UTeM

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DESIGN AND PRINTING OF ORIGAMI STRUCTURE WITH FUSED DEPOSITION MODELING 3D PRINTER

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

by

JUFRI HANINI BIN HASAN

FACULTY OF MANUFACTURING ENGINEERING

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DECLARATION

I hereby, declared this report entitled "Design and Printing of Origami Structure with Fused Deposition Modeling 3D Printer" is the result of my own research except as cited in references.

Signature : ……………………………………

Author's Name : JUFRI HANINI BIN HASAN

Date : 2 SEPTEMBER 2021

APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment of the requirement for Degree of Manufacturing Engineering (Hons). The member of the supervisory committee is as follow:

……………………..................................

(Prof. Madya Ts. Dr SHAJAHAN BIN MAIDIN)

ABSTRAK

Projek ini memperkenalkan teknik lipatan dari origami untuk berkembang dari bahan rata kepada keadaan penggunaan aplikasi pembuatan aditif. Kajian ini bertujuan untuk merancang pelbagai struktur origami dari teknik lipatan yang berbeza, memahami mekanisme asasnya, membuat model fizikal dan simulasi untuk menunjukkan dan membandingkan kemungkinan mereka. Lipatan gunung dan lembah, teknik lipatan lain dan bentuk origami, telah dikenal pasti. Semua konsep ini diterapkan dalam reka bentuk struktur origami. Bagi menentukan kebolehan struktur origami dalam lipatan, tujuh idea origami dikembangkan. Model ini dikembangkan menggunakan alat CAD (SolidWorks, Oripa, dan Origami Simulator). Tiga analisis pada tiga idea lipat telah menunjukkan hasil ubah bentuk reka bentuk menggunakan analisis regangan. Penyelidikan menunjukkan bahawa perubahan regangan pada lipatan mempunyai nilai selamat untuk dilipat berkali-kali. Perbezaan nilai regangan antara lembah dan gunung lipatan pada lipatan dengan lubang (regangan maksimum adalah 7.917E -03, regangan maksimum ketika lipatan berlaku 5.9387E -03) lebih rendah daripada lipatan tanpa lubang (regangan maksimum adalah 5.957E -03 , regangan maksimum ketika lipatan berlaku ialah 5.957E -03), membuktikan bahawa lipatan dengan lubang di titik tengah lebih kuat dan lebih selamat. Terakhir, Printer 3D FDM digunakan untuk menguji daya maju struktur origami pada bahan PETG. Hasilnya menunjukkan bahawa pencetak 3D FDM dapat membuat struktur origami dengan pelbagai reka bentuk origami dengan berkesan.

ABSTRACT

This project introduces folding techniques from origami to evolve from flat material to the additive manufacturing application's deployed state. This study aims to design various origami structures from different folding techniques, understand their underlying mechanisms, create physical models and simulations to demonstrate and compare their feasibility. Mountain and valley folds, among other folding techniques and origami shapes, have been identified. All this concept was applied in the design of the origami structure. To determine the structural abilities of origami on folding, seven origami ideas were developed. The model was developed using CAD tools (SolidWorks, Oripa, and Origami Simulator). Three analyses on three folding ideas have demonstrated the outcomes of design deformation using strain analysis. The research revealed that the change in the strain at the fold has a safe value for folding many times. The difference in strain values between the valley and mountain folds on folds with holes (maximum strain is 7.917E -03, maximum strain when folding occurs is 5.9387E -03) is lower than on folds without holes (maximum strain is 5.957E -03, maximum strain when folding occurs is 5.957E -03), proving that folds with holes in the center point are stronger and safer. Lastly, The FDM 3D Printer was used to test the origami structure's viability on PETG materials. The result demonstrates that an FDM 3D printer can create origami structures with a variety of design origami.

DEDICATION

Only
my beloved father, Hasan Bin Mohd
my appreciated mother, Jamilah Binti Husin
my adored sister and brother, Hasmawita, Jasny, Hafiz, Siti, Habib, Zulkifli, Faiz, Farah, Fazila, and Aina
for giving me moral support, money, cooperation, encouragement and also understandings
Thank You So Much & Love You All Forever

ACKNOWLEDGEMENT

In the name of ALLAH, the most gracious, the most merciful, with the highest praise to Allah that I manage to complete this final year project successfully without difficulty. My respected supervisor, Assoc.Prof.Dr. Shajahan Bin Maidin for the great mentoring given to me throughout the project. Besides that, I would like to express my gratitude to my beloved all lecturers and staff for their kind supervision, advice, and guidance and expose me with meaningful experiences throughout the study.

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LIST OF ABBREVIATIONS

AM - Additive Manufacturing

FDM - Fused Deposition Modeling

FFF - Fused Filament Fabrication

SLS - Selective Laser Sintering

STL - Standard Triangle Language

CAD - Computer Aided Design

3D - 3 Dimensions

2D - 2 Dimensions

ABS - Acrylonitrile Butadiene Styrene

PLA - Polylactic Acid

DDM - Direct Metal Part Fabrication

STL - Standard Tessellation/Triangulation Language

RP - Rapid Prototyping

RM - Rapid Manufacturing

LIST OF SYMBOLS

Mm/min - Millimeters per minute

Vc - Cutting speed

Kg - Kilogram

g - Gram

Mm - Millimeters

Mm - Micrometers

CHAPTER 1

INTRODUCTION

This chapter introduces the project and briefly describes the study's objectives and scope. This chapter will give an overview of the implementation of the project.

1.1 Project Background

According to Wang et al., (2019), origami structures are typically created by folding a two-dimensional sheet that makes for a certain crease pattern. The presence of abundant crease patterns suggests that diverse sheet materials, including thin-walled tubes and arcs, can be used to create several three-dimensional structures. It is also possible to use certain origami structures as core structures, sandwich plates, or arches. On the other hand, other structures of this type may be stacked to form metamaterials, which are materials meant to contain properties that are not readily available in nature. Since these structures' mechanical efficiency generally depends on their geometry, these structures' properties may be built and modified by choosing and optimizing the necessary geometric parameters.

For train collision prevention, the suggested origami-inspired framework is successfully applied. In optimizing the IPCF for the energy absorption method, the optimum structure is greatly beneficial (Wang et al., 2019). Origami, also known as paper folding, has shown the ability to create 3D structures on a flat sheet from designed crease patterns. This paper proposes a common six-crease basis for making axisymmetric 3D origami. The crease lines' lengths may be normal or unusual, inspired by the conventional six-crease bases, i.e. the waterbomb base or Yoshimura base, where six regular crease lines converge at the inner vertex. The design of crease patterns is based on this process (Zhao et al., 2018).

On the other hand, additive manufacturing is an apt name to characterize the innovations that create 3D structures by applying material layer-on-layer, whether plastic, metal, concrete, or human tissue is the material. This distinction is important because the first suggests that the item is usually made using subtractive processing as a replica of traditionally manufactured things. In comparison, additive manufacturing, without subtractive manufacturing restrictions, opens up a world of design opportunities. Powder Bed Fusion, Binder Jetting, VAT Photopolymerisation, Layer Jetting, Material Extrusion, Sheet Lamination, and Guided Energy Deposition are the seven standardized AM technologies ASTM International (Pelleg, 2020).

Additive manufacturing (AM) varies fundamentally from standard formative or subtractive production. Instead of casting or forming through technology such as welding or machining, it is the nearest to 'bottom-up' construction where a structure can be formed into its planned shape using a 'layer-by-layer technique. AM is versatile, scalable, highly adjustable, and can suit most industrial development sectors. Materials may be of a generally differing form to produce these parts/objects. This involves metallic, ceramic, and polymeric materials and plastic, hybrid, or mechanically graded material blends (FGMs). However, the challenge persists to translate these 'making' types and mechanisms through the acquisition of usable objects. In AM, a great deal of work is needed to overcome the problems associated with its two main technologies: ' materials' and 'metrology,' to accomplish this capability in a predictive and reproductive manner (Tofail et al., 2018). In industry, "One production line produces the same products a thousand times over while maintaining the same quality," says Löber. The still-young technology will develop its full potential on a wide front and pave the way for new products in many industries only when this leap is successful. For example, lightweight and vibration-damping engine mounts are of interest. Additive manufacturing may contribute greatly to the realization of these specifications.

Many current researchers like Wagner et al., (2020) demonstrate novel metamaterials featuring unique properties by Combining patterns inspired by origami and additive processing. In particular, flexural hinges have distinct benefits for miniaturization and processing, but due to the hinges' restricted loading and fatigue tolerance, there are limited applications. This research focuses on measuring and characterizing flexural hinges' mechanical properties so that their results in 3D-printed origami structures could have immediate applications—aramid fiber composite hinge on equating it to a polyamide single-material hinge and a photopolymer multi-material hinge.

Metamaterials inspired by origami were designed, tested mechanically, and modelled. When using a triangular based crease pattern, one novel origami model was folded, and the other was folded using a rectangular based crease pattern. Metamaterial sheets inspired by origami were made from polylactic acid using fused deposition additive manufacturing (Wickeler & Naguib, 2020).

This project introduces folding techniques from origami to evolve from flat material to the additive manufacturing application's deployed state. A review of recent origami and kirigami techniques used for this purpose will be done to understand their underlying mechanisms and create physical models to demonstrate and compare their feasibility through fused deposition modelling 3D printer (FDM). Many current researchers like (Ceretti et al., 2017), (Heidari-Rarani et al., 2019),(D. Yadav et al., 2020), and (Helú & Liu, 2020) are interested about FDM 3D printer as a good platform to produce product by using the additive manufacturing application.

1.2 Problem Statement

A new class of mechanisms is termed Multiloop Origami-Inspired Spherical Mechanisms (MOISM). Typically, designers use well-known origami frameworks when new origami-inspired techniques are created. This methodology has limits on the current systems in origami. Using conventional origami designs as building blocks for intrinsic spherical mechanisms produces limited instruments. Each building block has only one loop in classical origami folds due to the constraint posed by the need for folds to overlap to make more complicated building blocks (Barreto et al., 2021).

Grey et al., (2020) stated that engineers should be careful when using paper to analyze origami structures' mechanical properties. Paper folds' non-linear, pseudo-plastic behavior complicates the simulation of an origami system's mechanical properties. The majority of origami models available are limited to the idealization of folds as zero-order geometric continuity creases, which are not suitable for origami structures of non-negligible fold thickness or maximal curvature folds constrained by material limitations (Peraza Hernandez et al., 2016).

A door hinge, a thick interpretation of a single line fold, is the simplest thick rigid origami structure. In this case, the rotational axis is located on the fold line's valley side. Axis-shift as the axis is pushed to the side of the thick panel's valley. Axis-shift can also transform a corrugated surface without internal vertex to a folding screen consisting of thick plate mechanisms, such as repeated mountain and valley patterns. This type of structure can fold and unfold completely from 0 to π. However, for a standard rigid origami mechanism with interior vertices, the axis shift approach is not always useful (Tachi, 2016).

1.3 Aims

This project aims to investigate origami structures that can create 3D geometries from flat materials or that have emerged as an exciting manufacturing paradigm on a broad range of length scales and can be particularly useful in cost-sensitive or planar-limited fabrication applications. The project aims to design various origami structures from different folding techniques, understand their underlying mechanisms, create physical models and simulations to demonstrate and compare their feasibility.

1.4 Objective

The objectives are as follows:

a) To design various origami structures from different folding techniques
b) To simulate and study the folding mechanism of the designed origami structures using SolidWorks and Oripa origami
c) To study the folding efficiency of the 3D printed origami specimen

1.5 Scope of the Project

This project focuses on designing and printing origami structures with fuse deposition modeling 3D printers (FDM). Thus, this project introduces folding techniques from origami to evolve from flat material to the deployed state for the additive manufacturing application in the case of study. The CAD model was designed using CAD designs, reducing product development cycle time, simulation on folding technique, and applying origami structure design to the fuse deposition modeling (FDM) 3D printer.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter focuses on the design-related awareness of origami structure on additive processing for an application, advantages, disadvantages, and FDM machine parameters. The aim is to illustrate the origami model and procedures used in chronological order. The 100 percent origami structure theory will also be explored and turned into a product using the origami concept. Much of the references come from textbooks, papers, dissertations, and other tools.

2.2 Additive Manufacturing (AM)

2.2.1 Definition of AM

"Additive Manufacturing" (AM) is a layer-based automated fabrication process for producing scaled 3-dimensional physical objects immediately from 3D-CAD data without applying part-depending tools. It was called "3D Printing" and is still frequently called Additive manufacturing (AM) is an automated and revolving process built from the principle of layer-based technology. It is characterized by a process chain shown in Figure 2.1. It begins with the production represented by a (virtual) 3-dimensional CAD data set (solid). In engineering, 3D CAD design or scanning or other imaging methods such as computerized tomography scanning are usually used to collect data (CT-Scanning) (Gebhardt, 2011).

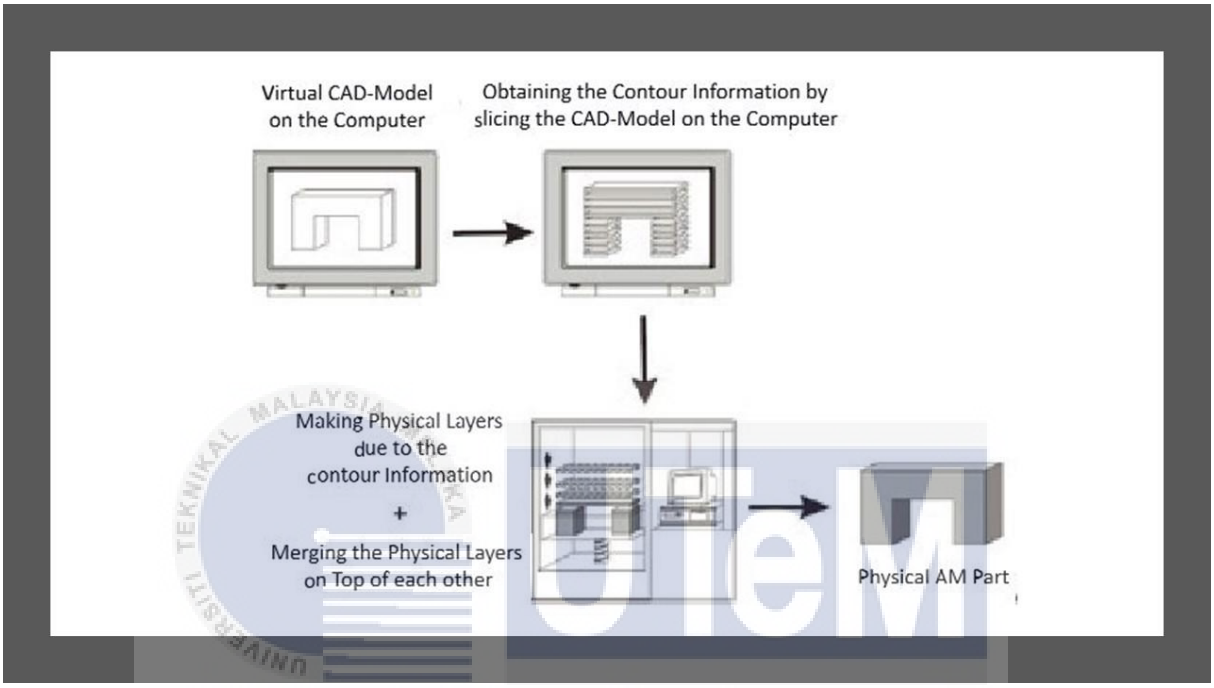


Figure 2.1: Additive Manufacturing process chain (Gebhardt, 2011).

AM technology involves three required steps (Huang et al., 2013):

a) A computerized 3D solid model is developed and transformed into a standard AM file format, such as the traditional standard tessellation language format (Kumar & Dutta, 1997) or the latest additive manufacturing file format.

b) The file is sent to an AM machine where it is manipulated, e.g., changing its position and orientation or scaling the part.

c) The part on the AM computer is assembled layer by layer.

Process AM technology that was done operate in real, Figure 2.2 below shows the process involved.

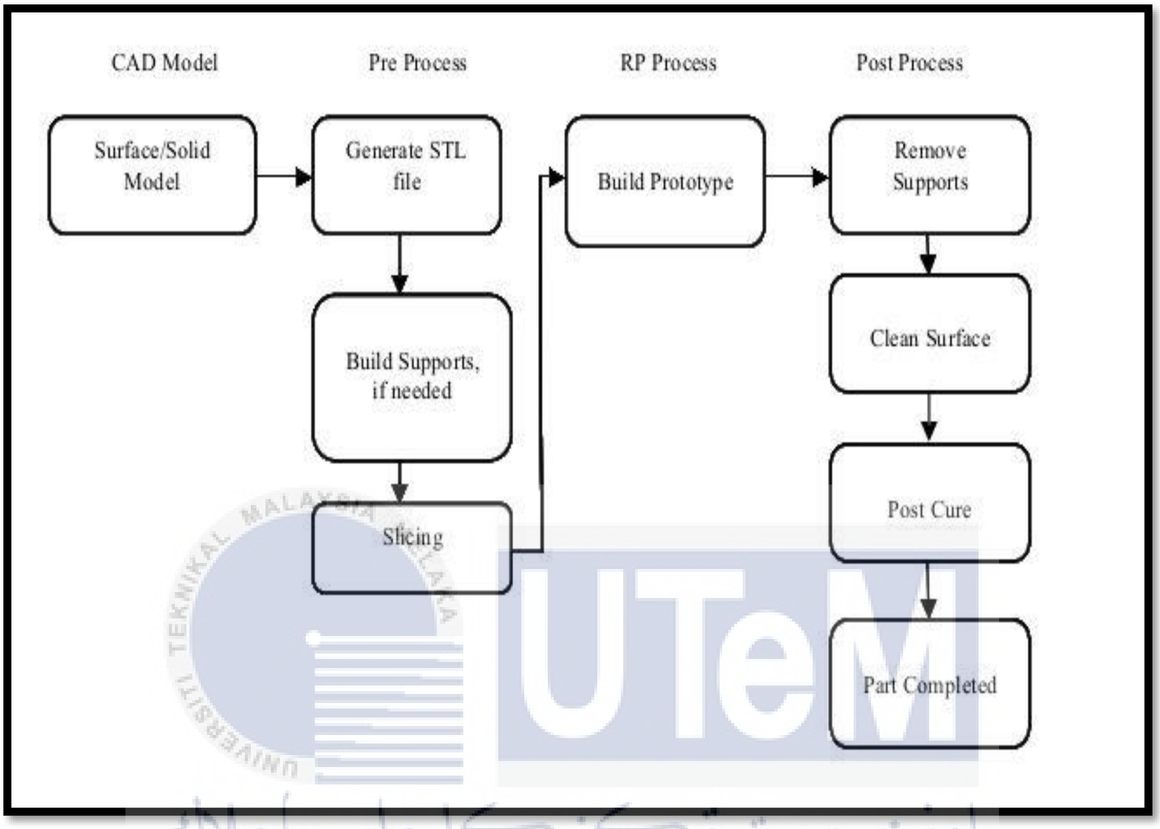


Figure 2.2: Rapid prototype process workflow (Prakash et al., 2018).

2.2.1 Application of AM

Gibson et al., (2010) when talking about AM applications, industrial applications are of interest. In addition to this professional approach, more and more consumers and, ultimately, business industries have chosen AM as a tool to improve their organization and put new ideas to reality. Mostly show interesting applications, parts, and real drivers for new results and inspirations for others.

2.2.1.1 Automotive industries and providers

For the automotive industry, innovative vehicle creation is important, but designing a new product is expensive and time-consuming. The automotive industry has been using AM technology as an important tool in designing and developing automotive components because it can reduce the development cycle and reduce manufacturing and product costs. AM processes also have been used to make small quantities of structural and functional parts, such as gearbox components, engine exhausts, driveshafts, braking systems for luxury, and low-volume vehicles. Unlike passenger cars, Motorsport vehicles often use lightweight alloys (e.g. titanium) and have extremely complex designs and limited output rates. Companies and research institutes also have effectively applied AM techniques to manufacture functional components for racing automobiles (Guo & Leu, 2013). Figure 2.3 and 2.4 below shows the component can produce in automotive industries.

Figure 2.3: Water pump for a motorsports car produced by SLM (Bartkowiak et al., 2011).

Figure 2.4: Automotive part produced with 3D-printed starch patterns and moulds (Kang & Ma, 2017).

2.2.1.2 Aerospace industry

AM technologies typically come into one of the following categories like DDM, rapid tooling, rapid prototyping, and fix for aerospace applications. DDM refers to the development of components to be used in an aircraft. These components may be vital components essential for the process (e.g. combustion chambers, nozzles) and non-critical parts necessary for the operation (e.g., fixtures, brackets, and accessories). Rapid tooling describes the fabrication of tools and patterns needed to fabricate the final part. It can be categorized into direct rapid tooling (e.g., dies and molds) and indirect rapid tooling (e.g., mold patterns). Rapid prototyping usually uses nonmetal technologies to the fabrication of nonfunctional parts. Finally, repair involves fixing and reinforcing metallic materials and joints, usually by DED and cold spray procedures (Najmon et al., 2019). Table 2.1 shows a breakdown of AM technologies into metal and nonmetal application groups.

Table 2.1: Technologies for metal and nonmetal additive manufacturing with select aerospace examples (Najmon et al., 2019).

	Application	AM technology	Aerospace examples
Metal	• DDM (direct metal part fabrication) • Rapid tooling • Repair	• DED • PBF • Cold spray	• Helicopter engine combustion • Chamber fabrication (DED) • Blisk airfoil repair (DED) • Lap joint reinforcement (SPD)
Nonmetal	• DDM (fixtures and accessories) • Rapid prototyping • Rapid tooling	• SLS • SLA • PolyJet • FDM	• Ratchet wrench printed by NASA on International Space Station (SLS) • UAV wing design (PolyJet) • Boeing 777-300ER door handle (FDM) • Camera case prototyping (FDM)

2.2.2 Advantages of AM

Manufacturing processes applying the life cycle assessment (LCA) method. Table 2.2 shows the area of application in AM and benefit.

Table 2.2: Advantages of additive manufacturing (Attaran, 2017).

Areas of Application	Advantages
Rapid Prototyping	• Reduce time to market by prototyping acceleration • Reduce the risks associated with product creation • Made firms more successful and competitive in the area of innovation
Production of Spare Parts	• Reducing repair times • Reducing the cost of labour • Avoid expensive warehousing
Small Volume Manufacturing	• Small batches can be produced cost-effectively. • Eliminate spending on instruments
Customized Unique Items	• Enable mass customization to be achieved at a low price • Fast on-site manufacturing of exact and personalized replacement parts • Eliminate the Overhaul Penalty
Very Complex Work Pieces	• Producing complicated workpieces at a low price
Machine Tool Manufacturing	• Reduce labor cost • Avoid costly warehousing • Enables mass customization at a low cost
Rapid Manufacturing	• Manufacturing assembled products directly • Relatively cheap manufacture of small numbers of component
Component Manufacturing	• Enable low-cost mass customization • Improve quality • Supply chain shortening

	- Reduce the cost involved in development Support to remove unused parts
On-Site and On-Demand Manufacturing of Customized Replacement Parts	- Eliminate charges for storage and shipping Preventing downtimes and save money - Reduces repair costs - Reducing the need for extensive inventory Enable leverage of the product lifecycle
Rapid Repair	- Drop-in maintenance time - Opportunity for restored parts to be updated to the new design

2.2.3 Disadvantages of AM

Owing to its ability to produce dynamic forms, versatility in design, and customization of a component, additive manufacturing is an imminent threat to the traditional production process. However, to be strong enough to identify real-time product implementations, AM has a steep challenge ahead. The key challenges that AM faces are part size, low manufacturing efficiencies, layer misalignment, gaps in the top layer, building overhanging parts, low accuracy, production cost involved, and under and over extrusion (Solomon et al., 2020). The other disadvantage of AM has shown in Table 2.3.

