TIME ESTIMATION FOR ADDITIVE MANUFACTURING

By

Mina Amini

A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science in Technology
with a Major in Industrial Technology
December 2014

Committee Members:

Farhad Ameri, Chair

Vedaraman Sriraman

Byoung Hee You

FAIR USE AND AUTHOR'S PERMISSION STATEMENT

Fair Use

Duplication Permission

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude to my advisor Dr. Farhad Ameri for his continuous support, guidance, patience, and immense knowledge in all the time of research and writing of this thesis.

I would like to thank the rest of my thesis committee: Dr. Vedaraman Sriraman, and Dr. Byoung Hee You, for their encouragement, and insightful comments.

I would like to thank my family, my husband, and my friends for their supports throughout writing of this thesis. I may not fulfill my educational goal without their helps.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

ABSTRACT

Additive Manufacturing (AM), also known as 3D printing or Rapid Prototyping (RP), refers to creation of solid objects with various complexities in a layer by layer fashion based on their 3D models. Time estimation for additive manufacturing is an essential requirement for production scheduling, machine selection, and cost estimation. Hence, the focus of this thesis is to build parametric model for time estimation in AM process. AM technology is increasingly becoming more efficient, available, and affordable. However, it is not yet as efficient as many traditional manufacturing processes such as casting and molding particularly when it comes to high volume production. Therefore, users should be provided with standard time and cost models such that they can conduct a comparative analysis when selecting manufacturing processes. The objective of this thesis is to identify the most influential geometric parameters that drive the overall print time and develop an empirical model for print time estimation. Also, the impact of geometric complexity on the print time is studied. For this purpose, multiple parts with different features and complexities are modeled in a CAD package. The parts are then made by the 3D printer and the print time is measured. Also, for collecting more data rapidly, print simulation is used. Multi-variable regression is used to determine the most influential parameters and the standard model for time estimation is generated accordingly. Eventually, the model is validated through comparing the generated estimates with the actual times measured on the 3D printer. The scope of this model is limited to particular part sizes and geometries. A secondary objective of this thesis is to conduct a predictive analysis about the future of the 3D printing technologies in different industries and applications. 3D printing technology has already demonstrated significant impacts in different industries sectors and will continue to be a game-changing technology in the years to come as the technology evolves.

KEY WORDS: Additive manufacturing, 3D printing, rapid prototyping, time estimation

CHAPTER I

INTRODUCTION

Additive Manufacturing (AM) is defined as "the process of joining materials to make objects from 3D model data, usually layer up on layer ,as opposed to subtractive manufacturing methodologies, such as traditional machining" (ASTM Standard). The other terms used interchangeably for Additive Manufacturing are 3D printing and Rapid Prototyping. AM enables the designers and manufacturers to create complex shapes rapidly with low cost (Ciurana, 2013). When new products have to be manufactured, AM technology helps designers build prototypes and analyze them with respect to form, fit, and functions at the early stages of design (Ciurana, 2013). AM, enables design and manufacturing engineers to verify different design concepts rapidly and select the best design more efficiently.

Additive Manufacturing eliminate some disadvantages of the traditional processes through providing the following advantages:

- Efficient use of resources: it minimizes the processing steps, assembly activities, energy, and environmental impacts.
- Small-lot production: it requires fewer quantities of products or produce parts. Consequently, less inventory or stock cost would be needed.
- Rapid manufacturing: it has capability to advance directly from design process to manufacturing phase. As a result, it minimize the tooling process and cycle times.

- Agile manufacturing: there is no need for managing the complex supply chain anymore, because different components of an assembly can be consolidated into a single part.
- Reverse engineering: 3D printing and digital scanning are suitable for replacing the legacy parts for which CAD models or drawing do not exist.
- Design freedom: it enables design and production of complex parts with less cost compared to the conventional technologies.

Various technologies have been invented in AM such as Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF), Electron Beam Freeform Fabrication (EBF3), Direct Metal Laser Sintering (DMLS), Electron-Beam Melting (EBM), Selective Laser Melting (SLM), Selective Heat Sintering (SHS), Selective Laser Sintering (SLS), Plaster-based 3D Printing (PP), Laminated Object Manufacturing (LOM), Stereolithography (SLA), and Digital Light Processing (DLP). These technologies will be discussed in chapter 3.

Almost all geometries that are producible through conventional processes such as machining or casting can be produced through additive manufacturing as well. One of the main factors used for comparing different candidate processes is the production cost which is driven by production time.

The focus of this research is on developing an empirical model for print time estimation. Estimation of total print time is essential for production scheduling, machine selection, and cost estimation. Hollis (2001) points out, “if poor estimates are continuously produced, then instability will be introduced into the business system causing irreparable harm”. Due to the growing availability of different additive manufacturing machines and technologies, users are usually exposed to a wide array of AM technologies to choose from (Valentan, Brajlih, Drstvensek, & Balic, 2011). The decisions that lead to selection of suitable AM technology are largely influenced by the cycle time offered by each technology.

Currently, most AM processes are used for one-off production and low volume prototyping. However, due to rapid technological advances in this emerging area, it is predicted that AM processes will be used for mass production of functional parts in near future. Therefore, there is a pressing need for developing the necessary cost and time estimation models that can provide economic justification for adopting AM technology in high-volume production.

Problem Statement

Additive manufacturing is being used increasingly in many fields such as automotive, aerospace, military, engineering, and civil applications as well as dental and medical industries. Accurate time estimation is a critical requirement for process planning, scheduling and machine selection. The focus of the main body of research in AM has been primary on improving the quality and efficiency of various AM processes and their associated equipment and material. There is a lack of quantitative methods that can be used for time and cost estimation in AM. The existing models are mostly process-specific and do not investigate the effect of different geometric attributes on time estimation. The **objective** of this research is to develop a standard model to estimate the cycle time of AM process based on various geometric parameters. Fused Deposition Modeling (FDM) technology will be used in this research.

Research Question

- What are the most influential geometric parameters in a predictive model for time estimation?
- What is the impact of geometric complexity on the print time?
- What is the future impact of Additive Manufacturing in different industry sectors?

Assumption

- FDM process parameters such as layer thickness, orientation, raster angle, raster width, and air gap are assumed to be fixed.
- The time estimated through simulation is assumed to be accurate enough for the purpose of this research.
- The average difference between actual time and estimated time for building the parts using FDM is assumed to be negligible if it is less than 10%.

Limitation

- The statistical methods that are used to identify the final print time model can only determine the correlation, not causation.
- The results of used tests for data findings are restricted by the reliability of the test.

Delimitation

- Only Fused Deposition Modeling (FDM) is used.
- Only parts with bounding box smaller than 10 inches in each dimensions is considered in this model.

Research Methodology

Stepwise regression and statistical hypothesis testing are the analytical methods that are used in this research. To acquire precise time estimates, several objects are designed with different complexities and features. The most important geometry parameters are identified. The actual time involved in creating the objects with a 3D printer is measured experimentally. A standard time estimation model id developed according to the most influential attributes. Eventually, the validation of the model is validated experimentally. This research is conducted through the following tasks.

TASK I: Part Design and Scope Definition

In Task I several parts with varying complexities are selected to form a sample. Some of the parts are modeled in a CAD software and some other parts are directly downloaded from cloud-based part repositories. The designs should meet with a certain set of properties with respect to size. The reason behind limiting the scope is that the eventual model cannot be generalized for all shapes and sizes.

TASK II: Time Study

Actual time associated to creating all selected parts with 3D printer are measured through simulation or direct time measurement. It should be noted that the experiments do not require replication because there isn't much variability in the process to alter the output significantly in different runs. Time study data is collected to accomplish the next step.

Task III: Model Development

According to the collected data, one of the efficient methods of the multiple variable regression techniques are used to identify the most influential geometric parameters. By categorizing the effective parameters, more experiments may be needed for getting adequate information. Eventually, the regression model will be created based on data analysis.

TASK IV: Validation and Benchmarking

To validate the final model, 10 parts are selected randomly and printed on the printer. Then, the actual print times are compared with the outputs of the final model. Furthermore, the model will be tested with different AM machines in order to figure out if the machine selection have an influence on time estimates.

The remainder of this thesis is organized as follows. Chapter 2 provide a literature review on time estimation for AM processes. In Chapter 3, different AM technologies are discussed. The proposed time estimation model is introduced in Chapter 4. In Chapter 5, the future of 3D printing and its impacts on different industries such as education, aerospace, and medical are discussed. Chapter 6 provides concluding remarks.

CHAPTER II

LITERATURE STUDY

Researchers have adopted different techniques for time estimation in various AM processes. Hollis (2001) applied three attributes to estimate the time for production of parts by SLA additive manufacturing technology: Z (height), VOL (volume), SA (surface area). Hollis (2001) used regression analysis to identify the model for build time. The final model is:

$$\text{Estimated Build Time} = (0.0341) + (2.0 * Z) + (2.17 * VOL) + (0.018 * SA)$$

Campbell (2008) suggested utilizing the basic volumetric shapes to estimate time for the Stereolithography (SLA) process. Campbell (2008) calculated time estimate by analyzing some geometric and process parameters such as laser scan speed, cure depth, layer thickness, re-coating time per layer, hatch spacing, laser power during the build, surface area of the parts, total volume of the parts, total volume of supports, number of parts to be built, boundary locations (x, y) in which the laser has to operate during the build, and total Z height of the build. Campbell (2008) used the TK Solver (Program the calculations into mathematical solving software) to determine the build time estimator.

The developed output from TK solver is shown in Figure 2.1

Variables

Sta	Input	Name	Output	Unit	Comment
		Vs	31.722849	cm/sec	Scan Speed per centimeter
	.01	hs		cm	Hatch spacing
	35	Pl		mW	Laser Power
	.01	Wo		cm	Raduis of laser beam
	13.5	Ec		mJ/cm^2	Critical exposure
	9	Cd		cm	Cure depth
	4.8	Dp		cm	Penetration depth
		td	11.1150168	sec	Scan time per layer (single pass)
	3.526	A		cm^2	Cross sectional area
	16.5	H		mm	Height of part
		z	110	number	Total layers in z direction
		re_coat	6529.6	sec	
		TOT_tp	2445.3037	sec	Total scan time
		TOT_t	8974.9037	sec	Total build time for part

Rules

St	Rule
	Vs = (2/pi())^0.5 *(Pl /(Wo * Ec))* (EXP (-Cd/Dp))
	td = A /(hs * Vs)
	TOT_tp =(td*2) * z
	TOT_t =(td*2+59.36) * z

Figure 2.1 Output Results From TK Solver

In Campbell (2008) calculation Vs (laser scan velocity) is given by:

$$Vs = \left(\frac{2}{\pi}\right)^{0.5} \left\{\frac{\mathrm{Pl}}{R \times \mathrm{Ec}}\right\} \exp\left(\frac{-\mathrm{Cd}}{\mathrm{Dp}}\right)$$

Where R is laser beam radius, and other inputs are identified in Figure 2.1. The value of 59.36 is the average of recoating time during part building which is constant for all parts.

Zhang and Bernard (2014) analyzed some process parameters such as time for machine preparations, time for layer drawing, time for layer preparation, and time for ending operation; and developed a model based on some geometric parameters such as volume, surface, length, width, and z-height. A method was presented to measure the speed and capability of various AM machines, enabling the potential users to evaluate the machines before making decisions (Zhang& Bernard, 2014). In this method, the average manufacturing speed (cm^3/h) was calculated by dividing the part's volume (cm^3) over manufacturing time (h). Therefore, the consumed time on AM process is a fundamental portion to evaluate the speed of AM machines. Based on Zhang& Bernard (2014) the total time for building part with SLS technology is calculated by:

$$T_{bn} = T_{lsn} + T_{lpn} + \frac{C}{n}$$

$$T_{lsn} = (V_n / l_h) / \left[N(d_l + d_h)S \right] + (A_n / l_h) / S$$

$$T_{lpn} = \left[\frac{(Z_1 / l_h)t_l}{n} + \frac{((Z_2 - Z_1)/l_h)t_l}{(n-1)} + \frac{((Z_3 - Z_2)/l_h)t_l}{(n-2)} + \ldots\ldots \frac{((Z_n - Z_{n-1})/l_h)t_l}{(n-(n-1))} \right]$$

$$C = T_{mp} + T_e$$

Where T_{bn} : build time estimation

T_{lsn} : layer scanning time

T_{lpn} : time for layer preparation

C : constant value and is given by:

T_{mp} : time for machine preparation

T_{bn} : time for ending operation

l_h : layer thickness

t_l : fixed time unit for preparing one layer

n (1,2,3,4,….) : number of parts

z_n ($z_1 < z_2 < z_3 < \ldots\ldots < z_n$): height of n parts produced in one build

v_n : part s' volume

d_l : laser diameter

d_h : hatching space

s : laser scanning speed

A_n : part's surface area

N : number of laser heads

In order to reduce the complexity of the parametric time estimation, Artificial Neural Network (ANN) was used to develop the method flexibility (Angelo and Stefano, 2011). In this method, some process and geometric parameters such as scanning time for materials and supports' contour, time for hatching materials and supports, time for repositioning of the material deposition tool, time for the repositioning of the supports' deposition tool, and total delay time between subsequent layer' deposition were analyzed. Angelo and Stefano (2011) identified eight influential driving factors which are shown in Figure 1.2. Furthermore, Figure 2.2 illustrates whether these eight factors have effects on time estimation for each Additive Manufacturing (AM) technologies.

Technologies	Build time driving factors							
	Material				Support			
	$\frac{V_{mat}}{L_{mat}}$	$\frac{b_{z-mat}}{L_{mat}}$	p_{mat}	$n_{r\text{-}mat}$	$\frac{V_{sup}}{L_{sup}}$	$\frac{b_{z-sup}}{L_{sup}}$	$p_{\text{-}sup}$	$n_{r\text{-}sup}$
FDM	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SLA	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
SLS	Yes	Yes	Yes	Yes	No	No	No	No
LOM	Yes	Yes	Yes	No	Yes	Yes	No	Yes
MJM	Yes	Yes	No	Yes	Yes	Yes	No	Yes
3DP	Yes	Yes	No	Yes	Yes	Yes	No	Yes
EBM	Yes	Yes	Yes	Yes	No	No	No	No
SLM	Yes	Yes	Yes	Yes	No	No	No	No

Figure 2.2 Effects of the Eight Influential Driving Factors on Each AM Technologies

Where V_{mat}: volume of material to be formed

L_{mat} : layer thickness

b_{z-mat} : prototype's height

p_{mat}: total length of the layers' contour

n_{r-mat} : number of repositioning movement

$V_{sup}, L_{sup}, b_{z-mat}, p_{sup}$, and n_{r-sup} indicated the same values that are described above respectfully but for supports instead of materials. Angelo and Stefano (2011) stated that the build time is a very complex and not linear function. Figure 2.3 shows the build time process by Angelo and Stefano (2011).

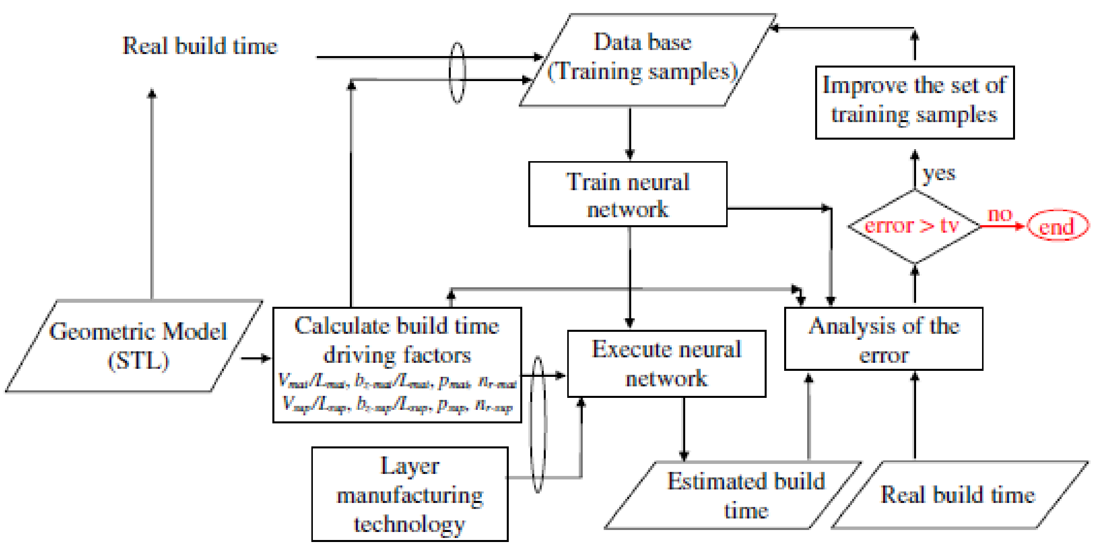


Figure 2.3 the Process for Build Time Estimation

The build time was proposed based on two components: layers' deposition time and total delay time between subsequent layers' deposition (Xu, Loh, & Wong, 1999). The following formula shows this build time:

$$t_f = T_{h-mat} + T_{delay} = (v_{mat} / l_{mat})^* \ t_s + (b_{z-mat} / l_{mat})^* \ t_w$$

Where V_{mat}: volume of material to be formed

L_{mat} : layer thickness

b_{z-mat} : prototype's height

T_{delay} : total delay time between subsequent layers' deposition

t_s : solidifying rate or material deposition rate in the build time

t_w : delay time between subsequent layers' deposition

Lan and Ding (2007) considered the layer counter depositions as an important component for time estimation. They introduced the following formula to estimate the build time:

$$t_f = T_{c-mat} + T_{h-mat} + T_{h-sup} + T_{delay}$$

WhereT_{c-mat}: total scanning time of the material contour

T_{h-mat}: total time for hatching material

T_{h-sup}: total time for hatching supports

T_{delay} : total delay time between subsequent layers' deposition

Although different models have been proposed for time estimation in AM, there is no generalizable model available yet that can be applied to a wide range of designs, machines, and processes. Most of the existing models are process or machine-specific. This research will focus on geometric parameters in order to develop a generalizable and reliable model.

As can be seen, the exiting models are mostly process-specific. These models do not illustrate the effect of geometric parameters on time estimation using AM. It is important to figure out the most influential geometric attributes on time estimation. Therefore, this research will investigate the geometric parameters in order to develop the cycle time of AM process.

CHAPTER III

DIFFERENT 3D PRINTING TECHNOLOGIES

Multiple 3D printing processes have been created since the late 1970s. The methods are separated based on the way of layer deposition and used materials. The differences among these methods are discussed in this chapter.

Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) was generated by Stratasys Inc. of Minneapolis, Minnesota, invented by married partners Scott and Lisa Crump in 1992. “The Fused Deposition Modeling (FDM) process creates parts by extruding material (normally a thermoplastic polymer) through a nozzle that traverses in X and Y to create each two-dimensional layers. In each layer separate nozzles extrude and deposit materials that forms the parts and material that form supports where required. The use of a nozzle with a diameter of typically ~0.3 mm limits resolution and accuracy” (Hopkinson, Hague, &Dickens, 2006, p. 75). Figure 3.1 shows a schematic of the FDM process and its separate components.

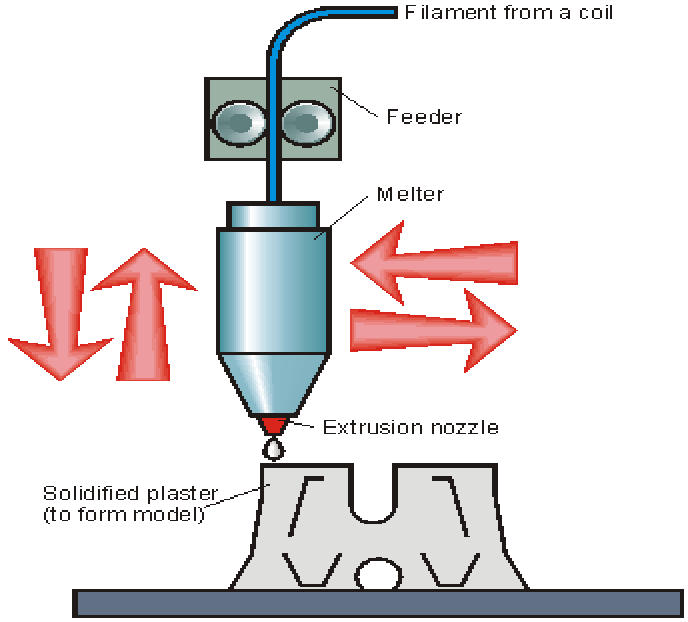


Figure 3.1 Schematic of the FDM

Stratasys (Wood, 1993, p. 72) claimed that the printers with the FDM technology have some important characteristics such as:

- Safe: In order to have the heat range between 180 to 220º F there is no need for exotic chemicals and lasers
- Fast: In order to eliminate the postcuring process
- Cheap: In order to have cheap units and materials
- Flexible: In order to use different materials such as polycarbonate, polyphenylsulfone, and most commonly acrylonitrate butadiene styrene (ABS) and not limited to using just photoactivated polymers

Furthermore, the simplicity of the FDM process provides opportunity as part of the variety of industries such as military and pharmaceutical industry.

Stereolithography (SLA)

Stereolithography (SLA) was invented in March 1986 in San Gabriel, CA, by Charles Hull and Raymond Freed. "Using an Ultraviolet (UV) laser to initiate a curing reaction in a photocurable resin. Using a computer aided design (CAD) file to drive the laser, a selected portion of the surface of a vat of resin is cured and solidified on to a platform. The platform is then lowered, typically by 100 µm, and a fresh layer of liquid resin is deposited over the previous layer. The laser then scans a new layer that bonds to the previous layer" (Hopkinson, Hague, &Dickens, 2006, p. 59). Supports are automatically created where the overhangs are built around the parts. The potential users may also create the supports prior to the building process. After building, parts rise from vat then are immerse in a chemical bath to be cleaned. Supports must be removed then parts are placed in a UV and/or thermal oven to cure any uncured resin. Figure 3.2 illustrates the schematic of SLA process.

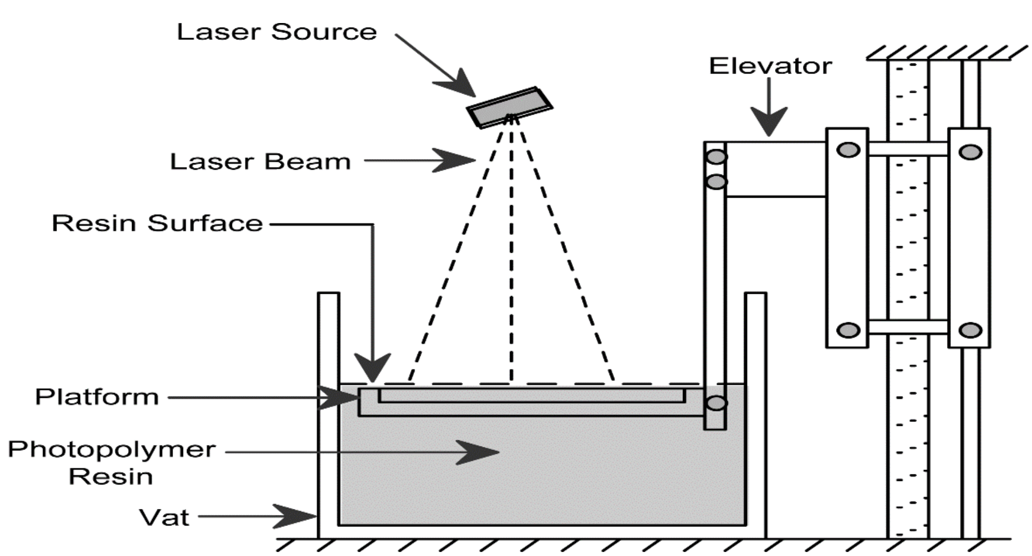


Figure 3.2 Schematic of the SLA Process

Generally, good surface finish, high accuracy of the complex geometry, and availability of transparent materials are the advantages of the parts which are created by SLA technology. However, models require the supports which need to be removed as a finishing operation. Moreover, resins and laser are hazardous and need the professional skills to work with them.

