INTEGRATION OF TOPOLOGY OPTIMIZATION AND DESIGN SELECTION FOR 3D PRINTING PRODUCT

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This report is submitted
in fulfillment of the requirement for the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2022

DECLARATION

I declare that this project report entitled “Integration Of Topology Optimization And Design Selection For 3d Printing Product” is the result of my own work except as cited in the references

Signature : ....

Name : ....

Date : ....

APPROVAL

I hereby declare that I have read this project report and in my opinion this report is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (Design & Innovation).

Signature : ....

Supervisor’s Name : ....

Date : ....

DEDICATION

To my beloved parents, siblings, and friends, all of whom I adore. Their support and inspiration have been a constant source of encouragement and motivation for me throughout my life.

ABSTRACT

Layer-by-layer material deposition techniques are used in additive manufacturing (AM) procedures in order to produce complicated shapes. Designers may express themselves more freely via the use of these procedures, which are well-known for producing intricate structures that would be impossible to make otherwise. It is possible to modify technical processes and redesign items thanks to the advancement of additive manufacturing. Design optimization via the integration of topology optimization techniques is one of the most often used approaches to assist additive manufacturing, and it allows for the creation of complicated forms. Using Topology Optimization (TO), this research offers a comparison of design processes for Fused Deposition Modelling (FDM) 3D printing and gravity die casting with the objective of decreasing the mass of a Steel Clevis Bracket while fully satisfying the design limitation. You may mount a cylinder or even an ordinary rod on any flat surface with this bracket. It is specifically designed for 3D printing and uses a limited topology optimization method for component development. With the help of a simulation, the advantages of the proposed FDM 3D printing design framework are shown and confirmed. The simulation shows a 14% increase in factor of safety and a 39% decrease in the bracket's weight. The reduction in production time and cost are among the other benefits discovered. Traditional manufacturing has many design restrictions that FDM 3D printing overcomes.

ABSTRAK

Teknik pemendapan bahan lapisan demi lapisan digunakan dalam prosedur pembuatan tambahan (AM) untuk menghasilkan bentuk yang rumit. Pereka bentuk boleh mengekspresikan diri mereka dengan lebih bebas melalui penggunaan prosedur ini, yang terkenal kerana menghasilkan struktur rumit yang mustahil untuk dibuat sebaliknya. Ia adalah mungkin untuk mengubah suai proses teknikal dan mereka bentuk semula butiran atas sebab kemajuan pembuatan tambahan. Pengoptimuman reka bentuk melalui penyepaduan teknik pengoptimuman topologi adalah salah satu pendekatan yang paling kerap digunakan untuk membantu pembuatan bahan tambahan, dan ia membolehkan penciptaan bentuk yang rumit. Menggunakan Pengoptimuman Topologi (TO), penyelidikan ini menawarkan perbandingan proses reka bentuk untuk cetakan 3D Pemodelan Pemendapan Terlakur (FDM) dan penuangan beracuan dengan objektif untuk mengurangkan jisim Pendakap Clevis Keluli sambil memenuhi had reka bentuk sepenuhnya. Anda boleh memasang silinder atau rod biasa pada mana-mana permukaan rata dengan pendakap ini. Ia direka khusus untuk pencetakan 3D dan menggunakan kaedah pengoptimuman topologi terhad untuk pembangunan komponen. Dengan bantuan simulasi, kelebihan rangka kerja reka bentuk pencetakan 3D FDM yang dicadangkan ditunjukkan dan disahkan. Simulasi menunjukkan peningkatan 14% dalam faktor keselamatan dan penurunan 39% dalam berat pendakap. Pengurangan dalam masa dan kos pengeluaran adalah antara faedah lain yang ditemui. Pembuatan tradisional mempunyai banyak halangan reka bentuk yang diatasi oleh percetakan 3D FDM.

ACKNOWLEDGEMENT

First and foremost, I would like to take this opportunity to express my sincere acknowledgement to my supervisor Dr. Faiz Redza Bin Ramli from the Faculty of Mechanical Engineering Universiti Teknikal Malaysia Melaka (UTeM) for his essential supervision, support and encouragement towards the completion of this project report. He never hesitated to give me advice and guidance whenever I confronted problems. I am thankful for his patience and advice while leading me in this project.

Special thanks to UTeM short term grant funding for the financial support throughout this project. Particularly, I would also like to express my deepest gratitude to all my peers, my beloved mother, father and siblings for their moral support in completing this degree. Lastly, thank you to everyone who had been to the crucial parts of realization of this project.

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LIST OF ABBEREVATIONS

3DSP	3D Sand Printing
AM	Additive Manufacturing
CAD	Computer Aided Design
TO	Topology Optimization
FEA	Finite Element Analysis
UTS	Ultimate Tensile Strength
SIMP	Solid Isotropic Penalty Material
DED	Directed Energy Deposition
ASTM	American Society for Testing and Materials
LENS	Laser Engineered Net Shaping
UV	Ultraviolet
EBM	Electron Beam Melting
SLS	Selective Laser Sintering
SHS	Selective Heat Sintering
LOM	Laminated Object Manufacturing
UAM	Ultrasonic Additive Manufacturing
SLA	Stereolithography
DLP	Digital Light Process
FDM	Fused Deposition Modelling
UTM	Universal Testing Machine

LIST OF SYMBOLS

F = External load

K = Stiffness matrix

u = Displacement of F

ρ_e = Pseudo-density of e

v_e = Volume of e

e = Element

V = Maximum allowed design volume

CHAPTER 1

INTRODUCTION

1.1 Background

3D sand-printing (3DSP) is a technique for creating physical items from a geometrical abstraction by adding layers of material one at a time. This 3D method has seen tremendous growth in recent years, with many people claiming it to be the most advanced in the world. Charles Hull was the first to commercialize 3D printing technologies, which occurred in the year 1980 (Shahrubudin et al., 2019). In contrast to conventional manufacturing methods such as subtractive, formative, and joining procedures, 3DSP or additive manufacturing (AM) fabricate a component layer by layer from a 3D model of the target component. Vat polymerization, sheet lamination, material extrusion, material jetting, binder jetting, powder bed fusion, and direct energy deposition are several additive manufacturing techniques (Wang et al., 2019).

Complex components, such as high-performance parts or highly customized and specialized parts, may be created utilizing additive manufacturing technology. It is now feasible to create components for practically any application or in virtually any shape or size. It is feasible to produce batches of unique components since component complexity and geometrical characteristics have little impact on product cost and manufacturing time. The ability to create prototypes and end-use components in a timely way is now possible because of the direct link between a computer-aided design (CAD) model and a produced component (Dalpadulo et al., 2020).

The outcome has been the replacement of various breakthroughs by additive manufacturing, despite the fact that this requires a full redesign of both the product and the manufacturing process. In the past, other technological advancements have impacted the manufacturing of parts and components as well. During the 2000s, for example, metal substitution or metal to plastic replacement became one of the most significant industry trends, impacting a broad variety of sectors and continuing to this day. In a similar vein, although more recently, AM technologies have played a similar role. The primary goal of these developments is to develop components that are lighter and more cost-effective to manufacture. AM will also benefit from its connection with topology optimization (TO), which may result in complicated morphologies and free form models, in addition to an increase in product customization.

To maximize the performance of the geometry, topology optimization (TO) is used. It is an optimization method that repeatedly determines the optimum arrangement of material in a component within a design space for a given combination of loads, boundary conditions, and restrictions. Many studies have emphasized TO's capacity to construct buildings that are both lightweight and structurally optimized. When it comes to the manufacturing of optimum design structures, it has been shown that AM makes full use of the advantages of TO, which are methods that have been used in traditional sand casting to redesign cast components and riser designs to improve yield and quality.

Traditional sand casting in metal castings provides only a limited amount of design flexibility due to the process's inherent design and production constraints. The rules for casting quality control and the regulations for mould-making are the two significant kinds of component construction regulations that must be followed in conventional sand casting. They are as follows: rules for casting quality control and regulations for mould-making. For quality control purposes, casting rules refer to those that govern filling, solidification, and distortion, such as minimum wall thickness, uniform sections, fillets, intersections, and axial solidification. On the other hand, Mould-making rules relate to component design restrictions that must be fulfilled for mould manufacturing to be successful before metal pouring. Examples include having consistent and plane parting lines, draught along the walls, and avoiding characteristics like as undercuts to remove a design from moulding sand without harming it successfully. The need to devote significant time and money to pattern and core box tooling and the storage and ultimate wear of component features resulting from this wear is an essential issue in the sand-casting manufacturing process.

On the other hand, three-dimensional solidification (3DSP) offers foundries a cost-effective and time-efficient method of producing moulds and cores for highly intricate. Also, specialized low-volume castings that would otherwise be prohibitively expensive to produce using traditional sand-casting methods.

1.2 Problem Statement

In general, a bracket is a tool used to secure a cylinder or a simple rod to a surface. The cylinder or the plain rod is often used to secure a large amount of weight. This is why the bracket is constructed of heavy-duty materials such as steel or iron, which allows it to bear a significant amount of weight. There are many different sorts of brackets, and each of those brackets is specifically designed to complement the architecture of a system while also providing the same function. The design of a Steel Clevis Bracket manufactured by a firm known as Parker Hannifin Corporation is chosen as the topic of this research project. It can be noticed that the design of this bracket has a solid flat surface and that there hasn't been any optimization done in the process. The Steel Clevis Bracket's mass may be lowered by using TO, and at the same time, its form will be altered while the size and qualities of the bracket remain same.

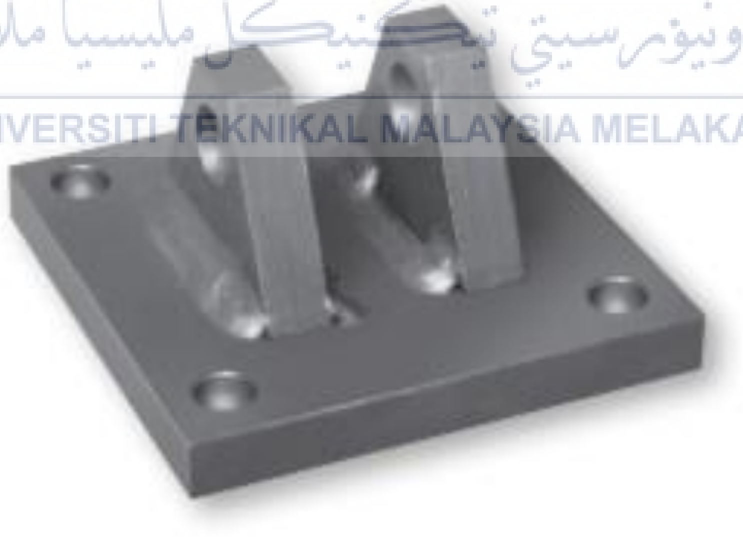


Figure 1.1: Steel Clevis Bracket

1.3 Objectives

The objectives of this project are as follows:

1. To reduce the mass of the steel clevis bracket without compromising the other relevant factors by using topology optimization tools in Solid Thinking Inspire.
2. To compare between traditional casting and 3D Printing process in term of material, cost and time.

1.4 Scope of Project

The scopes of this project are:

1. Comparison between conventional and AM method for the clevis bracket are studied in this report.
2. Topology optimization of the bracket is simulated through a software, SolidThinking Inspire.
3. Simulation of conventional and AM process using Inspire and Ultimaker Cura software.
4. Produce the component by utilizing the AM process available.

CHAPTER 2

LITERATURE REVIEW

2.1 Alcoa Aircraft Bracket Case Study

In this case study, a desired metal part for a basic mechanical loading application was created using a 3D-printed sand mould, and the component was cast using the mould. Design guidelines that had been devised for 3DSP, as well as casting limitations, were put into practice. Mechanical testing was carried out on the finished part to ensure that the design framework had been thoroughly validated. Four high-strength bolts secure this bracket to the control surface, which makes it a popular component on control surfaces, as in Figure 2.1.

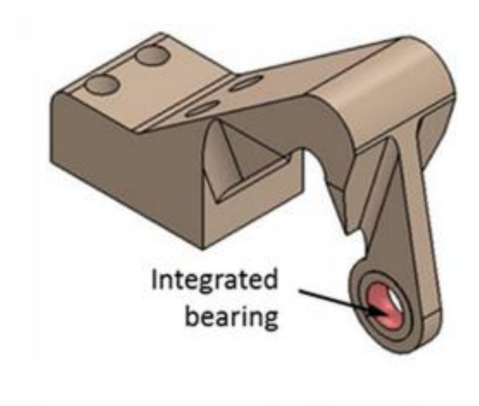


Figure 2.1(a): Alcoa bracket

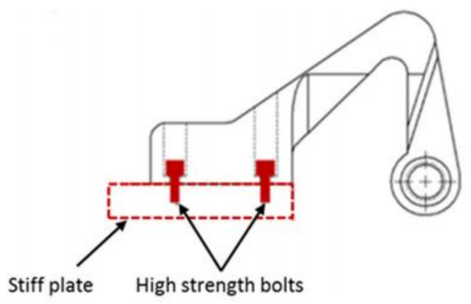


Figure 2.1(b): FBD of Alcoa boundary conditions

Topology optimization was carried out in Abaqus CAE 6.14, which is a topological optimization software package, using the Abaqus Topology Optimization Module as the primary tool (ATOM). ATOM is a SIMULIA TOSCA-based tool that integrates structural optimization with Abaqus finite element analysis. In Abaqus CAE, the desired bearing bracket was imported as a STEP file, and it was then modified. It was necessary to add four bolts and the area that interacted with the bearing in this example to be considered non-design space (Ntintakis et al., 2020). The design space was defined as the portion of the bracket that was not used. The stiff spherical bearing was excluded from the assembly in order to make the TO setup more straightforward. Instead, a kinetic coupling interaction was introduced between the surface supporting the bearing and the spherical centre of the bearing to imitate the movement of the bracket when a load is applied to it. This interaction might retain the geometry of the surface while forcing the surface to move in the same direction as its centre, allowing loads to be delivered directly to the centre of the surface.

Figure 2.2(a): Original loading conditions

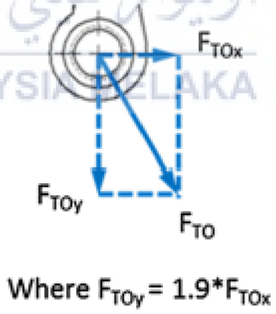


Figure 2.2(b): Assumed loading condition

The bracket was tested under three different load situations in the original Alcoa challenge, as in Figure 2.2(a). Meanwhile, Figure 2.2(b) shows an example of how the authors assumed that the bracket was only subjected to one load F_{TO} for the sake of this case study. A value for F_{TO} was computed so that the goal bracket has a safety factor of one to make it easier to compare the performance of the bracket before and after topology improvement. The permanent bounds were the non-design area, which was marked by the presence of four bolts. However, it should be emphasized that in this research, class 30 grey cast iron metal is employed instead of the original stainless steel 15-5PH metal that was recommended in the design competition (Hu et al., 2020). This is due to the melting restrictions imposed by the furnace to which the authors have access, which makes it impossible for them to melt all of their materials. The authors' principal goal, which seems to demonstrate that complicated topology-optimized structures may be cast quickly and efficiently without sacrificing their mechanical qualities, would not be affected by this adjustment. The Alcoa Bracket was selected not because it standardized qualities but rather because of its recognition in the structural optimization business, and therefore casting this difficult part will indeed effectively demonstrate the capacity of the AM process. Because Class 30 grey cast iron seems to have very low ductility, mechanical characteristics were specified in Abaqus CAE using both the elasticity and cast-iron plasticity models. 57 Material data, such as density, Young's modulus, Poisson's ratio, and hardening curves under tension and compression, were uploaded into Abaqus using a spreadsheet programme.

To decrease the volume of the bracket by 60 percent, TO was conducted on the bracket. The resultant design was saved as an STL file, imported. SolidThinking Inspire 2016 and SolidWorks 2016 were used to enhance and revise the final product. The PolyNURBS tool in Inspire was used to produce a solid body from the extracted mesh. The solid-body was based on the extracted mesh. PolyNURBS is a robust approach for generating smooth freeform solid bodies from meshes that is easy to learn and use. Part design changes were carried out over this solid object and use the same tool and redesign guidelines which included undercut, draught, uniform section, rounded edges, wall-to-wall thickness, and hole size, among others, as in Figure 2.3.

Figure 2.3: Rechecking on design guidelines

The designs must be adjusted for three elements throughout the review process, which are component requirements, sand-casting regulations, and 3DSP limitations as in Table 2.1.

Table 2.1: Design rules

Part requirements	**Part Rationale:** The output design from the TO of the casting should be a single closed volume part geometry, as shown in the illustration. For example, the TO function merely affects the design space. However, it is rather typical to create an outcome design with the material in the design space and the non-design space isolated from the design space itself. In such circumstances, the designer must manually make connections to create a single, utterly contained component shape.
	Geometric Requirements: In terms of part geometry, the redesigned design should satisfy all previously stated criteria, such as volume reduction, a maximum number of holes, and minimum, maximum thickness for all or recognised parts within the component volume.

	Aesthetics: Criteria for aesthetics such as symmetry, surface polish, fit and other aesthetic considerations.
Sand-casting rules	**Undercuts:** Undercuts are often found to be avoided in conventional sand cast pieces, which is a good thing. Despite the fact that packing cores may be used to create undercuts, the expense of doing so is much higher, and the chance of failure rises as a result of probable core displacement.
	Draft: The demands for drafting in traditional sand casting of metal components do not contribute to the component's behaviour in any way. However, there is an increase in cost, time, and process planning requirements because of the secondary machining and assembly tolerances. In addition, due to variations in component walls and geometry, a trade-off with uniformity of wall thickness is necessary to achieve the desired results.
	Datum: Casting datum characteristics, such as pilot holes for drilling, are critical for the ease with which pre-processing setting can be accomplished and the precision with which machining can be performed. However, because they are undercuts, data cannot be put on walls according to conventional wisdom. 3DSP, on the other hand, has the benefit of casting metal objects with datum characteristics on any surface, regardless of the material used.
	Uniform Section: The equality of section thickness in sand castings is determined by various variables, including the part requirements, the complexity of the part design, the manufacturability of the part, the casting rules, undercuts, and draught allowances. It is necessary to make the heavy C-section of this bracket much thicker than its base since casting the near-net form directly will need the insertion of cores, which will raise the cost of complex tooling. It is also necessary to instal a riser to compensate for shrinkage porosity, which lowers the total yield and may create possible heat transfer concerns.
	Rounded Edges: In castings, rounded edges or fillets are essential to minimise the formation of hot spots, rips, and stress concentrations. Additions of fillets to typical castings, on the other hand, would significantly increase the design complexity, mainly when cores are used in the casting process. For example, in classical casting, the edges along cores are often not rounded since doing so would result in more complicated designs for core extension.