Table 2.3: Problem occurs in AM (Ford & Despeisse, 2016).

Disadvantages	Explanation
Limited material selection	3D Printing can create items in selecting plastics and metals; the available selection of raw materials is not exhaustive. It is because not all metals or plastics can be temperature controlled enough to allow 3D Printing
Restricted Build Size	3D printers currently have small print chambers that restrict the size of parts that can be printed
Large Volumes	Scaled up to produce large volumes for mass production, the cost per unit does not reduce as it would with injection molding.

2.3 Fused Deposition Modeling (FDM)

Alabdullah, (2016) has presented that fused deposition modeling (FDM) technology is an AM method that constructs 3D forms by taking thermoplastic polymer content filaments and pushing them through a heated liquefier to be extruded onto a building platform via a small diameter nozzle. Technologies capable of processing metals include fused deposition modeling, electron beam melting, selective laser melting, laser engineered net shaping and direct metal laser sintering. According to Sai & Yeole, (2001), FDM, the name that one gives the concept that deposition of the fused material forms the parts in layers. This RP technique is handled in modeling, prototyping, and production applications. Figure 2.5 below shows how the process works in FDM.

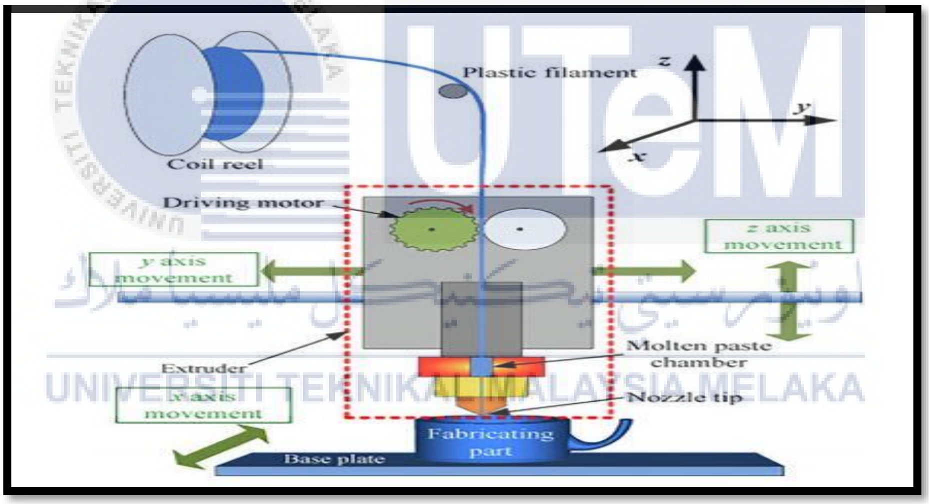


Figure 2.5: FDM method theory of working (Jin et al., 2015).

2.3.1 FDM process parameter

Mwema & Akinlabi, (2020) report that fused deposition modeling (FDM) is influenced by various parameters, as summarised in Figure 2.6. The parameters have been categorized into two large categories: machine and material parameters. System parameters are those parameters that the operator of the 3D printer will define during the generation of G-code files on the slicing program. On the other hand, the material parameters are the filament material features or compounds being extruded through the nozzle. Some of the machine parameters, as shown, include the raster angle, printing speed, melt flow rate through the nozzle, temperature, layer thickness, infill density, build orientation, and airgap (Valino et al., 2019).

The printed parts' consistency and efficiency depend on these criteria' choice. Different literature studies analyze the influence of different criteria on the prints' operation and consistency (Shim et al., 2020).

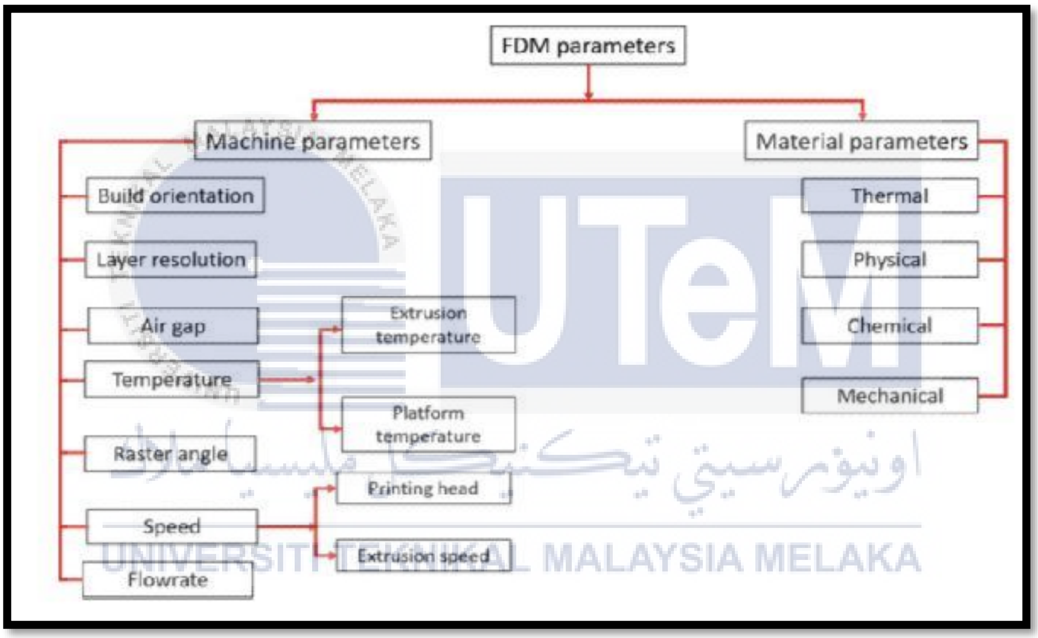


Figure 2.6: Parameters influencing the fused deposition modeling process (Mwema & Akinlabi, 2020).

2.3.2 Application of FDM

Application of the design of prototypes, shoe heels, prosthetics, gifting, household items, industrial applications, and architecture for FDM is an interesting example of ergonomic and mass customization (Mohamed et al., 2015). Figure 2.7 below shows the model result by FDM.

Figure 2.7: Sample forms printed by FDM (Dudek, 2013).

2.3.2.1 Pharmaceutical applications

Long et al., (2016) state that fused deposition modeling (FDM) is a low-budget extrusion-based 3D printing technique that can deposit materials layer-by-layer to produce solid geometries for personalized tablets' fabrication applications. Refer to Goole & Amighi, (2016), the most popular drug delivery instruments are tablets and capsules. The traditional drug processing strategies developed for immediate drug release are direct tableting and capsule filling. Figure 2.8 shows the step to produce the product.

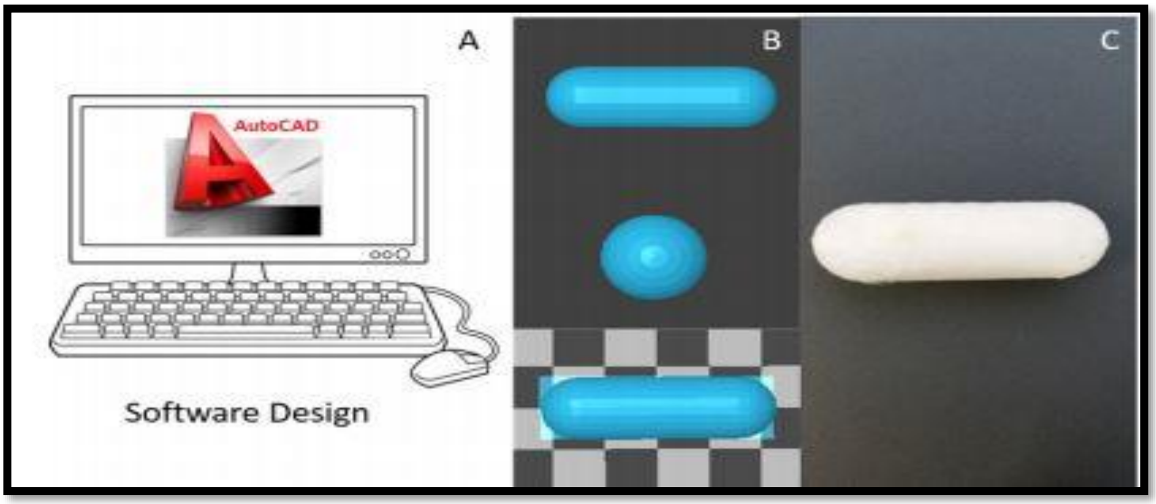


Figure 2.8: Personal tablet from the FDM method (Goole & Amighi, 2016).

2.3.3 Advantages of FDM

FDM is a 3D printing method that is low in cost, producing prototypes and functional parts faster. FDM is the most cost-saving option for printing 3D parts from its blueprint. FDM can create customized pieces and prototypes much easier than the other 3D printing processes. The turnaround time is also very low when compared with other technologies. Capable of using multiple fabrics and filaments for varying features and applications (Shanmugam et al., 2021). FDM devices are safe, effective, quick to use, office-friendly, free of hazardous chemicals, powder treatment, unnecessary heat or laser treatment. This has been one of the important reasons for the widespread adoption of FDM systems. Parts can be handled almost directly after fabrication. Except for support removal, almost no post-processing is needed. The maintenance cost is low. Machines can run unattended for hours (Masood, 2014).

2.3.4 Disadvantages of FDM

a) Limited Materials

Solomon et al., (2020) have proven that when choosing plastics and metals, the 3D printer will produce products, although the available variety of raw materials is not exhaustive. Not all metals or plastics are sufficiently temperature regulated to allow 3D printing. Besides, It is impossible to recycle all of these printable materials, and a few are suitable for food.

b) Reduction in Manufacturing Jobs

The possible reduction in human labor is another FDM technological disadvantage, as much of the processing is automated and printer. However, to keep their economies going, many third-world countries rely on low-skilled employment. This invention could place these manufacturing jobs at risk by reducing the need for production abroad for similar jobs (Bárcia De Mattos et al., 2020).

c) Design Inaccuracies

According to El-Katatny et al., (2010), The type of machine or process used is closely connected to another possible issue with the 3D printer. Some printers have lower tolerances, which means the final components can vary from the original design. Post-processing may be fixed, although it must be considered that this would further increase the manufacturing time and expense.

2.4 Origami Design

Materials and structures influenced by ancient paper art have drawn considerable research interest over the past few decades. Origami, a word originating from Japanese, refers to folding ("ori-") of paper ("gami-"). Kirigami, a variation of this paper art, involves cutting ('Kiri-') of paper. These techniques allow 3D structures to be created from the cutting, bending, and folding of thin sheets of paper. Recently, origami and kirigami principles have been extended to a wide range of science and engineering efforts that exploit out-of-plane deformations of 2D components to allow significant and reversible geometry changes of devices constructed from that position (Xu et al., 2017). Figure 2.9 below shows the concept origami can do and develop to other techniques.

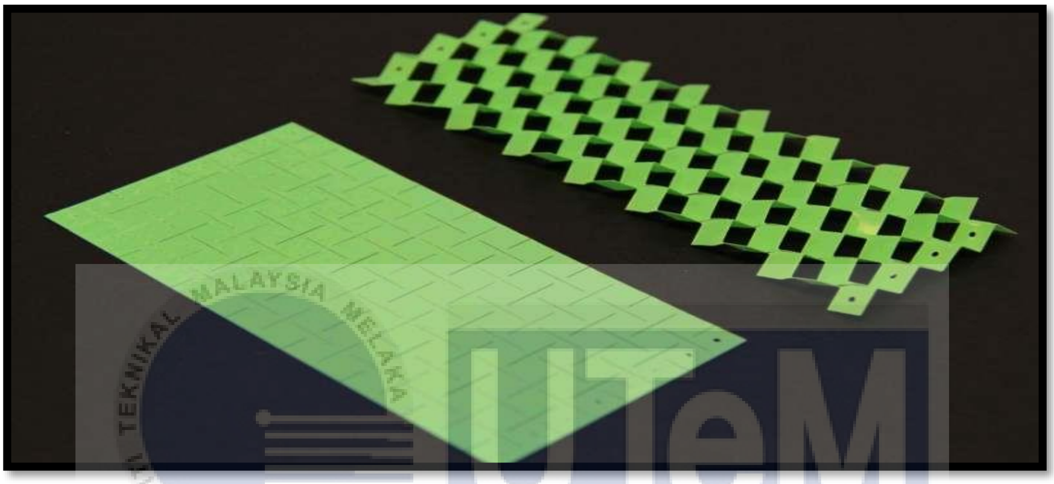


Figure 2.9: Origami and kirigami-inspired (Rafsanjani & Bertoldi, 2017).

2.4.1 Origami model

Since the original content is a flat surface, some origami versions are closely related to Euclidean geometry. As a fold is comparable to a straight line, the folding steps may replicate straight-edge-and-compass constructions. Folding paper in half causes two intervals between points to be built in a similar way to that of a compass. Indeed, depending on which simple construction principles can be used, which can be extended in paper folding, various angle values and other numbers (their sines and cosines) can be built. A complex model on the unfolded paper that focuses on straight-edge folds and a planar developable case can be partially represented in the folds network (Dureisseix, 2012).

2.4.2 Crease pattern

Feng et al., (2020) have proven that the folds can be divided into two groups, seen from one side of the unfolded paper refer on mountain or valley folds, as shown by two simple origami bases which are known as 'waterbomb' and 'preliminary'. Mountain folds lead to a 3D convex shape locally, as predicted. Besides, valley folds contribute to a concave 3D shape locally. Indeed, by shifting the point of view, i.e., the paper's face, the two-fold sets are interchanged. The two forms of folds can be viewed as dual to each other.

Its 'crease pattern' is called to characterize an origami model only by representing the creases with several types on the unfolded flat piece of paper. The details found on the crease pattern are normally inadequate to explain the folded model with the full version. The evaluation of a crease pattern's general ability to fold flat is a non-trivial issue. In comparison, if a crease pattern corresponds to a flat model, it does not guarantee its uniqueness. In the two bases of Figure 2.10, the crease pattern is similar (to a paper reverse dualization) and corresponds to two separate versions that can both be defined as dual. A flat folded model needs only 6 radiating folds over 8, but that 8 folds retain a high symmetry in the models (Feng et al., 2020).

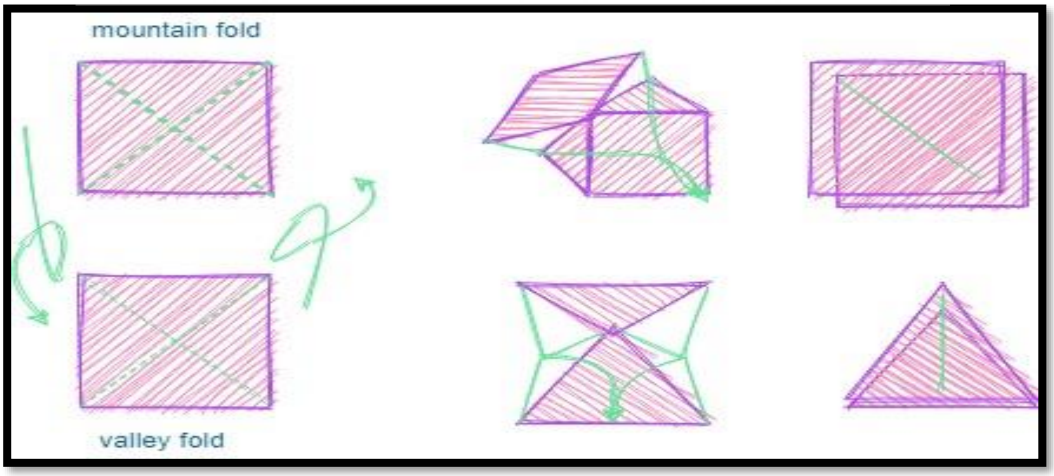


Figure 2.10: For the preliminary base (top) and waterbomb base, crease patterns, and folding steps (bottom) (Feng et al., 2020).

2.4.2.1 Mountain fold

According to Peng et al., (2018), the opposite of a valley fold is a mountain fold. The paper folds to the opposite side. This implies either keeping the paper in the air to allow the paper to fold beneath, or merely flipping the paper over and treating it as a valley fold. Usually, this is simpler. Therefore, it is easier to fold the paper away from the body instead of against it. Figure 2.11 below shows the characteristic of the mountain fold.

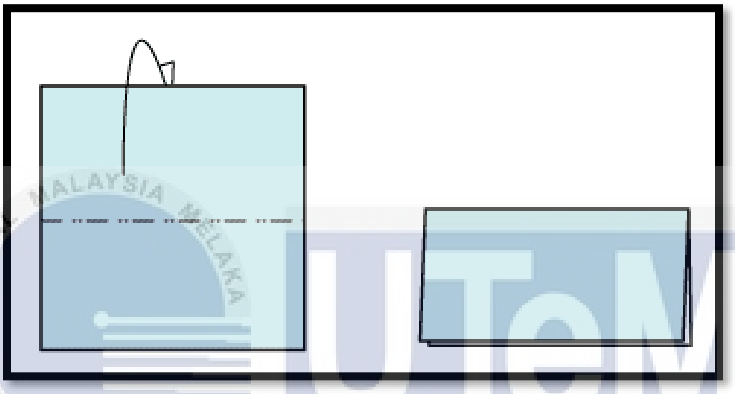


Figure 2.11: Mountain fold (Source: https://britishorigami.info/valley-mountain-folds/. 2/3/2020).

2.4.2.2 Valley fold

The valley fold is the most common origami technique. In origami, fold one edge to meet another edge, as shown below. The arrow shows the lower edge to the opposite edge in the first picture. This is folding in half, in other words. The second picture shows the outcome. The diagram may show the relative location of the paper or not. Folding an edge to hit a crease or an overlap of creases is equally possible. The exact position may be conspicuous and not clearly indicated, or tiny dots or circles may be indicated. It's pretty certain here that the corner folds to touch the middle. The goal point is just above the centre, indicating tiny dots at the arrow's start and end. At the goal end, there can often only be one dot. Most origami diagrams show an overhead view, like a 2D architect's plan (Peng et al., 2018). Figure 2.12 and 2.13 below shows the characteristic of the valley fold.

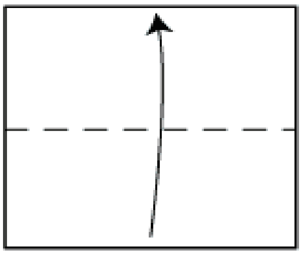


Figure 2.12: The bottom edge to the edge opposite (Source: https://britishorigami.info/valley-mountain-folds/. 2/3/2020).

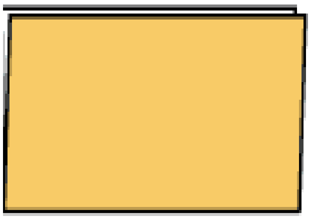


Figure 2.13: Folding result (Source: https://britishorigami.info/valley-mountain-folds/. 2/3/2020).

2.4.3 Yoshimura pattern (diamond pattern)

Stavric & Wiltsche, (2014) have presented that a diamond-shaped fold in one of its diagonals is the origin of this pattern. It is named after a Japanese scientist who found that, under axial tension, thin-walled cylinders exhibit this kind of buckling pattern. If all one-way parallel diagonals are folded as valley folds in a regular diamond pattern, and the edges get a cylindrical form as mountain fold one. This pattern can be obtained by mirroring a reverse fold at its inflexion point K. At the base point of its lateral creases, S. The diamond's diagonals are identical to the main crease of the reverse fold and the diamond's borders to the side creases. The outline of the diamonds determines the folded pattern curve. The greater the angle between the diagonal of the diamond and its edge. The bending of the pattern flatters. A distortion alters the curve's inflexion from diamond to kite form. This makes every continuous curve approximated (circle segment, parabola). Another version of this pattern can be obtained by separating the diamond or kite outline and extending it around the folded diagonal. The result is a hexagonal pattern formed by symmetrical trapezoids. Figure 2.14 demonstrates the design of Yoshimura.

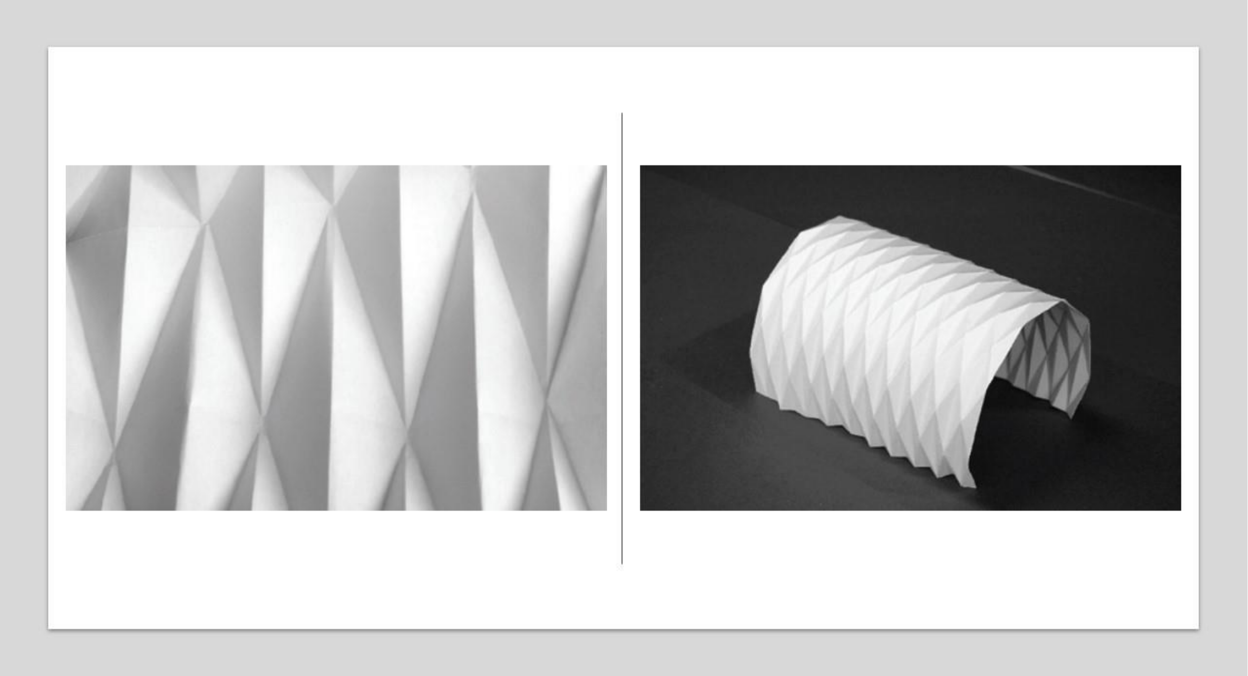


Figure 2.14: Yoshimura pattern (Buri & Weinand, 2008).

2.4.4 Diagonal pattern

A parallelogram folded onto its diagonal is the basis of this pattern. The sides are twisted up diagonally from a parallel location. A sequence of parallelograms, so folded, forms a twisted helical fold. When a thin-walled cylinder shell is compressed with distortion, a related buckling pattern shows up. Yoshimura- and diagonal- patterns are close to each other. It varies primarily because the diamond pattern's valley folds shape a polygonal plane line, while the valley folds of the diamond pattern form a helical polygonal line (Stavric & Wiltsche, 2014). Figure 2.15 below shows the origami can produce this pattern.