Selective Laser Sintering (SLS)

Selective Laser Sintering (SLS) was generated by Carl Deckard at the University of Texas at Austin in the late 1980s. “You deposit a layer of powder in a chamber that is heated nearly to the powder’s melting point. You sweep a laser across it to form a slice of the object that you are building, just as is done in stereolighography, except that the laser has to be somewhat stronger. The particles hit by the laser are raised to their sintering point and bond to the particles around them. The rest of the powder is unaffected and can offer support for overhangs, etc. Further layers are deposited and sintered, and, when the process is finished, the unused powder can be poured out” (Wood, 1993, p. 57). Figure 3.3 shows the schematic of SLS process.

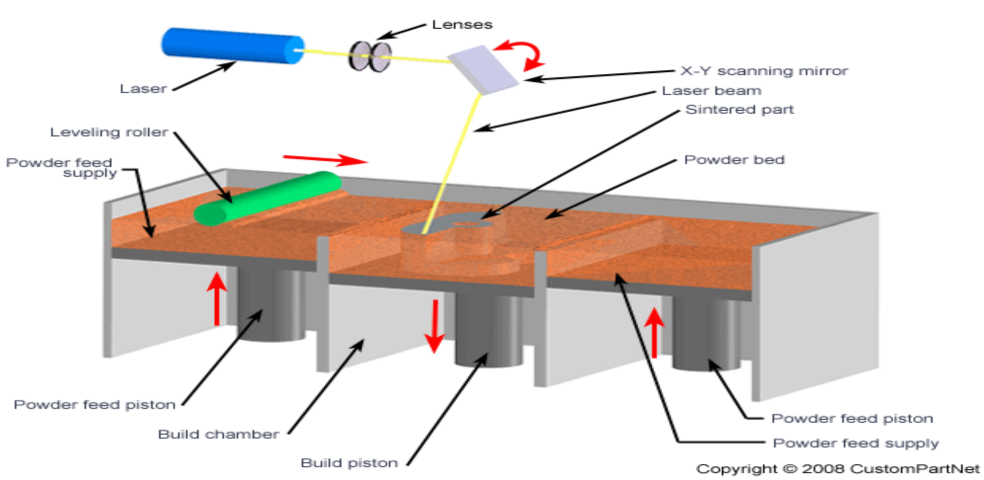


Figure 3.3 Schematic of SLS Process

The advantages of the SLS is the ability to use a variety of materials such as casting wax, polycarbonate, nylon, crystalline polymers, ceramic and metals. Moreover, according to the role of powder as a support during the process, SLS is able to create the complex shapes which cannot be made by traditional manufacturing methods. On the other hand, the finish parts are rough and porous. There is limited choice to build the colorful parts. Compared with the SLA, details of parts are not crisp and sharp. Furthermore, the machine are large, heavy and expensive. Therefore, these machines are not convenient for home use.

Selective Laser Melting (SLM)

Selective Laser Melting (SLM) was generated at the Fraunhofer Institute ILT in Aachen, Germany, in 1995 with a German research project. SLM process is similar to SLA, except SLM uses a laser to fully melt whereas SLS uses a laser to the point that the powder can fuse together. "During the SLM process, a powder layer is deposited onto a base plate attached to the building platform of machine. The laser beam scans the powder bed according to the slice data of the CAD model, and the powder being fully molten forms the first layer on the base plate. Then, the building platform is lowered with an amount equal to the layer thickness and a fresh layer of powder is deposited on the already solidified layer" (Bártolo et al., 2009, p. 207). Figure 3.4 shows the schematic of the SLM process.

SLM builds parts with high density and good mechanical properties. Fully functional parts can be created directly from standard metal powder since there is no need to use any intermediate binders or any post-processing steps. However, SLM is an expensive and slow process.

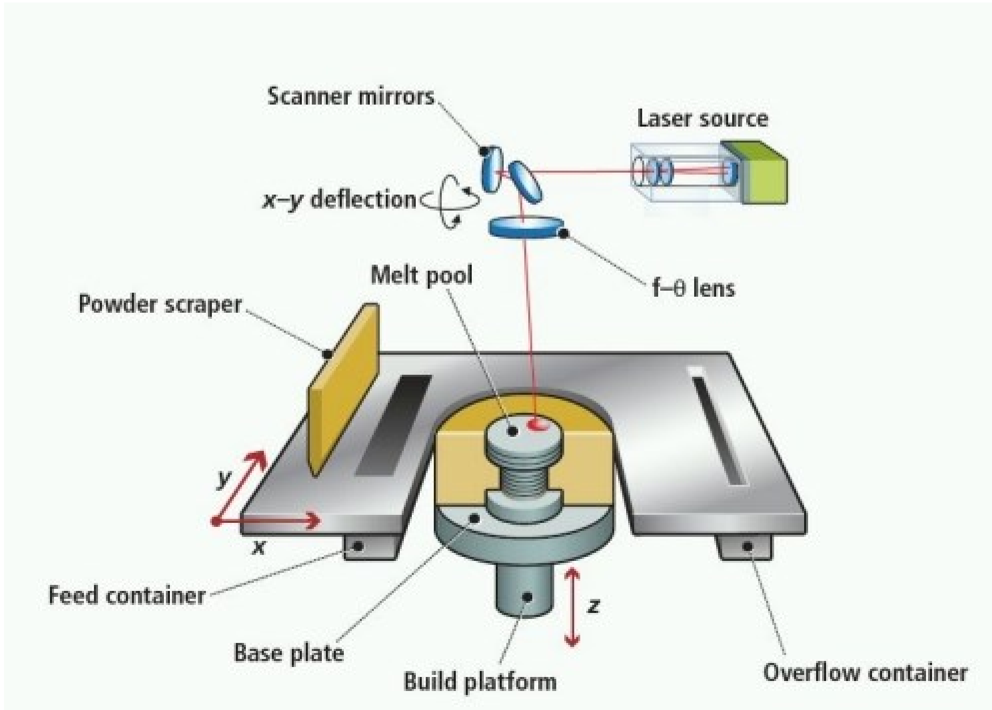


Figure 3.4 Schematic of SLM Process

<u>Laminated Object Manufacturing (LOM)</u>

Laminated Object Manufacturing (LOM) was developed by Helisys around 1985. “The LOM machines lay down, from a roll, a sheet of paper or plastic with a film of heat-activated glue on one side. After the material is laminated to previous layer by a hot roller, a laser incise the outline of the slice. The unused material is left in place, automatically supporting any overhangs, although it may be diced with cross-hatches by the laser for easy removal. Then, the next layer is laid, laminated, and incised, etc.,” (Wood, 1993, p. 92). The schematic of the LOM process is shown in the Figure 3.5.

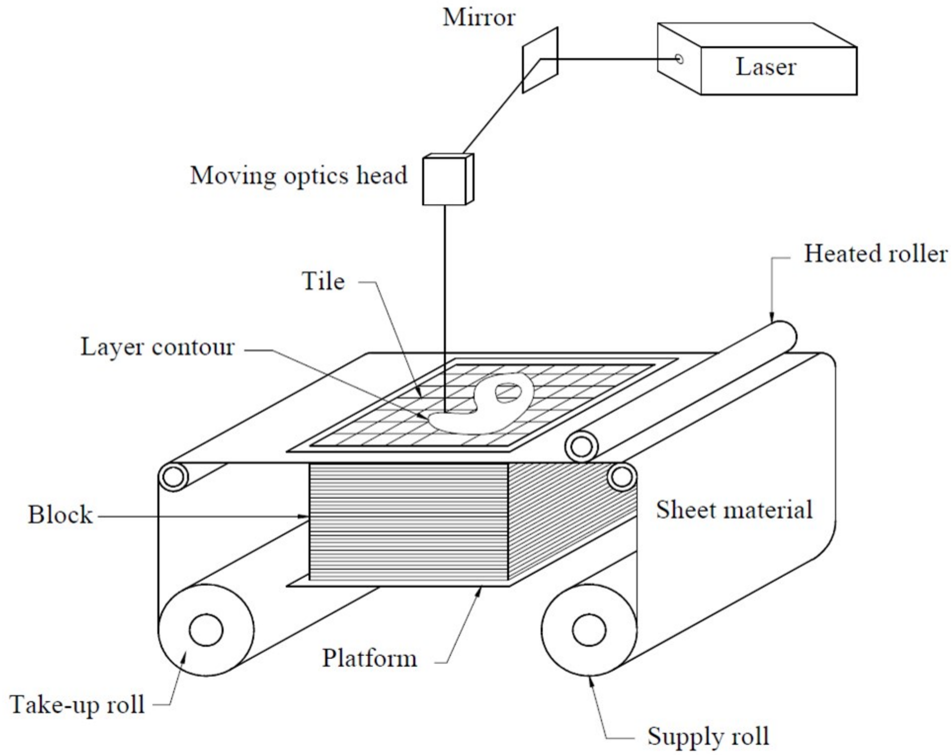


Figure 3.5 Schematic of the LOM Process

Helisys (Wood, 1993, p. 92) pointed out the LOM process possesses some benefits such as:

- Accuracy: In order to minimize the shrinking
- Simplicity: In order to not hold any overhangs, postcuring, and exotic chemicals
- Speed: In order to build large parts faster
- Cheap: In order to carry paper as the required material

Kamrani. A and Abouel Naser. E (2010) identified some disadvantages of the LOM Process:

- Dimensional stability: the LOM paper tend to swelling in order to humanity. Therefore, parts may have some Z-axis defects.
- Internal cavities: In some cases, parts need to be split to eliminate the internal cavities.
- Postproduction time: Postproduction time needs to be considered based on the complexity of the parts.
- Secondary processes: In order to create precisely functional parts, secondary processes should be accomplished. (p. 348)

Electron-Beam Melting (EBM)

Electron-Beam Melting (EBM) was first developed by Arcam in Gothenburg, Sweden, in 1997. The process is similar to SLS, except the electron beam is replaced the laser. “Before the process starts a three–dimensional CAD model is sliced into certain thin layers. These slices determine where the electron beam melts the powder. During the EBM process the current layer of metal powder is preheated and afterwards the electron beam melts the powder according to the layer data. Once the layer is melted the build platform is lowered by one layer thickness and the rake distributes a new powder layer” (Y. Chen, Wang, & S. Chen, 2014). Figure 3.6 illustrates the schematic of the EBM process.

EBM does not require the scanning mirror and can increase the scanning process. In order to create a high power of electron beam, wide range of metals such as titanium can be fully melted with the high speed of scanning rate. However, the process is narrowed to conductive materials and surfaces. Also, extensive finishing is required in this method.

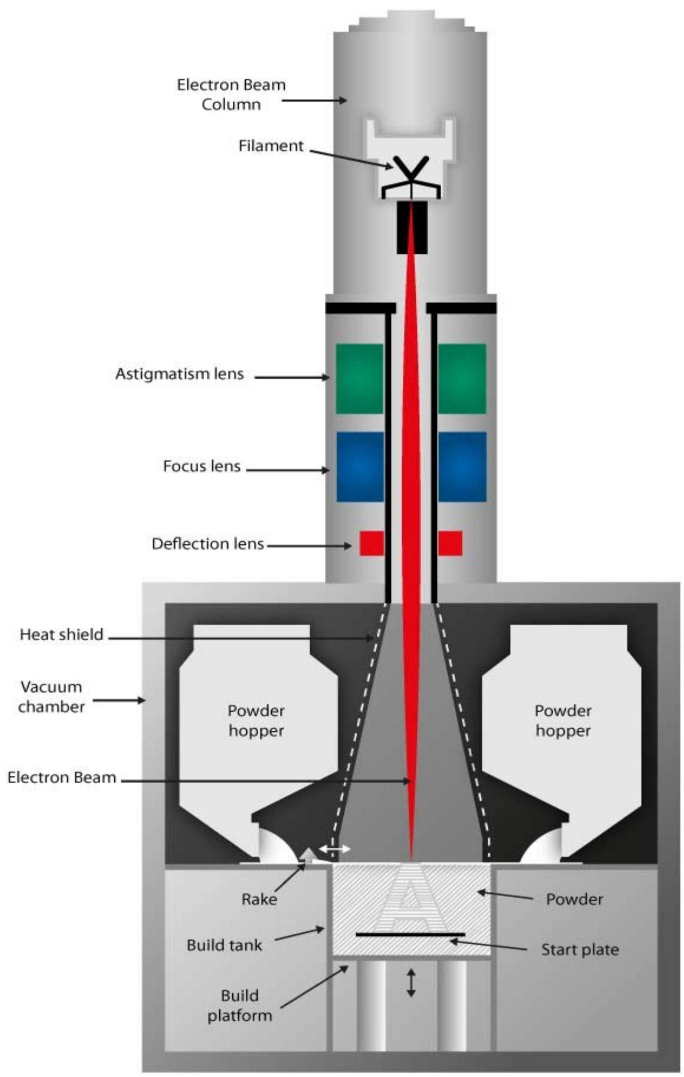


Figure 3.6 Schematic of the EBM Process

Electron Beam Freeform Fabrication (EBF3)

Electron Beam Freeform Fabrication (EBF3) was developed by National Aeronautics and Space Administration (NASA). "In reality, EBF3 works in a vacuum chamber, where an electron beam is focused on a constantly feeding source of metal, which is melted and then applied as called for by a drawing—one layer at a time—on top of a rotating surface until the part is complete" (Banke , 2009). Figure 3.7 shows the schematic of this technology.

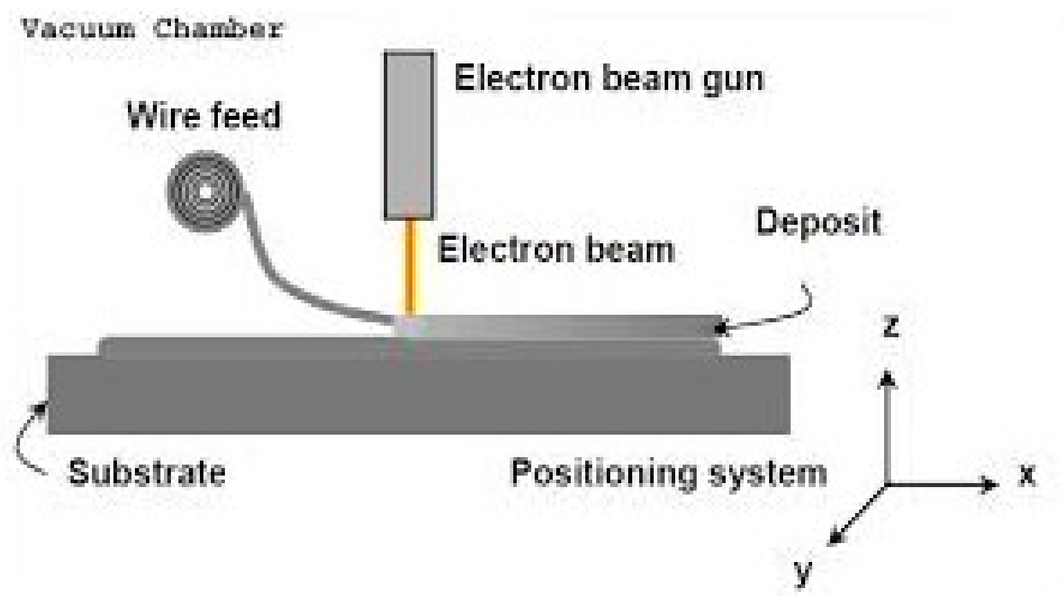


Figure 3.7 Schematic of the EBF3 Process

Products are built in the vacuum chamber which makes the welding process easier in outer space. Models are strong with smooth surfaces. Despite the other 3D technologies, EBF3 works in the 3D environment instead of closed box. Also, it makes a possibility to change the chemistry and incorporate sensors since the product is being built. On the other hand, it is an expensive 3D printing technology because of the price of machine, and material. Besides, working with this technology requires people who are professional in this field.

Direct Metal Laser Sintering (DMLS)

Direct Metal Laser Sintering (DMLS) was generated by Electro Optical Systems (EOS) GmbH, Germany during 1990s. “The machine begins the first layer by spreading out a very thin layer of powdered metal on the construction platform. A high-power fiber optic laser then accurately melts the metal in the appropriate areas as instructed by the CAD model. Each successive layer is built on top of the last layer and is fused to the layer below it” (“How DMLS Works,” n. d., para. 2). Figure 3.8 illustrates the schematic of DMLS process.

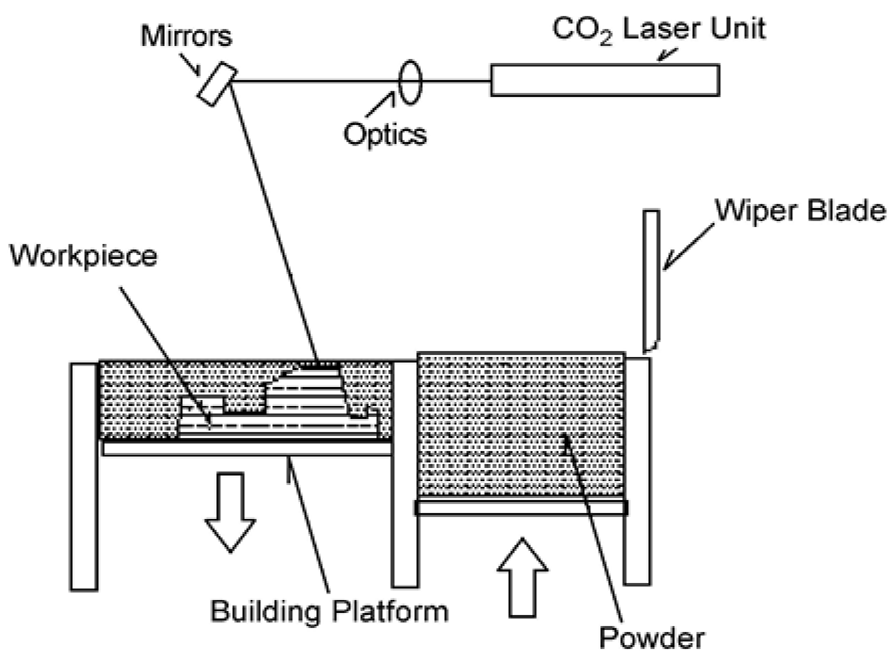


Figure 3.8.Schematic of DMLS Process

Models created by this technology have high accuracy with great detail. Also, they can possess some mechanical properties such as moving parts. The metal used in this process is similar to the metal that is used through the general manufacturing process. However, Models are small. Parts require post-processing which is time consuming.

Plaster-based 3D Printing (PP)

Plaster-based 3D printing (PP) was first developed at Massachusetts Institute of Technology in 1993 and Z Corporation achieved an exclusive license in 1995. “Particles of material are selectively joined together using a liquid binding agent (e.g., glue). Inks may also be deposited in order to impart color. Once a layer is formed, a new one is created by spreading powder over the top of the object and repeating the process. This process is repeated until the object is formed. Unbound material is used to support the object being produced, thus reducing the need for support systems” (Cotteleer, Holdowsky, & Mahto, 2014). The schematic of this process is shown in Figure 3.9.

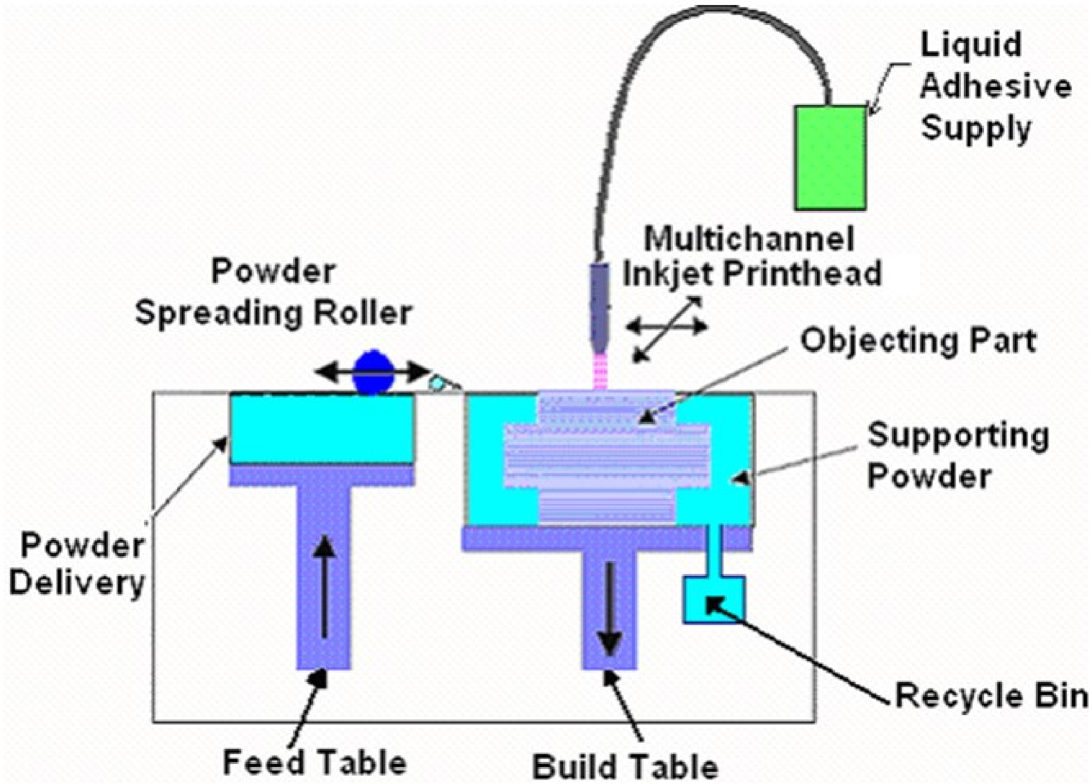


Figure 3.9 Schematic of PP Process

This technology can print about an inch per hour. So, it counts as a fast technology. It is an opportunity to build products with colorful layers. Also, it does not require the support materials. The machine is capable of printing multiple parts at once. However, products require some post-processing and finishing such as spraying on a layer and air blasting.

