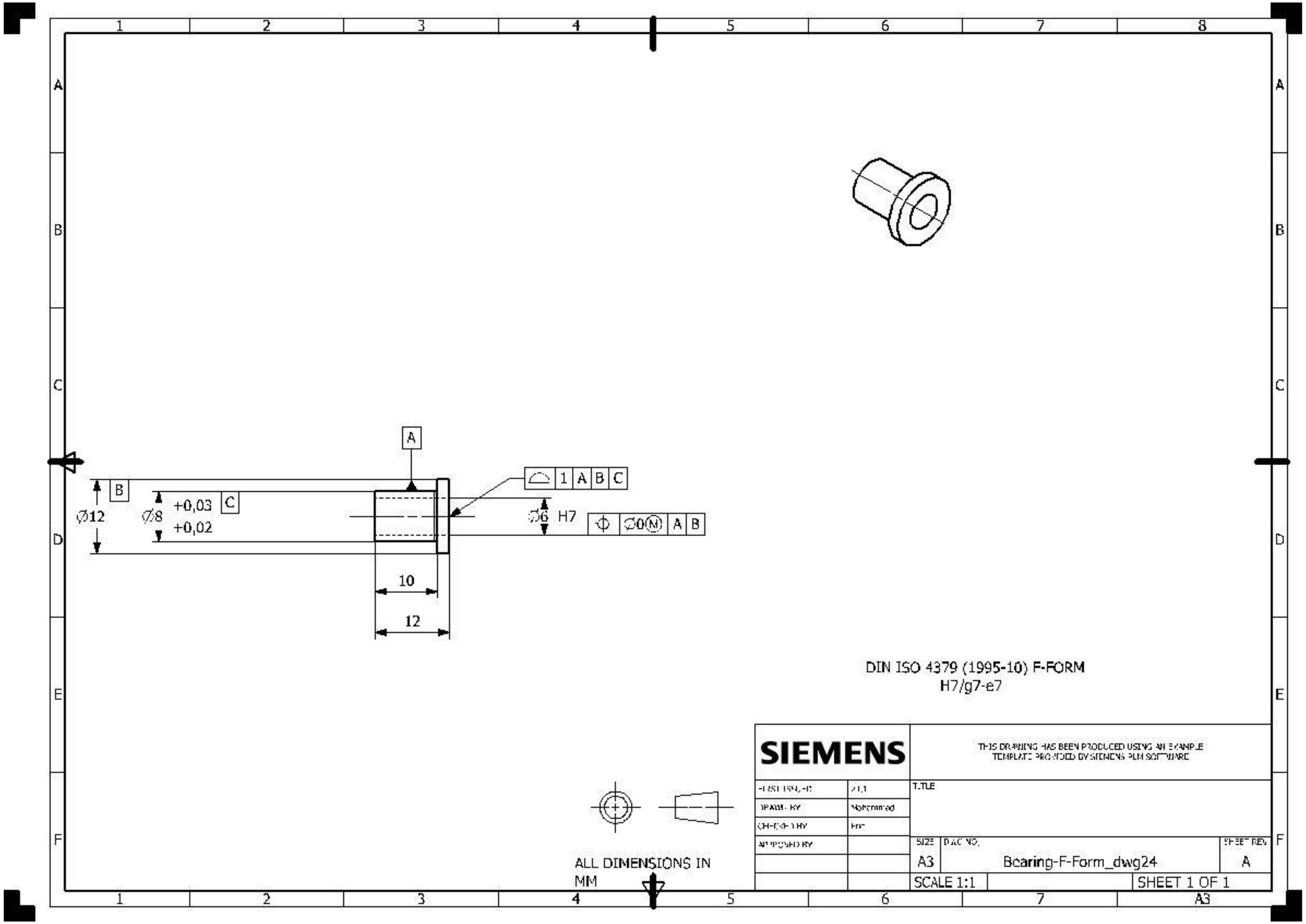
SCALE 1:1
SHEET 1 OF 1
A3


A
B
Ø12
Ø8
+0,03
+0,02
C
1 A B C
Ø6 H7
Ø0Ⓜ A B
10
12
DIN ISO 4379 (1995-10) F-FORM
H7/g7-e7
ALL DIMENSIONS IN
MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE
TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
DRAWN BY
Mohammad
CHECKED BY
APPROVED BY
TITLE
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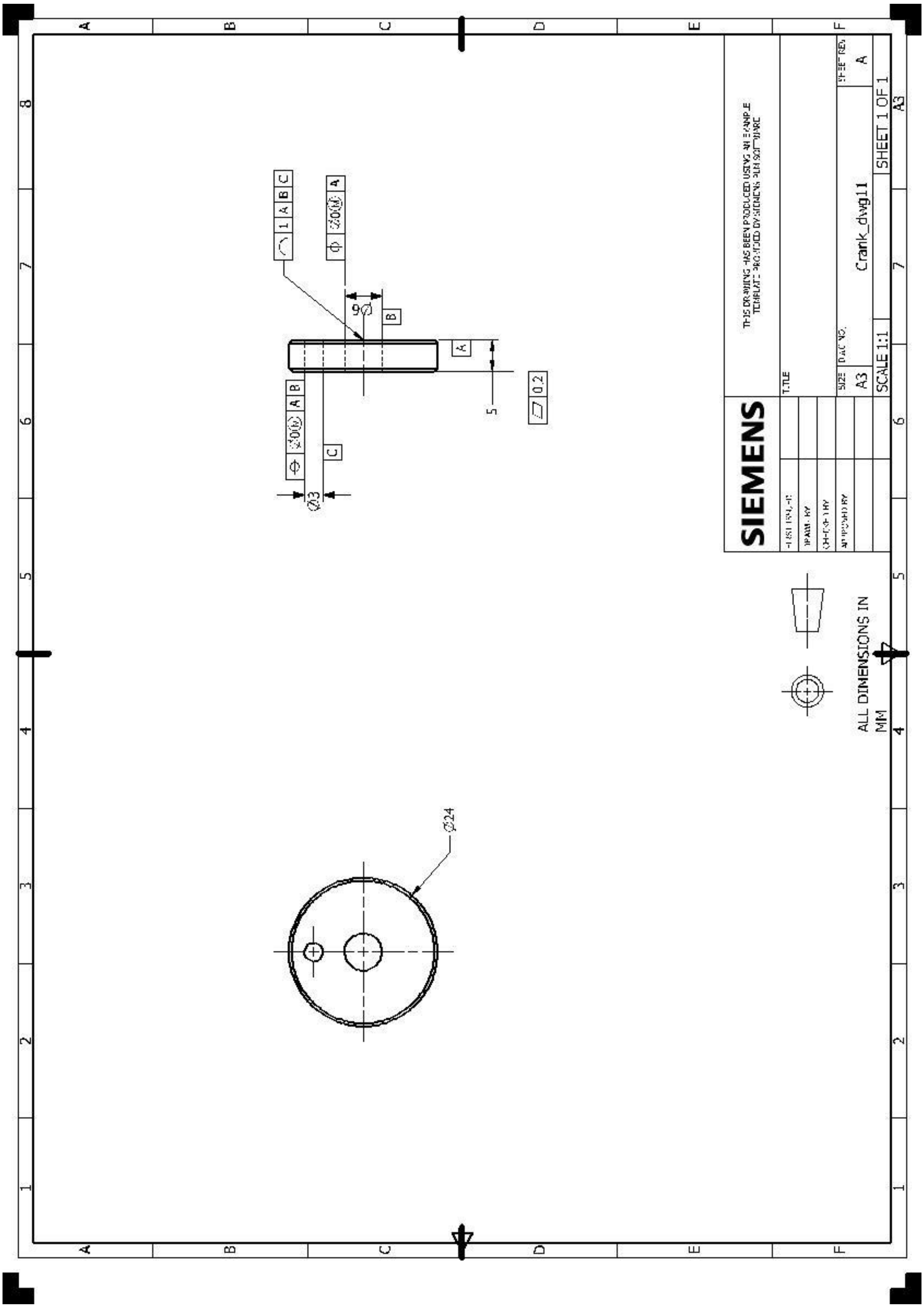