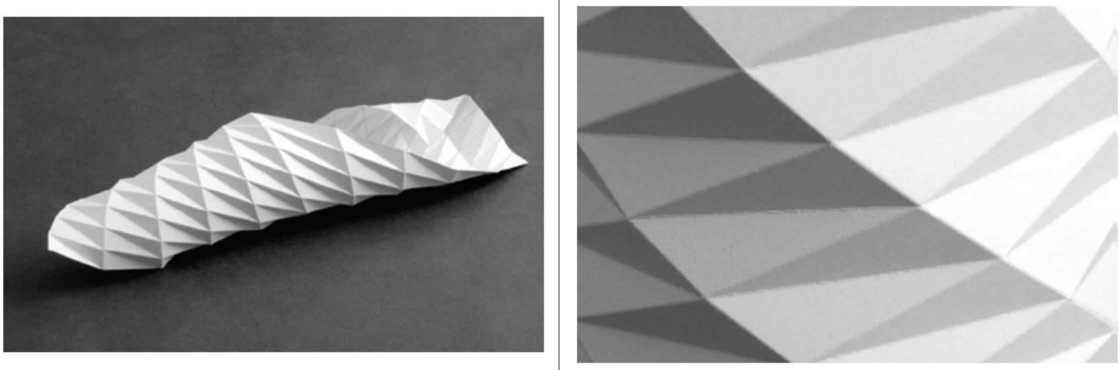


Figure 2.15: Diagonal pattern (Buri & Weinand, 2008).

2.4.5 Miura ori pattern (herringbone pattern)

Stavric & Wiltsche, (2014) stated that a repetition of reverse folds could obtain the diamond pattern. These are repeated inline instead of mirroring the reverse folds so that the main crease represents a zigzag line. Therefore, the folded pattern has a distinctive two-way zigzag corrugation. This helps the sequence in all directions to be extended and retracted. This skill was used by Miura to build solar sails for satellites packaged in a very compact way and to have the full extension until unfolded. The pattern is made up of symmetric trapezoids that form a tessellation of the herringbone. In the same way, the trapezoid legs (non-parallel sides) are inclined. The zigzag line of the central fold follows a curve in general. This is because of the disparity between the legs' tendency. If the legs are parallel such that a rhomboid forms the trapezoid, the manifold's zigzag line extension is straight. If the bases (parallel sides) of the trapezoid are decreased to zero, the pattern consists of a symmetrical triangle that forms a dart. And where the legs of the trapezoid are not straight is it possible. Figure 2.16 illustrates the pattern that can apply in origami.

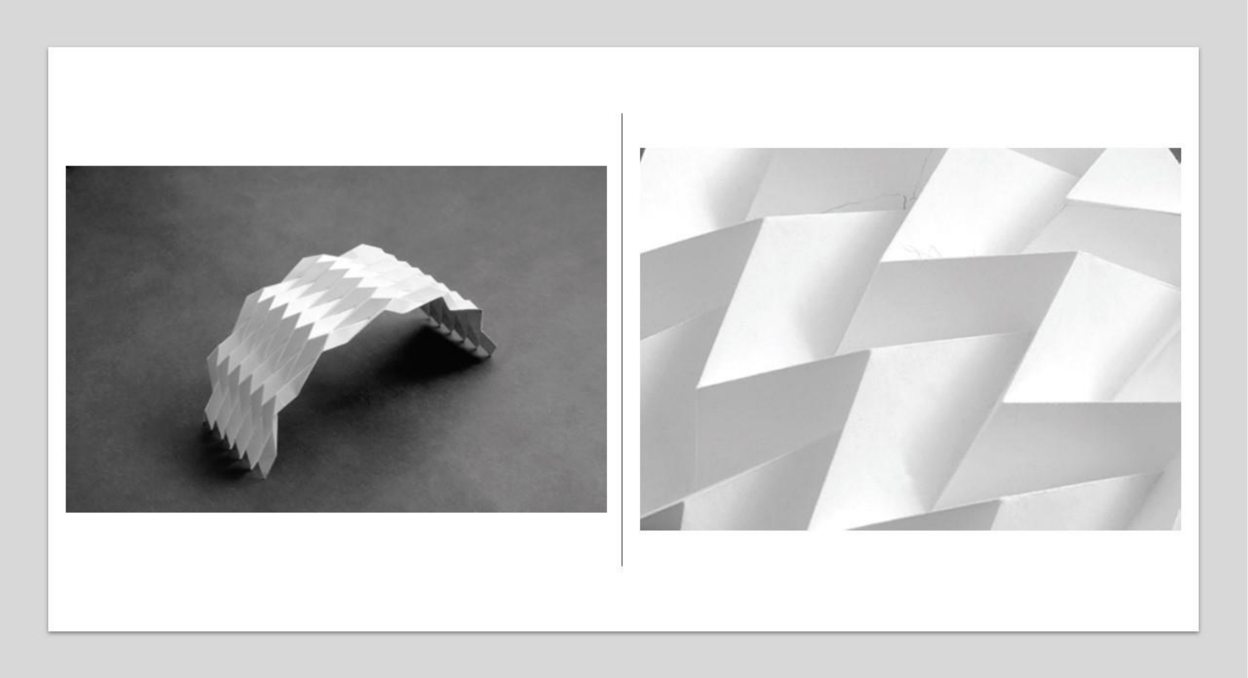


Figure 2.16: Miura ori pattern (Buri & Weinand, 2008).

2.4.6 Design optimization of origami and kirigami structures

Kwok et al., (2015) stated that a better result could be achieved by incorporating interior-only cuts while fabricating the model from the 2D pattern. In the wave shape model, the designed initially fillets make it nonflattenable. Only vertices of a mesh are moved during the shape optimization iterations. Fabricate a model by self-folding. The 3D form must be flattenable, that is, without stretching, it can be flattened into a 2D pattern. Flattenable is the term for a 3D surface that has such a geometric property. A modeled 3D shape is always non-flattenable, and if a non-optimized self-folding structure fabricates such a shape in the previous work of self-folding structures, any geometric details can not be reconstructed. Deng & Chen, (2015) have reported the 3D models to be created are sliced into strips to be flattened. Nevertheless, after folding, artifacts are left at the sites where cuts are introduced. The further breaks, the more artifacts on the final folded portion have resulted. Figure 2.17 shows the fabricated component of objects caused by long edge length inserted cuts.

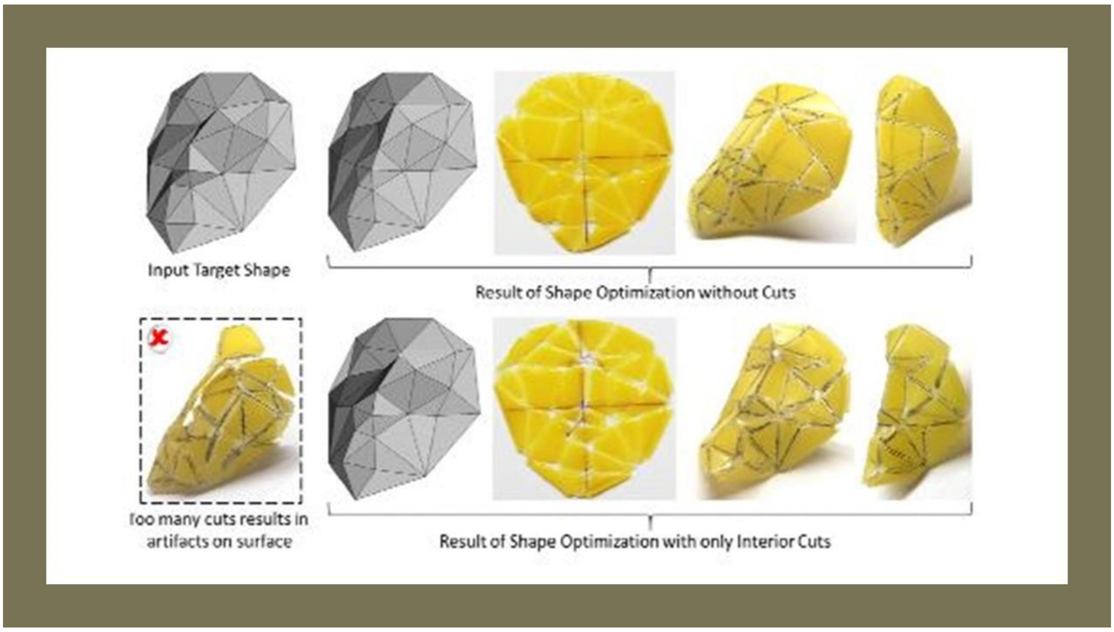


Figure 2. 17: Shape optimization will create a 2D pattern for the creation of a self-folding structure by AM for a freeform input surface to be generated by Origami-structure of the face model, which can be folded into a face model by heating (see the top row) (Kwok et al., 2015).

2.4.7 Self-folding origami

Self-folding of flat-state complex origami-inspired structures enables many surface-related functionalities to be integrated into the final 3D machine. Therefore, to produce such multi-functional devices, many self-folding techniques have been created, combining two types of kirigami elements that permanently deform. The elastic layer generates self-folding fundamental components, much as work based on either multi-stability or plastic deformation. Using the kirigami cut patterns and the elastic sheet measurements, the folding angles of these components could be controlled and precisely predicted using computer models (van Manen et al., 2020). Figure 2.18 shows the example of a self-folding design and technique.

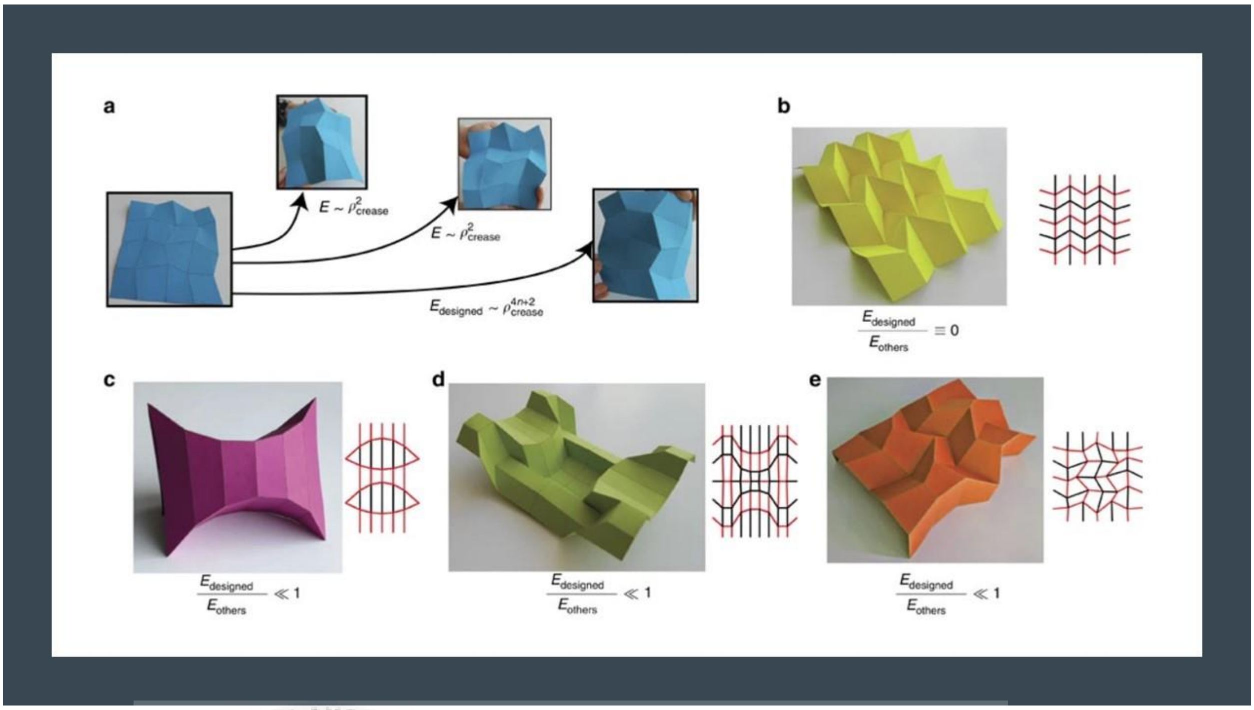


Figure 2.18: Designing self-folding origami (Pinson et al., 2017).

2.4.7.1 Uniform heat

An et al., (2018) have presented that Robotic sheets made of stiff tiles and joint actuators are self-folding origami structures. Each joint folds into a pre-programmed corner when exposed to heat. These folding gestures transform into a structure that can be used as a 3-D origami robotic body, including walkers, rotary actuators, microcell grippers, and analogue circuits. The design algorithm automatically produces a schematic printing design of the structure's sheet shape, a 3-D model. The geometric knowledge is contained in the sheet design, such as the folding angles and the folding sequences. The sheet is printed and baked in an oven, and the 3-D model is self-folded. Figure 2.19 below shows the experiment self-folding by concept origami and kirigami through heat concept.

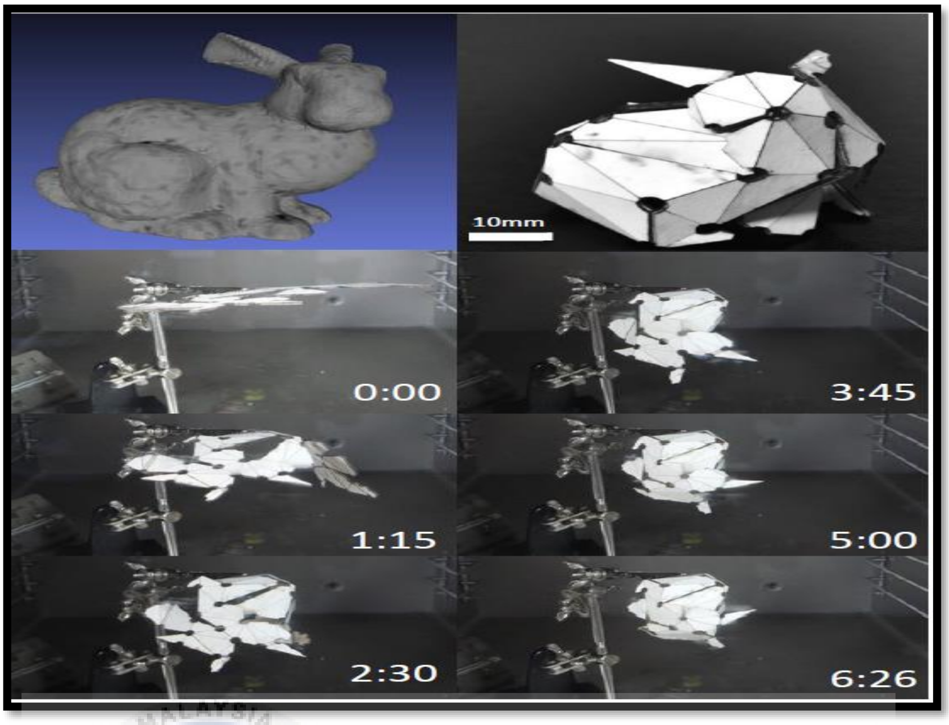


Figure 2.19: Self-folding Stanford bunny with (Top-left) 3D visual feedback from the self-folding experiment by uniform heating (An et al., 2018).

2.4.7.2 Self-Folding materials

The self-folding technique has been established at the micrometer scale widely (Ionov, 2011). The millimeter scale, and the centimeter scale (Felton et al., 2013). With heat, circuitry, light, cells, surface tension, and microwaves, various self-folding materials operate. Recently, 3D printing technology has been suggested for self-folding form memory polymers as an on-demand synthesis method (SMP) (Mao et al., 2015). As a result, the constructed structures' complexity and size have increased, and machine methods have become more significant. Figure 2.20 explains that temperature values can change an object's shape by using the self-folding concept.

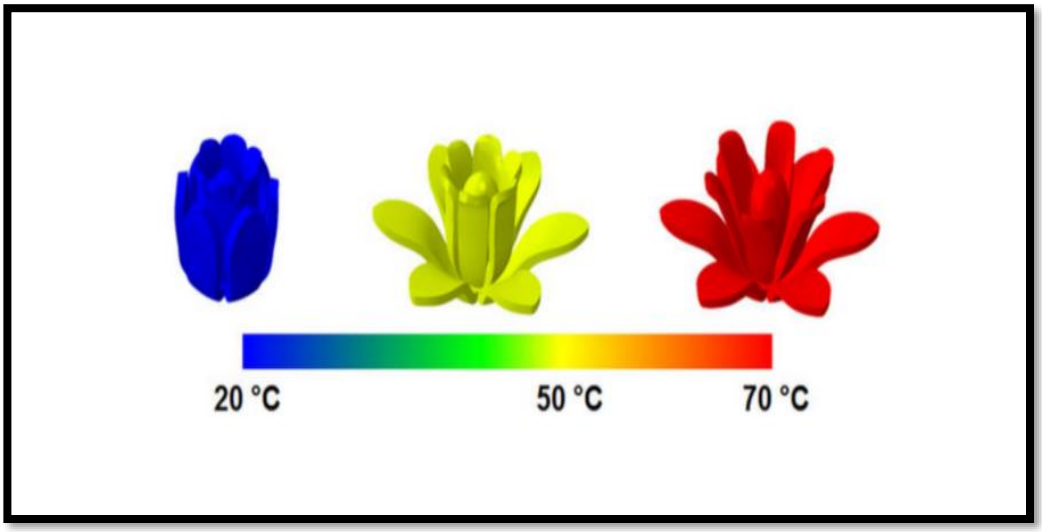


Figure 2.20: Polymers with shape memory are performed using a high-resolution micro stereolithography projection (Pµsl) technique (Hasan et al., 2016).

2.4.8 Thick folding techniques

2.4.8.1 Hinge shift

The hinge change technique moves the hinge from a plane to match material thickness (Hoberman, 2010). This technique is difficult to use in 2D crease-pattern links, but it is easily usable in producing one-dimensional folding of dense material. In order not to build on current construction strategies beginning from a coplanar folding pattern, hinges originate from a plane. Besides, the full scope of folding motion is reduced. The solution expands the principle of hinge shifting to higher degree crease pattern vertices, but this strategy is geometrically restricting in the angles and thicknesses allowed (Chen et al., 2015). Figure 2.21 shows the thick material applies to folding techniques.

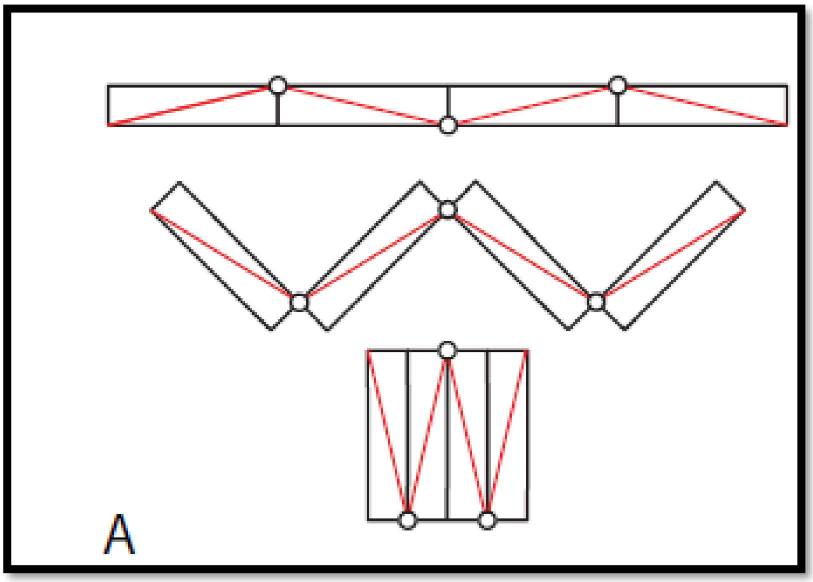


Figure 2.21: Hinge shift (Ku & Demaine, 2015).

2.4.8.2 Volume trimming

Base on the strategy in Lang et al., (2017) trims the edges of a thickened surface to overcome many of the hinge shift technique's difficulties. This technique often suffers from a reduced range of motion and practice. The slanted surfaces can be challenging to produce. The thick material is related to folding techniques, as seen in Figure 2.22.

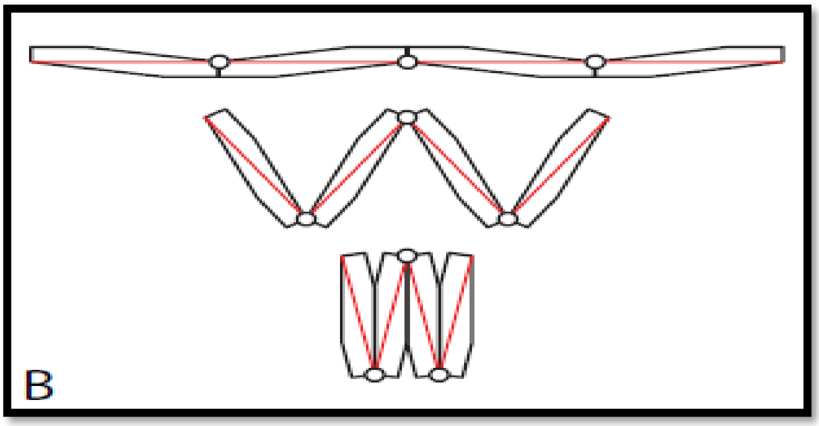


Figure 2.22: Volume trimming concept (Ku & Demaine, 2015).

2.4.8.3 Offset panel

The offset panel technique Edmondson et al., (2015) in deployment is perhaps the most exciting because it is versatile, supporting a maximum range of movement. This form preserves hinges in the folding plane but moves the bulky material away from the folding plane. Although promising, it can be difficult to manufacture such structures, requiring sturdy standoffs to link thick material to hinges. Figure 2.23 shows the thick material applies to folding techniques.

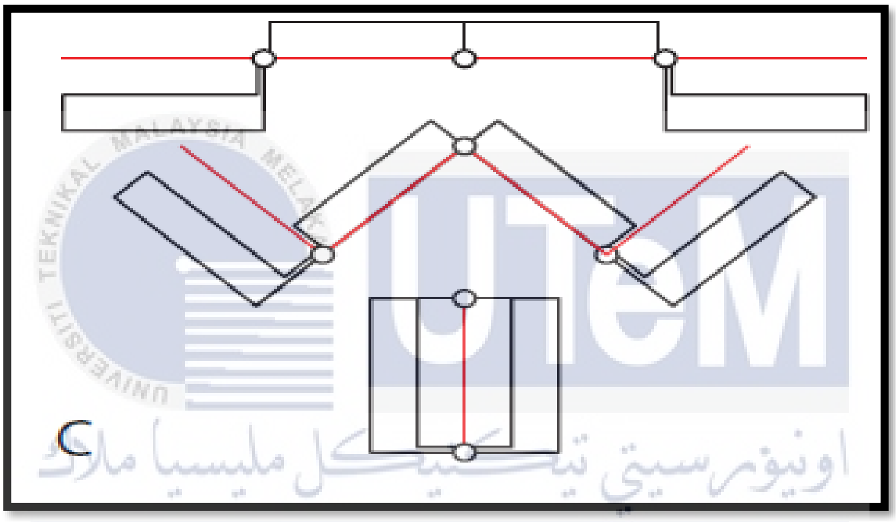


Figure 2.23: Offset panel concept (Ku & Demaine, 2015).

2.4.8.4 Offset crease

This paper builds on the thoughts raised in the L.Markusson, (2017), encompassing layer thickness by expanding versatile materials' creases, forming a hinge from a material's two-dimensional area. This suggests changing the offset crease method that routinely widens creases, substituting two suitable hinges for each crease without depending on versatile materials. While this method does not maintain the same structure of the input crease pattern, it produces a structure that would be simpler to produce than other techniques. Besides, the proposed technique requires original facets in both flat and folded configurations to be parallel, possibly allowing surface-mounted components to be matched. A few other approaches for accommodating material thickness are the recommended solution. Hoberman Zirbel et al., (2013) patent offsets creases to accommodate thickness in a non-parallel manner and suffers from a reduced fold angle spectrum and can not treat crease patterns with internal vertices in a usual way. Still, some approaches include introducing degrees of freedom by allowing faces to slide along creases longitudinally, but it can be challenging to produce (Ku & Demaine, 2016). Figure 2.24 shows the thick material applies to folding techniques.

