APPLICATION OF ANALYTIC HIERARCHY PROCESS TO DETERMINE AND OPTIMIZE FDM PRINTING PROCESS PARAMETERS

This report is submitted in accordance with requirement of the University Teknikal Malaysia Melaka (UTeM) for Bachelor Degree of Manufacturing Engineering (Hons.)

by

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DECLARATION

I hereby, declared this report entitled "Application of Analytic Hierarchy Process to Determine and Optimize FDM Printing Process Parameters" is the results of my own research expect as cited in reference.

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Hons.). The members of the supervisory committee are as follow:

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ABSTRAK

Analytic Hierarchy Process (AHP) adalah salah satu alat matematik yang popular yang dapat menyelesaikan masalah. Kaedah AHP memberi tumpuan kepada masalah dalam tiga bahagian yang merupakan bahagian pertama adalah objektif masalah yang perlu diselesaikan. Kemudian bahagian kedua adalah alternatif yang dapat menyelesaikan masalah sementara bahagian penting terakhir adalah kriteria yang digunakan untuk menilai penyelesaian alternatif. *Fused Deposition Modeling (FDM)* adalah proses yang mendapan lapisan bahan bersatu mengikut model CAD. Projek ini bertujuan untuk menggunakan AHP untuk menyiasat pengaruh parameter proses seperti ketebalan lapisan, kepadatan pengisian, orientasi binaan, dan sudut raster pada kekuatan tegangan objek bercetak FDM yang diperoleh dari tinjauan. Setelah mendapat hasil dari analisis AHP, kekuatan tegangan dianalisis dari parameter proses yang dioptimumkan. Dengan menggunakan *Computer-Aided Three-Dimensional Interactive Application (CATIA),* spesimen yang akan menjadi standard *American Society for Testing and Materials (ASTM) D638 Type 1* telah dilukis. Spesimen bahan yang digunakan adalah *Polylactic Acid (PLA)*. Kemudian, spesimen itu dihiris dengan menggunakan perisian Ultimaker Cura dan dicetak dengan menggunakan pencetak 3D Ender 3 V2. Setelah menguji kekuatan tegangan, analisis kepekaan AHP dilakukan untuk menguji ketepatan semua parameter proses pada peringkat analisis AHP dengan menggunakan perisian Super Decision V3.2. Hasil untuk projek ini menunjukkan bahawa dari analisis AHP parameter proses terbaik untuk kekuatan tegangan teknologi FDM adalah pilihan 3 yang mempunyai skor tertinggi pertama iaitu 0.717. Untuk mengesahkan hasil dari analisis AHP, kekuatan tegangan pilihan 3 diuji dengan ketebalan lapisan yang berbeza kerana ketebalan lapisan mempunyai berat kriteria tertinggi dalam analisis AHP. Ini menunjukkan bahawa pilihan 3 mempunyai kekuatan tegangan tertinggi iaitu 2556 N/m^2. Terakhir, analisis kepekaan menunjukkan bahawa Dalam analisis AHP, pengujian kepekaan menunjukkan bahawa perubahan nilai semasa tidak mempengaruhi peringkat, menunjukkan bahawa pembuat keputusan dilayan dengan baik oleh proses keputusan.

ABSTRACT

Analytic Hierarchy Process (AHP) is one of the popular mathematical tools that can solve the problem. The AHP method focus on the problem in three parts which are the first part is the objective of the problem that needs to be solved. Then the second part is the alternatives that can solve the problem while the last important part is the criteria that are used to evaluate the alternative solutions. Fused Deposition Modeling (FDM) is a process that deposits fused material layers according to the CAD models. This project aims to use the AHP to investigate the effect of process parameters such as layer thickness, infill density, build orientation, and raster angle on the tensile strength of FDM printed objects got from the surveys. After getting the result from the AHP analysis, the tensile strength was analyzed from the process parameters that were optimized. Using the Computer-Aided Three-Dimensional Interactive Application (CATIA) software, the specimen that would be the American Society for Testing and Materials (ASTM) D638 Type 1 standard was drawn. The material specimen used is Polylactic Acid (PLA). Then, the specimen was sliced by using Ultimaker Cura software and printed by using Ender 3 V2 3D printer. After tested the tensile strength, AHP sensitivity analysis is conducted to test the accuracy of all the process parameters on the ranking of the AHP analysis by using Super Decision V3.2 software. The result for this project shows that from the AHP analysis the best process parameter for tensile strength of FDM technology is option 3 which has the first highest score which is 0.717. To validate the result from the AHP analysis, the tensile strength of option 3 is tested with different layer thicknesses due to layer thickness has the highest criteria weight in AHP analysis. It shows that option 3 has the highest tensile strength which is 2556 N/m^2. Lastly, the sensitivity analysis shows that In AHP analysis, sensitivity testing revealed that changes in current values do not affect ranking, indicating that decision-makers were well served by the decision process.

DEDICATION

I would love to dedicate this project to

my beloved parents

my dearest siblings

my honorable supervisor and lecturers

my supportive friends and mates

ACKNOWLEDGEMENT

I would love to express my gratitude to my supervisor Professor Madya Technologist Doctor Shajahan Bin Maidin for allowing me to do my final year project. I would also like to thank him for his kind consideration, excellent guidance, brilliant ideas, and his advice to help me complete this project from the beginning to the end of this project.

Next, I would love to express my appreciation and gratitude to my family for their prayers, support, and motivation for the successful development of the project.

Not to mention my friends and all the individuals who have assisted, encouraged and contributed to the completion of this project. Without the support of all the people I mentioned above, it would be difficult for me to do this project.

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LIST OF ABBREVIATIONS

AM	-	Additive Manufacturing
RP	-	Rapid Prototyping
3D	-	3-Dimensional
FDM	-	Fused Deposition Modeling
AHP	-	Analytic Hierarchy Process
ASTM	-	American Society for Testing and Materials
ABS	-	Acrylonitrile Butadiene Styrene
PLA	-	Poly Lactic Acid
STL	-	Stereolithography
SLA	-	Stereolithography
SLS	-	Selective Laser Sintering
NASA	-	National Aeronautics and Space Administration
W	-	Weight
CI	-	Consistency Index
CR	-	Consistency Ratio
RI	-	Randomly Index

LIST OF SYMBOLS

°C	-	Degree Celsius
MPa	-	Mega Pascal
%	-	Percent
mm/s	-	Millimetre Per Second
mm	-	Millimetre
λ	-	Lambda
N/m^2	-	Newton Per Meter Square

CHAPTER 1

INTRODUCTION

This final year project is part of the courses that will be taken in the Bachelor of Manufacturing Engineering. This project is about the application of AHP to determine and optimize FDM printing process parameters on tensile strength. Then, the result will be validated with the tensile strength test and AHP sensitivity analysis. Therefore, it is necessary to complete this project to achieve a good tensile strength quality printed object. The project for the final year also aims at providing students with the ability and trust to complete work with lecturers' supervision.

1.1 Background of Study

Additive manufacturing (AM) is one of the different methodologies used to construct a 3-dimensional (3D) structure. Additive processes, which involve successive material layers under machine power, are used for 3D printing. These objects can be of almost any shape or geometry and are created from 3D or another source of digital information. A 3D printer is a type of industrial robot. 3D printing refers to processes that deposit material sequentially onto a powder bed with inkjet printer heads in the authentic experience of the word. More recently, the scope of the term has extended to include a broad range of methods entirely based on processes such as extrusion and sintering. Technical specifications typically use the term AM in this wider sense (Surange & Gharat, 2016).

AM has a lot of benefits which are it can reduce time due to fast prototyping. It also can reduce the cost of product development and directly manufacturing finished components (Attaran, 2017). Other than that, (Gayette, 2019) stated that additive manufacturing will save on material waste and energy due to it may need to do the finishing such as to file off burrs or supports that hold the part but overall waste is minimal. The applications of AM have a lot of variety due to it is widely used in this era such as functional prototypes. A prototype is a very important part of the development process to show how does the product works before fabricating the real one (Patel, 2016). Next, AM also has gotten into the medical industry with biomedical applications and produce medical tools to ease the visualization of specific anatomy (Ystems, 2016).

Yan et al., 2016 specified a fast-prototyping printer typically based on plastic printing with plasticity, the most rapidly growing and state-of-the-art technology for the modern 3D printing industry is the Fused Deposition Modeling (FDM) 3D Printing and also the largest used 3D Printing System. The 3D printer is entirely based on FDM technology. The control system, the host computer, and the bottom control are separated into two sections. In general, the computer system runs 3D design software, slicing software, and printing software. The bottom control consists of an integrated microcontroller, motherboard, stepper motor, motor driver, limit switch, an extruder of thermoplastic material, printing base, and temperature sensor. The nozzle mechanism, wire feeder, movement mechanism, heating work mechanism, and operating platform are the key working components of the FDM 3D printer.

One of the most commonly used approaches in the selection process is the Analytical Hierarchy Process (AHP) methodology. The goal is to measure the relative priority of the given value according to the acceptable value scale. Typically, the selection is based solely on the interpretation of the person who makes the final decision and decides the goals, demonstrating the importance of continuity and the correlation of the choices as opposed to the overall decision-making process. The AHP approach is flexible since it offers a convenient way to find the relation between standards and alternatives. In the form of complex problems with multiplicated criteria and a sufficient set of alternatives, this approach assesses the validity of the criteria in the real world, to determine the relationship between the criteria. By applying this technique, complex problems could be decomposed into precise hierarchies, such that the assessment would consist of quantitative and qualitative components of the issue. All hierarchical ranges are linked by AHP. This helps us to see how one criterion's alternative influences the other criteria and alternatives (Pachemska et al., 2014).

There are three basic steps in the implementation of the AHP which are, first, the creation of a hierarchical model of decision-making problems. At the top, the model has its goal, the criteria defined at the lower level, and the possibilities available at the bottom of the model. Next, the elements are in contrast to each other in pairs on each level of the hierarchical structure. The selector preferences are expressed through the Saaty Relative Scale of Importance, which has five main levels and four intermediate levels of verbally defined intensities and corresponding numerical values within the 1-9 range. Thirdly, it is possible to derive the use of a mathematical model from estimating the relative value of variables from an acceptable level of hierarchical structure, weight criteria, and local selection priorities, which can be outlined later in the alternatives' overall priorities. You can determine the overall priority of an alternative by summarizing the local priorities multiplied by the weight of the criterion (Peko et al., 2018).

The main goal of this project is to optimize the best process parameters that will influence the tensile strength of FDM specimen. AHP was used to select the best process parameters. Then, the optimum proses parameter was validated by testing it by using the tensile strength test and AHP sensitivity analysis to show how the process parameters obtained from AHP analysis can affect the tensile strength of the FDM specimen.

1.2 Problem Statement

FDM has some limitations such as the weakness of the 3D printed leading to poor tensile strength. The poor tensile strength great discovered in end products of the fused deposition modeling (FDM) process has usually been due to the layer upon layer deposition of the building method and is additionally influenced by the original CAD model and slicing software. Even the taller models have cracks in them. An unexpected difficulty with 3D printing is that it tends to show up in larger prints, and usually when the user is not looking for it. Some user prints are missing, while others are fragile and come apart despite the outer quality of user print appearing to be perfect. In some cases, the final print has geometric issues that make no sense, or sections of the print seem completely different from the print preview. Under-extrusion is the term given to the printer not supplying sufficient material for the print. Many clear indicators of under-extrusion can be identified, including thin layers, undesirable gaps, and even missing layers (Jennings, 2021).

It is found that the mechanical strength of the specimen of the FDM process, such as tensile strength, flexural strength, and surface roughness, is highly anisotropic. The mechanical strength, surface roughness, and geometric precision can be improved by choosing the most efficient procedure settings. To achieve the required mechanical strength of the FDM components, a variety of authors have attempted to determine the most efficient process parameter settings. The FDM components may also be usable components or prototypes, behave differently under loading conditions, and depend on layer thickness and raster coordination in the direction of loading. Adaptive layer thicknesses may optimize the surface roughness, depending on the shape and function of the element, but can also have a non-uniform impact on the strength of the components (Garg & Bhattacharya, 2017).

1.3 Objectives

The objectives are as follows:

(a) To understand the application of the AHP and to list the most effective criteria on the FDM process parameter for tensile strength from the research journal and user committee survey.

(b) To investigate the optimum process parameters for tensile strength with the AHP analysis.

(c) To validate the AHP analysis for tensile strength of the FDM specimen by using the tensile strength test and AHP sensitivity analysis.

1.4 Scopes

This project covers the application of the AHP to determine and optimize FDM printing process parameters that affect mechanical properties such as tensile strength concurrently during FDM. The specimen of ASTM D638 Type 1 was drawn using the CATIA software and convert into STL file format then, sliced by using Ultimaker Cura software and print the PLA specimens by using Ender 3 V2 3D Printer. To get the better tensile strength of printed objects, AHP analysis was used to select the best selection-making processes from the surveys. By using the AHP analysis, the FDM process was selected based on their performance due to AHP analysis is a flexible decision-making process. After getting the result from the AHP analysis, a tensile strength test was performed to validate the process parameter from the AHP analysis. Lastly, AHP sensitivity analysis was done to test the stability of the ranking under different criteria weights by using the Super Decision V3.2 software.

CHAPTER 2

LITERATURE REVIEW

The literature review and context analysis of the project are discussed in this chapter. To achieve an effective system, the literature review is necessary because it helps to recognize issues that have arisen in the current system. Besides that, it also helps to determine the best strategy based on the analysis to achieve the project goal. This chapter focuses on details about AHP and FDM process parameters on tensile strength.

2.1 Analytic Hierarchy Process (AHP)

2.1.1 Definition of AHP

A framework for decision-making, based on arithmetic and psychology, is the analytic hierarchy process (AHP). The widely used method was once developed in the 1970s by Thomas L. Saaty, a Distinguished University Professor at the University of Pittsburgh. Saaty noted that it is difficult to make choices. It's much more complicated to know how to make the "right" option. The AHP is used in the organization and study of complex decisions as an attempt to introduce structure. The goal of the process of analytical hierarchy is no longer simply to have a single, right judgment (Cole, 2020). Figure 2.1 below shows the analytic hierarchy process system.

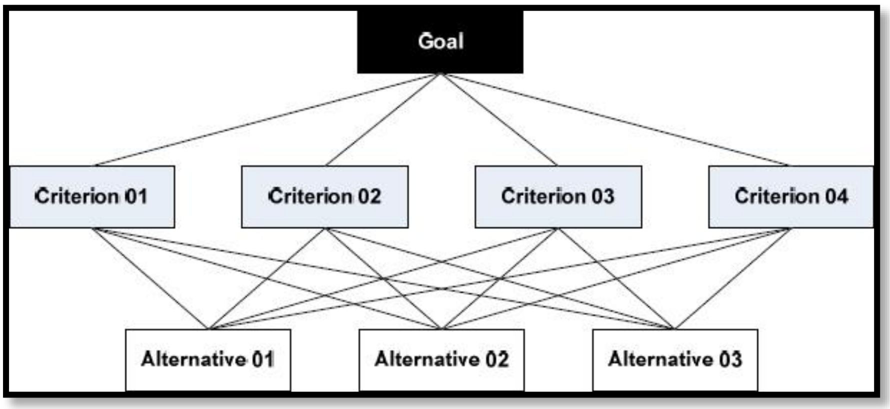

Figure 2.1: Analytic Hierarchy Process Structure

2.1.2 Advantages of AHP

AHP is one of the decision-making methods and widely spread and connected in distinctive fields like sciences, Engineering and Medicine so surely this method will have a lot of advantages such as this method is usability, the system is effortlessly reasonable, extract problem issues by separating it into precise steps and does not need genuine details sets (Karthikeyan et al., 2017). Next, the AHP also combines the few inputs from several data to merge output. Then mostly the outcome will usually agree with the outcoming priorities stated by (Goepel, 2011). (Awang, 2012) Specified that analytic hierarchy process is straightforward to use, simplicity by using pairwise comparisons and consistency in evaluation.

2.1.3 Disadvantages of AHP

Instead of having the strengths in this approach, this method often has a few disadvantages because of the precise characteristics of human AHP use for judgments such as in beneficial situations, human thoughts are difficult to understand and the chiefs may also be unable to correct the careful numerical characteristics to the examination judgments anymore. The AHP for this scenario is no longer material. It can evaluate direct models. One whose yield corresponds, in particular, to its data. It cannot unravel non-straight models such as one whose yield does not fit its details directly. (Karthikeyan et al., 2017). The other disadvantages are pair-wise contrast is a quite artificial set of items and if consistency index is above ten percent, the problems to explain the appeal to reconsider inputs (Goepel, 2011).

2.1.4 Application of AHP

Applications of the multiple-criteria decision techniques purposes specifically popular in the last few decades. Every day, starting from simple problems to very complex circumstances, we face decision-making problems. These circumstances are often irrelevant to individuals or the entire company. One way to make a correct decision is by using the principle of multifactor optimization.

a) Mobile value service

Mobile value service with the tremendous usage of smart mobile devices, mobile services, and apps are becoming more and more profitable and part of the daily life of end-users is one of the applications of the analytical hierarchy process, but why are some devices and offerings effective while others are not? The selection and understanding of key success elements driving the acceptance and adoption of mobile devices and unique mobile services are definitely of great importance. A restricted collection of adoption factors are mainly considered by conventional models, concentrating on the perceived values of mobile services such as utility, ease of use, cost, etc. (Brunneli, 2015).

b) Healthcare research

Next, the AHP in healthcare research has been implemented inconsistently. All the related aspects were identified in a minority of studies. Thus, the assertions in this evaluation can also be biased, since they are limited to the knowledge available in the reports. Further study is also needed to find out who needs to be interviewed and how to deal with contradictory solutions and how to present the result and the steadiness of the consequences. Furthermore, the latest insights to assess which target category should cope with the challenges of the AHP first-class (Schmidt et al., 2015).

c) The productivity of costs of quality

Quality Cost is an important tool for managing costs and preserving the product's quality. The present find out about objectives to understand the significance of the cost of prevention, the use of the hierarchical process of indices, and approaches to expand cost efficiency and quality. Using real data from the Tobacco Company of Orumieh, the analysis is used and the software program EXCEL-Expert Option is used to analyze the data. The factors involved in the efficacy of quality costs are established to highlight the value of prevention measures and assess the quality of costs through library studies and research. They then proceeded to create a hierarchy. Finally, after the introduction of policies and proposing solutions, cost efficiency was once evident (Nezhad et al., 2015).

d) Process of conflict management

The incitement and the occurrence of the conflicts, their escalation, ceasefire, and de-escalation are approaches that are consistently appearing, lasting, and resolving. Consequently, the conflicts typically pull migratory flows. Migration is an issue that nowadays is very present, and it desires to be resolved. The migration normally starts where conflicts arise. Having that in mind, the main concept in the paper is targeted at the conflicts and the emergence of the migration flows. It also suggests how the conflicts can be resolved in the Middle East countries. The reason for this research is to locate out actual reasons for a look at migrations and the most rational options for their solving. For doing that the Analytical Hierarchy Process (AHP) method is applied. A quick overview was given of the primary elements of the AHP method and how it is utilized in conflict resolution. AHP approach is enforceable and leads to concrete guidelines for similarly fighting resolution. The effects of the research will show that resolving the conflicts may make contributions in the suppression of migration and it can additionally protect countries from additional armed conflicts and undesirable migration flows (Lego, 2017).

2.2 Fused Deposition Modeling (FDM)

2.2.1 Definition of FDM

Scott Crump, the founder of Stratasys, was once the developer of Fused Deposition Modeling (FDM). The FDM was once created by Scott Crump, Stratasys' creator. FDM is an additive processing technology widely used for modeling, prototyping, and production applications. FDM consists of three pre-processing, development, and post-processing stages. A pre-processed CAD model is developed that converts the FDM process into stereolithography (STL) format. Before completing the model, the layers are designed. The model and any supports are removed during the post-processing, washing, or removal. The surface of the model is then finished and refined (Dandgaval & Bichkar, 2016). Figure 2.2 shows one example of an FDM 3D printer which is Prusa i3.

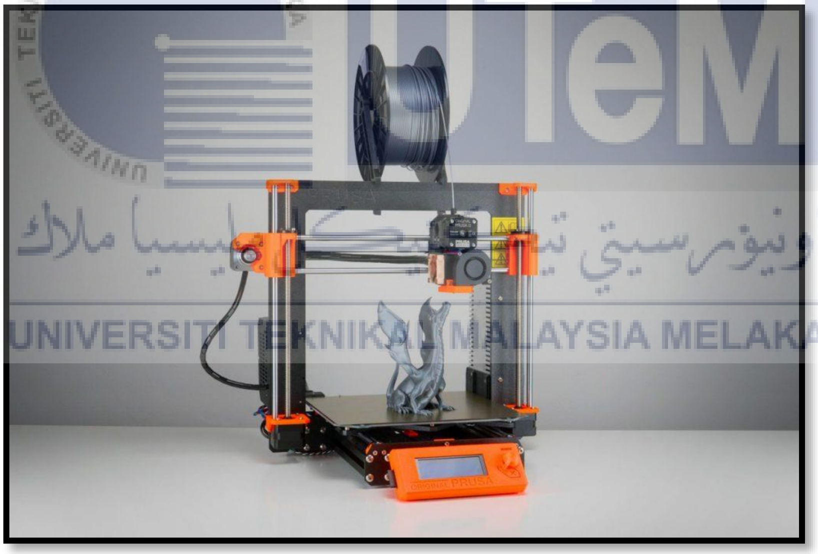

Figure 2.2: FDM Prusa i3 3D Printer

2.2.2 How FDM works

The fundamental concepts of FDM are summarized in Figure 2.3. The build material and support material are positioned on reels located at the sides of the machine. They are fed upwards via a tube into the extrusion head through drive wheels controlled by using the machine. The build material is the material that will make up the final part, while the support material is sacrificial. Parts that have free-hanging parts have to have support structures because the filaments cannot be deposited in mid-air (Christopher W. Lim, 2015).

An extrusion nozzle is supplied with a plastic filament or metal cables that enable and disconnect the flow. The material is heated to melt the material and can be pushed in either horizontal and vertical direction through a computer-aided design directly controlled by the design software computer. The formation of the model or part is carried out with the extrusion of small beads of thermoplastic material, as the material is hardened from the nozzle immediately after extrusion (Alabdullah, 2016). Support elimination of fabricated parts which have completed parts are removed from FDM machines and support structures are directly cut out from the model (Jha & Narasimhulu, 2018).