Bearing-F-Form_dwg24
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3


A
B
C
D
E
F
1
2
3
4
5
6
7
8
∅24
∅3
∅6
5
A
B
C
⌓ 1 A B C
⌖ ∅0(M) A
⌖ ∅0(M) A B
⏥ 0.2
ALL DIMENSIONS IN MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
TITLE
FIRST ISSUE
DRAWN BY
CHECKED BY
APPROVED BY
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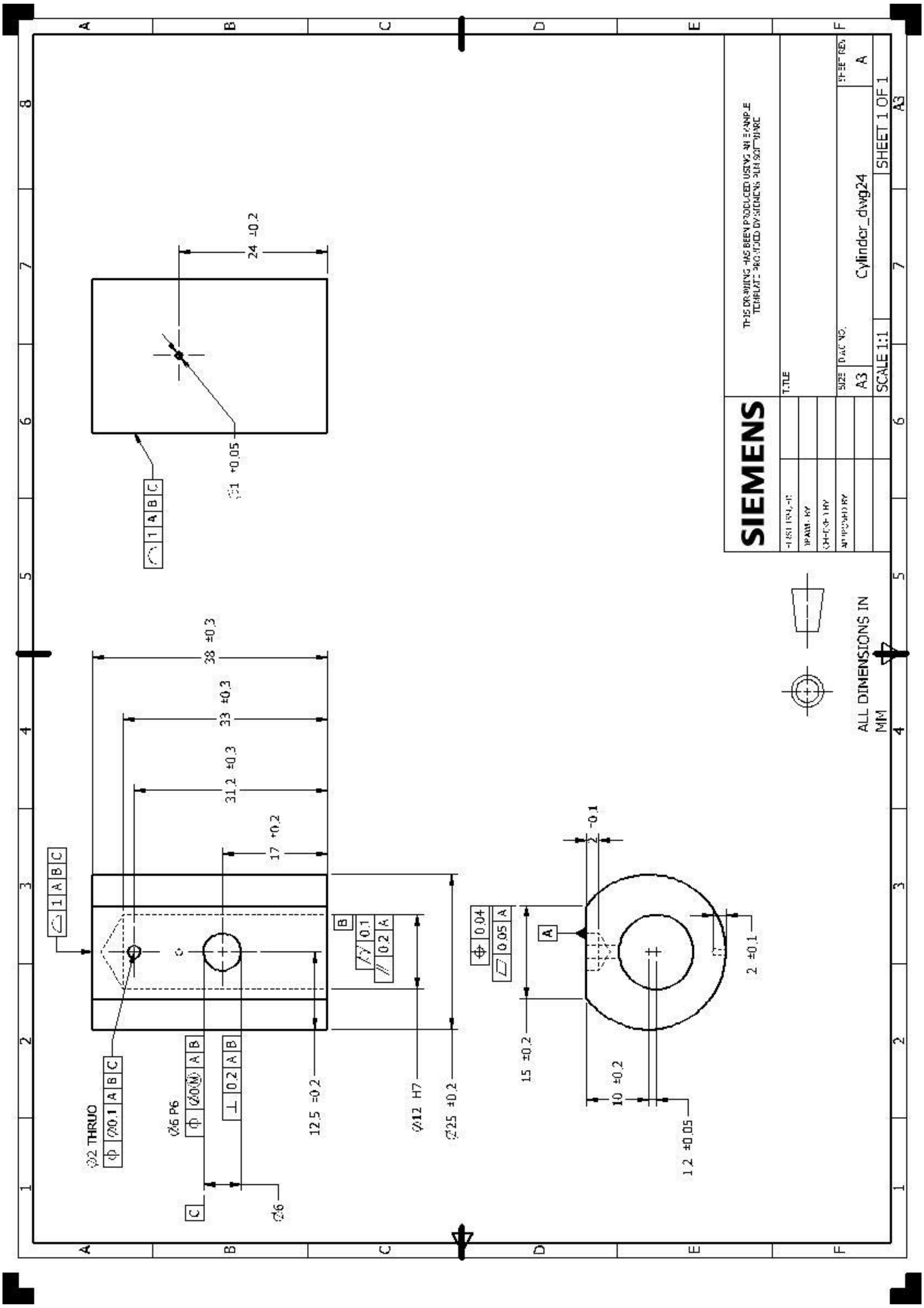
DWG NO.
Crank_dwg11