	Intersections: When numerous segments overlap at one site, the most frequent technique for avoiding hot spots is to core the heaviest junction with a central hole, which is the most frequent technique. Nevertheless, it is sometimes difficult to successfully implement this criterion because of the need for an additional core in traditional sand-casting design.
3DSP constraints	**Build Volume:** 3DSP systems are often equipped with limited construction chambers, limiting the maximum capacity of printed moulds and cores to a certain extent. In the event of big castings, if the size of a component of the mould exceeds the machine's build volume, the portion may be partitioned into two or more mould parts, each of which is printed separately and then combined once it has been produced.
	Minimum Feature Size: A minor feature, such as a wall that can be correctly 3D-printed and durable during the casting process, is known as the minimum feature size. The thickness of the cast component from wall to wall and the number of holes in the component must be equal to or greater than the minimum feature size of the 3DSP system. As a result of their fragility during cleaning, handling, and pouring, high aspect ratios and thin wall sections without ribs or support should be avoided wherever possible.

Compared to PolyNURBS, the SolidThinking Inspire version employed in this research featured fewer characteristics that could be utilised to effectively produce crisp and precise features that could be combined with the solid body created by PolyNURBS. The solid model was saved as a STEP file and then transferred into SolidWorks when the modification was completed. Loft, smooth surfaces, precise cuts, and fillets were all incorporated to complete the layout of the space (Wu et al., 2016). By running FEA simulations in Abaqus CAE, the mechanical performance of the optimised geometry was assessed and compared to the desired model. When comparing the optimised design to the target design using finite element analysis, the optimised design demonstrated a 30 percent increase in the safety factor while reducing product volume by 50%. Table 2.2 presents a summary of the findings of the design and simulation phases.

Table 2.2: Comparison of the performance of the target and the optimized designs

	Original design	Optimized design
Safety factor (FEA)	1.0	1.3 (30% improvement)
Volume (CAD)/mm^3	110,613	53,913 (51% reduction)
Weight (actual)/g	786	390 (50% reduction)

Mechanical testing was carried out using MTS hydraulic load-controlled tensile testing machine. In order to keep the grey cast iron bracket in place between the tensile grips, a pair of fittings had to be devised and built. The bracket's base was fixed to one fixture with four bolts, and the bracket's front was pin linked to the other fixture using a pin. In addition, finite element analysis (FEA) was used to anticipate the failure of the bracket beneath mechanical testing circumstances and contrast it to the results of the physical testing. In Figure 2.4, it can be seen that the failure position predicted by the FEA is accurate.

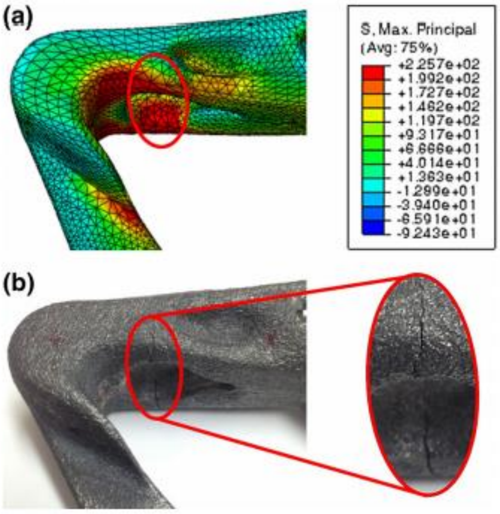
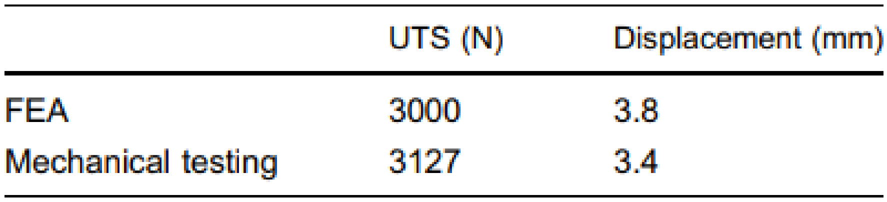


Figure 2.4: The failure location of the bracket in (a) FEA simulation and (b) the mechanical testing

Table 2.3: Comparison of the UTS and Displacement Between the FEA and Mechanical Testing Results



	UTS (N)	Displacement (mm)
FEA	3000	3.8
Mechanical testing	3127	3.4

Furthermore, according to Table 2.3, the results of the FEA and the mechanical testing were determined to be a good match in terms of ultimate tensile strength (UTS) and displacement of the bracket. In conclusion, the FEA findings produced were credible, and the design criteria used in this case study were shown to be effective. Geometric design guidelines used in traditional mold-making are rigorously examined, and they are modified to make use of the potential presented by 3D sand-printing technology. This research study illustrates the capacity of 3DSP to adapt to casting specifications and demonstrates benefits over traditional mold-making techniques in terms of cost and time savings.

2.2 Topology Optimization

To optimize the material distribution pattern in an installation area, topology optimization is a mathematical technique that is used to determine the lowest material distribution pattern under specified load circumstances. For more than two decades, academics have been delving extensively into the area of topology optimization to understand it better. Bendsoe and Kikuchi (Martin Philip Bendsoe & Noboru Kikuchi, 1988) provide a seminal article in the field, while Sigmund and Bendsoe (Gersborg-Hansen et al., 2006) provide a complete explanation of the process. Researchers have attempted to integrate manufacturability restrictions into the topology optimization problem on a number of occasions in the past. TO is based on the finite element technique

(FEM), which involves discretizing the design space into finite elements. In addition to its remarkable accuracy, TO has the added benefit of assessing the optimization outcomes after each iteration via the use of finite element analysis (FEA). The following is an example of the design difficulty of a common TO task:

$$\begin{aligned} &\text{min} && f = F^T u \\ &\text{Subject to:} && Ku = F \\ & && \sum \rho_e v_e \leq V \end{aligned} \tag{2.1}$$

where F denotes an external load, K denotes the stiffness matrix and u denotes the displacements caused by F, ρ_e and v_e represent the pseudo-density and volume of element e, respectively, and V is the maximum allowed design volume. There have been many optimization techniques created in order to address design issues. These include techniques based on density, level, topology derivation, phase field, evolution, and many more. As a result of its simplicity and efficiency, a density-based technique known as Solid Isotropic Penalty Material (SIMP) has emerged as one of the most frequently used TO algorithms.

2.3 Additive Manufacturing Process

Additive manufacturing (AM), often known as 3D printing, has sparked our creative mind and given rise to the bizarre idea of bioprinting aircraft and organs, among other things. Even though this access to tremendous speciality promises future development and has already had a significant effect on our immediate surroundings, these ideas are still a long way from being fulfilled to their full potential. However short-term or long-term the result, management authorities will unavoidably alter the way they do their business.

Objects are produced in layers via the use of 3D printing, which is a manufacturing technique. An individual layer is carved out of a digital 3D model made using computer-aided design software (CAD) or 3D scanning, and a path code is generated for use by a 3D printer. The machine follows a predetermined procedure following the particular technology and recreates the model in the physical world from its foundation to its tip until the item is finished.

It is possible to use the AM system to execute seven distinct kinds of 3D printing techniques. These include binder jetting, directed energy deposition (DED), material extrusion, powder bed fusion, sheet lamination, and vat photopolymerization.

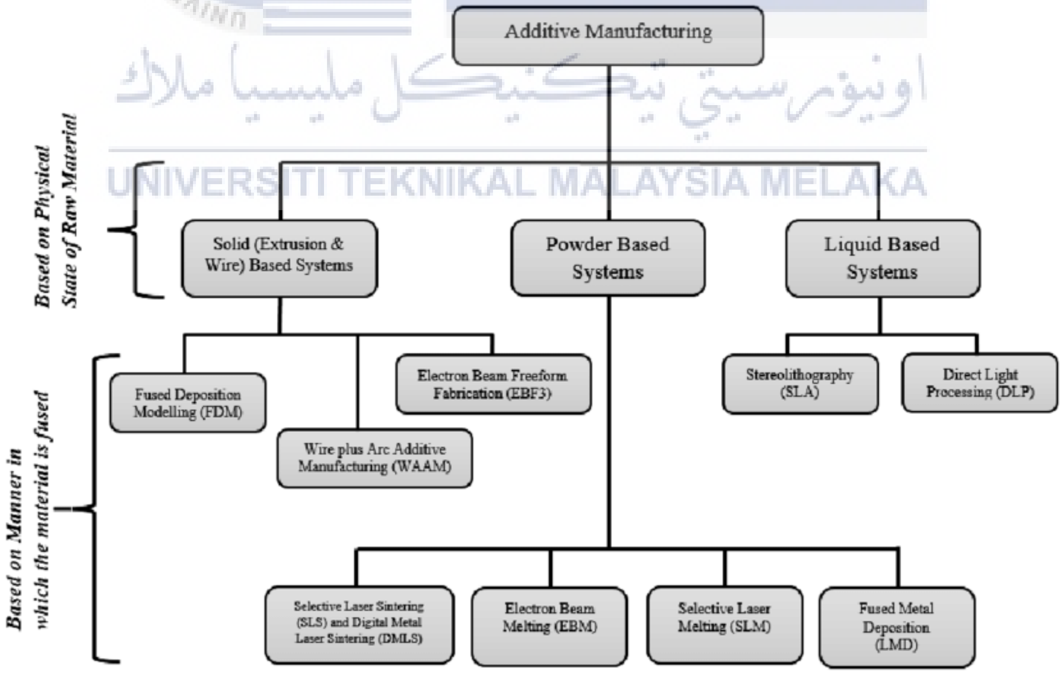


Figure 2.5: Classification of AM Process

2.4 Additive Manufacturing Technology

Several different 3D printing technologies have been created, each with a unique set of capabilities. The American Society for Testing and Materials (ASTM) classified 3D printing technologies into seven categories: binding jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization, according to ASTM Standard F2792. There are no arguments over whether equipment or technology performs better than the other since each has a specific purpose for which it is designed (Ferro et al., 2016). Nowadays, 3D printing technologies are no longer restricted to prototyping but are rapidly being utilized to produce a wide range of goods.

2.4.1 Binder jetting

Rapid prototyping and 3D printing with binder jetting is a technique in which a liquid binding agent is applied to powder particles in a targeted manner to connect them. Binder jetting technique forms a layer by spraying a chemical binder over a dispersed powder surface. Producing casting patterns, raw sintered goods, or similar large-volume goods from the sand would explain how binder jetting might be used. Binder jetting can print a wide range of materials, comprising metals, minerals, polymers, hybrid materials, and ceramics. Several substances, such as sand, may not require any further processing. Furthermore, since the powder particles are bonded together, the binder jetting process is simple, quick, and inexpensive. Finally, binder jetting has the capability of printing massive objects (Weiss, 2018).

2.4.2 Directed energy deposition

A more sophisticated printing technique, directed energy deposition (DED), is frequently used to repair or add extra material to existing components. Directed energy deposition has a great degree of control over the grain structure and may create objects of excellent quality due to the fine-grain control. The technique of directed energy deposition is closely related to material extrusion, except that the nozzle is not locked to a particular axis and may travel in any direction. More importantly, although the technique may be utilized with ceramics and polymers, it is most often associated with metals and metal-based hybrids, usually produced as wire or powder. Laser deposition and laser engineered net shaping are two examples of this kind of technological advancement (LENS). Laser deposition is a new technique used to manufacture or fix components with dimensions ranging from a few millimetres to several metres. Laser deposition technology has received popularity in various industries, including tooling, transportation, aircraft, and oil and gas. It can offer scalability and a wide range of capabilities in a single system. Meanwhile, laser LENS may use heat energy to melt during the casting process, and components are produced due to the process (Spanoudakis et al., 2020).

2.4.3 Materials jetting

According to ASTM Standards, material jetting is a 3D printing method in which drop by drop of build material is selectively deposited on a build surface in layers. Material jetting is a process in which a printer distributes droplets of a photosensitive material that hardens when exposed to ultraviolet (UV) light, resulting in the construction of a component layer by layer. The process of material jetting, on the other hand, produces components with a very smooth surface finish and excellent dimensional precision. Multiple materials may be printed simultaneously, and a diverse variety of materials, including polymers, ceramics, composite materials (including biologicals), and hybrid materials, are accessible for material jetting (Tyflopoulos et al., 2021).

2.4.4 Powder bed fusion

The powder bed fusion method involves three different printing techniques: electron beam melting (EBM), selective laser sintering (SLS), and selective heat sintering (SHS). The material powder is melted or fused using an electron beam or a laser, depending on the technique. Examples of materials that have been utilized in this technique include metals, ceramics, polymers, composites, and hybrid materials. SLS (selective laser sintering) is the most common powder-based 3D printing technique and is often used. In 1987, Carl Deckard invented the SLS (superconducting laser). SLS is a 3D printing technique that is functionally fast, has excellent precision, and has a variable surface polish (Tiwari et al., 2015). It is also known as stereolithography. Objects made of metal, plastic, and ceramic may be created using selective laser sintering techniques. SLS utilized a high-power laser to sinter polymer particles together to create a three-dimensional product. Another component of 3D printing technology, SHS technology, uses a thermal head print to melt the thermoplastic powder to produce a 3D printed item. Finally, electron beam melting improves the efficiency of an energy source used to heat the material (Harzheim & Graf, 2006).

2.4.5 Sheet lamination

The American Society defines a sheet lamination process for Testing and Materials as the 3D printing method in which sheets of materials are bonded together to create a portion of an item. Laminated object manufacturing (LOM) and ultrasonic additive manufacturing (UAM) are two examples of 3D printing technologies that use this technique. Sheet lamination has many benefits, including the ability to print in full colour, the fact that it is very cheap, the ease with which it can be handled, and the fact that surplus material may be recycled. Laminated object manufacturing (LOM) can fabricate complex geometrical components at a cheaper cost of fabrication and less operating time than other methods (Rozvany, 2009). This cutting-edge process technique, known as ultrasound additive manufacturing (UAM), utilizes sound to join layers of metal taken from a featureless foil source to create complex shapes.

2.4.6 Vat Photopolymerization

Photopolymerization is the most widely used 3D printing method, and it refers to the curing of photo-reactive polymers using a laser, light, or ultraviolet radiation (UV). Stereolithography (SLA) and digital light processing (DLP) are two examples of 3D printing technologies that use photopolymerization to create objects. In the SLA, it was affected by the optical aggressor and the irradiate exposure specific circumstances, as well as any colours, pigment, or other UV absorbers that were used to supplement the exposure. Meanwhile, digital light processing, which uses photopolymers, is a technique that is similar to stereolithography in that it works with light. The most significant distinction is the light source. When a more traditional light source, such as an arc lamp, is combined with a liquid crystal display screen, the result is called Digital Light Process. It can apply to the whole surface of a vat of photopolymer resin in a single pass, making it much quicker than stereolithography in most cases (Agarwal et al., 2018). The duration of exposure, the wavelength, and the quantity of power supplied are the most significant factors in Vat Photopolymerization. The materials employed originally are liquid, and when the liquid is subjected to UV radiation, it will solidify and become more durable. Photopolymerization is an excellent method for producing a high-end product with fine details and a top rate of surface integrity.

2.4.7 Materials extrusion

Extrusion-based 3D printing technologies, such as material extrusion, may be used to print polymers in various colours and many materials, such as food or live cells. This procedure has been extensively used, and the associated expenses are very cheap. Furthermore, this technique may be used to create portions of a product that are completely functioning. Materials extrusion systems were initially shown using fused deposition modelling (FDM).

2.5 Conventional Versus Additive Manufacturing Process

2.5.1 Gravity Die Casting

For die casting process, there are two types of methods that are usually used, which are HPDC (High-Pressure Die Casting) and Gravity Die Casting (also known as sand casting) (Low-Pressure Die Casting). However, although they cater to distinct scenarios, the outcome is achieved by a similar method in both cases. One of humans' oldest die casting methods is gravity die casting. It is still in use today. The equipment and overall process efficiency have seen significant advances over time in terms of the equipment and the overall process efficiency. For large-scale manufacturing, gravity die casting is a sort of die-casting method that may be used. Several sectors use it because of the low cost and high-quality product it produces with the least amount of human intervention. Typically, non-ferrous alloy components such as aluminium, copper, and zinc-based alloys are utilized in this method, which is a fusion process.

Automating a significant portion of the contemporary gravity die casting process is possible. Large, thick items needing high degrees of detail are the ideal candidates for this fabrication. Compared to sand casting, the goods produced by this method have a better finish and mechanical qualities. When compared to aluminium sand casting, it also has a greater casting rate. Gravity die casting is used in various sectors, including kitchen equipment, automotive, lighting components, and others. Engine cylinder heads, engine blocks, pistons, and other similar components may be produced with this method with great success. Manufacturing products in big quantities is made easier by the uncomplicated nature of the manufacturing process. Gravity die casting is quite popular due to the fact that it is a clutter-free and reasonably easy method of production. This method involves the bare minimum of equipment, and the output may be customized to a certain degree. Especially if you are aiming to produce large quantities, you may automate a considerable portion of the process.

2.5.2 Fused Deposition Modelling (FDM)

In this project, AM technology that will be used is Fused Deposition Modelling (FDM). FDM was first created in the early 1990s, and it is a technique in which polymer is used as the primary material (Stansbury & Idacavage, 2016). Using thermoplastic filament that has been heated and extruded, FDM creates components layer by layer, starting at the bottom and working their way up. Figure 2.6 depicts a variety of components that have been manufactured using FDM technology.