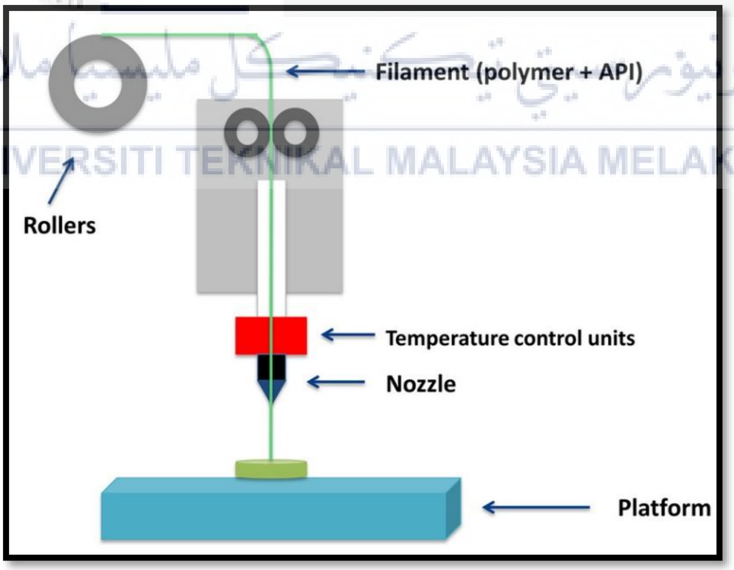

Figure 2.3: Fundamental Concept of FDM

2.2.3 FDM material

The material must be able to stream into place sensibly and then solidify for the material to be used for FDM printing. For that application, thermoplastics are suitable. A variety of final properties, such as distinctive rigidity and flexibility, may be desirable, but there are a few FDM properties that have suitable ranges for generation purposes (Wa & Wa, 2017).

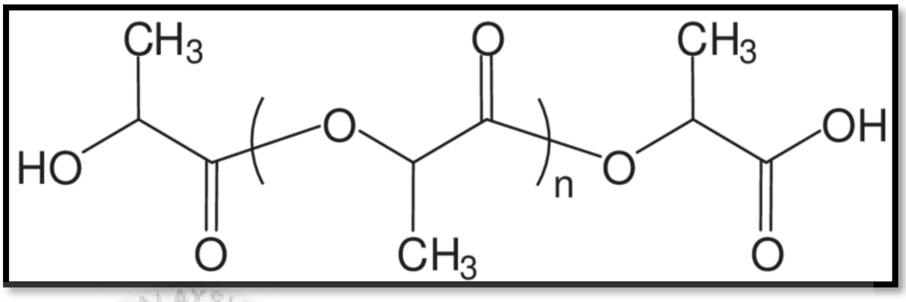

Figure 2.4: Polylactic Acid Chemical Structure

Figure 2.4 above shows the polylactic acid (PLA) is well known as a biodegradable polymer derived from renewable sources such as corn starch, one of the most common FDM materials. For medical implants that are intended to break down harmlessly over time and alter tissue growth, certain levels of PLA are used, because lactic acid is naturally produced and extracted by the human body.

The processing of lactic acid produces equivalent components of the dextrorotatory and levorotatory enantiomers through chemical synthesis, so poly-DLlactic acid (PDLLA) is also available from each monomer and is less biodegradable and not suitable for medical implants. One identifies a variety of different products with different behaviors, like most polymers. The best benefit of PLA's biodegradability in FDM printing is that it does not release toxic fumes during melting and therefore be printed without an airflow system and its low glass transition temperature.

At the glass transition temperature of 60-65°C, most PLA formulations weaken, where the material unexpectedly loses its rigidity but does not exchange phases anymore. In parts that need to stay rigid in heated environments, this can be a concern, but it also allows extruded PLA to have extra time to ease any inner stresses as it cools. This means that due to the reduced stresses it maintains from cooling shrinkage, PLA components can also be printed in an unheated environment with no create plate warmth and no extraordinary adhesives except warping. However, because of its low impact on strength and temperature balance relative to other FDM plastics, PLA is usually no longer considered to be a suitable structural material. PLA will melt at around 175 °C, but flows and is extruded at around 215 °C (Wa & Wa, 2017). Table 2.1 below shows the PLA properties.

Table 2.1: Mechanical Properties of PLA

Properties	Value
Tensile strength, MPa	10-70
Elongation at break, %	1.5-380
Modulus of elasticity, MPa	2,500-4,500
Flexural Strength, MPa	55-80
Flexural Modulus, MPa	2,500-4,000

2.2.4 FDM process parameter

The FDM process has many process parameters and has a major effect on the output and the product characteristics. An air gap, build orientation, extrusion temperature, infill density, infill pattern, layer thickness, the quantity of the shell, print speed, raster orientation, raster width, post-processing parameter are some of the most common parameters. The parameters of the basic method are given below.

1. Air Gap

The distance between a deposited substrate and two adjacent rasters. When two adjacent layers are overlaid, the air gap is called negative. (Dey & Yodo, 2019). Figure 2.5 below shows the air gap when printing the product.

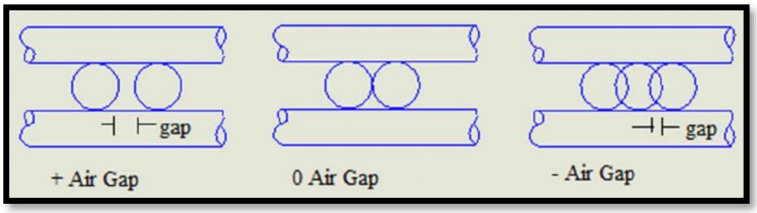

Figure 2.5: Air Gap

2. Build Orientation

Figure 2.6 below shows Essentially, the build orientation means the angle at which the largest size is angled towards the base of the plate. Depending on the user's choice, the printed elements can also be inclined at 0°, 45°, 90° (Madaraka Mwema & Titilayo Akinlabi, 2020).

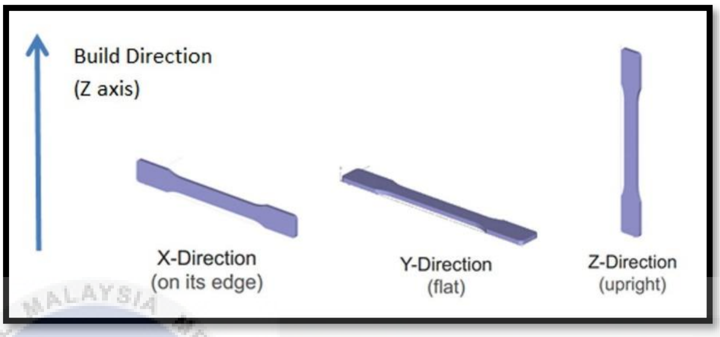

Figure 2.6: Build Orientation

3. Extrusion Temperature

Extrusion temperature is the temperature at which the material is extruded from the nozzle. This temperature is set at a value where the material is transformed into a semi-liquid state. With an increase in the extrusion temperature, the material tends to shift barely onto a liquid state, and this affects a reduction in viscosity. With a lower viscosity, the extruded material loses its sectional circular structure and turns into an oval. This tends to be one way or the other useful, considering it makes the contact area between layers bigger. Also, one can assume that with an increase of temperature, at the end the material tends to emerge as more brittle. Hence, a larger contact area tends to increase the strength but the increase is very less. The results indicate Impact strength reduces drastically with an increase in extrusion temperature, It is due to the truth that due to much less viscosity at greater temperatures the overall thickness of the section reduces which in turn reduces the have an impact on strength (Jatti et al., 2019).

4. Infill Density

The approach of FDM has the parameters of the method are infill percentage of the object’s extent that is filled with the material is the process parameter that investigated and analyzed with different percentage of infill density (20%, 35%, 50%, 65%, and 80%) whilst the different parameters are saved constant which print speed is 50mm/s, the layer thickness is 0.1mm, Shell thickness is 1.2mm (Ali, 2018). Figure 2.7 below shows the different percentages of infill density.

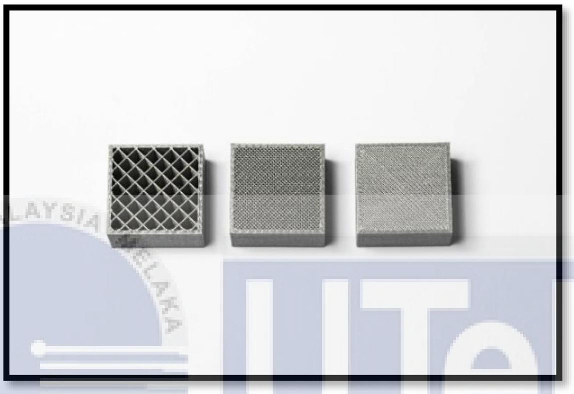

Figure 2.7: Infill Density

5. Infill Pattern

Figure 2.8 shows a pattern is used by using every infill pattern to produce a solid and long-lasting structure within the print. There are different options for infill patterns, each with benefits and trade-offs within the part that receives print time, material use, or strength. Infill sample alternatives for users are typically supported by 3D printing software. For instance, Simplify3D, along with Honeycomb, Complete Honeycomb, Triangular, Grid, and Rectilinear infill patterns, provides users with five infill pattern options. (Dudescu & Racz, 2018).

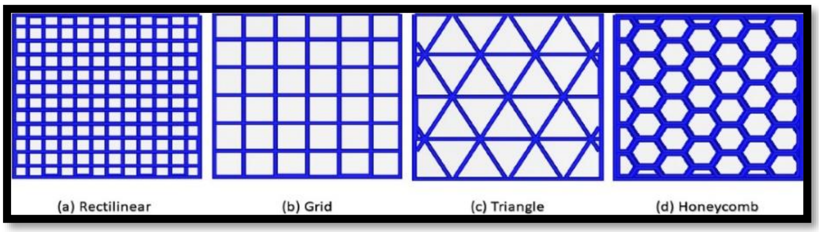

Figure 2.8: Infill Pattern

6. Layer Thickness

The thickness of the layer is the maximum of the layer put through the nozzle and it depends on the material used and the nozzle type. It typically has less than the extruder nozzle diameter and depends on the nozzle diameter (Abdullah et al., 2018). Figure 2.9 below shows the layer thickness of the filament.

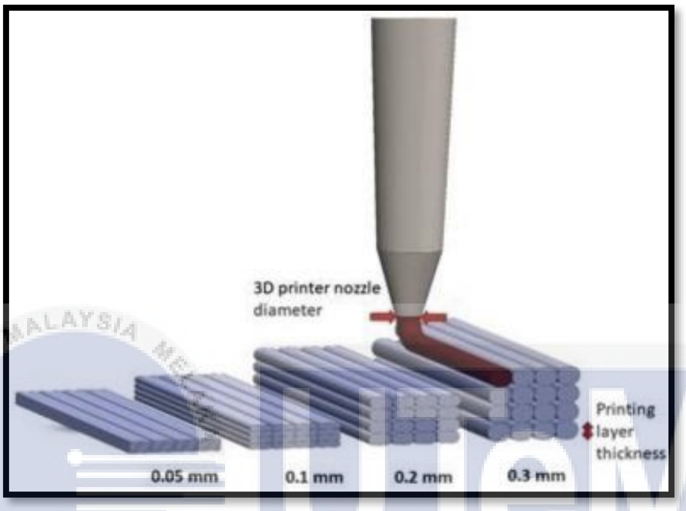

Figure 2.9: Layer Thickness

7. Print Speed

This is the distance traveled per unit time during extrusion alongside the XY plane through the extruder. The print time is dependent on the speed measured in mm/s. (Dey & Yodo, 2019).

8. Raster Width

The width of the raster or road width refers to the width of the direction of deposition related to the size of the tip as shown in Figure 2.10 below. It also refers to the width of the raster pattern's instrument path used to fill the part curves' interior areas (Rayegani & Onwubolu, 2014).

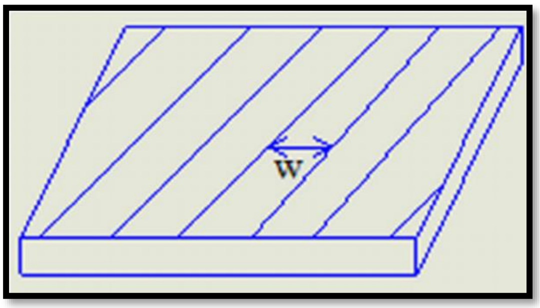

Figure 2.10: Raster Width

9. Raster Angle

Figure 2.11 is showing that the raster angle refers to the angle across the FDM between the nozzle's position and the X-axis of the printing platform. By using 90◦, the raster angles between two adjacent layers differ. The raster angle affects the precision of formation and the printed sample's mechanical efficiency. The raster angle can typically be picked from 0 to 90◦. Therefore, four raster angle stages were selected which are 0◦, 15◦, 30◦ , and 45◦ (Wu et al., 2017).

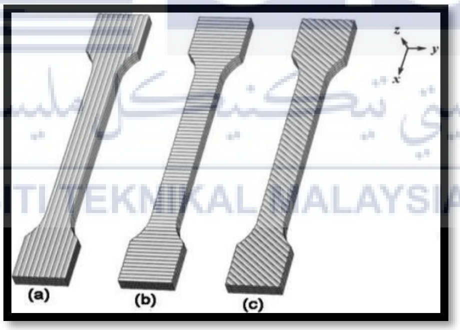

Figure 2.11: Raster Angle

2.2.5 Advantages of FDM

FDM has a lot of advantages that the benefit of using FDM is the lack, as is present in the electron beam melting process, of high-priced lasers fitted with sintering processes or an electron beam. In comparison to sintering and melting technologies, less expensive materials and systems are available which use FDM technology. Other than that, it doesn't take too much time to print the entire piece. In much less than a day, it can get easy prints. It almost ever takes any longer than a day for complex design. But for the majority of 3D printers, it does not need to waste time on post-processing. Use them as soon as they are printed. Well, some other aspects make it cheaper (Arora, 2019).

Since printers use a thermoplastic filament which is heated to a melting point and then removed to create a three-dimensional object in layers, FDM is also accurate. Following the School of Computer Science at Carnegie Mellon University, the process is accurate to within 0.005 inches, (Lyell-Otis, 2018). The industrial-scale goals of rapid manufacturing strategies in the medical zone have recently emerged for the provision of specialized clinical devices and products, with the above-mentioned advantages and benefits of the techniques (Jumani et al., 2014).

2.2.6 Disadvantages of FDM

The downside of FDM is that if want to print a 3D model with high-quality details, you will also find that the expectations of the consumer will not be met by the FDM 3D printer. Many experts consider that when dealing with extremely complex designs, the SLA method provides far better performance. With objects created by passing the ultraviolet laser beam over the filament, SLA 3D printers use resin-like material. SLA enables objects with a layer resolution of as great as twenty-five microns to be produced, whereas the consumer can expect a simple hundred-micron resolution to be provided by an FDM 3D printer with a lower price range. This improved SLA 3D printing resolution is the secret to creating very high-quality and small-featured objects.

Next, the consistency of the finished product may also be adversely affected by removing the finished item from the 3D printer tray. One of the most sensitive 3D printing operations is carefully removing the support material. There is no hundred percent guarantee that the support material can be removed without the item being scratched or even more seriously damaged. Even if extraordinarily detailed artifacts are no longer made, FDM can still be unable to produce the top-notch product that the consumer needs. Users may often observe that in a way that leaves a line between the printed layers, the filament is extruded. Users can also sand or use special finishing products to get rid of these lines, but this is additional work (Organiscak, 2016). The scaled or irregular outer surface of the objects is the normal downside of modern 3-axis AM procedures. This is an unavoidable step-stepping effect associated with the layered production theory (Giberti et al., 2016).

2.2.7 Application of additive manufacturing

In more than a few industries, such as aerospace, automotive, jewellery, coin producing, tableware, saddle trees, and biomedical, rapid prototyping technologies are used. It is used to produce design models, purposeful models, investment and vacuum casting patterns, medical models, and engineering analysis fashions.

a) Aerospace industry

Aerospace icons such as National Aeronautics and Space Administration (NASA) and piper Aircraft, for instance, use the most exciting FDM purposes in the world, which have 70 components with complex shapes, to apply FDM. In each industry, FDM can be used, such as design providing design flexibility and rapid prototyping to create customized housings for complex assemblies. (Dandgaval & Bichkar, 2016). Figure 2.12 below shows the printed air vent by using FDM.

Figure 2.12: Air Vent

b) Automotive industry

One of the applications in fused deposition modeling is the manufacturing process in automotive which customized tooling and investment casting. The materials that have been used to produce the parts of the automobile are polymers, wax, hot work steels (Gangula et al., 2014).

Automotive aspects which have to be cast into steel if they are damaged or faulty are very vital in terms of mobility in these zones as they prevent motion unless they are replaced, even though many factors can be replaced these cannot be changed easily (Madhav et al., 2016). Figure 2.13 below shows the car mirror is printed by using FDM.

Figure 2.13: 3D Printed Car Mirror

c) Medical industry

In biomedical medicine, advances in radiological imaging have helped patient anatomy to produce CAD reconstructions, allowing patient-specific, custom-made surgical instruments to be developed and manufactured. Most surgical instruments are meant to work for most patients (Ahangar et al., 2019).

Figure 2.14 below shows a new model of prosthetic hand designed to overcome the drawbacks. Here the most important intention is to satisfy the minimal requirements of human needs. This generally works with the assist of servomotor and nylon string with wireless operation. The input data is extracted from the sufferers with ECG, another way of taking input is measuring the dimensions whomsoever required. Very first, this prosthetic hand has to be designed in Pro/E GUI and printed in FDM. The three-dimensional design of the prosthetic hand aspects used to be carried out with commercially accessible design software like Pro/E software (Venkatesh & Ajay Kumar, 2018).

Figure 2.14: 3D Printed Prosthetic Hand

d) Sport industry

Figure 2.15 shows the 3D printed gun that explains the shooting sport has massive scope for innovation in equipment used through shooters, beginning with Foresight to the butt of the rifle, from pistol grip to large bore cheek. We have experimented and developed cheeks, pistol grips, triggers, forehand grip, peep sights with ABS using FDM. Some 3D models are shown which are printed (Raza et al., 2019).

AM allows faster prototype creation for the visualization of prototypes, performance studies, and personalization in the footwear industry for sports activities. SLA, PolyJet, SLS, and three-dimensional printing have been used among the available AM techniques for prototyping shoes for sporting activities. A five-point scoring system was once used to test the performance of AM methods in four main features, specifically precision, surface finish, supported range of materials, and time construction. (Manoharan et al., 2013).

Figure 2.15: 3D Printed Gun

2.3 Application of Analytic Hierarchy Process in Additive Manufacturing

AM is a method of creating a three-dimensional solid model from a digital model of any structure. Different mechanisms occur today in the international market. By making use of the material layer by layer, all these processes create components. It is difficult to choose an acceptable method for a consumer or company interested in additive manufacturing technology in a wide variety of special methods. The use of analytic hierarchy process methods is possible to solve such a problem. This demonstrates some of the applications of the method of analytical hierarchy in additive processing.

a) Selection of the additive manufacturing process using the analytic hierarchy process

The word rapid prototyping refers to the manufacturing of a physical prototype or a basic model that can provide rise to new models and the final product. The term rapid prototyping is significantly changed by the term additive manufacturing over time. The higher quality of the workpieces and the similarity of the finished products lead to parts that can be used immediately after completion in practical applications or which, in their entirety, can replace products produced by traditional technological processes. Unlike traditional technological methods of material removal such as spinning, milling, and drilling, all components are created by the application of the material in layers.

These variations affect the dimensional accuracy of the workpiece, the mechanical properties, the roughness of the surface, the speed of the technological process, the requirement of post-processing, and the overall cost of the machine and the technological process. The validated production of the CAD 3D model with three special additive manufacturing processes will be demonstrated in this paper which are 3D printing, FDM, and SLS. The purpose of this analysis is to choose one of the three methods that are most suitable for practical application. Then some parameters are specified and the AHP approach is used for decision-making (Peko et al., 2015). Figure 2.16 below shows the AHP model and Figure 2.17 shows the overall priorities of alternatives.

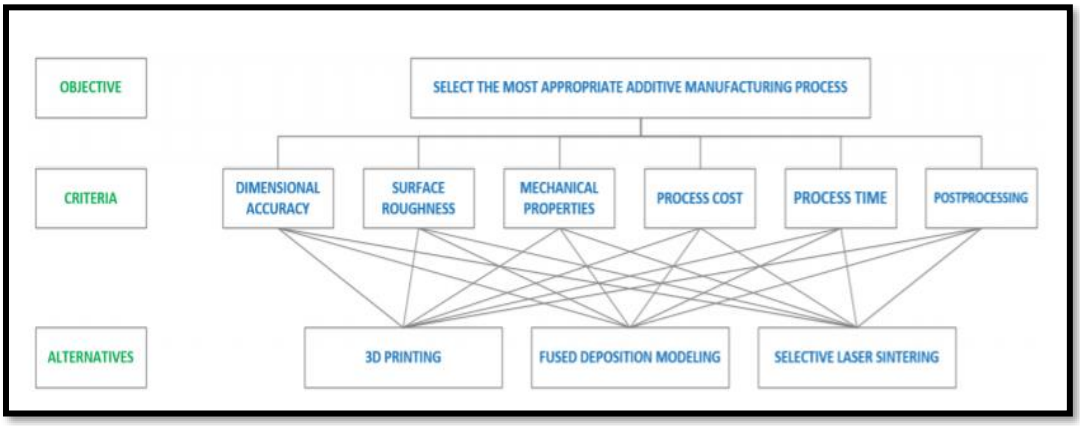

Figure 2.16: AHP Model with Objective, Criteria and Alternatives

ALTERNATIVES	CRITERIA AND WEIGHTS						OVERALL PRIORITIES OF ALTERNATIVES
	DIMENSIONAL ACCURACY	SURFACE ROUGHNESS	MECHANICAL PROPERTIES	PROCESS COST	PROCESS TIME	POSTPROCESSING	
	0,335	0,335	0,193	0,064	0,042	0,031	
3D PRINT	0,250	0,261	0,241	0,393	0,558	0,311	0,276
FDM	0,190	0,453	0,330	0,450	0,252	0,498	0,334
SLS	0,559	0,286	0,429	0,157	0,189	0,191	0,390

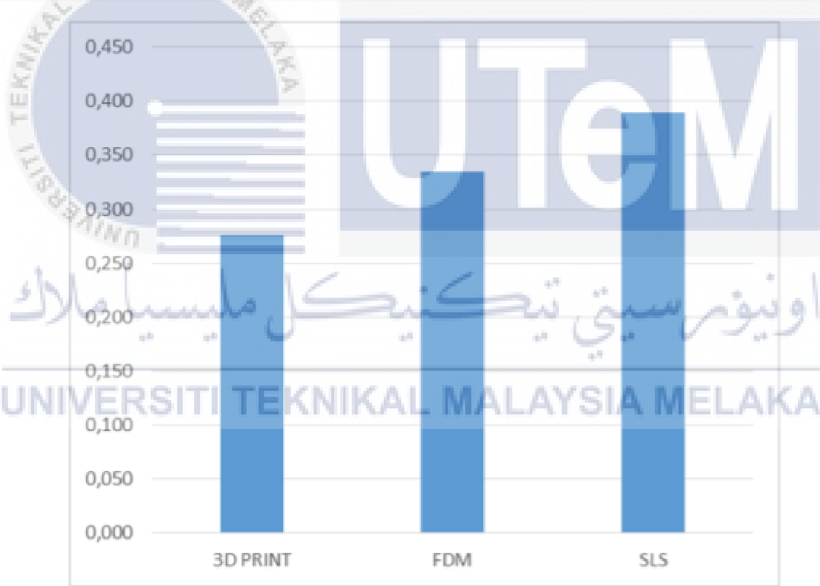

Figure 2.17: Overall Priorities of Alternatives

b) Selection of affordable 3D printer by using the analytic hierarchy process method

To analyze the overall output of low-cost 3D printers, the reason for this paper is to form a selection strategy focused entirely on an analytical hierarchy approach in the case study structure, which benefits from quantitative details. With a growing number of companies manufacturing and promoting machines, the demand for personal 3D printers has seen a major increase over the past decade. The large range of models available below $5000 has become a complex task to choose from for 3D printers, often involving more than one question. As a way of determining the overall performance of these devices in terms of geometric, mechanical, and methodological aspects, several benchmarking components have been proposed, with no consensus on the most suitable model for each case. Furthermore, different decision-making approaches have been used to rationalize the choice of such equipment, usually based solely on qualitative contrast. The assessment criteria taken into account in the system were derived from a common purpose, arranged in a hierarchical structure, and then compared with the research context.