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3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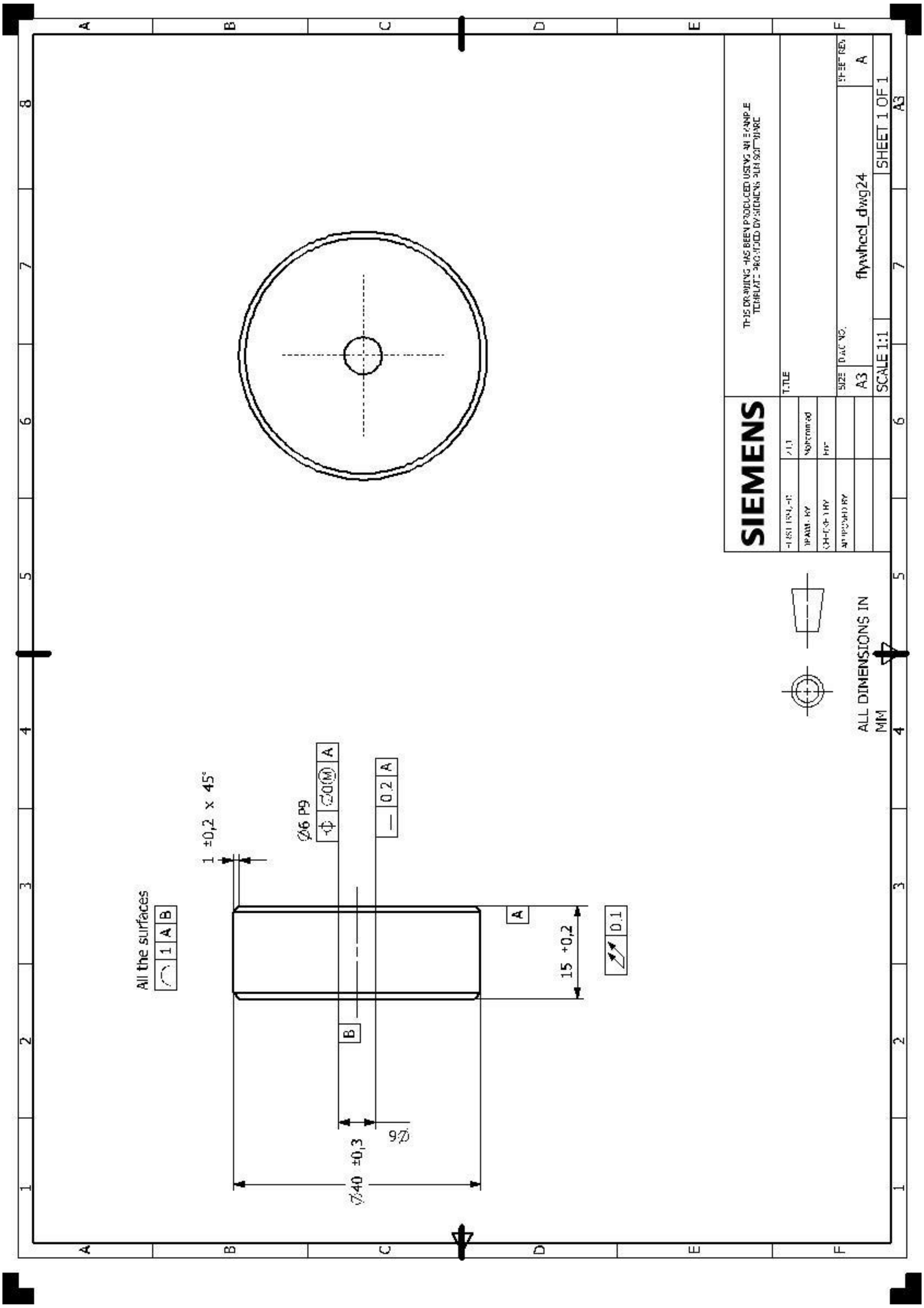
REV A
SCALE 1:1
SHEET 1 OF 1
A3
ALL DIMENSIONS IN MM
24 ±0.2
Ø1 +0.05
1 A B C
38 ±0.3
33 ±0.3
31.2 ±0.3
17 +0.2
12.5 ±0.2
Ø12 H7
Ø25 ±0.2
Ø2 THRU
Ø0.1 A B C
Ø6 P6
Ø0 Ⓜ A B
⊥ 0.2 A B
Ø6
0.1
0.2 A
0.04
0.05 A
15 ±0.2
10 ±0.2
1.2 ±0.05
2 ±0.1
2 -0.1
A
B
C