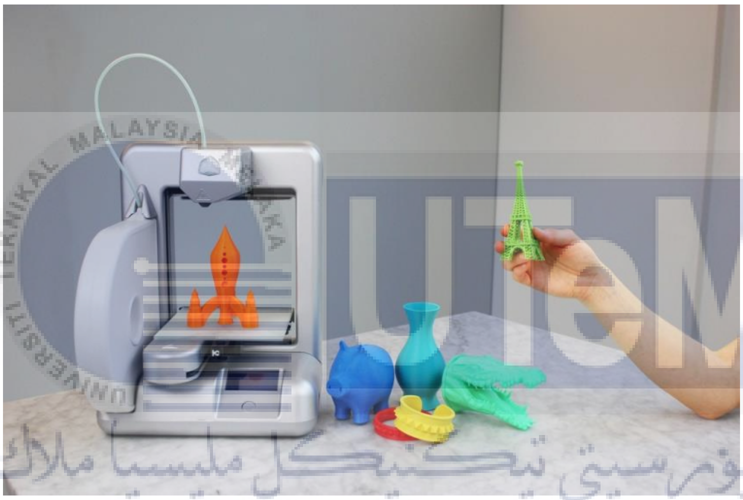


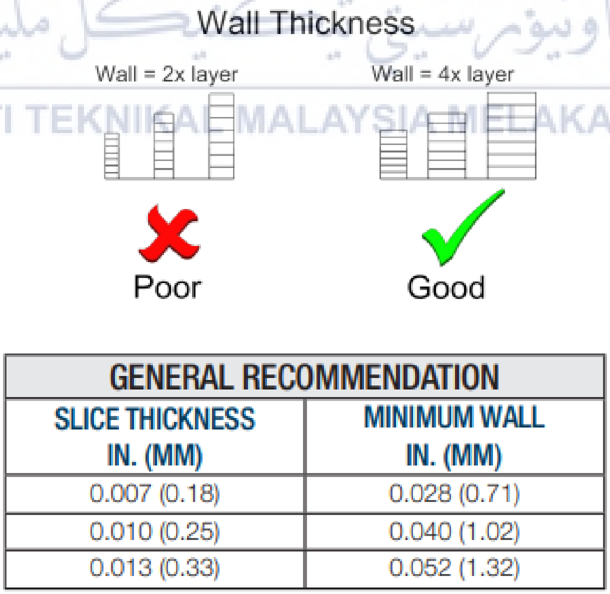
Figure 2.6: Parts fabricated by using FDM

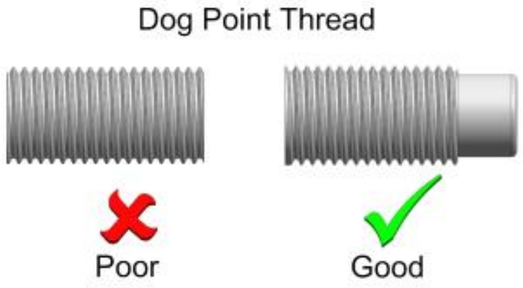
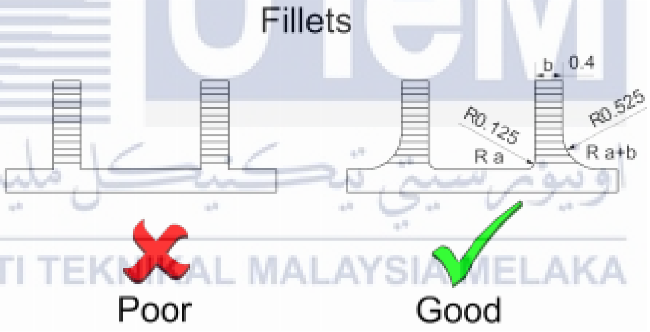
A significant amount of research has been carried out at universities and research institutes to broaden the uses of FDM and to enhance the FDM process itself. Some organizations are also engaged in the research and development of novel metallic or ceramic materials for the fast manufacture of functional components by FDM with improved mechanical characteristics, which is now underway. On the other hand, the development and testing of novel materials may be problematic in certain cases due to the nature of closed systems. It is not possible to replace cartridges with different types of material since the printer uses cartridges to hold the filament. As a result, the Department of Manufacturing Systems (KSW) at AGH University of Science and Technology has acquired a production 3D printer that feeds material from trays reels, allowing for the use of a variety of materials, including those that have been designed and produced by our group. There are several advantages to using the Inspire D290 printer, such as the previously stated method of feeding material and the increased choices for slicing components. It also contains a chamber that can be heated to temperatures of up to 100 degrees Celsius and a dual-nozzle head with one nozzle for building material and another for support. However, it has one disadvantage that is to alter the temperature of the printing head, and it is essential to utilize a bypass. To utilize different materials with this machine, it is essential to alter the electronics or bypass the thermocouple, which is impossible with the original design. ABS, PC (polycarbonate), ABS-PC, PPSF (polyphenylsulfone), and ULTEM 9085 are just a few of the materials that may be used in Stratasys Ltd.'s production systems. Following modification, our method is capable of using these and a variety of other materials, including PE (polyethene), PLA (polylactide), and PA (polyamide). Using composite materials, which may be created by combining one of these elements with any other material, particularly in the form of powder, and then spinning the resulting filaments, is also an option.

Compared to SLA or 3D Printing, this technique is less costly in terms of cost per part. Material costs and post-processing fees are the only expenses associated with the FDM system, and they are the only expenses associated with the FDM system. The only material that goes to waste is the support materials. When compared to SLA, 3D Printing, and even SLS, it generates much less waste. Materials may be recycled several times throughout the SLS process. After then, it gets overheated and becomes unusable again (Dudek, 2013).

Table 2.4 below shows the design consideration in manufacturing a product using FDM.

Table 2.4: FDM design consideration

Shrinkage	It is unnecessary to design shrink factors since the machine automatically incorporates shrink rates into the component as it processes it.
Warp	Because FDM systems add a tiny quantity of molten material in a hot environment, ribs must be added to the walls to prevent the material from melting.
Holes	Because holes in an FDM component are often fractionally undersized, holes will be drilled or reamed to verify that the diameter is correct before being used.
Wall thickness	The most negligible possible wall thickness for FDM components varies depending on the slice thickness utilized to construct the item throughout its construction. In multiple layers of minimum–consistency vertical walls without supporting features such as ribs or a support material tower, the part will become brittle, and warp may occur. In the case of multiple layers of minimum–thickness vertical walls with no supporting features such as ribs or a support material tower, warping may occur.  GENERAL RECOMMENDATION SLICE THICKNESS IN. (MM) — MINIMUM WALL IN. (MM) 0.007 (0.18) — 0.028 (0.71) 0.010 (0.25) — 0.040 (1.02) 0.013 (0.33) — 0.052 (1.32)
Threads	A radius on the root of the built-in thread should prevent sharp edges while constructing it. Sharp edges in plastic components have the potential to act as stress concentrators. When working with FDM, it has been discovered that creating an ACME thread

	pattern with rounded roots and crests works nicely. Also, make use of a “dog point” head at least 1/32 inch in diameter (0.8 mm). The use of a dog point design makes it much simpler to get the thread started. We do not advocate or allow for the production of tiny threads using the FDM method. A tap or die may be used as a quick and straightforward option to thread holes or posts. 
Fillets	In FDM components, while they are not required, fillets have the advantage of reducing stress concentrations while simultaneously increasing the overall strength of the part. Fillets should have an outer radius equal to the inner radius plus the wall thickness to maintain a constant consistency throughout the structure. 

Christoph Klahn states that the benefits of additive manufacturing as a manufacturing technique stem primarily from the fundamental concept of adding layers in a cyclic process based on a 3D CAD model, which eliminates the need for any tools or fixtures during the production process (Klahn et al., 2015). On the production cost front, this fundamental concept has two implications.

Initial stages consist of breaking down a complicated three-dimensional item into simple two-dimensional manufacturing processes. As a result, the difficulty of the component no longer has a significant impact on production time and costs. The intricacy of the design influences the number of support structures needed in SLM and FDM. However, this effect is not as significant as it is in traditional methods. The phrase "complexity for free" is frequently used to describe this phenomenon.

The second significant distinction between additive manufacturing and traditional manufacturing methods is the minimal effect of lot size on production costs and lead time in additive manufacturing. Individual tooling or CAM programming is not required in the case of Additive Manufacturing, which is a CAD-driven process. The absence of this prior investment in manufacturing implies that creating many similar components or the same number of unique products requires the same amount of work. Having a cost advantage in small lot sizes enables the manufacturing of single pieces and bulk customization at affordable prices. Figure 2.7 below shows that AM process reduce a lot of waste from the material manufacturing than the conventional process.

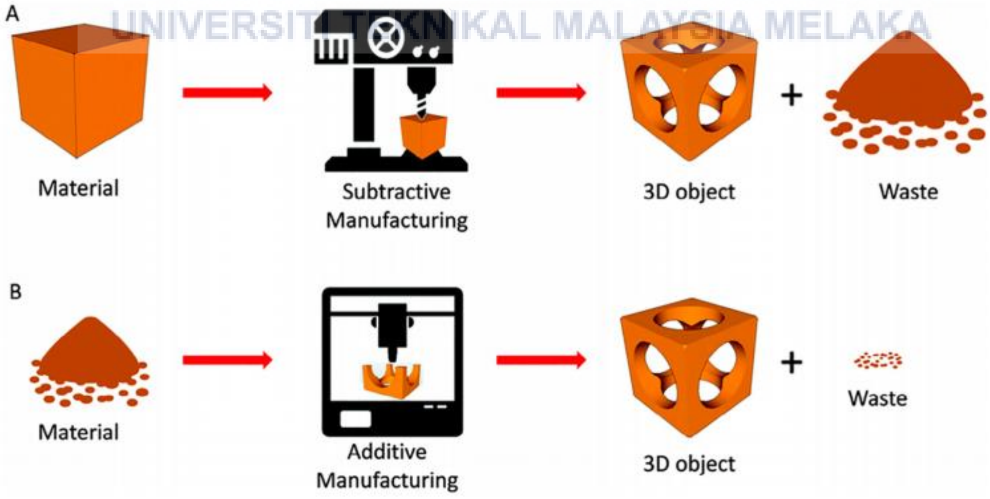


Figure 2.7: Part geometry manufacturing using conventional method (machining) and AM process

As an alternative, additive manufacturing is already proving to be a helpful addition to current manufacturing methods. The methods allow for almost limitless design flexibility as well as cost-effective manufacture of individual components. As a result, additive manufacturing helps to overcome the limits of traditional manufacturing procedures.

2.6 Topology Optimization Tool & Software

Topology optimization software has to simulate and optimize a wide range of mechanical reactions in industrial settings. While the traditional topology optimization issue involves reducing compliance at a given volume, many components will be needed to sustain some vibratory stress. As a result, the resonant frequency will become critical to forecast or limit. The ability to restrict or optimize for a given first natural frequency has emerged as a vital element in deciding which software tools are most suited for developing functional components for additive manufacturing (AM) applications.

These tools can solve a wide range of issues under a variety of production restrictions. They often include symmetry planes, minimum member size, pattern repetition, and draw direction. All static and dynamic mechanical responses relevant to structural performance are accessible for constraint and objective functions, and they encompass all static and dynamic mechanical responses appropriate to structural performance. Design and optimization formulations may make use of a variety of accessible responses. These include displacement and velocity and acceleration; volume and mass; stress and strain; compliance and frequency; buckling factor; the moment of inertia; factor of safety; composite failure; and so on.

One of the best software for topology optimization is SolidThinking Inspire. SolidThinking Inspire, a product of Altair Engineering, allows design engineers and product designers to develop and explore structurally efficient ideas rapidly. Engineers may use traditional structural models to determine whether or not a design will be able to withstand the necessary loads. Using the loads as input, Inspire improves the efficiency of this procedure by creating a whole new material layout inside a package area. Working in conjunction with current CAD tools, the programme assists in designing structural components that are accurate the first time, thus lowering costs, development time, material consumption, and overall product weight. Inspire is a concept design tool created for design engineers and designers to help them build quicker, smarter, and lighter things. It was created to help users build things that are quicker, smarter, and lighter. Inspire rapidly produces the optimal form for a design issue given the package space and loading constraints. Consequently, you will have structurally efficient concept ideas that you may utilise as a starting point for computer-aided design (CAD).

With the help of the SolidThinking Inspire tool, the workflow was able to refresh the conventional design process by adding new phase types and removing others from the process. Presented below is a common stream type with the flow shown graphically (see Figure 2.8.

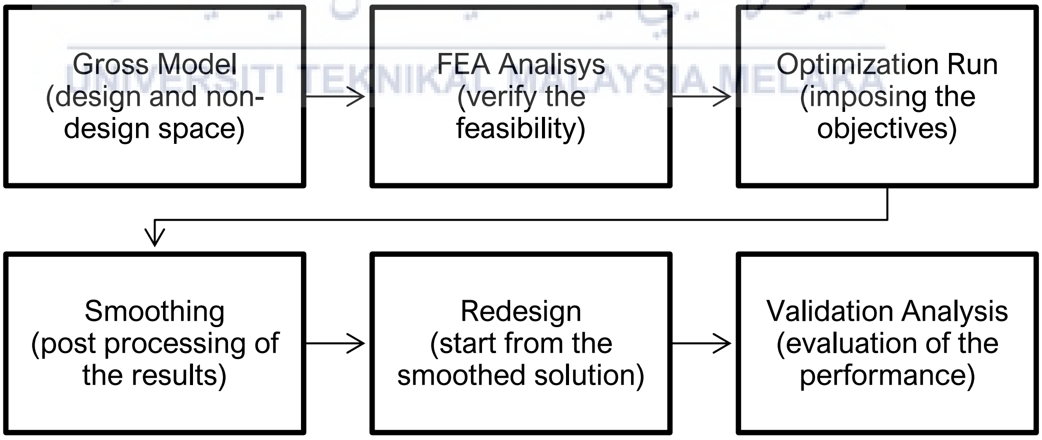


Figure 2.8: Stream of design

The distinction between design and non-design space is critical in this software, and it must be established before anything else. The design space is the area where the component's whole partition may be changed and optimized, while the non-design space is the area where the component is required to remain in its current configuration. For example, in Figure 2.9, the yellow region represents the design space, while the grey region represents the non-design space, which is where all of the loads and restrictions were placed. Note that the load and restrictions must be placed exclusively in the non-design space; otherwise, their point of application will vary as the optimization cycle progresses.

Figure 2.9: Pedal model in TO software

CHAPTER 3

METHODOLOGY

3.1 Introduction

It is described in detail in this chapter how the technique used in this project to get the optimum design for topology optimization in 3D Printing was developed. Figure 3.1 depicts a flow chart for the project's overall process. The first step in this project is to investigate the kind of technology utilized in the 3D Printing process, and the original CAD model created using the SolidWorks software. After that, Solid Thinking Inspire is used for topological optimization and to analyze the best design that can be obtained by considering the design rules discussed in Chapter 2. Then, the design will be run on a simulation of 3D printing and die casting process using SolidThinking Inspire software. FEA validation via ANSYS is carried out once again to ensure that the component has the necessary factor safety.

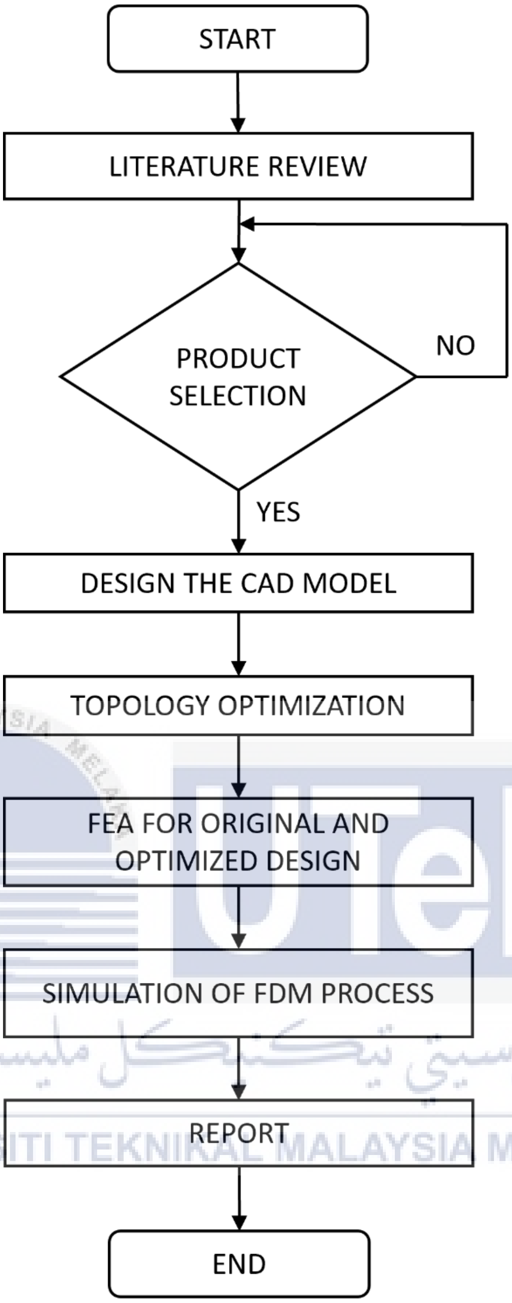
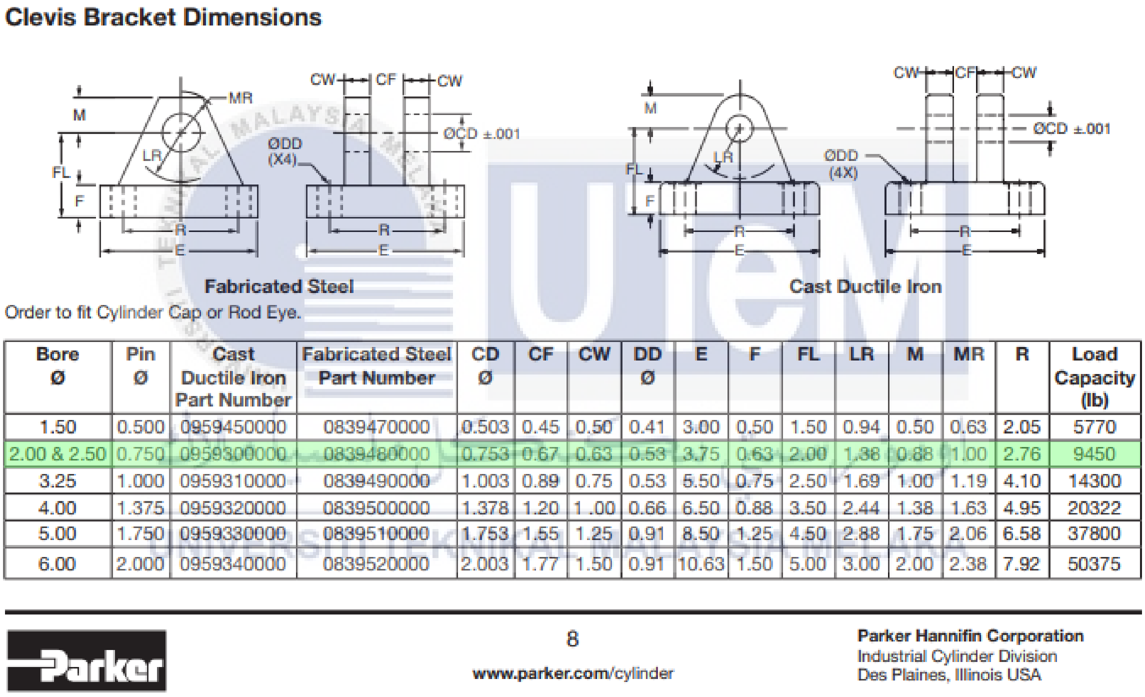


Figure 3.1: Flow chart of the methodology

3.2 3D CAD Model Preparation

The first step is to draw 3D CAD model of the bracket in a CAD software. SolidWorks software is being utilized to build the 3D CAD model of the product for this project. Here is where the reverse engineering approach is used to model the same product. All the dimension of the bracket is according to the manufacturer's specifications in a catalogue as in Figure 3.2(a). From the catalogue, second row dimension is selected. Complete 3D CAD model of the Steel Clevis Bracket is shown in Figure 3.3.