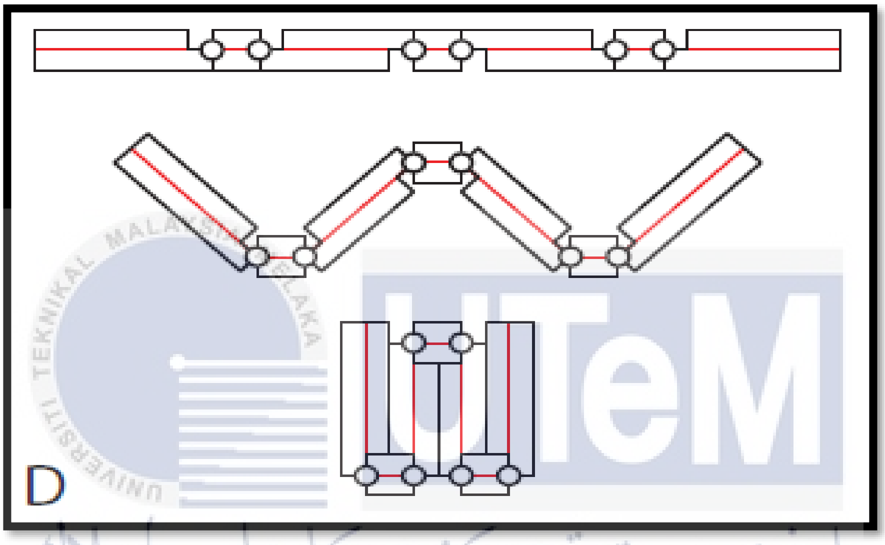


Figure 2.24: Offset crease concept (Ku & Demaine, 2015).

2.4.8.5 Swelling of the layer

The concept of lowering the surface area of the fold line or the thickness of the fold line. Using a shape-memory polymer layer that exhibits self-assembly at the meso-scale, this technology was used to create a printed robot. However, it produces little torque and is difficult to manage the folding angle and sequence. The torsion actuator is the third type of mechanism (Koh et al., 2014). Figure 2.25 shows the thick material applies to folding techniques.

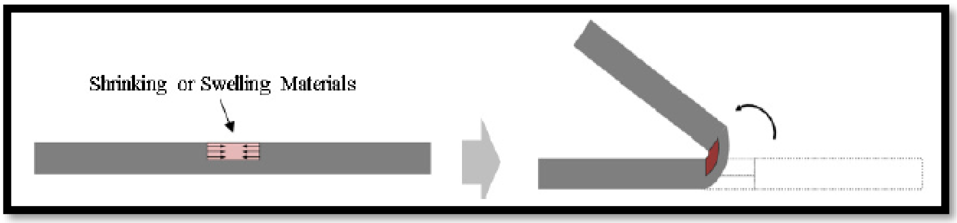


Figure 2.25: Swelling of the layer (Koh et al., 2014).

2.5 Material Selection

A large range of usable FDM materials, fast material shift, low maintenance costs, simple production of thin components, total resistance equal to 0.1 mm, no hazardous materials, and very compact scale, operating at low temperatures, and so on (Yadav et al., 2019). Guo & Leu, (2013) stated that thermoplastics-Acrylonitrile butadiene styrene, Polylactic acid, Polyether ether ketone, Polycarbonate, High effect polystyrene, Thermoplastic polyurethane, aliphatic polyamides, and waxes are the most commonly used materials in FDM processes.

2.5.1 ABS

Design and analysis of parts for automotive application of acrylonitrile butadiene styrene (ABS) via the Fused Deposition Modeling (FDM) process (D. K. Yadav et al., 2019). As a general remedy for rough parts of acceptable strength, acrylonitrile butadiene styrene (ABS). Acrylonitrile butadiene styrene is short for ABS, and it is an amorphous polymer used in 3D printing. ABS is typically created from 3 elements or recycled from itself via the emulsion process. It's widely used in producing many everyday goods when pieces need more strength; ABS is used; however, some reinforced composites eventually begin to displace it. ABS's benefits are rigidity and toughness, recyclable, easy to post-process and paint, abrasive tolerance, higher temperatures of 212 ° F (around 100 ° C), many colors and composites available can be machined (Dawoud et al., 2016). Figure 2.26 shows the example of the ABS product, and the flat sheet product can be produced.

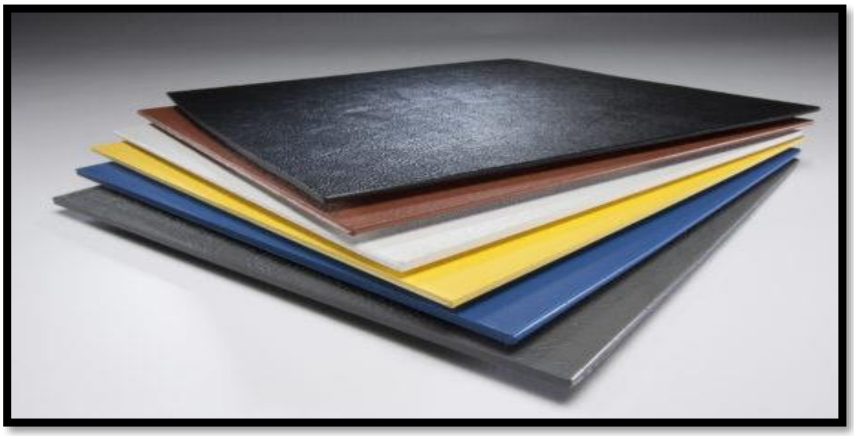


Figure 2.26: ABS product (Source: https://www.polymershapes.com/product/abs/ 2/3/2017).

2.5.2 PLA

According to Dawoud et al., (2016), Polylactic acid (PLA) is a stiff and environmentally safe substance found in widely used materials. PLA is a thermoplastic polyester that is biodegradable and bioactive, manufactured from renewable materials such as corn starch, making it more environmentally friendly than most plastics. Suitable PLA applications include parts, prototypes, and products that are not needed to endure extreme stress. Figure 2.27 shows the example of the PLA product.

Figure 2.27: PLA product (Source: https://www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes 6/9/2016).

2.5.3 PET

In the material selection of plastics for 3D printer filaments, the ELECTRE multi-criteria decision-making approach was used. Among the alternatives being weighed, the virgin LDPE has outranked the virgin HDPE, PET, and PP. In comparison, compared with virgin PET, recycled PET is stronger. As an alternative filament for 3D printing, PET recycling has also shown potential. PET Advantages is can be food-safe after finishing the piece, layers look excellent and smooth, have some flexibility, resistant to moisture, are recyclable, are very strong and shock-resistant, can be semi-transparent, can be post-processed and painted (Exconde et al., 2019). Figure 2.28 shows the material PET.

Figure 2.28: PET (Polyethylene terephthalate) 3D printing product (Source: https://www.creativemechanisms.com/blog/learn-about-polylactic-acid-pla-prototypes 6/9/2016).

2.5.4 PETG

PETG is practically indestructible in the layer direction due to its flexibility. Surface finishes improve when layer adhesion improves. It's a good choice for printing larger things because of its low shrinkage. Glycol-modified PET (PETG) is becoming increasingly popular because it is more durable than other filament materials. The addition of glycol prevents crystallization so it won’t become brittle when heated. Glycol prevents crystallisation, which means it won't become brittle when heated (Amalina et al., 2017). Figure 2.29 shows the material PETG.

Figure 2.29: PET (Polyethylene terephthalate) 3D printing product (Source: https://www.3djake.uk/extrudr/mf-petg-gold 6/7/2021).

2.6 Computer and Computer-Aided Design (CAD)

Mwema & Akinlabi, (2020) state some CAD tools used to produce 3D models, including AutoCAD, Inventor®, Solidworks®, CATIATM, and so many more, to create visual 3D models using a computer computer-aided design (CAD). This software is open source or closed source software (Junk & Kuen, 2016). The technologist or engineer interested in additive manufacturing can realize, through these innovations, how to use applications for successful manufacturing. These CAD tools can create complex 3D models based on the user's experience. It specifies the amount of material to be extruded by the 3D printer and its time to construct the 3D model. The information is generated in a G-code file that the printer can quickly understand (Song et al., 2018).

2.6.1 SolidWorks application

The SolidWorks program creates parametric 3D solid geometry to construct sketches, animations, full-color renderings, and other forms of paper. Regardless of the object's size, the development process is straightforward and follows the same basic steps (Dassault Systemes, 2019). There are two main modes for running a SolidWorks design analysis: assessment and optimization. Evaluation allows users to assign individual values and use sensors as limitations for each attribute. The program uses different variations of the meaning of the analysis and records each mixture's performance (Chang, 2015).

2.6.2 Solidworks software methodology

First, it generates a sketch that becomes a part of the foundation. Therefore, incorporating functions that integrate or remove information from the base component would further boost the base functionality. In order to construct assemblies reflecting the final configuration, different versions of parts may then be used. The modeling and production process was documented after creating the 3D component or assembly models (Lad & Rao, 2014).

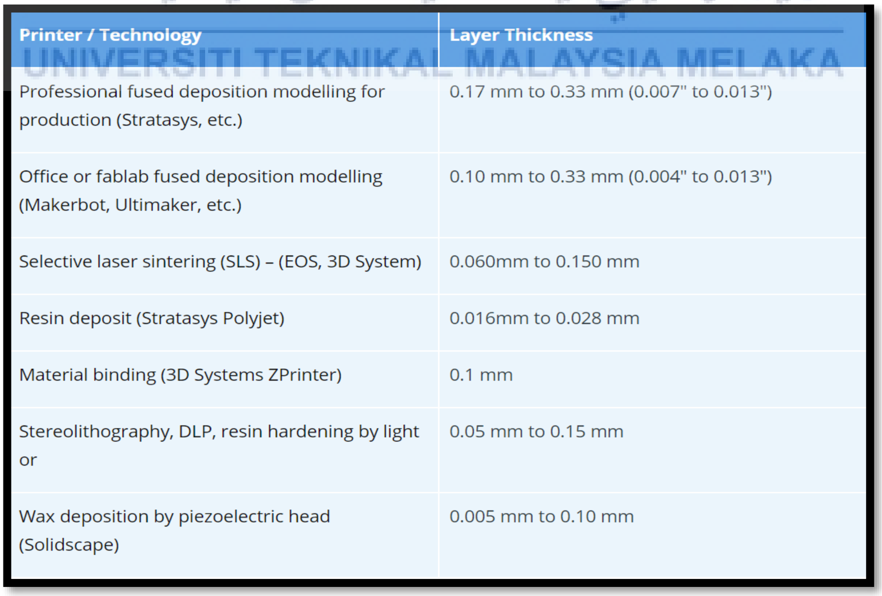
2.6.3 Solidworks software simulation

SolidWorks will also provide simulation analysis. It guarantees the consistency and reliability of product design before it enters service. The research method also makes it easy to evaluate the product early in the design process, making it easier to find lower weight and material costs with the details available (Design et al., 2015).

2.7 Process Parameters of 3D Printer

2.7.1 Layer thickness

Camposeco-Negrete, (2020) has presented that it is one of the key hi-tech characteristics of a 3D printer like the vertical resolution of the z-axis is effectively the layer height. Three different dimensions are concerned with developing a project using additive manufacturing: X, Y, and Z-axis. (Kovan et al., 2017), adhesion theorySurface roughness is caused by the strength of adhesive bonding between three-dimensional printed components. Experimental research has been performed on the effects of layer thickness and print orientation on the adhesion ability of components produced by three-dimensional printing. As a result of the study, it was observed that the edgewise orientation has the lower layer thicknesses in the strongest bonding strength. The flat's direction in higher layer thicknesses had the highest bonding strength. Figure 2.30 shows the Standard Layer thickness of the 3D Printer.



Printer / Technology	Layer Thickness
Professional fused deposition modelling for production (Stratasys, etc.)	0.17 mm to 0.33 mm (0.007" to 0.013")
Office or fablab fused deposition modelling (Makerbot, Ultimaker, etc.)	0.10 mm to 0.33 mm (0.004" to 0.013")
Selective laser sintering (SLS) – (EOS, 3D System)	0.060mm to 0.150 mm
Resin deposit (Stratasys Polyjet)	0.016mm to 0.028 mm
Material binding (3D Systems ZPrinter)	0.1 mm
Stereolithography, DLP, resin hardening by light or	0.05 mm to 0.15 mm
Wax deposition by piezoelectric head (Solidscape)	0.005 mm to 0.10 mm

Figure 2.30: Standard Layer thickness of 3D Printer (Source: https://www.sculpteo.com/en/glossary/layer-thickness-definition/. 1/12/2020).

2.7.2 Raster angle

The raster angle is the point of the raster tool's direction deposited on the x-axis of the building table. The standard raster angles permitted in steps of 15° are 0-90 ° or 0 ° to −90 °. For example, in the first bottom layer, a selection of 45 ° will produce a raster tool path inclined at 45 ° to the x-axis, the direction of the tool path will alternate in each successive layer. Figure 2.31 shows an example of some FDM method parameters in a deposited layer of a circle section (Masood, 2014).

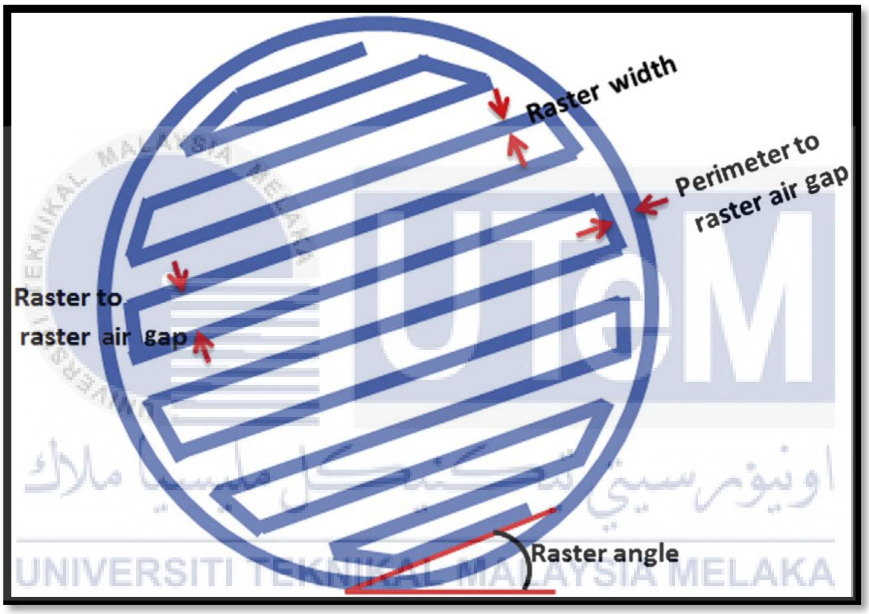


Figure 2.31: FDM process parameters in a layer created by deposited roads (Masood, 2014).

2.8 Summary

This chapter covers additive manufacturing, as well as the design and printing of origami structures using a fused deposition modeling 3D printer. The mechanism by which materials are joined to create a 3D model is known as AM. These materials are joined layer by layer, and in the subtractive processing process, it opposes the substance removal process. AM is commonly used today in many industries as it can minimize the cost of output and time when used correctly. The seven fundamental steps are contained in the AM working standards. It begins with the CAD model's configuration, followed by the conversion of CAD to STL file, STL slicing, system set-up, 3D printing, removal, and post-processing processes. There are several types of AM implementations, and each of these implementations comes with its pros and cons. FDM is one of the most widespread methods used in 3D printing. FDM requires no chemical processing, and it is cost-effective, but inside the parts produced, unpredictable shrinkage can occur. The AM method's advantages and weaknesses are also discussed in this chapter. AM will manufacture complicated and personalized modules, but it will take a lot of time to create and require post-processing. AM is used in different areas, including lightweight equipment, engineering, medicine, and sports. Following that, this chapter explains how to understand origami's design, which includes a type of fold and mechanism. The printing specifications for the 3D printer, such as the raster angle and layer width, are also covered in Chapter 2. The information for the literature review came from reading journals and previous research.

CHAPTER 3

METHODOLOGY

This chapter describes the overall progress of research development that includes the procedures involved in this research and the flowchart methodology.

3.1 Introduction

This section outlines the methodology, which includes the concepts and methods used to complete the study. Research, material, design, simulation, and printing were all done to identify origami structures that could be used in the fused deposition modeling method. The process flow begins from the title selection until the conclusion of the research according to the research flow methodology.

3.2 Project Planning

Project preparation has been done on the paperwork to assure its completion in project management. In the documents, new plans have been described, planned, and arranged. The project strategy has been implemented from the beginning to the end of the project's operations.

3.2.1 Flow chart

The process flow diagram clarifies the research report's progress flow. The process flow is arranged according to the sequence from the flow chart. The flow chart shows how the problem was solved from top to down. Figure 3.1 shows the overall process flow for completing this research report.

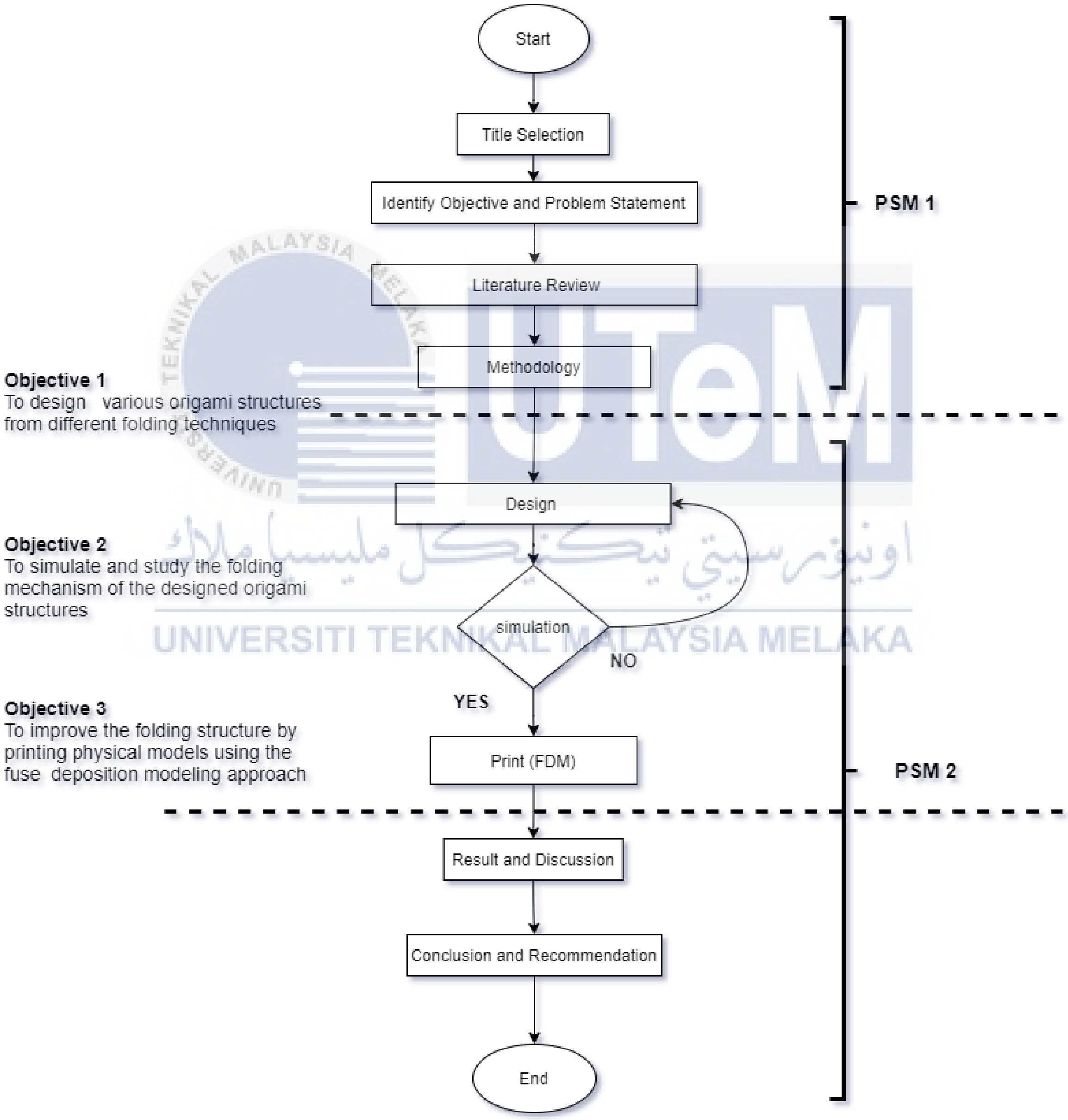


Figure 3.1: Flow chart methodology.

3.3 Problem Statement and Objectives

The main components that have been identified before designing the origami are the problem statement and research objectives. The overall progress of the research has fulfilled the criteria of the research scope in order to meet the problem statement and objective standards.

3.4 Research and Literature Review

The research was conducted using a variety of sources and information, including books, journals, online databases, articles, and conferences, to complete the literature review. The design approach, comparisons between each data, design, folding structure information, fused deposition modeling method, and material were all observed.

3.4.1 Understand origami structure and folding technique

Basic folds such as valley folds and mountain folds have been clearly understood in the construction of the concept of origami. There are also many other varieties of folding that have been discovered as a result of this research, including reverse folds, squash folds, and sinks. There are other standards known as bases that are used in many models, such as a bird base, which is an intermediate stage in the development of the flapping bird. The preliminary base (square base), fish base, waterbomb base, and frog base are all optional bases. This project made use of a few of the techniques mentioned above. In Chapter 4, the techniques used were discussed.

3.5 Design Origami Structure

3.5.1 Sketching drawing

Valley and mountain components were used to create the sketches. All of the concepts from the literature review were gathered and incorporated into sketches. This sketch is a representation of a drawing created in SolidWorks. Figure 3.2 below illustrates an example of a sketch that meets the structural origami requirements.

Figure 3.2: Flat plate origami structure sketching.

3.5.2 CAD design

Concept Computer-aided design (CAD) software has been used in origami to develop, modify, test, and improve designs. CAD software was used to increase designer efficiency, improve manufacturing quality, improve document communication, and create an origami structure database. Significant engineering technology is widely used in several areas, including automotive, shipbuilding, aircraft, engineering, and architecture. In Chapter 4, this tool was fully utilized in the design of seven origami concepts.

3.5.2.1 ORIPA software

ORIPA was used to create the proper fold in this project. All line crease patterns have been solved in an automatic manner using this application. It's a drawing application that helps make origami crease designs. The folded form is determined by the pattern, which is a unique feature. The program was used to identify and measure the folds that needed to happen. The ORIPA program was used on the project, as shown in Figure 3.3 below.

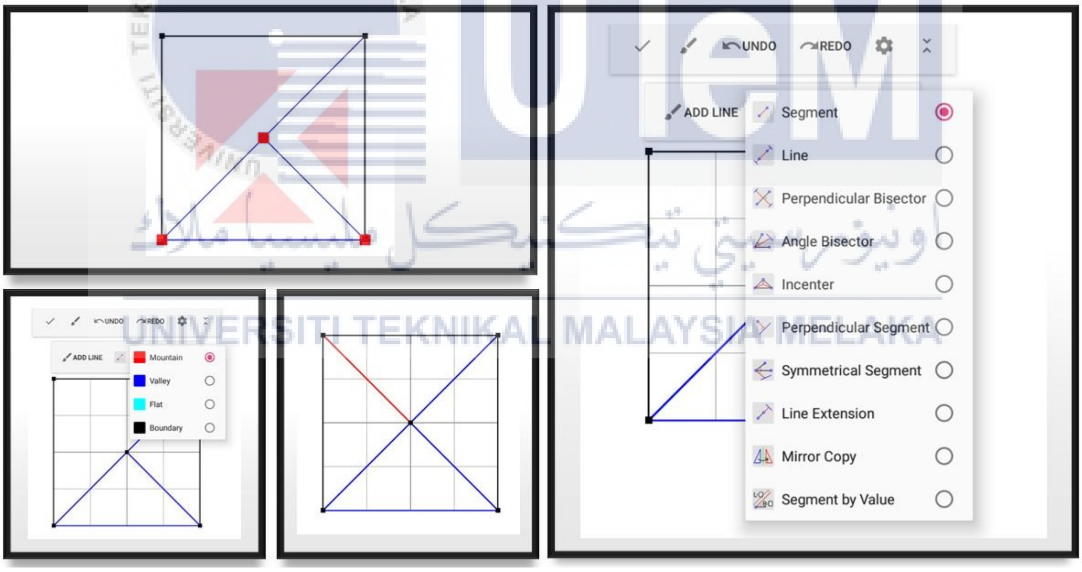


Figure 3.3: Make it fold line and calculate the fold can be possible for this pattern.