Using three separate devices, a real application model focused on an innovative project was manufactured and then tested on a variety of parameters of great importance. Surface roughness, dimensional and geometric precision, construction time, and measurements of material used were covered in the comparison. The case study demonstrates a much less subjective way of considering the overall efficiency of such devices, which can be carried out easily, taking into account various situations and even different technologies, across the academic and 3D printing communities (Justino Netto et al., 2019). Figure 2.18 below shows the decision hierarchy, Figure 2.19 shows the attributes for 3D printers in the relation of each sub-criterion, and Figure 2.20 shows the final score and ranking of the assessed 3D printers.

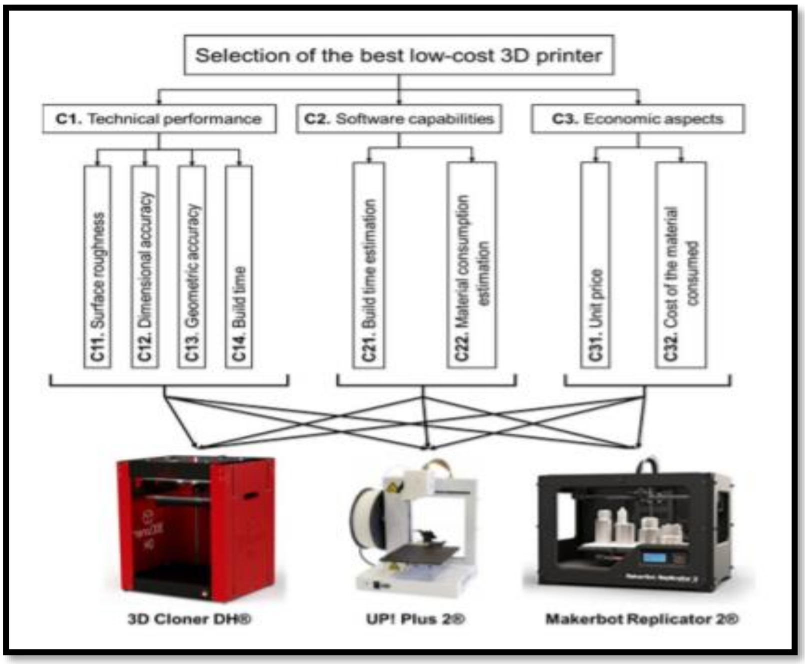

Figure 2.18: Decision Hierarchy

Criterion	Subcriterion	Rating		
		3D Cloner DH*	UP! Plus 2*	MakerBot Replicator 2*
1. Technical performance	1.1 Surface roughness	0.3603	0.4145	0.2253
	1.2 Dimensional accuracy	0.4920	0.1320	0.3760
	1.3 Geometric accuracy	0.5482	0.2188	0.2330
	1.4 Build time	0.3865	0.2759	0.3376
2. Software capabilities	2.1 Build time estimation	0.8399	0.1057	0.0544
	2.2 Material consumption estimation	0.0797	0.8612	0.0591
3. Economic aspects	3.1 Unit price	0.3438	0.3811	0.2752
	3.2 Cost of the material consumed	0.3564	0.3256	0.3179

Figure 2.19: Attributed for the 3D Printers in Relation to Each Sub criterion

Alternative	Final score	Rank
3D Cloner DH*	0.4255	1
UP! Plus 2*	0.3232	2
MakerBot Replicator 2*	0.2513	3

Figure 2.20: Final Score and Ranking

2.4 Research Journal of Process Parameter Optimization on Tensile Strength

Due to the obvious variety of process parameters involved in the printing of a 3D model, the mechanical properties or characteristics of the FDM printed component do not continue to be known as the thermoplastic filament material used (Jaisingh Sheoran & Kumar, 2020). Excellent research efforts have been carried out to determine the influence or effect of these FDM process parameters on the mechanical characteristics of the component. (Popescu et al., 2018).

Greater strength is achieved by increasing the layer height and infill levels. The flexural and tensile strength of the samples with 80% infill was higher. It's also important to understand the implications of the specified parameters on the manufacturing time of the test specimens. The highest tensile strength is obtained for 0.3 mm layer height, 0° orientation, and 80% infill. As the aim of rapid manufacturing is to build parts with considerable strength in low time, therefore the parameters that provided the lowest time for both the flexural and tensile test specimens are 0.3 mm layer height, 0° part orientation, and 80% infill (Bardiya et al., 2020).

The effect of various printing parameters such as build orientation, raster orientation, nozzle diameter, extruder temperature, infill density, shell number, and extrusion speed on tensile strength utilizing Polylactic acid (PLA) filament. However, only three process parameters, build orientation (on-edge), nozzle diameter (0.5), and infill density (100%), were statistically significant and significantly impacted the final product's strength, the data showed. Tensile strength is influenced largely by construction orientation (44.68%) (Hikmat et al., 2021).

On the mechanical qualities of the infill density, patterns, extrusion temperature, layer thicknesses, nozzle diameters, raster angles, and build orientation. Studies on layer thickness have shown it to be the most important element among those evaluated. The layer thickness parameter was discovered to be directly related to impact resistance and compressive strength of parts. Greater layer thickness improves compressive strength, therefore improving overall strength. The researcher also indicated that increasing the layer thickness would improve mechanical qualities because fewer layers would be required. (Syrlybayev et al., 2021).

The filament material appears to affect the effect of layer height. The ABS part was shown to be only slightly responsive to the effect of layer thickness on its performance characteristics. (Rodríguez-Panes et al., 2018) stated that studied the effect of layer height on ABS and PLA filaments and discovered that the influence of layer height on ABS is negligible, whereas the effect of layer height on PLA is considerable.

The 0.4mm layer thickness and 30°/60° raster angle were found to have the maximum tensile strength in PLA specimens. 0.2 mm and 0.3 mm layer thicknesses had the highest tensile strength, according to a tensile test conducted at a constant raster angle. For PLA material, the highest tensile strength may be achieved by using raster angles of 30°/60°. Layers of solid 0.4 mm thickness have a substantially better strength than those of 0.3 and 0.22 mm, which both require additional layers to bind them together, resulting in the required total layer height. The number of layers will decrease as layer thickness increases. (Abdullah et al., 2018).

Layer height, building direction, and extrusion temperature has a considerable impact on mechanical properties, while infill patterns, especially high infill percentage specimens, and printing speed have a less significant impact. Increased layer height and extrusion temperature are required to increase mechanical qualities, as well as the correct construction direction (Alafaghani et al., 2017).

Tensile strength improves as layer thickness increases from 0.05 to 0.1 mm in the horizontal direction, as seen in the above results. However, the cooling rate has little effect on tensile strength. The sample with a layer thickness of 0.2 mm had the greatest tensile strength when oriented vertically. But as the layer thickness increases, the tensile strength decreases (Giri et al., 2021).

Although the effect is more pronounced with PLA than ABS, infill percentage is a manufacturing parameter that has a large influence on the output. This material is stiffer and stronger than ABS, according to the test results. PLA has a very strong adhesive between layers, making it ideal for additive manufacturing. In PLA, the effect is more pronounced than in ABS. However, increasing the infill up to 50% (with a 16% weight increase) considerably enhances mechanical strength, as can be observed (27%) (Rodríguez-Panes et al., 2018).

When the infill percent is increased from 20 to 100%, the tensile stiffness increases from 2 to 2.5 GPa (Alafaghani et al., 2017). (Pandzic et al., 2019) concluded that that infill type and infill density affect ultimate tensile strength and yield strength. Tensile and yield strength both rise when density increases from 10 to 90%. With 90% of the infill, maximum strength is achieved. If a product must have maximum tensile strength, it must be 3D printed with 100% infill, according to the company.

The air spaces in the material may shrink fast as the fill rate increases, causing the material layers and filaments to become more closely linked, increasing the PLA molecular segment movement resistance. Print material's storage modulus, loss modulus, and loss factor rise as a result (Wang et al., 2020).

PLA resin was used to study the construction orientation and, there are five different levels of control, as follows: X0° Y0°, X90° Y0°, X0° Y90°, X0° Y45°. For this experiment, we used tensile strength and maximum fracture load. It was possible to reach maximum tensile strength of 29.36 MPa, as well as a maximum fracture load of 1409.09 N, by building in the X0° Y0° orientation a study has found that as the Y-component of build orientation grows, PLA parts mechanical behavior degrades (Abdelrhman et al., 2019).

(Syrlybayev et al., 2021) stated that the influence of construction orientation on PLA printed parts was also researched 0°, 60°, and 90° levels of control were used to regulate the parts. Results of the Taguchi L27 design experiment demonstrated that the best orientation for FDM pieces was 0°.

For PLA, build orientation provides ideal mechanical properties alongside Y-direction, while ABS build orientation provides the best mechanical properties alongside X-direction (Attoye et al., 2019).

The specimen's strength increases due to an increase in layer thickness interlayer and intralayer bonding could be a factor. Tensile strength is best at 30°/60° raster angle and 0.4mm layer thickness (Leon et al., 2016).

The build orientation contributed 44.68% to the final product while raster orientation contributed only 0.46% to the final product. Statistically significant was just three parameters in the ANOVA table: build orientation, nozzle diameter, and infill densities Tensile strength of 58.05 MPa is achieved with the ideal combination of the process parameters. (Basturk et al., 2020).

Summary: According to the research journal examined, it shows that high tensile strength can be accomplished by high layer thickness, high infill density, the lowest degree of build orientation, and the suitable raster angle. This process parameter is desirable to achieve better tensile strength 3D printed product.

2.5 Computer Aid Design Drawing

A significant industry within the tech world is computer-aided design or CAD. It involves using computers for a wide variety of projects to help with engineering and design. Metal manufacturing, carpentry, and 3D printing, as well as others that have influenced current production and various business processes, are common forms of computer-aided design. (Richard Becker, 2020). The development, modification, and optimization of the design process are authorized by CAD. Thanks to CAD, engineers can build and monitor more realistic representations without problems to improve the quality of the design. Additionally, the software program takes into consideration how different materials communicate. This is especially important as extra significant points are applied to drawings by subcontractors. Drawings or plans can now be stored in the cloud, enabling contractors to view CAD-based drawings or plans on the worksite. Entire teams, along with the contractor and subcontractors, can quickly take a look at layout changes. In this way, relevant events will identify the feasible effect that the changes might have on the creation and adjust as required. Such prepared access to plans enhances coordination through the right of entry (Larry Bernstein, 2020). Figure 2.21 shows the example of computer aid design.

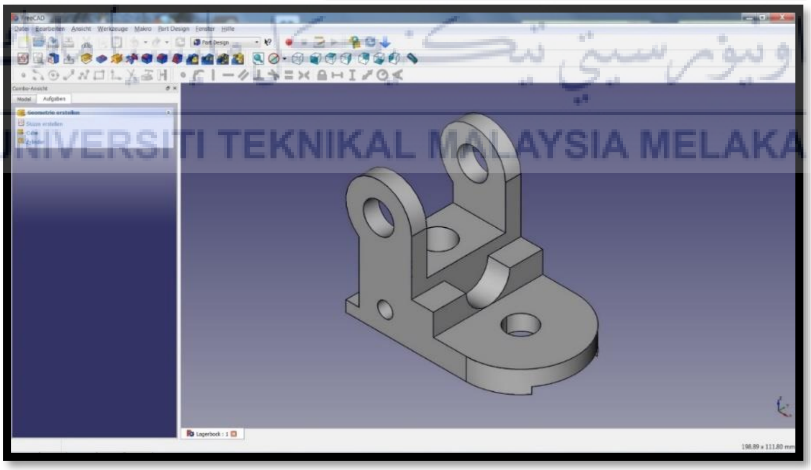

Figure 2.21: Example of Computer Aid Design

2.6 Slicer Software

A slicer tells the printer everything it needs to know to print an object in the best possible way. We call it a “Slicer” because of its main function: dividing the model into individual material layers throughout the z-axis or “slices”. No geometric file (STL) is sent to a 3D printer, but rather G code. This detailed list of commands can be read by a printer to optimize the operation (Alejandro Auerbach, 2020).

A 3D printer cannot directly print a 3D model. A slicing software provides the geometric interpretation of the model. Software known as "Slicing" or simply "Slicer" is used to turn 3D models into codes or paths that 3D printers can understand and use to make prints (MANUFACTUR3D, 2021). Figure 2.22 shows the example of slicing software.

Figure 2.22: Example of Slicing Software

2.7 Tensile Strength Test

For a variety of reasons, tensile tests are conducted. As new materials and procedures are being developed, tensile characteristics are routinely measured to compare them. Uniaxial tension is not the only type of loading that may be predicted by using tensile characteristics. Often, the strength of a material is the most important factor. Strong materials can be determined by measuring either the stress required to generate substantial plastic deformation or the maximum stress that material can withstand, respectively. They are employed in engineering design, albeit with caution (in the form of safety considerations). Dextility, which measures how much the material can be bent before breaking, is another factor to consider (Davis, 2004).

To determine a material or component's strength, it is necessary to execute a tensile test. To determine the maximum force, a handheld force gauge can be used to perform tensile testing at its most basic level. There are also more sophisticated tensile testing systems, which are equipped with advanced testing software and accompanying instruments, such as extensometers, on one end of the spectrum. These testing devices can pull the sample under test to a target at an extremely exact velocity. For force and distance, or stress and strain, a large sample size helps provide high-resolution data, allowing for highly accurate measurements to be recorded, analyzed, and reported (Clinton, 2018). Figure 2.23 shows how the tensile strength test is performed.

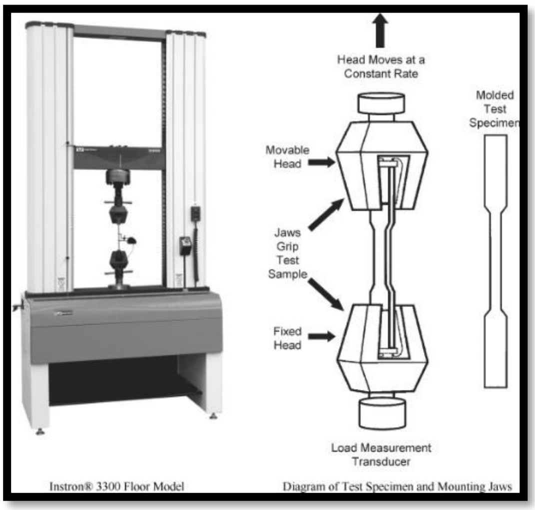

Figure 2.23: Tensile Strength Test

2.8 AHP Sensitivity Analysis

Sensitivity analysis is changing the weight values and computing the new solution. By altering one parameter progressively at a time, it calculates the new answer and graphically displays how the global ranking of alternatives changes. These weights are a linear function of the local weights. Given this property, the global priorities of alternatives can be expressed as a linear function of the local weights. (Librantz et al., 2017).

When it comes time to rank the alternatives, their final rankings are heavily influenced by how much weight is given to the primary criteria. This means that little adjustments might have a large impact on the final ranking. Since these weights are frequently based on highly subjective evaluations, it is necessary to test the stability of the ranking under different criteria weights. Based on scenarios that depict possible future events or differing opinions about the relative relevance of criteria, a sensitivity analysis can be undertaken for this reason (Chang et al., 2007).

According to this method, a model is deemed to be "sensitive" or "insensitive" to changes in its parameter values or its structure. Our research in this study focuses on the sensitivity of a parameter's values. Normally, parameter sensitivity is assessed by running a series of experiments in which the modeler tries out different parameter values to observe how they affect the dynamic behavior of the stock market over time. Analyzing sensitivity provides insight into how model behavior responds to changes in parameter values, making it a valuable tool both in the development of models and in their evaluation. Sensitivity Analysis can also be used to determine the model resemblance with the process under study. Financial applications, risk analysis, etc., use this technique extensively. Because it evaluates the repercussions of inaccurate scenarios and estimates the accuracy of data, it's also quite valuable in this regard (Shashikumar & Sarkar, 2018).

CHAPTER 3

METHODOLOGY

This chapter will cover the specifics of the approach that is being used to complete and perform well on this project. Technique such as AHP, tensile strength test and sensitivity analysis are used to accomplish the target of a project that will achieve a perfect outcome.

3.1 Flow Chart

A flow chart is used to describe the flow of a process from beginning to end of this project. The flow chart below provides a clear path and a better understanding of the implementation of the project based on the objective of this project as depicted in this flow chart. Figure 3.1 shows the flowchart that is related to objective 1, Figure 3.2 shows the flow chart that is related to objective 2, and Figure 3.3 shows the flow chart that is related to objective 3.

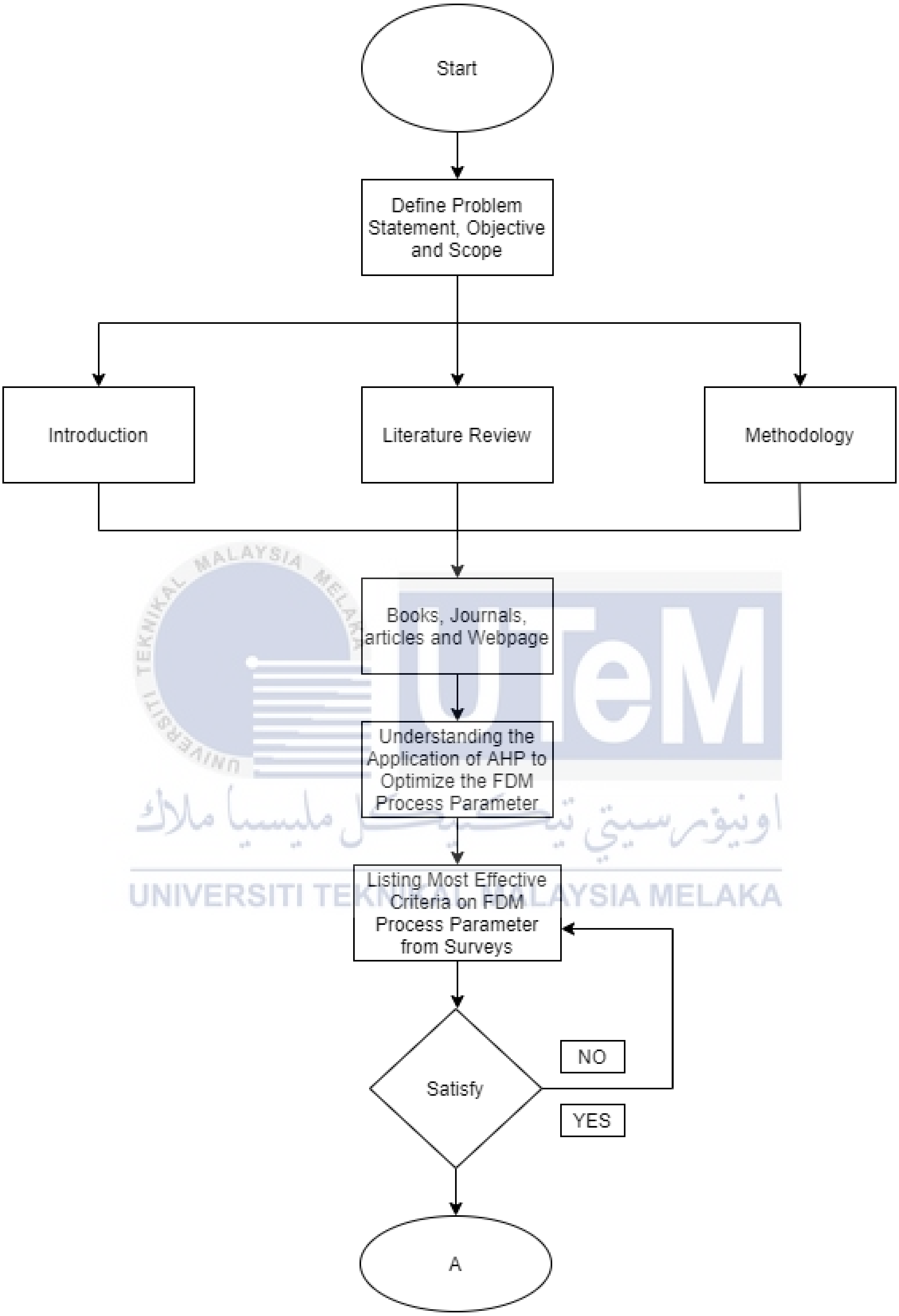

Figure 3.1: Flow Chart That Related to Objective 1

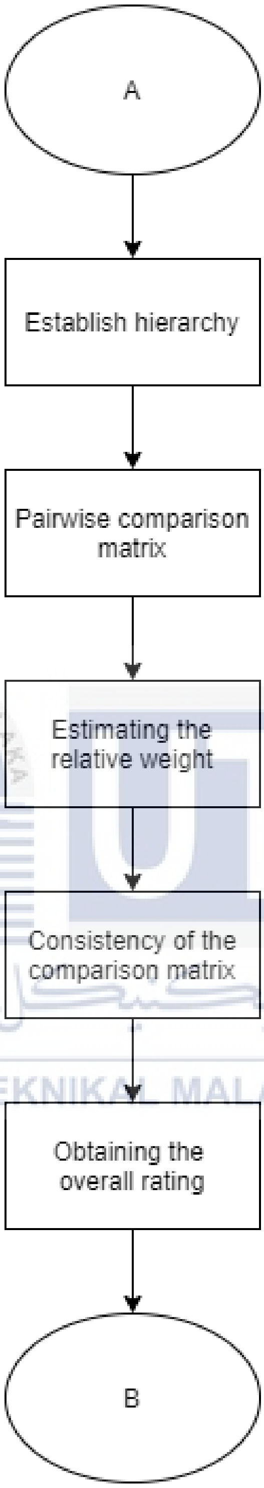

Figure 3.2: Flow Chart That Related to Objective 2

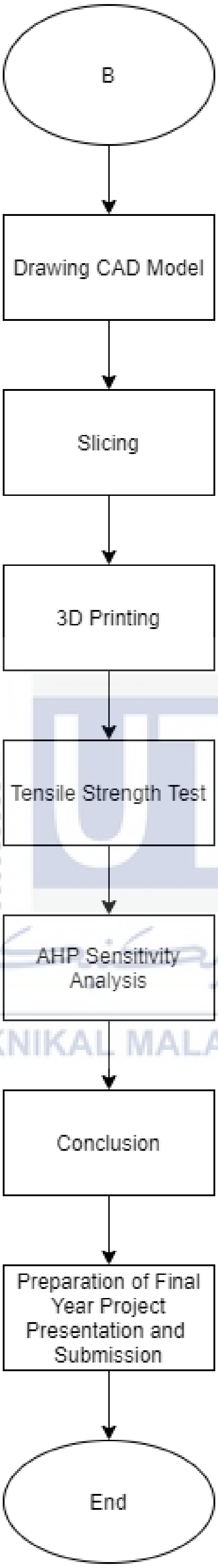

Figure 3.3: Flow Chart That Related to Objective 3

3.2 Survey Data Collection

The data collection method is the most important part of the project. In part, because all following processes are dependent on it. To determine the relative importance of tensile strength, a detailed literature survey was conducted to list the most effective criteria of FDM for tensile strength. Next, studies using the AHP are common in survey-based research for user committees. Participants in AHP studies can range from a few specialists to hundreds of people. Finding the right sample size is crucial when conducting survey research (Melillo & Pecchia, 2016). The studies were constructed based on the hierarchy tree to allow pairwise comparisons of all the selection criteria at each level of the tree. As a result of the pairwise comparison process, a group's strength can be determined. Furthermore, all studies used to arrive at the rankings were carefully and critically selected.