Clevis Bracket Dimensions

Fabricated Steel

Cast Ductile Iron

Order to fit Cylinder Cap or Rod Eye.

Bore Ø	Pin Ø	Cast Ductile Iron Part Number	Fabricated Steel Part Number	CD Ø	CF	CW	DD Ø	E	F	FL	LR	M	MR	R	Load Capacity (lb)
1.50	0.500	0959450000	0839470000	0.503	0.45	0.50	0.41	3.00	0.50	1.50	0.94	0.50	0.63	2.05	5770
2.00 & 2.50	0.750	0959300000	0839480000	0.753	0.67	0.63	0.53	3.75	0.63	2.00	1.38	0.88	1.00	2.76	9450
3.25	1.000	0959310000	0839490000	1.003	0.89	0.75	0.53	5.50	0.75	2.50	1.69	1.00	1.19	4.10	14300
4.00	1.375	0959320000	0839500000	1.378	1.20	1.00	0.66	6.50	0.88	3.50	2.44	1.38	1.63	4.95	20322
5.00	1.750	0959330000	0839510000	1.753	1.55	1.25	0.91	8.50	1.25	4.50	2.88	1.75	2.06	6.58	37800
6.00	2.000	0959340000	0839520000	2.003	1.77	1.50	0.91	10.63	1.50	5.00	3.00	2.00	2.38	7.92	50375

8

www.parker.com/cylinder

Parker Hannifin Corporation
Industrial Cylinder Division
Des Plaines, Illinois USA

Figure 3.2(a): Dimension of the bracket in CAD catalogue

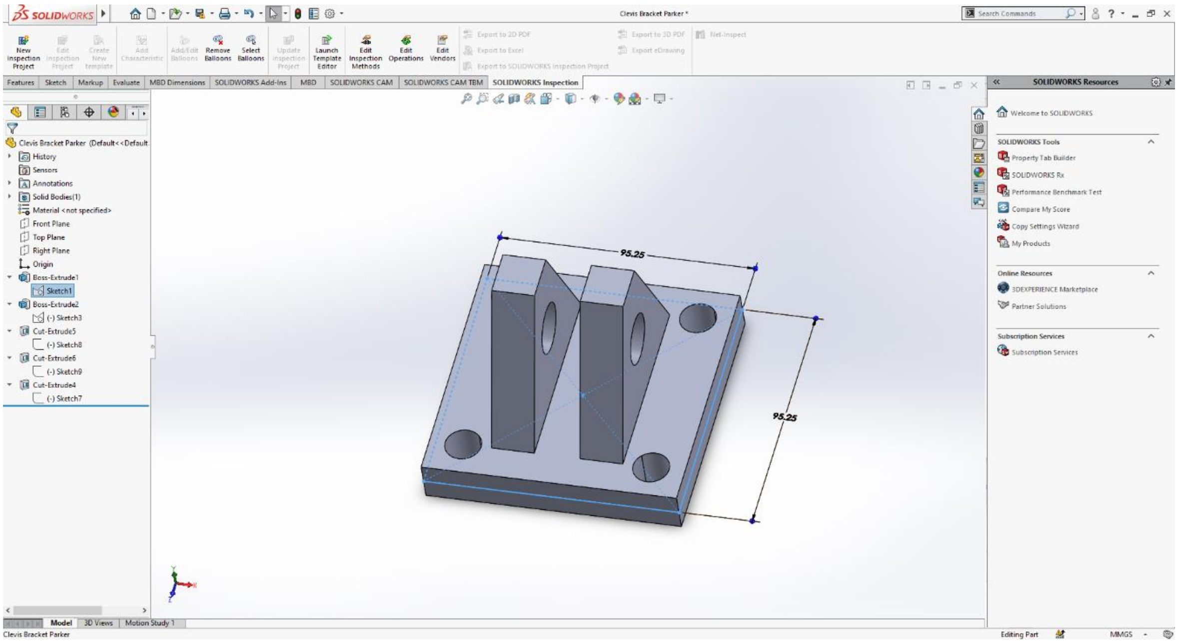


Figure 3.2(b): Dimension of the bracket in CAD model

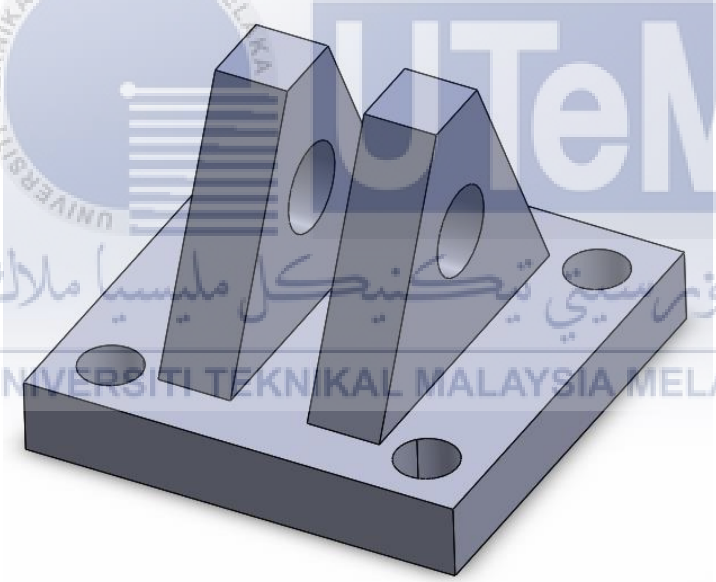


Figure 3.3: Completed 3D CAD model of the bracket

3.3 Topology Optimization on 3D CAD Model

As previously stated in Chapter 2, the idea overview of Topology Optimization, this subject describes the method to be followed to conduct Topology Optimization on the bracket utilizing Solid Thinking Inspire software.

3.3.1 Load and Constraint Analysis

First step is the CAD model of the bracket was imported from SolidWorks file to SolidThinking Inspire software. Figure 3.4 shows the main layout of the software. The are many functions included in the top toolbar such as Geometry, PolyMesh, PolyNURBS, Structure, Motion, Manufacture, Print 3D. The structure module is the most essential for now since it includes the function required to establish loads and restrictions for the FEA and topology optimization study that will be performed later.

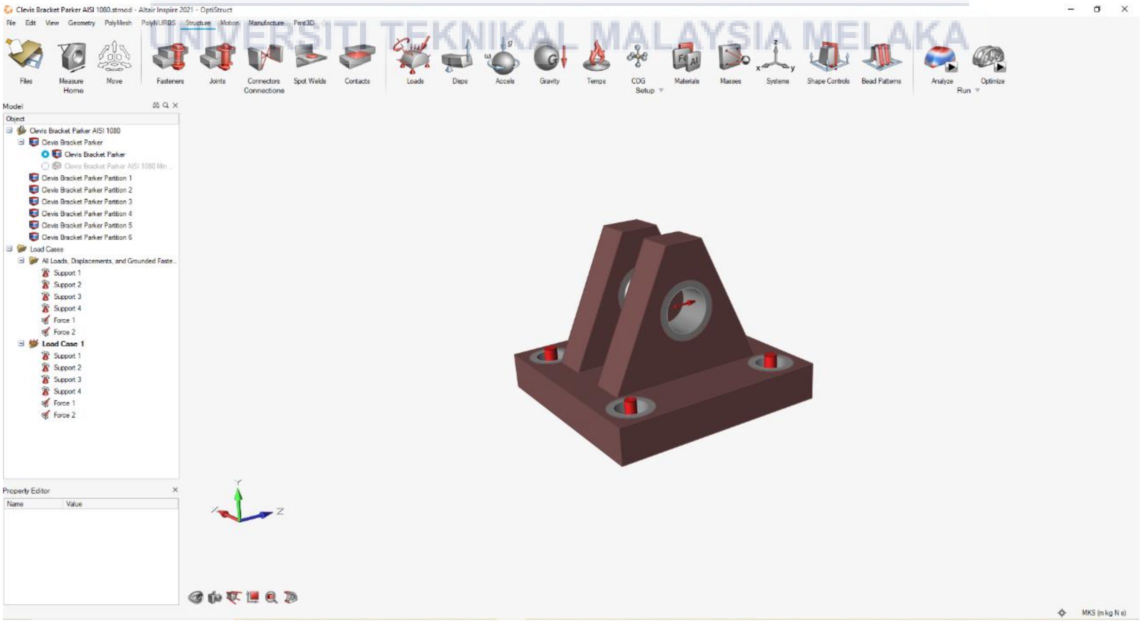
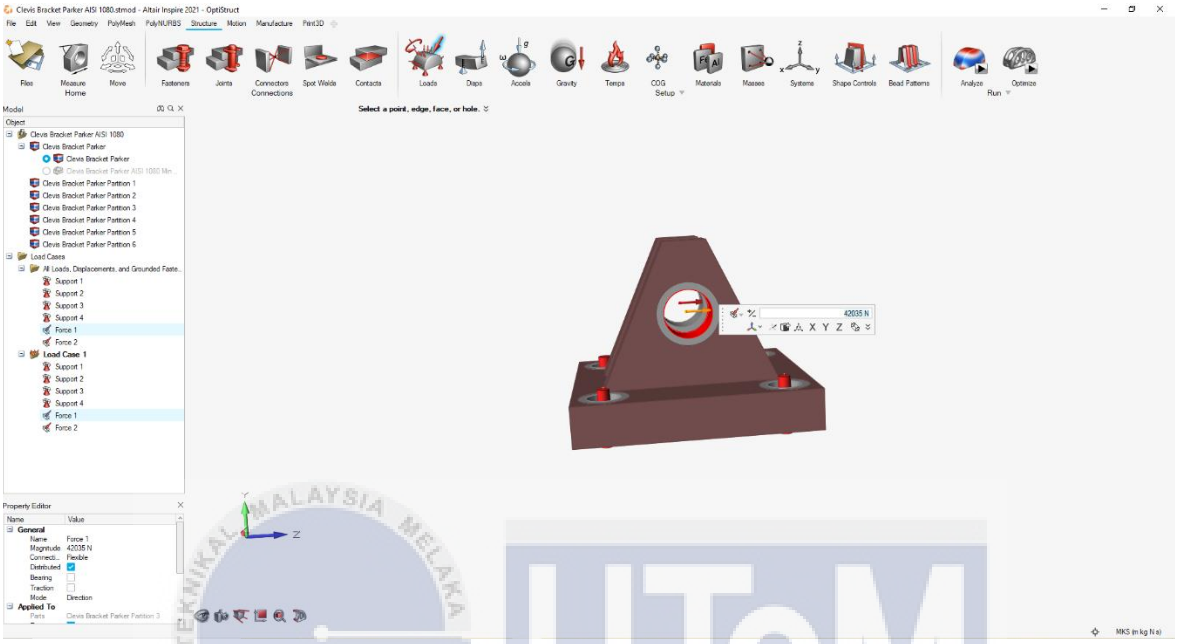


Figure 3.4: Layout of the Inspire

Figure 3.5 shows the loads and constraints applied on the bracket. The 42035 N load is applied to two big holes in the middle of the bracket as in the figure. Then, support constraints were applied on other four holes.



Name Value

General

Name Force 1

Magnitude 42035 N

Connecti... Flexible

Distributed ☑

Bearing ☐

Traction ☐

Mode Direction

Applied To

Parts Clevis Bracket Parker Partition 3

Figure 3.5: Load and constraint application

3.3.2 Define Design Space

For this bracket, the design space of the product is red colour region while the non-design space is around each hole which is where the constraints and loads are applied. Also, the material of the product must be determined first in order to run the optimization.

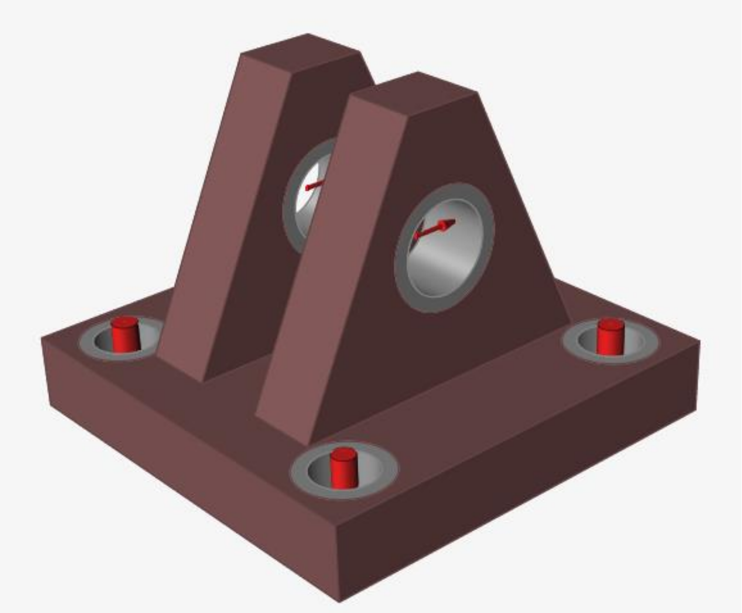
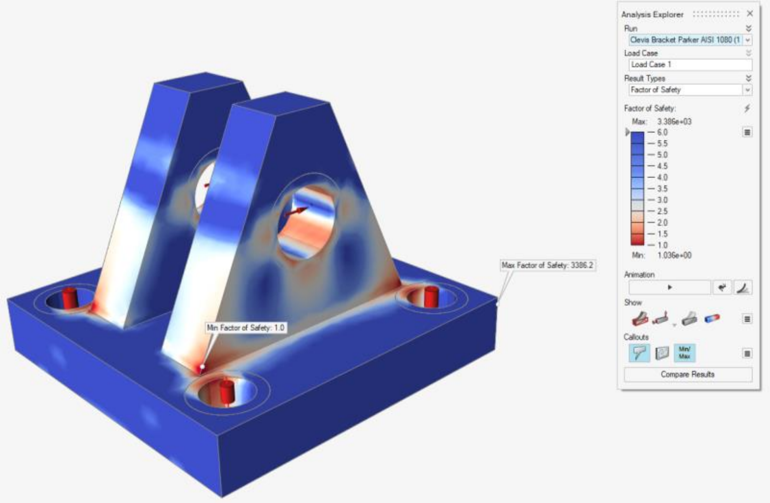


Figure 3.6: Design and non-design space of the bracket

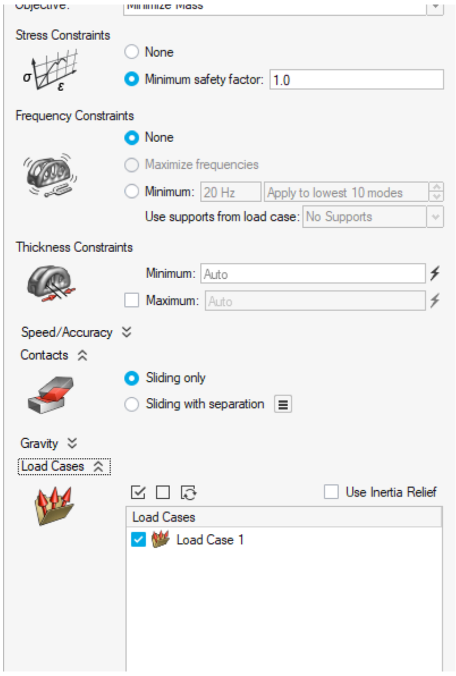
3.3.3 Perform TO

The next step is to define the objective of the analysis which is to minimize the mass of the product. Analysis was run first to obtain the safety factor of the bracket (see Figure 3.7) and proceed to topology optimize the bracket by setting the system as in Figure 3.8. For this project, the part was topology optimized for a minimum safety factor of 1.0.



Analysis Explorer
Run: Clevis Bracket Parker AISI 1080 (1
Load Case: Load Case 1
Result Types: Factor of Safety
Factor of Safety:
Max: 3.386e+03
Min: 1.036e+00

Figure 3.7: Analysis of the bracket



Objective: Minimize Mass

Stress Constraints

○ None

● Minimum safety factor: 1.0

Frequency Constraints

● None

○ Maximize frequencies

○ Minimum: 20 Hz Apply to lowest 10 modes

Use supports from load case: No Supports

Thickness Constraints

Minimum: Auto

☐ Maximum: Auto

Speed/Accuracy

Contacts

● Sliding only

○ Sliding with separation

Gravity

Load Cases

☐ Use Inertia Relief

Load Cases

☑ Load Case 1

Figure 3.8: Optimization setup

3.4 Redesign and Refining of the Optimization Output

For the topology optimization output, it must be refined to get a smooth surface of the component. Using PolyNURBS in SolidThinking Inspire software, the refinement can be done with ease. But in order to obtain aesthetic appearance, SolidWorks is used to redesign again the design as in Figure 3.9. Also, in this stage the design limitation must be considered in order to ensure that the printing process using FDM can be run smoothly.