<u>Selective Heat Sintering (SHS)</u>

Selective heat sintering was founded by a Danish start-up company Blueprinter. This company was set up in 2009 as a solution for affordable office printer. The process is similar to SLS but it uses a thermal printhead as opposed to a laser in the SLS process. "A 3D model is designed in a CAD software then it is sliced into layers using another program. When the "print" button is pressed, the printer spreads plastic powder in a thin layer across the build chamber. The thermal printhead starts to move back and forth, and heat from the printhead melts each cross section into the plastic powder layer. Again the 3D printer prepares new layers of plastic powder, and the thermal printhead continues to apply heat onto layers of powder. Eventually the 3D model is made in the build chamber - surrounded by unmelted powder" ("Affordable Blueprinter," 2012). The schematic of SHS process is illustrated in figure 3.10.

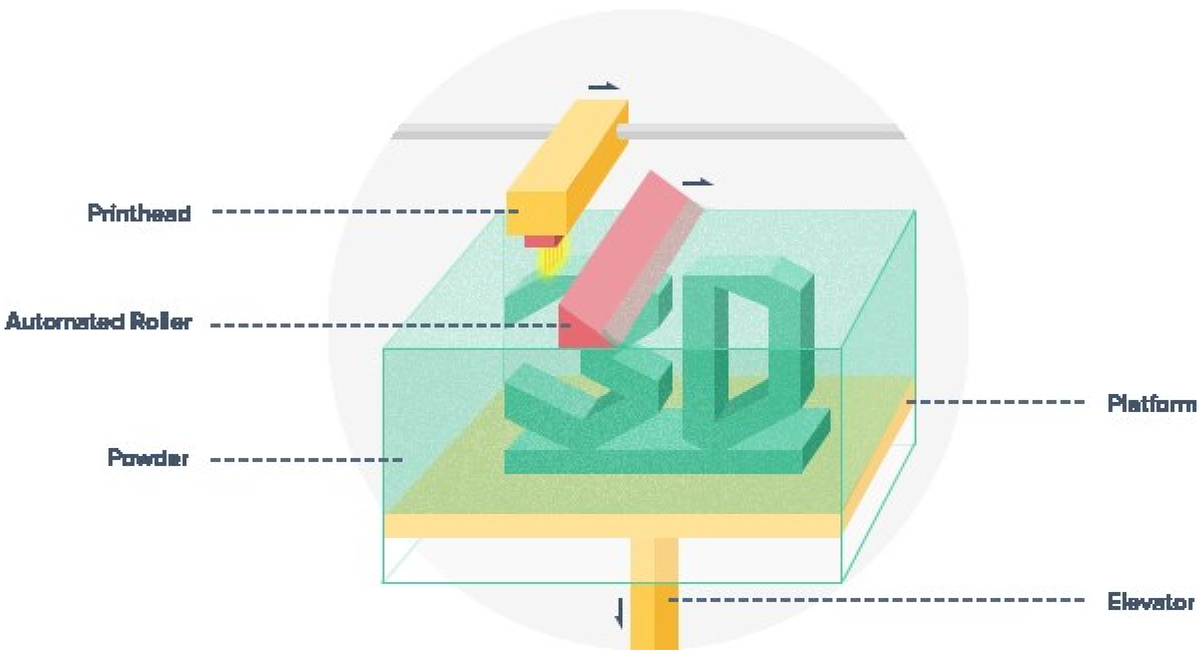


Figure 3.10 Schematic of SHS Process

This technology is capable of printing the complex geometries with moving parts. The technology is efficient because of possessing possibility to load and create multiple 3D models at the same time. It has lower cost than the SLS technology. Moreover, it does not require the support materials or post-curing of models.

CHAPTER IV

TIME ESTIMATION

Introduction

This chapter is focused on developing an empirical model for estimating the print time for parts produced using Fused Deposition Modeling (FDM) technology. Time estimation is essential for production scheduling, machine selection, and cost estimation. Acquisition of the accurate result requires an understanding of the factors that influence the printing time. In this research, the FDM process parameters such as layer thickness, orientation, raster angle, raster width, and air gap are assumed to be fixed. As mentioned earlier, one of the main objectives of this research is to statistically illustrate the relation between the geometric attributes and build time of the parts. Hence, the effect of the most important geometric parameters is analyzed. The final model that will be developed in this work cannot be applied to all parts and processes. The scope of this research is limited to the parts that can fit in a bounding box that is less than 10 inches in all dimensions.

Every mechanical part has a set of geometric attributes that define the DNA of the part. Different geometric attributes impact the total build time with varying degrees of strength. Table 4.1 illustrates the most important geometric attributes.

The length (X), width (Y), and height (Z) of the bounding box are regarded as the basic geometric parameters that should be included in the set of influential parameters. Volume of the part is another major variable that should be considered in the initial set of candidate variables.

The next parameter is surface area (SA). The surface area is calculated through adding up the areas of all exposed surfaces of a part.

Table 4.1 Geometric Attributes

Attribute	Description
X	Basic Geometry, length
Y	Basic Geometry, width
Z	Basic Geometry, height
V	Basic Geometry, volume
SA	Surface Area
ZSA	Product of the part height and surface area
XY	Projected area of part to the working plane
EV	Product of X, Y, and Z, considered the working envelope

The combination of height (Z) and surface area (SA) may have impact on the build time. This variable is denoted by ZSA. Projected area of the part to the working plane is another parameter that is included in the candidate set and is represented by XY. This attribute is a fundamental factor in plastic manufacturing in order to identify the machine sizes for production. XY provides the value of parallel working area which may have some impacts on the final build time. The last selected attribute is the EV which is product of the X, Y, and Z and also describes the working envelop of the part.

Approach

The purpose of this chapter is to identify which geometric attributes are the most influential ones in estimating the build time for a part using FDM technology. Since there are more than two variables that need to be analyzed, *multiple variable regression* technique is used to determine the effect of the eight described variables. Regression analysis is a statistical method that is useful for analyzing two or more independent variables and their effects on a dependent variable. The objective of multiple regression analysis is to study the relationship between a dependent (predicted) variable which is total print time in this work and the independent (predictor) variables that are shown in table 3.1. The result of this technique is a linear equation between the dependent variable and multiple independent variables. There are several types of multiple regression analysis such as standard, hierarchical, and stepwise. The *stepwise regression* will be used in this research because the focus of the stepwise regression is to analyze the combination of the independent variables in order to predict the dependent variable. In the stepwise regression procedure, the final model is built from a set of candidate predictor variables by adding or removing predictors until there is not any justifiable reason to add or remove more predictors. Therefore, the final model will include the variables which have the most impacts on build time. This method can be easily extended to the other regression problems if it is necessary. Furthermore, it is easy to explain and easy to compute. However, not all independent variables may end up in the final equation. The final equation will include the most influential independent variables.

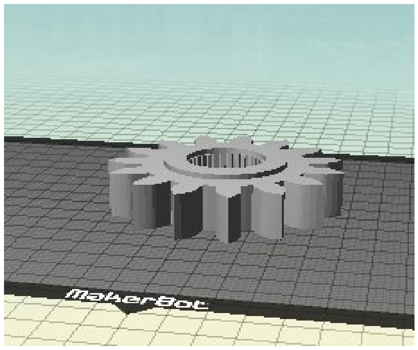
Stepwise regression is the process of analyzing the independent variables by adding or removing them based on the t-statistics of their estimated coefficients in order to predict the dependent variable. This process can either start with no variables in the model and proceed forward by adding one variable at a time, or start with all variables and proceed backward by removing one variable at a time. In this research, the backward stepwise is used. The result of this procedure includes the values of the Coefficient, Standard Error, t Stat, and P-value of the each independent variable. The variables with p-value less than the level of significant are considered as influential variables. At each step, one independent variable with highest p-value will be removed. This process will be stopped when all existing independent variables possess the p-value less than level of significant. These variables are the most influential parameters to be used in the predictive model. The final equation takes the following form:

$$Y=a_0 + a_1x_1 + a_2x_2+a_3x_3 + a_4x_4 + \cdots + a_nx_n \qquad (4\text{-}1)$$

Where a_n denotes the coefficient and x_n denotes the value of independent variables.

Analysis

In order to examine the effects of the identified attributes, 25 parts with different shapes are selected from Thingiverse website (http://www.thingiverse.com/). Thingiverse is the website that includes over 36,000 3D design files in stl. format. The files can be used or altered under a Creative Commons license. Figures 4.1, 4.2, 4.3, and 4.4 show two selected parts from different views.



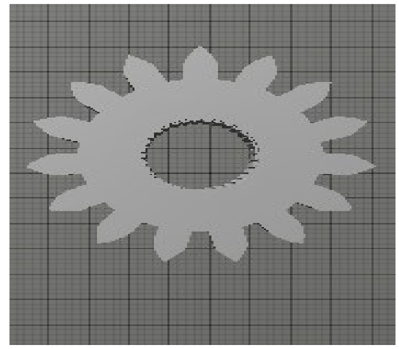


Figure 4.1 Egranaje_carro-3D View **Figure 4.2 Egranaje_carro-Top View**

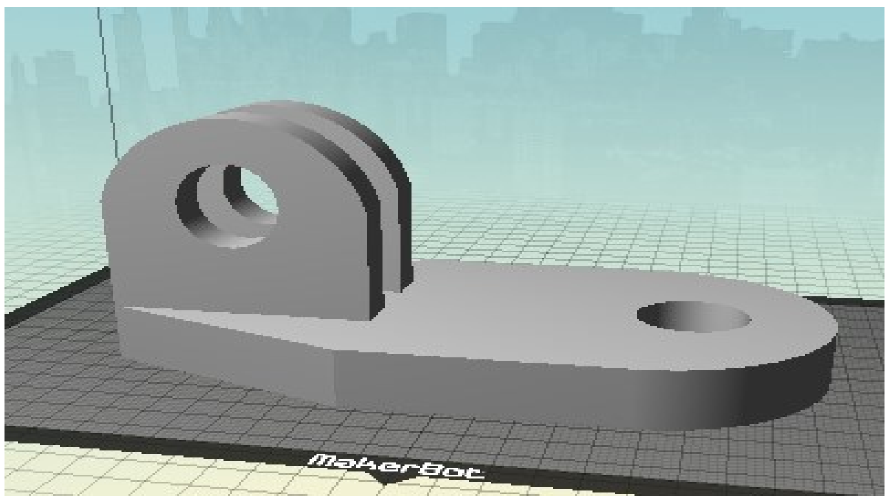


Figure 4.3 Gopro_adapter-3D View

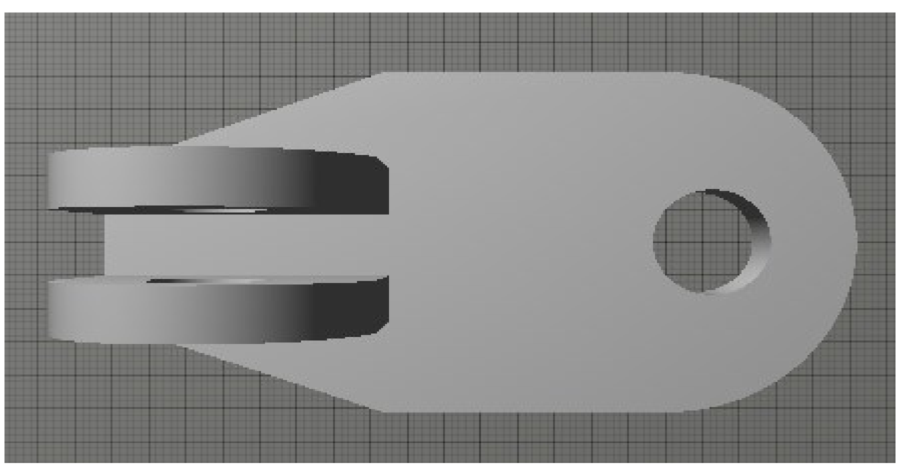


Figure 4.4 Gopro_adapter-Top View

Table 4.2 shows the values for different parameters of the selected parts.

Table 4.2 Dataset of Parts with Their Dimensions

part	x	y	z	SA	v	xy	ZSA	EV
calibration_angle	1.97	1.97	0.20	5.05	0.17	3.88	0.99	0.76
clip_mk1	0.39	0.26	0.30	0.73	0.01	0.10	0.22	0.03
DCU224C-M4-adapter	1.26	2.05	0.16	6.07	0.37	2.58	0.96	0.41
Desk_Knob	1.08	1.08	0.66	3.31	0.22	1.17	2.18	0.77
drawer_bracket	2.36	1.68	1.63	16.12	1.07	3.98	26.21	6.47
egranaje_carro	3.19	3.16	0.85	28.03	3.83	10.06	23.85	8.56
embudo_con	5.12	4.72	5.12	76.55	3.17	24.18	391.81	123.76
eninge	2.49	2.49	4.14	50.77	10.96	6.18	210.23	25.59
gear	4.17	4.17	1.13	44.39	13.80	17.38	50.16	19.64
gopro_adapter	7.51	3.77	3.30	92.51	22.89	28.34	305.60	93.63
HotTub	2.79	2.47	1.65	35.62	7.00	6.89	58.87	11.39
InnerCircle	5.63	5.63	0.89	52.61	1.98	31.70	46.87	28.24
knob2	0.77	0.77	0.65	3.30	0.22	0.60	2.14	0.39
M8_nut_knob	5.67	5.67	0.71	42.51	9.33	32.14	30.13	22.78
motor_mount(1)	1.10	1.43	1.18	8.86	0.44	1.58	10.47	1.86
patita_qav500	8.84	4.26	1.06	81.68	19.10	37.69	86.82	40.06
pinza_izquierda	9.21	3.68	0.55	47.41	9.10	33.91	26.19	18.73
rod_holder	6.11	2.01	3.38	69.39	16.83	12.28	234.58	41.51
saw_elbow	2.68	2.68	4.33	62.05	4.26	7.17	268.71	31.04
SpoolHolder1	2.56	2.56	0.98	15.12	2.35	6.55	14.88	6.45
Teil1_Light	4.72	4.72	1.10	45.77	1.77	22.32	50.46	24.60
thumb_screw	1.15	1.15	0.39	3.48	0.23	1.32	1.37	0.52
K8200_webcam_mount1	2.56	2.56	0.53	12.61	0.85	6.55	6.71	3.49
Spool_sleeve1	1.78	1.78	3.27	31.55	1.80	3.15	103.11	10.30
1inch_filter_adapter	2.00	2.00	0.35	10.05	0.38	4.00	3.56	1.42

MakerWare is a software that enables the users to open stl. files and send them to the FDM 3d printers. This software is capable estimating the total print time of the imported part. In order to check the accuracy of the predicted print time by the software, two cubes with different sizes and features were designed and printed by the FDM 3D printer. These parts are shown in Figure 4.5 and 4.6. The estimated times by MakerWare for building the first and second parts were 10 and 55 minutes respectively and the actual times for building these parts with the 3D printer were12 and 54 minutes. Because of the negligible difference between the estimated time and the actual time, the software will be used for generating reference time estimates in this research.

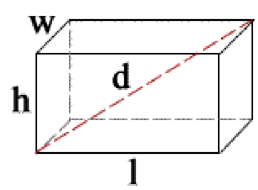


Figure 4.5 First Cube

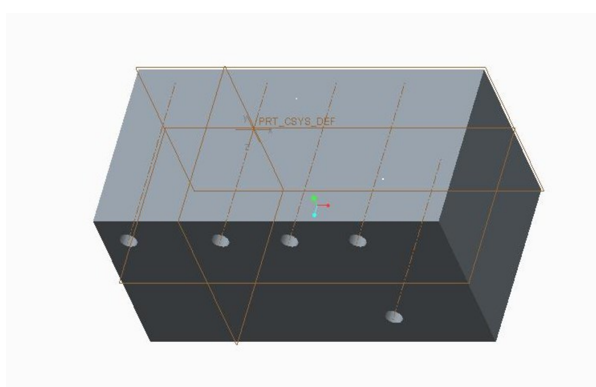


Figure 4.6 Second Cube

Table 4.3 illustrates the parts and their respective build time generated by the MakerWare software.

Table 4.3 Dataset of Parts with Their Build Time

Part Name	Total Print Time (hrs)
calibration_angle	0.33
clip_mk1	0.07
DCU224C-M4-adapter	0.37
Desk_Knob	0.28
drawer_bracket	1.10
egranaje_carro	2.02
embudo_con	4.53
eninge	3.98
gear	3.90
gopro_adapter	7.55
HotTub	2.92
InnerCircle	3.07
knob2	0.23
M8_nut_knob	3.30
motor_mount(1)	0.58
patita_qav500	6.73
pinza_izquierda	3.57
rod_holder	5.90
saw_elbow	4.00
SpoolHolder1	1.20
Teil1_Light	2.90
thumb_screw	0.23
K8200_webcam_mount1	0.83
Spool_sleeve1	2.03
1inch_filter_adapter	0.55

. In this model, the dependent variable is the total print time, independent variables are the attributes shown in Table 4.1, and the significant level is equal to 0.05. As discussed earlier, the first step is to identify the variables which have the most impact on the build time. Table 4.4 illustrates the regression results based on the values of the independent variables of the 25 selected parts and build time that is shown in table 4.2.

Table 4.4 First Stepwise Regression

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.01	0.06	-0.17	0.86	-0.13	0.11	-0.13	0.11
x	0.03	0.02	1.45	0.17	-0.02	0.08	-0.02	0.08
y	-0.02	0.03	-0.62	0.54	-0.07	0.04	-0.07	0.04
z	0.01	0.04	0.18	0.86	-0.07	0.09	-0.07	0.09
SA	0.07	0.00	21.37	0.00	0.06	0.07	0.06	0.07
v	0.10	0.00	20.90	0.00	0.09	0.11	0.09	0.11
xy	-0.02	0.01	-2.65	0.02	-0.03	0.00	-0.03	0.00
ZSA	0.00	0.00	-2.03	0.06	0.00	0.00	0.00	0.00
EV	0.00	0.00	0.81	0.43	0.00	0.01	0.00	0.01

As can be seen in table 4.4, the Z parameter (height) has the highest p-value which is also more than level of significant (5 %). Therefore, it is concluded that, the Z does not have a significant impact on the build time and requires to be removed from the table. The regression analysis needs to be run with the collected data excluding the Z. The results is shown in Table 4.5.

Table 4.5 Second Stepwise Regression

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.01	0.05	-0.12	0.91	-0.11	0.10	-0.11	0.10
x	0.03	0.02	1.49	0.16	-0.01	0.08	-0.01	0.08
y	-0.02	0.02	-0.63	0.54	-0.07	0.04	-0.07	0.04
SA	0.07	0.00	22.77	0.00	0.06	0.07	0.06	0.07
v	0.10	0.00	22.41	0.00	0.09	0.11	0.09	0.11
xy	-0.02	0.01	-2.76	0.01	-0.03	0.00	-0.03	0.00
ZSA	0.00	0.00	-2.60	0.02	0.00	0.00	0.00	0.00
EV	0.00	0.00	0.84	0.41	0.00	0.00	0.00	0.00

In this step, Y (width) is deleted from the data and regression analysis is run again. Table 4.6 shows the result after eliminating Y factor.

Table 4.6 Third Stepwise Regression

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.03	0.03	-1.10	0.28	-0.09	0.03	-0.09	0.03
x	0.04	0.02	2.11	0.05	0.00	0.08	0.00	0.08
SA	0.07	0.00	24.04	0.00	0.06	0.07	0.06	0.07
v	0.10	0.00	23.89	0.00	0.09	0.11	0.09	0.11
xy	-0.02	0.01	-4.02	0.00	-0.03	-0.01	-0.03	-0.01
ZSA	0.00	0.00	-2.60	0.02	0.00	0.00	0.00	0.00
EV	0.00	0.00	0.87	0.39	0.00	0.00	0.00	0.00

According to the result, EV (working envelope) does not have a significant impact on build time and requires to be removed. By running the regression model for another round, X (length) is the next insignificant parameter on build time. Table 4.7 illustrates the result. The p-value of the remaining parameters are equal to zero which is less than the level of significant. The regression model is run one more time to confirm that the p-value of the variables are less than the 5%.

Table 4.7 Forth Stepwise Regression

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.03	0.03	-1.06	0.30	-0.09	0.03	-0.09	0.03
x	0.04	0.02	2.03	0.06	0.00	0.08	0.00	0.08
SA	0.06	0.00	27.75	0.00	0.06	0.07	0.06	0.07
v	0.10	0.00	24.68	0.00	0.09	0.11	0.09	0.11
xy	-0.02	0.00	-4.64	0.00	-0.03	-0.01	-0.03	-0.01
ZSA	0.00	0.00	-3.54	0.00	0.00	0.00	0.00	0.00

Table 4.8 illustrates the last step of the regression analysis. This analysis is terminated because all p-values are less than the level of significant (5%). According to this result, SA, V, XY, and ZSA are the most significant geometric parameters on time estimation.

Table 4.8 Fifth Stepwise Regression

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.01	0.02	0.22	0.83	-0.05	0.06	-0.05	0.06
SA	0.06	0.00	26.23	0.00	0.06	0.07	0.06	0.07
v	0.10	0.00	25.99	0.00	0.09	0.11	0.09	0.11
xy	-0.01	0.00	-4.24	0.00	-0.02	-0.01	-0.02	-0.01
ZSA	0.00	0.00	-3.48	0.00	0.00	0.00	0.00	0.00

Based on the equation 4-1, the time estimator can be derived from following formula:

Print Time=0.005390527+(0.064608959*SA)+(0.102169623*V)-(0.011981463*XY)-(0.001236407*ZSA) (4-2)

To validate the above equation, 10 parts with dimensions less than 10 inches are selected from Thingiverse website. Table 4.9 shows the names of the parts with their respective dimensions, time estimation based on the obtained equation and the actual build time obtained through printing the parts on the 3D printer.

Table 4.9 Dataset of Parts for Validation of Linear Equation

part	x	y	z	SA	v	xy	ZSA	Actual Time (hr)	Time Estimation (hr)	Error percentage
FPV250	2.02	2.02	0.07	7.96	0.24	4.10	0.53	0.45	0.49	9.79
PRN3D	1.18	0.79	0.79	7.31	0.33	0.93	5.76	0.50	0.49	-1.31
Manifold	4.08	4.08	4.20	131.30	23.84	16.63	551.48	10.35	10.04	-2.96
Ring	1.34	1.55	0.40	4.49	0.26	2.07	1.78	0.30	0.29	-1.81
RocketPlug	5.13	5.12	4.78	81.55	35.98	26.27	389.92	8.30	8.15	-1.77
WheelHub-3	5.63	5.63	2.36	92.78	28.15	31.70	219.15	8.00	8.22	2.81
Print_Bed	6.30	5.63	1.34	92.51	30.16	35.46	123.97	8.28	8.49	2.44
i3support	7.87	4.85	1.92	72.92	15.53	38.18	140.24	5.40	5.67	5.06
i3_LCD	8.67	3.47	1.03	54.41	6.53	30.12	56.29	3.98	3.76	-5.68
AC_Adapter	0.49	0.49	0.48	0.87	0.03	0.24	0.42	0.08	0.06	-26.61

The average difference between the actual build time and estimated time by the formula is negligible (6.02%). Therefore, it is concluded that equation (3-2) produces satisfactory results for the family of parts that is within the scope of this work.