3.3 Analytical Hierarchy Process Method

The Analytical Hierarchy Process is one of the most inclusive structures that is known to have multiple criteria because this approach provides a hierarchical formulation of the problem and therefore a combination of quantitative and qualitative criteria. Step by step, this section will detail the method of analytical hierarchy.

3.3.1 Establish the hierarchy

Figure 3.4 below shows the structure of the AHP, which hierarchically introduced the issue and purpose of decision-making to the scene of the relevant decision elements at the first level. Decision-making elements are decision signals and decisions by creating a hierarchy following the figure below that must represent the problem of understudy. (Taherdoost, 2018).

A complex decision is to be arranged in a hierarchy descending to more than a few criteria from a general target, sub-criteria until the lowest level. At the top level of the hierarchy, the general purpose of the decision is portrayed. At intermediate levels, the criteria and sub-criteria which contribute to the decision are represented. Finally, the alternatives to the decision are laid down at the final hierarchical level. According to Saaty, with the help of creative thinking, imagination, and using people's perspectives, a hierarchy can be created.

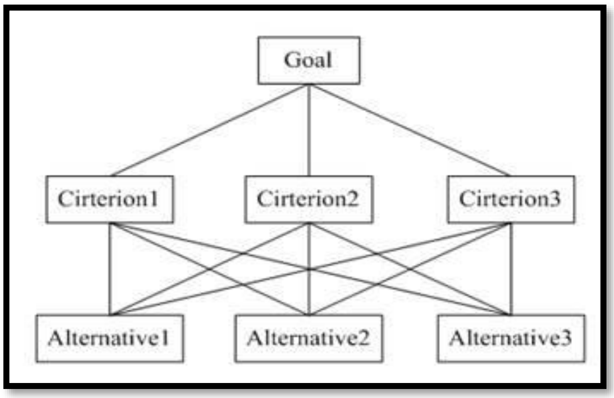

Figure 3.4: AHP Structure

3.3.2 Pairwise comparison matrix

Comparison is made at all levels of hierarchy in pairs of structure variables, where the decision-priorities makers are articulated using the Saaty scale of relative significance levels. The scale consists of 5 levels and 4 sub-levels that define the intensity verbally, with numerical values in the range of 1 to 9 corresponding to each other (Pachemska et al., 2014).

The scale ranges from one to 9 where one implies that the two elements are identical or are equally important. On the other hand, range 9 implies that one element is extraordinarily more important than the different one in a pairwise matrix. The pairwise scale and the importance value attributed to every number are illustrated (Taherdoost, 2018). Figure 3.5 shows the score for the important variable.

Importance Scale	Definition of Importance Scale
1	Equally Important Preferred
2	Equally to Moderately Important Preferred
3	Moderately Important Preferred
4	Moderately to Strongly Important Preferred
5	Strongly Important Preferred
6	Strongly to Very Strongly Important Preferred
7	Very Strongly Important Preferred
8	Very Strongly to Extremely Important Preferred
9	Extremely Important Preferred

Figure 3.5: Score for The Important Variable

(Ibraheem & Atia, 2017) stated that to determine the relative preferences for two elements of the hierarchy in matrix A, an underlying semantically scale is employed with values from 1 to 9 to rate, and for every factor of the hierarchy structure all the related elements in low hierarchy are compared in pairwise contrast matrices as follows Figure 3.6.

$$A = \begin{bmatrix} 1 & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & 1 & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{bmatrix}$$

where
A = comparison pairwise matrix,
w_1 = weight of element 1,
w_2 = weight of element 2,
w_n = weight of element n.

Figure 3.6: Pairwise Comparison Matrix

3.3.3 Estimating the relative weights

(Ibraheem & Atia, 2017) also stated that some strategies like the eigenvalue technique are used to calculate the relative weights of elements in each pairwise comparison matrix. The relative weights (W) of matrix A are got from the following Equation 3.1.

Equation 3.1

$$(A - \lambda_{max}\, I) \times W = 0$$

Where λ_{max} = The biggest eigenvalue of matrix A,

I = Unit matrix

From the point of view of engineering applications, own-value problems are among the most important matrix-related problems. Let A = $[a_{jk}]$ be a given n×n matrix and consider the vector equation that shows from Equation 3.2.

Equation 3.2

$$Ax = \lambda x$$

Here, x is an unidentified vector and λ is an unknown scalar. Clearly, for any value of λ, the zero-vector x=0 is the solution of equation (3). It is of no fair interest. A value of λ that has a response of x≠0 is known as the matrix A's value or characteristic value (or latent root). The corresponding options x to 0 of equation (3) are referred to as proprietary vectors or A vector attributes corresponding to the proprietary value λ. The spectrum of A is called the set of Eigenvalues. The largest of the absolute values of A's values is defined as A's spectral radius.

3.3.4 Consistency of the comparison matrix

Equation 3.3

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Equation 3.4

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

Equations 3.3 and 3.4 show the maximum eigenvalue is a sum of y1, y2, ... yn and denoted via λ max. CI= λ max-n/n-1, where n is the total number of elements being compared, CR= CI/RI, where RI is a random consistency number of equal matrix size. RI is the consistency index of a randomly generated pair-wise comparison matrix which is the value of RI varies with several elements to be in contrast. The CR provides a measure of the likelihood that the matrix was once filled in simply at random; it is an evaluation between the current matrix and an in simple terms random answering of questions. The acceptability of CR is $\leq$ 0.1 (Harker, 1989), in some cases, it can be tolerated up to 0.2, however in no way extra than that (Saaty and Kearns, 1985). If CR is now not suitable then revise the judgments via extra cautious analysis (Ngo-Hoang, 2019).

3.3.5 Obtaining the overall rating

Equation 3.5 shows the obtaining relative weight of the decision that the rankings of preference are mixed with the criterion weights in a closing step to produce an overall score for each choice. Following the relative importance of the criterion, the extent to which the alternatives satisfy the criteria is weighted. Via simple weighted summation, this is done. Finally, after decisions have been made on the influence of all the elements and objectives have been measured for the hierarchy as a whole, from time to time and with care, due to their incredibly limited impact on the overall goal, the much fewer essential factors can be dropped from similar consideration. The targets may then be recalculated throughout, whether with or without changing the decisions.

Equation 3.5

$$Overall(factor) = \sum C_i W_i$$

3.4 Tensile Strength Test

After getting the result of which process parameter has the highest rank that can optimize the tensile strength of the printed product, the process parameter needs to be validated by doing the tensile strength test on how the process parameter affects the tensile strength.

3.4.1 Modelling ASTM D638 type 1 specimen

The first step was to design the specimens to be constructed on additive production technologies such as Fused Deposition Modelling (FDM) technology. Since the test specimens that used to be constructed on the FDM process have been subjected to mechanical property tests such as tensile testing, compressive testing, and hardness testing, the specimens must be developed according to ASTM specifications, which are a standard dog bone structure specimen for tensile testing and a standard block form specimen for compressive testing as well as for hardness testing. This gripping head is 32.86mm in size and 19mm high. The test specimen has a gauge length of 57 mm and a gauge width of 13 mm.

To do this experiment, firstly the specimen needs to be drawn in CATIA software with the exact length of the specimen as shown in Figures 3.7, 3.8, and 3.9 below. The dimension of the specimen is 165mm × 19mm × 3.2 mm.

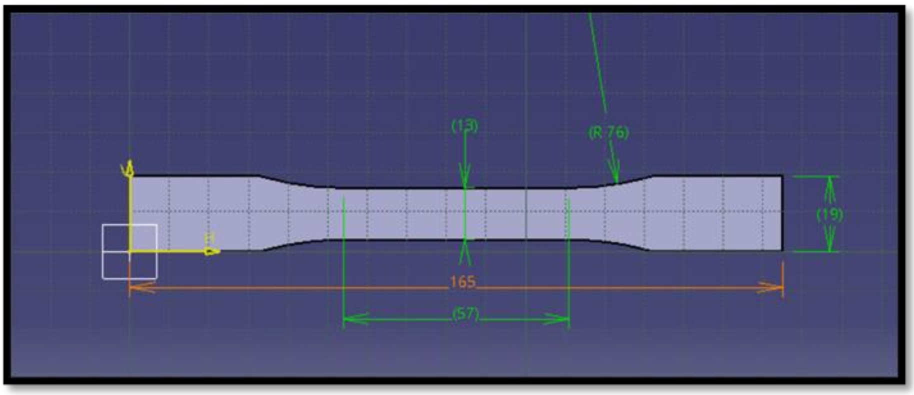

Figure 3.7: The Dimension of ASTM D638 Type 1

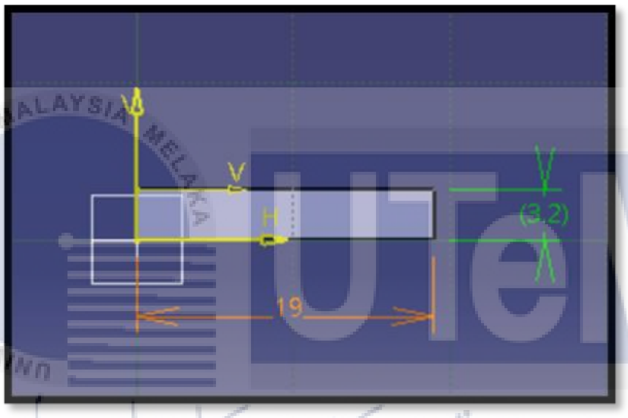

Figure 3.8: The Dimension of ASTM D638 Type 1

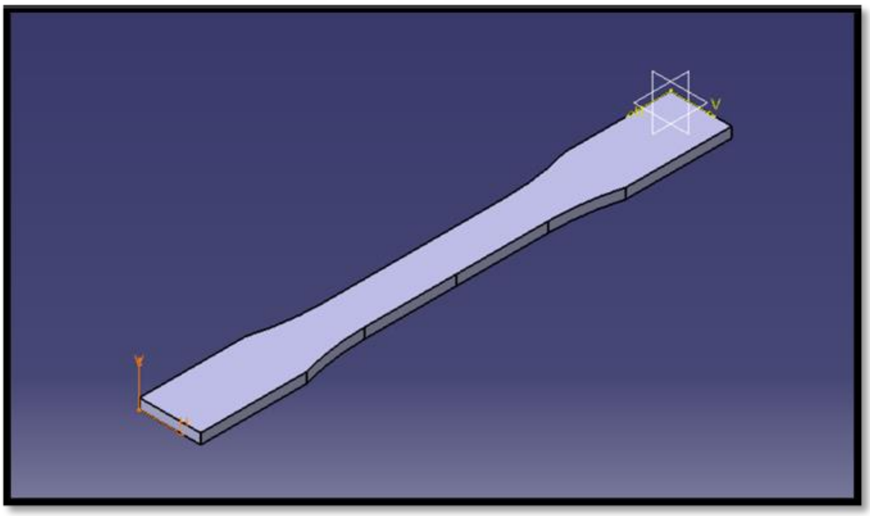

Figure 3.9: The model of the ASTM D638 Type 1

3.4.2 Slicing

First, a 3D model must be converted into an STL file before it can be sliced. In the three-dimensional Cartesian coordinate system, an STL file consists of a set of points that represent the nodes of all the triangles into which the model is spliced when it has meshed, and eventually, the entire model when it is assembled. Matlab, a computer language, requires this step to interpret and display the model. In a script, the model coordinates are read and sliced, and then the tool path can be created (Adams & Turner, 2020).

After drawing the specimen, the file needs to be saved as an STL file. The slicing software that has been used for this project is Ultimaker Cura software shown in figure 3.10. From this software, the specimen has been sliced with 3 different types of layer height which are 0.1mm, 0.2mm and 0.3mm with constant infill density, build orientation, and raster angle. Figure 3.10 shows the Ultimaker Cura slicing software.

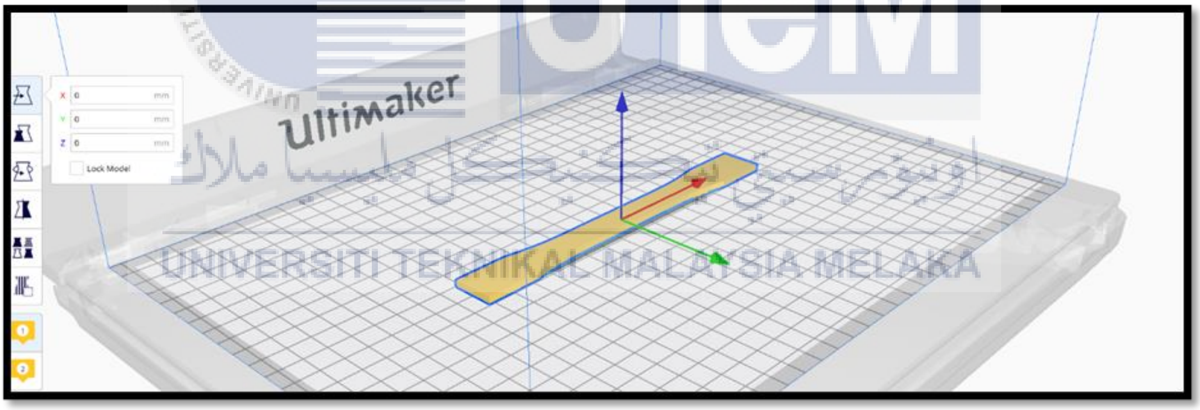

Figure 3.10: Ultimaker Cura Slicing Software

3.4.3 3D printing

This material is unwound from a coil and supplied through an extrusion nozzle during printing. Sometimes termed a build platform or a table, the nozzle melts the filaments and extrudes them onto a base. It's controlled by a computer, which converts the dimensions of an object into X, Y, and Z coordinates that are followed by the nozzle and base during printing, respectively (Elizabeth Palermo, 2013).

After the specimen has been sliced, now the specimen can be printed by using Ender 3 V2 3D printer which is FDM technology in Figure 3.11. 3 specimens have been printed to proceed with this tensile strength test as shown in Figure 3.12.

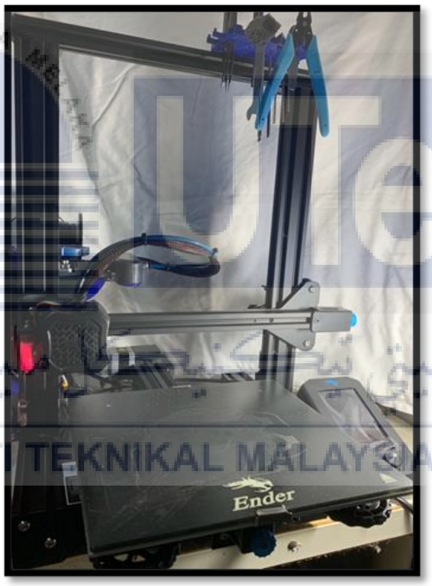

Figure 3.11: Ender 3 V2 3D Printer

Figure 3.12: The ASTM D638 Type 1 Specimens

3.4.4 Tensile strength test specimen

The tensile strength of the specimen is tested using a tensile strength test machine. The tensile test specimen is modeled according to the standard ASTM D638 tensile test specimen, which complies with the ASTM D695 standard. To conduct the test, the Type I standard ASTM D638 is selected.

Finally, after printing the specimens, the tensile strength test will have proceeded. The tensile strength machine will grip the specimens. Aligning the specimen's long axis with an imaginary line connecting the grips to the machine. Do not overtighten grips. They should be tight enough to prevent slippage, but not so tight that the specimen is crushed. Then set the speed of testing at the proper rate which is 5mm/min shown in Figure 3.13.

After running the test, the data was collected which is the force that is required to break the specimen due to the tensile strength formula which is tensile strength is equal to the force divided with the cross-sectional area of the specimens.

Figure 3.13: Tensile Strength Test Machine

3.5 Performing AHP Sensitivity Analysis

The sensitivity AHP analysis for this project was conducted by using Super Decision V3.2 software. Firstly, sensitivity analysis to analyze how the priorities of alternatives change as we vary the priority of criterion. To obtain the graph of the sensitivity, first, select the computations sensitivity in the software and edit the independent variable. Then, set up the parameter type to the super matrix as the parameter data source. Select the first criteria for this project which is the layer thickness and select the alternatives which are options 1,2 and 3 and update the model. The graph will be shown, move the vertical line at the rank reverse point to see the results change according to the layer thickness priority change. The point means that when the layer thickness is above a certain point, the best choice will be shown below the graph. After done with the layer thickness, proceed to check the sensitivity for other criteria such as the infill density, build orientation, raster angle with options 1,2, and 3. This sensitivity analysis will show the stability of the ranking under different criteria weights.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter will show the results that has been conducted to achieve the objectives in this project. The results data such as survey data collection, AHP analysis, tensile strength test and sensitivity analysis was performed.

4.1 Survey Data Collection

According to the research journal examined in chapter 2 literature review, it showed that high tensile strength can be accomplished by high layer thickness, high infill density, the lowest degree of build orientation, and the suitable raster angle. This process parameter is desirable to achieve better tensile strength 3D printed product. Next, the survey from the user committees showed the result for giving the value for the comparison pairwise matrix of AHP analysis as the bar graph figures below. Scale of number 1 is equally important preferred and 9 is extremely important preferred based on the score for the importance variable.

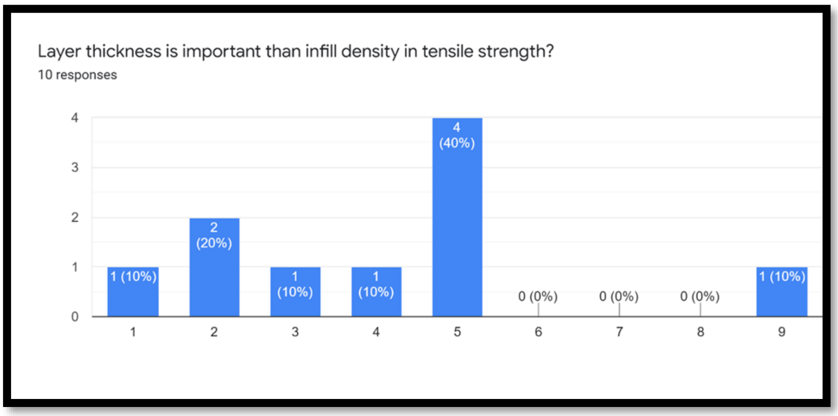

Figure 4.1: Survey Bar Graph Question 1

This bar graph in Figure 4.1 shows that layer thickness is strongly important preferred than infill density in tensile strength due to a scale of 5 has the highest percentage which is 40%.

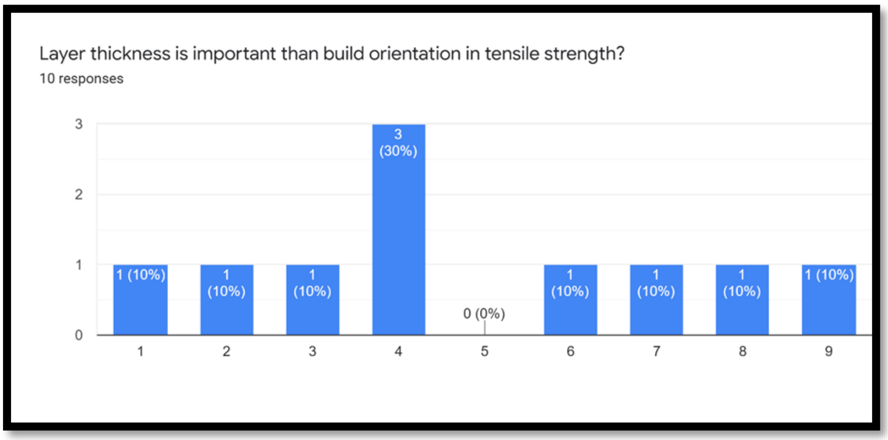

Figure 4.2: Survey Bar Graph Question 2

This bar graph in Figure 4.2 shows that layer thickness is moderately to strongly important preferred than build orientation in tensile strength due to scale of 4 has the highest percentage which is 30%.