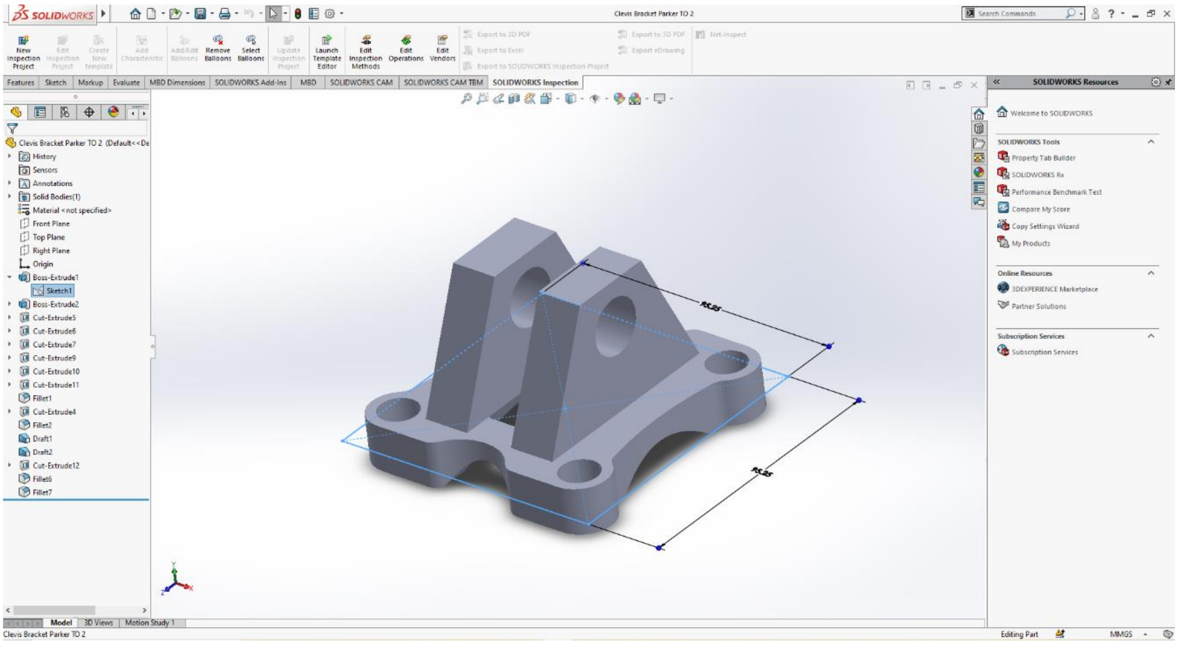
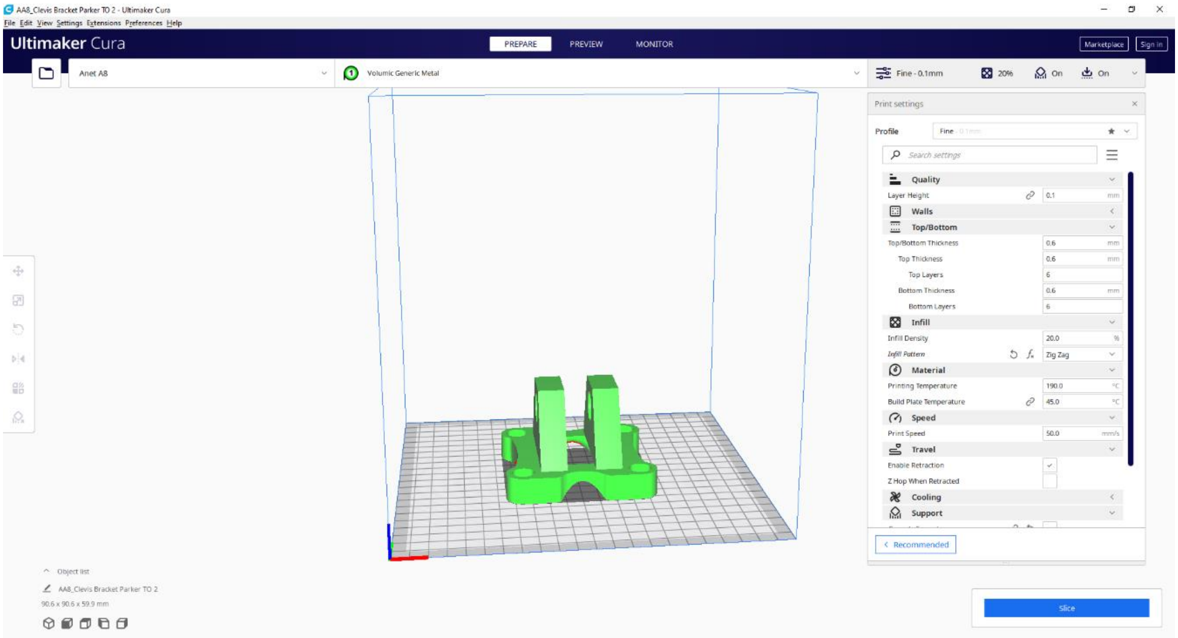


Figure 3.9: Redesign of the TO output using SolidWorks

3.5 Simulation of 3D Printing Process

In 3D print process, a software called Ultimaker Cura is used to slice the components that need to be print. By extracting the CAD file of the bracket as STL file, the bracket now can be run on the Ultimaker Cura. First, in order to obtain the simulation analysis, the bracket must be sliced by setting up the printer, material and parameter of printing options. The slicing method is a must for a 3D Printing process. This is because it is to convert the model of 3D object to specific instructions or code for the printer to print the object. The code is called G-Code. Anet A8 is selected as the printer setup and the material is Volumic Generic Metal. Then, the simulation of the bracket can be done.



Profile: Fine - 0.1mm

Layer Height: 0.1 mm

Top/Bottom Thickness: 0.6 mm

Top Thickness: 0.6 mm

Top Layers: 6

Bottom Thickness: 0.6 mm

Bottom Layers: 6

Infill Density: 20.0 %

Infill Pattern: Zig Zag

Printing Temperature: 190.0 °C

Build Plate Temperature: 45.0 °C

Print Speed: 50.0 mm/s

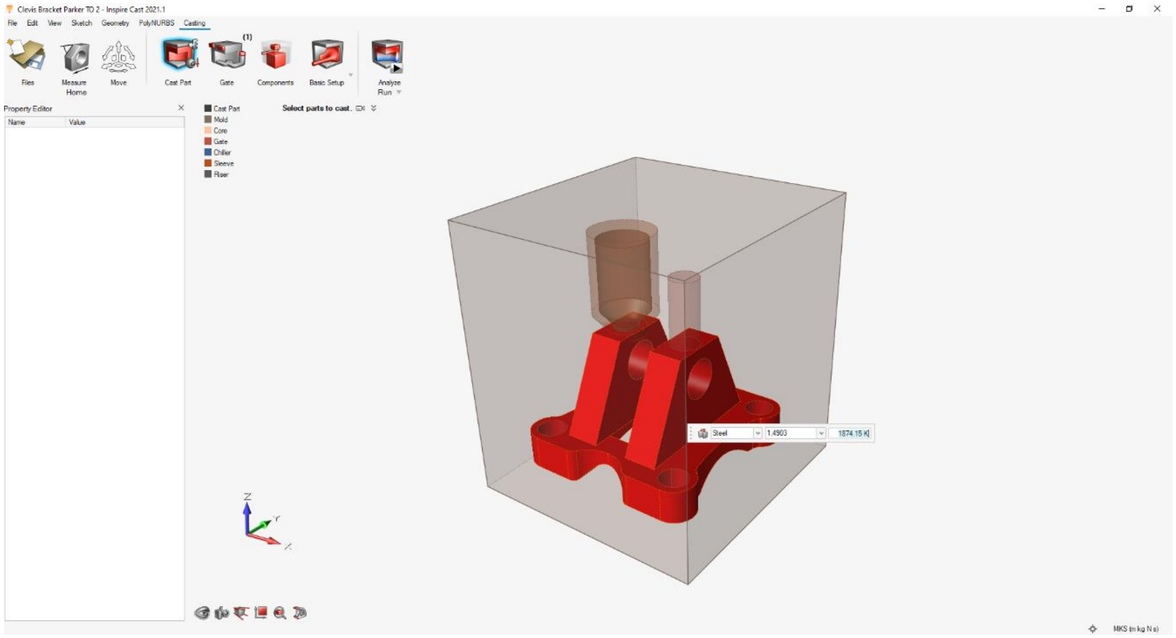
Enable Retraction: ☑

Z Hop When Retracted: ☐

Figure 3.10: Layout of Ultimaker Cura

3.6 Simulation of Gravity Die Casting Process

For the casting simulation process, Inspire Cast software is used. This software is the extent of the SoldThinking Inspire software which mainly focus on run a casting simulation of a product. First, the casting part is determined (Figure 3.11) before setting the core, mold, chiller and riser of the casting. The core used in this casting simulation is Cromite-Sand at 293.15 K (Figure 3.12(a)) while the mold used is Green-Sand at same temperature (Figure 3.12(b)). The Copper chiller used also at 293.15 K (Figure 3.12(c)). Finally, the simulation can be run.



Select parts to cast.

Steel 1.4903 1874.15 K

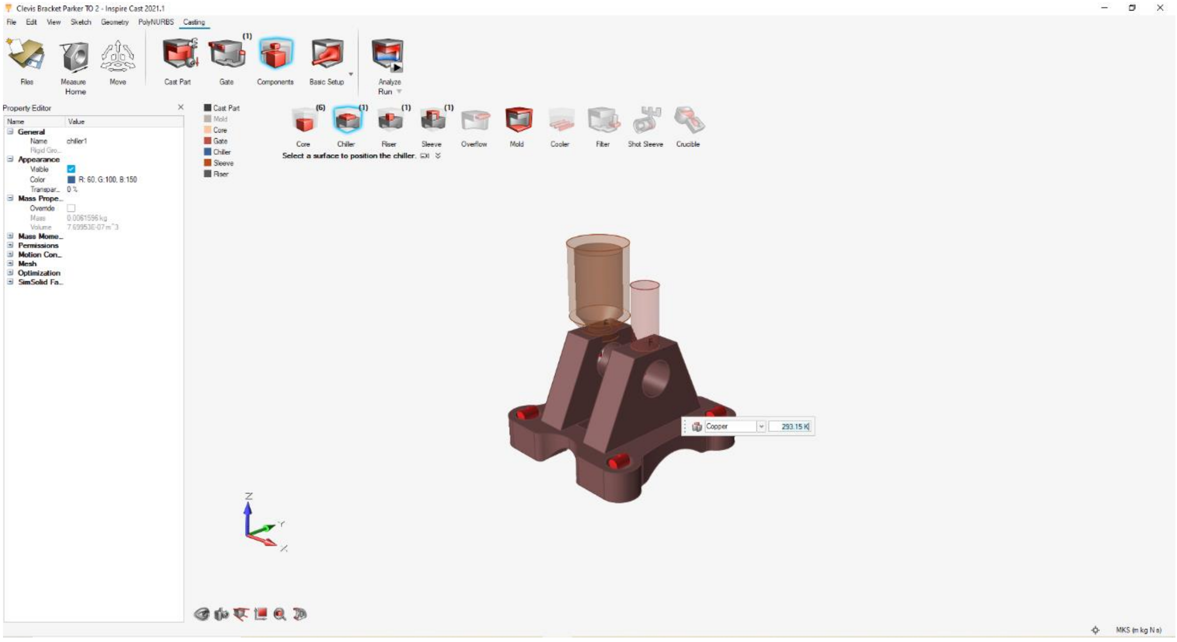
Figure 3.11: Defining casting part

Name	Value
General	
Name	core6
Rigid Gro...	
Appearance	
Visible	☑
Color	R:250, G:200, B:160
Transpar...	0 %
Mass Prope...	
Override	☐
Mass	0.017884 kg
Volume	2.27824E-06 m^3
Mass Mome...	
Permissions	
Motion Con...	
Mesh	
Optimization	
SimSolid Fa...	

Click a selected cavity to create a core.

Cronite-Sand 293.15 K

Figure 3.12(a): Defining the core

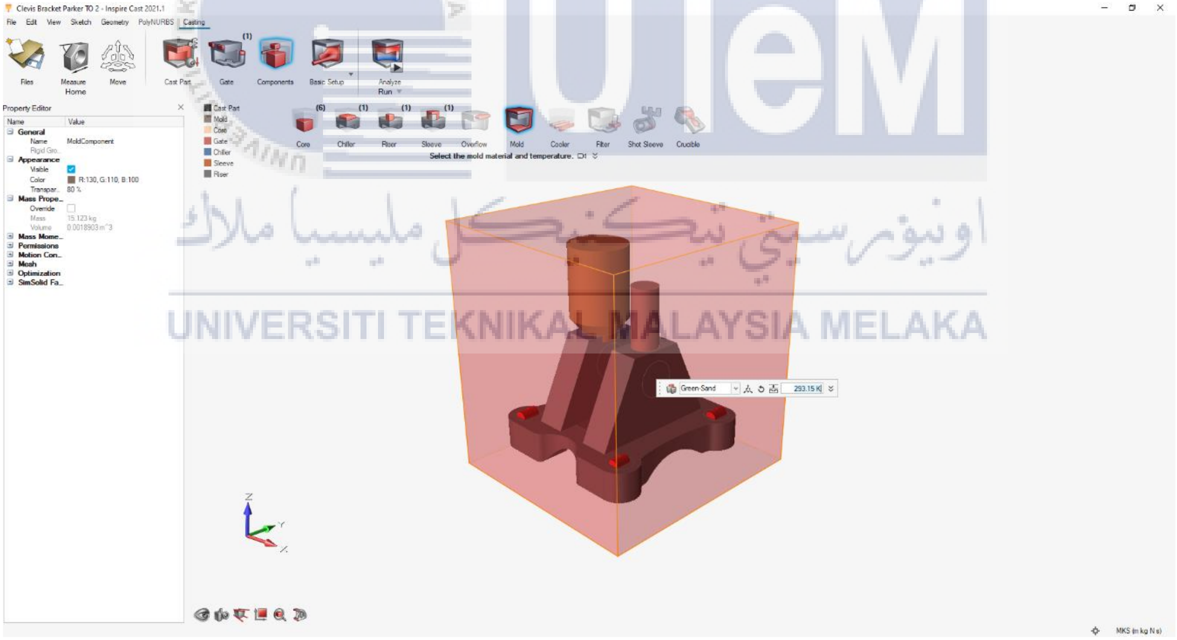


Select a surface to position the chiller.

Name	Value
General	
Name	chiller1
Appearance	
Visible	☑
Color	R: 60, G:100, B:150
Transpar...	0 %
Mass Prope...	
Override	☐
Mass	0.0061596 kg
Volume	7.69953E-07 m^3

Copper 293.15 K

Figure 3.12(b): Defining the chiller



Select the mold material and temperature.

Name	Value
General	
Name	MoldComponent
Appearance	
Visible	☑
Color	R:130, G:110, B:100
Transpar...	80 %
Mass Prope...	
Override	☐
Mass	15.123 kg
Volume	0.0018903 m^3

Green Sand 293.15 K

Figure 3.12(c): Defining the mold

CHAPTER 4

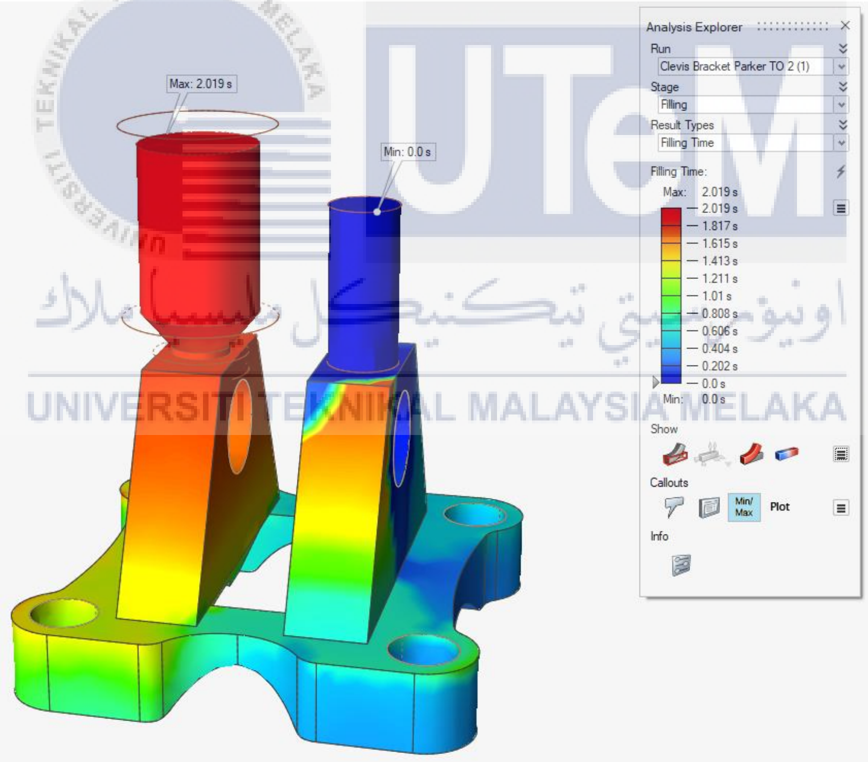
RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, the results obtained from software such as SolidThinking Inspire, Altair Inspire Cast, Ultimaker Cura, and ANSYS are explained in detail. The process comparison between conventional and additive method are explained in this chapter. For the conventional process, Gravity Die Casting is chosen, and the simulation is done in Altair Inspire Cast. Meanwhile, for additive, FDM method is used. The simulation of the 3D print is done in Ultimaker Cura software. The first result obtained in this project is the comparison of conventional and additive process in term of design process, time and price. The next result obtained is the topology optimization of the bracket by using SolidThinking Inspire software. After that, SolidWorks is used for redesigning the bracket's optimization output. Finally, FEA validation of the design is done by using ANSYS software.

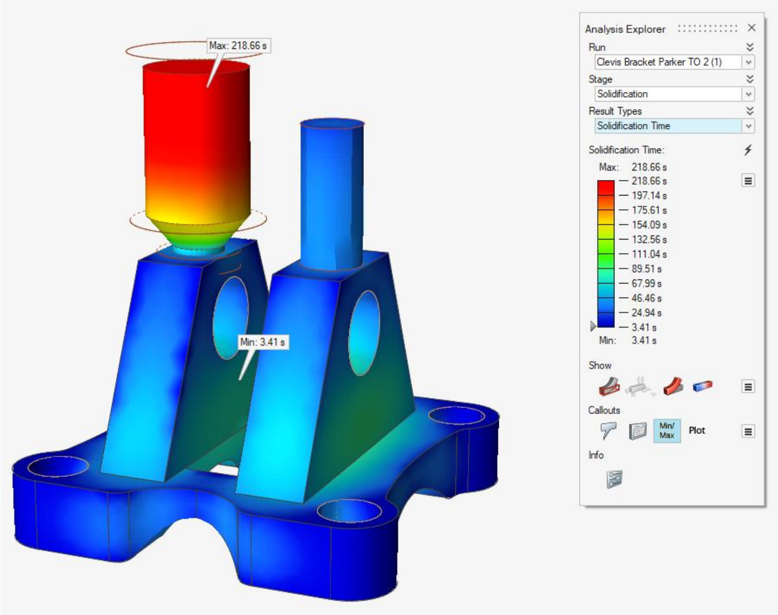
4.2 Simulation of Gravity Die Casting Process

Result of simulation for gravity die cast process have been obtained by using Altair Inspire Cast software (Figure 4.1, Figure 4.2). The time required to fill the molten into the mold is 220. 68 seconds as in Table 4.1 and the total weight of the casting product is 0.99696 kg ≅ 1 kg as shown in Figure 4.3. The price is determined by the total weight of the molten metal used and mold material. For this bracket, stainless steel is used as molten. As for the mold, green sand and cromite sand are used (Figure 4.4). The price for 1 kg stainless steel is RM 14.07 for the casting molten metal. This price excludes the the mold material cost, tax, equipment cost and tooling cost.