Complexity Analysis

Equation (4-2) is obtained based on different parts (see Table 4.2) with different complexities. The variables participating in this equation (SA, V, XY, and ZSA) are all geometric variables. However, these variables do not encode the complexity of the parts. It is necessary to investigate if the complexity of parts has any impact on the build time. In other words, we would like to study if two parts with similar geometric attributes but different complexity levels yield similar build time. Parts in Figure 4.7 and 4.8 have the same bounding boxes. It is obvious that the first part is more complex than the second part. If a traditional subtractive process is used for producing these parts, it is recognizable that the parts shown in Figure 4.7 will take much longer to produce compared to the part shown in Figure 4.8. FDM 3D printer builds the first part in 16.2 minutes and the second part in 16.8 minutes. In this example, the more complex part has shorter build time but only in the order of a fraction of minute.

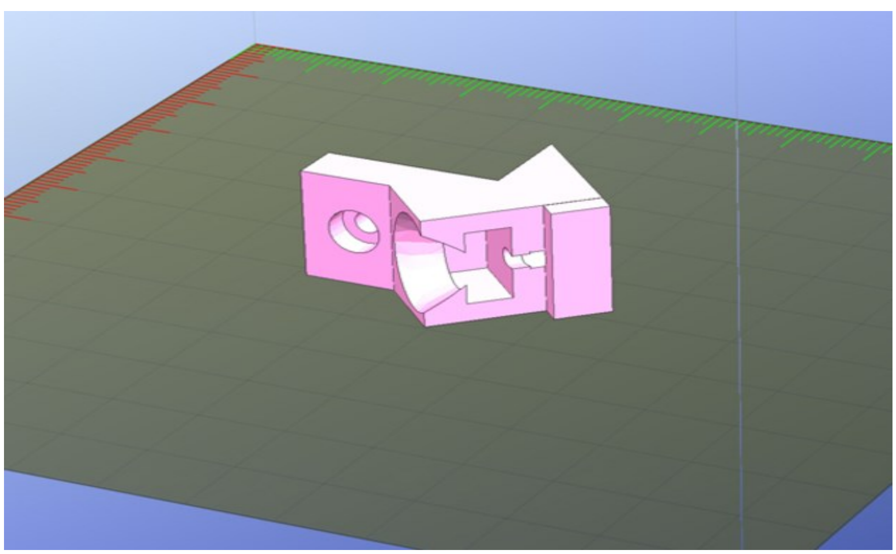


Figure 4.7 Complex Part

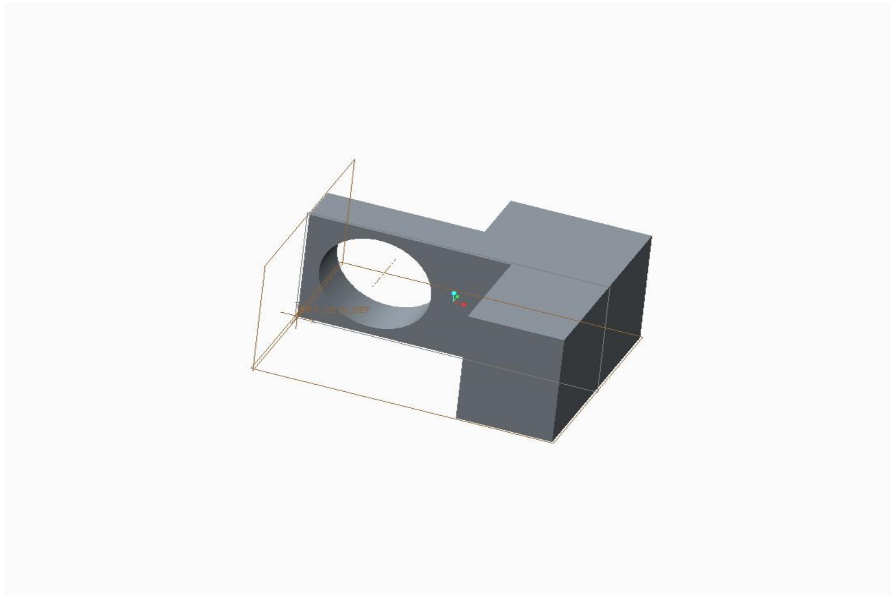
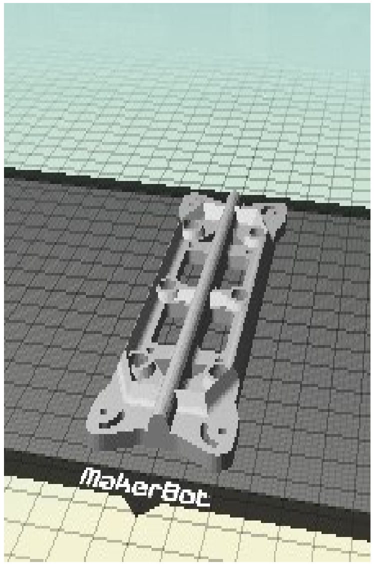


Figure 4.8 Simple Part

For analyzing the difference statically, a hypothesis testing was formulated with the null hypothesis being “the complexity of parts have no significant impact on the build time”. To test the described hypothesis, two groups of parts were created. One group consists of multiple complex objects. The other group includes the simple parts which are designed based on the each complex objects with roughly same dimensions. The parts in the simple group were created by eliminating the complicating features of the complex parts. For instance, Figures 4.9 and 4.10 show one of the complex parts from two different views. The required time to build this part is 1.45 hours.



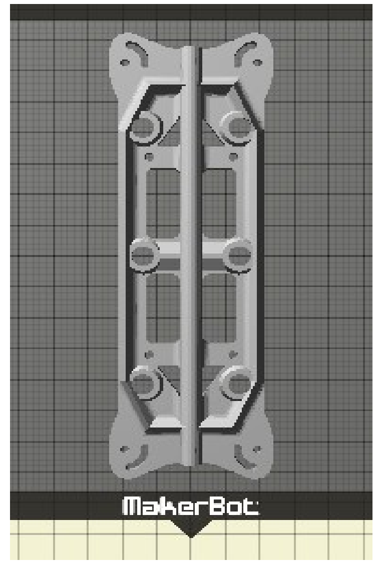
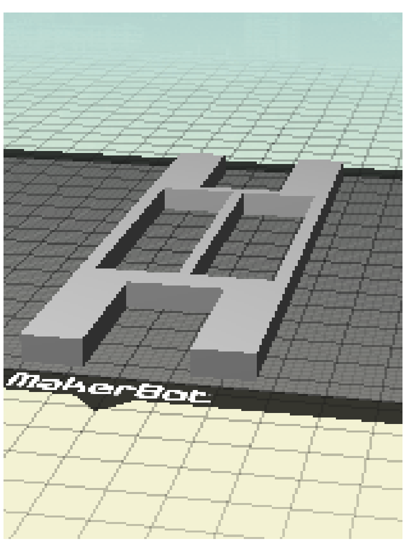


Figure 4.9 Reinbezcarbon-3D View **Figure 4.10 Reinbezcarbon-Top View**

The simple part corresponding to the part Figure 4.9 was designed by eliminating some geometric features while keeping the overall dimensions. Also, volume and surface area were kept equal. This part is shown in Figure 4.11 and 4.12 from different views. The required time to build this simple part is 1.2 hours. Nine pairs of parts were designed and their actual print times were measured.



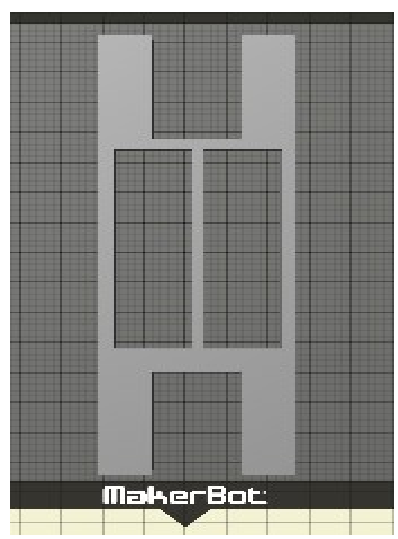


Figure 4.11 Simple Reinbezcarbon-3D View **Figure 4.12 Simple Reinbezcarbon-Top View**

A t-test was designed to compare the means of two samples. The t-test is helpful when the variances of two distribution is unknown and the sample size is small. Also, it is assumed that the population is normally distributed. The null hypothesis assumes the samples belong to the same populations, thus having equal means. Figure 4.13 illustrates the t-test model.

Null hypothesis: $H_0: \mu_1 - \mu_2 = \Delta_0$

Test statistic:

$$T_0 = \frac{\overline{X}_1 - \overline{X}_2 - \Delta_0}{S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

Alternative Hypothesis	Rejection Criterion
$H_1: \mu_1 - \mu_2 \neq \Delta_0$	$t_0 > t_{\alpha/2, n_1+n_2-2}$ or $t_0 < -t_{\alpha/2, n_1+n_2-2}$
$H_1: \mu_1 - \mu_2 > \Delta_0$	$t_0 > t_{\alpha, n_1+n_2-2}$
$H_1: \mu_1 - \mu_2 < \Delta_0$	$t_0 < -t_{\alpha, n_1+n_2-2}$

Figure 4.13 T-test Model

S_p is pooled estimator of σ and is defined by the formula shown in Figure 4.14.

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}$$

Figure 4.14 Pooled Estimator of σ

Where $\bar{x}_1$ and $\bar{x}_2$: sample means of the first and second group

n_1 and n_2: sample size of the first and second group

s_1 and s_2: sample variance of the first and second group

α: level of significant

10 complex parts and 9 simple parts were built by FDM technology and time involved to build the parts were estimated through simulation. These observations are summarized in Table 4.10 and 4.11.

Table 4.10 Group 1 Complex Parts

part	x	y	z	SA	v	xy	ZSA	Time (hr)
shiny_juttuli-fulffy	2.87	3.99	0.59	38.20	3.87	11.48	22.56	2.68
flag_piece_1_red	6.39	3.73	1.58	160.10	18.29	23.86	252.63	10.35
Filamento_Filtro_UP	1.01	1.33	0.59	4.18	0.23	1.35	2.47	0.27
calibrator_50mm	2.68	3.03	0.79	19.59	2.21	8.12	15.43	1.32
reinbezcarbon	1.84	5.63	0.28	22.40	1.18	10.36	6.22	1.45
rodToPvcElbow3	1.13	1.94	1.56	14.79	1.11	2.19	23.14	0.93
Multirotor_Motor	2.65	1.30	3.00	13.84	0.51	3.45	41.51	1.13
i3carriage_fuse	5.34	5.45	2.52	89.79	7.63	29.10	226.28	5.75
DriveBlockLeverLeft	1.64	1.28	0.37	4.48	0.25	2.10	1.68	0.28
Prusa_I3_Rework	1.58	1.57	2.01	14.28	0.46	2.48	28.75	0.88

Table 4.11 Group 2 Simple Parts

part	x	y	z	SA	v	xy	ZSA	Time (hr)
simple shiny	2.87	3.99	0.59	37.57	4.15	11.45	22.17	2.68
simple flag	6.39	3.73	1.58	105.13	18.26	23.83	166.10	7.63
simple filamento	1.01	1.33	0.59	4.07	0.36	1.34	2.40	0.28
simple calibrator	2.68	3.03	0.79	19.67	3.82	8.12	15.54	1.52
simple reinbezcarbon	1.84	5.63	0.28	18.14	1.23	10.36	5.08	1.20
simple rodtopvc	1.13	1.94	1.56	14.99	2.13	2.19	23.39	0.98
simple multirotor	2.65	1.30	3.00	13.94	0.41	3.45	41.81	1.27
simple driveblock	1.64	1.28	0.37	4.04	0.35	2.10	1.49	0.27
simple prusa	1.58	1.57	2.01	16.92	0.77	2.48	34.00	0.98

Based on the procedure shown in Figure 4.13, t-test is applied and Table 4.12 illustrates the results of the t-test.

Table 4.12 T-test Result

	Time (hr), First Group	Time (hr), Second Group
	2.68	2.68
	10.35	7.63
	0.27	0.28
	1.32	1.52
	1.45	1.2
	0.93	0.98
	1.13	1.27
	5.75	
	0.28	0.27
	0.88	0.98
Mean	2.50	1.87
Standard Deviation	3.19	2.28
n (participant)	10.00	9.00
Variance	10.18	5.18
$S_p^{\ 2}$	7.825	
S_p	2.797	
t_0	0.495	
α	0.05	
$t_{\frac{\alpha}{2},n1+n2-2}$	2.11	

$-t_{\frac{\alpha}{2}+n1+n2-2} < t_0 < t_{\frac{\alpha}{2}+n1+n2-2}$ or -2.11<.495<2.11

According to the results, with the given level of significant, we fail to reject the null hypothesis. Therefore, with %95 confidence, the sample means of the complex and simple parts are equal. In other words, increasing the complexity of parts will not increase the print time.

Conclusion

This chapter described the regression analysis for creating a predictive model for print time. The most influential geometric attributes in time estimation for FDM technology were found to be SA, V, XY, and ZSA. Based on these attributes, a linear equation for time estimation was derived. The linear equation was validated with examination of 10 more parts with different complexities. Furthermore, the effects of complexity on the total build time was studied. The null hypothesis was accepted at the %5 significant level by using the t-test. Acceptance of the null hypothesis confirmed that the time estimation mainly depends on the described geometric attributes of the parts rather than the features of the parts.

CHAPTER V

FUTURE OF 3D PRINTING

Introduction

3D printing technology has already had significant impacts in different industry sectors and will continue to be a game-changing technology in the years to come as the technology evolves. Also, it is increasingly becoming more efficient, available, and affordable. During the early years of introduction, 3D printing technologies had many limitations in terms of printable materials, achievable geometry and quality. However, as the additive manufacturing technologies gained more maturity in time, they started to be widely used in various industries such as manufacturing, medical, aerospace, automotive, and the military. The accelerating growth of 3D printing technologies and their associated equipment have opened up many new possibilities in advanced manufacturing of complex products. At the other end of the spectrum, due to the simplicity and affordability of some 3D printing technologies, they are being used in simple prototyping by non-expert users.

In this chapter, the future of 3D printing technologies, their impacts, and their implications in various industry sectors is investigated. The objective is to provide a predictive analysis on how the product design and development practice will change due to the availability of different 3D printing processes and machines.

According to Wohlers Associates, the revenues from some firms' products and services in 3D printing industry is $2.2 billion today. It would be increased to $6 billion by 2017 and $100 to $200 billion annually by 2025, by which time about 30% to 50% of complicated and low-volume parts would be printed. About 28% of investment on this technology is for final products. The research firm estimates that this number will increase to more than 50% by 2016 and over 80% by 2020. 3D printing is finding its way into almost all industries. Therefore, the price of some machines has dropped quickly over the last two years from $20,000 to $1,000 now.

3D printing will change the current processes of many fields such as entertainment, education, aerospace, medical, manufacturing and so on. Some of the fundamental changes in different sectors are discussed below.

Entertainment

Researchers predict that 3D printers will be part of our daily lives (Bilton, 2013). The machines will be as valuable at every home as they are in the industrial fields. People will fix their problems by themselves, such as printing their broken blenders, clocks, replacement for a dishwasher rack, or parts of the espresso machines by downloading their 3D designs online. Some existing websites, such as Thingiverse (thingiverse.com) which holds more than 36,000 downloadable designs, are populated by hobbyists on a daily basis. Users design and print plastic parts such as sculpture, bottle opener, key chain, phone case, iPhone car holders, and shoes, which they can then share the printable files on web portals. Figure 5.1 illustrates how people can take advantage of 3D printers to build their desirable sculpture. Despite the advanced capabilities of current 3D printers, the machines will evolve to become simple enough for novice users. Based on the described predictions about the role of 3D printing for hobbyists, people will have 3D printers at home as necessary as their TVs. The number of websites such as Thingiverse will increase and provide numerous downloadable designs for consumers. Users will print out most of their requirements by using 3D printers instead of buying or repairing them, only by downloading the required designs and importing them to the 3D printers. Thus, this technology will change the way that people provide their suppliers and make it easier for them.

Figure 5.1 Sculpture Created By 3D Printing

Education

3D printing is worming into the education system as well. Some schools in different countries such as Youngstown, Ohio, have plans to use this technology in their education system (Bilton, 2013). “The University of Virginia has been working to introduce 3D printers into some programs from kindergarten through 12th grade in Charlottesville to prepare students for a new future in manufacturing" (Bilton, 2013). Figure 5.2 shows a group of students familiarizing themselves with this new technology by creating their own objects. Glen L. Bull, professor and co-director of the Center of Technology and Teacher Education, stated that "We have 3D printers in classrooms, and in one example, we are teaching kids how to design and print catapults that they analyze for efficiency. We believe that every school in America could have a 3D printer in the classroom in the next few years" (Bilton, 2013). By using 3D printers at schools, children can build and test their ideas in real space. This opportunity will assist them to improve their creativeness. Based on the rising utilization of 3D printers in different sectors of industries, children will encounter this technology in their future careers. Therefore, education systems need to be equipped by 3D printers to prepare the children for solving challenges in their future jobs.

Figure 5.2 Building Parts With 3d Printers by Children at School

Aerospace

Since complex parts can be built as easy as simple parts by 3D printers without using any special tools, this technology has fundamental effects on the aerospace field. GE, the world's largest supplier of jet engines, stated that additive manufacturing is the "next chapter in the industrial revolution" (Regan, 2014). GE Aviation estimates that 100,000 parts will be 3D printed by 2020. These parts will decrease 1,000 pounds of the weight of an aircraft engine, improve the fuel economy, and reduce the CO2 emission.

Additive manufacturing provides an opportunity to utilize Titanium for creating parts without wasting materials. "Titanium is low density, high strength, corrosion resistant, and biocompatible—ideal for use in both the aerospace and implant industries" (Regan, 2014). It is not an affordable option to use Titanium in traditional manufacturing because of its price and high amounts of waste. Moreover, GE takes advantage of 3D printing to build their critical fuel nozzle instead of using casting and welding. Each nozzle includes 18 parts which were welded together by traditional methods. But with this new technology each part is made separately. Eventually, the nozzle is lighter by 25% compared to the nozzle manufactured by conventional processes. Also, it lasts five times longer. Each CFM LEAP (Leading Edge Aviation Propulsion) engine consists 19 fuel nozzles. Now, GE and the French aerospace company Snecma have received 4,500 engine orders. All these nozzles will be built by additive manufacturing. The number of nozzles will be increased over 35,000 annually by 2016. Figure 5.3 shows a nozzle that is created by a 3D printer.

Figure 5.3 Nozzle Created By 3D Printers

McKinsey Global Institute, a global management consulting firm, also reported that 3D printers will reduce product costs by 40 to 55 percent because of decreases the tooling cost, handling cost, and material waste. Furthermore, 3D printing technologies promote green manufacturing. "Comparing hinges that were cast in steel in the traditional manner to hinges that were 3D printed in titanium, they found the greatest environmental impact was in the parts' use phase. A plane with 3D- printed titanium hinges may weigh 10 kilograms less than a plane with conventional hinges, leading to reduced fuel consumption and CO2 emissions nearly 40 percent lower" (Regan, 2014). Figure 5.4 illustrates the hinges that are built by additive manufacturing.

Figure 5.4 Hinges Created By Additive Manufacturing

Medical Industry

Medical scientists do not deprive themselves from advantages of 3D printing. The 3D printers in medical fields, also known as bioprinters, print cells usually in a liquid or gel. The purpose of these bioprinters is to assemble living tissue. Researchers have been working to create cells layer by layer through a print-head without killing them. In the future, they will be able to make cartilage, bone, skin, blood vessels, small bits of liver, and other tissues by using bioprinters. "Dr. D' Lima, who heads an orthopedic research lab at the Scripps Clinic here, has already made bioartificial cartilage in cow tissue, modifying an old inkjet printer to put down layer after layer of a gel containing living cells. He has also printed cartilage in tissue removed from patients who have undergone knee replacement surgery" (Fountain, 2013). Researchers have already reached to some improvements in this field:

- A bioprinter has been made to create strips of liver, about 20 cells thick, by Organovo Company in San Diego
- Printing of skin cells have been experimented on by a lab at the Medical Schools in Germany
- Sheets of heart cells have been successfully printed by another German lab
- Fat tissues have been made by Thomas Boland at the university of Texas at El Paso

Figure 5.5 and Figure 5.6 illustrate the first 3D-printed human stem cells, and a layer of human skin that is made from stem cells by a 3D printer.

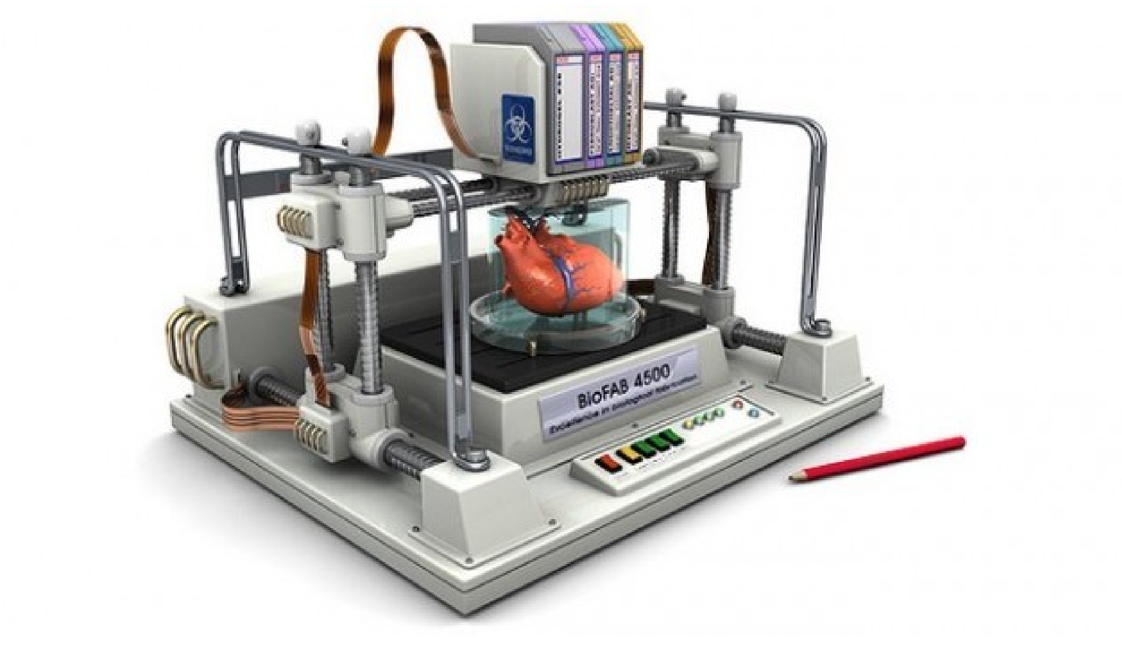


Figure 5.5 First 3D-Printed Human Stem Cells

Figure 5.6 Layer of Human Skin by 3D Printer

Despite these developments, there are some major problems that remain to be solved. One of the most challenging problems is to keep printed tissue nourished so that the cells can stay alive. This problem becomes more challenging as the shape, the composition, the type of cells, and the orientation of the cells need to be changed each layer during the printing process.