3.5.2.2 SolidWorks design

SolidWorks Software is a mechanical design automation application that allows designers to quickly sketch concepts, experiment with characteristics and proportions, and produce models and instructive drawings. This software has been used to create origami structures. Standard tessellation/triangulation language (STL) has been assigned to the origami structure. As a result, the design of an origami structure can be used for additive manufacturing (FDM technology). These are the steps to run Solidworks software:

i. Run the SolidWorks Software.
ii. Sketch the concepts using the software with the required dimensions.
iii. Generate and solve the modeling parts to create 3D sketching.

3.5.2.3 SolidWorks simulation

In a single, modern, easy-to-use setting, with every step from geometry creation to optimization and result generation, This program has been designed to be a complete solution for design engineering simulations. The folding structure has been optimized for advances in engineering analysis, optimizing alternatives, and design innovation. The simulation was used to determine if origami can fold well or not. This platform has been used to simulate a variety of constraints, including distance constraints, which prevent the sheet from stretching or compressing, as well as stress and strain analyses. The strain research was carried out in order to identify and comprehend structural origami. Figures 3.4 show how origami can be moved. The strain used to determine the ability of a folding structure to fold is shown in Figure 3.5.

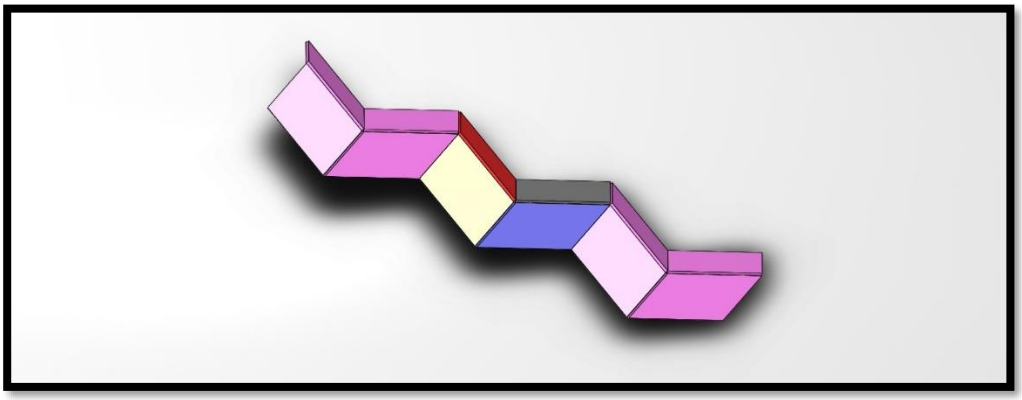


Figure 3.4: Movement part.

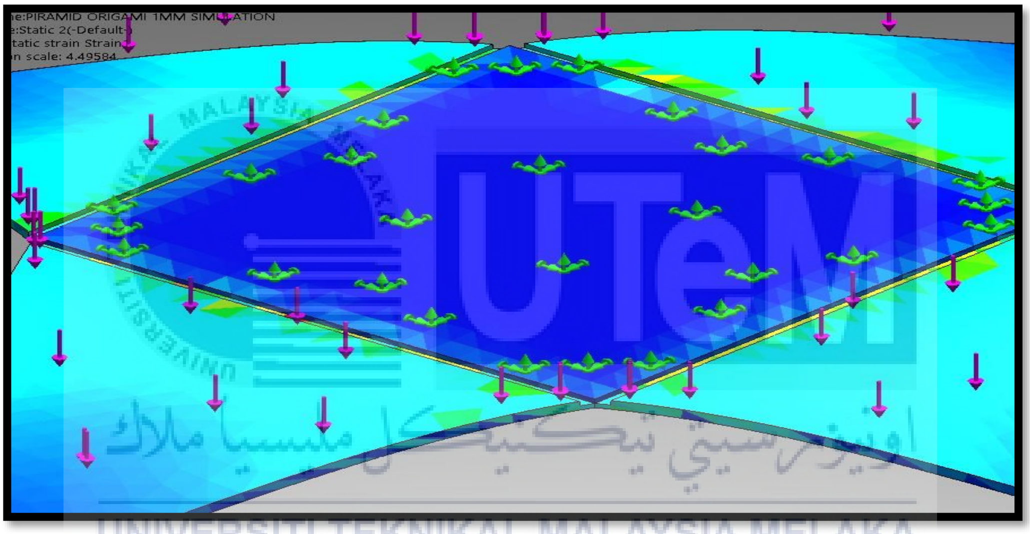


Figure 3.5: Strain analysis on origami structure.

3.6 Material Selection

3.6.1 PETG (polyethylene terephthalate glycol)

PETG was chosen for this project because it contains all of the elements required for origami. These are the characteristic of polyethylene terephthalate glycol:

i. It is more durable and flexible.
ii. The added glycol prevents the material from crystallizing and becoming breakable.
iii. It is highly impact-resistant.
iv. It can be sterilized.

Figure 3.6 below shows the PETG that has been used in this project.

Figure 3.6: PETG filament.

3.7 FDM

The nozzle used in this project was 0.4mm, and the layer thickness was 0.02mm. By melting a string of plastic and adding it layer by layer to a building platform, the FDM / FFF process works. The 3D printed parts have identical mechanical properties to those of injection molding since the material is completely molten, with sufficient thickness. Due to the comparatively slow printing process, rather than being printed solid, solid models' interior is normally filled with a stabilizing space-fame. The Infill Rate determines the spaceframe- the proportion of the volume filled with solid material. Usually, this is set at 20-25% of the interior. The origami product shown in Figure 3.7 below was produced by FDM.

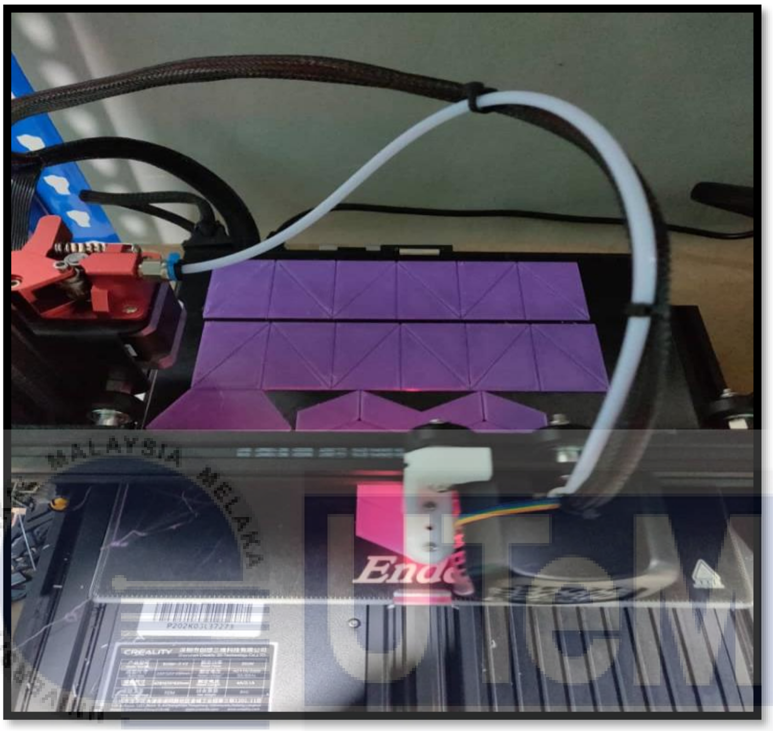


Figure 3.7: Ender 3 v2 (3D Printer).

3.7.1 Overview process FDM

Figure 3.8 shows the flow chart in the process of the FDM. This basic step in all FDM devices is required.

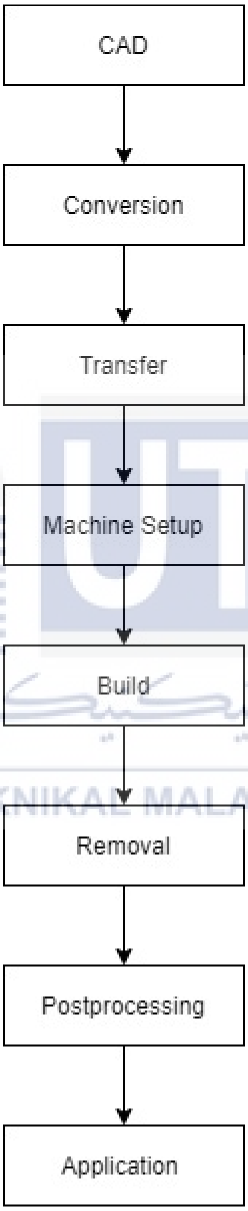


Figure 3.8: 8 Step of the process FDM (Product-prototyping, 2019).

3.7.2 Step FDM

Step 1: CAD

The first stage in the 3D printing process is preparing a 3D model origami. 3D model creation can make use of the help of 3D modeling software to help obtain the correct shape and size

Step 2: Conversion

3D models origami that have been created using software assistance are necessary to convert to format. STL (stereolithography). Stl format represents the shape of the 3D model.

Step 3: Transfer

STL files have to go through a manipulation process so later have the machine work setting information size, position, orientation, velocity, temperature, structure, etc.). This process will generate a G Code file (.gcode / .gco) to send to a 3D printer (via memory/wireless) to run the printing process

Step 4: Machine Setup

3D printers must be prepared before running the process of printing. Several processes that must be done include: Ensure availability of power & backup power, set up the bed or work area (adhesive, flatness, etc.), and supply printed material for airtight packaging, filters.

Step 5: Build

3D printer work process takes place automatically, so it does not require continuous surveillance. Users only need to observe periodically to avoid conditions such as material runs out, software errors, power outages, etc.

Step 6: Removal

Ensure that the 3D printer is neutral (motion, Temperature/nozzle) so that the component does not damage and ruin the result. When extracting the part, ensure that the heat bed is cool to ensure that it does not melt. Using sharp-ended instruments (scrap) so that items will easily come off.

Step 7: Postprocessing

Printed objects from the print base. The mould usually has an auxiliary structure and yields fibers mold that can be removed for a smoother finish.

Step 8: Application

Printouts can already be used after postprocessing; however, thus several conditions require treatment before the object can be used, such as append priming before painting.

3.8 Summary

This chapter describes a method or procedure used to obtain the results needed to fulfill the purpose of this report. This chapter also discusses information and easy-to-understand statements that detail each step in the study's implementation. This chapter is crucial for the next chapter 4, which deals with the results and discussion necessary to achieve the desired end.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter will provide the outcomes of seven SolidWorks concept designs that demonstrate different types of folding techniques by using basic folds such as valleys and mountains. The simulation was carried out using analytical engineering. The strain was described in order to define and understand the folding structure. A nozzle of 0.4mm was used to learn about the origami product in FDM.

4.2 Product Description

Origami principles are now used in a wide variety of applications from the design of satellites to heart stents, to self-assembling robots, and much more. Solar energy, wind energy, and mechanical energy have attracted many interests in the field of science and engineering on origami features (Zhang et al., 2020). The origami used these days are currently not fully use and complicated enough for application. When it comes to origami, there are some issues to consider, particularly in terms of material, fold type, and structure. Other materials, like plastic, steel, and many others, have some limits, such as the thickness of the material. It's impossible to produce satisfactory folding outcomes.

As a result, this project is built on the crease pattern (origami), with the fuse deposition modeling approach being used to create the origami design structure. The purpose of this product is to learn origami and build multiple origami patterns using a 3D printer. Most origami already in use is made of paper, and the new era will require new materials and technology for origami. Other materials, such as PETG, could be used to create new innovations. The material is flexible enough to be folded into origami. The material PETG was used to make this product. The design concept is shaped by valley lines, mountain lines, boundary lines, and flat shapes. However, the line and thickness of material that can be folded properly without difficulty and return to its original shape have been highlighted, and origami has been achieved using the fuse deposition modeling method.

Figures 4.1 and 4.2 show the full designs of the seven concept origami transformations, which each consist of several folds lines (valley and mountain). Each picture features an origami structure of a different type. Picture 1 shows concept 1, picture 2 shows concept 2, picture 3 shows concept 3, picture 4 shows concept 4, picture 5 shows concept 5, picture 6 shows concept 6 and picture 7 shows concept 7. This product can be transformed and returned to its flat shape.

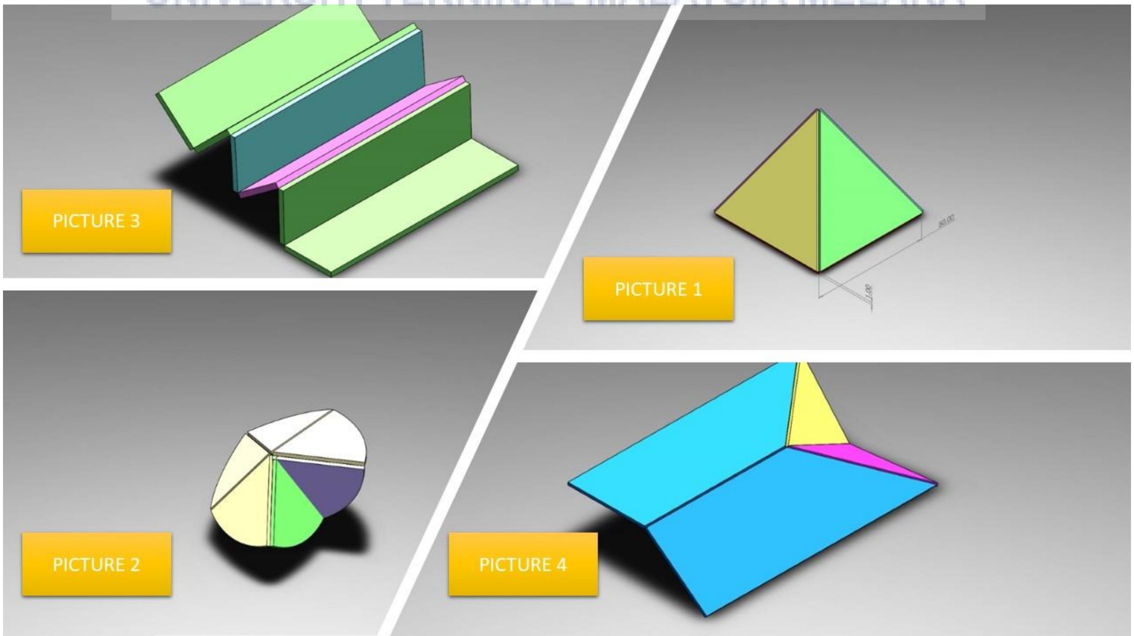


Figure 4.1: Four concept.

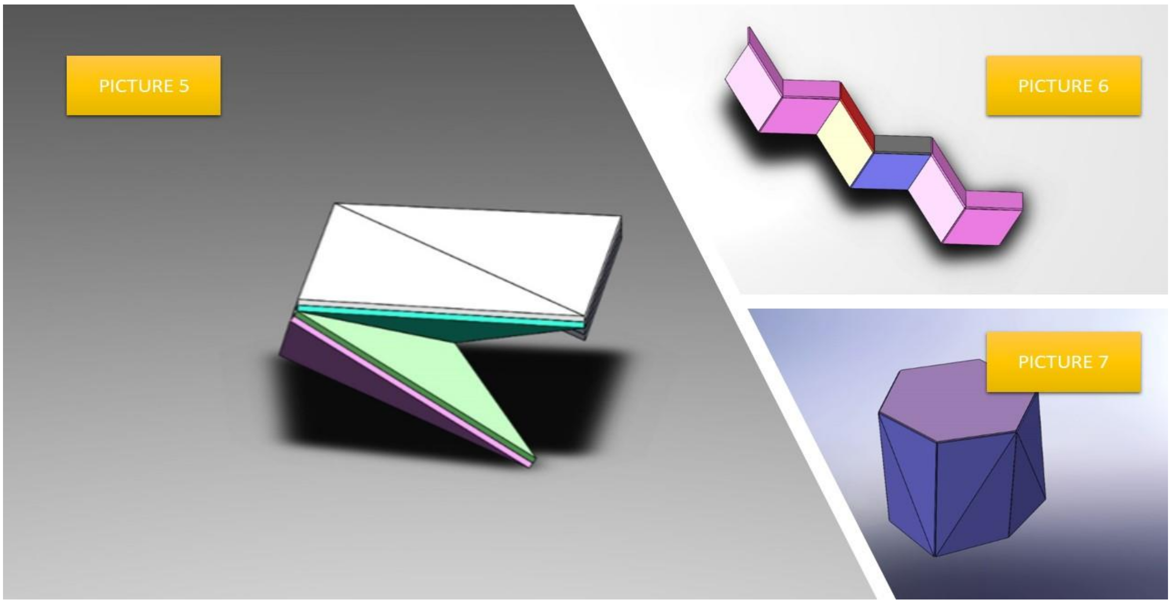


Figure 4.2: Three concept.

4.3 Element of Product

There are a few elements that made up this product has been designed. Each element plays an important role and is essential in making sure this product can be used and function well as intended. Based on the available crease pattern, journals, and new inspiration from the mind, seven concept designs were developed. The design material was chosen based on the design requirements; polyethylene terephthalate glycol (PETG) was chosen due to its flexibility, toughness, and long-term durability. Basic origami folds, such as valley and mountain folds, were used in all of these concepts; valley folds are inner folds while mountain folds are outer folds. The maximum thickness of this origami is 1mm, while the minimum thickness is 0.5mm. On folds measuring 1mm, this thickness has caused issues. The “swelling of the layer” (drain) method was taken to allow folding to happen. The “swelling of the layer” section has a thickness of 0.5mm. A drain was made at the top of the origami surface (flat) on the valley line, and a drain was made at the bottom of the origami surface (flat) on the mountain line. All of the above elements have been combined to ensure that all concepts can be implemented successfully.

4.3.1 Concept 1

Concept 1 is a pyramid design that was printed using the fuse deposition modeling technique (FDM). Only the valley fold was used in this concept. There are no lines that cross between the lines. The four-line valley fold (blue line) was guided by a pyramid design crease pattern and was situated on a flat structure. Due to its thickness, this mechanism has been proven to be inappropriate for the folding concept. So, the technique “swelling of the layer” has been used as a line of valley folds. Figure 4.3 below shows the design and element of concept 1.

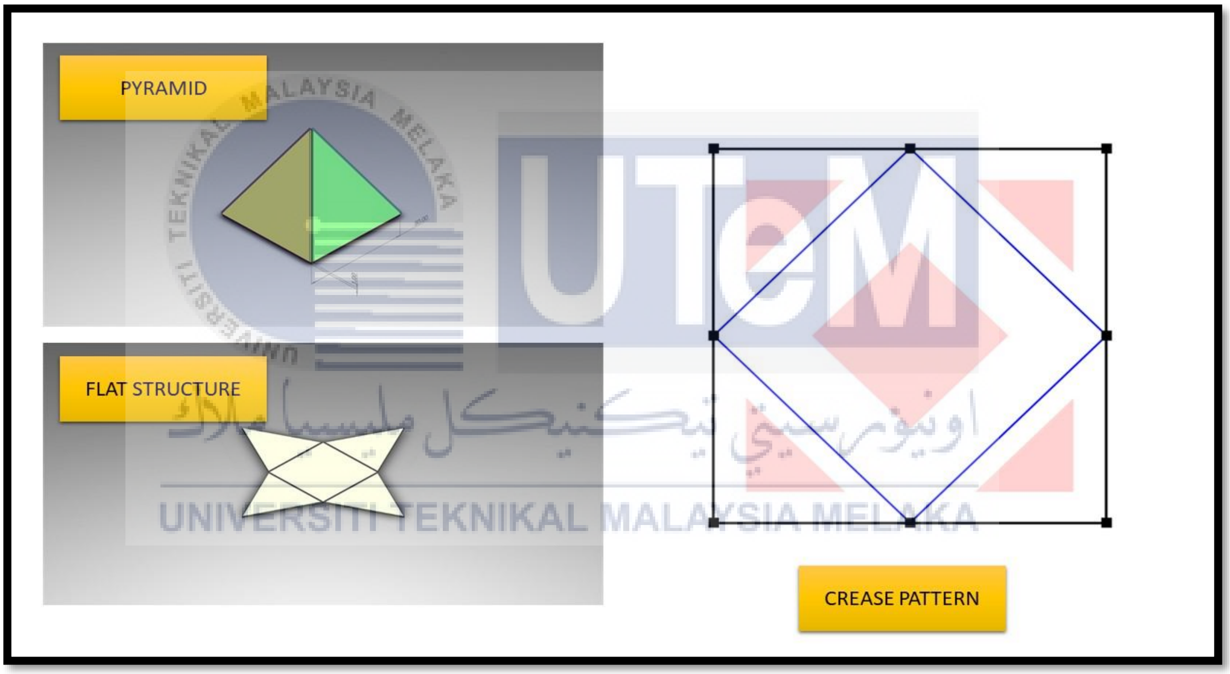


Figure 4.3: Pyramid element.

4.3.2 Concept 2

Figure 4.4 below shows the design and element of concept 2 is a circle fold design that was printed using the fuse deposition modeling (FDM). The valley fold has been fully utilized in this concept. Lines of intersection between lines have emerged as a result of this concept. A circular fold design crease pattern led the six-line valley fold (blue line), which was situated on the flat structure. Due to its thickness, this mechanism has been found to be unsuitable for the folding concept. As a result, a line of valley folds was created using the technique " swelling of the layer ".

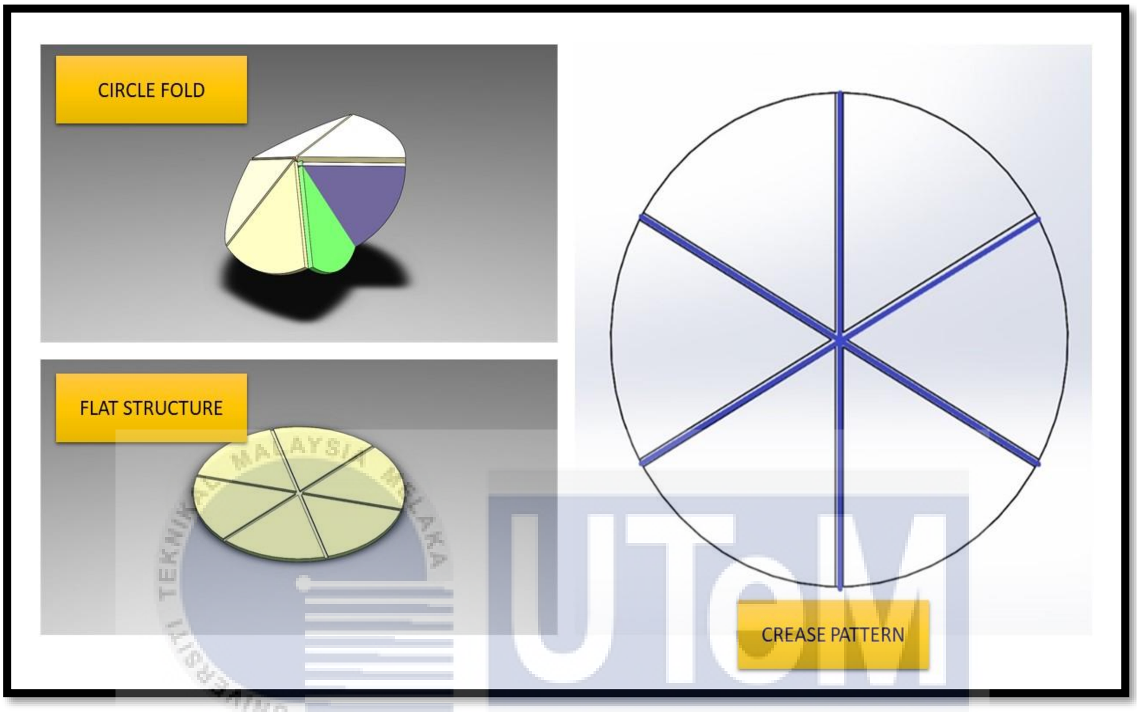


Figure 4.4: Circle fold element.

