# CONCEPTUAL DESIGN OF THE CRUTCHES USING TRIZ-BIOMIMETICS METHOD

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# CONCEPTUAL DESIGN OF THE CRUTCHES USING TRIZ-BIOMIMETICS METHOD

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**A report submitted**
**in fulfillment of the requirements for the degree of**
**Bachelor of Mechanical Engineering**

**Faculty of Mechanical Engineering**

**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

**2020**

## DECLARATION

I declare that this project report entitled "Conceptual design of the crutches using TRIZ-Biomimetics method" 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.

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|---|---|---|
| Signature | : | .................................. |
| Supervisor's Name | : | .................................. |
| Date | : | .................................. |

# DEDICATION

To my beloved mother and father

## ABSTRACT

Crutch is a medical device that give assistance to disabled people in walking. Most of the crutches are made of hollow tube that consists low resistance of local buckling and ovalization. This study explained the conceptual design processes of the crutches using Theory of Inventive Problem Solving (TRIZ) with the integration of Biomimetics method. There are still many constraints in order to implement the nature technology into engineering designs discipline. Biomimetics known as a method in mimicking the technology of the nature were used in this study to be the bridge of the technology transfer. The objectives of this study are to generate the design concepts of crutch based on TRIZ Function Oriented Search (FOS) with Biomimetics method and selecting the best design concepts using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. This study has been carried out through eight processes namely problem identification, function analysis, TRIZ (FOS) – Biomimetics method, biological strategies, design concept generation, performance analysis, results/data gathering and final design concept selection. The preliminary result shows that the design concept 1 (DC1) using carbon fiber reinforced polymer (CFRP) composites material is the ideal solution among the 20 design variables. Then, the design of the DC1 was optimized to achieved the optimum results. The final result shows that the optimized design concept 1 (DC1-new) with CFRP material is the most ideal solution among 6 design variables (CFRP material). The weight of the DC1-new has been reduced by 28% (from 0.540 kg to 0.385 kg) and the safety factor has been improved from 10.31 to 4.52. As a conclusion, TRIZ (FOS) – Biomimetics method succesfully shows that

it can be the medium in transferring the nature technology into engineering design to generate the design concepts while TOPSIS method can evaluate multiple alternatives (design concepts) with multiple criteria to select the ideal solution of the design for the crutches. The integrated method of TRIZ (FOS) – Biomimetics and TOPSIS can assists designers, engineers and researchers in transferring the biological technology into engineering designs to solve the engineering problems.

# ABSTRAK

Topang adalah alat perubatan yang membantu orang kurang upaya untuk berjalan. Kebanyakan topang diperbuat daripada tiub berongga yang mempunyai rintangan yang rendah ke atas lengkungan dan perubahan bentuk bujur. Kajian ini menerangkan tentang proses konsep rekabentuk bagi topang menggunakan kaedah Teori Penyelesaian Masalah Inventif (TRIZ) dengan integrasi kaedah Biomimetik. Masih terdapat banyak kekangan dalam melaksanakan pemindahan teknologi alam semula jadi ke dalam disiplin rekabentuk kejuruteraan. Biomimetik dikenali sebagai kaedah dalam meniru teknologi alam semula jadi akan digunakan dalam kajian ini untuk menjadi pengantara pemindahan teknologi. Objektif kajian ini adalah untuk menjana konsep rekabentuk topang berdasarkan keadah TRIZ – Carian Berorientasikan Fungsi (FOS) dengan kaedah Biomimetik dan memilih konsep rekabentuk yang terbaik dengan menggunakan Teknik Pilihan Urutan Mengikut Kesamaan dengan Penyelesaian Ideal (TOPSIS). Kajian ini telah dilaksanakan melalui lapan proses iaitu pengenalpastian masalah, analisis fungsi, kaedah TRIZ (FOS) – Biomimetik, strategi biologi, penghasilan rekabentuk konsep, analisis prestasi, pengumpulan keputusan/data dan pemilihan akhir rekabentuk konsep. Keputusan awal menunjukkan bahawa rekabentuk konsep 1 (DC1) yang menggunakan polimer gentian karbon (CFRP) adalah penyelesaian yang ideal antara 20 pembolehubah rekabentuk. Kemudian, rekabentuk DC1 telah dioptimumkan untuk mencapai hasil yang lebih memberangsangkan. Keputusan akhir kali ini menunjukkan bahawa konsep reka bentuk yang dioptimumkan 1 (DC1-baru) dengan bahan CFRP adalah penyelesaian yang paling ideal di antara 6 pembolehubah rekabentuk (bahan CFRP). Berat DC1-baru ini berkurang sebanyak 28% (dari 0.540 kg kepada 0.385 kg) dan faktor keselamatan telah bertambah baik daripada 10.31 kepada 4.52. Kesimpulannya, keadah TRIZ (FOS) – Biomimetik menunjukkan bahawa ia boleh menjadi medium dalam pemindahan teknologi alam semulajadi ke dalam rekabentuk kejuruteraan untuk menjana rekabentuk konsep manakala kaedah TOPSIS boleh menilai pelbagai alternatif (rekabentuk konsep) dengan pelbagai kriteria dalam memilih penyelesaian yang ideal bagi rekabentuk topang. Kaedah bersepadu TRIZ (FOS) – Biomimetik dan TOPSIS dapat membantu pereka, jurutera dan penyelidik dalam memindahkan teknologi biologi ke dalam rekabentuk kejuruteraan bagi menyelesaikan masalah kejuruteraan.