Run: Clevis Bracket Parker TO 2 (1)
Stage: Filling
Result Types: Filling Time

Figure 4.1: Filling time

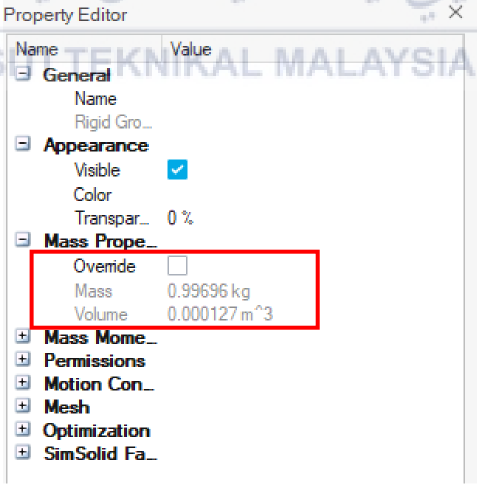


Run: Clevis Bracket Parker TO 2 (1)
Stage: Solidification
Result Types: Solidification Time

Figure 4.2: Solidification time

Table 4.1: Total time for casting

Filling Time (s)	Solidification Time (s)	Total Time (s)
2.02	218.66	220.68



Name: Rigid Gro...
Visible: ☑
Color
Transpar...: 0 %
Override: ☐
Mass: 0.99696 kg
Volume: 0.000127 m^3

Figure 4.3: The casting product mass

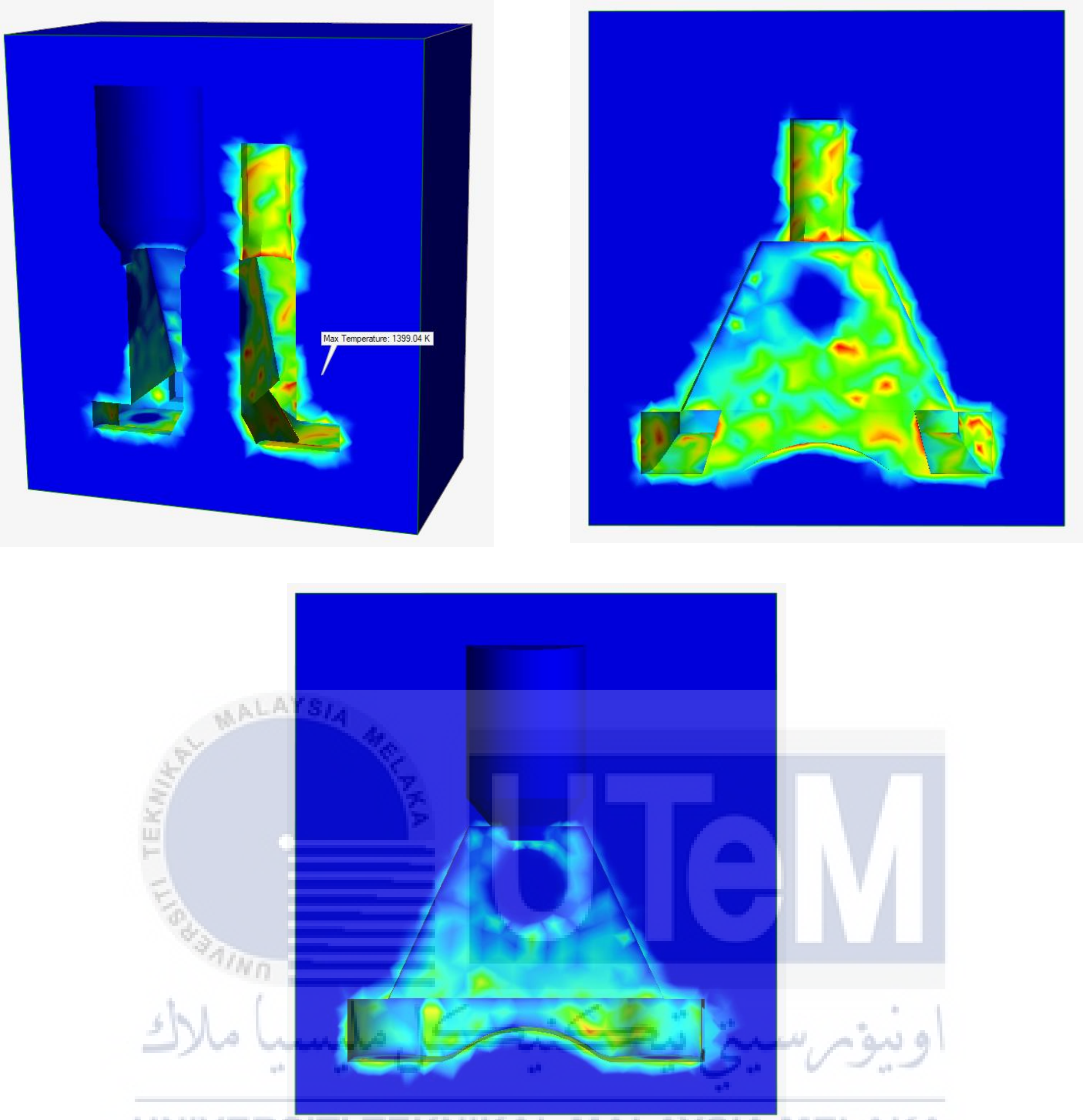


Figure 4.4: Mold of the bracket

4.3 Simulation of FDM Process

Result of simulation for 3D print process have been obtained using Ultimaker Cura software (Figure 4.5). Time required to print a complete product is 13 hours 14 minutes and total weight of the bracket is 182 g as shown in Figure 4.6 (a). The price is determined by the total length and type of the filament used. For this bracket, the material used is a metal composite filament which is Volumic Metal CUIVRE80 Ultra (Figure 4.6 (b)). The filament cost is RM 410.43 for 750 g, so the cost per meter is RM 4.48. As for the bracket, it only cost RM 99.49 since only 22.23 meter of the filament was used.

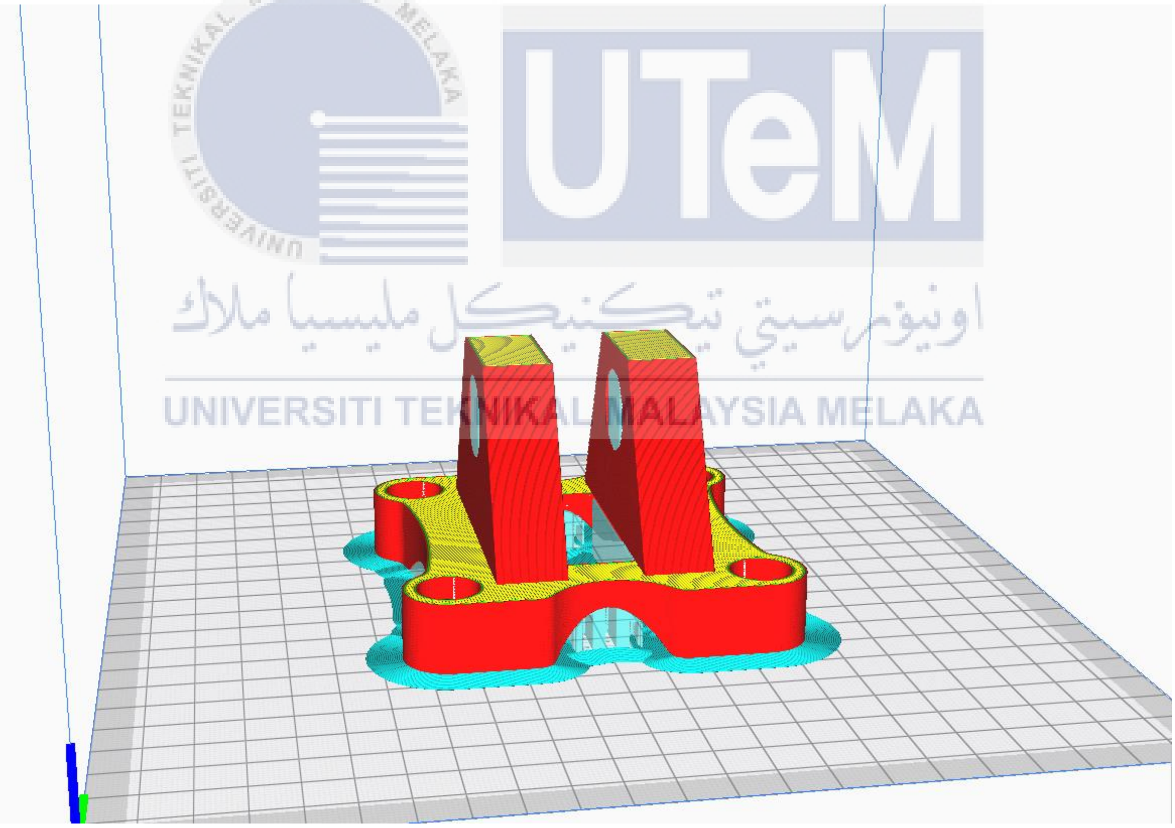
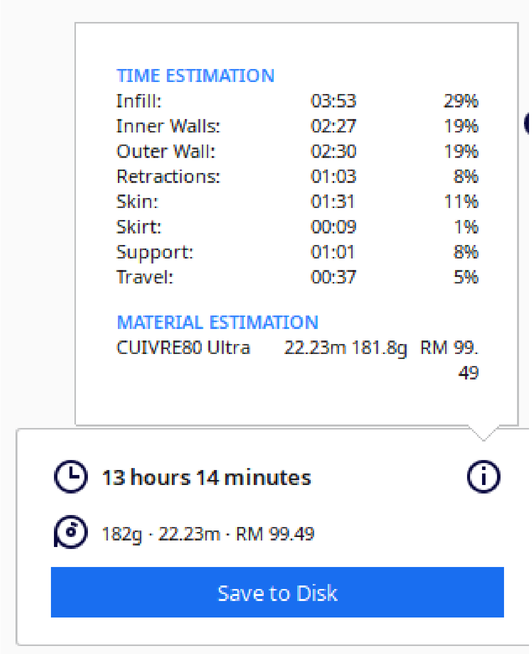


Figure 4.5: 3D Printing simulation



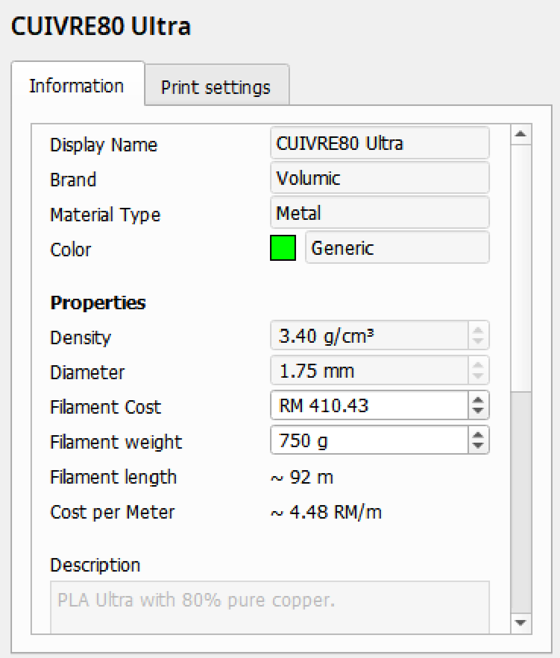
```
TIME ESTIMATION
Infill:           03:53    29%
Inner Walls:      02:27    19%
Outer Wall:       02:30    19%
Retractions:      01:03     8%
Skin:             01:31    11%
Skirt:            00:09     1%
Support:          01:01     8%
Travel:           00:37     5%

MATERIAL ESTIMATION
CUIVRE80 Ultra    22.23m 181.8g  RM 99.
                                    49

13 hours 14 minutes

182g · 22.23m · RM 99.49
```

Figure 4.6 (a): Printing details



CUIVRE80 Ultra

Display Name	CUIVRE80 Ultra
Brand	Volumic
Material Type	Metal
Color	🟩 Generic
Properties	
Density	3.40 g/cm³
Diameter	1.75 mm
Filament Cost	RM 410.43
Filament weight	750 g
Filament length	~ 92 m
Cost per Meter	~ 4.48 RM/m

Description

PLA Ultra with 80% pure copper.

Figure 4.6 (b): Material properties

4.4 Comparison on Conventional VS Additive Method

In term of time of production, FDM is faster than casting method. The time for the casting process is longer because it needs to consider the mold setup, equipment and tool setup which require a lot of time to completely ready for casting process (Figure 4.7(a)). Meanwhile, FDM machine only need to pre heat the extruder and the platform. In term of mass, the casting product mass is slightly higher than 3D print product since the material of the 3D print filament is metal composite. Next, the cost of the casting process is higher than the FDM process (Figure 4.7(b)). This is because of the expensive mold material price, tax and high-cost equipment and tool for casting. Meanwhile, FDM only need to consider the filament price.

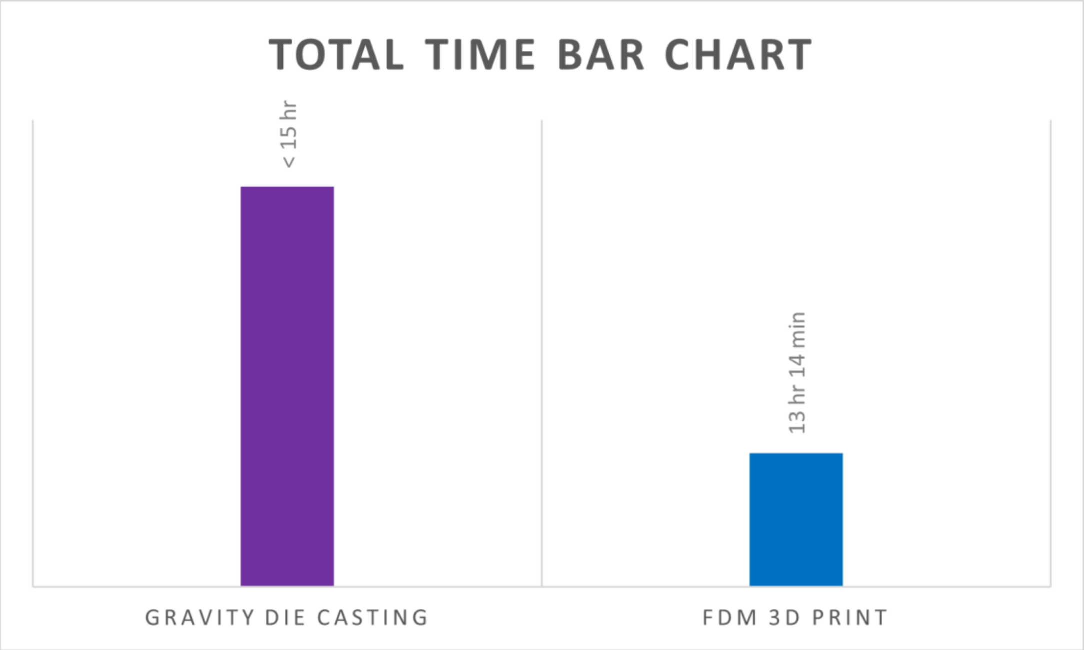


Figure 4.7(a): Time comparison bar chart

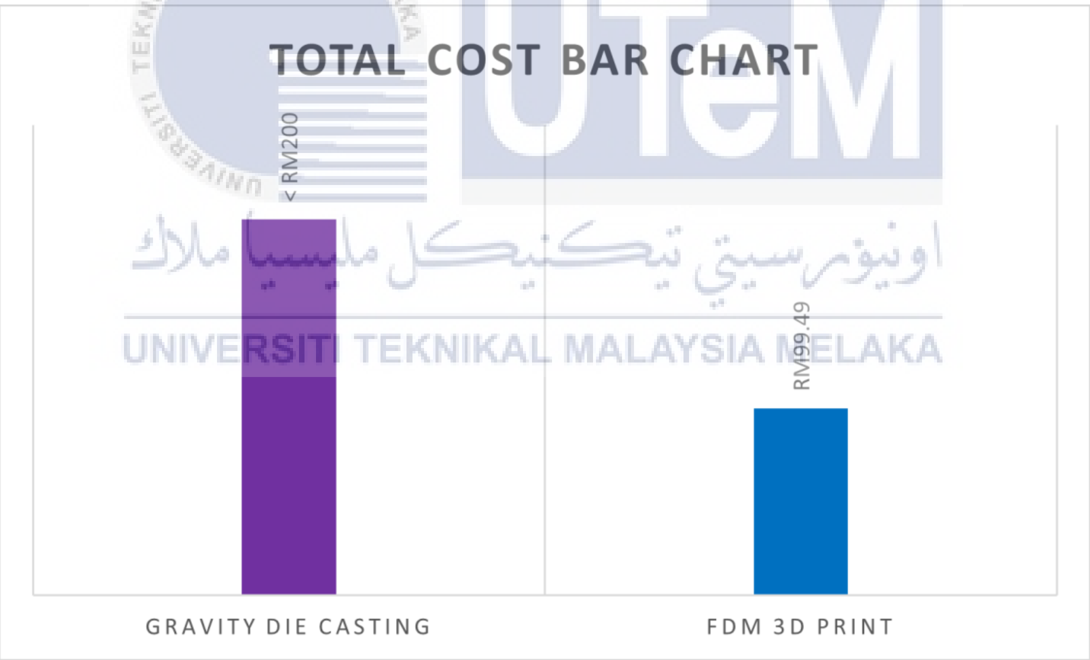


Figure 4.7(b): Cost comparison bar chart

4.5 Results & Analysis of Original and Optimized Bracket

4.5.1 Original Clevis Bracket Analysis

Analysis of the original design has been done to determine the strength of the original design when the desired load applied on it. For the analysis of equivalent von-Mises stress, the maximum stress is 366.9 MPa (Figure 4.8) and the safety factor that was calculated is 1.0 (Figure 4.9). Next, the maximum deformation of the bracket is 0.07867 mm which locate at the tip of the bracket as shown in Figure 4.10 below.