4.3.3 Concept 3

Fused deposition modeling (FDM) was used to print Concept 3, which is a poly fold design. Throughout the design, valley and mountain folds have been used. The fold lines don't cross or clash with one another. A poly fold design crease pattern guided the three-line valley fold (blue line) and two-line mountain fold (red line) that were positioned on the flat structure. Because of its thickness, this mechanism has proven impractical for the folding concept. As a line of valley folds and mountain folds, the technique " swelling of the layer " was applied to address this problem. Figure 4.5 below shows the design and element of concept 3.

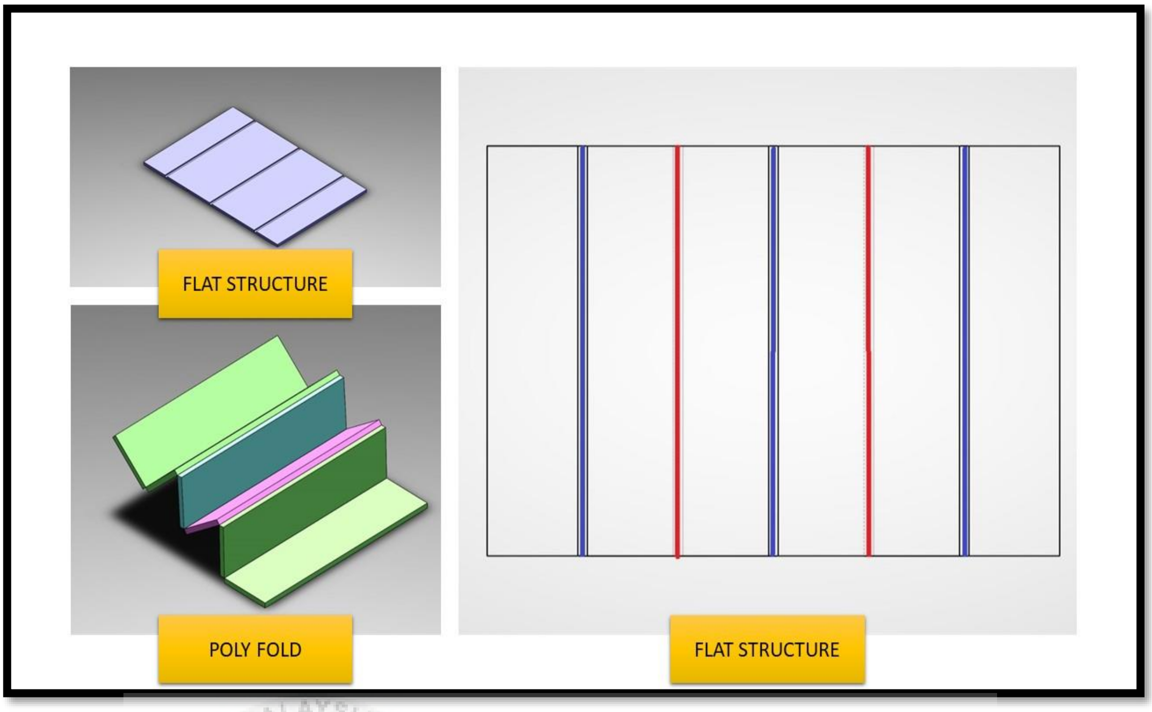


Figure 4.5: Poly fold element.

4.3.4 Concept 4

Concept 4 is a single vertex design produced through fuse deposition modeling (FDM). There are two types of folds used in this concept: valley and mountain folds. While creating the planned line, the lines clashed between them (there has been a crossing of lines). A single vertex design folding pattern guided the three-line valley fold (blue line) and the one-line mountain fold (red line) on a flat structure. A single vertex is a point where three coordinates are present at the same time (line intersection). This has caused some issues throughout the folding process, especially towards the midpoint. As a solution, a hole was made in the middle of the three lines (valley fold, mountain fold, and valley fold). In this situation, the process is similar to one that has previously happened, in which the thickness is the reason for the folding difficulty. So, the technique "swelling of the layer" has been used as a line of valley folds and mountain folds. Figure 4.6 below shows the design and element of concept 4.

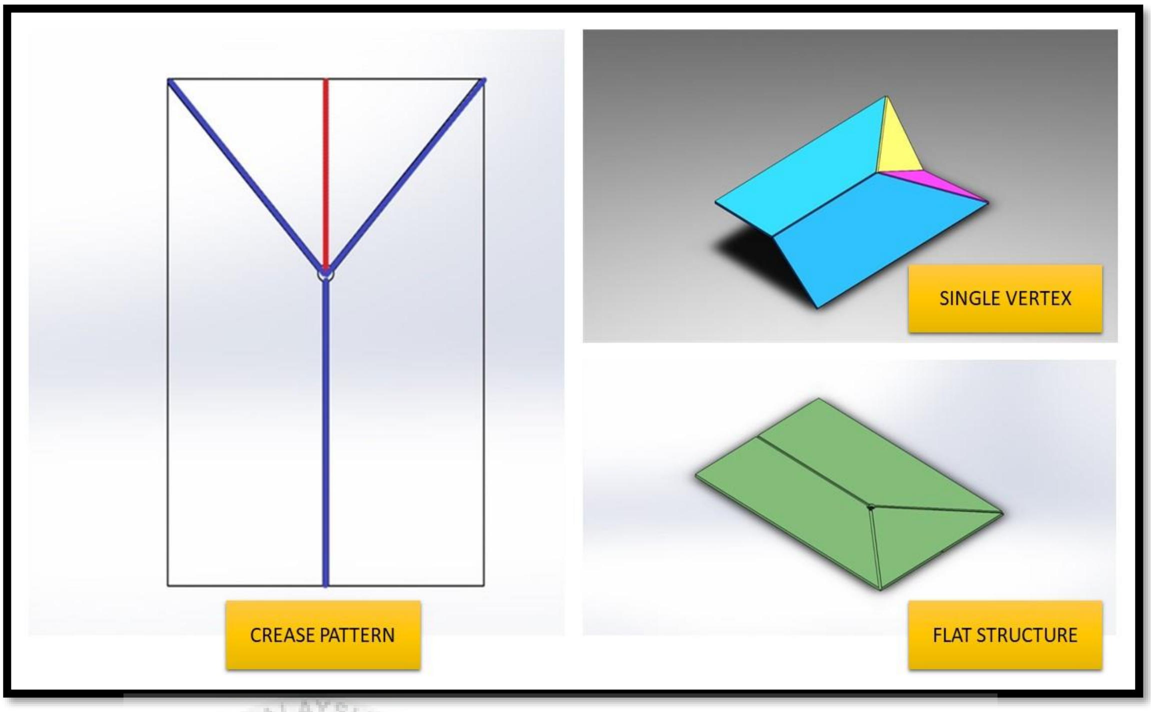


Figure 4.6: Single vertex element.

4.3.5 Concept 5

The design and element of concept 5 is a Kawasaki theorem that was produced using fuse deposition modeling (FDM) that is shown in Figure 4.7. In order to create this design, the valley and mountain folds were used fully. The intersection of the valley and the mountain fold has emerged from this concept. For the point of failure, holes were made between the intersections of the lines. On the flat structure, an eight-line valley fold (blue line) and four-line mountain fold (red line) have been driven by a Kawasaki theorem fold design crease pattern. The Kawasaki theorem concept may be folded to form a flat figure. This design was improved to be the double design of the Kawasaki theorem.

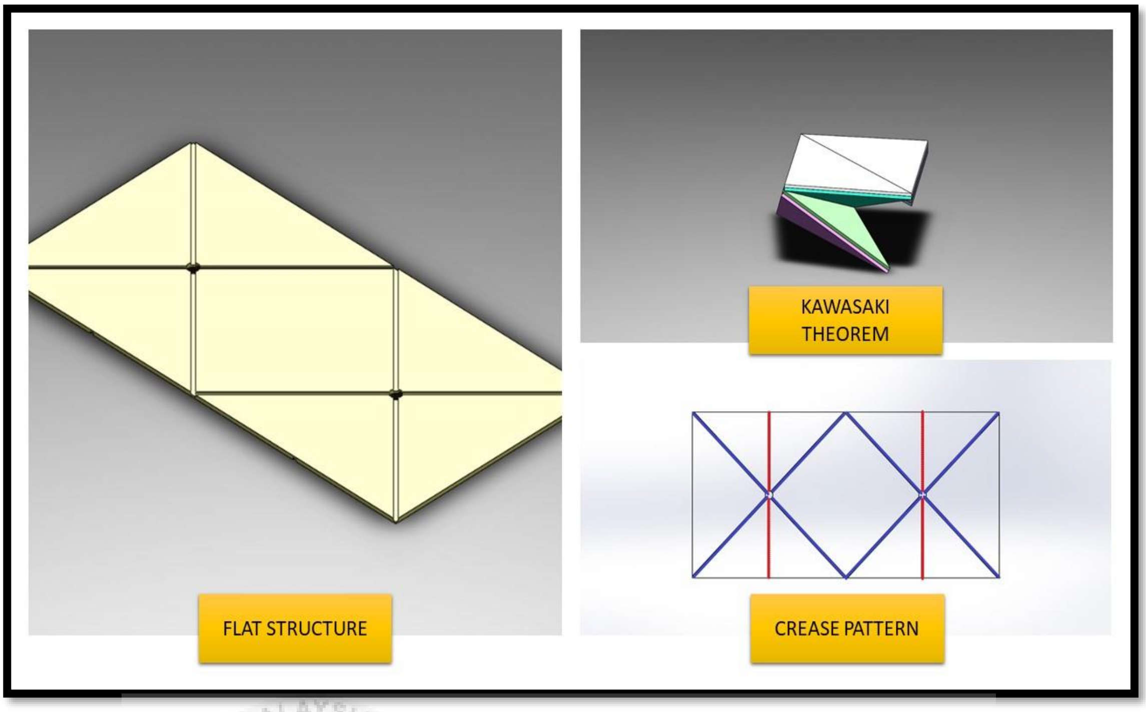


Figure 4.7: Kawasaki theorem element.

4.3.6 Concept 6

Fused deposition modeling (FDM) was used to print Concept 6, which is a spring fold design. This concept was built using basic folds, such as valley and mountain folds. The shape used in this concept is a parallelogram, which has a line of intersection between other lines. The seven-line valley fold (blue line) and three-line mountain fold (red line) were guided by a spring fold design crease pattern and are positioned within the flat structure. The valley folds at the top of the flat structure have been designed, as have the mountain folds at the bottom. A hole was used in the middle between the four lines to allow for folds to be made without being obstructed (valley folds and mountain folds). Figure 4.8 below shows the design and element of concept 6.

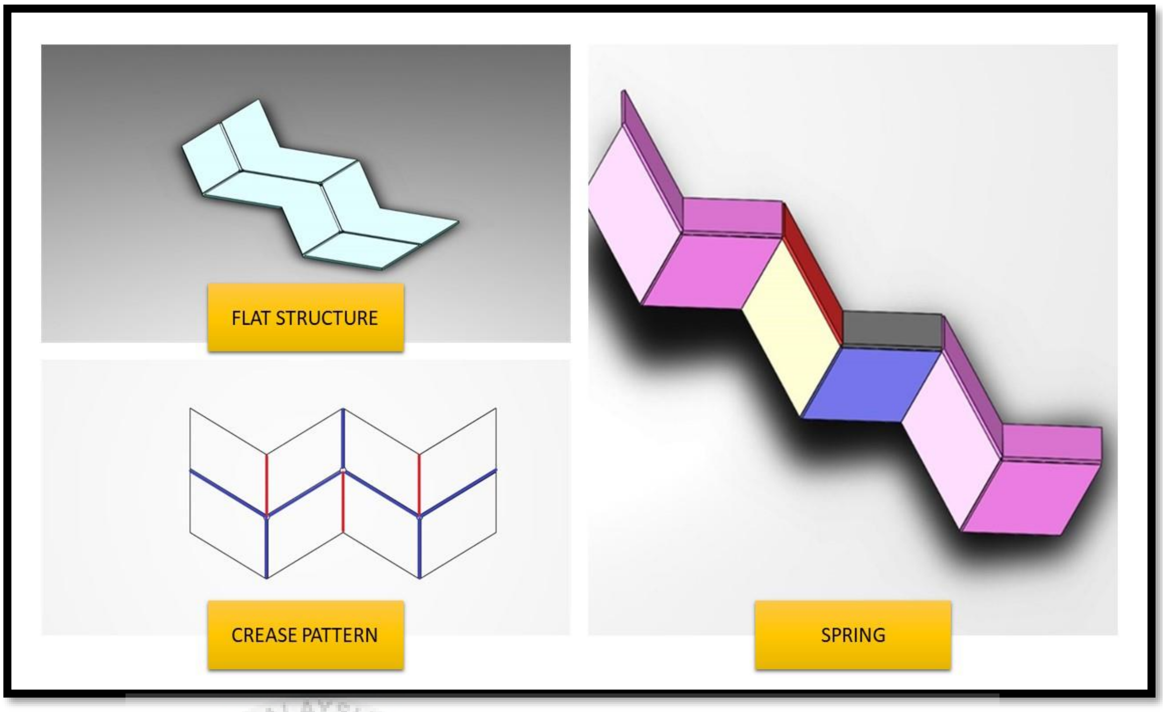


Figure 4.8: Spring element.

4.3.7 Concept 7

The design and concept element 7 is an origami chair that was printed using fuse deposition modeling (FDM), as shown in Figure 4.9. The valley fold was used entirely in this concept, and the pentagon structure was used as a shape reference. The twelve-line valley fold (blue line) was guided by an origami chair design crease pattern and was situated on a flat structure. This design is unique in that when viewed from the side, front, or top, the origami structure reveals multiple different viewpoints. This origami has given on a distinctive shape and has evolved into an aesthetics product.

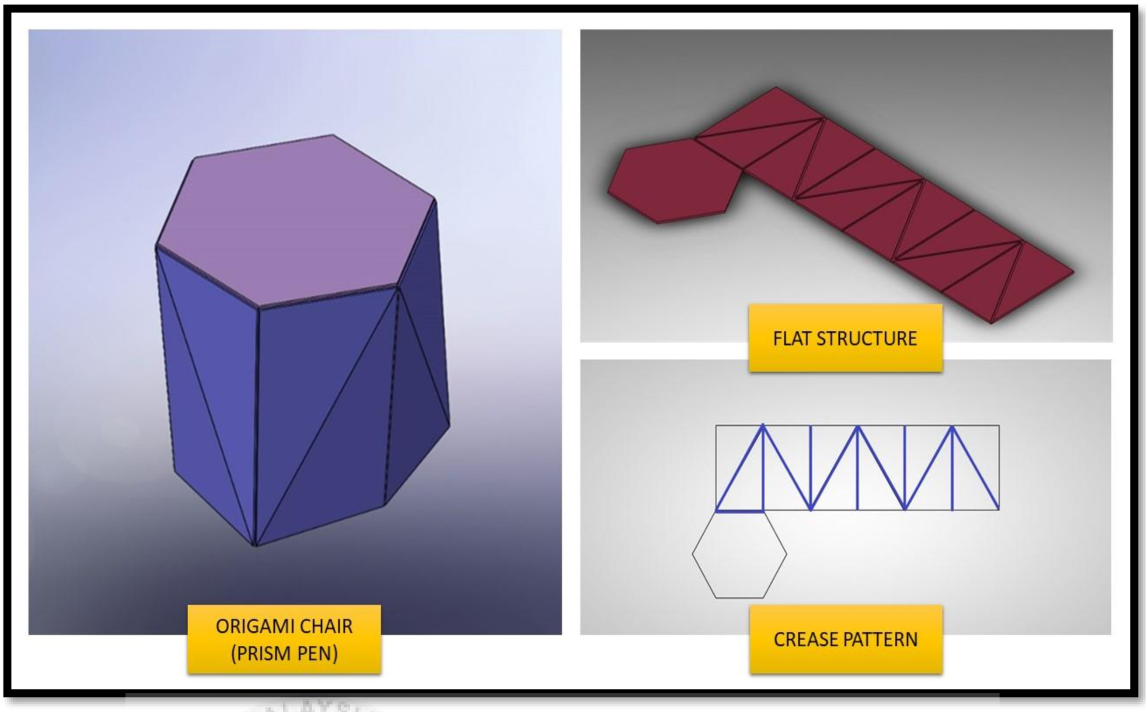


Figure 4.9: Origami chair element.

4.4 Simulation

Simulating structural analysis techniques that use Finite Element Analysis (FEA) to forecast a product's real-world physical performance by virtually testing CAD models makes it easier to check and identify them. Solidworks simulations (FEA) were used to determine the folding capabilities and design limitations of this Origami product. The structure of origami has been studied using this simulation. A stress and strain study was carried out to see what changes had occurred during the folding process. The failure of the PETG structure is described by the maximum strain value. Each of the three analyses has a different structure. On three strain analyses, several observations have been made.

4.4.1 Analysis 1

The product is made of polyethylene terephthalate glycol (PETG). Only fold valleys were used in this analysis, and the lines did not overlap. A force of about 2N has been applied from the top of the body. The center of the body has become a fixed component; this analysis replicated the real situation when the user folding a product. Table 4.1 showed the analysis 1 properties.

Table 4.1: Pyramid flat structure properties.

Model Reference: Pyramid flat structure	**Properties**
	Material: PETG Elastic Modulus: 2.01E 09 N / m^2 Poisson’s Ratio: 0.4 N / A Shear Modulus: 6.3E 07 N / m^2 Tensile Strength: 6E 06 N / m^2 Compresive Strength: 5.5E 07 N / m^2 Yield Strength: 4.79E 07 N / m^2 Specific Heat: 1200 J / (kg C)

The strain result is shown below in Table 4.2. The strain's maximum value was calculated to be 2.684E -3. When folding occurs, the highest strain value is 2.013E -03. The lowest amount of strain is 0. This indicates that the maximum strain value for folding (folding occurs) is less than the maximum strain value. The change in strain value indicates that the fold has elongated. The design can be folded when folding happens, according to this analysis. This analysis also gave a favorable result, indicating that the design is acceptable as an origami concept.

Table 4.2: Strain result for pyramid.

Type Analysis:	**Minimum:**	**Maximum:**	**Maximum (folding occur):**
Strain-Test	0	2.684E -3	2.013E -03

The simulation work on a product is represented in Figure 4.10 below. The color of the strain appears to be safe for repeated folds.

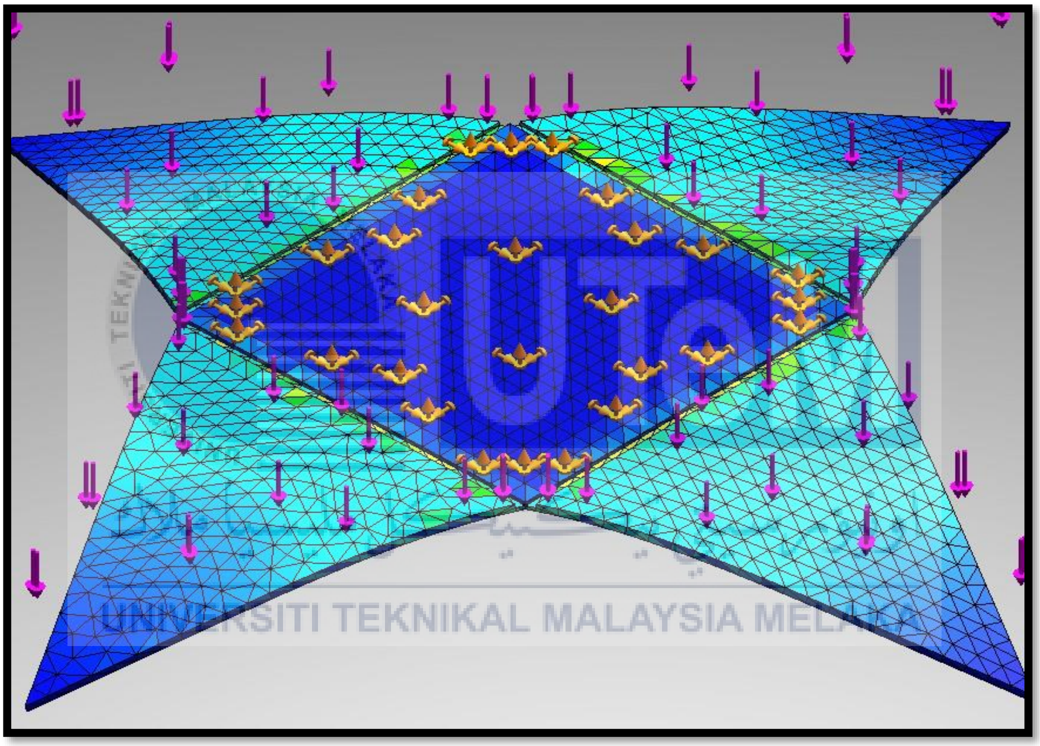
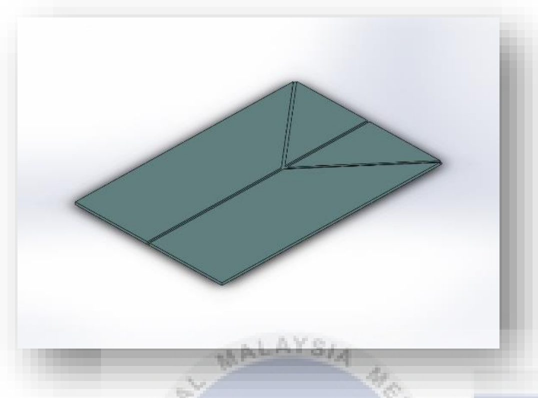


Figure 4.10: Valley fold simulation.

4.4.2 Analysis 2

The product is made of polyethylene terephthalate glycol (PETG). The folds have valleys and mountains, and the fold lines have intersected between them, according to this analysis. A force of about 2N has been applied from the top of the body. The right side of the body has become a fixed component; this analysis replicated the real situation when the user folding a product. Table 4.3 showed the analysis 2 properties.

Table 4.3: Single vertex flat structure (without a hole) properties.

Model Reference: Single vertex flat structure	**Properties**
	Material: PETG Elastic Modulus: 2.01E 09 N / m^2 Poisson’s Ratio: 0.4 N / A Shear Modulus: 6.3E 07 N / m^2 Tensile Strength: 6E 06 N / m^2 Compresive Strength: 5.5E 07 N / m^2 Yield Strength: 4.79E 07 N / m^2 Specific Heat: 1200 J / (kg C)

The strain result is shown below in Table 4.4. The strain's maximum value was calculated to be 5.957E -3. When folding occurs, the maximum strain value is 5.957E -3 at the intersection of the valley and mountain folds. The lowest amount of strain is 0. This means that the maximum strain value for folding (folding occurs) and the maximum strain value are the same. When folding occurs, this analysis shows that the design can be folded, but the point of failure will be the cause of damage to the fold line, such as a break or the fold does not reach its maximum potential. A change in strain value indicates fold elongation. Although this analysis gave a negative result, the design is still acceptable but not recommended.

Table 4.4: Strain result for single vertex (without hole).