## ACKNOWLEDGEMENTS

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| | |
|---|---|
| AD | Axiomatic Design |
| AHP | Analytic Hierarchy Process |
| CFRP | Carbon Fiber Reinforced Polymer |
| DFMA | Design for Manufacture and Assembly |
| FMEA | Failure Mode and Effect Analysis |
| FOS | Function Oriented Search |
| GFRP | Glass Fiber Reinforced Polymer |
| MCDM | Multiple Criteria Decision Making |
| NLP | Neuro-Linguistic Programming |
| QFD | Quality Function Deployment |
| SCAMPER | Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse |
| TOC | Theory of Constraints |
| TOPSIS | Technique for Order of Preference by Similarity to Ideal Solution |
| TRIZ | Teoriya Resheniya Izobreatatelskikh Zadatch |
| U.S.S.R. | Union of Soviet Socialist Republics |
| VIKOR | VlseKriterijumska Optimizacija I Kompromisno Resenje |
| 6σ | Six Sigma |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Crutch is a medical tool or walking aids that used by people who were unable to use their legs due to short-term injuries or lifelong disabilities and crutch able to assist them to move (Physiopedia Contributors, 2019). There are three types of crutches which are underarm or axillary crutches, forearm crutches and platform crutches. Most of the crutches available in the market are made of hollow cylindrical aluminium tube. The advantages of aluminium are their strength, high rigidity and low density that can provides comfortability to the users when they move (Stojanovic, Bukvic and Epler, 2018). Nevertheless, in order to enhance the crutches design and performance, design optimization process is required. Therefore, implementation of problem-solving tools is required in order to assist the designers or researchers in the process of design optimization and one of the most familiar and famous problem-solving tools is the Theory of Inventive Problem Solving (TRIZ).



TRIZ is a collection of tools and techniques which founded by Genrich S. Altshuller and his colleagues during the former Union of Soviet Socialist Republics (U.S.S.R.). TRIZ able to define the problem at a functional level precisely and provides highly effective and innovative solutions. Besides that, TRIZ has integrated with different types of problem-solving tools, techniques and philosophies such as Quality Function Deployment (QFD), Six Sigma (6σ) and one of the well-known problem-solving tool is the contradiction matrix with 40 inventive principles. A new TRIZ-based tool which is Function Oriented Search (FOS) has developed by S. S. Litvin (2004) where it requires less time and effort to prove the potency of the new solution due to the method that can adapts the existing technology, product or process to solve problem. Nonetheless, Bogatyrev (2000) and Vincent and Mann

(2002) as cited in Vincent et al. (2006) stated that TRIZ is well-known in transferring of functionality and integration of knowledge from one field to another as well as biomimetics. Therefore, TRIZ seems as an ideal point of departure and as an important linkage for nature-engineering problem solving.

Biomimetics or biomimicry define as a subject that imitate nature or biological characteristics and it was implemented in product design to solve engineering problems (Biomimicry Institute, 2015; Pathak, 2019). In other words, biomimetics also known as technology transfer method as its copy the nature strategies to solve the engineering problems. Wahab, Rose and Osman (2011) defined that technology transfer is closely link to the transfer of information, know-how, technical knowledge embodied in products, processes and management. Pathak (2019) stated that biomimicry claims that nature is the most prominent and assured source of inspiration for the designers by imitate the design features from nature due to nature’s 3.8 billion years of evolution, as it has adapted and transformed based on the experience of solving limitation of the environment to meet their needs.

The purpose of this project is to create a new design concept of the crutches based on biological strategies by implementation of TRIZ (FOS) – Biomimetics method that able to reduce the weight and enhancing the performance and quality of crutches at the same time. In addition, it can create a breakthrough in design process and manufacturing process therefore change the perspective for the combination of biological and engineering. Besides that, it also allows user breakthrough in material selection. User can choose composite materials rather than just apply the conventional materials (mainly metals). Daniel *et al.* (1994) stated that composite materials consist a lot of advantages compare to conventional materials. For instance, high strength, high stiffness, low density and etc.

## 1.2 Problem Statement

There are still many drawbacks in conducting and practicing the technology transfer discipline, which varies from biological cases to engineering cases. Bogatyrev and Bogatyreva (2015) mentioned that there are variations in methodologies and societies between biological and engineering. Therefore, it is very difficult to develop a strong bridge between nature and engineering. In addition, Baldussu and Cascini (2015) also stated that engineers and designers lack knowledge and guidance to adopt the principle of technology transfer through the integration of biological and nature with engineering, and this is the barrier for engineers and designers to find a suitable biological strategy to solve engineering problems and the widespread application of biomimetics in industrial research and development activities.

Other than that, most of the crutches are made of hollow tube due to hollow tube are lightweight. Nevertheless, Karam and Gibson (1994) and Vincent (2002) stated the weakness of the hollow tube or cylindrical shell structures that hollow tube is usually unable to resist of local buckling and ovalization. From the previous statement, it can make the assumptions that it may cause injury again to the user due to failure design of crutches. In order to overcome the local buckling and ovalization issue, the stiffener will be adding in the hollow tube but most of the crutches are made in aluminium material with around $2700 kg/m^3$ of density and this will increase the weight of the crutches. Therefore, different materials need to be applied in order to achieve lightweight target.

## 1.3 Objective

The objectives of this project are as follows:

1. To develop the design concepts for the crutches using TRIZ (FOS) -Biomimetics method.
2. To study the performance of the design concepts through finite element analysis (FEA) using Autodesk Fusion 360 software.
3. To select the best design concept of the crutch using Multiple Criteria Decision Making (MCDM) method.