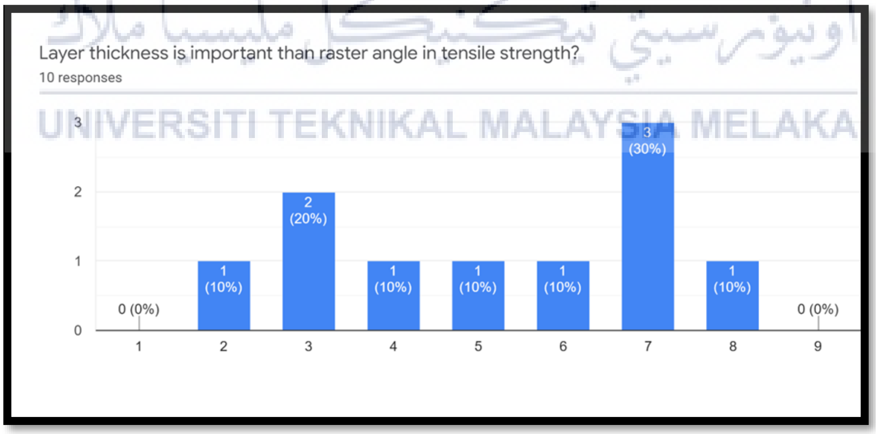

Figure 4.3: Survey Bar Graph Question 3

This bar graph in Figure 4.3 shows that layer thickness is very strongly important preferred than raster angle in tensile strength due to scale of 7 has the highest percentage which is 30%.

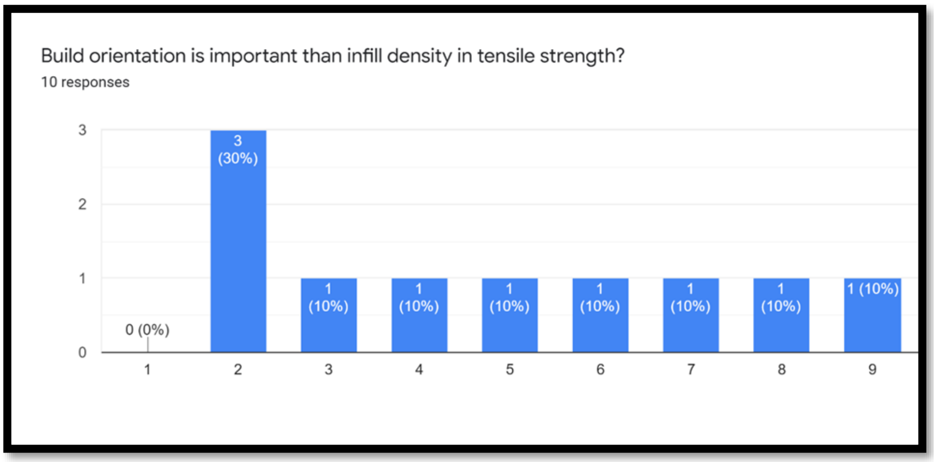

Figure 4.4: Survey Bar Graph Question 4

This bar graph in Figure 4.4 shows that build orientation is equally to moderately important preferred than infill density in tensile strength due to scale of 2 has the highest percentage which is 30%.

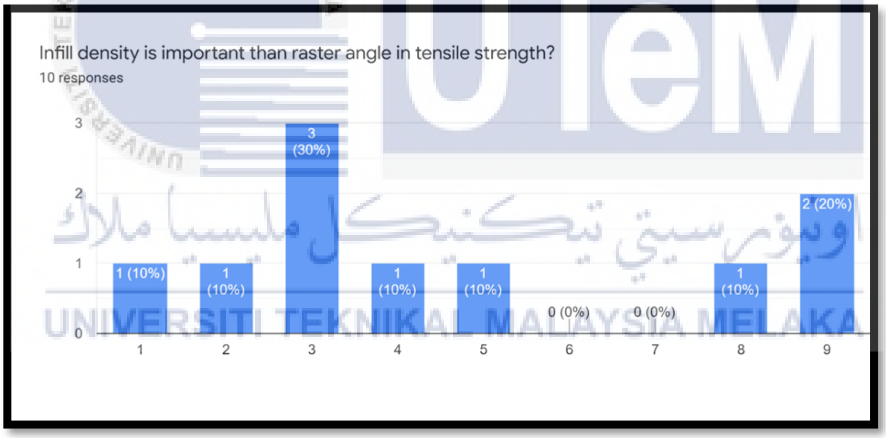

Figure 4.5: Survey Bar Graph Question 5

This bar graph in Figure 4.5 shows that infill density is moderately important preferred than raster angle in tensile strength due to scale of 3 has the highest percentage which is 30%.

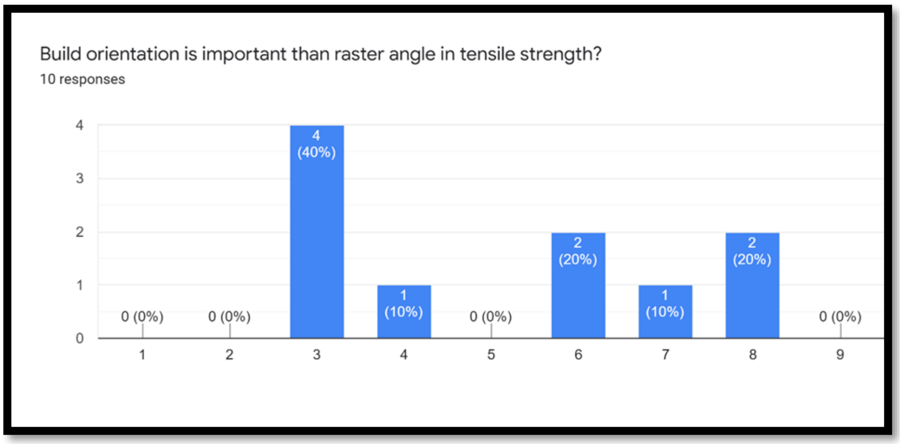

Figure 4.6: Survey Bar Graph Question 6

This bar graph in Figure 4.6 shows that build orientation is moderately important preferred than raster angle in tensile strength due to scale of 3 has the highest percentage which is 30%.

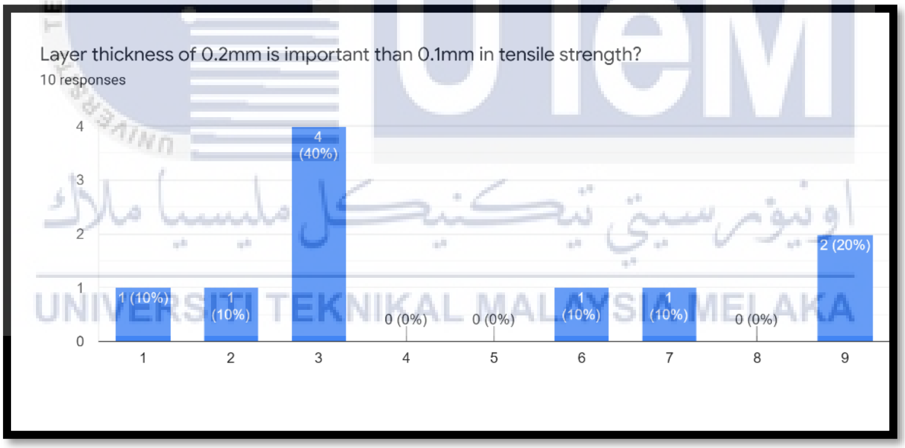

Figure 4.7: Survey Bar Graph Question 7

This bar graph in Figure 4.7 shows that layer thickness of 0.2mm is moderately important preferred than 0.1mm in tensile strength due to scale of 3 has the highest percentage which is 40%.

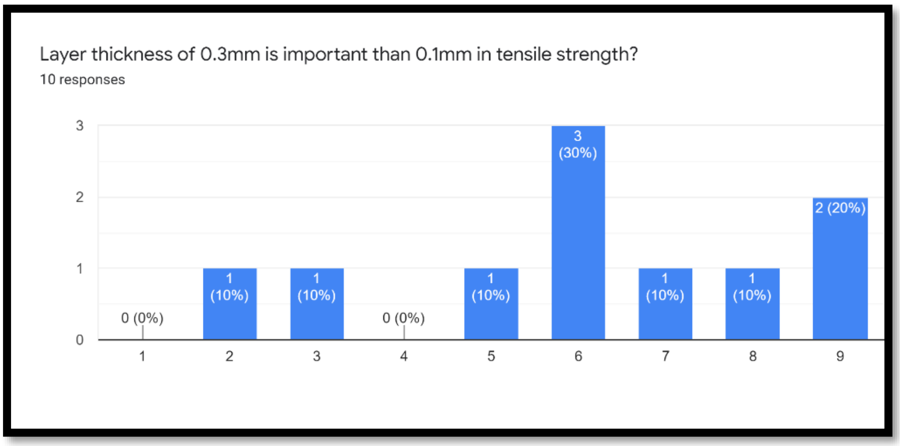

Figure 4.8: Survey Bar Graph Question 8

This bar graph in Figure 4.8 shows that layer thickness of 0.3mm is strongly to very strongly important preferred than 0.1mm in tensile strength due to scale of 6 has the highest percentage which is 30%.

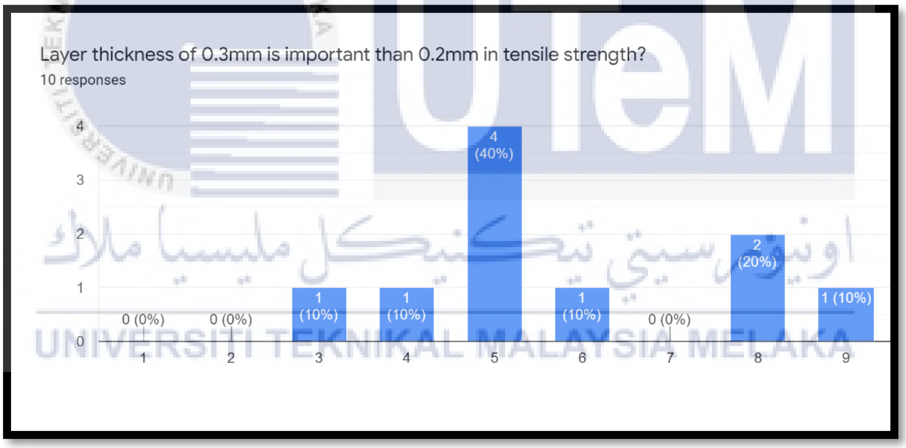

Figure 4.9: Survey Bar Graph Question 9

This bar graph in Figure 4.9 shows that layer thickness of 0.3mm is strongly important preferred than 0.2mm in tensile strength due to scale of 5 has the highest percentage which is 40%.

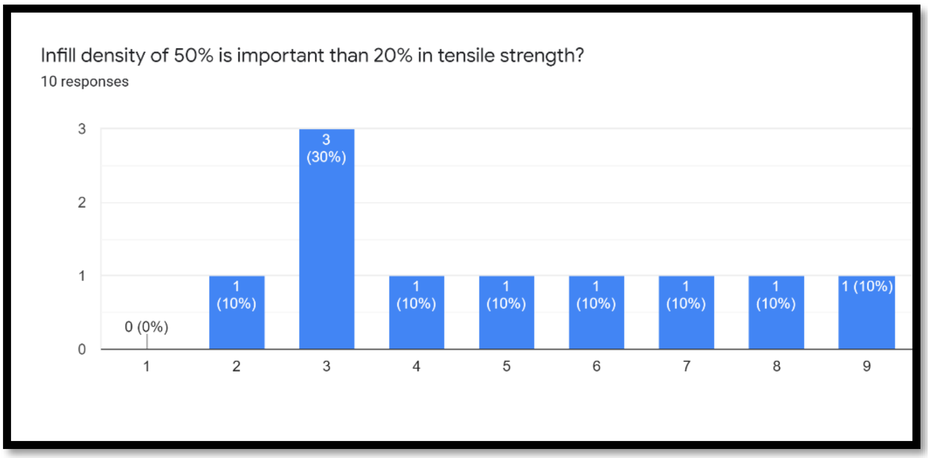

Figure 4.10: Survey Bar Graph Question 10

This bar graph in Figure 4.10 shows that an infill density of 50% is moderately important preferred than 20% in tensile strength due to scale of 3 has the highest percentage which is 30%.

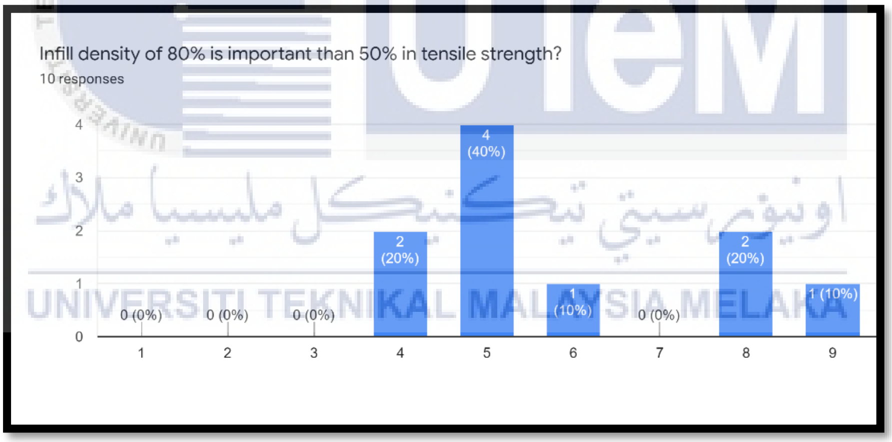

Figure 4.11: Survey Bar Graph Question 11

This bar graph in Figure 4.11 shows that an infill density of 80% is strongly important preferred than 50% in tensile strength due to scale of 5 has the highest percentage which is 40%.

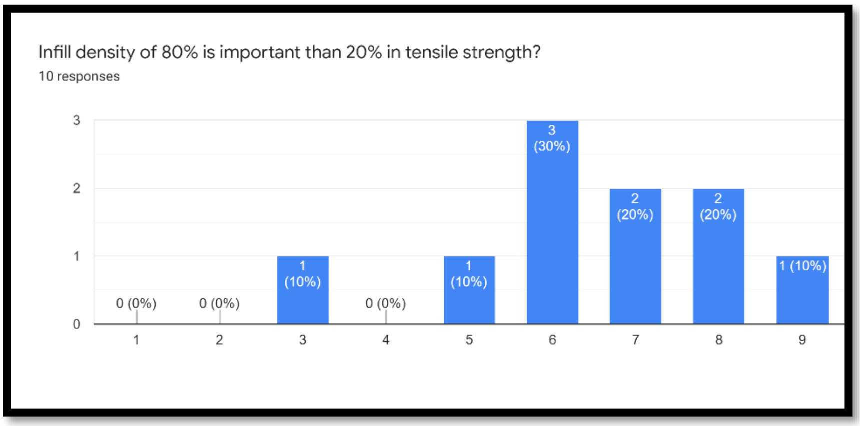

Figure 4.12: Survey Bar Graph Question 12

This bar graph in Figure 4.12 shows that infill density of 80% is strongly to very strongly important preferred than 20% in tensile strength due to scale of 6 has the highest percentage which is 30%.

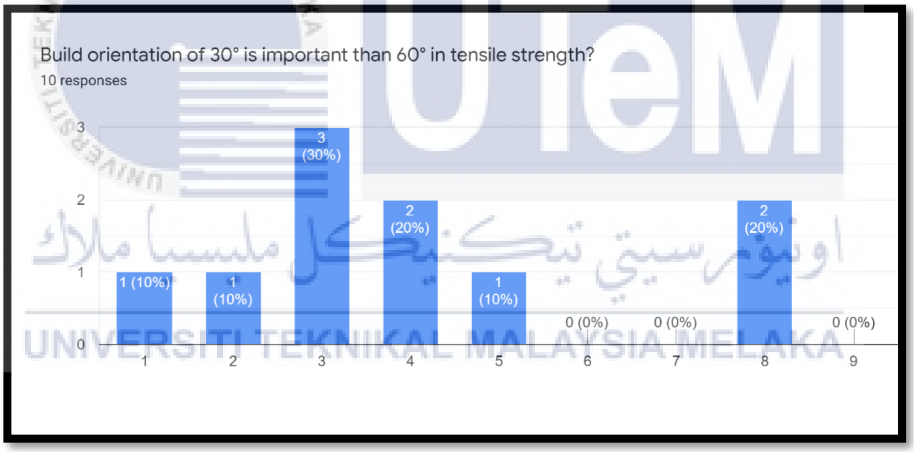

Figure 4.13: Survey Bar Graph Question 13

This bar graph in Figure 4.13 shows that build orientation of 30° is moderately important preferred than 60° in tensile strength due to scale of 3 has the highest percentage which is 30%.

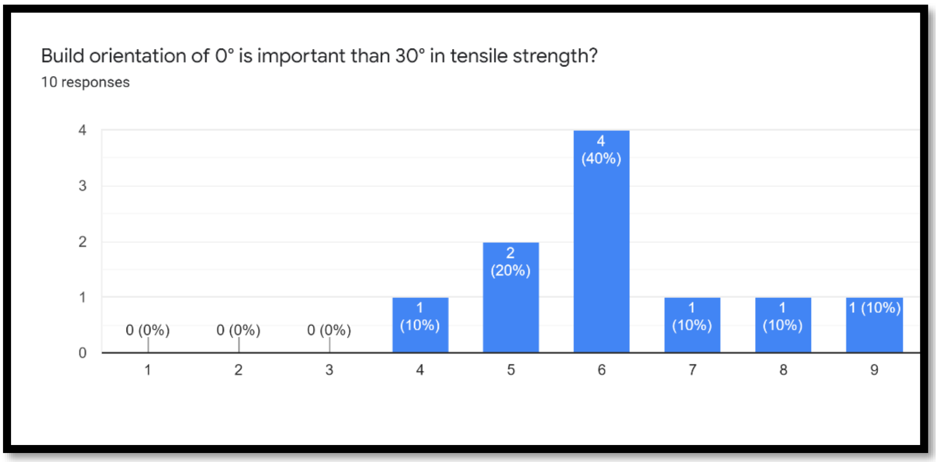

Figure 4.14: Survey Bar Graph Question 14

This bar graph in Figure 4.14 shows that build orientation of 0° is strongly to very strongly important preferred than 30° in tensile strength due to scale of 6 has the highest percentage which is 40%.

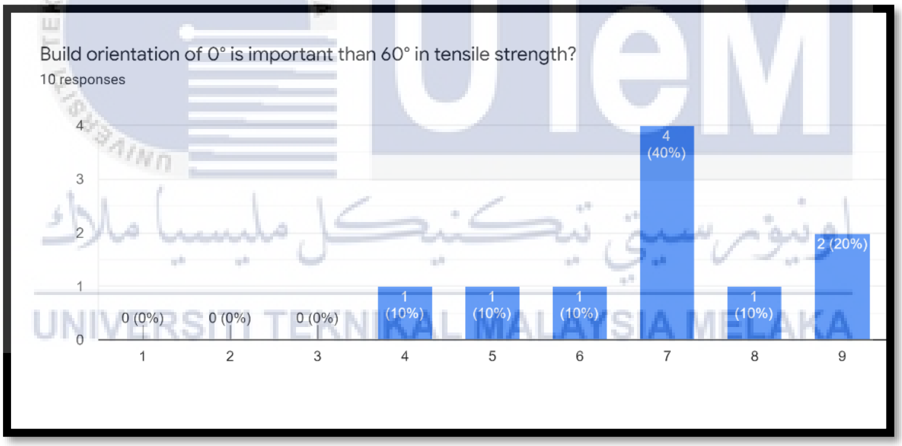

Figure 4.15: Survey Bar Graph Question 15

This bar graph in Figure 4.15 shows that build orientation of 0° is very strongly important preferred than 60° in tensile strength due to scale of 7 has the highest percentage which is 40%.

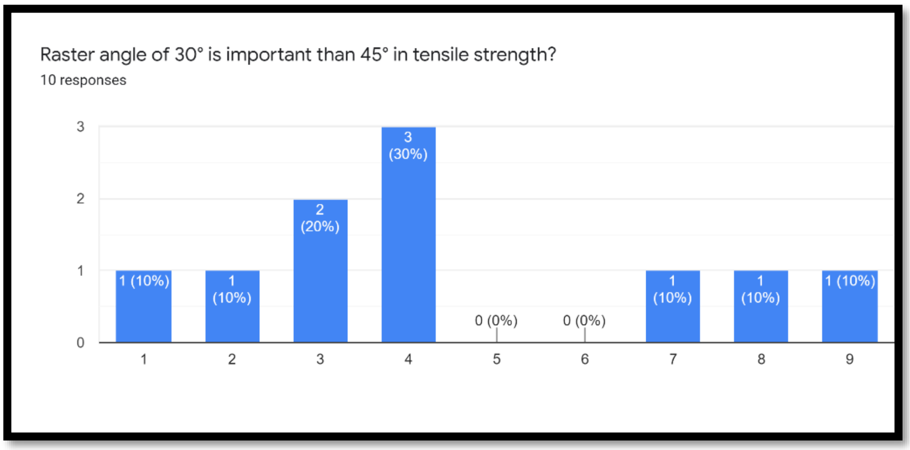

Figure 4.16: Survey Bar Graph Question 16

This bar graph in Figure 4.16 shows that a raster angle of 30° is moderately to strongly important preferred than 60° in tensile strength due to a scale of 4 has the highest percentage which is 30%.

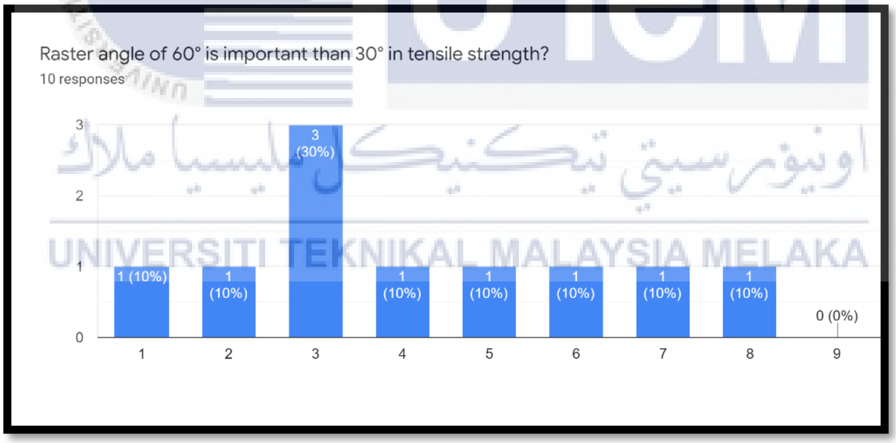

Figure 4.17: Survey Bar Graph Question 17

This bar graph in Figure 4.17 shows that a raster angle of 60° is moderately important preferred than 30° in tensile strength due to a scale of 3 has the highest percentage which is 30%.