Type Analysis:	**Minimum:**	**Maximum:**	**Maximum (folding occur):**
Strain-Test	0	5.957E -3	5.957E -3

The simulation work on a product is represented in Figure 4.11 below. The color of the strain area shows signs of damage. The failure point is located in the middle of the valley-mountain fold.

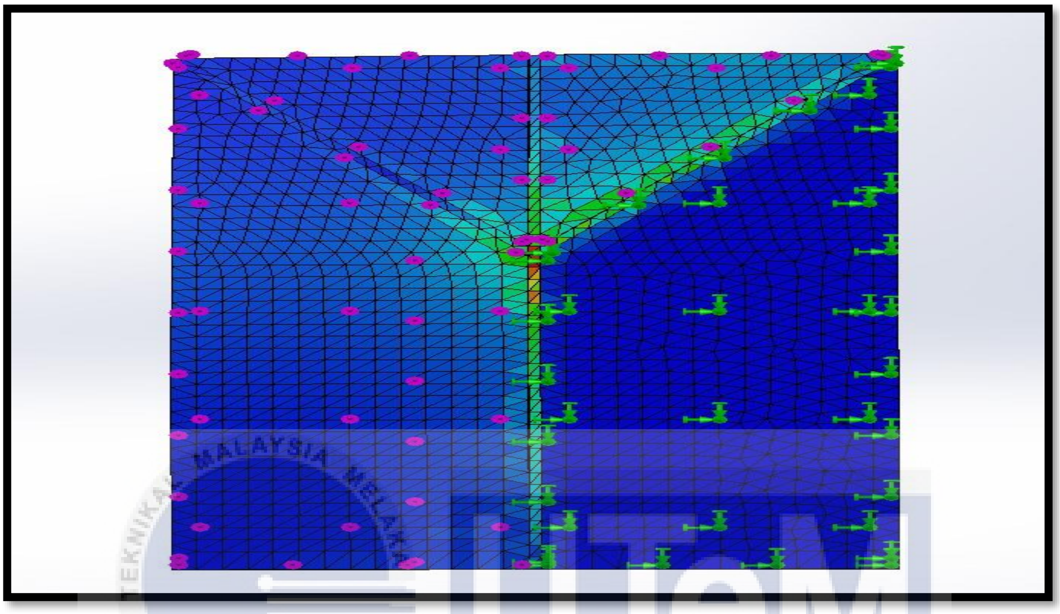


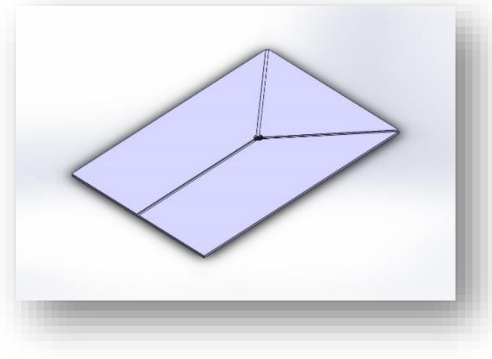
Figure 4.11: Valley and mountain fold (without a hole) simulation.

4.4.3 Analysis 3

The product is made of polyethylene terephthalate glycol (PETG). Valley fold and mountain fold were used to construct the concept in this analysis. At the intersection of the folds, holes have been made at the centre point. This analysis was carried out in order to improve analysis 2. A force of about 2N has been applied from the top of the body. The right side of the body has become a fixed component; this analysis replicated the real situation when the user folding a product. Table 4.5 showed the analysis 3 properties.

Table 4.5: Single vertex flat structure (with a hole) properties

Model Reference: Single vertex flat structure With a hole	**Properties**

	Material: PETG Elastic Modulus: 2.01E 09 N / m^2 Poisson’s Ratio: 0.4 N / A Shear Modulus: 6.3E 07 N / m^2 Tensile Strength: 6E 06 N / m^2 Compresive Strength: 5.5E 07 N / m^2 Yield Strength: 4.79E 07 N / m^2 Specific Heat: 1200 J / (kg C)

The strain result is shown below in Table 4.6. The strain's maximum value has been calculated to be 7.917E -3. When folding happens, the maximum strain value is 5.938E -03. The minimum amount of strain is 0. The maximum strain value for folding (folding occurs) is less than the maximum strain value. The design can be folded as a result of this analysis. Elongation of the fold is indicated by a change in strain value. This analysis also gave a favorable result, indicating that the design is acceptable as an origami concept.

Table 4. 6: Strain result for single vertex (with a hole).

Type Analysis:	Minimum:	Maximum:	Maximum (folding occur):
Strain-Test	0	7.917E -3	5.938E -3

The simulation has been applied to a product, as seen in Figure 4.12 below. After creating a hole in the middle point between the valley and mountain folds, the color of the strain area is safe to fold repeatedly.

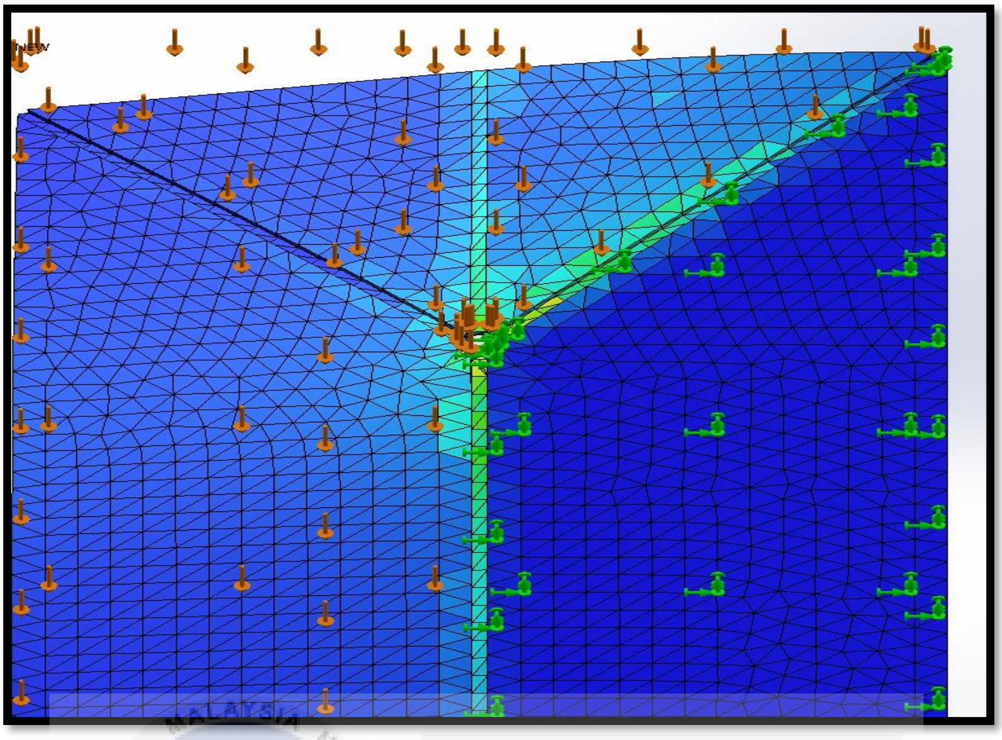


Figure 4.12: Valley and mountain fold (with a hole) simulation.

4.4.4 Analysis comparison

A comparison analysis was performed to determine which structure is better for origami folding. The maximum strain value (during folding) is lower than the maximum strain value on the structure, as seen in Analyses 1 and 3. Analyses 1 and 3 found significant favourable findings for use in the development of seven concepts. The maximum strain value (during folding) and the maximum strain value on the structure are the same in analysis 2, demonstrating that failure occurred when folding. Analysis 3 was created as a result of a failure in analysis 2. Analysis 3 has the same structure as analysis 2, but the fold cross structure has been modified. The hole was formed between the intersections of the lines in analysis 3 to change the structure in analysis 2. The results of the analysis are shown in Table 4.7.

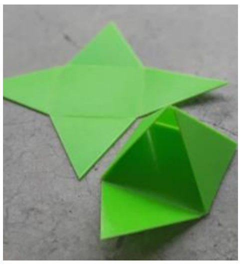
Table 4.7: Analysis comparison for understanding the folding mechanism.

Type of analysis	Structure	Potential	Usable
1	Valley fold	Folding is safe and easy	Yes
2	Valley and mountain fold (without a hole) simulation	It's easy to break and damage	No
3	Valley and mountain fold (with a hole) simulation	Folding is safe and easy	Yes

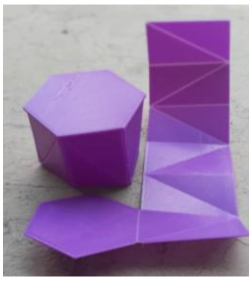
4.5 Printed Product

Origami products were successfully printed using FDM. Quality products have been produced. Seven design concepts can be folded successfully and repeatedly without causing damage. Origami's folding structure resembles a chain thread, making it sturdy and difficult to break. All seven designs are foldable if they are folded according to the specifications. On origami that had been printed, experiments were conducted. During folding, a central hole between the fold lines represents the point of failure that was eliminated in order to prevent the lines from colliding (valley and mountain). This proves that the failure point occurs when folding origami without a centre hole. When one fold line intersects with another, a centre hole is necessary. PETG has a great deal of potential in origami. Because of its remarkable flexibility and efficacy in origami, PETG is highly suggested for usage in origami. As it comes to origami, the thickness of the folds and the type of fold line structure are important factors to consider when creating a design. The product has been printed, as shown in Table 4.8 below.

Table 4. 8: Origami structure in FDM.

	**Concept 1**
	• Valley fold • No crossing line
	Concept 2

	- Valley fold - Crossing line
	**Concept 3** - Valley fold - Mountain fold - No crossing line
	**Concept 4** - Valley fold - Mountain fold - Crossing line - With a hole
	**Concept 5** - Valley fold - Mountain fold - Crossing line - With a hole - Kawasaki theorem structure
	**Concept 6** - Valley fold - Mountain fold - Crossing line - With a hole - Parallelogram structure
	Concept 7

	• Valley fold • Pentagon structure • Single vertex

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The final year project that is carried out over two semesters required a great deal of research and development of the origami design using the fused deposition method. The aims and objectives of this research have generally been achieved. Addictive manufacturing can be employed in origami methods, according to this study. Previous research has offered insight into the structure of origami and the issues that might arise during folding, such as origami thickness, which is a difficult issue in origami manufacturing. The type of origami has been known in the implementation of origami through previous research. The basic core of origami techniques, namely valley and mountain fold, may be used to produce a variety of concepts when applying origami design. Because of the availability of this line, origami has been successfully manufactured. The creation of a design with a distinct structure and aesthetics, such as the seven concepts that have been developed. Design origami allows engineers to use their creativity to come up with fresh design concepts. FDM has proved to be a successful solution for origami. As a result, origami will become more helpful and popular in the future in the industry. The Solidworks simulation can be used to better understand the stress and strain distribution in the origami designs under compression loads. It showed the maximum strain appearing in the structure while folding occur and along crease lines in the design origami. Depending on the fold angle and the design, the strain for these designs may be adjusted for specific engineering needs by changing the fold parameter.

5.2 Recommendation

Although the goals of the research have been accomplished, a lot can be done to make the best origami products. There are many suggestions for further enhancing work, such as:

a) Improvements could be made by experimenting with different materials as additives in 3D printed origami products and comparing them.
b) Research on origami's engineering applications, such as energy absorption.
c) Origami can be renewed by using various material thicknesses.
d) The effect of origami on medical and engineering fields is studied using a more complex structure in FDM.

5.3 Sustainability Element

Sustainability refers to meeting people's needs without risking future generations' ability to meet those needs. Sustainability is not only involved in the environmental element but also involved in social and economic elements. In AM, it shows the improvement in reducing the need for energy-intensive and resource-intensive manufacturing processes. It reduces the amount of material needed in the supply chain and more environmentally benign practices are enabled in AM. By reducing the type of material used in this project, it contributes to the sustainability of AM. The sustainability element of AM could be improved in this opportunity, such as waste minimization and cost savings on the product.

As with all plastics has a potentially negative environmental impact if not disposed of properly. It can take decades for microplastics to degrade, resulting in microplastics being released into the world's oceans. PETG material can give a sustainable environmental impact on the world because PETG is easily recyclable, hence these issues are no longer an issue.

5.4 Lifelong Learning Element

The learning process in terms of revolutionizing reused, reduced, and recycled waste material to offer eco-friendly material in AM is described in this project. The recycled PETG material can be used to make an origami product using 3D printing procedures. The ability of recycled materials to reduce the number of raw materials used in AM, such as new filaments and recycled waste plastic, benefits both AM and the environment. The origami structure in FDM can be commercialized by making origami for children to learn how to fold the structure. As a result, the child's brain can be trained to be more creative. Origami in FDM is tougher than paper origami due to the use of PETG material, which makes origami better than the previous.

5.5 Complexity

The complexity that has arisen in this project while designing origami, some people may believe that origami is a simple design. In reality, origami in FDM is not as simple as it sounds. When making origami, the thickness of the origami must be chosen carefully. The thickness of origami has been affected by the folding structure. Analysis and modifications to the fold structure are required to change the structure of the folding pattern. Furthermore, origami designs must be defined using the software so that they can fold properly. Repeated observations of design have been made. Every concept design has been done with the strain value as a reference. Every concept should be put to the test with a strain simulator. The complexity of the 3D printing process, such as inconsistency in printing temperature and nozzle clogging during the creation of the origami product.

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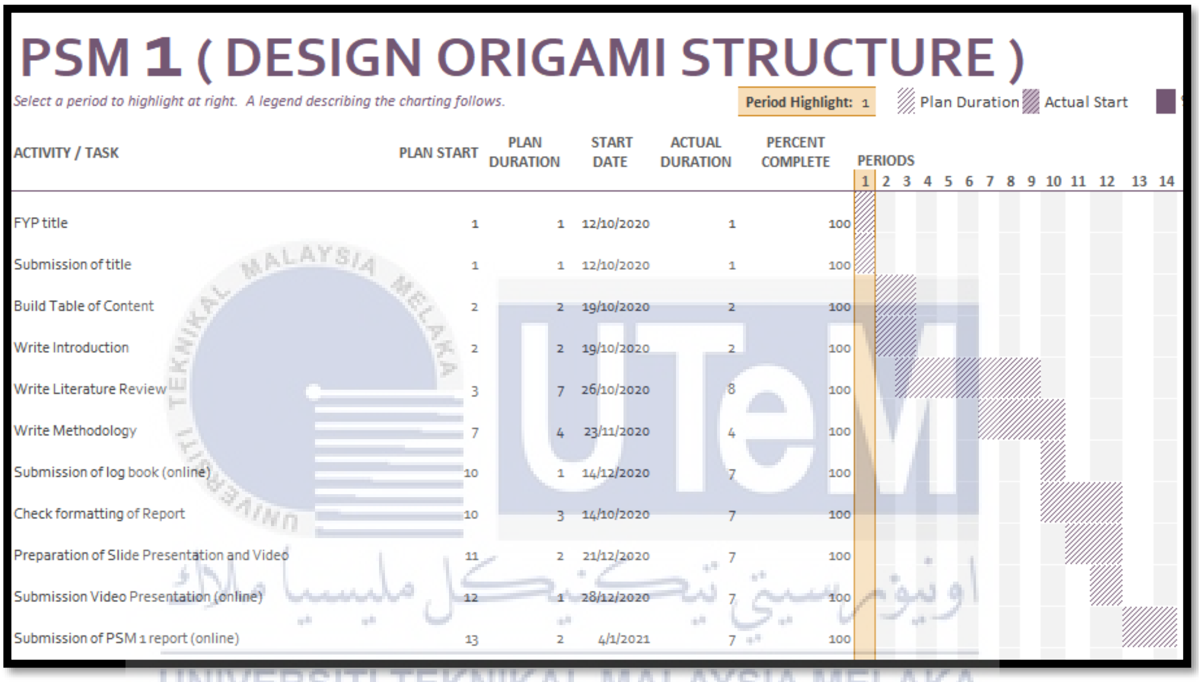
APPENDICES

Appendices A – Gantt Chart of Final Year Project 1 and 2

GANTT CHART OF PSM 1



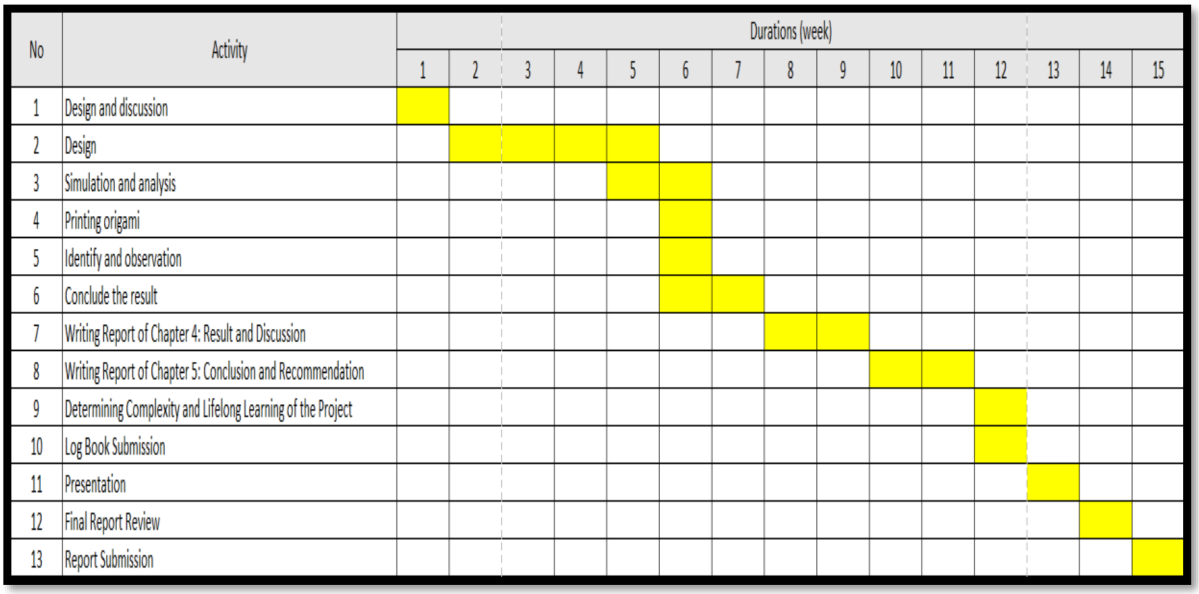
PSM 1 (DESIGN ORIGAMI STRUCTURE)

Select a period to highlight at right. A legend describing the charting follows.

Period Highlight: 1 ▨ Plan Duration ▨ Actual Start

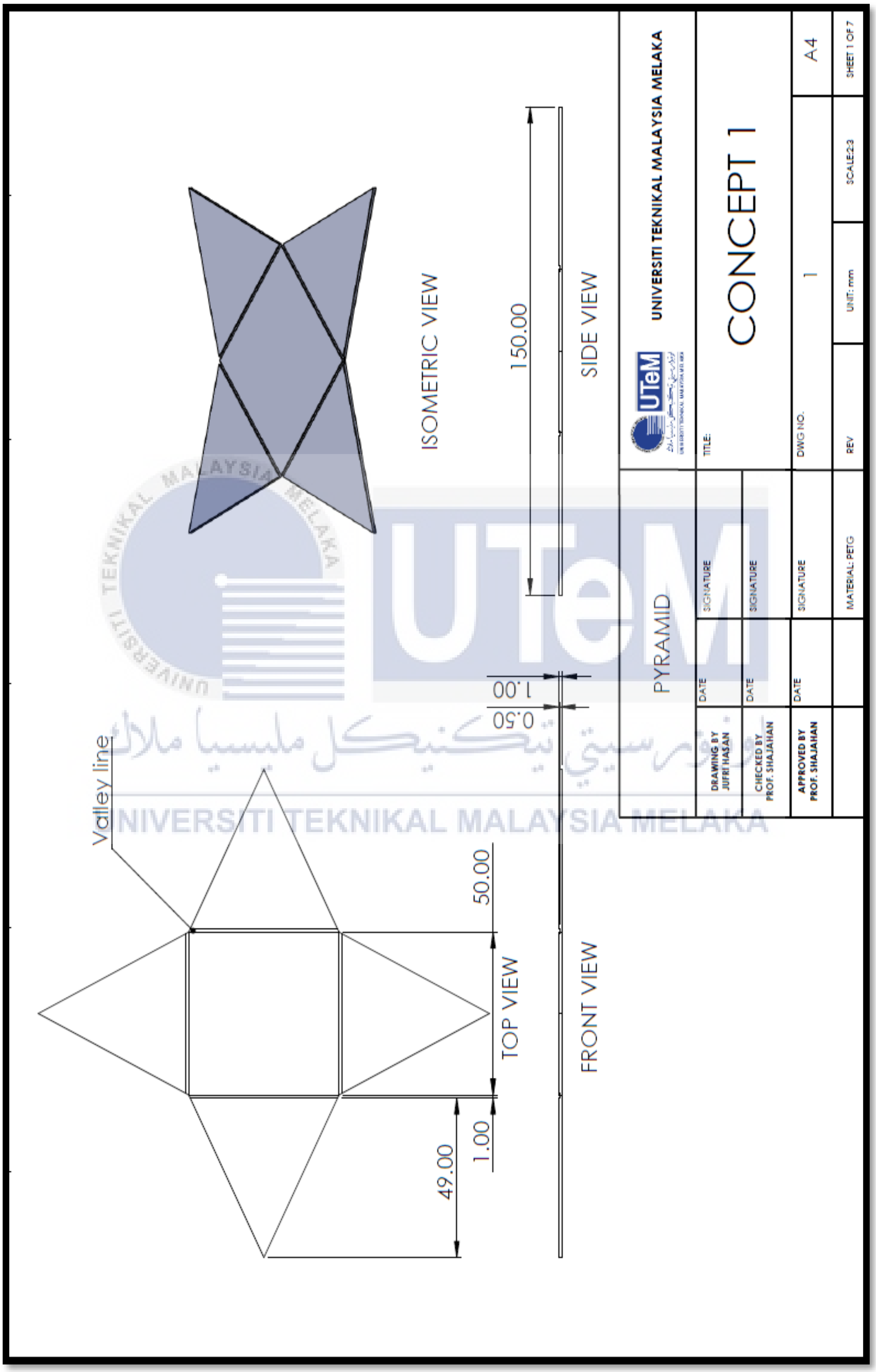
ACTIVITY / TASK	PLAN START	PLAN DURATION	START DATE	ACTUAL DURATION	PERCENT COMPLETE
FYP title	1	1	12/10/2020	1	100
Submission of title	1	1	12/10/2020	1	100
Build Table of Content	2	2	19/10/2020	2	100
Write Introduction	2	2	19/10/2020	2	100
Write Literature Review	3	7	26/10/2020	8	100
Write Methodology	7	4	23/11/2020	4	100
Submission of log book (online)	10	1	14/12/2020	7	100
Check formatting of Report	10	3	14/10/2020	7	100
Preparation of Slide Presentation and Video	11	2	21/12/2020	7	100
Submission Video Presentation (online)	12	1	28/12/2020	7	100
Submission of PSM 1 report (online)	13	2	4/1/2021	7	100