## 1.4 Scope of Project

The scopes of this project are:

1. This project will focus on the axillary (underarm) crutches.
2. The performance criteria of the design concepts which is stress, displacement, weight and safety factor are simulated in this project.
3. The Multiple Criteria Decision Making (MCDM) method used in this project is Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to select of the final design concept of the crutch.

# CHAPTER 2

# LITERATURE REVIEW

Morphology of design demonstrate detailed description of the design process shows in Figure 1 was introduced by Asimow (1962) (Dieter and Schmidt, 2013). The design process was divided into three phases namely, conceptual design, embodiment design and detail design. Conceptual design refers the problem statement that have been analyzed based on the needs and generates various of ideas and preliminary solutions (French, 1985). Problem definition is the first and the most important stages in the product design process to create a statement explains about what the requirements that product must meet. A thorough understanding of problems are essential in order to find an excellent solution. Besides that, gather information can be made through various of sources such as internet, journal and technical article. However, designers and engineers are required to validate the gathered information to ensure that the information is reliable. In order to generate innovative concept design solution, the gather information step is placed between the problem definition and concept generation steps as shown. Dieter and Schmidt (2013) also stated that gather information is an important step in product design process because it brings great influences for the embodiment and detail design phases. In addition, concept generation includes creating a wide range of design concepts that might meet the product needs and satisfy the problem statement. In order to generate extraordinary and reliable design concept, designers and engineers required to think creatively and critically with fully utilization of gathered information by using problem-solving tool such as brainstorming, mind mapping and Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, Reverse (SCAMPER). Finally, Multiple Criteria Decision Making (MCDM) method is used in this project for evaluation of design concepts that function as selection the final ideal design concept among various of design concepts with contradiction of multiple design criteria before proceeds to embodiment design phase. Hsu and Liu (2000) and Wang *et al.* (2002) identified that conceptual design is the most important phases in product design because it gives a vast impact to the product such as total cost, performance, quality and others. Therefore, this project focus on conceptual design phase which requires the problem identification, information gathering, design concept development and design concept evaluation for the crutches.

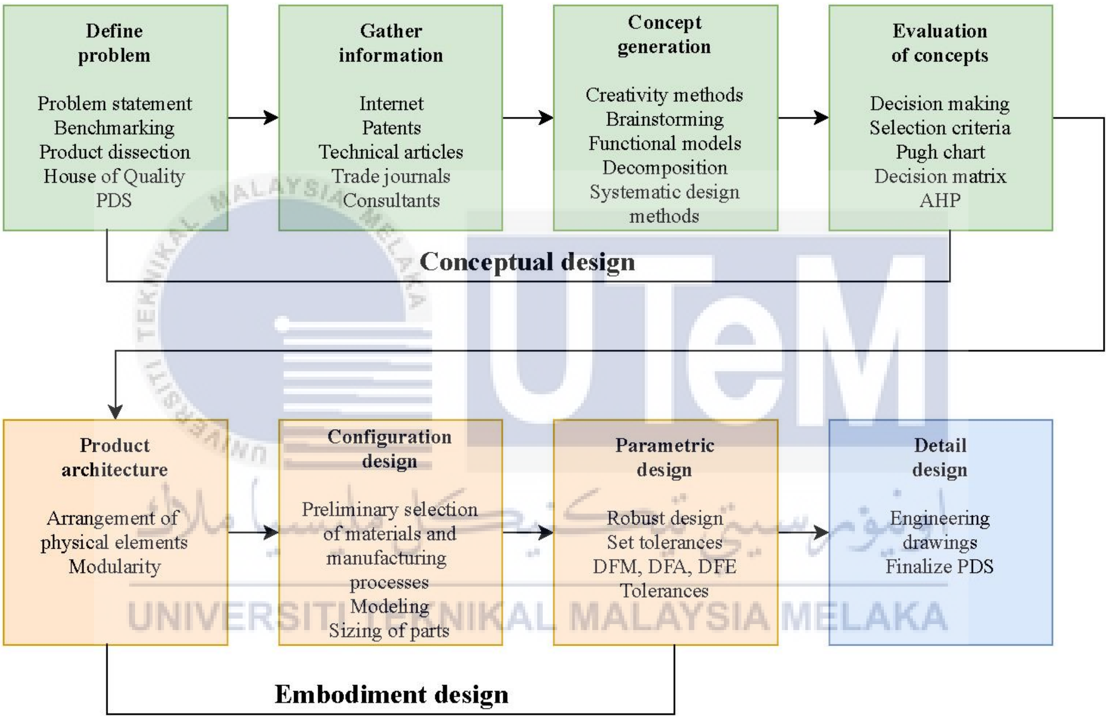



Figure 1: Morphology of design (From Dieter and Schmidt, 2013)

Crutch is a mobility device and walking support used by those who are unable to use their limbs because of short-term accidents and permanent disabilities (Edelstein, 2019; Physiopedia Contributors, 2019). Figure 2 shows three main types of crutches which are axillary (underarm) crutches, forearm crutches and gutter (platform) crutches. Axillary (underarm) crutches are the most common crutches and used by positioning the pad against the ribcage below the armpit and holding the grip. Forearm crutches has a forearm cuff that allows user inserts the arm into the forearm cuff and hold the handgrip. Gutter (platform) crutches are suitable used by people with poor hand or grip strength due to arthritis, cerebral palsy, or other disabilities. The forearm sits on a horizontal platform and is typically attached with Velcro straps.