All the surfaces
1 A B
1 ±0,2 × 45°
∅6 P9
∅0Ⓜ A
0.2 A
A
B
15 +0,2
0.1
∅40 ±0,3
∅6
ALL DIMENSIONS IN MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
DRAWN BY
Mohammad
CHECKED BY
APPROVED BY
TITLE
SIZE
A3
DWG NO.
flywheel_dwg24
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3
A
B
C
D
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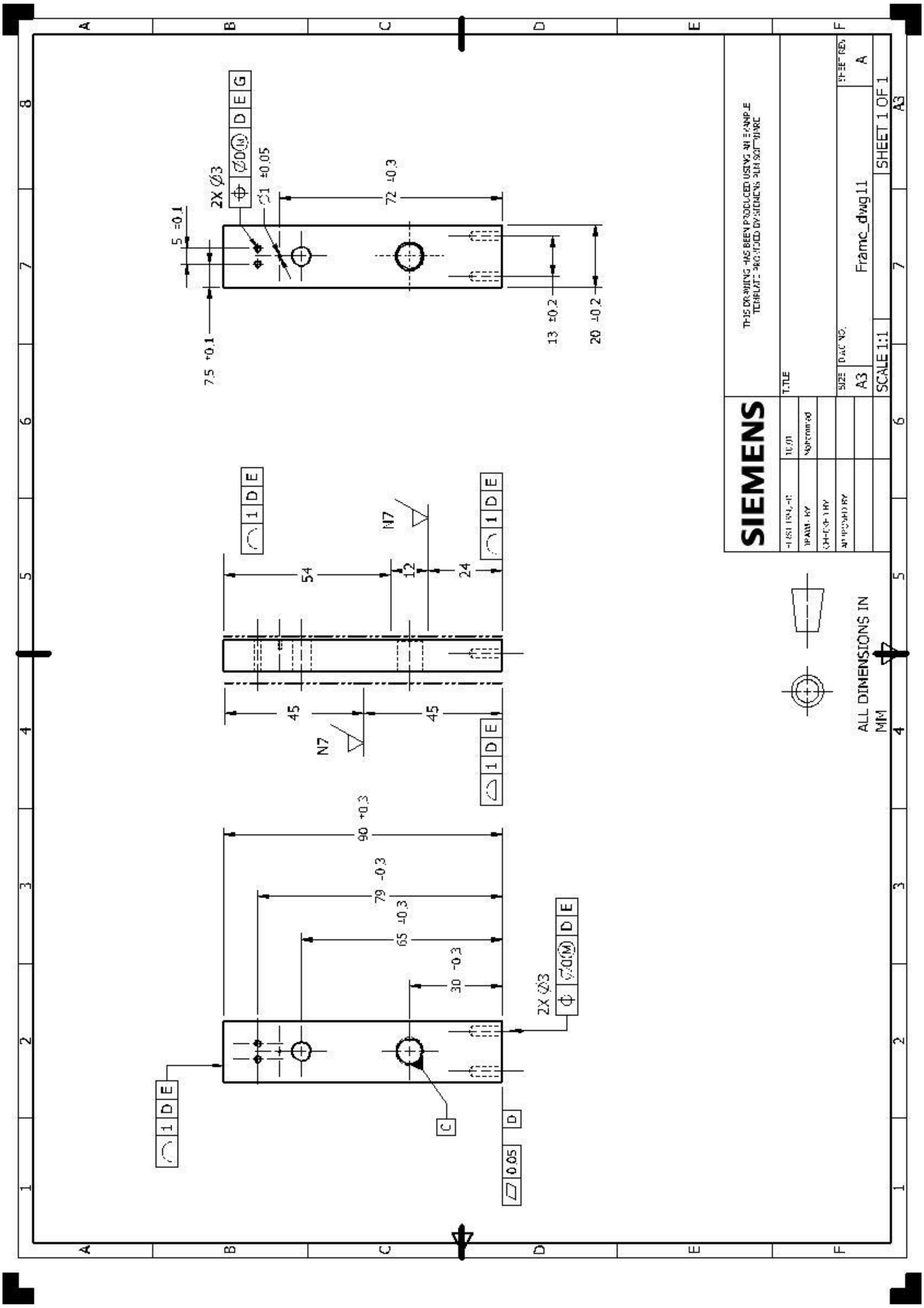