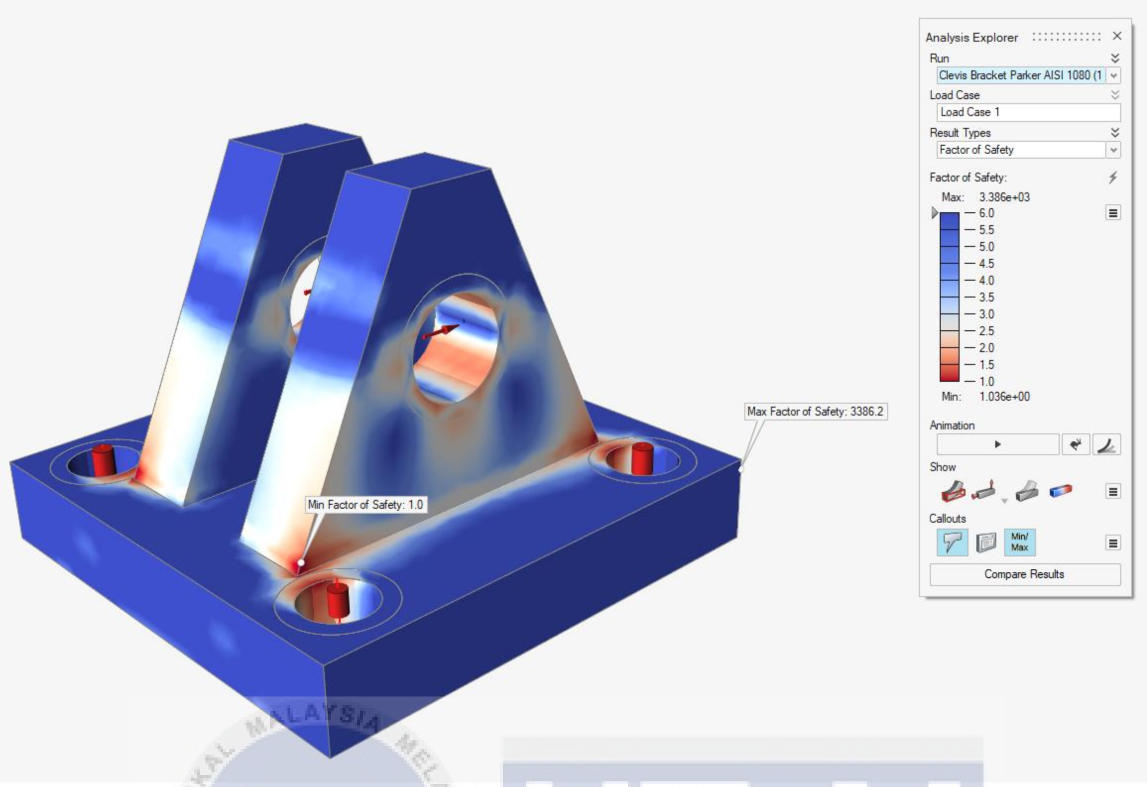
Analysis Explorer

Run: Clevis Bracket Parker AISI 1080 (1

Load Case: Load Case 1

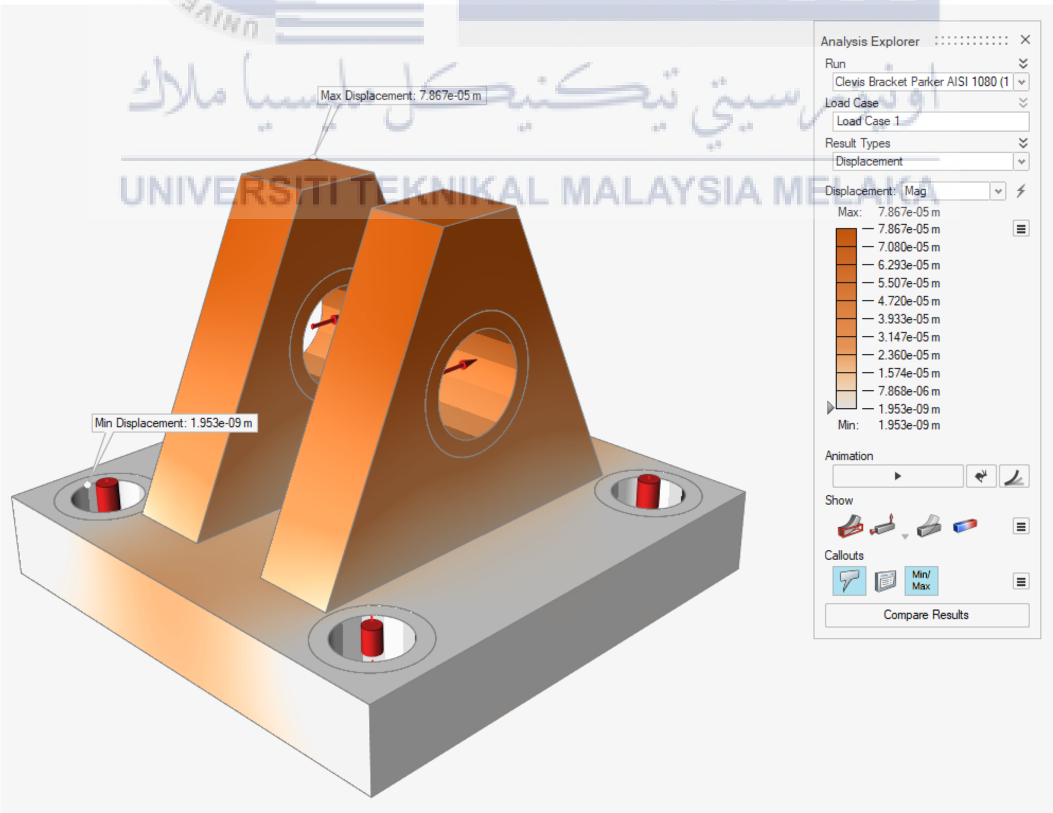
Result Types: von Mises Stress

Figure 4.8: Result analysis of von-Mises stress for original bracket



Analysis Explorer
Run: Clevis Bracket Parker AISI 1080 (1
Load Case: Load Case 1
Result Types: Factor of Safety
Factor of Safety:
Max: 3.386e+03
Min: 1.036e+00

Figure 4.9: Result analysis of safety factor for original bracket

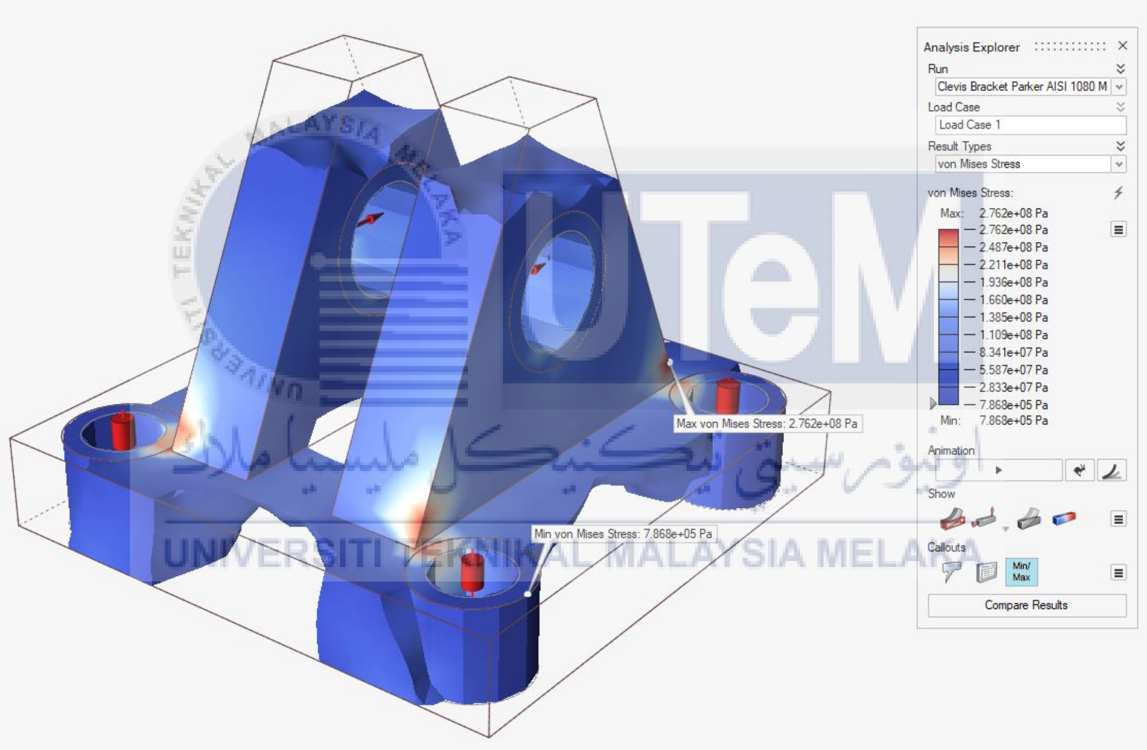


Analysis Explorer
Run: Clevis Bracket Parker AISI 1080 (1
Load Case: Load Case 1
Result Types: Displacement
Displacement: Mag
Max: 7.867e-05 m
Min: 1.953e-09 m

Figure 4.10: Result analysis of displacement for original bracket

4.5.2 Optimized Clevis Bracket Analysis

Analysis of the optimized design has been done to determine the strength of the design when the desired load applied on it. For the analysis of equivalent von-Mises stress, the maximum stress is 276.2 MPa (Figure 4.11) and the safety factor that was calculated is 1.4 (Figure 4.12). This means that the optimized design is applicable and safe to use to the desired load which is 42035 N. Next, the maximum deformation of the bracket is 0.08098 mm which locate at the tip of the bracket as shown in Figure 4.13 below.

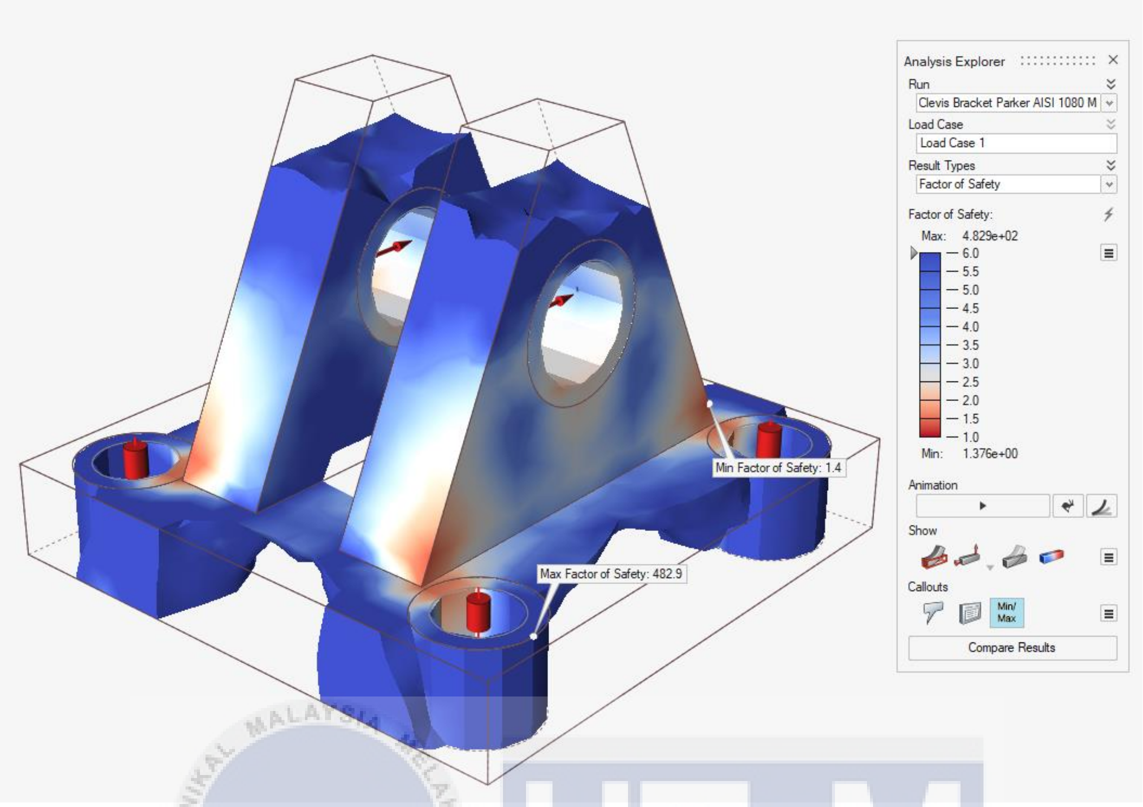


Run: Clevis Bracket Parker AISI 1080 M

Load Case: Load Case 1

Result Types: von Mises Stress

Figure 4.11: Result analysis of von-Mises stress for optimized bracket



Analysis Explorer

Run: Clevis Bracket Parker AISI 1080 M

Load Case: Load Case 1

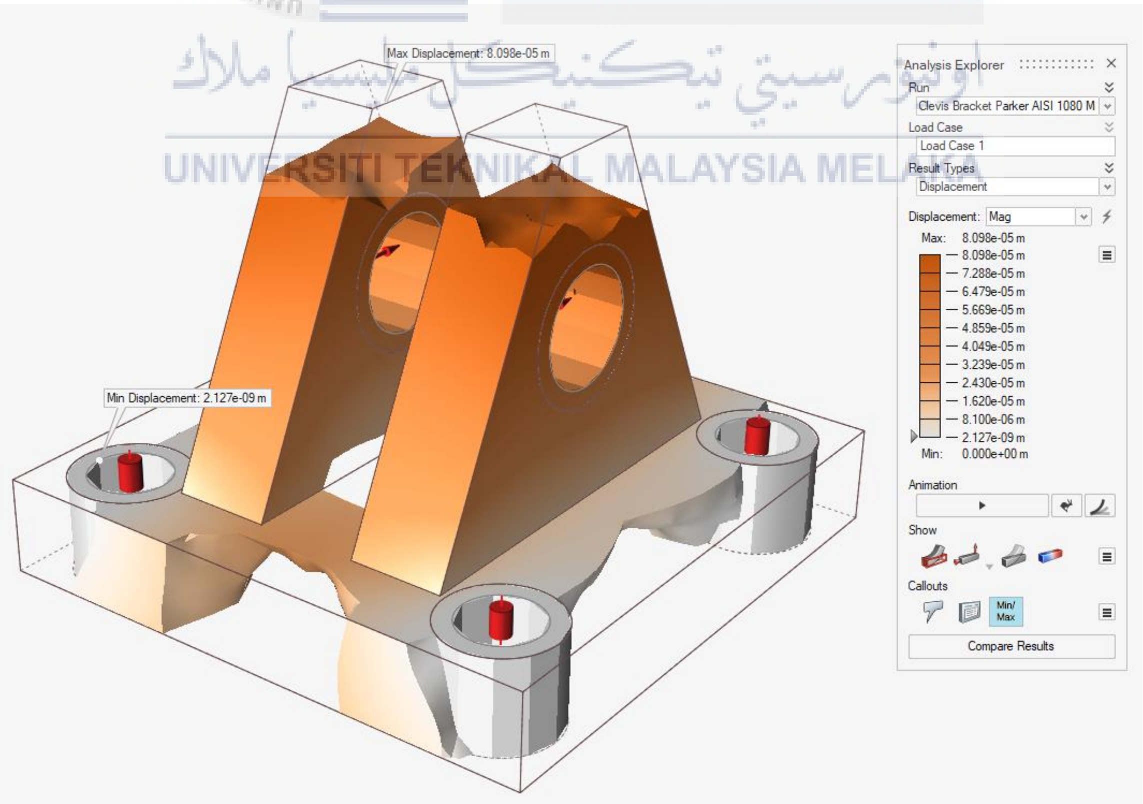
Result Types: Factor of Safety

Factor of Safety:

Max: 4.829e+02

Min: 1.376e+00

Figure 4.12: Result analysis of safety factor for optimized bracket



Analysis Explorer

Run: Clevis Bracket Parker AISI 1080 M

Load Case: Load Case 1

Result Types: Displacement

Displacement: Mag

Max: 8.098e-05 m

Min: 0.000e+00 m

Figure 4.13: Result analysis of displacement for optimized bracket

4.5.3 Discussion on Original and Optimized Bracket Analysis

From the results obtained, there is an improvement in safety factor of the bracket which is from 1.0 to 1.4. The mass of the original bracket is 1.624 kg and after topology optimization the mass reduce to 0.8734 kg. The product has achieved about 46.2 percent mass reduction. This shows that the cost of production for a single product can be reduce a lot by using topology optimization on a product. Figure 4.14 below shows the total mass before and after optimization. The calculation for the mass reduction is shown below.

Compare Factor of Safety ▼

Run	Load Case	Min Factor of Safety	Mass Total	System
Clevis Bracket Parker AISI 1080 (1)	Load Case 1	1.0	1.624e+00 kg	Global
Clevis Bracket Parker AISI 1080 Min Mass SF 1.5 (2)	Design			Global
Clevis Bracket Parker AISI 1080 Min Mass SF 1.5 (3)	Load Case 1	1.4	8.734e-01 kg	Global

Figure 4.14: Factor of safety and mass comparison

Calculation of mass reduction:

$$\left|\frac{Original\ Mass - Final\ Mass}{Original\ Mass}\right| \times 100\%$$

$$\left|\frac{1.624\ kg - 0.8734\ kg}{1.624\ kg}\right| \times 100\% = 46.22\%$$

4.6 Redesign of Clevis Bracket Analysis

The bracket optimization output is redesigned by using SolidWorks software to get a more manufacturable design. Figure 4.15 shows the optimization output of the bracket before the redesign process while Figure 4.16 shows the output after redesign process.