Figure 2: Types of crutches

At present, most of the crutches are made from hollow tube of aluminium or magnesium. Karam and Gibson (1994) and Vincent (2002) stated that hollow tube or cylindrical shell structures usually fail to resist of local buckling and ovalization. Therefore, additional of stiffener or foam core in the tube is added in order to overcome the ovalization and local buckling issue. Nevertheless, the weight of the hollow tube will increase by adding the stiffener or foam core. Alternatively, composite material indicates as an ideal solution in order to produce the product with high strength and low weight of properties. Composite material is a material that compound of two or more different materials and present extraordinary of material properties with high strength-to-weight ratio (Alberto, 2013). In this project, the composite materials that studied are carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). CFRP and GFRP are the composite material made of polymer such as polyester thermosetting plastic, epoxy, vinyl ester or nylon and reinforced with carbon and glass fiber (Alberto, 2013; Che *et al.*, 2014). Besides of material properties, generating adequate ideas are also important in order to develop several of adequate design concepts.

Nowadays, there are many tools to generate good idea to solve the problems such as Ishikawa diagram (or fishbone diagram), failure mode and effect analysis (FMEA), morphology chart, brainstorming and the Theory of Inventive Problem Solving (TRIZ) (Mansor *et al.*, 2017). Recently, TRIZ is getting familiar and popular within engineering field. It helps designers or researchers to determine the keyword or main problem and generating ideas or solutions that gives the positive output in design process.

TRIZ, the acronym of 'Teoriya Resheniya Izobreatatelskikh Zadatch' in Russian term which means the Theory of Inventive Problem Solving. TRIZ was developed by Genrich S. Altshuller and his colleagues in the former Union of Soviet Socialist Republics (U.S.S.R.) between 1946 and 1985. TRIZ is a collection of tools and techniques that ensures an accurate definition of a problem at a functional level and then provides strong indicators towards successful and often highly innovative solutions. In addition, Hua *et al.* (2006) listed the problem-solving tools, techniques and philosophies that have been integrated or compared with TRIZ such as Quality Function Deployment (QFD), Six Sigma (6σ), Design for Manufacture and Assembly (DFMA), Robust Design, Axiomatic Design (AD), Theory of Constraints (TOC), Brainstorming, De Bono's theories, Mind Mapping, Neuro-Linguistic Programming (NLP) and others. Abramov *et al.* (2015) and Li *et al.* (2015) also constructed a TRIZ based innovation roadmap as shown in Figure 3. The roadmap consists of four stages namely target definition, problem identification, problem solving and solution evaluation. Target definition stage is to identify and select the products which target specifically on the product parameters and features to be improved and optimized. Next, problem identification stage is to identify the specific problems of the product that should be solved from different perspective by using system analysis tools and there are several of tools such as function analysis, flow analysis and cause-effect chain analysis. After that, there are several of tools that can be utilise for problem solving in order to generate design concept. For instance, the contradiction matrix with 40 inventive principles is one of the most popular and the most recommended of problem-solving tool by designers and engineers. Finally, evaluation solution process will be carried out before implementation of solution in order to ensure the feasibility and reliability of the solution.

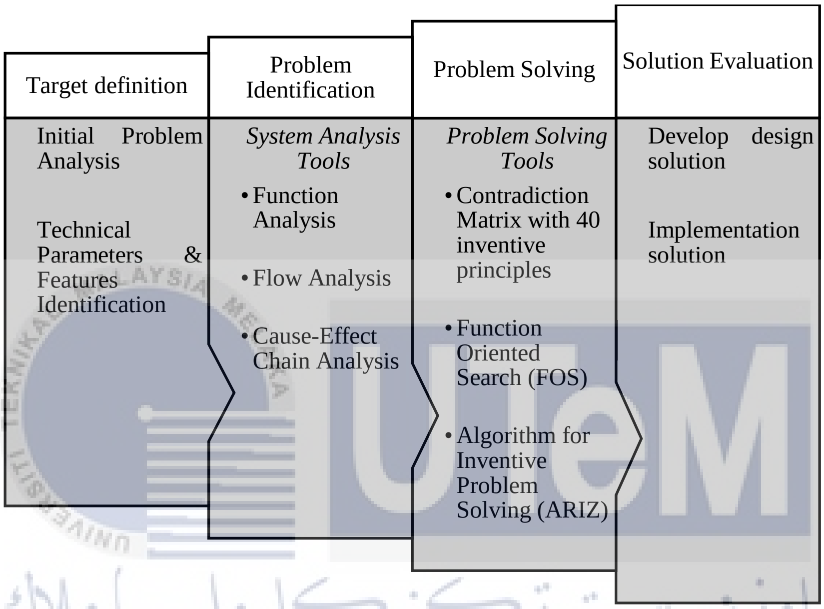



Figure 3: TRIZ based innovation roadmap



In other research, Litvin (2004) stated that one the major problems to implement the TRIZ is a contradiction within TRIZ itself. So, he has developed a new TRIZ-based tool which is Function-Oriented Search (FOS). Savelli and Abramov (2017) agree that FOS is a practical and efficient approach to open innovation. FOS offers very effective action principle to solve the initial problem through finding and adapting an existing technology, product or process from remote areas of science and engineering to solve problem that needs innovation. FOS also able to reduce the user's time and effort to prove the effectiveness of the new solution. Bogatyrev (2000) and Vincent and Mann (2002) as cited in Vincent *et al.* (2006) stated that TRIZ is leading for its successful transfer of functionality and integrating knowledge from one field to another as well as biomimetics. Therefore, TRIZ seems as an ideal point of departure and as a missing link for nature-engineering problem solving.