3D printing holds enough potential to inspire scientists to revolutionize the world of physicians. Their goal is "to have a printer in the operating room that could custom-print new cartilage directly in the body to repair or replace tissue that is missing because of injury or arthritis" (Fountain, 2013).

Manufacturing

Since the 3D printers were invented, they have been used to build the prototypes in different fields of industries. 3D printing technologies also impact manufacturing process. According to Wohlers Associates, final products will be made by 3D printers as well as prototyping parts (McCue, 2013). Tim Caffrey, senior consultant at Wohlers Associates, stated that “The money is in manufacturing, not prototyping. The opportunity for more commercial production activity from additive manufacturing is immense” (McCue, 2013). Aerospace and automotive industries are willing to use this technology in their production process. For instance, General Electric and Rolls Royce are planning to build the 3D printed components for their respective jet engines (Reis, 2014). As discussed earlier, the sale of 3D printing products and services will be increased. “In four years, Wohlers Associates believes that the sale of 3D printing products and services will approach $6 billion worldwide. By 2021, Wohlers Associates forecasts the industry to reach $10.8 billion. It took 3D printing industry 20 years to reach $1 billion in size. In five additional years, the industry generated its second $1 billion. It is expected to double again, to $4 billion, in 2015” (McCue, 2013). The predictions of increasing the sale of 3D printing products illustrate that it will be used in manufacturing the final products as much as the prototyping parts.

Stratasys, a world leader in 3D printing, claimed that they have been the pioneer of using the 3D printers in prototyping processes since 1989 (Nelson, 2012). This company has already utilized 3D printers in the manufacturing process as well. Melissa Hanson who is the marketing manager of RedEye on Demand, a business unit of Stratasys, stated that “We’re really the pioneer in taking this technology from rapid prototyping into manufacturing applications, making end-use parts that traditionally were made through injection molding" (Nelson, 2012). Figure 5.7 illustrates 3D printers in the production line of the RedEye Company. Using the 3D printing technologies to produce the final parts will expand to other manufacturers in few years.

Figure 5.7 3D Printers in the Production Line of the Redeye Company

Conclusion

This chapter described the future of 3D printing and their impacts on different fields of industries. 3D printing will be part of the daily activities of every person at home. It will change people from passive consumers to active innovators. Users will be able to fix damaged parts at home by using 3D printers and eliminate the cost of buying replacement parts. 3D printers enable people to customize their world by unleashing their creativeness and converting imaginary products to physical products. For instance, they can print out their desirable phone cases, stands, bracelets, earrings, and toys for their children. As discussed earlier, schools have been working on adopting this innovative technology as well. Teachers can take advantage of 3D printing by showing their students the three dimensional visual parts as necessary in their classrooms, and helping students grasp the concept of materials easily. It will increase the students' interest for learning and create opportunities for interactive class activities.

According to the obtained results from chapter 3, 3D printers take the same amount of time to create complex parts as they do to create simple parts. Aerospace industry can benefit from this opportunity to manufacture their complex parts without being concerned about their production-time. The other important point about producing aerospace parts through 3D printing is that the final parts will be much lighter and durable. Consequently, it will improve the fuel efficiency of the products, thus reducing their environmental impacts. The medical industry is the next field that 3D printing will change. For many years, human cells have been being reproduced by medical scientists in the laboratory in order to create blood vessels, urine tubes, skin tissue and other living body parts. However, reproducing full organs that possess complex cell structures is a complicated process in laboratories. Medical researchers believe that 3D printers have potential to create human organs. They have already reproduced the tiny strips of organ tissue by using this technology. As discussed earlier, scientists could create strips of liver about 20 cells thick. However, the most challenging problem that scientists confront with is to reproduce cells with adequate thickness which can stay alive. Nevertheless, they predict that a special kind of 3D printer will be created that can fit directly into the body in order to reproduce and replace the missing organs. By fulfilling this dream, the methods of the surgeries will be changed in the operating rooms. For instance, physicians will able to send the 3D printer to the patient's body due to reproduce the kidney and replace it with the missing one instead of doing surgery and take out one of the depraved kidney. In this way, patients will not suffer from having just one kidney.

Traditionally, 3D printings have been used for rapid prototyping and early stages of design concept developments. The next frontier for 3D printing is to manufacture the final products. Some companies such as General Electric, Rolls Royce, NASA, and Stratasys have been using 3D printers in their producing lines. Since the 3D printing technologies have been growing rapidly, it will be possible to utilize these technologies beyond the prototyping for most companies. As the results, manufacturers will reduce the cost associated with man-made involvement while the final products will be lighter with lower costs. Considered to all advantages of using 3D printing technologies in most sectors of industries, it is not far-fetched to call 3D printer as a revolution of technology in the next few years.

CHAPTER VI

CONCLUSION AND FUTURE WORK

The focus of this research was to identify which geometric parameters have the most impacts on time estimation using FDM technology and crested the build time based on these geometric attributes. In Chapter 3, the eight most important geometric attributes were identified. According to some researches, *multiple regression analysis* is helpful when there are two or more independent variables. The objective of this method is to analyze the independent variables and their effects on dependent variable. In this research, there are more than two variables, the independent variables are the eight selected geometric attributes, and the dependent variable is time estimation. There are several types of multiple regression analysis. The *stepwise regression analysis* was selected to figure out the most influential parameters and the final build time. The focus of stepwise regression is to analyze the predictor variables and their effects on predicted variable. The result of this method is the linear equation including multiple independent variables in order to predict the dependent variable. The stepwise regression method is capable to create the final model by removing or adding the predictor variables until there is no justifiable reasons to add or remove more variables. Therefore, the final model can be created by capturing all influential parameters. Moreover, if it is necessary, this method can be easily extended to the other regression problems. It is easy to explain and easy to compute as well.

To validate the final linear equation, 10 parts with different complexities were selected. The required time for creating these parts using FDM technology were identified. Moreover, the build times based on the obtained formula were measured. The average difference between the actual build time and estimated build time was negligible (-2). Therefore, the formula can be valid for the parts which fit into the scope of this research.

The answers to the research questions that were identified in Chapter 1 are provided in this chapter. Also, the future research direction in this area is discussed towards the ends of this chapter.

Answers to Research Questions

Research Question 1: What are the most influential geometric parameters in a predictive model for time estimation?

Response: As discussed earlier, the eight most important geometric attributes were identified in Chapter 3 which are length (X), width (Y), height (Z), volume (V), surface area (SA), product of the part height and surface area (ZSA), projected area of part to the working plane (XY), and product of X, Y, and Z or the working envelope (XYZ). 25 parts with different shapes and complexities were designed. The scope of this research was limited based on the size of the parts which was 10 inches at most for every main dimensions. The time involved for creating these parts by 3D printers were measured. Eventually, by applying the stepwise regression analysis, the results illustrated that the most influential geometric parameters are SA, V, XY, and ZSA. Furthermore, the final model is calculated by following formula:

Print Time=0.005390527+(0.064608959*SA)+(0.102169623*V)-(0.011981463*XY)-(0.001236407*ZSA)

Research Question 2: What is the impact of geometric complexity on the print time?

Response: According to the selecting parts regardless of their complexities, it was conceived that complexities may not have important role on build time and the described geometric parameters have the most impacts on time estimation. To prove this hypothesis, two groups included the simple and complex parts with the same main dimensions were designed. The actual build time for these parts were measured. By applying the t-test, the results showed that the mean of these two groups are equal. Therefore, the 4 described geometric parameters have the most impacts on time estimation rather than the complexities.

Research Question 3: What is the future impact of Additive Manufacturing in different industry sectors?

Response: As discussed in Chapter 4, 3D printing has already had significant impacts in different fields of industries such as manufacturing, education, aerospace, and medical. However, it is predicted that 3d printing will continue to change the methodology of the most industries. Most people will provide 3D printers at their houses as a necessary device. They will create their requirements at home by downloading the related files and transfer them to the machine. In manufacturing field, 3D printers will be used beyond the prototyping. 3D printers are capable to create the products lighter and more durable. Therefore, manufacturers will produce their final products by using this technology. Consequently, they can reduce the human resource's involvements and the defective products. Education system will be changed by using 3D printers at the schools. It will be beneficial for both teachers and students.

It can be a good opportunity for teachers to explain the materials in the practical manners. For instance, in biology class, teacher can print out the human's organs to teach students about human body. Therefore, it will make the materials more understandable for students and increase their interests on studying. Aerospace industry can also take advantages of 3D printing. In this industry, it is important to create parts with less weight. Because, lightness of the plane can reduce the fuel consumption and CO2 emissions. As presented earlier, 3D printing can build parts lighter and more durable. Therefore, using 3D printing will improve the fuel efficiency and green manufacturing. Furthermore, 3D printers give a chance to aerospace industry to utilize titanium in order to create lighter parts with less wasting. Medical industry is another sector which will be effected by 3D printing. Medical researchers have already created the tiny strips of organ tissue by using this technology. They believe that 3D printing will evolve the current methodology in laboratory in order to reproduce the human's organs with the complex cell structures. Furthermore, researchers will predict the creation of a special 3D printer which can place in a body and reproduce the missing human's organ.

Conclusion

Additive Manufacturing (AM) is the process of creating objects from 3D model data by adding materials layer by layer. AM eliminated some disadvantages of the traditional manufacturing processes such as welding and casting. It assists designers and manufacturers to produce the prototypes easier, faster, and cheaper. AM consists different processes or technologies which have been created since the late 1970s. Each technology possess some advantages and disadvantages. There are different machines and materials are used for each technologies. These technologies were discussed in Chapter 2. The acquisition of knowledge about differences in AM technologies allows manufacturers to compare the machines in terms of their sizes, qualities, speed of productions, and materials and select the best options based on their existing processes.

As mentioned in Chapter 1, there are different approaches to estimate the build time using additive manufacturing. Most of these methods are focused on the process parameters. In this research, the effect of the geometric parameters using FDM technology were analyzed and the build time model were identified in Chapter 3. By recognizing the most influential geometric parameters on build time using FDM technology, designers will create their projects by focusing on these important parameters in order to reduce the consuming time to build the objects. Furthermore, industrialists can select the 3D printers based on the machines' manufacturing speed through predicting the consuming time. One of the fundamental requirement to estimate the associated cost is consuming time. Therefore, time estimation can proceed to predict the involving cost of the AM process.

Based on the advantages of the 3D printing and its future impacts on the different fields of industry, it deserves to be called as the "next chapter in the industrial revolution" (Regan, 2014) or "future shock" (Kurutz, 2013). Therefore, it is significant for the most sectors of industry to improve the associated time and cost models that can provide the necessary infrastructures for adopting of AM technology.

Future Works

As discussed in Chapter 1, Hollis (2001) expressed a model for time estimation using Stereolithography (SLA) technology based on the geometric attributes which is:

Estimated Build Time= (0.0341) + (2.0 * Z) + (2.17 * VOL) + (0.018 * SA)

The most influential parameters in this model are height (Z), volume (VOL), and surface area (SA). These parameters are different from the geometric parameters which are obtained by this research using Fused Deposition Modeling (FDM) technology. According to have the same scope of work for these two researches, this differences might be because of the using different technologies or machines. Therefore, machine selection might have effects on time estimation. There is important to prove this theory. Because, if machine selection do not have the effects on time estimation, it will be possible to create the general model that can provide time estimation for all the current AM technologies. However, in case of having different models for each AM technologies, it can be beneficial to investigate the most influential geometric attributes for different AM technologies.

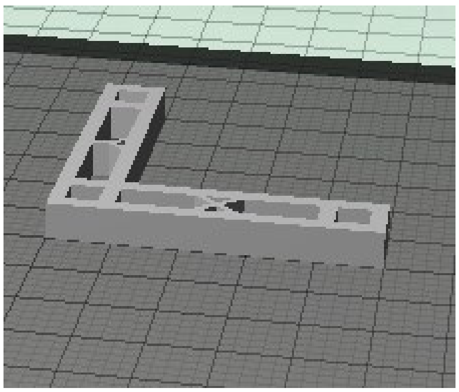
Furthermore, the presented final model for time estimation in this research are valid for the family of parts which possess main dimensions less than 10 inches. The similar process can be done for different sizes of products based on the each industries' requirements to figure out the build time using FDM technology.