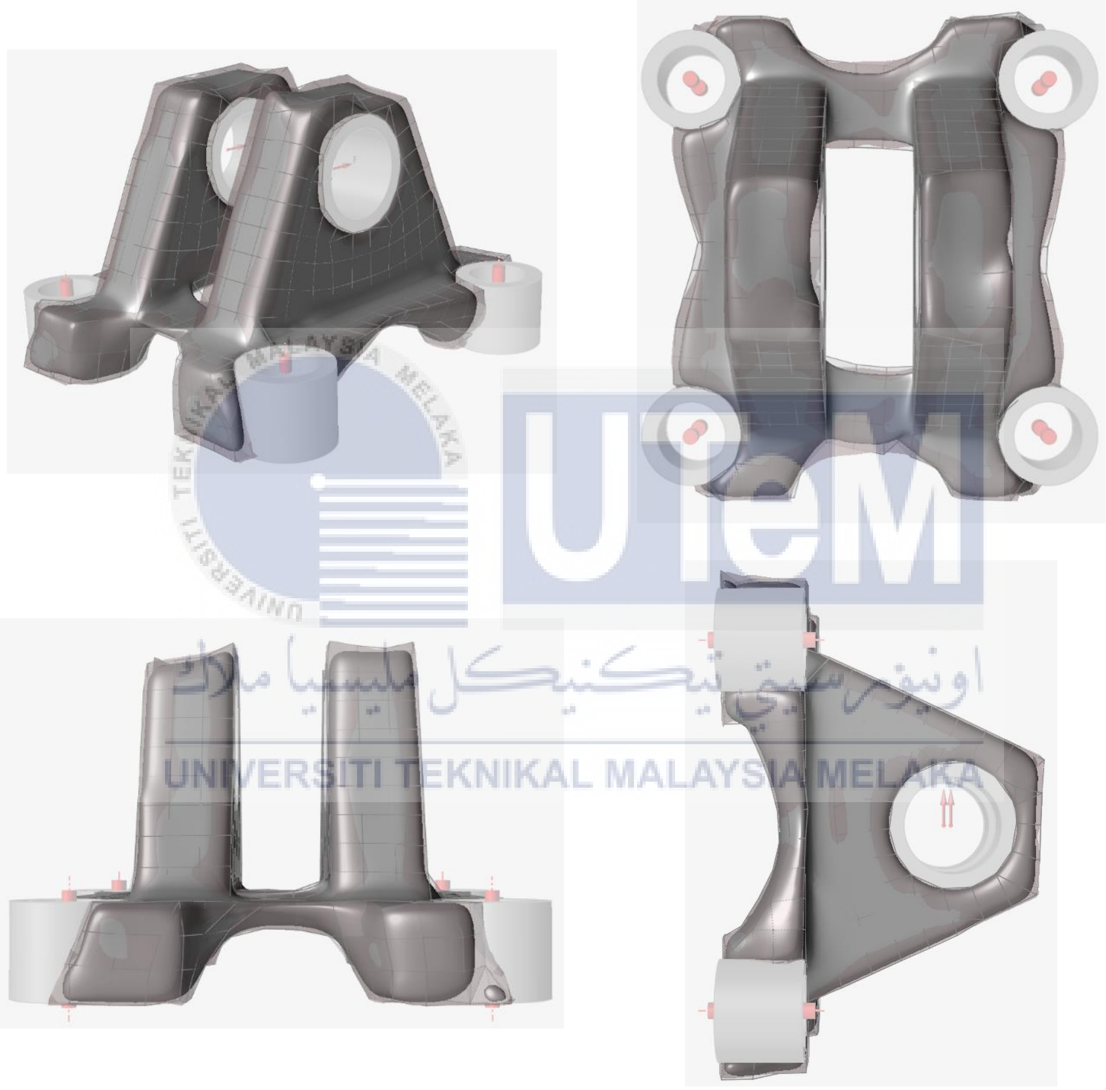


Figure 4.15: Solid design before redesign process

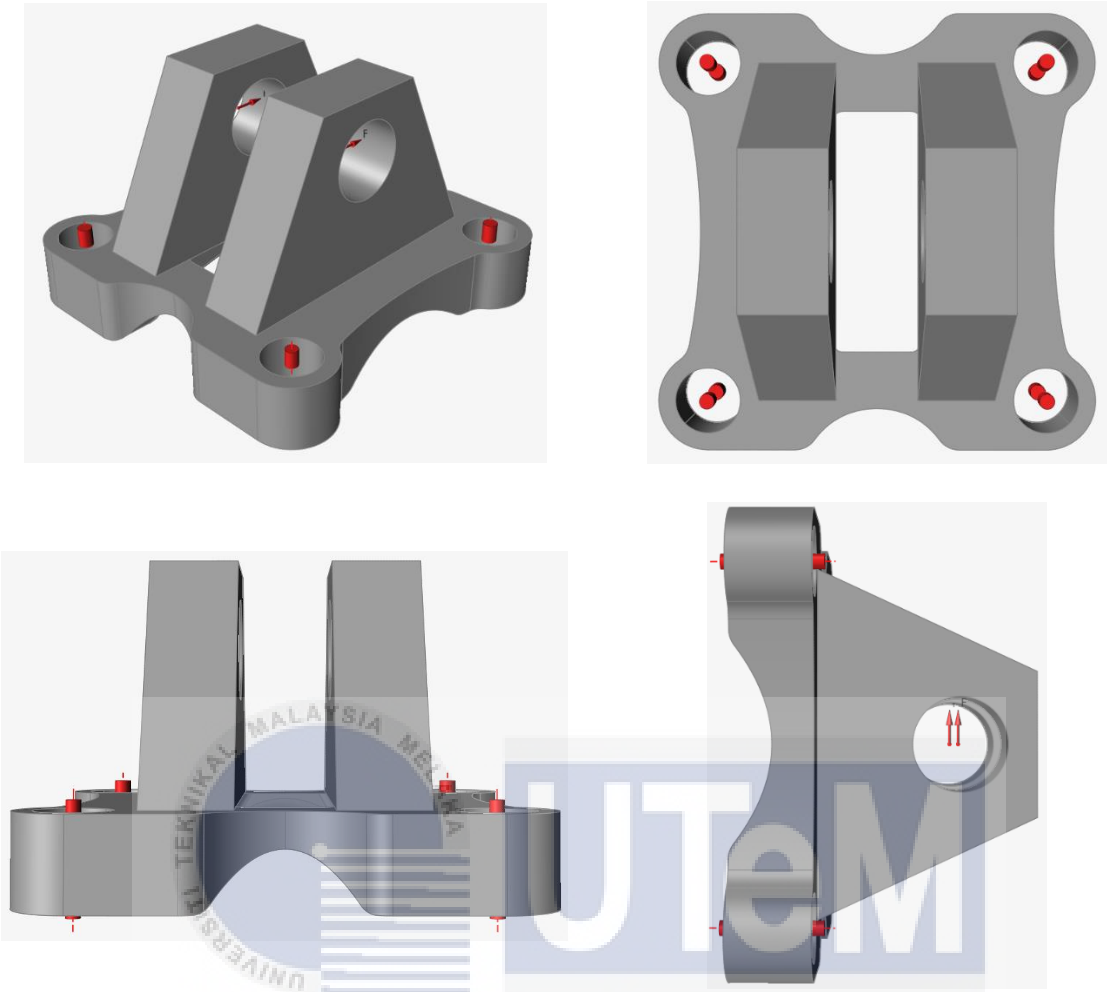
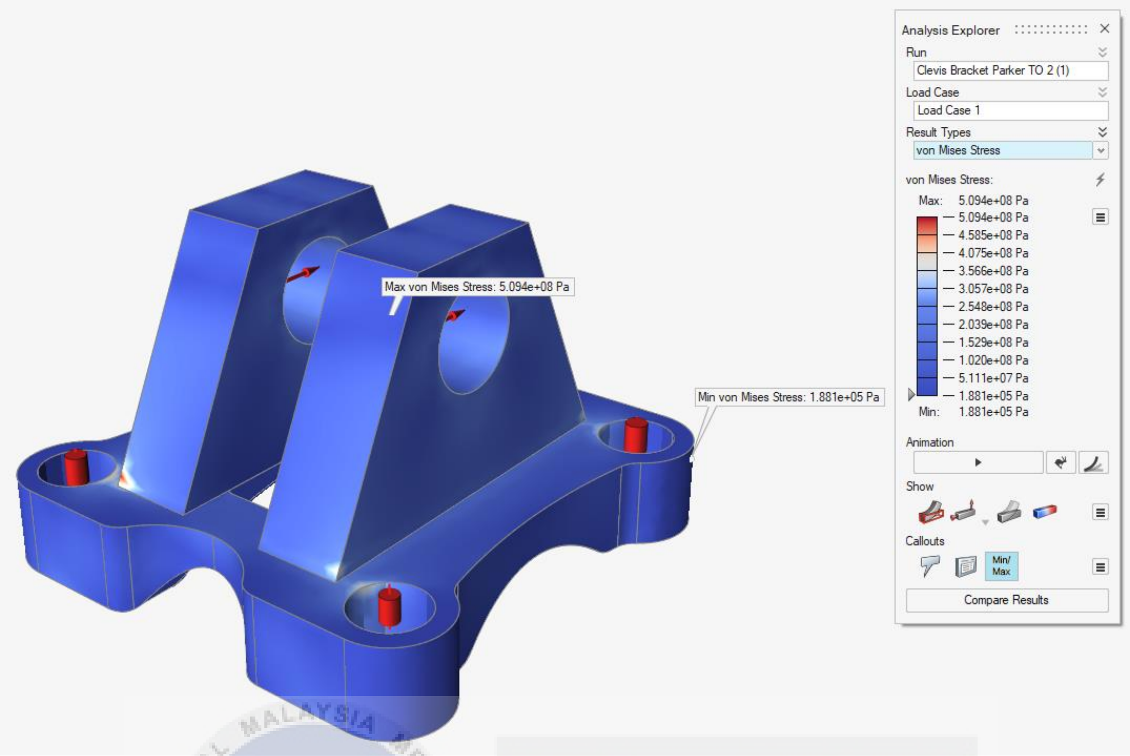


Figure 4.16: Solid design after redesign process

Then, analysis of the final design has been done to determine the strength of the final design when the desired load applied on it. For the analysis of equivalent von-Mises stress, the maximum stress is 509.4 MPa (Figure 4.17) and the safety factor that was calculated is 1.2 (Figure 4.18). This means that the design is applicable and safe to use to the desired load which is 42035 N. Next, the maximum deformation of the bracket is 0.09376 mm which locate at the tip of the bracket as shown in Figure 4.19.



Max von Mises Stress: 5.094e+08 Pa

Min von Mises Stress: 1.881e+05 Pa

Analysis Explorer

Run: Clevis Bracket Parker TO 2 (1)

Load Case: Load Case 1

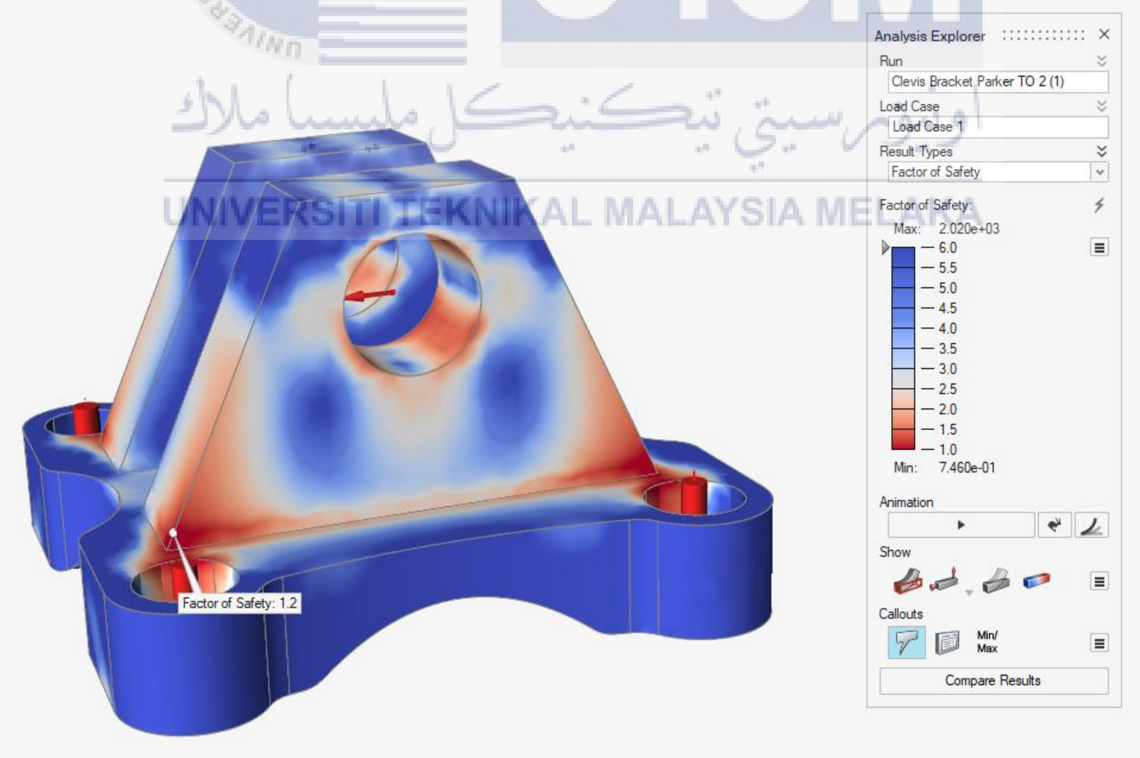
Result Types: von Mises Stress

von Mises Stress:

Max: 5.094e+08 Pa

Min: 1.881e+05 Pa

Figure 4.17: Result analysis of von-Mises stress for final design bracket



Factor of Safety: 1.2

Analysis Explorer

Run: Clevis Bracket Parker TO 2 (1)

Load Case: Load Case 1

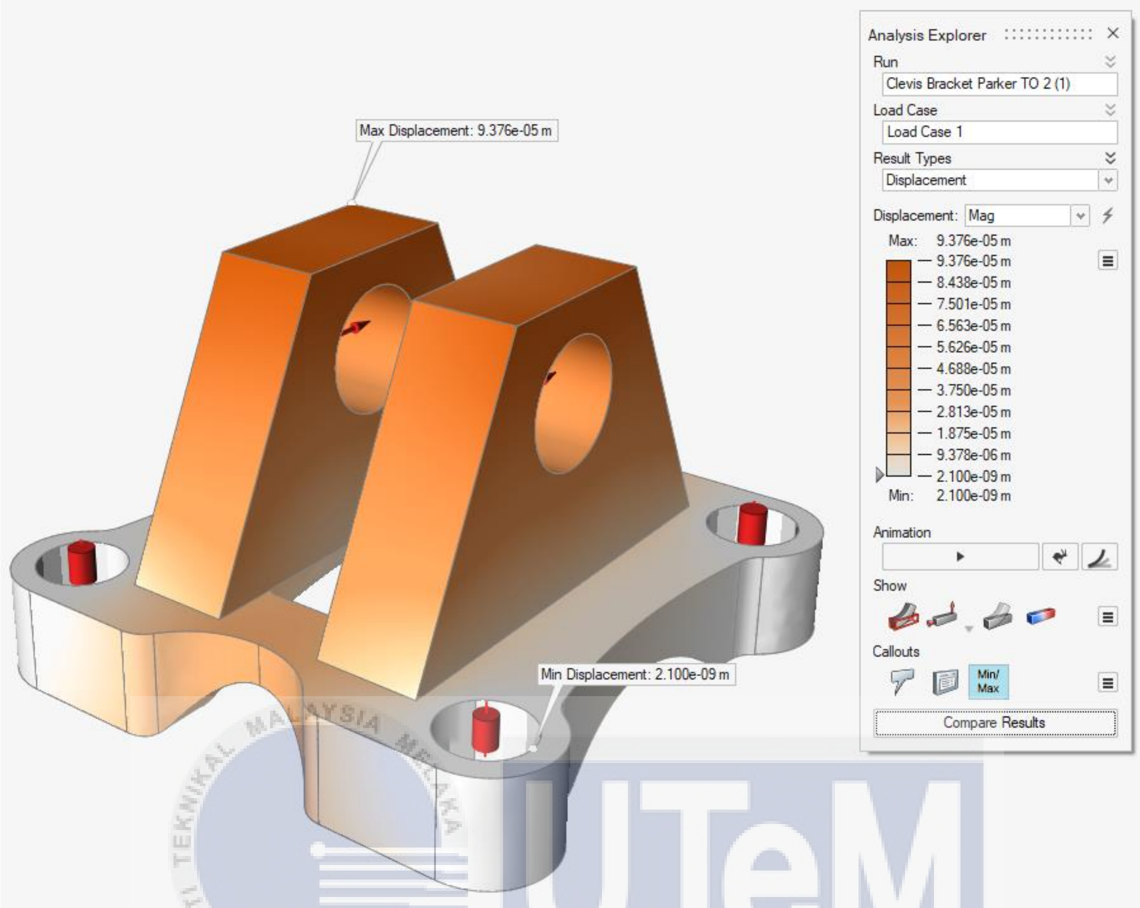
Result Types: Factor of Safety

Factor of Safety:

Max: 2.020e+03

Min: 7.460e-01

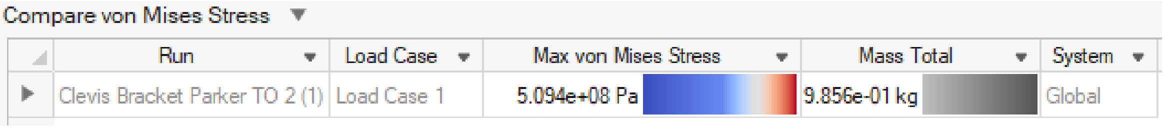
Figure 4.18: Result analysis of safety factor for final design bracket



Run: Clevis Bracket Parker TO 2 (1)
Load Case: Load Case 1
Result Types: Displacement
Displacement: Mag
Max: 9.376e-05 m
Min: 2.100e-09 m

Figure 4.19: Result analysis of displacement for final design bracket

The safety factor value acquired via the redesign process is 1.2, which is somewhat lower than the value gained through the optimization method, which is 1.4. The final design has a mass of 0.9856 kg, which is slightly higher than the optimum output design, with a mass of 0.8734 kg, as shown in Figure 4.20. The following diagram illustrates the computation of the percentage inaccuracy of the safety factor and the mass of the final design.



Compare von Mises Stress

Run	Load Case	Max von Mises Stress	Mass Total	System
Clevis Bracket Parker TO 2 (1)	Load Case 1	5.094e+08 Pa	9.856e-01 kg	Global

Figure 4.20: Mass of the bracket final design

Percentage error calculation:

1. *Factor of safety (FS)*

$$\left|\frac{Optimized\ FS - Redesign\ FS}{Optimized\ FS}\right| \times 100\%$$

$$\left|\frac{1.4 - 1.2}{1.4}\right| \times 100\% = 14.29\%$$

2. *Mass*

$$\left|\frac{Optimized\ Mass - Redesign\ Mass}{Optimized\ Mass}\right| \times 100\%$$

$$\left|\frac{0.8734\ kg - 0.9856\ kg}{0.8734\ kg}\right| \times 100\% = 12.85\%$$

The safety factor has a margin of error of 14.29 percent, whereas the mass has a margin of error of 12.85 percent. As a result, the situation is still acceptable since the safety factor value is still within the acceptable range (1 – 3). As a result, according to the calculations below, the final design mass reduction of the bracket is 39.31 percent in total.

Calculation of final design mass reduction:

$$\left|\frac{Original\ Mass - Final\ Redesign\ Mass}{Original\ Mass}\right| \times 100\%$$

$$\left|\frac{1.624\ kg - 0.9856\ kg}{1.624\ kg}\right| \times 100\% = 39.31\%$$

Figure 4.21: FEA results comparison between original and optimized bracket bar chart

From Figure 4.21, we can see that there is a lot of improvement in mechanical properties when using TO method. For example, the max von-Mises stress and safety factor of the Steel Clevis Bracket is improved. In addition, the mass of the bracket is also reduced from 1.624 kg to 0.9856 kg (39.31% mass reduction). This result proves that by using TO method, a higher specs and quality of the product can be achieved.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the AM method offers many opportunities in producing more complex design structures due to less restriction of the design part. In comparing gravity die casting and FDM process, we can say that a lot of cost and time can be conserved when using FDM compared to the gravity die casting process. The simulation and literature study result shows that the cost for the gravity die casting of the Steel Clevis Bracket is higher than the FDM process. This is because the casting process requires a lot of setup costs such as tooling cost, mold cost, pre-process and post-process cost, and manpower cost. The lead time of the entire casting process is longer than the FDM process due to multiple tooling setup requirements for the casting process. Not to mention the numerous complex cores because the bracket has many holes and undercuts. As a result, it can take a lot of time to prepare the mold and cores. The structural analysis simulations prove that despite a 39% reduction in the bracket weight, the mechanical performance of the optimized design is observed to be increased by 16%. Thus, it is safe to say that a lot of improvement can be made when using topology optimization method. Besides, it can reduce the waste of material and cost of production.

5.2 Recommendations

The cost and time comparison for conventional casting can be done in more detail by using other software than SolidThinking Inspire for future work. This is due to a lack of the simulation details, such as the total cost and time taken to complete the process. Alternative AM method that can be use is powder bed fusion. This is to obtain more comparable results to the casting process for metal objects since FDM metal filament has lower strength than real metal material. Powder bed fusion can use a steel powder obtained from real steel, which is not an infused one. Every recommendation is useful for gaining more results in the design process between the conventional and AM methods for future work.

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