Biomimetics or biomimicry (from bios, meaning life, and mimesis, meaning to imitate) literally means, “to imitate life” (Pathak, 2019). Biomimetics is the practice of applying lessons or emulating from nature either the formation, structure or function to solve human problems and needs by transfer of ideas from biology to technology. Biomimetics able to help designers or researchers to develop sustainable new products, systems and processes or improve existing design and solve engineering problems by imitating or mimicking the biological strategies (Biomimicry Institute, 2015; Pathak, 2019). There were successful products of biomimetics method such as Japan’s Shinkansen Bullet Train by Eiji Nakatsu designed the forefront of the Shinkansen train based on Kingfisher’s beak (AskNatureTeam, 2017), Pangolin backpack which mimicking the pangolin animal’s biomechanics which is more durable, impact-proof and protects contents better than a cloth pack (AskNatureTeam, 2016a) and WhalePower Corporation developed tubercle-enhanced blades which mimicking the Humpback whale flippers (Fish *et al.*, 2011). Biomimetics able to lead engineers or designers to develop new products, processes and systems, or improve existing designs. It also able to change point of view in analysing design problems and objectives and discover “new” solutions for complicated problems (Biomimicry Institute, 2015). In this project, the integration method of TRIZ (FOS) and biomimetics was implemented as the new concept of idea generation technique for product development process in the conceptual design stage.

In order to evaluate the concept, Multiple Criteria Decision Making (MCDM) is executed. Ewa (2011) stated that MCDM refers to assist decision makers to decide the best solution from among several of proposed solutions or concepts which integrated with multiple of contradictory criteria. MCDM consists several of method such as Analytic

Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) are the well-known methods. Nevertheless, TOPSIS method has been selected and used in this project due to TOPSIS method is simple, understandable, high productivity and straightforward in computation process and able to identify the best performance of solution or concept by using simple mathematical equation (Ewa, 2011; García-Cascales and Lamata, 2012). TOPSIS was developed by Hwang and Yoon in 1981 (Pavić and Novoselac, 2013). Krohling and Pacheco (2015) mentioned that user able to identify the ideal solution which is nearest to the ideal best solution that consists of all best values of criteria and furthest from ideal worst solution that consists of all worst values of criteria by using TOPSIS method.

In a nutshell, the purpose of this project is to enhance the design of the crutches by develop the design concepts using TRIZ (FOS)-Biomimetics method. After that, generate the design concepts 3D model and study the performance of the design concepts through finite element analysis (FEA) using Autodesk Fusion 360 software. Finally, the new crutch design is selected among several of design concepts by using Multiple Criteria Decision Making (MCDM) method.

# CHAPTER 3

# METHODOLOGY

## 3.1 Introduction

The methodology used in this study to generate ideas in the conceptual design stage for crutches were based on TRIZ (FOS) – Biomimetics method. The framework of this project are shown in Figure 4. There are eight main processes in the framework used in this study which is problem identification, function analysis, TRIZ Function Oriented Search (FOS) in Biomimetics, biological strategies, design concepts generation, performance analysis, results/data gathering and selection for final design concept.