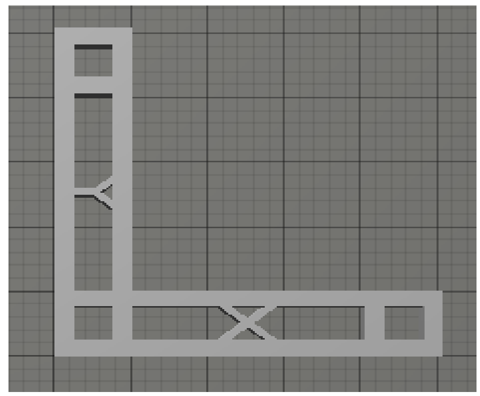
APPENDIX SECTION

APPENDIX A

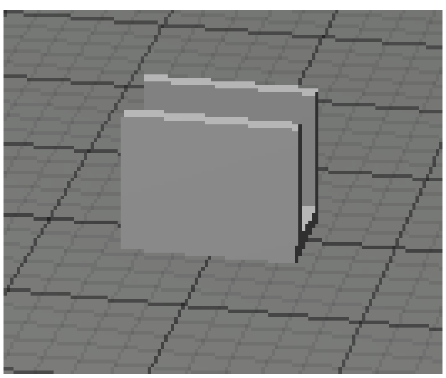
<u>25 Selected Parts</u>

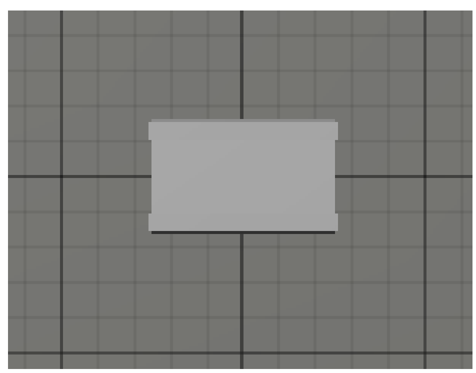
1) Calibration_angle



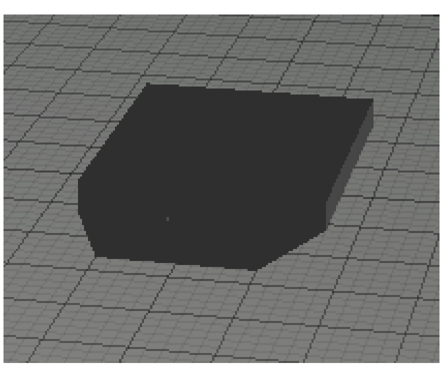


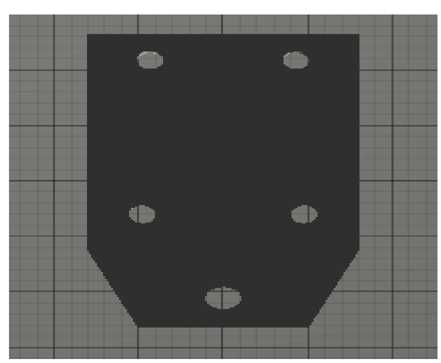
2) Clip_mk1



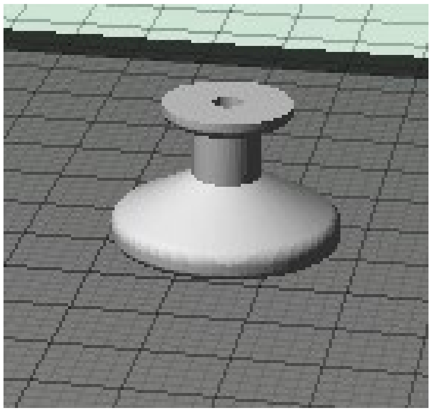


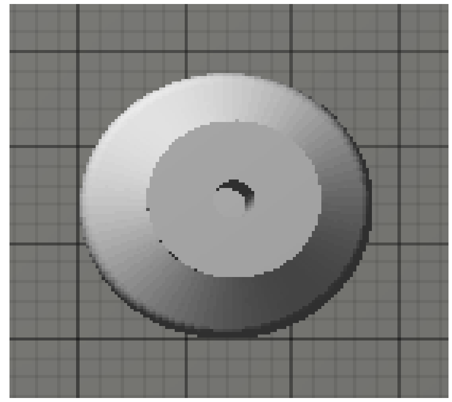
3) DCU224C-M4-adapter



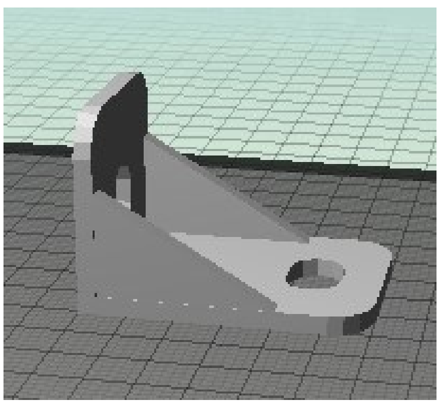


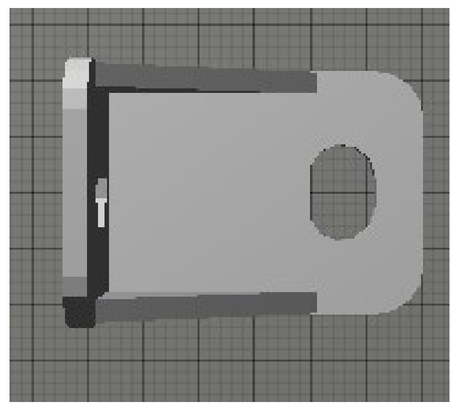
4) Desk_Knob



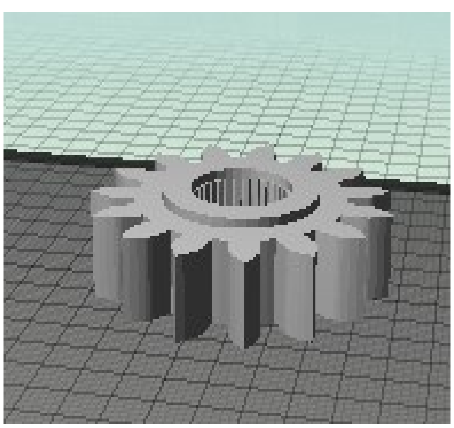


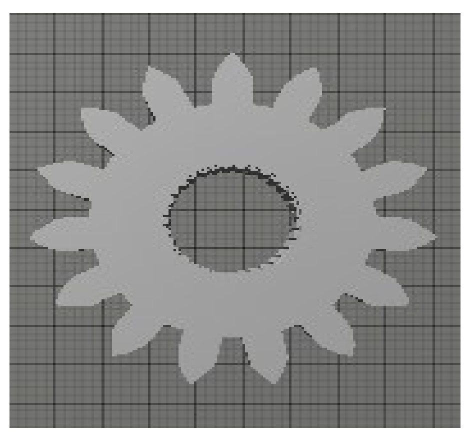
5) Drawer_bracket



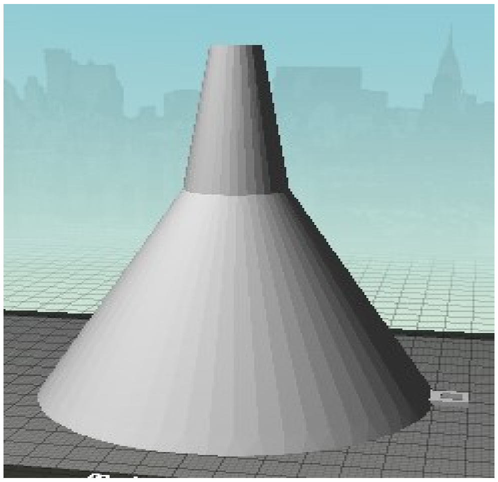


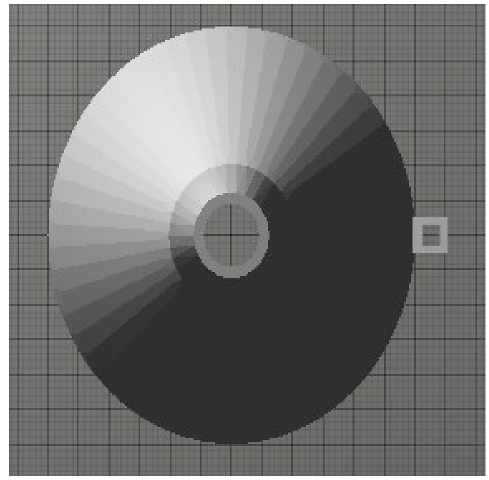
6) Egranaje_carro



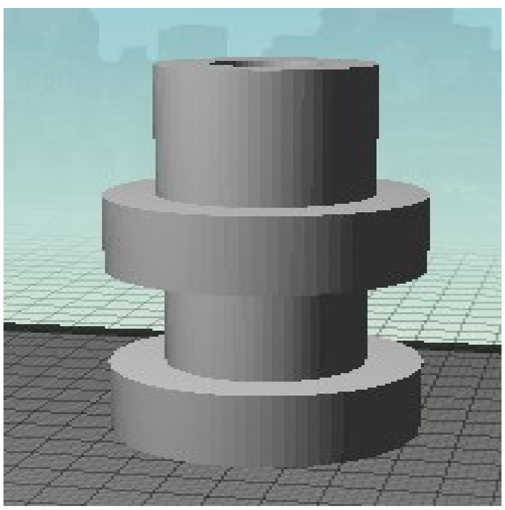


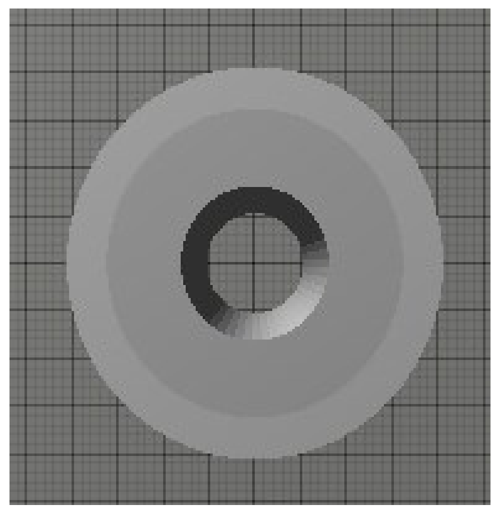
7) Embudo_con



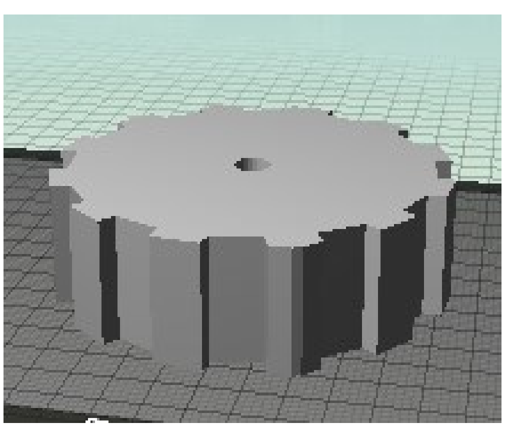


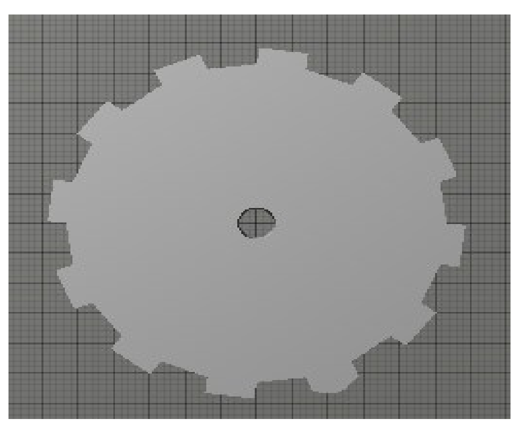
8) Eninge



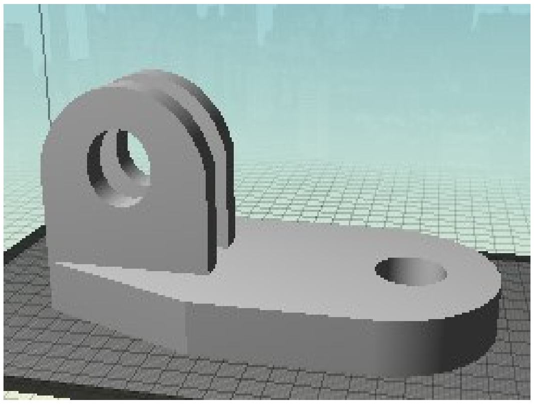


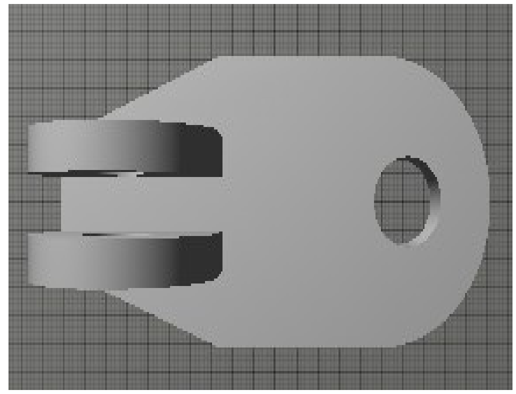
9) Gear



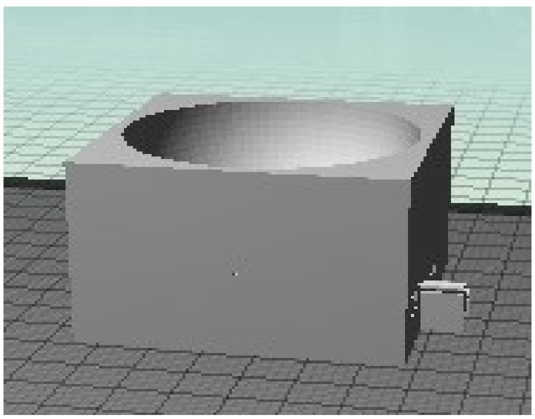


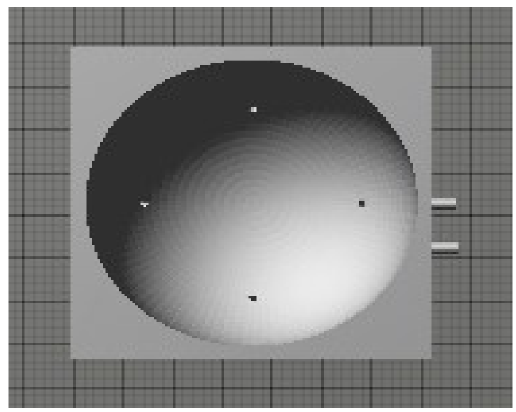
10) Gopro_adapter_2



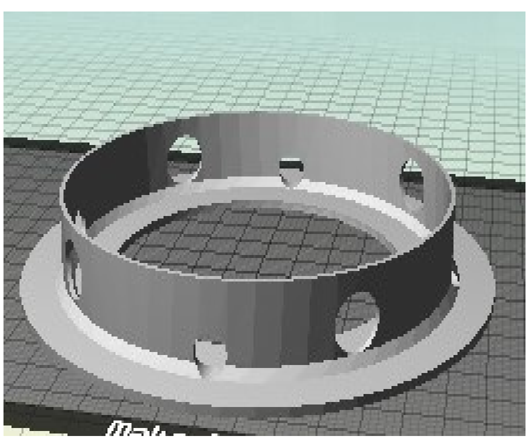


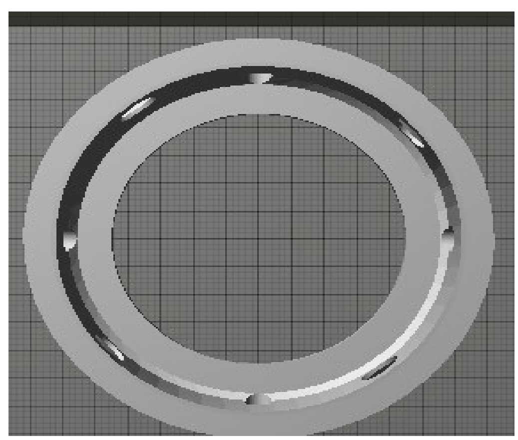
11) HotTub



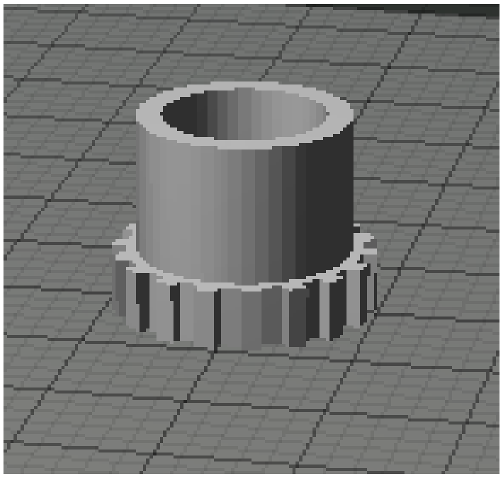


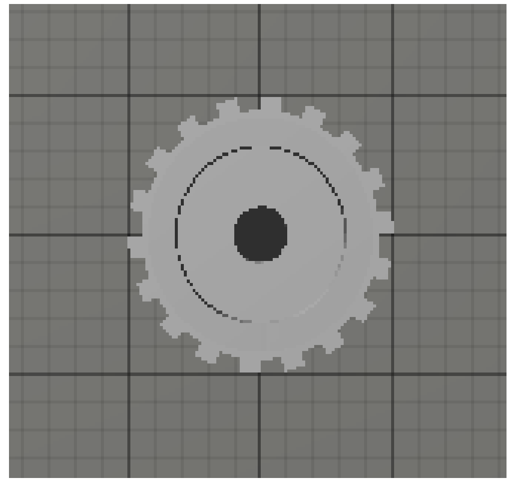
12) InnerCircle



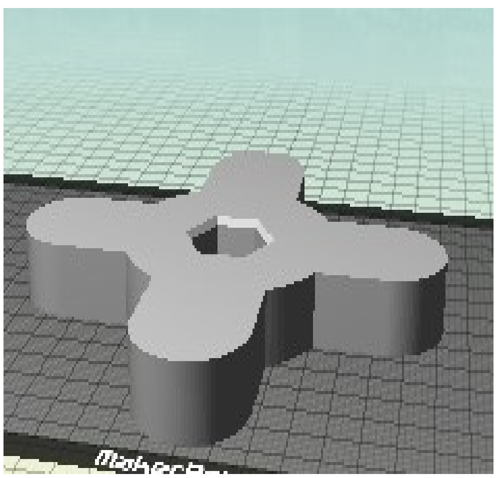


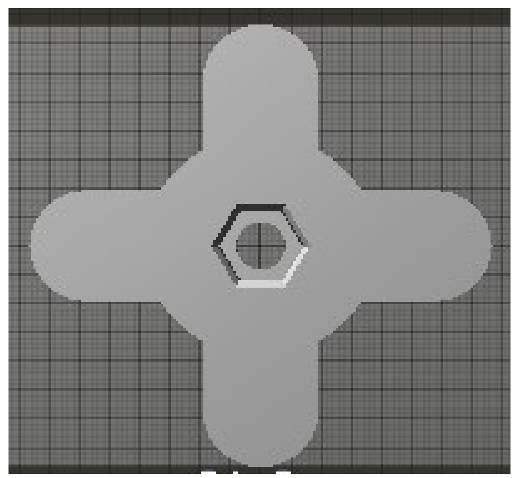
13) Knob2



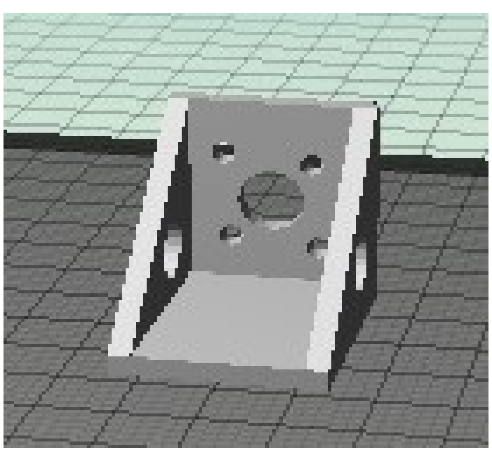


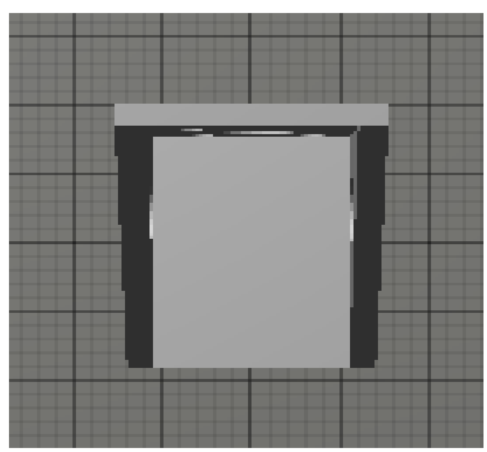
14) M8_nut_knob



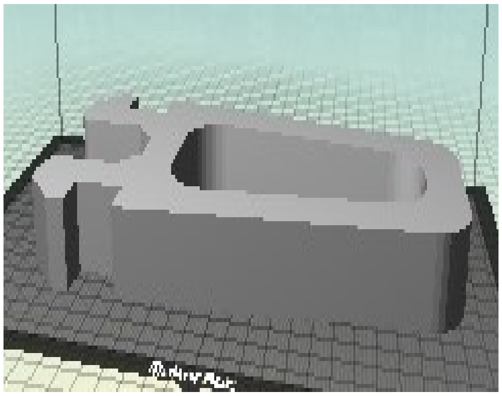


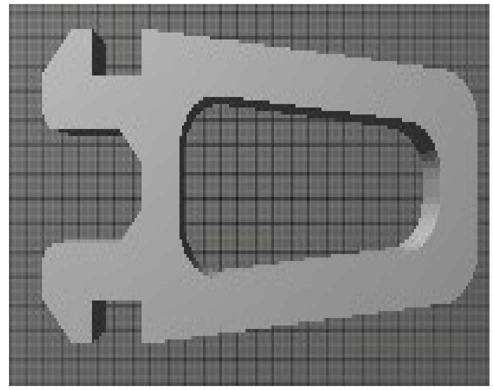
15) Motor_mount(1)



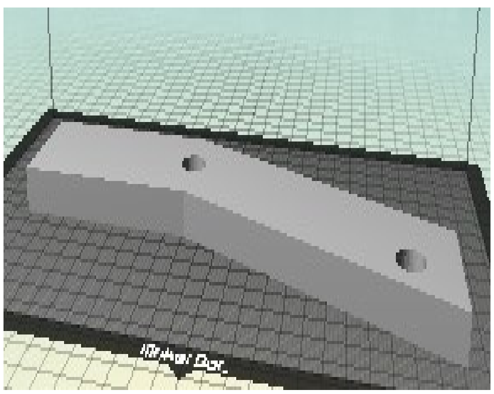


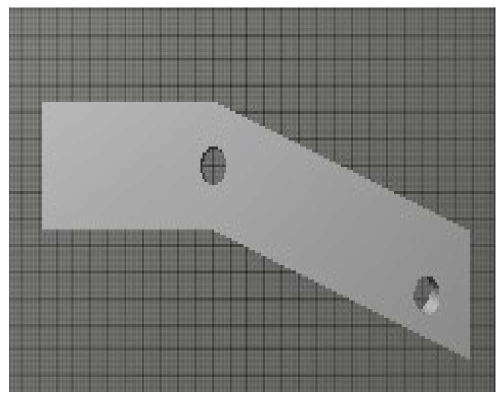
16) Patita_qav500



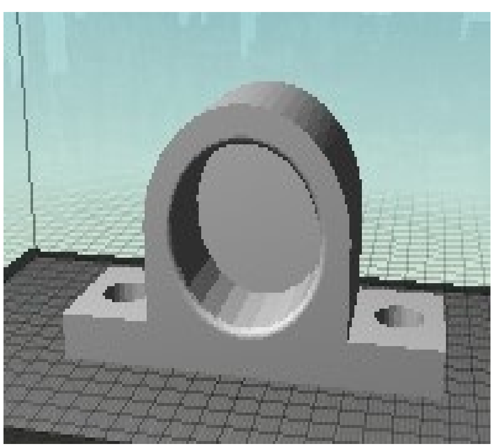


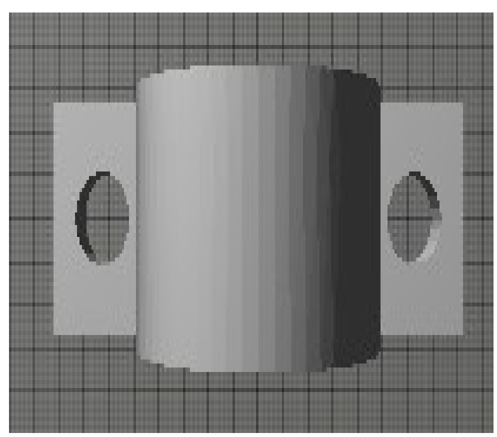
17) Pinza_izquierda



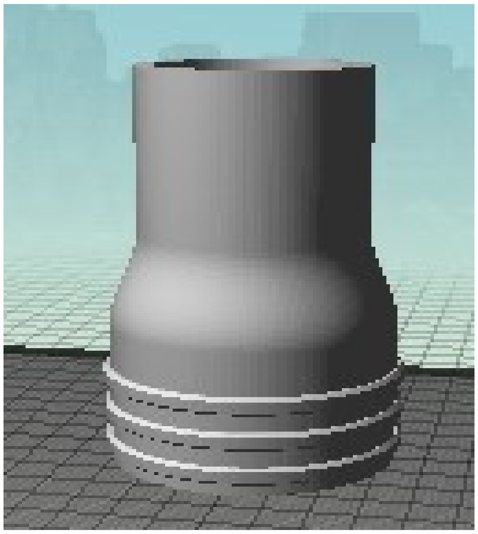


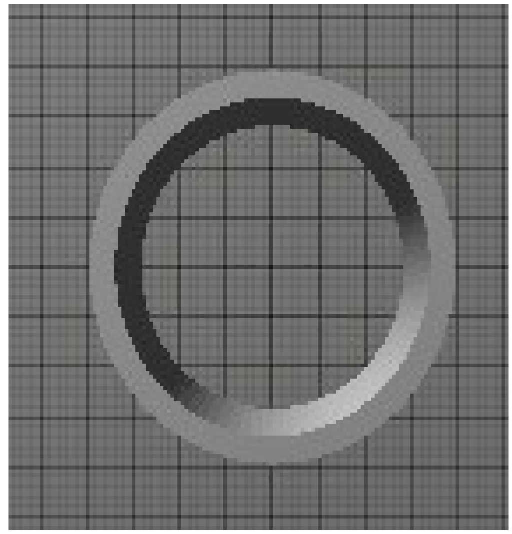
18) Rod_holder



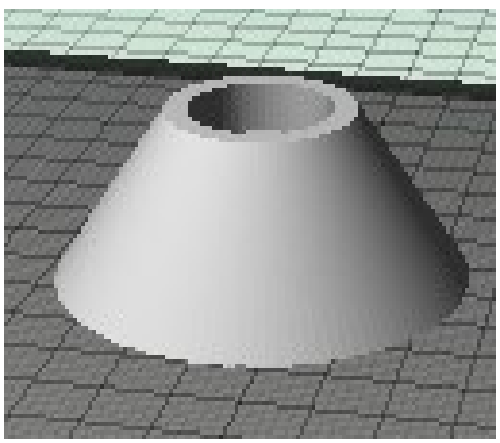


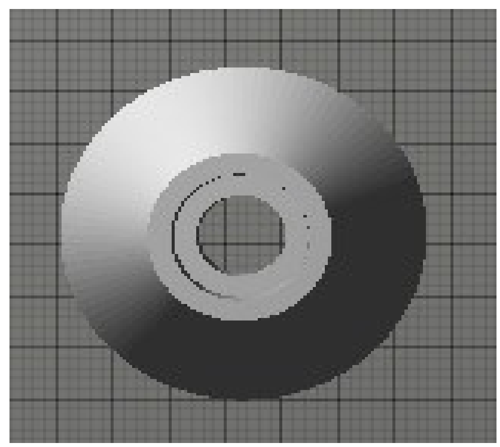
19) Saw_elbow



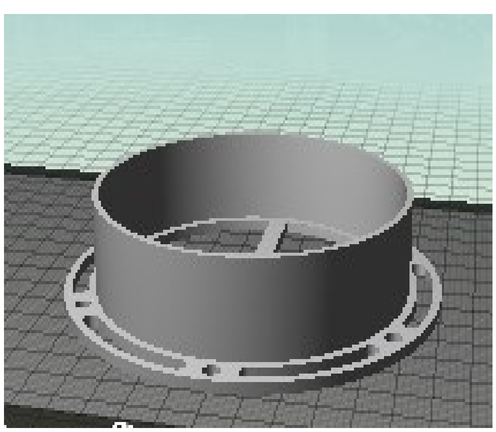


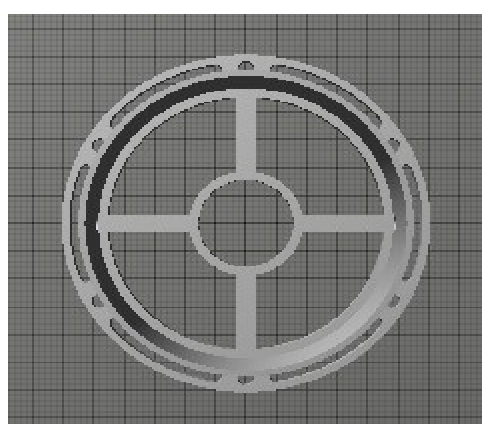
20) SpoolHolder1



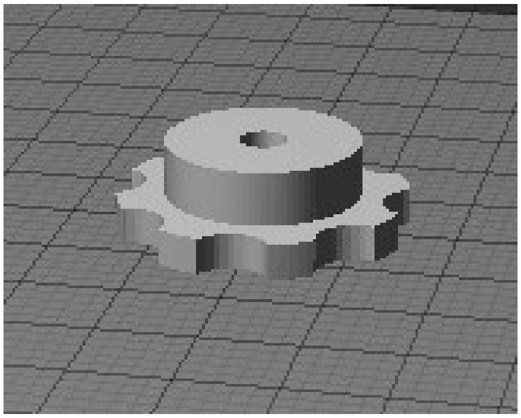


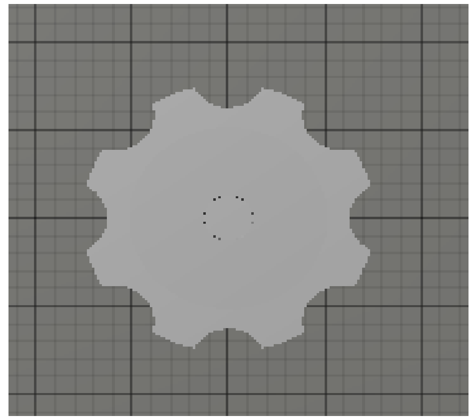
21) Teil1_Light



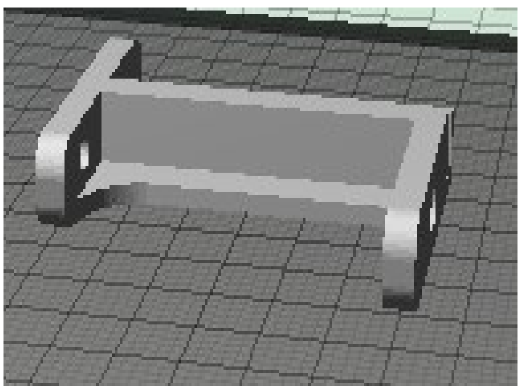


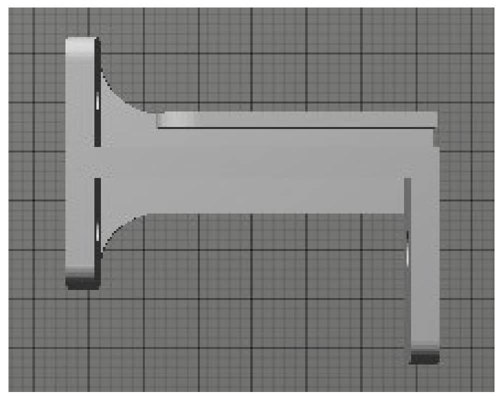
22) Thumb_screw



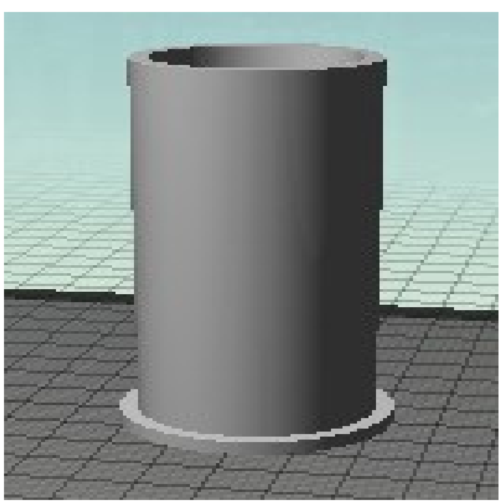


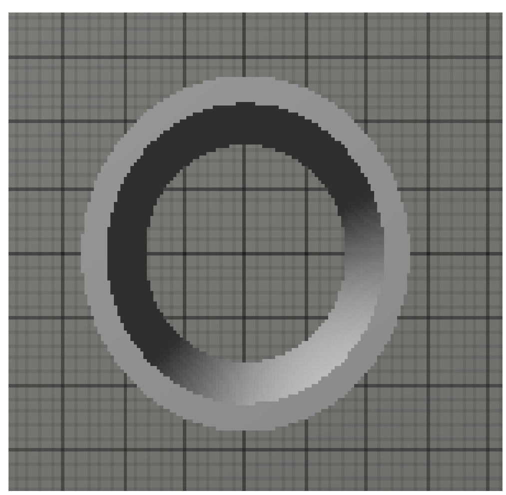
23) K8200_webcam_mount1



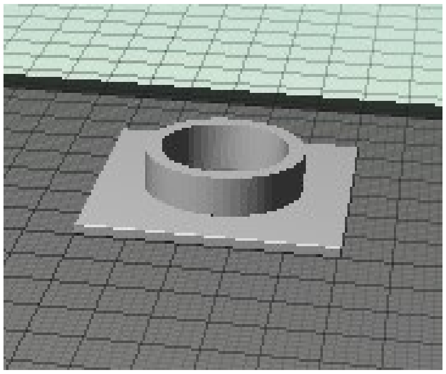


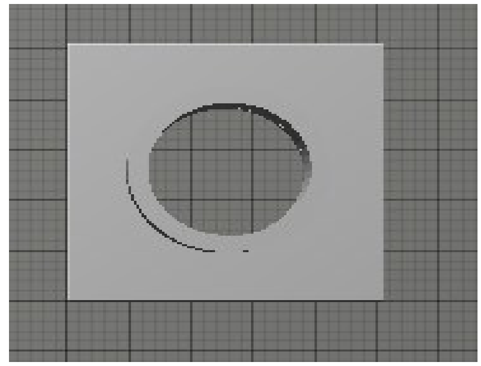
24) Spool_sleeve1





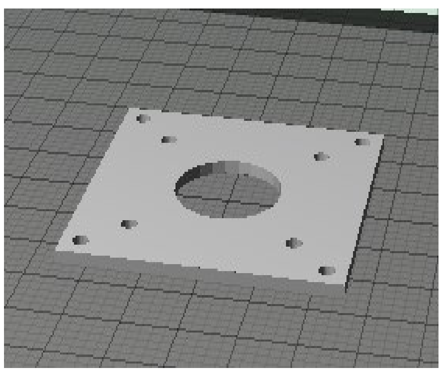
25) 1inch_filter_adapter

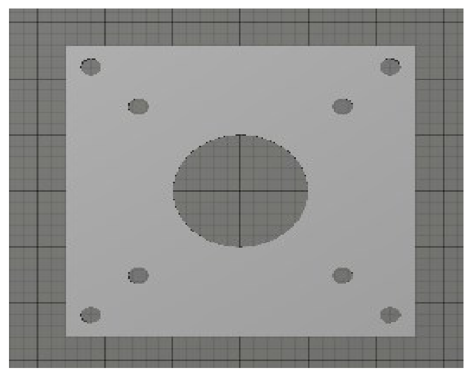




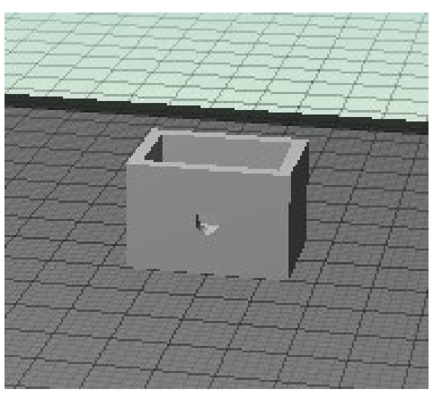
<u>10 Parts for Validation of the Final Model</u>