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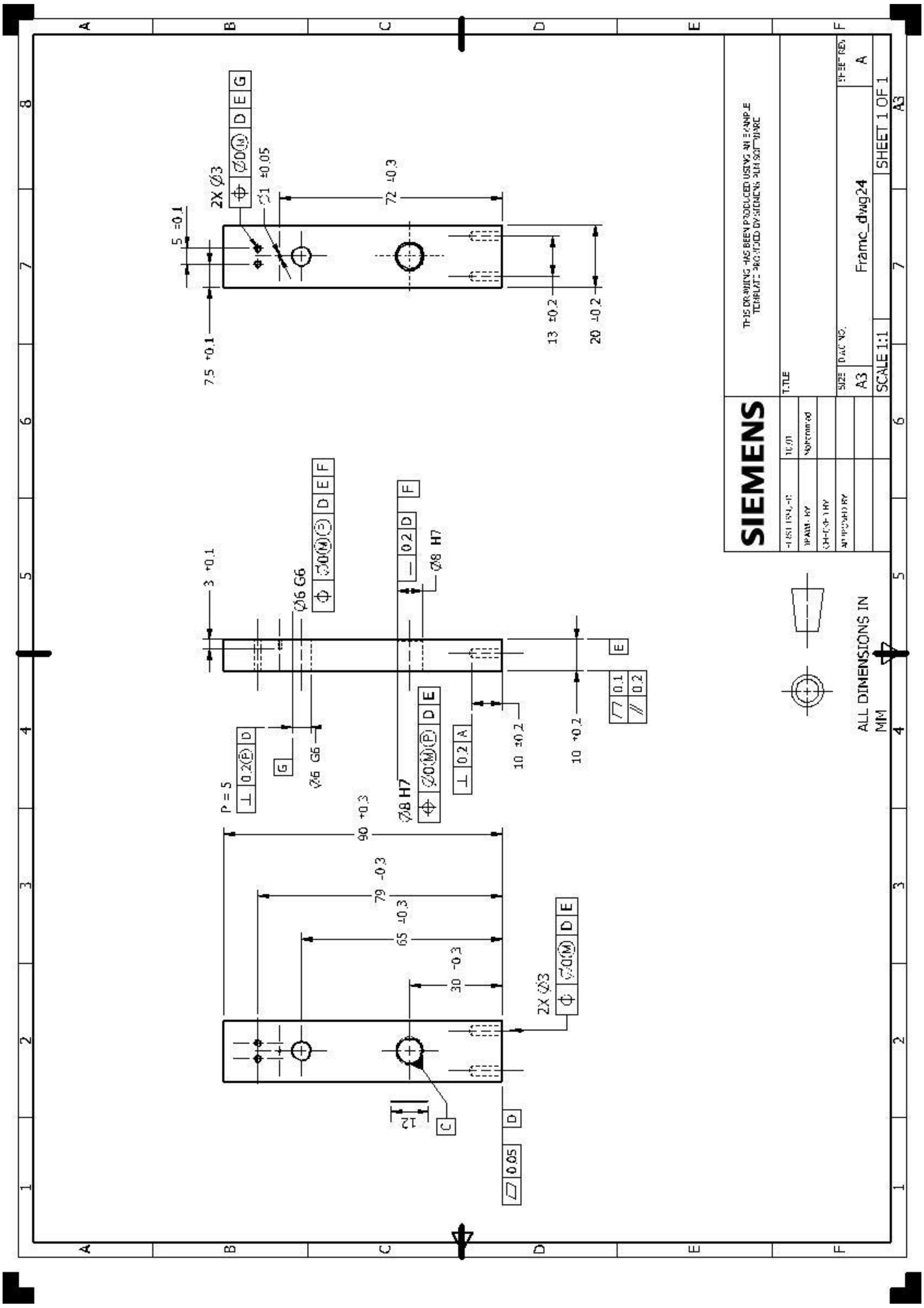
Frame_dwg11
SHEET REV A
SCALE 1:1
SHEET 1 OF 1
A3
ALL DIMENSIONS IN MM
90 +0.3
79 -0.3
65 ±0.3
30 -0.3
2X Ø3
72 ±0.3
13 ±0.2
20 ±0.2
5 ±0.1
7.5 ±0.1
∠1 ±0.05
54
12
24
45
45
N7
N7
1 D E
D E G
0.05
C
D


2X Ø3
Ø1 ±0.05
5 ±0.1
7.5 ±0.1
72 ±0.3
13 ±0.2
20 ±0.2
3 ±0.1
Ø6 G6
Ø8 H7
P = 5
10 ±0.2
10 ±0.2
90 ±0.3
79 ±0.3
65 ±0.3
30 ±0.3
12