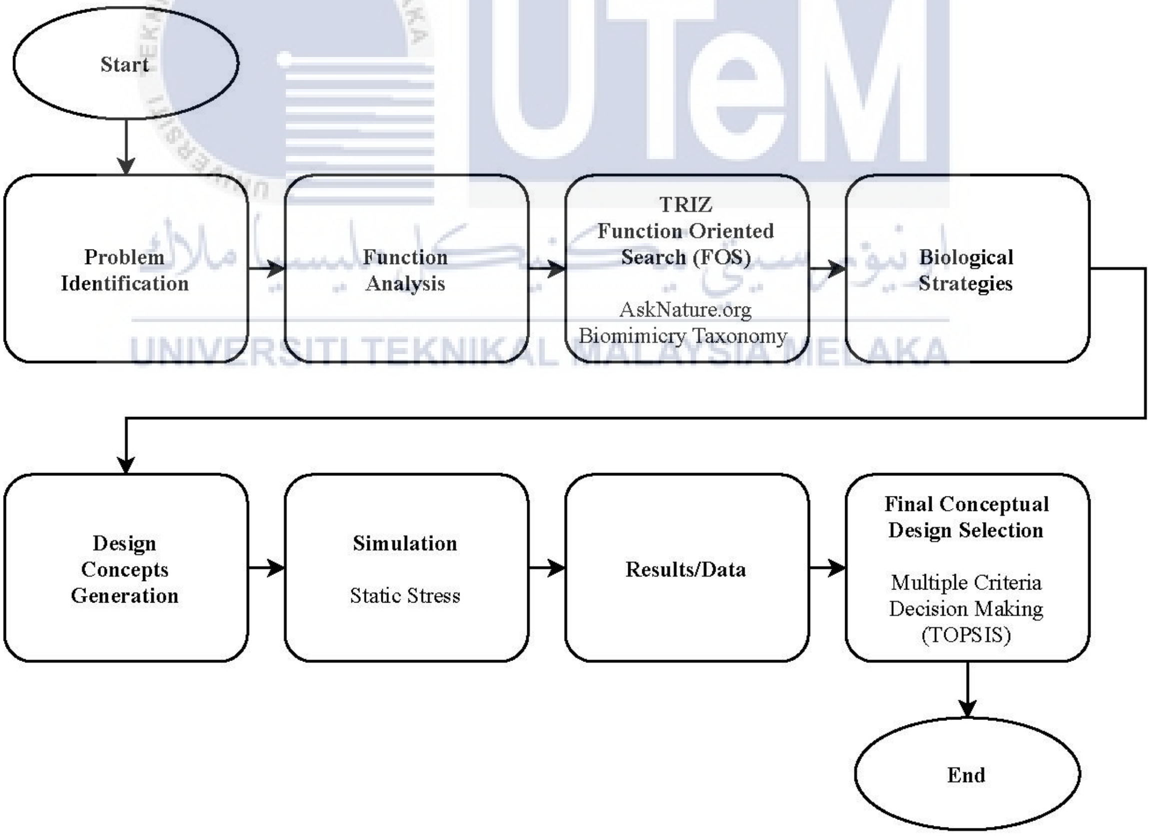



Figure 4: Framework of the TRIZ (FOS) - Biomimetics method

## 3.2 Framework of TRIZ (FOS) – Biomimetics method

The framework starts with identifying the problem of the products which available in current market and list out the problem statement that are significant. After that, function analysis in TRIZ is to identify the functions and characteristics of the products. The purpose of the function analysis is to understand the function of every parts or component in the product and identify what function that want to solve for the product by applying TRIZ Function Oriented Search (FOS) which is one of the TRIZ tool while for biomimetics was based on AskNature.org (Biomimicry Institute, 2006) and Biomimicry Taxonomy (Biomimicry Institute, 2008). Keywords of the function analysis can give ideas to the users for TRIZ FOS in biomimetics. There are 2 methods in order to carry out for the TRIZ FOS – Biomimetics, as follows:

Method 1 is to find the TRIZ FOS – Biomimetics, user can insert the keywords of the function analysis in the AskNature.org search bar as shown in Figure 5.

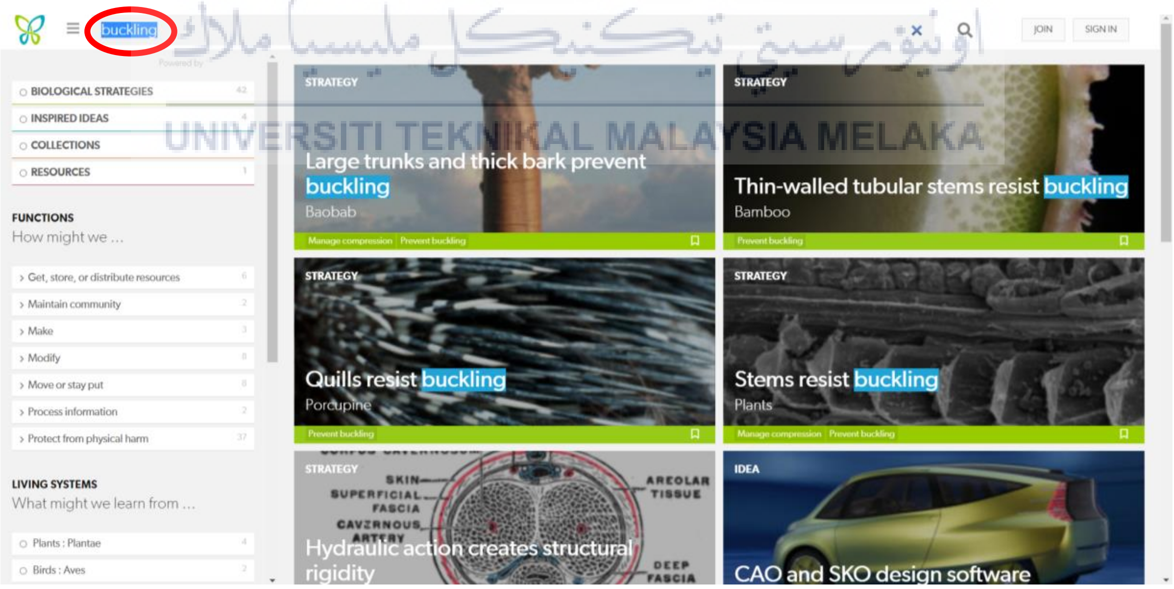



Figure 5: AskNature.org



In the other hand, user can appply the second method which is using the function keywords on the Biomimicry Taxonomy as shown in Figure 6. Biomimicry Taxonomy is a classification system developed by Biomimicry Institute that features of 8 groups and 30 sub-groups that contain more than 160 functions where user can use it as a guidance in order to carry out TRIZ FOS – Biomimetics in AskNature.org. From the Biomimicry Taxonomy, user can identify the function keyword to solve the current engineering problem for the product faster.