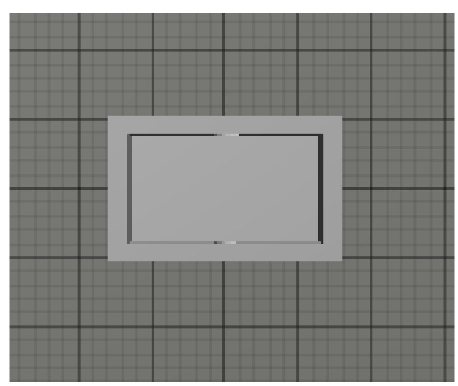
1) FPV250



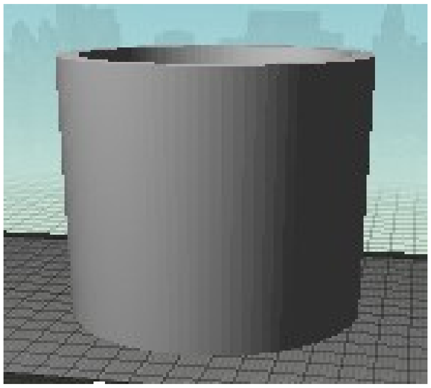


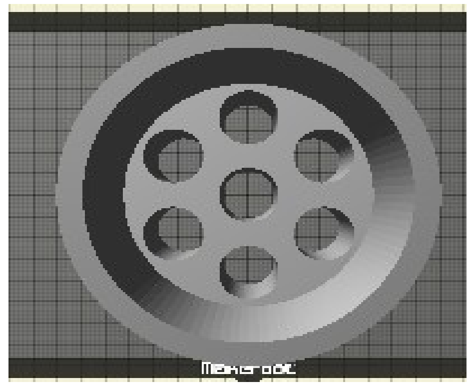
2) PRN3D



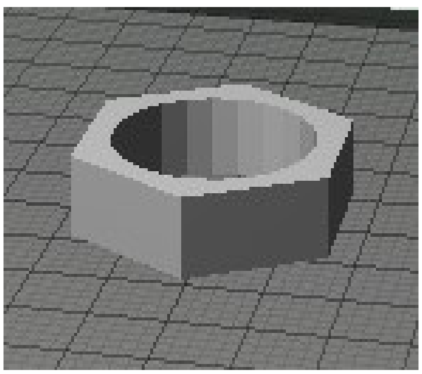


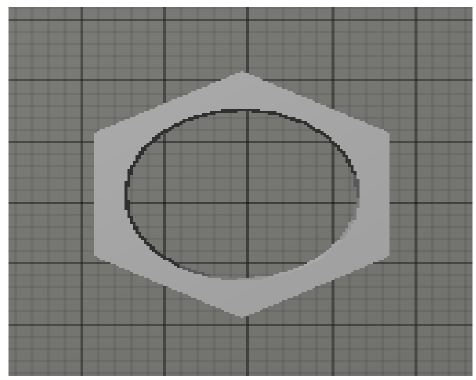
3) Manifold



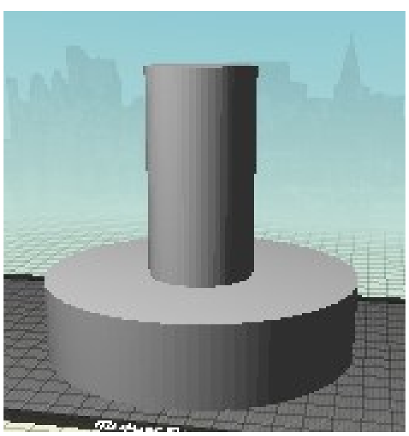


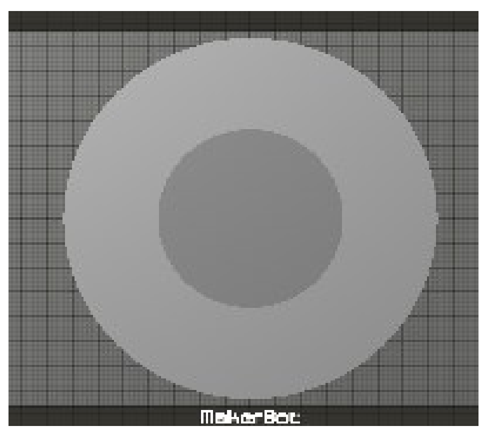
4) Ring



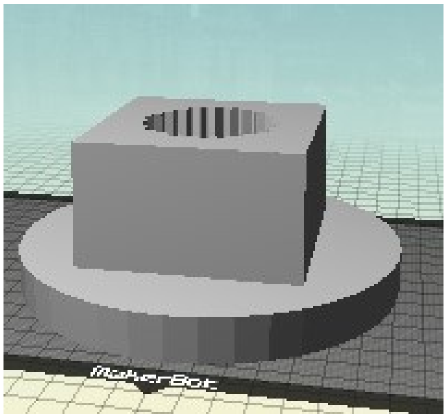


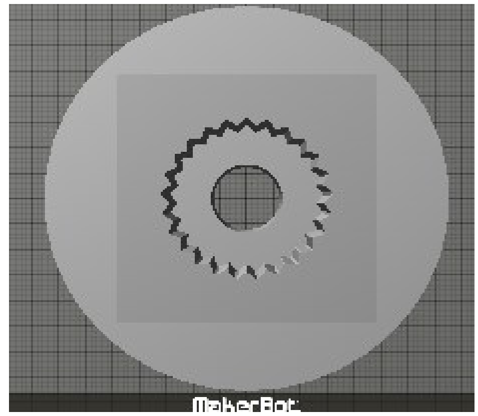
5) RocketPlug



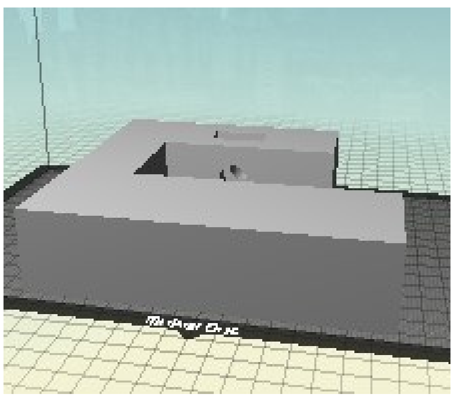


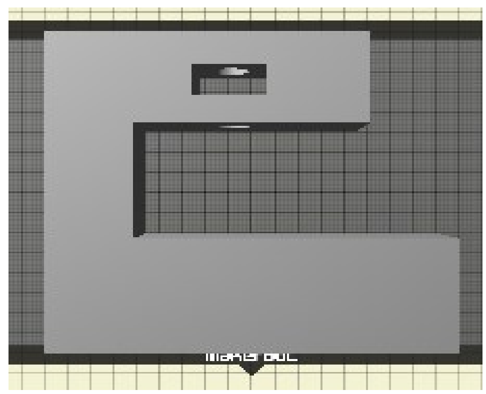
6) WheelHub-3



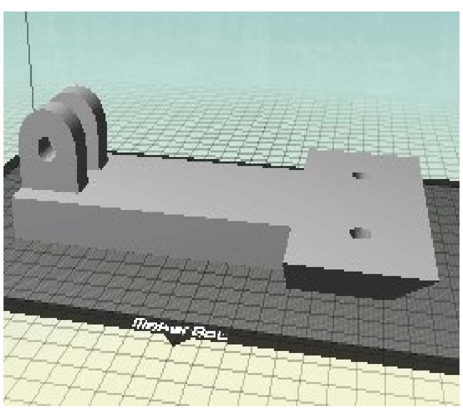


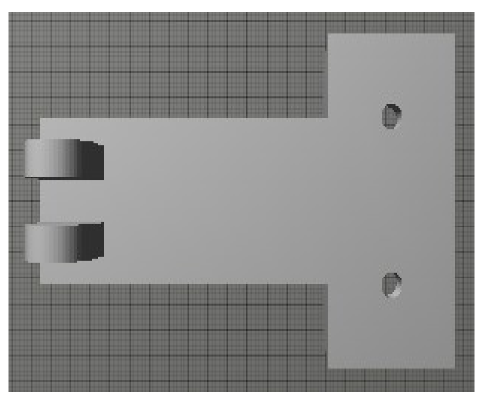
7) Print_Bed



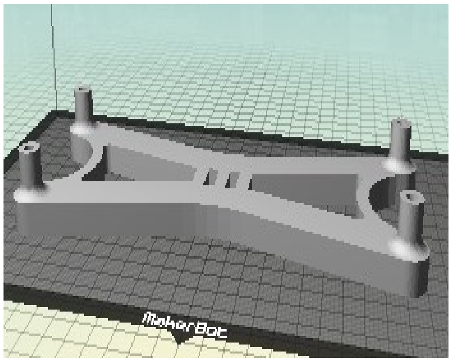


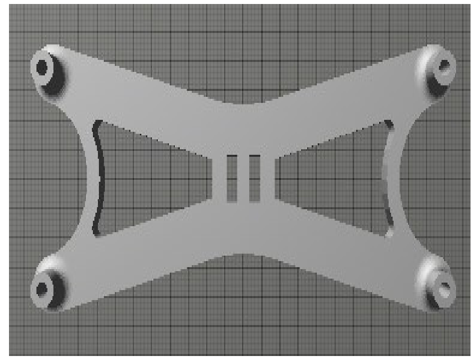
8) I3support



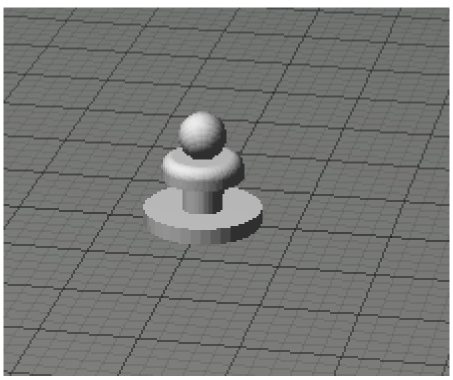


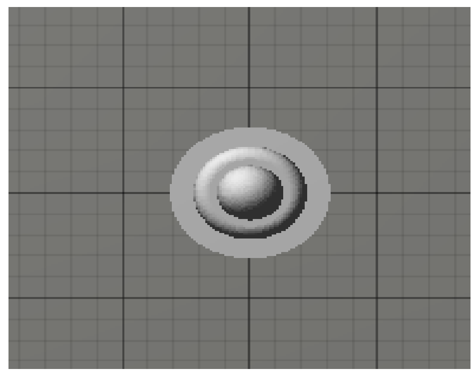
9) I3_LCD





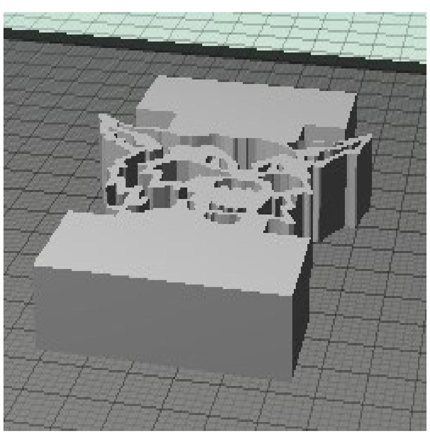
10) AC_Adapter

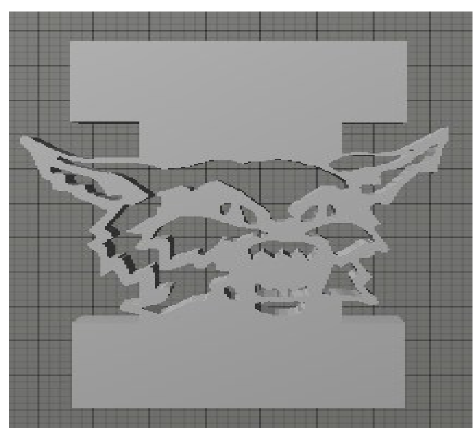




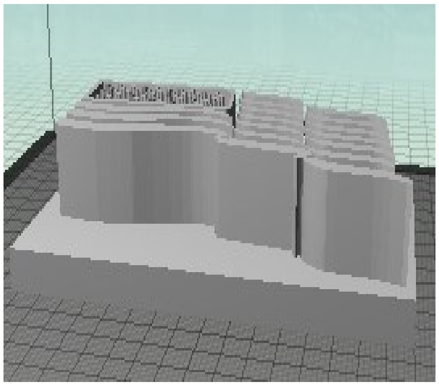
Complex Parts

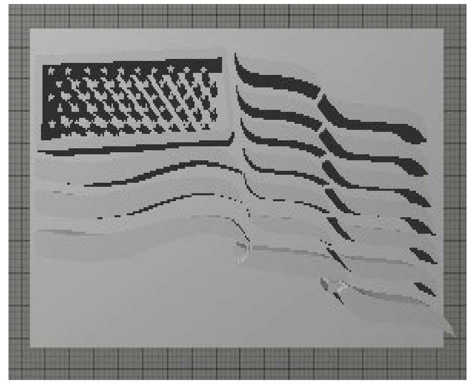
1) Shiny_juttuli-fulffy



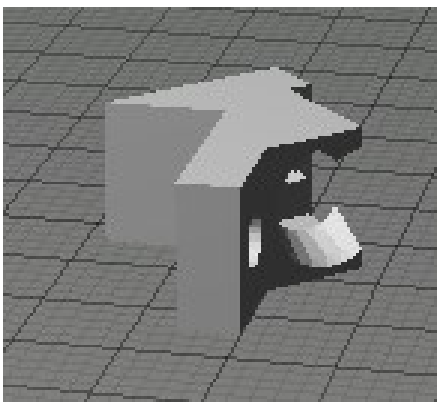


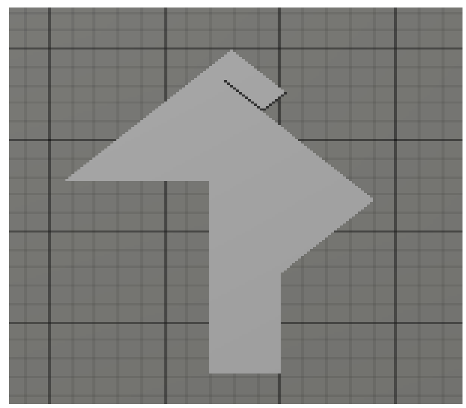
2) Flag_piece_1_red



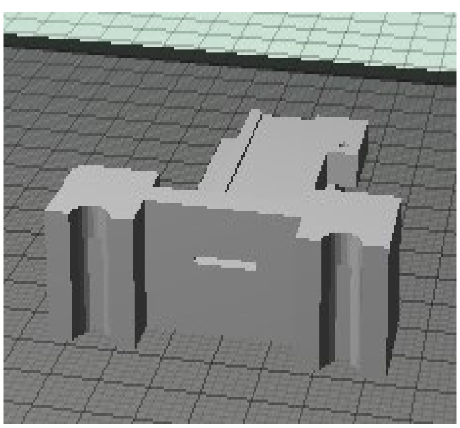


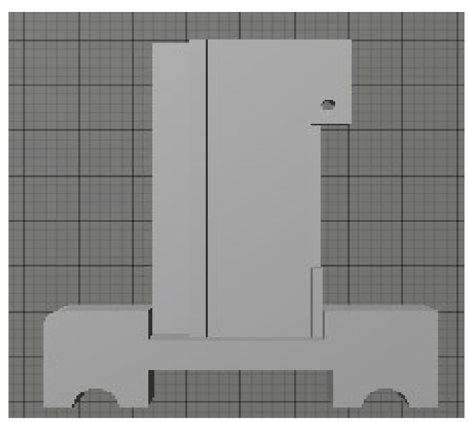
3) Filamento_Filtro_UP



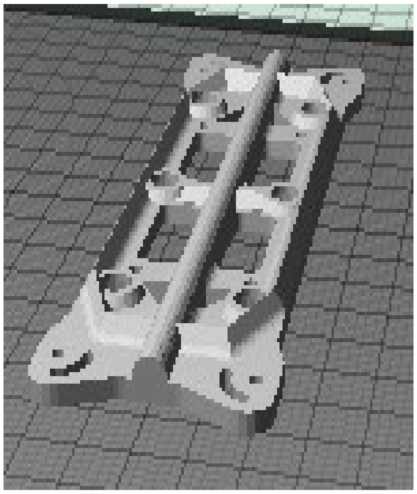


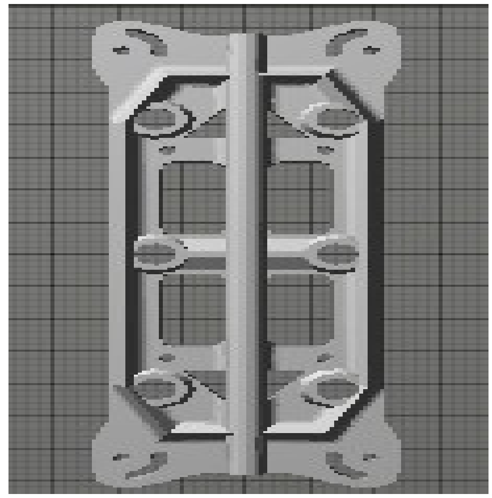
4) Calibrator_50mm



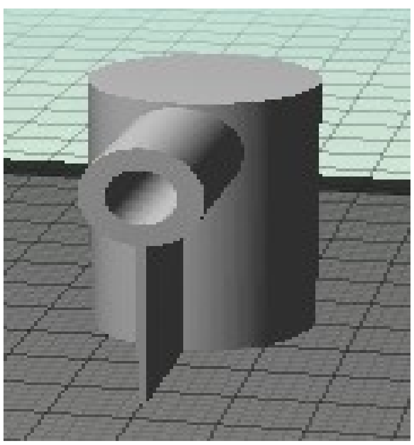


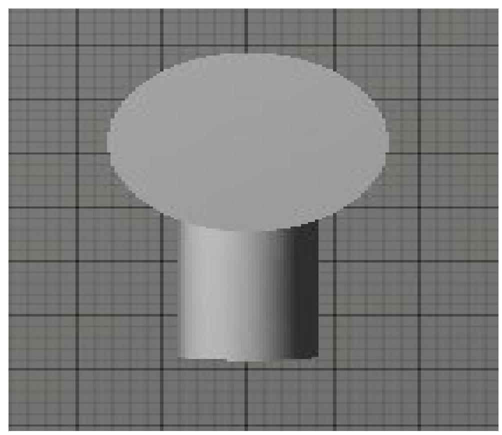
5) Reinbezcarbon



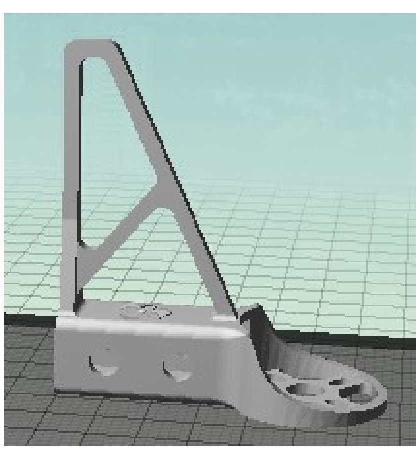


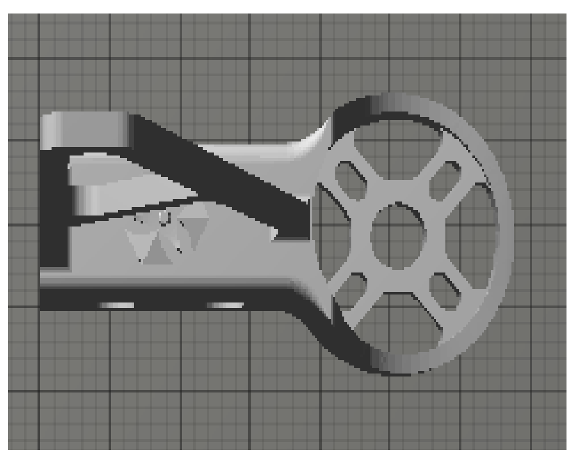
6) RodToPvcElbow3



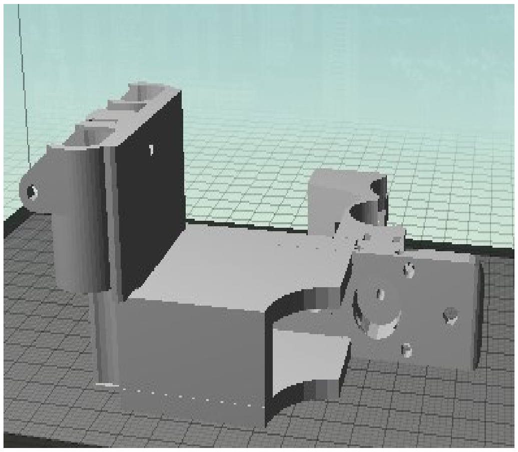


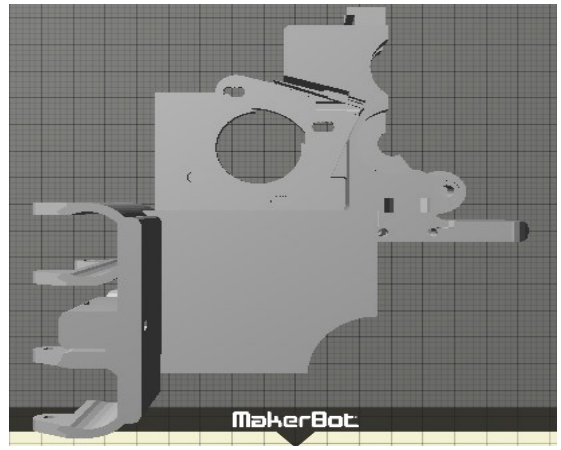
7) Multirotor_Motor



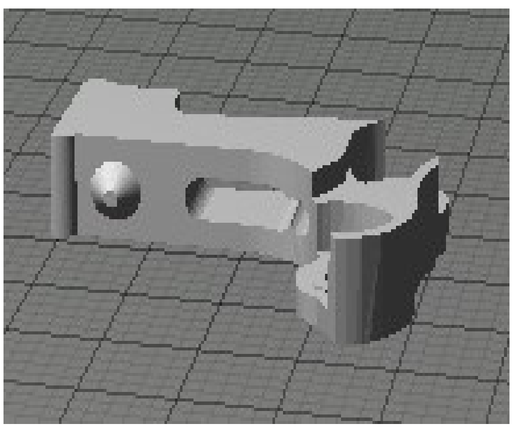


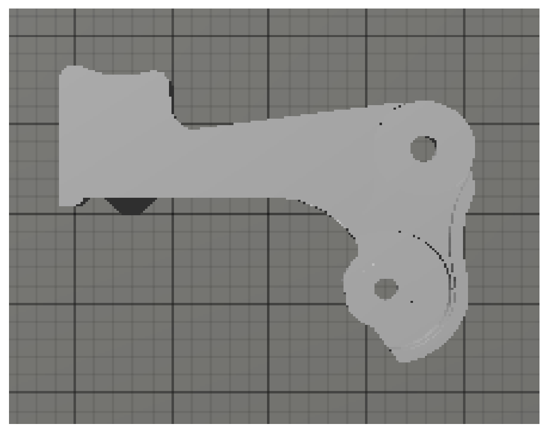
8) I3carriage_fuse



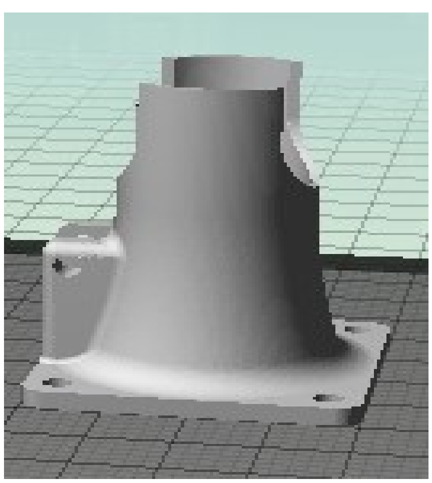


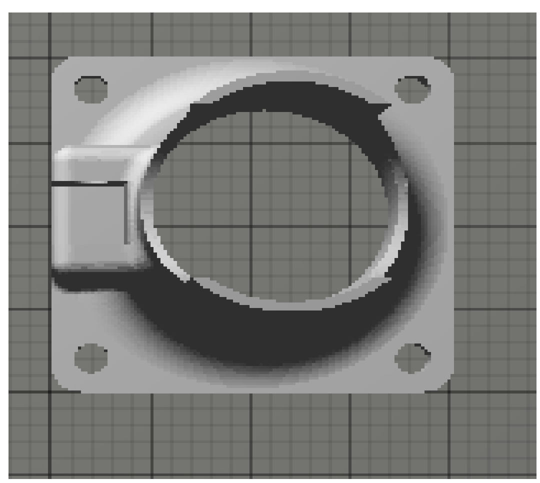
9) DriveBlockLeverLeft





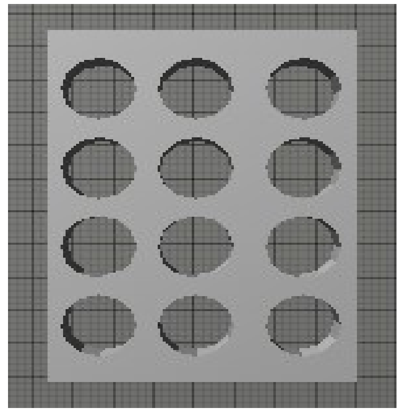
10) Prusa_I3_Rework



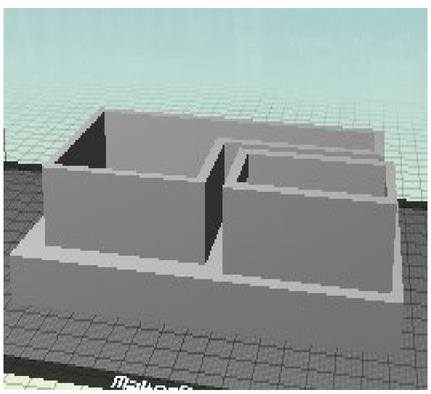


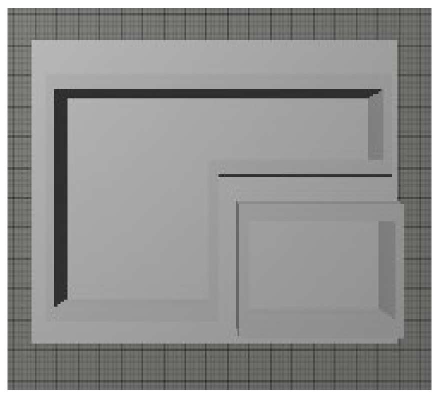
<u>Simple Parts</u>

1) Simple shiny

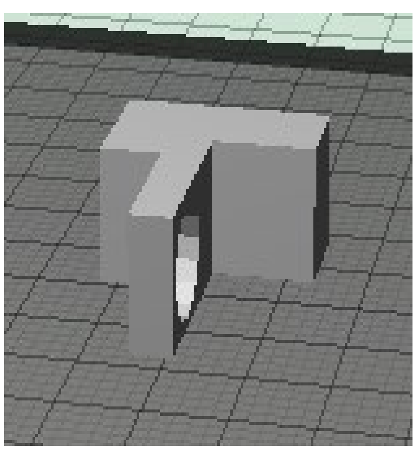


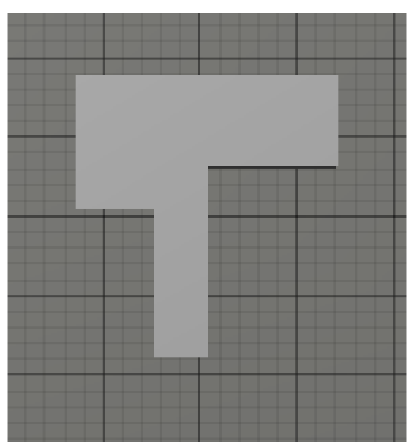
2) Simple flag



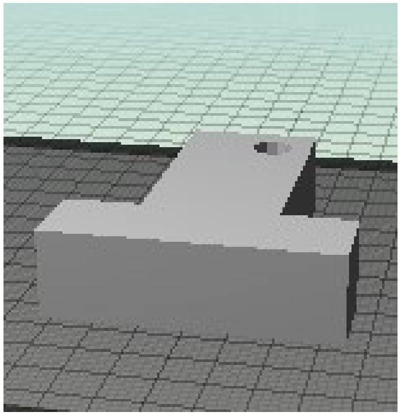


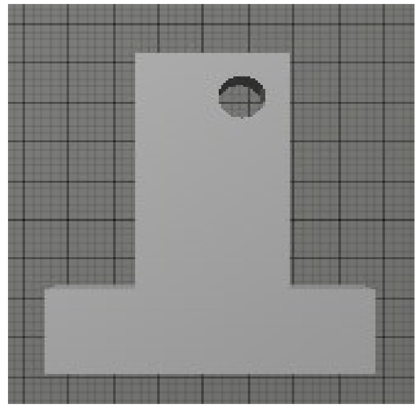
3) Simple filament



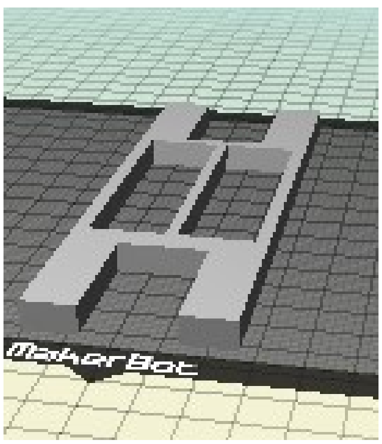


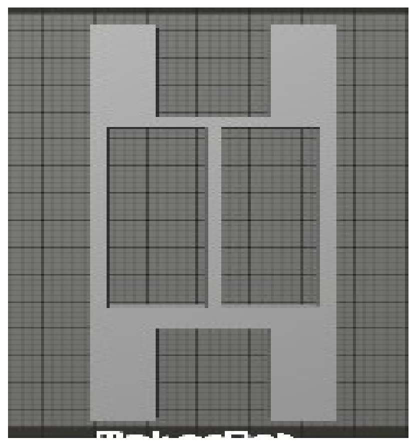
4) Simple calibrator



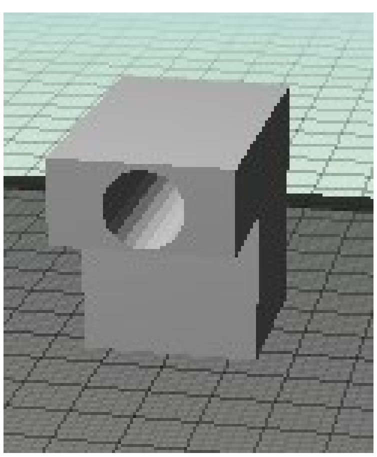


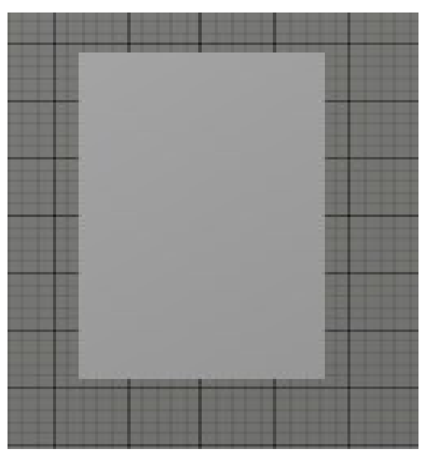
5) Simple reinbezcarbon



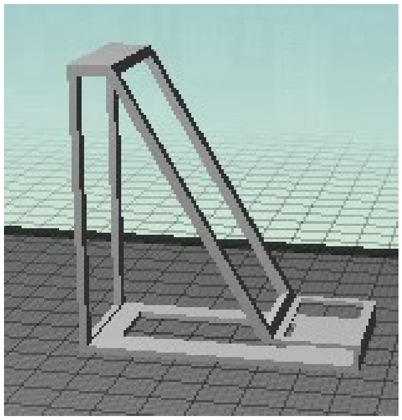


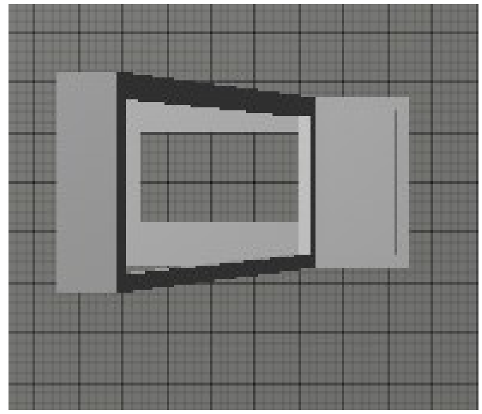
6) Simple rodtopvc



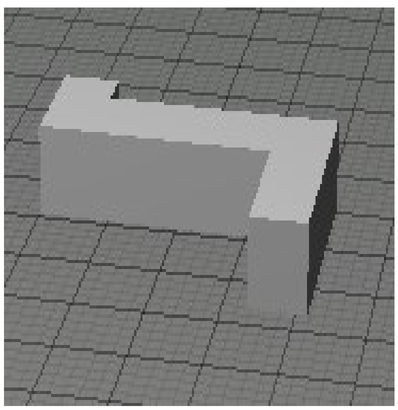


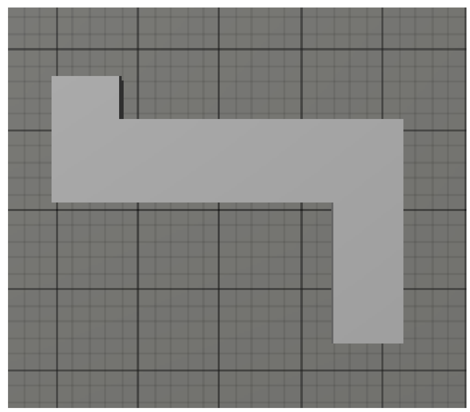
7) Simple multirotor



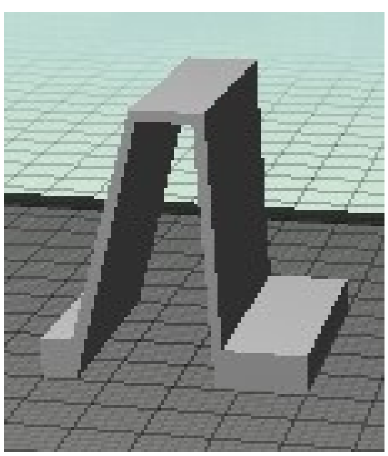


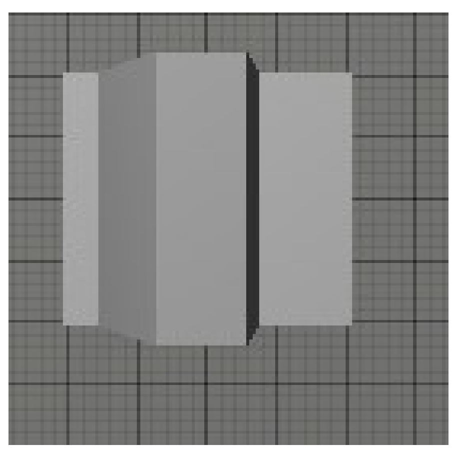
8) Simple driveblock





9) Simple prusa





REFERENCES

Affordable Blueprinter SHS 3D printer for desktop sintering. (2012). Retrieved March 21, (2012), from http://www.3ders.org/articles/20120321-affordable-blueprinter-shs-3d-printer-for-desktop-sintering.html

ASTM Standard, Standard Terminology for Additive Manufacturing Technologies, vol. 10.04.

Bagley, Rebecco O. (2014, May 03). How 3D Printing Can Transform Your Business. *Forbes.* Retrieved from http://www.forbes.com/sites/rebeccabagley/2014/05/03/how-3d-printing-can-transform-your-business/

Banke. J. (2009, September 23). From Nothing, Something: One Layer at a Time. *NASA*. Retrieved from http://www.nasa.gov/topics/aeronautics/features/electron_beam.html#.-U9cVm7Fupmo

Bilton, Nick. (2013, February 17). Disruptions: On the Fast Track to Routine 3-D Printing. *The New York Times*. Retrieved from http://bits.blogs.nytimes.com/2013/02/17/disruptions-3-d-printing-is-on-the-fast-track/?_php=true&_type=blogs&_r=0

Brajlih, T., Valentan, B., Balic, J., & Drstvensek, I. (2011). Speed And Accuracy Evaluation Of Additive Manufacturing Machines. *Rapid Prototyping Journal, 17*(1), 64-75. Doi: 10.1108/13552541111098644

Bártolo. P. J. et al. (2009). Materials: Experimental investigation of Charpy impact tests on metallic SLM parts. *Innovation Developments in Design and Manufacturing:*

Advanced Research in Virtual and Rapid Prototyping (1st ed., pp 207-279). London, UK: CRC Press.

Campbell, I., Combrinck, J., De Beer, D., & Barnard, L. (2008). Stereolithography Build Time Estimation Based On Volumetric Calculations. *Rapid Prototyping Journal, 14*(5), 271-279. Doi: 10.1108/13552540810907938

Chen. Y., Wang. X., & Chen. S. (2014). The effect of electron beam energy density on temperature field for electron beam melting. *Advanced Materials Research, 900* (2014), 631-638. doi:10.4028/www.scientific.net/AMR.900.631