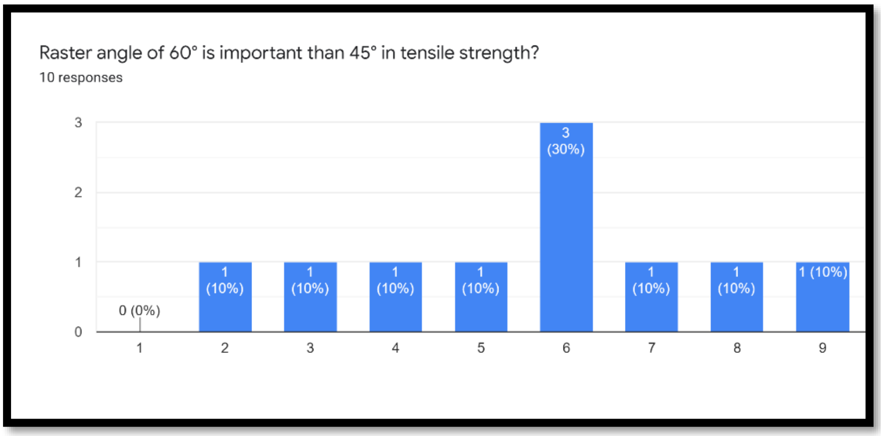

Figure 4.18: Survey Bar Graph Question 18

This bar graph in Figure 4.18 shows that a raster angle of 60° is strongly to very strongly important preferred than 45° in tensile strength due to a scale of 6 has the highest percentage which is 30%.

4.2 AHP Analysis

4.2.1 Developing hierarchical structure

The first step was to develop a hierarchical structure with a goal at the top level, criteria at the second level, and alternatives at the third level. Each alternative has its value associated with them. Figure 4.19 shows that the goal at the top level was to evaluate the capability of the FDM process parameters for tensile strength in the AHP. Next for the criteria at the second level was the layer thickness, infill density, build orientation, and raster angle. The last level which was the alternative shows that it has three options which were option 1, option 2, and option 3.

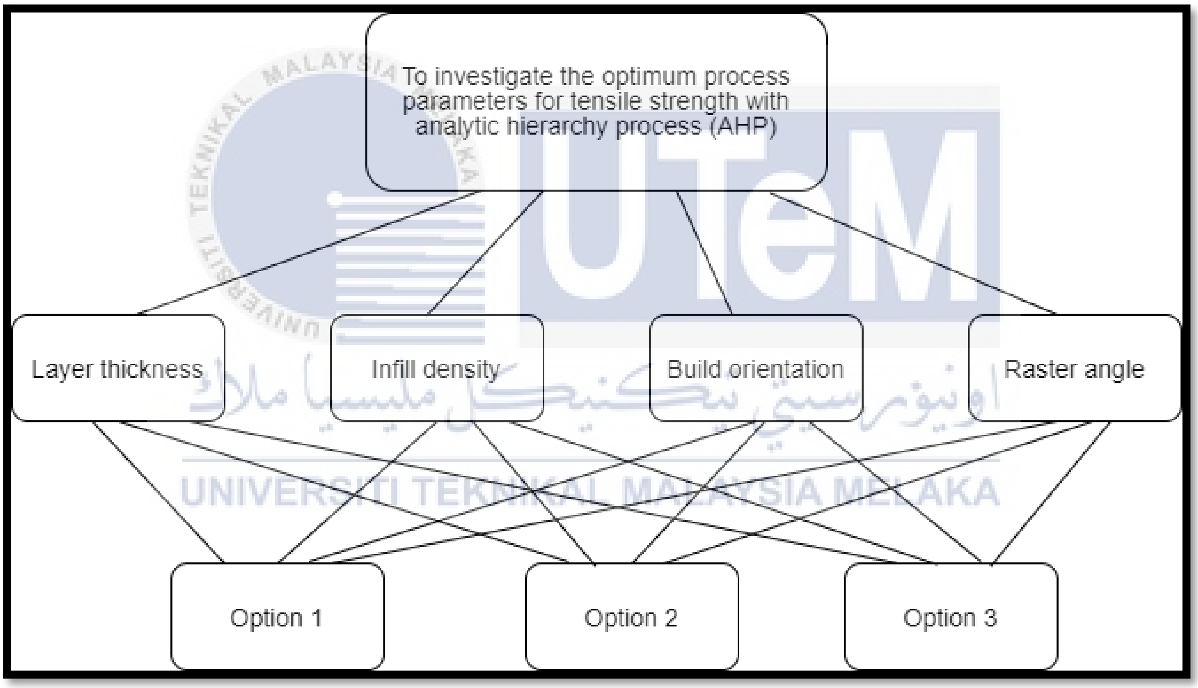

Figure 4.19: Hierarchical Structure

4.2.2 Pairwise comparison matrix

From the survey of the research journal for data collected in chapter 2, the best 4 criteria that affect the tensile strength have been chosen. The ranking of the chosen criteria as listed below:

1. Layer thickness
2. Infill Density
3. Build Orientation
4. Raster Angle

The second step was to create a pairwise comparison matrix based on the survey by the user that has been conducted. The pairwise comparison matrix gave the relative importance of various attributes concerning the goal. It showed how important each criterion is to get the best tensile strength. This pairwise comparison matrix was created with the help of a scale of relative importance. The length of the pairwise matrix was equivalent to the number of criteria used in the decision-making process. So, the 4×4 matrix has four criteria which were layer thickness, infill density, build orientation, and raster angle. The value in the pairwise matrix depends upon the decision-maker based on the journal research that has been made in chapter 2 and the survey from the user. It started with how important was layer thickness to infill density for a good tensile strength of a 3D FDM printed product. The survey that has been made showed that layer thickness was strong important than infill density. For infill density was given x value then, the layer thickness was given 5x value which showed layer thickness have strong importance based on the score of the important variable. Next, divided the row element by the column element. The sum of each value was also calculated like shown in Table 4.1 below.

Table 4.1: Pairwise Comparison Matrix

	Layer thickness	Infill density	Build orientation	Raster angle
Layer thickness	1	5	4	7
Infill density	$\frac{1}{5}$ = 0.200	1	$\frac{1}{2}$ = 0.500	3
Build orientation	$\frac{1}{4}$ = 0.250	2	1	3
Raster angle	$\frac{1}{7}$ = 0.143	$\frac{1}{3}$ = 0.333	$\frac{1}{3}$ = 0.333	1
Sum	1.593	8.333	5.833	14

Then, the normalized pairwise matrix was calculated. All elements of the column were divided by the sum of the column. After that, calculate the criteria weights. The weighted calculated by averaging all the elements in the row that need to be added all the elements and divided it with the number of criteria which gave the criteria weight shown in Table 4.2 below.

Table 4.2: The Normalised Pairwise Matrix

	Layer thickness	Infill density	Build orientation	Raster angle	Criteria weight
Layer thickness	$\frac{1}{1.593} = 0.628$	$\frac{5}{8.333} = 0.600$	$\frac{4}{5.833} = 0.686$	$\frac{7}{14} = 0.500$	0.6035
Infill density	$\frac{0.2}{1.593} = 0.126$	$\frac{1}{8.333} = 0.120$	$\frac{0.5}{5.833} = 0.086$	$\frac{3}{14} = 0.214$	0.1365
Build orientation	$\frac{0.25}{1.593} = 0.157$	$\frac{2}{8.333} = 0.240$	$\frac{1}{5.833} = 0.171$	$\frac{3}{14} = 0.214$	0.1955
Raster angle	$\frac{0.143}{1.593} = 0.090$	$\frac{0.333}{8.333} = 0.040$	$\frac{0.333}{5.833} = 0.057$	$\frac{1}{14} = 0.071$	0.0645

4.2.3 Finalized weights

These weights indicated which parameters should be prioritized when selecting the optimum tensile strength and they provided exact numbers that represented the relative importance of each creation in the process. Table 4.3 shows that layer thickness has the highest criteria weight followed by build orientation, infill density, and raster angle.

Table 4.3: Finalized Weight

	Criteria weight
Layer thickness	0.6035
Infill density	0.1365
Build Orientation	0.1955
Raster angle	0.0645
Sum	1

4.2.4 Consistency analysis

The third step was to calculate the consistency that is to check whether the calculated value is correct or not. This step needs to take the same pairwise comparison matrix which is not normalized. Multiplied each value in the column with the criteria value. On solving, after the matrix that has been got, the weighted sum value is calculated by taking the sum of each value in the row shown in Table 4.4 below.

Table 4.4: Consistency Analysis

	Layer thickness	Infill density	Build orientation	Raster angle	Weighted Sum Value
Layer thickness	$1(0.6035) = 0.6035$	$5(0.1365) = 0.6825$	$4(0.1955) = 0.782$	$7(0.0645) = 0.452$	2.5200
Infill density	$0.2(0.6035) = 0.1207$	$1(0.1365) = 0.1365$	$0.5(0.1955) = 0.0978$	$3(0.0645) = 0.1935$	0.5485
Build orientation	$0.25(0.6035) = 0.1509$	$2(0.1365) = 0.2730$	$1(0.1955) = 0.1955$	$3(0.0645) = 0.1935$	0.8129
Raster angle	$0.143(0.6035) = 0.0863$	$0.333(0.1365) = 0.0455$	$0.333(0.1955) = 0.0651$	$1(0.0645) = 0.0645$	0.2614

Next, the ratio of weighted sum value and criteria weight was calculated. This was to get the lambda value shows in Table 4.5.

Table 4.5: Lambda Value

Weighted Sum Value	Criteria weight	Lambda value
2.5200	0.6035	$\frac{2.5200}{0.6035} = 4.1756$
0.5485	0.1365	$\frac{0.5485}{0.1365} = 4.0183$
0.8129	0.1955	$\frac{0.8129}{0.1955} = 4.1581$
0.2614	0.0645	$\frac{0.2614}{0.0645} = 4.0527$

The λ_{max} was calculated by taking the average of all these values. The λ_{max} was calculated by dividing the weighted summation value in Table 4.3 by the number of criteria. This is shown in Equation 4.1 below.

Equation 4.1

$$\lambda_{max} = \frac{4.1756 + 4.0183 + 4.1581 + 4.0527}{4} = 4.1012$$

Next, calculate the consistency index (CI) which was given by the formula λ_{max} minus n upon n minus 1 based on Equation 4.2 below.

Equation 4.2

$$Consistency\ Index\ (CI) = \frac{4.1012 - 4}{4 - 1} = 0.0337$$

Then, calculate the consistency ratio which was given by dividing the consistency index (CI) with random index (RI) shown in Equation 4.3. The random index in Figure 4.20 was the consistency index of the randomly generated pairwise matrix.

Random Index (RI)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

Figure 4.20: Random Index

Equation 4.3

$$Consistency\ ratio = \frac{CI}{RI} = \frac{0.0337}{0.90} = 0.0374 < 0.10$$

The proportion of inconsistency consistency ratio was less than 0.10 which was standard can assume that the matrix was reasonably consistent so may continue with the process of decision making by using AHP.

4.2.5 Obtaining the overall rating

From the experiments and investigation of the impact process parameter on the tensile strength (Bardiya et al., 2020), the authors used the following criteria to choose the best tensile strength shown in Table 4.6. To make all criteria comparable, the pairwise comparison matrix in Tables 4.7, 4.11, 4.15, and 4.19 showing preferences for the options in terms of the criteria have been calculated. Then in Tables 4.8, 4.9, 4.12, 4.13, 4.16, 4.17, 4.20, and 4.21 synthesized the judgments by the sum of the columns in the pairwise comparison matrix and divided the elements by the column total. The total of the sum needs to be equal to 1. After getting the 1 value, in Tables 4.10, 4.14, 4.18, and 4.22 priority vector of the criteria was calculated by sum all the rows and divided by 3 due to it has 3 options. The priority vector of the criteria also needs to be equal to 1. To obtain the overall rating, Table 4.23 shows that the criteria weight multiplied with priority vector that has been obtained to get the ranking and the overall rating importantly need to be equal with 1.

Table 4.6: The Value for Tensile Strength Criteria in Three Different PLA Material

PLA material	Layer thickness (mm)	Infill density (%)	Build orientation (°)	Raster angle (°)
Option 1	0.1	50	30	30
Option 2	0.2	20	60	45
Option 3	0.3	80	0	60

Table 4.7: Pairwise Comparison Matrix of Layer Thickness

Layer thickness	Option 1	Option 2	Option 3
Option 1	1	$\frac{1}{3} = 0.333$	$\frac{1}{6} = 0.167$
Option 2	3	1	$\frac{1}{5} = 0.200$
Option 3	6	5	1

Table 4.8: Synthesizing Judgements of Layer Thickness

Layer thickness	Option 1	Option 2	Option 3
Option 1	1	$\frac{1}{3} = 0.333$	$\frac{1}{6} = 0.167$
Option 2	3	1	$\frac{1}{5} = 0.200$
Option 3	6	5	1
Sum	10	6.333	1.367

Table 4.9: Elements Divided by the Sum of Column

Layer thickness	Option 1	Option 2	Option 3
Option 1	$\frac{1}{10} = 0.1$	$\frac{0.333}{6.333} = 0.053$	$\frac{0.167}{1.367} = 0.122$
Option 2	$\frac{3}{10} = 0.3$	$\frac{1}{6.333} = 0.158$	$\frac{0.200}{1.367} = 146$
Option 3	$\frac{6}{10} = 0.6$	$\frac{5}{6.333} = 0.790$	$\frac{1}{1.367} = 0.732$
Sum	1	1	1

Table 4.10: Priority Vector for Layer Thickness

Layer thickness	Option 1	Option 2	Option 3	Sum	Sum/3
Option 1	$\frac{1}{10} = 0.1$	$\frac{0.333}{6.333} = 0.053$	$\frac{0.167}{1.367} = 0.122$	0.275	$\frac{0.275}{3} = 0.092$
Option 2	$\frac{3}{10} = 0.3$	$\frac{1}{6.333} = 0.158$	$\frac{0.200}{1.367} = 146$	0.604	$\frac{0.604}{3} = 0.201$
Option 3	$\frac{6}{10} = 0.6$	$\frac{5}{6.333} = 0.790$	$\frac{1}{1.367} = 0.732$	2.122	$\frac{2.122}{3} = 0.707$
					Sum of the column = 1

The priority vector for the options with respect to layer thickness

Option 1 = 0.092

Option 2 = 0.201

Option 3 = 0.707

Table 4.11: Pairwise Comparison Matrix of Infill Density

Infill density	Option 1	Option 2	Option 3
Option 1	1	3	$\frac{1}{5} = 0.200$
Option 2	$\frac{1}{3} = 0.333$	1	$\frac{1}{6} = 0.167$
Option 3	5	6	1

Table 4.12: Synthesizing Judgement of Infill Density

Infill density	Option 1	Option 2	Option 3
Option 1	1	3	$\frac{1}{5} = 0.200$
Option 2	$\frac{1}{3} = 0.333$	1	$\frac{1}{6} = 0.167$
Option 3	5	6	1
Sum	6.333	10	1.367

Table 4.13: Elements Divided by the Sum of Column

Infill density	Option 1	Option 2	Option 3
Option 1	$\frac{1}{6.333} = 0.158$	$\frac{3}{10} = 0.3$	$\frac{0.200}{1.367} = 0.146$
Option 2	$\frac{0.333}{6.333} = 0.053$	$\frac{1}{10} = 0.1$	$\frac{0.167}{1.367} = 0.122$
Option 3	$\frac{5}{6.333} = 0.790$	$\frac{6}{10} = 0.6$	$\frac{1}{1.367} = 0.732$
Sum	1	1	1

Table 4.14: Priority Vector for Infill Density

Infill density	Option 1	Option 2	Option 3	Sum	Sum/3
Option 1	$\frac{1}{6.333} = 0.158$	$\frac{3}{10} = 0.3$	$\frac{0.200}{1.367} = 0.146$	0.604	$\frac{0.604}{3} = 0.201$
Option 2	$\frac{0.333}{6.333} = 0.053$	$\frac{1}{10} = 0.1$	$\frac{0.167}{1.367} = 0.122$	0.275	$\frac{0.275}{3} = 0.092$
Option 3	$\frac{5}{6.333} = 0.790$	$\frac{6}{10} = 0.6$	$\frac{1}{1.367} = 0.732$	2.122	$\frac{2.122}{3} = 0.707$
					Sum of the column = 1

The priority vector for the options with respect to infill density

Option 1 = 0.201

Option 2 = 0.092

Option 3 = 0.707

Table 4.15: Pairwise Comparison Matrix of Build Orientation

Build orientation	Option 1	Option 2	Option 3
Option 1	1	3	$\frac{1}{6} = 0.167$
Option 2	$\frac{1}{3} = 0.333$	1	$\frac{1}{7} = 0.143$
Option 3	6	7	1

Table 4.16: Synthesizing Judgements of Build Orientation

Build orientation	Option 1	Option 2	Option 3
Option 1	1	3	$\frac{1}{6} = 0.167$
Option 2	$\frac{1}{3} = 0.333$	1	$\frac{1}{7} = 0.143$
Option 3	6	7	1
Sum	7.333	10	1.31

Table 4.17: Elements Divided by the Sum of Column

Build orientation	Option 1	Option 2	Option 3
Option 1	$\frac{1}{7.333} = 0.136$	$\frac{3}{10} = 0.3$	$\frac{0.167}{1.31} = 0.127$
Option 2	$\frac{0.333}{7.333} = 0.045$	$\frac{1}{10} = 0.1$	$\frac{0.143}{1.31} = 0.109$
Option 3	$\frac{6}{7.333} = 0.818$	$\frac{7}{10} = 0.7$	$\frac{1}{1.31} = 0.763$
Sum	1	1	1

Table 4.18: Priority Vector for Build Orientation

Build orientation	Option 1	Option 2	Option 3	Sum	Sum/3
Option 1	$\frac{1}{7.333} = 0.136$	$\frac{3}{10} = 0.3$	$\frac{0.167}{1.31} = 0.127$	0.563	$\frac{0.563}{3} = 0.188$
Option 2	$\frac{0.333}{7.333} = 0.045$	$\frac{1}{10} = 0.1$	$\frac{0.143}{1.31} = 0.109$	0.254	$\frac{0.254}{3} = 0.085$
Option 3	$\frac{6}{7.333} = 0.818$	$\frac{7}{10} = 0.7$	$\frac{1}{1.31} = 0.763$	2.281	$\frac{2.281}{3} = 0.760$
					Sum of column = 1

The priority vector for the options with respect to build orientation

Option 1 = 0.188

Option 2 = 0.085

Option 3 = 0.760

Table 4.19: Pairwise Comparison Matrix of Raster Angle

Raster angle	Option 1	Option 2	Option 3
Option 1	1	4	$\frac{1}{3} = 0.333$
Option 2	$\frac{1}{4} = 0.25$	1	$\frac{1}{6} = 0.167$
Option 3	3	6	1

Table 4.20: Synthesizing Judgments of Raster Angle

Raster angle	Option 1	Option 2	Option 3
Option 1	1	4	$\frac{1}{3} = 0.333$
Option 2	$\frac{1}{4} = 0.25$	1	$\frac{1}{6} = 0.167$
Option 3	3	6	1
Sum	4.25	11	1.5

Table 4.21: Elements Divided by the Sum of Column

Raster angle	Option 1	Option 2	Option 3
Option 1	$\frac{1}{4.25} = 0.235$	$\frac{4}{11} = 0.364$	$\frac{0.333}{1.5} = 0.222$
Option 2	$\frac{0.25}{4.25} = 0.059$	$\frac{1}{11} = 0.091$	$\frac{0.167}{1.5} = 0.111$
Option 3	$\frac{3}{4.25} = 0.706$	$\frac{6}{11} = 0.545$	$\frac{1}{1.5} = 0.667$
Sum	1	1	1

Table 4.22: Priority Vector for Raster Angle

Raster angle	Option 1	Option 2	Option 3	Sum	Sum/3
Option 1	$\frac{1}{4.25} = 0.235$	$\frac{4}{11} = 0.364$	$\frac{0.333}{1.5} = 0.222$	0.821	$\frac{0.821}{3} = 0.274$
Option 2	$\frac{0.25}{4.25} = 0.059$	$\frac{1}{11} = 0.091$	$\frac{0.167}{1.5} = 0.111$	0.261	$\frac{0.261}{3} = 0.087$
Option 3	$\frac{3}{4.25} = 0.706$	$\frac{6}{11} = 0.545$	$\frac{1}{1.5} = 0.667$	1.918	$\frac{1.918}{3} = 0.639$
					Sum of the column = 1

The priority vector for the options with respect to raster angle

Option 1 = 0.274

Option 2 = 0.087

Option 3 = 0.639

Table 4.23: Developing Overall Priority Ranking

Criteria weight	0.6035	0.1365	0.1955	0.0645
Criteria/alternative	Layer thickness	Infill density	Build orientation	Raster angle
Option 1	0.092	0.201	0.188	0.274
Option 2	0.201	0.092	0.085	0.087
Option 3	0.701	0.707	0.760	0.639

Equation 4.4

$$Overall(factor) = \sum C_i W_i$$

By using the equation above in Table 4.23, the values that have been calculated are:

Option 1 = 0.6035(0.092) + 0.1365(0.201) + 0.1955(0.188) + 0.0645(0.274) = 0.137

Option 2 = 0.6035(0.201) + 0.1365(0.092) + 0.1955(0.085) + 0.0645(0.087) = 0.156

Option 3 = 0.6035(0.701) + 0.1365(0.707) + 0.1955(0.760) + 0.0645(0.760) = 0.717

The total sum of the overall rating is equal to 1. Therefore, the best option is option 3 which is the first ranking as the best process parameter to optimize the tensile strength followed by option 2 as the second ranking and option 3 as the third ranking. The overall number calculated above gives an accurate impression about the quality of the factor in the end product.

4.3 Tensile strength test

This tensile strength test was to validate the data that has been got in AHP analysis. From AHP analysis shows that option 3 had the best process parameter to optimize the tensile strength. Layer thickness has the greatest weight score in AHP analysis. When selecting the ideal tensile strength, these weights suggest which characteristics should be given the highest priority. They also provide exact values that show the relative importance of each creation in the process. The highest layer thickness with a high amount of infill density, the right build orientation, and the suitable raster angle gave the highest tensile strength for printed PLA products. So, this project decided to validate whether the increasing layer thickness will affect the tensile strength or not from the AHP analysis.