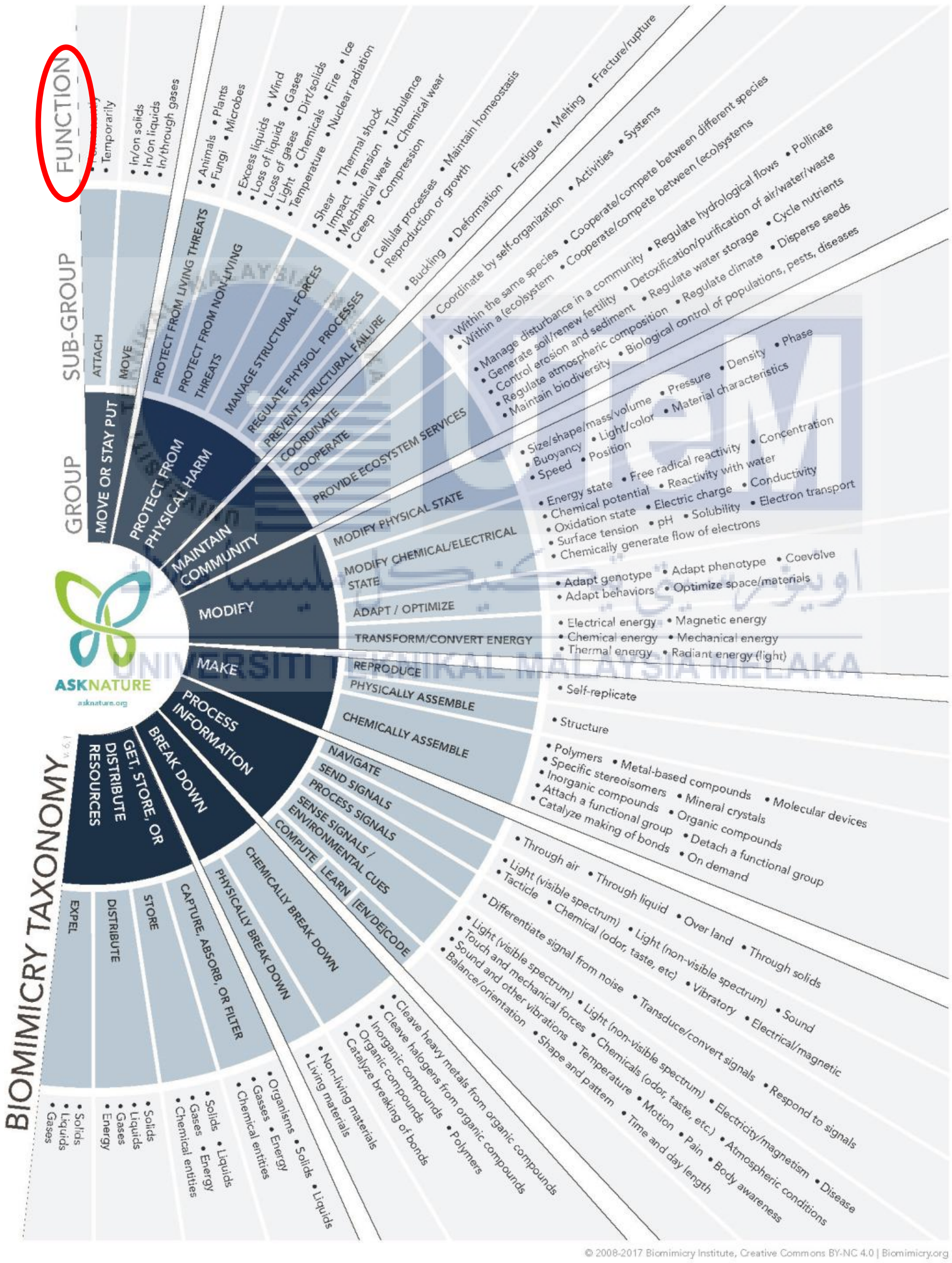



Figure 6: Biomimicry Taxonomy

Once the user has identified the function keyword by using Biomimicry Taxonomy, user has to visit AskNature.org website to find out and classify the biological strategies which are related with the function keyword. For instance, user has identified that buckling is the function that need to be solve for the product. According to the Biomimicry Taxonomy, buckling function is under sub group of prevent structural failure which is under group of protect from physical harm. Therefore, user can just click on the Biomimicry Taxonomy category panel in AskNature.org according to the grouping sequences based on Biomimicry Taxonomy as shown in Figure 7.

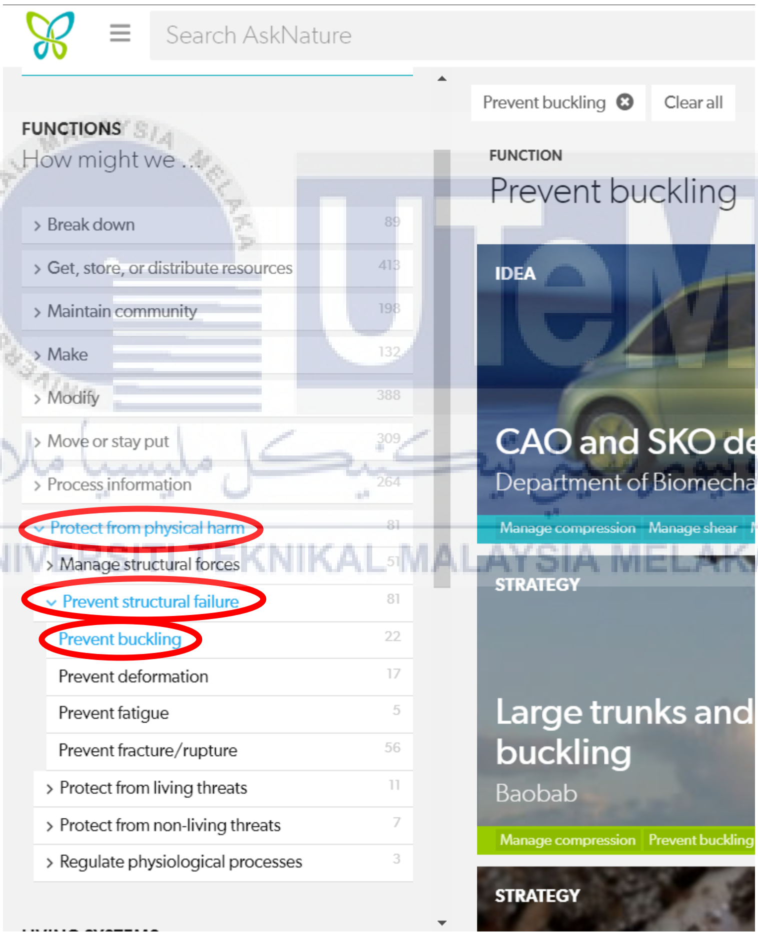



Figure 7: Biomimicry Taxonomy category panel in AskNature.org

Once the procedure of TRIZ FOS – Biomimetics is completed, there are several of biological strategies that listed out as shown in Figure 8. User need to study all the listed biological strategies in order to find suitable biological strategies that able to solve the problem of the product. Each of biological strategies consists of references either web page, journal article or book. This allow user to study the listed strategy for better understanding of the general biological solution.