Ciurana, J. (2013). *New Opportunities and Challenges for Additive Manufacturing to Oroduce Biomedical Devices.* University of Grona.

Cotteleer, M., Holdowsky, J., Mahto, M. (2014, March 6). The 3D opportunity primer: The basics of additive manufacturing. *Deloitte University Press.* Retrieved from http://dupress.com- /articles/the-3d-opportunity-primer-the-basics-of-additive-manufacturing/

Di Angelo, L., & Di Stefano, P. A neural network-based build time estimator for layer manufactured objects. *International Journal of Advanced Manufacturing Technology, 57*(1-4), 215-224. doi: 10.1007/s00170-011-3284-8

Fountain, Henry. (2013, August 18). At the Printer, living Tissue. *The New York Times*. Retrieved from http://www.nytimes.com/2013/08/20/science/next-out-of-the-printer-living-tissue.html

Hansell, Saul. (2007, May 7). Beam It Down From the Web, Scotty. *The New York Times.* Retrieved from http://www.nytimes.com/2007/05/07/technology/07copy.html?pagewanted=all

Hollis, R. L. (2001). *Geometry-Based Estimation For Additive Fabrication.* (Doctor Of Philosophy), Alabama In Huntsville, Huntsville, Alabama.

Hopkinson. N., Hague. R.J.M., & Dickens. P. M. (2006). Emerging Rapid Manufacturing Process: Fused Deposition Modeling. *Rapid Manufacturing: An industrial revolution for the digital age* (1st ed., pp 55-79). London, UK: John Wiley& Sons, Ltd.

Hopkinson. N., Hague. R.J.M., & Dickens. P. M. (2006). Emerging Rapid Manufacturing Process: Stereolithography. *Rapid Manufacturing: An industrial revolution for the digital age* (1st ed., pp 55-79). London, UK: John Wiley& Sons, Ltd.

How DMLS Works. (n. d). *Direct Metal Laser Sintering.* Retrieved from http://www.directmetallaser- sintering.net/dmls

Kameroni. A., &Abouel Naser. E. (2010). Rapid Prototyping: Advantages and disadvantages of Laminated Object Manufacturing. *Engineer Design and Rapid Prototyping* (1st ed., pp 339-355). New York, NY: Springer.

K.P. Karunakaran, S. S. N., Vishal Pushpa, Sreenathbabu Akula. (2010). Low Cost Integration Of Additive And Subtractive Processes For Hybrid Layered Manufacturing. *Robotics And Computer-Integrated Manufacturing, 26*(2010), 10.

Kurutz, Steven. (2013, February 20). A Factory on Your Kitchen Counter. *The New York Times.* Retrieved from http://www.nytimes.com/2013/02/21/garden/the-3-d-printer-may-be-the-home-appliance-of-the-future.html?pagewanted=all&_r=0

Lan HB, Ding YC (2007) Price quotation methodology for stereolithography parts based on STL model. Comput Ind Eng 52(2):241–256

M. Baumers, C. T., R. Wildman, I. Ashcroft, E. Rosamond, And R. Hague. (2012). Combined Build–Time, Energy Consumption And Cost Estimation For Direct Metal Laser Sintering. *Additive Manufacturing And 3d Printing Research Group, Faculty Of Engineering*, 13.

McCue, TJ. (2013, December 30). 3D Printing Stock Bubble? $10.8 Billion By 2021. *Forbes*. Retrieved from http://www.forbes.com/sites/tjmccue/2013/12/30/3d-printing-stock-bubble-10-8-billion-by-2021/

Nelson, Nick. (2012, December, 21). 3D printing shop RedEye ventures beyond the prototype *TECH{dot}MN.* Retrieved from http://tech.mn/news/2012/12/21/redeye-on-demand-stratasys/

Regan, Maria. (2014, March 21). Airplanes To Medical Devices, Breaking Ground In 3D printed Titanium. *Forbes*. Retrieved from http://www.forbes.com/sites/ptc/2014/03/21/airplanes-to-medical-devices-breaking-ground-in-3d-printed-titanium/

Reis, Michelle. (2014, March 04). What 3D Printing Means For Manufacturers. *Forbes*. Retrieved from http://www.forbes.com/sites/ptc/2014/03/04/what-3d-printing-means-for-manufacturers/

Stephen Mellor, L. H., David Zhang. (2013). Additive Manufacturing: A Framework For Implementation. *College Of Engineering, Mathematics And Physical Science, 149*, 8.

Valentan, B., Brajlih, T., Drstvensek, I., & Balic, J. (2011). Development Of A Part-Complexity Evaluation Model For Application In Additive Fabrication Technologies. *Strojniski Vestnik, 57*(10), 709-718. Doi: 10.5545/Sv-Jme.2010.057

Wood. L. (1993). Fused Deposition Modeling. *Rapid Automated Prototyping: An Introduction* (1st ed., pp 71-89). New York, NY: Industrial Press Inc.

Wood. L. (1993). Lamination Methods. *Rapid Automated Prototyping: An Introduction* (1st ed., pp 89-107). New York, NY: Industrial Press Inc.

Wood. L. (1993). Selective Laser Sintering. *Rapid Automated Prototyping: An Introduction* (1st ed., pp 57-71). New York, NY: Industrial Press Inc.

Xu, F., Oh, TL., Wong, YS., (1999) Consideration of optimal orientation for different rapid prototyping. *Rapid Prototyping* J 5 (2):54–60

Zhang, Y., & Bernard, A. (2014). *Generic Build Time Estimation Model For Parts Produced By Sls.* Paper Presented At The 6th International Conference On Advanced Research In Virtual And Physical Prototyping, Vr@P 2013, October 1, 2013 - October 5, 2013, Leira, Portugal.