ALL DIMENSIONS IN MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
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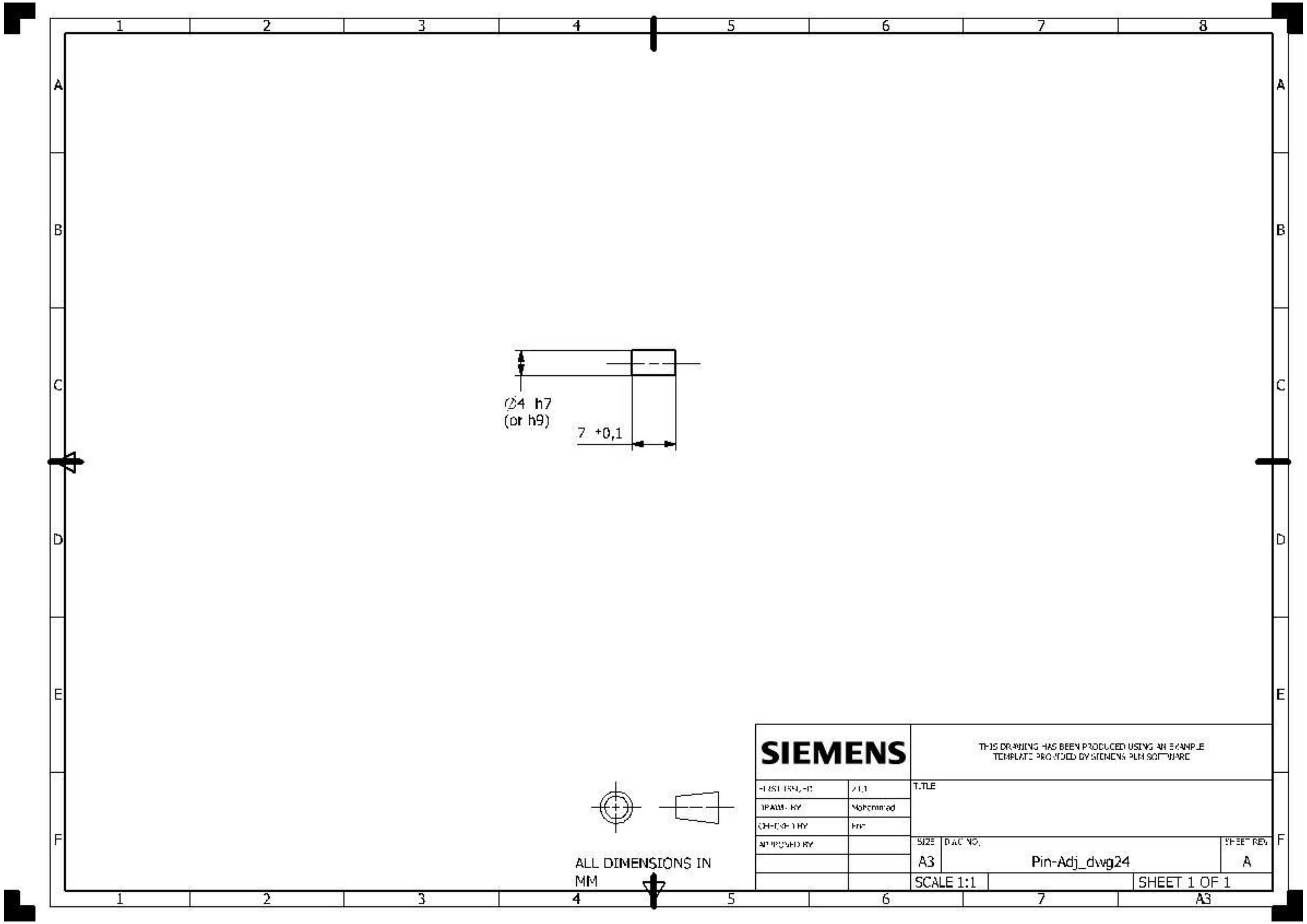
REV A
SCALE 1:1
SHEET 1 OF 1


Ø4 h7
(or h9)
7 +0,1
ALL DIMENSIONS IN
MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE
TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
FIRST ISSUED
DRAWN BY
Mohammad
CHECKED BY
APPROVED BY
TITLE
SIZE
A3
DWG NO.