With the help of slicing software, the specimen has been sliced into three different layer heights of 0.1mm, 0.2mm, and 0.3mm, while maintaining constant infill density which was 100%, 0°build orientation, and 60° raster angle.

Thereafter, the tensile strength test was conducted. The specimens were being held in place by the tensile strength machine, which will grip the specimens. Using an imaginary line to connect the grips to the machine to align the specimen's long axis with the grips. This needs to give extra care to not overtighten the grips. To prevent slippage, they should be snug enough to prevent the specimen from being crushed. Then, set the testing speed to 5mm/min.

A tensile strength formula based on force divided by cross-sectional area was used to determine how much force was required for a specimen to break. After the test has been run, data was collected to determine how much force was required for the specimens to break. Figure 4.21 shows how the specimen was tested.

Figure 4.21: The Specimen was Tested

Table 4.24: Tensile Strength Based on Layer Thickness

Layer thickness, mm	Tensile strength, N/m^2
0.1	2400
0.2	2412
0.3	2556

The data in Table 4.24 above, proves that option 3 with the highest layer thickness which was 0.3mm with infill density which was 100%, 0° build orientation, and 60° raster angle had the highest tensile strength compared to 0.1 mm and 0.2mm. This is because the research that has been made stated that layer thickness increases enhancing overall strength. Increased layer thickness would also increase mechanical properties, as fewer layers would be required. The three process parameters were statistically significant and significantly impacted the final product's strength. According to other studies ' findings also stated that aiming for high-strength components in a short amount of time, 0.3 mm layer height, 0° part orientation, 80% infill are the criteria that resulted for tensile test specimens.

4.4 AHP sensitivity analysis

The sensitivity analysis was to validate the AHP analysis that has been obtained from the AHP analysis. For this sensitivity analysis, all the process parameters were validated to prove that the accuracy of the ranking that has been obtained. The stability of the ranking under varying criteria weights such as layer thickness, infill density, build orientation, and raster angle have to be tested. For this purpose, sensitivity analysis was performed based on scenarios that reflect alternative future developments or different views on the relative importance of the criteria. Through increasing or decreasing the weight of individual criteria, the resulting changes of the priorities and the ranking of the alternatives were observed. Sensitivity analysis, therefore, provided information on the stability of the ranking. If the ranking was highly sensitive to small changes in the criteria weights, a careful review of the weights was recommended. Variations in the local priority weights of chosen subjective factors are varied by using Super Decision V3.2 software. The performance graph below displayed how the alternatives perform to the criteria.

a) Sensitivity analysis on layer thickness

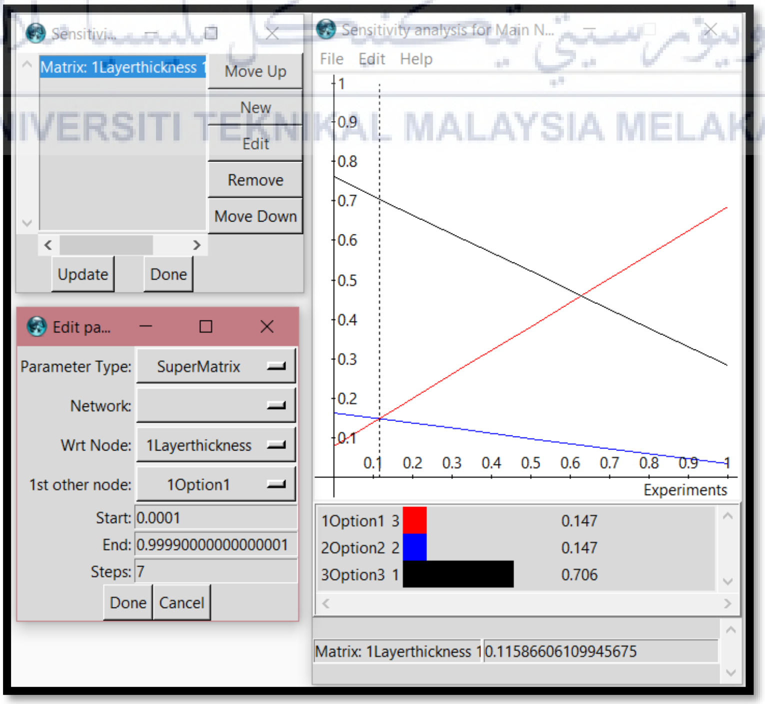

Figure 4.22: Sensitivity Analysis on Layer Thickness at Option 1

Figure 4.22 above shows the graph for criteria of layer thickness at the alternative of option 1 was performed. When layer thickness priority is greater than 0.116, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

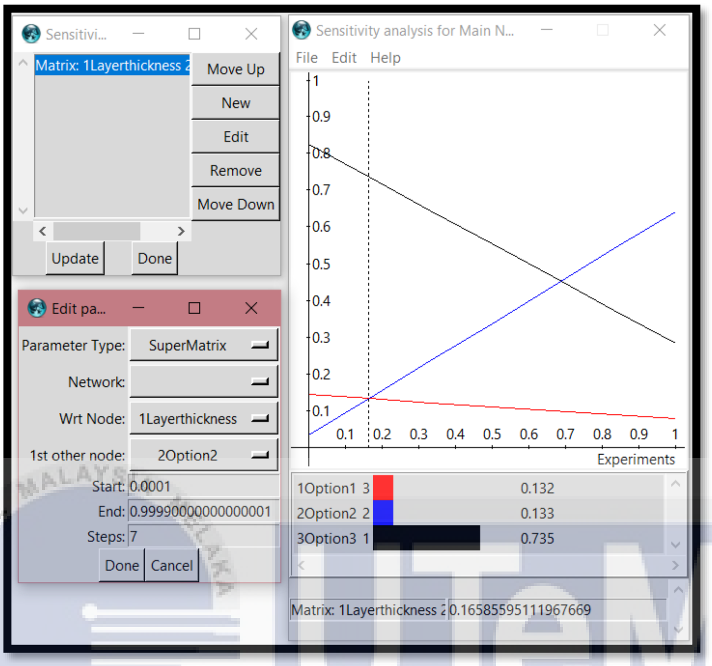

Figure 4.23: Sensitivity Analysis on Layer Thickness at Option 2

Figure 4.23 above shows the graph for criteria of layer thickness at the alternative of option 2 was performed. When layer thickness priority is greater than 0.166, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

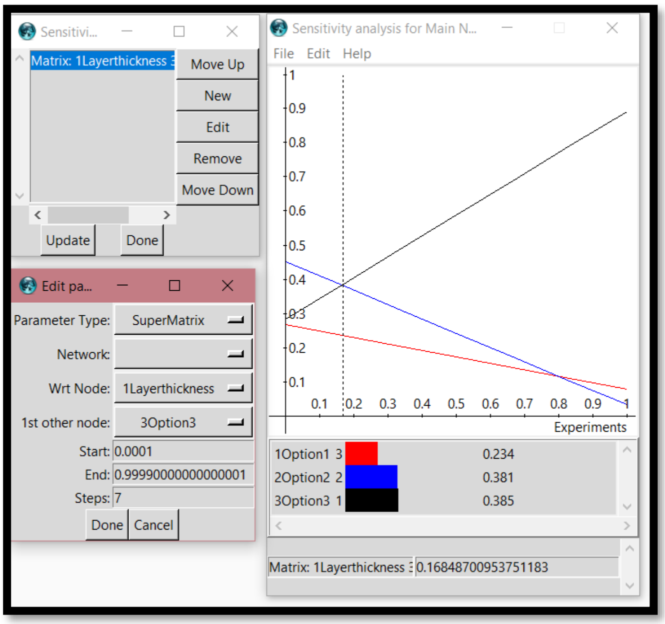

Figure 4.24: Sensitivity Analysis on Layer Thickness at Option 3

Figure 4.24 above shows the graph for criteria of layer thickness at the alternative of option 3 was performed. When layer thickness priority is greater than 0.168, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

b) Sensitivity analysis on infill density

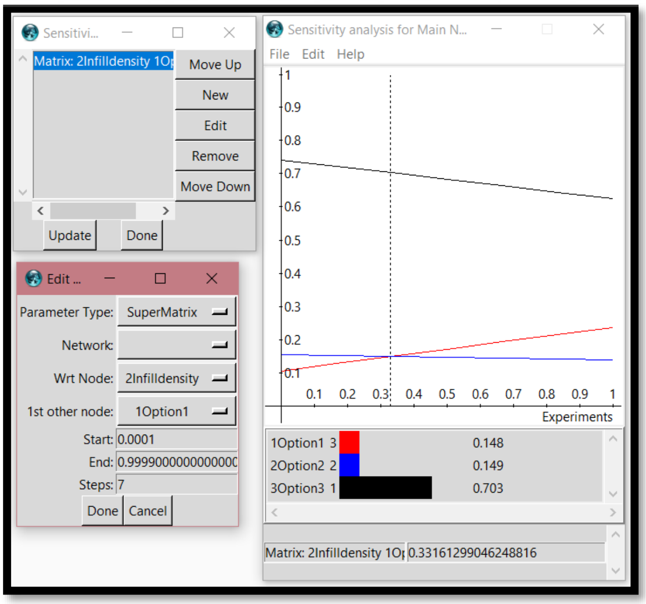

Figure 4.25: Sensitivity Analysis on Infill Density at Option 1

Figure 4.25 above shows the graph for criteria of infill density at the alternative of option 1 was performed. When infill density priority is greater than 0.332, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

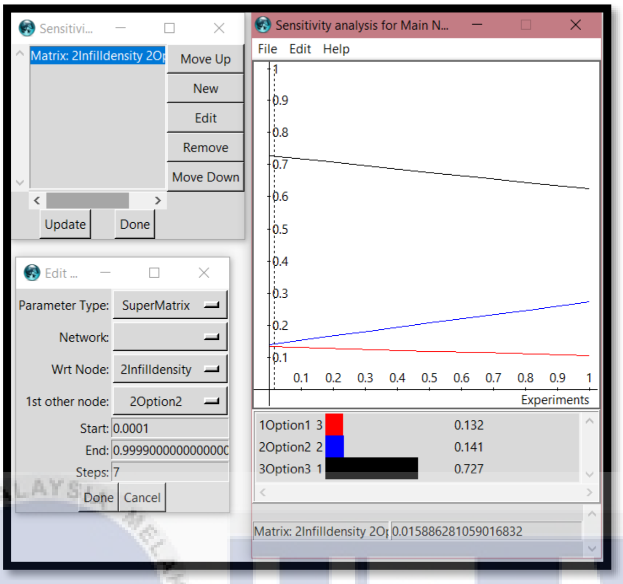

Figure 4.26: Sensitivity Analysis on Infill Density at Option 2

Figure 4.26 above shows the graph for criteria of infill density at the alternative of option 2 was performed. When infill density priority is greater than 0.016, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

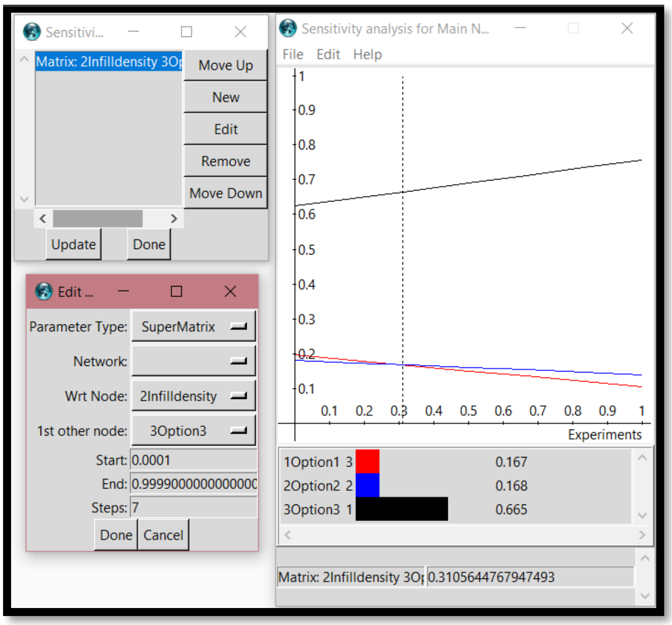

Figure 4.27: Sensitivity Analysis on Infill Density at Option 3

Figure 4.27 above shows the graph for criteria of infill density at the alternative of option 3 was performed. When infill density priority is greater than 0.311, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

c) Sensitivity analysis on build orientation

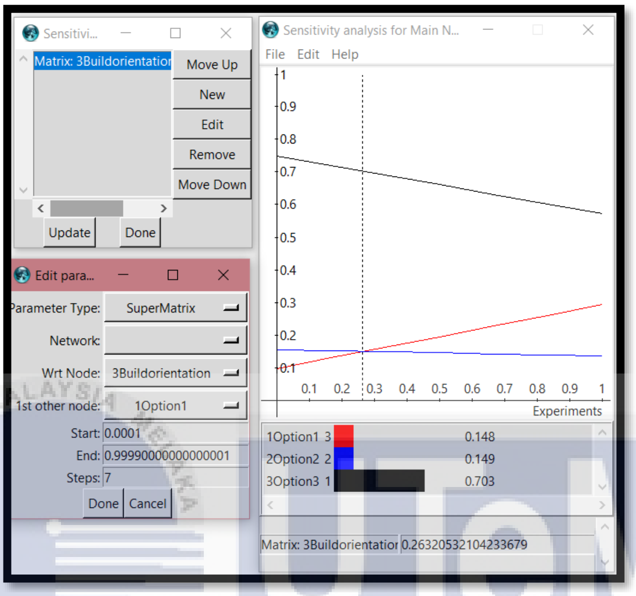

Figure 4.28: Sensitivity Analysis on Build Orientation at Option 1

Figure 4.28 above shows the graph for criteria of build orientation at the alternative of option 1 was performed. When build orientation priority is greater than 0.263, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

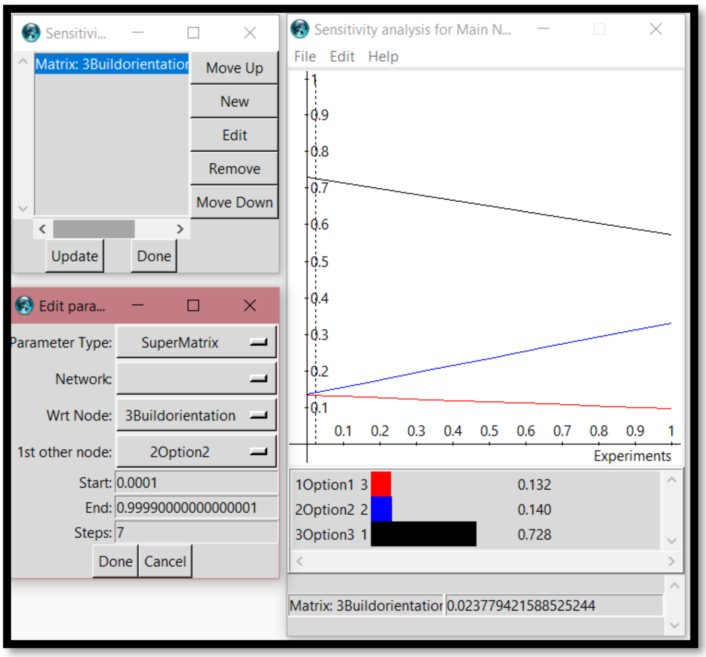

Figure 4.29: Sensitivity Analysis on Build Orientation at Option 2

Figure 4.29 above shows the graph for criteria of build orientation at the alternative of option 2 was performed. When build orientation priority is greater than 0.024, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

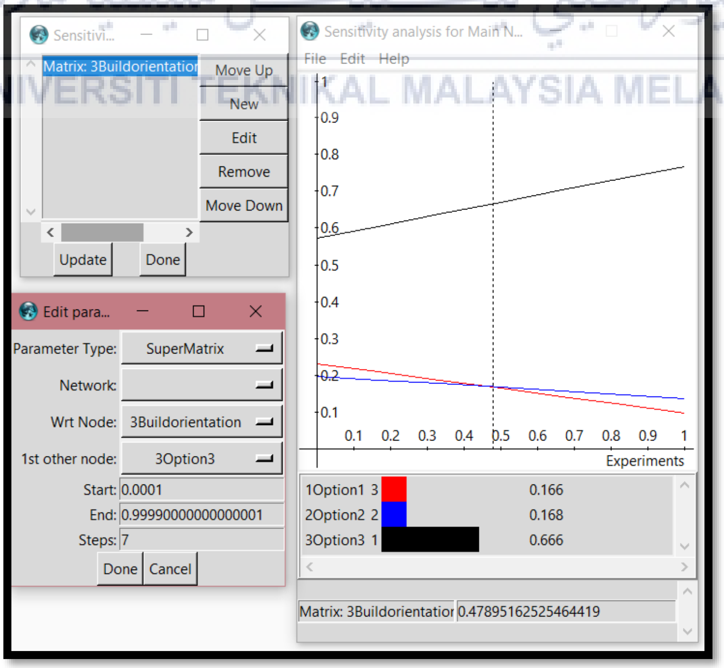

Figure 4.30: Sensitivity Analysis on Build Orientation at Option 3

Figure 4.30 above shows the graph for criteria of build orientation at the alternative of option 3 was performed. When build orientation priority is greater than 0.479, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

d) Sensitivity analysis on raster angle

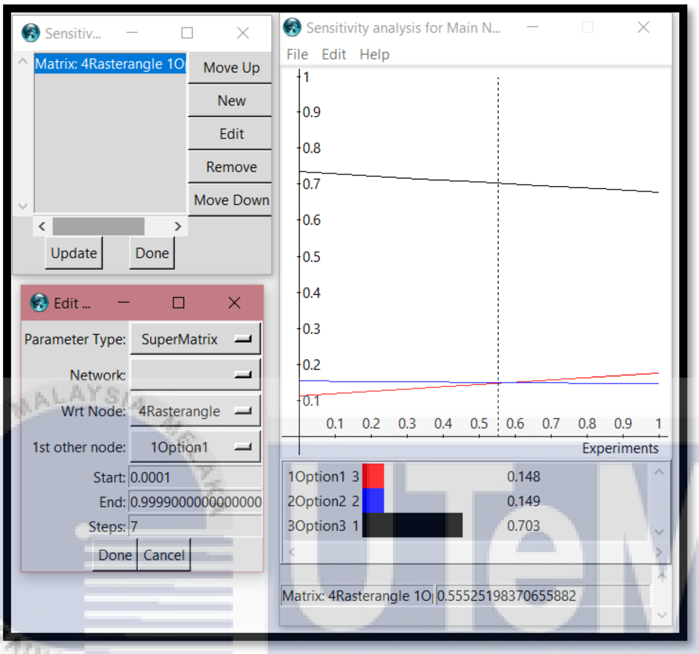

Figure 4.31: Sensitivity Analysis on Raster Angle at Option 1

Figure 4.31 above shows the graph for criteria of raster angle at the alternative of option 1 was performed. When raster angle priority is greater than 0.555, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

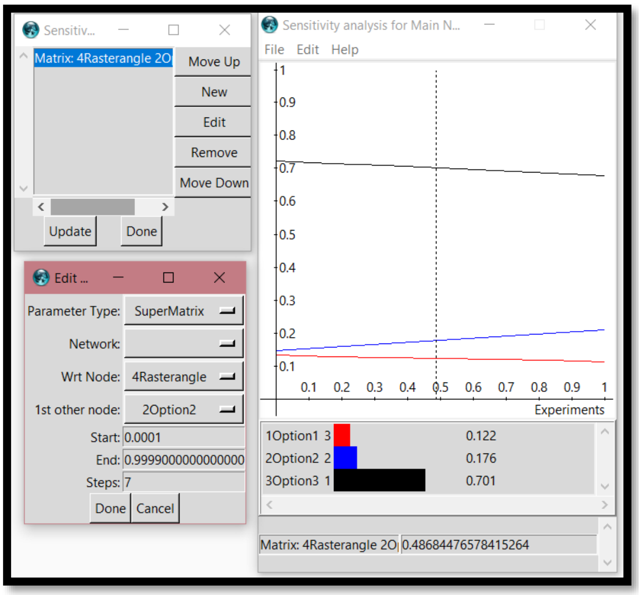

Figure 4.32: Sensitivity Analysis on Raster Angle at Option 2

Figure 4.32 above shows the graph for criteria of raster angle at the alternative of option 2 was performed. When raster angle priority is greater than 0.487, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

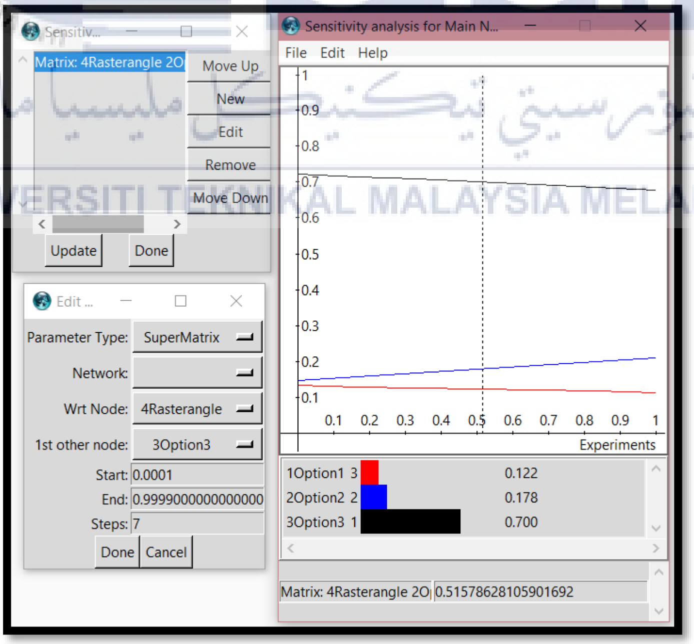

Figure 4.33: Sensitivity Analysis on Raster Angle at Option 3

Figure 4.33 above shows the graph for criteria of raster angle at the alternative of option 3 was performed. When raster angle priority is greater than 0.515, the overall ranking of option 3 becoming the best choice instead of option 2 and option 1.

The sensitivity analysis on every criterion for the alternatives showed that it did not result in any changes in the overall rank which is the first rank is option 3, the second rank is option 2 and the third or last rank is option 1 as in AHP analysis that has been conducted. The sensitivity analysis performed in this study showed that changes in current values do not lead to ranking changes showing that the decision process was well-conducted, being useful for decision-makers. Overall, based on the sensitivity analysis, it can be concluded that the final decision is consistent, stable, and reliable.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

In conclusion, chapter 1 shows that the overall concept of the project that has the background, problem statement, objectives, and scope of the application of AHP to determine and optimize FDM printing process parameters on the tensile strength that needed to understand and achieve the goal of the project.