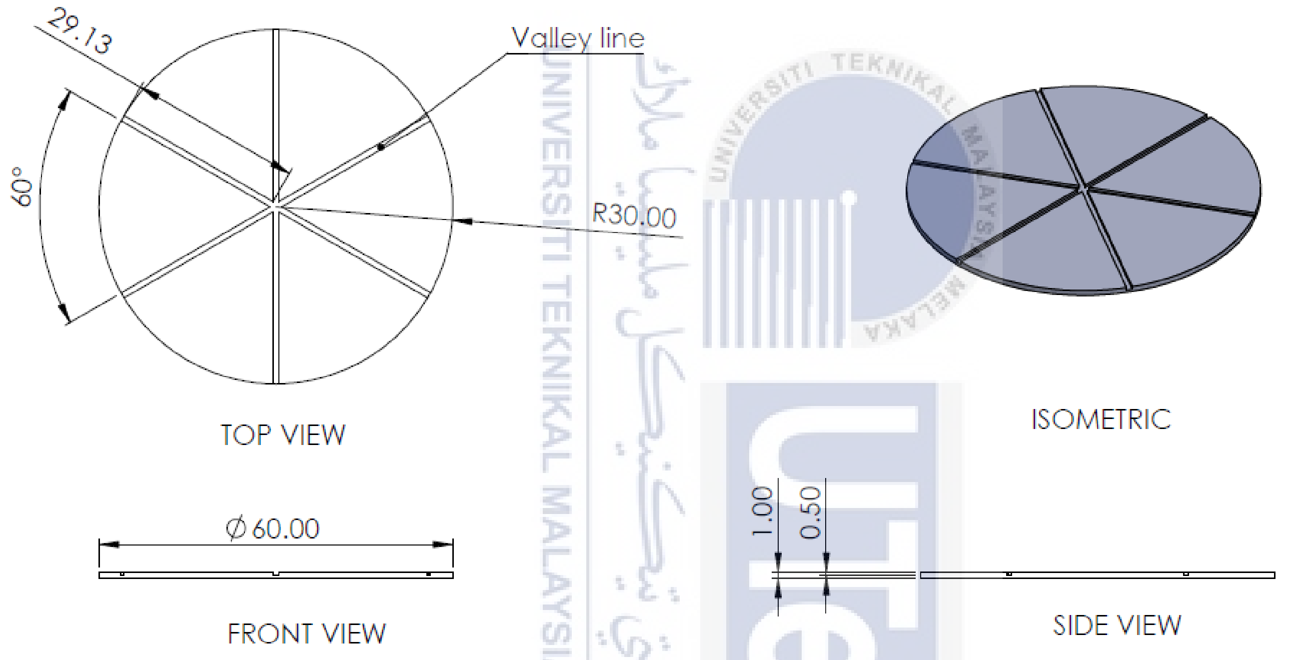
GANTT CHART OF PSM 2



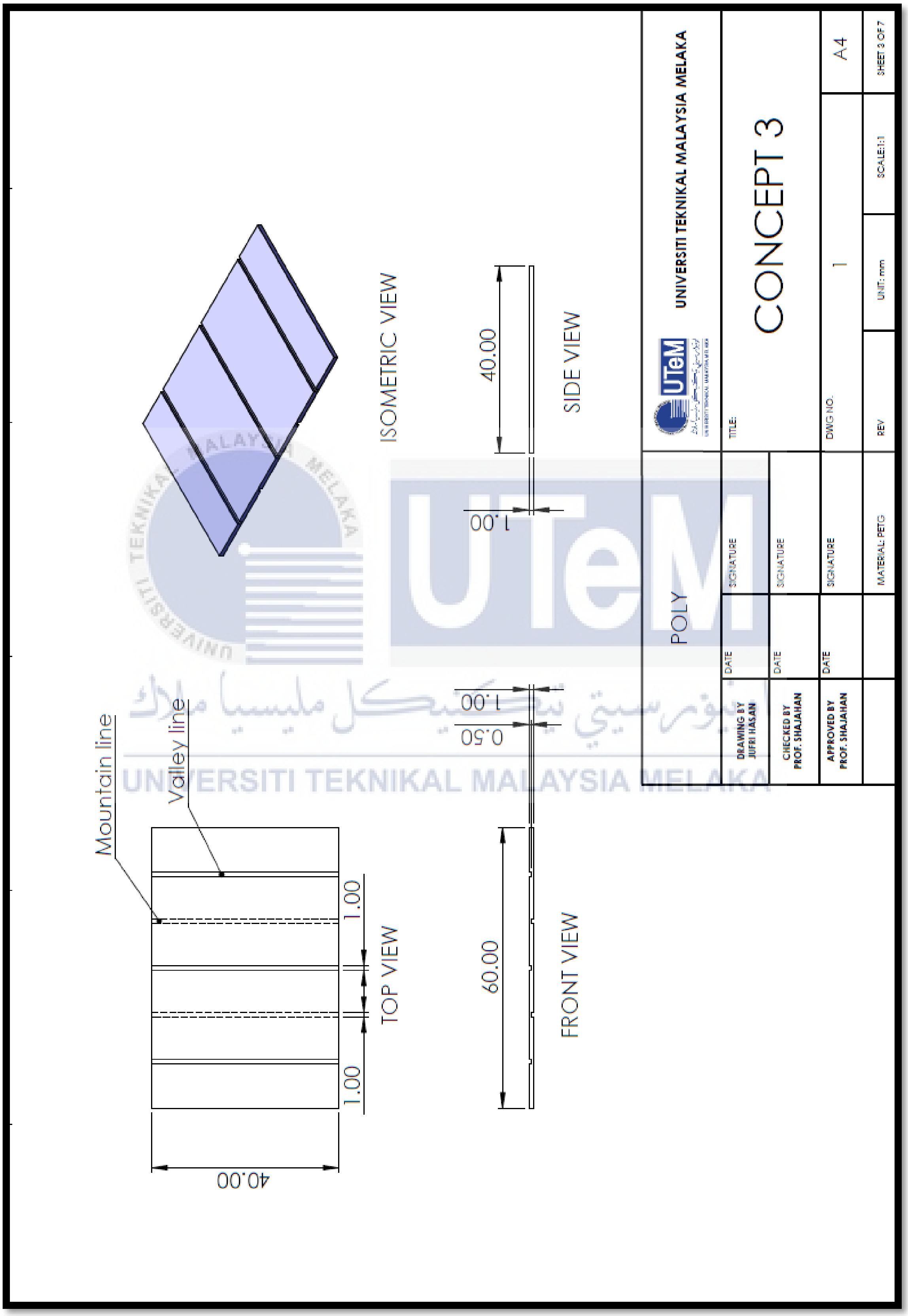
No	Activity	Durations (week)														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Design and discussion	🟨														
2	Design		🟨	🟨	🟨	🟨										
3	Simulation and analysis					🟨	🟨									
4	Printing origami						🟨									
5	Identify and observation						🟨									
6	Conclude the result						🟨	🟨								
7	Writing Report of Chapter 4: Result and Discussion								🟨	🟨						
8	Writing Report of Chapter 5: Conclusion and Recommendation										🟨	🟨				
9	Determining Complexity and Lifelong Learning of the Project												🟨			
10	Log Book Submission												🟨			
11	Presentation													🟨		
12	Final Report Review														🟨	
13	Report Submission															🟨

Appendices B – Origami Drawing

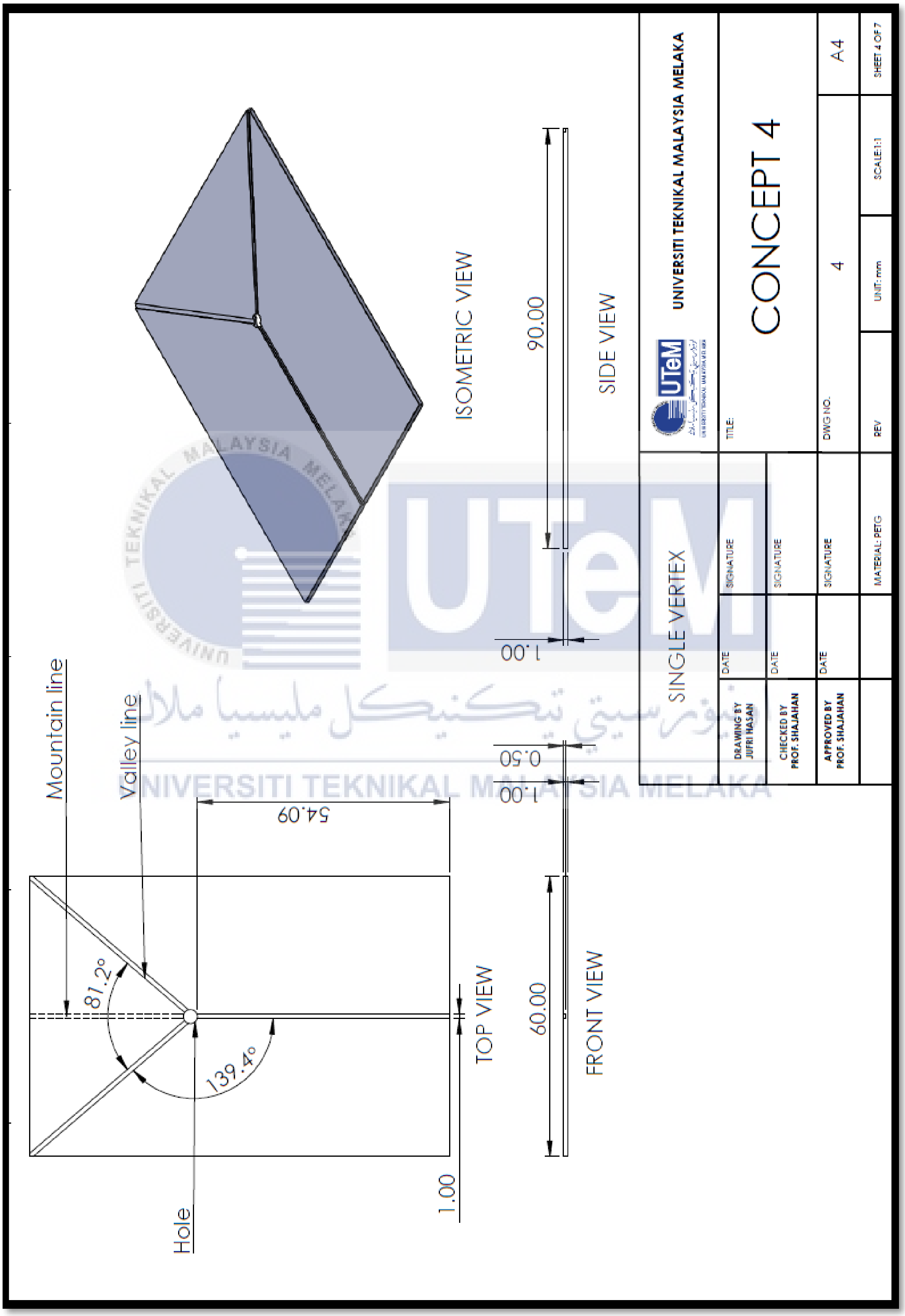


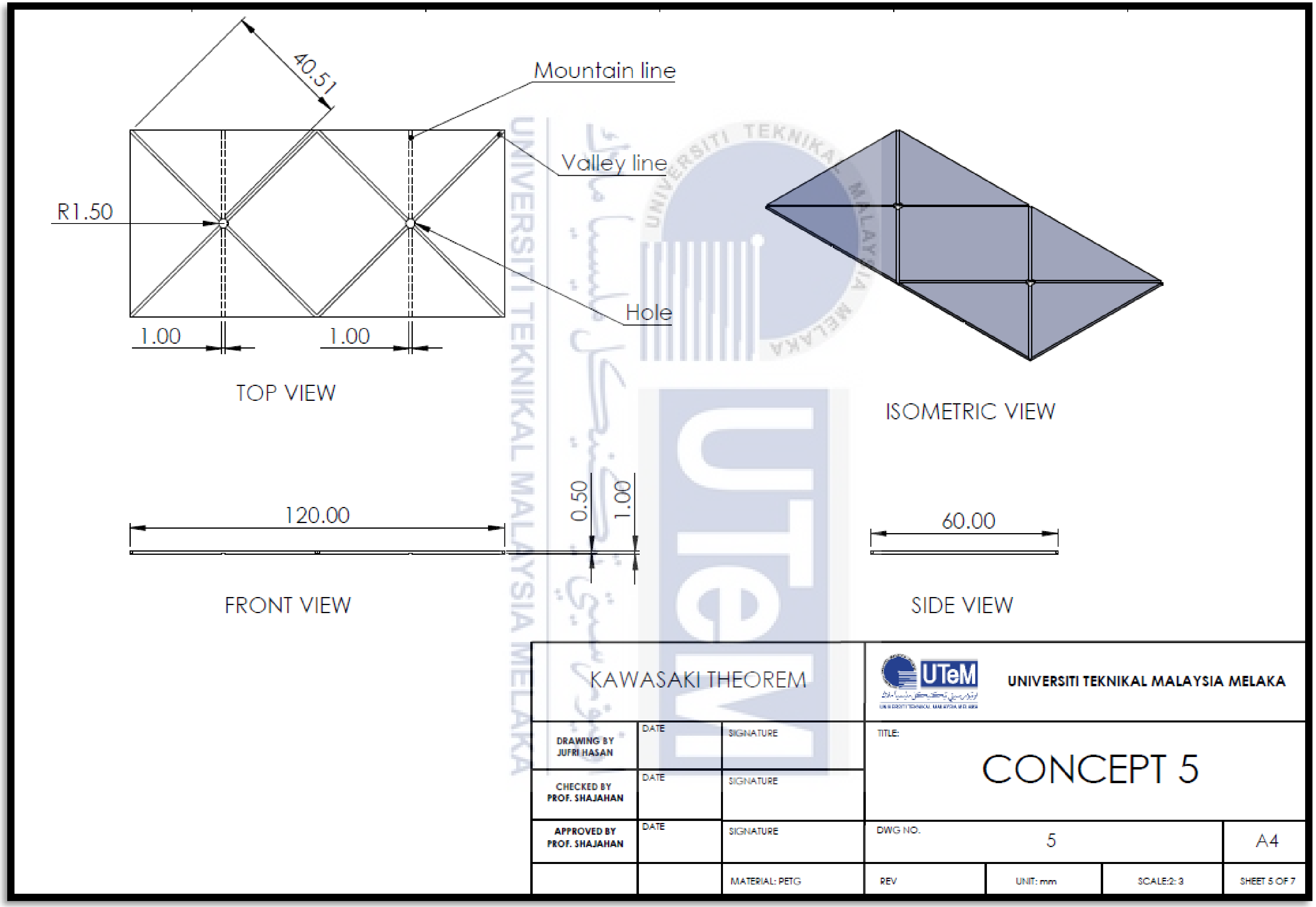


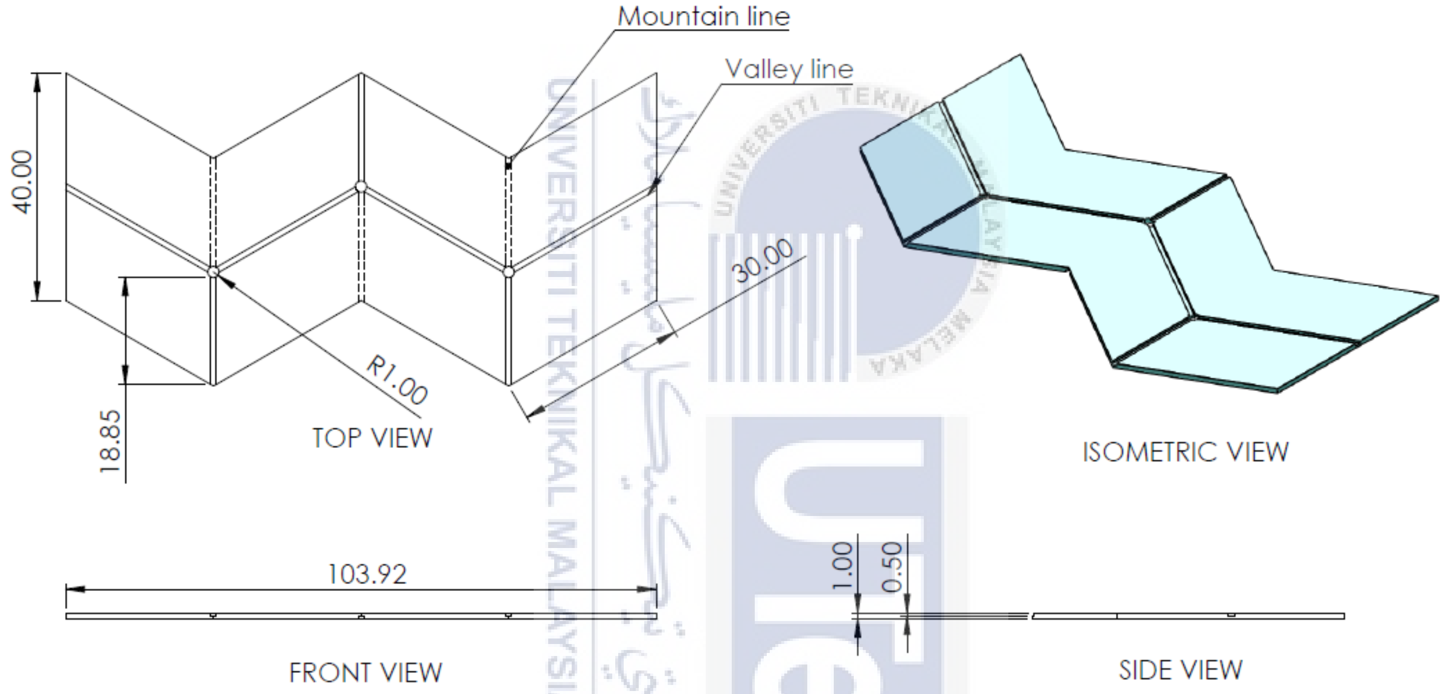
CIRCLE			UNIVERSITI TEKNIKAL MALAYSIA MELAKA			
DRAWING BY JUFRI HASAN	DATE	SIGNATURE	TITLE: CONCEPT 2			
CHECKED BY PROF. SHAJAHAN	DATE	SIGNATURE				
APPROVED BY PROF. SHAJAHAN	DATE	SIGNATURE	DWG NO.	2		A4
		MATERIAL: PETG	REV	UNIT: mm	SCALE:1:1	SHEET 2 OF 7



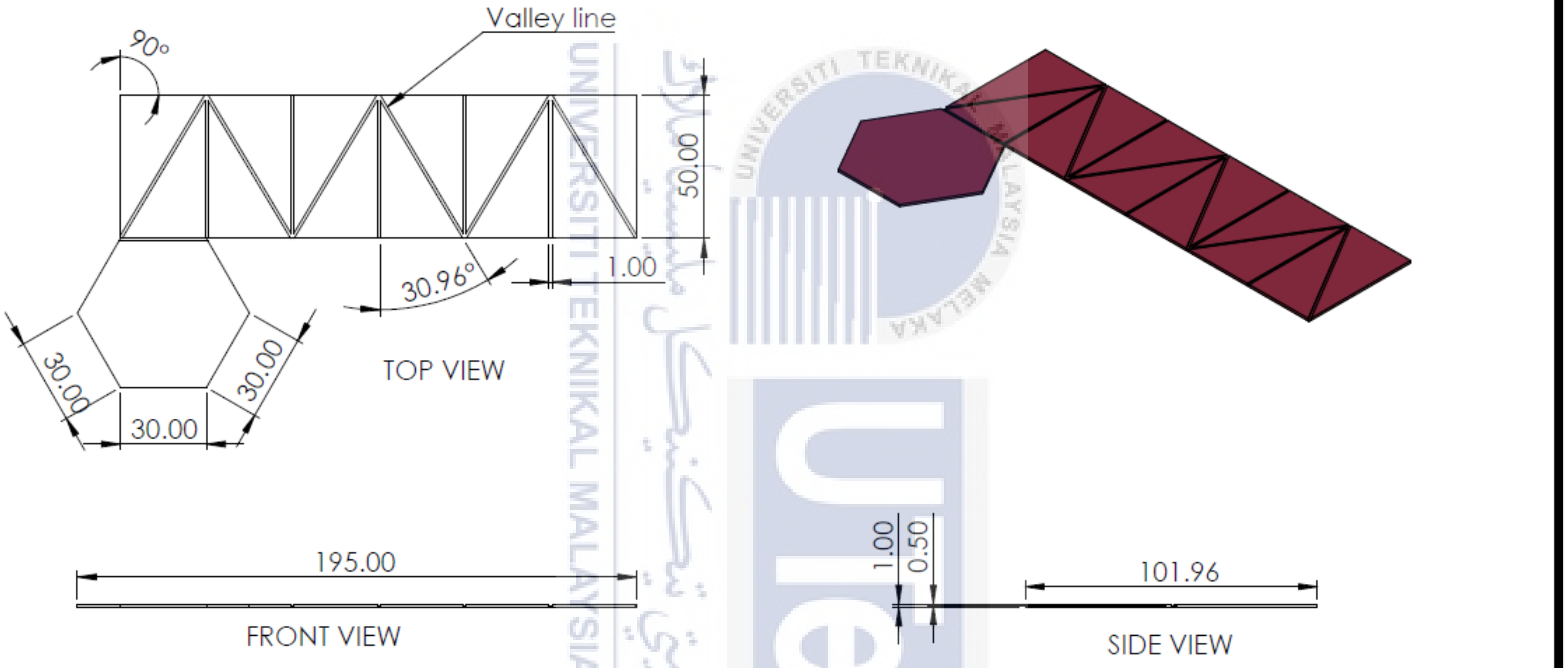
Mountain line
Valley line
40.00
1.00
1.00
TOP VIEW
60.00
FRONT VIEW
0.50
1.00
1.00
40.00
SIDE VIEW
ISOMETRIC VIEW
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
TITLE:
CONCEPT 3
DWG NO.
1
A4
REV
UNIT: mm
SCALE:1:1
SHEET 3 OF 7
POLY
DRAWING BY JUFRI HASAN
DATE
SIGNATURE
CHECKED BY PROF. SHAJAHAN
DATE
SIGNATURE
APPROVED BY PROF. SHAJAHAN
DATE
SIGNATURE
MATERIAL: PETG


Mountain line
Valley line
Hole
81.2°
139.4°
54.09
1.00
TOP VIEW
60.00
0.50
1.00
FRONT VIEW
1.00
90.00
SIDE VIEW
ISOMETRIC VIEW
SINGLE VERTEX
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
TITLE:
CONCEPT 4
DWG NO.
4
A4
REV
UNIT: mm
SCALE:1:1
SHEET 4 OF 7
DRAWING BY JUFRI HASAN
DATE
SIGNATURE
CHECKED BY PROF. SHAJAHAN
DATE
SIGNATURE
APPROVED BY PROF. SHAJAHAN
DATE
SIGNATURE
MATERIAL: PETG


40.51
Mountain line
Valley line
R1.50
Hole
1.00
1.00
TOP VIEW
ISOMETRIC VIEW
120.00
0.50
1.00
60.00
FRONT VIEW
SIDE VIEW
KAWASAKI THEOREM
UNIVERSITI TEKNIKAL MALAYSIA MELAKA
DRAWING BY JUFRI HASAN
DATE
SIGNATURE
CHECKED BY PROF. SHAJAHAN
DATE
SIGNATURE
APPROVED BY PROF. SHAJAHAN
DATE
SIGNATURE
MATERIAL: PETG
TITLE:
CONCEPT 5
DWG NO.
5
A4
REV
UNIT: mm
SCALE:2:3
SHEET 5 OF 7



SPRING			UNIVERSITI TEKNIKAL MALAYSIA MELAKA			
DRAWING BY **JUFRI HASAN**	DATE	SIGNATURE	TITLE: CONCEPT 6			
CHECKED BY **PROF. SHAJAHAN**	DATE	SIGNATURE				
APPROVED BY **PROF. SHAJAHAN**	DATE	SIGNATURE	DWG NO.	6		A4
		MATERIAL: PETG	REV	UNIT: mm	SCALE:1:1	SHEET 6 OF 7



ORIGAMI CHAIR			UNIVERSITI TEKNIKAL MALAYSIA MELAKA			
DRAWING BY JUFRI HASAN	DATE	SIGNATURE	TITLE: CONCEPT 7			
CHECKED BY PROF. SHAJAHAN	DATE	SIGNATURE				
APPROVED BY PROF. SHAJAHAN	DATE	SIGNATURE	DWG NO.	7		A4
		MATERIAL: PETG	REV	UNIT: mm	SCALE:1:2	SHEET 7 OF 7