Pin-Adj_dwg24
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3
1
2
3
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6
7
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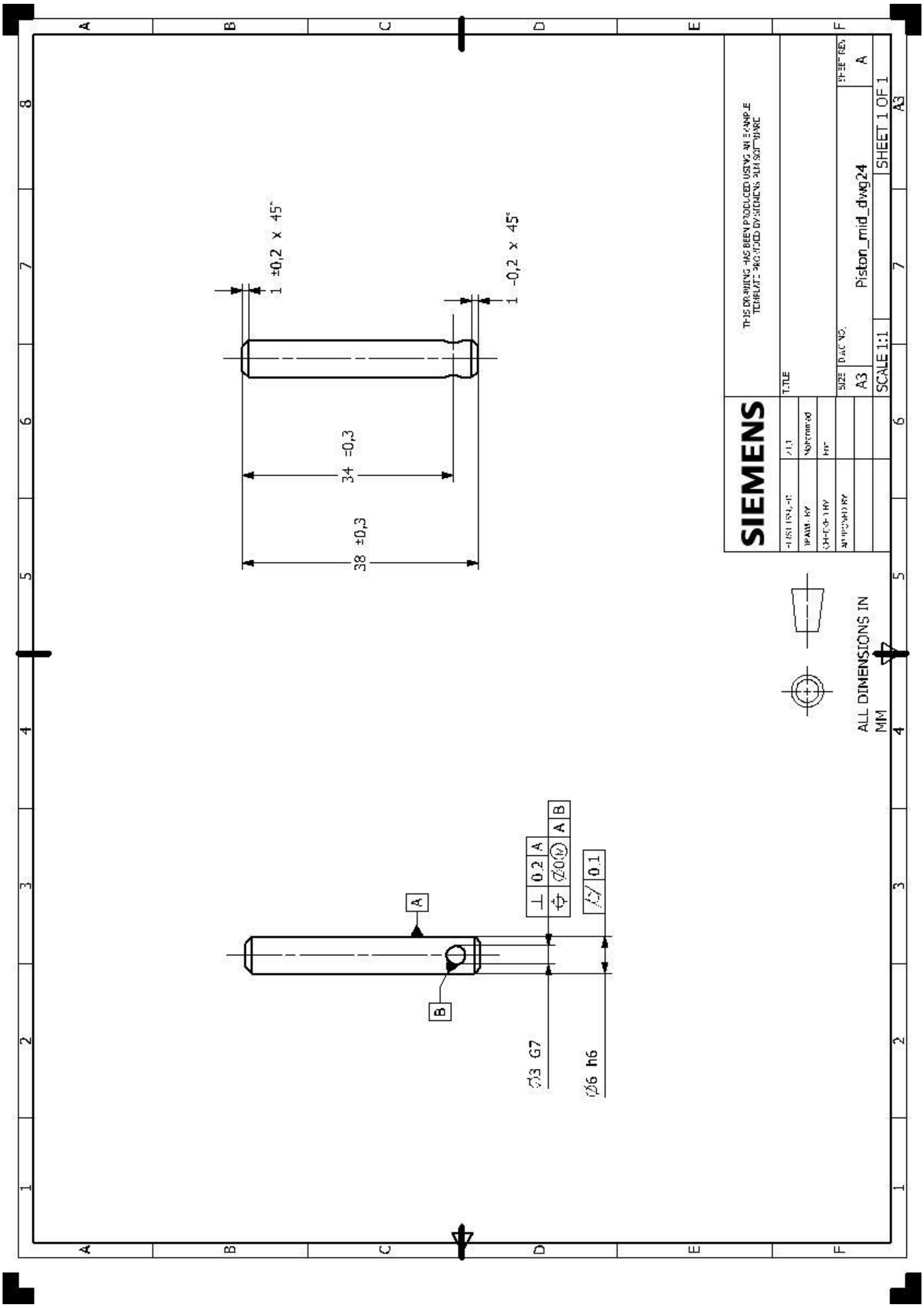
A
B
C
D
E
F


1 ±0,2 x 45°
1 -0,2 x 45°
34 ±0,3
38 ±0,3
A
B
⊥ 0.2 A
⌖ ⌀0 Ⓜ A B
⌭ 0.1
⌀3 G7
⌀6 h6
ALL DIMENSIONS IN MM
SIEMENS
THIS DRAWING HAS BEEN PRODUCED USING AN EXAMPLE TEMPLATE PROVIDED BY SIEMENS PLM SOFTWARE
TITLE
DRAWN BY
Mohammad
CHECKED BY
APPROVED BY
SIZE
A3
DWG NO.