In chapter 2, objective 1 has been achieved which is to understand the application of AHP and to list the most effective criteria on the FDM process parameter for tensile strength from the research journal and user committee survey. The information about the AHP and FDM technology was described such as the definition, advantages, disadvantages, and application. A literature and user committee survey to get the data about the process parameter that affect the tensile strength to proceed for AHP analysis. By the end of this chapter, the first objective of this project was achieved by systematically reviewing the literature and user committee survey to list the most effective criteria on FDM process parameters which are tensile strength.

Next in chapter 3, the methodology for this project has been elaborated which are the method of applying AHP and the step to perform tensile strength test. The AHP analysis is used to propose choosing the best criteria for tensile strength of the FDM process parameter. The methods that need to be done for AHP analysis are developing a hierarchical structure, pairwise comparison matrix, finalized weight, consistency analysis, and obtaining an overall rating. For the tensile strength test, the method that needs to be done are by drawing the ASTM D638 Type 1 specimen, slicing the specimen, print the specimen, and test the tensile strength test by using the tensile strength machine.

In chapter 4, objective 2 which is to investigate the optimum process parameters for tensile strength with AHP analysis has been achieved. The AHP analysis has been conducted to calculate the weights of the different criteria that affect each factor. The weights were verified by the consistency analysis. As for the criteria, the layer thickness (0.6035) has the top tensile strength factor. The second rank is build orientation, the third rank is infill density and the last one is raster angle. After analyzed the consistency of the weight criteria, an overall rating is obtained to know which option is the best FDM process parameter for tensile strength. The result is option 3 (0.709) which has the highest layer thickness, high value of infill density, zero degrees of build orientation, and sixty degrees of raster angle.

Last but not least, to validate the result from AHP, objective 3 has been achieved which is to validate the tensile strength of the FDM specimen by using the tensile strength test and AHP sensitivity analysis. A tensile strength test was made which tests the increasing and decreasing the layer thickness with the same infill density, build orientation, and raster angle. The result proved that option 3 has the highest tensile strength (2556 N/m^2). The AHP sensitivity analysis shows that it did not result in any changes in the rank which is the first rank is option 3, the second rank is option 2 and the third or last rank is option 1 as in AHP analysis.

5.2 Recommendation

During the year 2021, humanity was battling a deadly global pandemic that touched every aspect of our lives. We couldn't undertake trials to prove that our analytical mathematical approach is very accurate due to the pandemic. Furthermore, the AHP analysis should be conducted on the rest of the FDM parameters as we in this project only focused on one mechanical property which is the tensile strength. AHP analysis also can be conducted on other AM processes as this project only focused on FDM technology.

REFERENCES

Abdelrhman, A. M., Wei Gan, W., & Kurniawan, D. (2019). Effect of part orientation on dimensional accuracy, part strength, and surface quality of three dimensional printed part. *IOP Conference Series: Materials Science and Engineering*, *694*(1). https://doi.org/10.1088/1757-899X/694/1/012048

Abdullah, Z., Ting, H. Y., Ali, M. A. M., Fauadi, M. H. F. M., Kasim, M. S., Hambali, A., Ghazaly, M. M., & Handoko, F. (2018). The effect of layer thickness and raster angles on tensile strength and flexural strength for fused deposition modeling (FDM) parts. *Journal of Advanced Manufacturing Technology*, *12*(Specialissue4), 147–158.

Adams, D. W., & Turner, C. J. (2020). Implicit slicing method for additive manufacturing processes. *Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2017*, 844–857.

Alabdullah, F. (2016). Fused Deposition Modeling (FDM) MechAlabdullah, F. (2016). Fused Deposition Modeling (FDM) Mechanism. International Journal of Scientific & Engineering Research, 7(5), 41–43. https://doi.org/10.1287/opre.2014.1301anism. *International Journal of Scientific & Engineering Research*, *7*(5), 41–43. http://www.ijser.org

Alafaghani, A., Qattawi, A., Alrawi, B., & Guzman, A. (2017). Experimental Optimization of Fused Deposition Modelling Processing Parameters: A Design-for-Manufacturing Approach. *Procedia Manufacturing*, *10*, 791–803. https://doi.org/10.1016/j.promfg.2017.07.079

Alejandro Auerbach. (2020). *3D Slicer Software: How it Works and What to Expect | Solid Print3D*. https://www.solidprint3d.co.uk/3d-slicer-software-how-it-works-and-what-to-expect/

Ali, H. B. (2018). Investigation and Analysis of Infill Density on Impact Property of Pla in 3D Printing. *INTERNATIONAL JOURNAL OF RESEARCH SCIENCE and MANAGEMENT*, *5*(2), 115–120. https://doi.org/10.5281/zenodo.1185587

Arora, S. (2019). *Top advantages of Fused Deposition Modeling 3D Printers*. https://www.mystem3d.in/blog/advantages-of-fused-deposition-modeling-3d-printers-india.html

Attaran, M. (2017). The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Business Horizons*, *60*(5), 677–688. https://doi.org/10.1016/j.bushor.2017.05.011

Attoye, S., Malekipour, E., & El-Mounayri, H. (2019). Correlation between process parameters and mechanical properties in parts printed by the fused deposition modeling process. *Conference Proceedings of the Society for Experimental Mechanics Series*, 35–41. https://doi.org/10.1007/978-3-319-95083-9_8

Awang, M. F. (2012). *Analytic Hierarchy Process Managerial Decision Analysis Journal Summary PREPARED BY : MOHD FARID AWANG NORHAIZUM SAHRIL KARTINI ABD MANAF NOR SAKINAH ABDUL EANICH*.

Bardiya, S., Jerald, J., & Satheeshkumar, V. (2020). The impact of process parameters on the tensile strength, flexural strength and the manufacturing time of fused filament fabricated (FFF) parts. *Materials Today: Proceedings*, *39*, 1362–1366. https://doi.org/10.1016/j.matpr.2020.04.691

Basturk, S. B., Dancer, C. E. J., & McNally, T. (2020). Jo ur na l P re. *Pharmacological Research*, 104743. https://doi.org/10.1016/j.rineng.2021.100264

Brunneli, M. (2015). Introduction to the Analytic Hierarchy Process. In *Learning from Failures*.

Chang, C. W., Wu, C. R., Lin, C. T., & Chen, H. C. (2007). An application of AHP and sensitivity analysis for selecting the best slicing machine. *Computers and Industrial Engineering*, *52*(2), 296–307. https://doi.org/10.1016/j.cie.2006.11.006

Christopher W. Lim. (2015). *UC Irvine UC Irvine Electronic Theses and Dissertations UNIVERSITY ! OF ! CALIFORNIA , !* 1982–2004.

Clinton, J. M. (2018). *Tensile Testing Principles: Fundamentals, Methods and Challenges | 2018-08-01 | Quality Magazine*. https://www.qualitymag.com/articles/94867-tensile-testing-principles-fundamentals-methods-and-challenges

Cole, Z. (2020). *What Is the Analytic Hierarchy Process? | erwin, Inc.* https://erwin.com/blog/what-is-the-analytic-hierarchy-process/

Dandgaval, O., & Bichkar, P. (2016). Rapid Prototyping Technology -Study Of Fused Deposition Modelling Technique. *International Journal of Mechanical And Production Engineering*, *4*(44), 2320–2092. http://www.iraj.in/journal/journal_file/journal_pdf/2-244-146200069444-47.pdf

Davis, J. R. (2004). Introduction to Tensile Testing. *Tensile Testing*, 1–13.

Dey, A., & Yodo, N. (2019). A systematic survey of FDM process parameter optimization and their influence on part characteristics. *Journal of Manufacturing and Materials Processing*, *3*(3). https://doi.org/10.3390/jmmp3030064

Dudescu, C., & Racz, L. (2018). Effects of Raster Orientation, Infill Rate and Infill Pattern on the Mechanical Properties of 3D Printed Materials. *ACTA Universitatis Cibiniensis*, *69*(1), 23–30. https://doi.org/10.1515/aucts-2017-0004

Elizabeth Palermo. (2013). *Fused Deposition Modeling: Most Common 3D Printing Method | Live Science*. https://www.livescience.com/39810-fused-deposition-modeling.html

Garg, A., & Bhattacharya, A. (2017). An insight to the failure of FDM parts under tensile loading: finite element analysis and experimental study. *International Journal of Mechanical Sciences*, *120*(September 2016), 225–236. https://doi.org/10.1016/j.ijmecsci.2016.11.032

Gayette, M. (2019). *5 Major Benefits of Additive Manufacturing You Should Consider*. https://www.cmtc.com/blog/benefits-of-additive-manufacturing

Giberti, H., Strano, M., & Annoni, M. (2016). An innovative machine for Fused Deposition Modeling of metals and advanced ceramics. *MATEC Web of Conferences*, *43*. https://doi.org/10.1051/mateccont/20164303003

Giri, J., Chiwande, A., Gupta, Y., Mahatme, C., & Giri, P. (2021). Effect of process parameters on mechanical properties of 3d printed samples using FDM process. *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2021.04.283

Goepel, K. D. (2011). AHP-ANP practical application. *Http://Bpmsg.Com/Wp-Content/Uploads/2011/07/BPMSG_AHP_ANP.Pdf*, retrieved May 2012. http://bpmsg.com/wp-content/uploads/2011/07/BPMSG_AHP_ANP.pdf

Hikmat, M., Rostam, S., & Ahmed, Y. M. (2021). Investigation of tensile property-based Taguchi method of PLA parts fabricated by FDM 3D printing technology. *Results in Engineering*, 100264. https://doi.org/10.1016/j.rineng.2021.100264

Ibraheem, A. T., & Atia, N. S. (2017). Applying Decision Making with Analytic Hierarchy Process (AHP) for Maintenance Strategy Selection of Flexble Pavement. *Global Journal of Research In …*, *16*(5). http://www.engineeringresearch.org/index.php/GJRE/article/view/1526

Jaisingh Sheoran, A., & Kumar, H. (2020). Fused Deposition modeling process parameters optimization and effect on mechanical properties and part quality: Review and reflection on present research. *Materials Today: Proceedings*, *21*, 1659–1672. https://doi.org/10.1016/j.matpr.2019.11.296

Jatti, V. S., Jatti, S. V., Patel, A. P., & Jatti, V. S. (2019). A study on effect of fused deposition modeling process parameters on mechanical properties. *International Journal of Scientific and Technology Research*, *8*(11), 689–693.

Jennings, A. (2021). *3D Printing Troubleshooting All Common Problems | All3DP*. https://all3dp.com/1/common-3d-printing-problems-troubleshooting-3d-printer-issues/

Jha, J. K., & Narasimhulu, A. (2018). *A Critical Review of Process Parameters of Fused Deposition Modeling*. *5*(3), 138–141.

Jumani, M. S., Shaikh, S., & Shah, S. A. (2014). Fused deposition modelling technique (FDM) for fabrication of custom-made foot orthoses: a cost and benefit analysis. *Sci.Int(Lahore)*, *26*(5), 2571–2576. http://www.sci-int.com/pdf/13620457821 a--2571-2576-JUMANI-, M. S., JAMSHORo-Ind. Engn.GP.pdf

Justino Netto, J. M., Ragoni, I. G., Frezzatto Santos, L. E., & Silveira, Z. C. (2019). Selecting low-cost 3D printers using the AHP method: a case study. *SN Applied Sciences*, *1*(4). https://doi.org/10.1007/s42452-019-0352-4

Karthikeyan, R., Venkatesan, K. G. S., & Chandrasekar, A. (2017). A Comparison of strength and weakness for analytical hierarchy process. *International Journal of Pure and Applied Mathematics*, *116*(8), 29–33.

Larry Bernstein. (2020). *What is Computer-Aided Design (CAD) and Why It's Important*. https://www.procore.com/jobsite/what-is-computer-aided-design-cad-and-why-its-important/

Lego, J. (2017). Tilbe , F ., Iskender , E ., Sirkeci , I . (2017). The Migration Conference 2017 Proceedings . London : Transnational Press London Tilbe , F ., Iskender , E ., Sirkeci , I . (2017). The Migration Conference 2017 Proceedings . London : Transnational Pr. *The Migration Conference 2017 Proceeding*, *2017*, 173–180.

Leon, R., Ling, T., & Lease, J. (2016). *Optimizing Layer Thickness and Print Orientation* *of 3D objects for Enhanced Mechanical Property using STRUCTO 3D Printers*.

Librantz, A., Santos, F., Dias, C., Cunha, A., Costa, I., Librantz, A., Santos, F., Dias, C., Cunha, A., Costa, I., & Modelling, A. H. P. (2017). *AHP Modelling and Sensitivity Analysis for Evaluating the Criticality of Software Programs Mauro Mesquita Spinola To cite this version : HAL Id : hal-01615750 AHP Modelling and Sensitivity Analysis for Evaluating the Criticality of Software Programs*. 0–8.

Lyell-Otis, R. (2018). *5 Advantages of Fused Deposition Modeling - Faro Industries, Inc. - Rochester | NearSay*. https://nearsay.com/c/481844/86372/5-advantages-of-fused-deposition-modeling

Madaraka Mwema, F., & Titilayo Akinlabi, E. (2020). *Basics of Fused Deposition Modelling (FDM)*. https://doi.org/10.1007/978-3-030-48259-6_1

Madhav, C. V., Kesav, R. S. N. H., & Narayan, Y. S. (2016). Importance and Utilization of 3D Printing in Various Applications. *Journal of Cachexia, Sarcopenia and Muscle*, *5*(3), 199–207.

Manoharan, V., Chou, S. M., Forrester, S., Chai, G. B., & Kong, P. W. (2013). Application of additive manufacturing techniques in sports footwear: This paper suggests a five-point scoring technique to evaluate the performance of four AM techniques, namely, stereolithography (SLA), PolyJet (PJ), selective laser sintering (SLS) and t. *Virtual and Physical Prototyping*, *8*(4), 249–252. https://doi.org/10.1080/17452759.2013.862958

Manufactur3d. (2021). *2021 Best Free Slicing Software for 3D Printing - MANUFACTUR3D*. https://manufactur3dmag.com/best-free-slicing-software-3d-printing/

Melillo, P., & Pecchia, L. (2016). *What Is the Appropriate Sample Size To Run Analytic Hierarchy Process in a Survey-Based Research? 2003*, 1–2. https://doi.org/10.13033/isahp.y2016.130

Nezhad, A. S., Rezaei, A. Z., & Branch, U. (2015). *Available at www.jcrs010.com*. *3*(2), 179–185.

Ngo-Hoang, D.-L. (2019). *Method of Analytic Hierarchy Process (AHP)*. *December 2019*. https://doi.org/10.31220/osf.io/87xr4

Organiscak, M. (2016). *Fused Deposition Modeling (FDM) and Its Main Limitations | IC3D Printers*. https://ic3dprinters.com/fused-deposition-modeling-fdm-and-its-main-limitations/

Pachemska, T. A.-, Lapevski, M., & Timovski, R. (2014). Analytical Hierarchical Process (AHP) method application in the process of selection and evaluation. *Proceedings. Gabrovo: Internatinal Scientific Conference "UNITECH". 21-22 November 2014, November*, 373–380. https://www.researchgate.net/publication/276985609_Analytical_Hierarchical_Process_Ahp_Method_Application_In_The_Process_Of_Selection_And_Evaluation

Pandzic, A., Hodzic, D., & Milovanovic, A. (2019). Effect of infill type and density on tensile properties of pla material for fdm process. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, *30*(1), 545–554. https://doi.org/10.2507/30th.daaam.proceedings.074

Patel, D. B. (2016). *Additive Manufacturing – Process , Applications and Challenges*. *2*(5), 883–889. www.ijariie.com

Peko, I., BajiĆ, D., & VEŽA, I. (2015). Selection of additive manufacturing process using the AHP method. *International Conference: Mechanical Technologies and Structural Materials*, *2018*, 119–129.

Peko, I., Gjeldum, N., & Bilić, B. (2018). Application of AHP, fuzzy AHP and PROMETHEE method in solving additive manufacturing process selection problem. *Tehnicki Vjesnik*, *25*(2), 453–461. https://doi.org/10.17559/TV-20170124092906

Popescu, D., Zapciu, A., Amza, C., Baciu, F., & Marinescu, R. (2018). FDM process parameters influence over the mechanical properties of polymer specimens: A review.

Polymer Testing, *69*(April), 157–166. https://doi.org/10.1016/j.polymertesting.2018.05.020

Rayegani, F., & Onwubolu, G. C. (2014). Fused deposition modelling (fdm) process parameter prediction and optimization using group method for data handling (gmdh) and differential evolution (de). *International Journal of Advanced Manufacturing Technology*, *73*(1–4), 509–519. https://doi.org/10.1007/s00170-014-5835-2

Raza, I., Saurabh, K., & Salavane, S. (2019). *Fused Deposition Modelling in Shooting Sports*. *February*.

Richard Becker. (2020). *What is Computer-Aided Design (CAD)? - Definition from Techopedia*. https://www.techopedia.com/definition/2063/computer-aided-design-cad

Rodríguez-Panes, A., Claver, J., & Camacho, A. M. (2018). The influence of manufacturing parameters on the mechanical behaviour of PLA and ABS pieces manufactured by FDM: A comparative analysis. *Materials*, *11*(8). https://doi.org/10.3390/ma11081333

Schmidt, K., Aumann, I., Hollander, I., Damm, K., & Von Der Schulenburg, J. M. G. (2015). Applying the Analytic Hierarchy Process in healthcare research: A systematic literature review and evaluation of reporting. In *BMC Medical Informatics and Decision Making* (Vol. 15, Issue 1, pp. 1–27). BioMed Central. https://doi.org/10.1186/s12911-015-0234-7

Shashikumar, G., & Sarkar, P. B. (2018). *AHP and Sensitivity Analysis to Study Cost-Dependency of Decision Variables in Facilities Layout Selection*. *V*(Vi), 32–37.

Surange, V. G., & Gharat, P. V. (2016). Using Fused Deposition Modelling (FDM) Vinod. *International Research Journal of Engineering and Technology (IRJET)*, *3*(3), 1403–1406.

Syrlybayev, D., Zharylkassyn, B., Seisekulova, A., Akhmetov, M., Perveen, A., &

Talamona, D. (2021). Optimisation of strength properties of FDM printed parts—A critical review. *Polymers*, *13*(10). https://doi.org/10.3390/polym13101587

Taherdoost, H. (2018). Decision Making Using the Analytic Hierarchy Process (AHP); A Step by Step Approach. *International Journel of Economics and Management Systems*, *2*(January 2017), 244–246. https://www.researchgate.net/publication/322887394

Venkatesh, B., & Ajay Kumar, M. (2018). Design and development of wireless operated low cost prosthetic hand by fused deposition modeling. *International Journal of Mechanical and Production Engineering Research and Development*, *8*(1), 393–398. https://doi.org/10.24247/ijmperdfeb201843

Wa, M., & Wa, L. (2017). Materials for 3D Printing by Fused Deposition. *Technician Education in Additive Manufacturing and Material*, 1–21.

Wang, S., Ma, Y., Deng, Z., Zhang, S., & Cai, J. (2020). Effects of fused deposition modeling process parameters on tensile, dynamic mechanical properties of 3D printed polylactic acid materials. *Polymer Testing*, *86*(January), 106483. https://doi.org/10.1016/j.polymertesting.2020.106483

Wu, W., Ye, W., Wu, Z., Geng, P., Wang, Y., & Zhao, J. (2017). Influence of layer thickness, raster angle, deformation temperature and recovery temperature on the shape-memory effect of 3D-printed polylactic acid samples. *Materials*, *10*(8). https://doi.org/10.3390/ma10080970

Yan, L., Sun, H., Qu, X., & Zhou, W. (2016). *The Fused Deposition Modeling 3D Printing*. *Icemie*, 201–203. https://doi.org/10.2991/icemie-16.2016.50

Ystems, S. (2016). *a Dditive M Anufacturing for I Ntegrated S Pacecraft P Ropulsion*. *January*.

APPENDIX

Gantt chart of FYP I

TITLE: APPLICATION OF ANALYTIC HIERARCHY PROCESS TO DETERMINE AND OPTIMIZE FDM PRINTING PROCESS PARAMETERS														
	2020													
TASK/WEEK	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Title Selection for the Project														
Registration FYP Title														
Chapter 1: Introduction														
Chapter 2: Literature Review														
Chapter 3: Methodology														
Submission of Logbook														
Presentation of PSM 1														
Completion of Report														
Submit of Report														

Survey Questions

Application of Analytic Hierarchy Process to Determine and Optimize FDM Printing Process Parameters

I am Amirah Atiqah Binti Sah Azmi with no matric B051710204, a year four student from Universiti Teknikal Malaysia Melaka. I am now doing user committee survey for my final year project about application of AHP to determine and optimize FDM printing process parameters. The result from this questionnaire will be used to give the scale for effective process parameters for tensile strength that will be used in AHP analysis. With the user knowledge of FDM in 3D printing, I really appreciate if you could fulfill the following questions. Thank you.

---

*Required

1. Layer thickness is important than infill density in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

2. Layer thickness is important than build orientation in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

3. Layer thickness is important than raster angle in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

4. Build orientation is important than infill density in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

5. Infill density is important than raster angle in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred										Extremely Important Preferred

6. Build orientation is important than raster angle in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred										Extremely Important Preferred

7. Layer thickness of 0.2mm is important than 0.1mm in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred										Extremely Important Preferred

8. Layer thickness of 0.3mm is important than 0.1mm in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred										Extremely Important Preferred

9. Layer thickness of 0.3mm is important than 0.2mm in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred										Extremely Important Preferred

10. Infill density of 50% is important than 20% in tensile strength? *

Mark only one oval.

1 2 3 4 5 6 7 8 9

11. Infill density of 80% is important than 50% in tensile strength? *

Mark only one oval.

Equally Important Preferred										Extremely Important Preferred

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

12. Infill density of 80% is important than 20% in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

13. Build orientation of 30° is important than 60° in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

14. Build orientation of 0° is important than 30° in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

15. Build orientation of 0° is important than 60° in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

16. Raster angle of 30° is important than 45° in tensile strength? *

Mark only one oval.

1 2 3 4 5 6 7 8 9

17. Raster angle of 60° is important than 30° in tensile strength? *

Mark only one oval.

	1	2 3	4	5	6	7	8	9		
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred

17. Raster angle of 60° is important than 45° in tensile strength? *

Mark only one oval.

	1	2	3	4	5	6	7	8	9	
Equally Important Preferred	◯	◯	◯	◯	◯	◯	◯	◯	◯	Extremely Important Preferred