Piston_mid_dwg24
SHEET REV
A
SCALE 1:1
SHEET 1 OF 1
A3
A
B
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D
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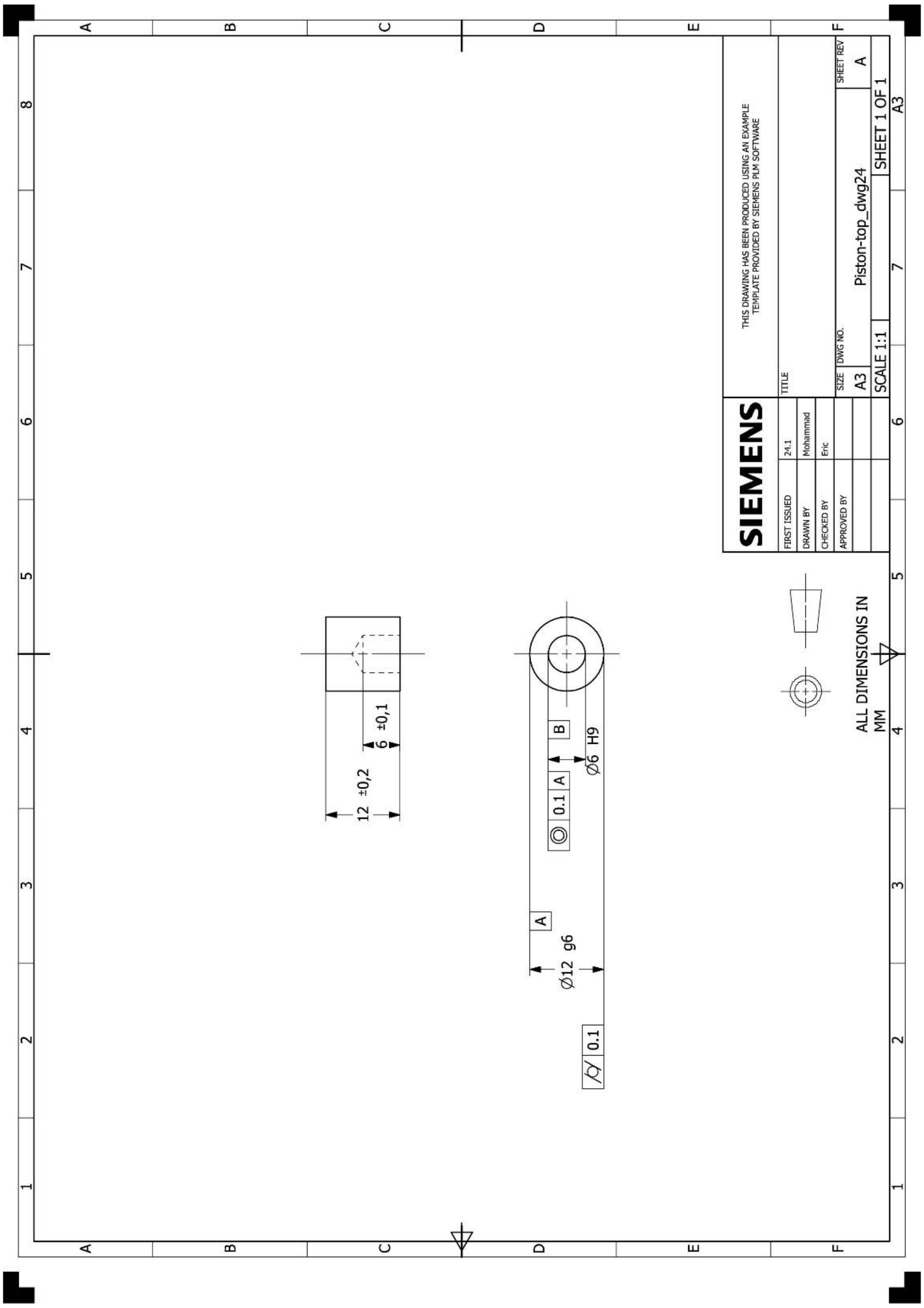
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SIEMENS
FIRST ISSUED 24.1
DRAWN BY Mohammad
CHECKED BY Eric
APPROVED BY
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SCALE 1:1
SHEET 1 OF 1
A3
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12 ±0,2
6 ±0,1
Ø12 g6
A
Ø6 H9
B
◎ 0.1 A
⌭ 0.1
A B C D E F
1 2 3 4 5 6 7 8