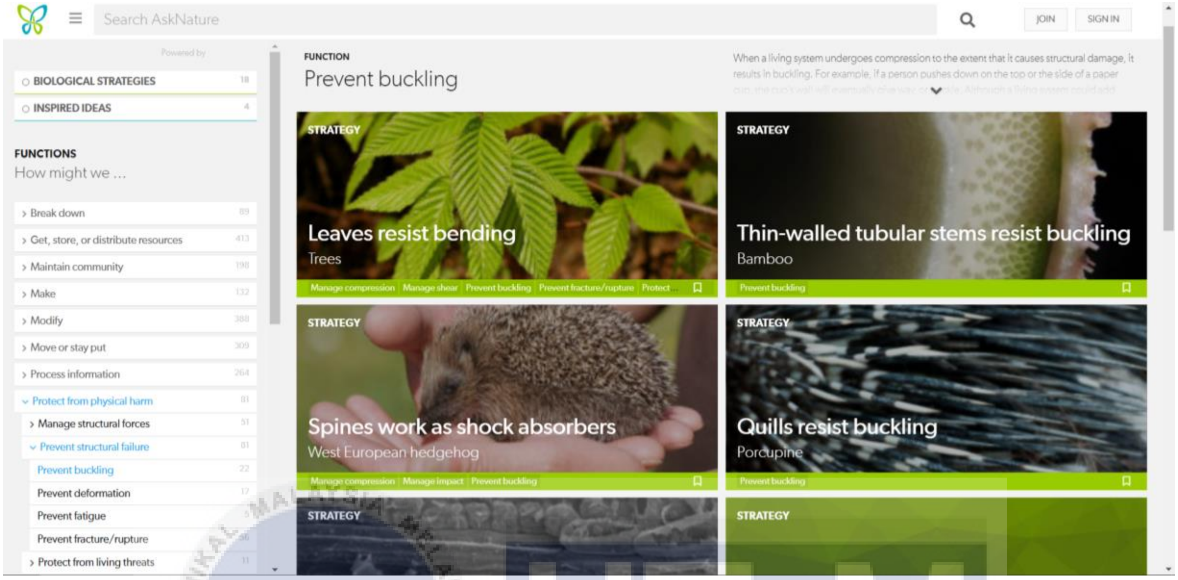



Figure 8: Biological Strategies in AskNature.org

Then, develop the design concept which related to the engineering problems that need to solve for the product through the biological strategies by using Autodesk Fusion 360 to create 3D part. At least five design concepts are needed to compare and analyze each of their performances.

After the generation of design concepts, performance analysis need to be perform to determine their deformation and failure that helps users understand the design performance. In this study, Autodesk Fusion 360 were used to carry out the finite element analysis (FEA). The performance analysis will be based on static stress where it analyzes the deformation and calculate the stress into the model from structural loads and constraints. From the results, users can investigate the displacement, stresses and common failure criteria. There are several steps needed to carry out for the FEA, as follows:

Step 1 is to create the design concept in 3D Computer Aided Design (CAD) modeling part by using Autodesk Fusion 360 in design workspace as shown in Figure 9.

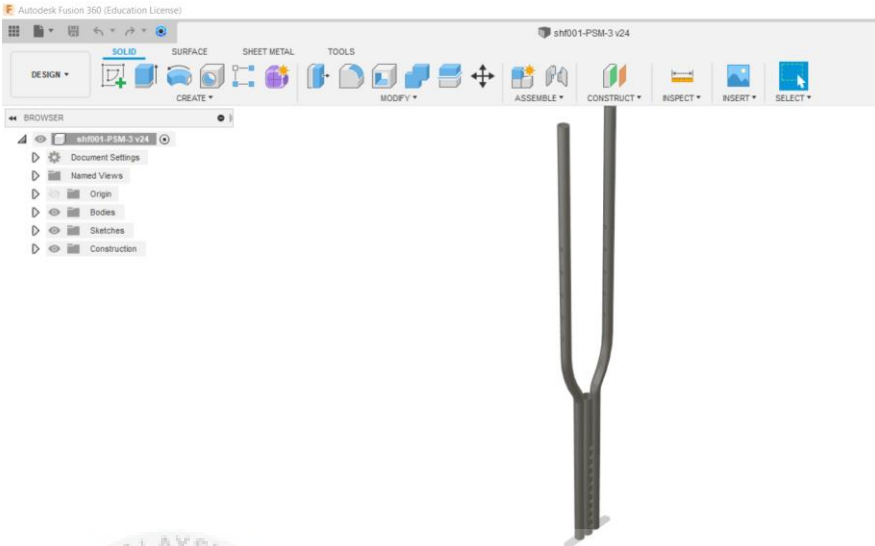



Figure 9: Design workspace in Autodesk Fusion 360

Step 2 change the workspace from design workspace into simulation workspace as shown in Figure 10.

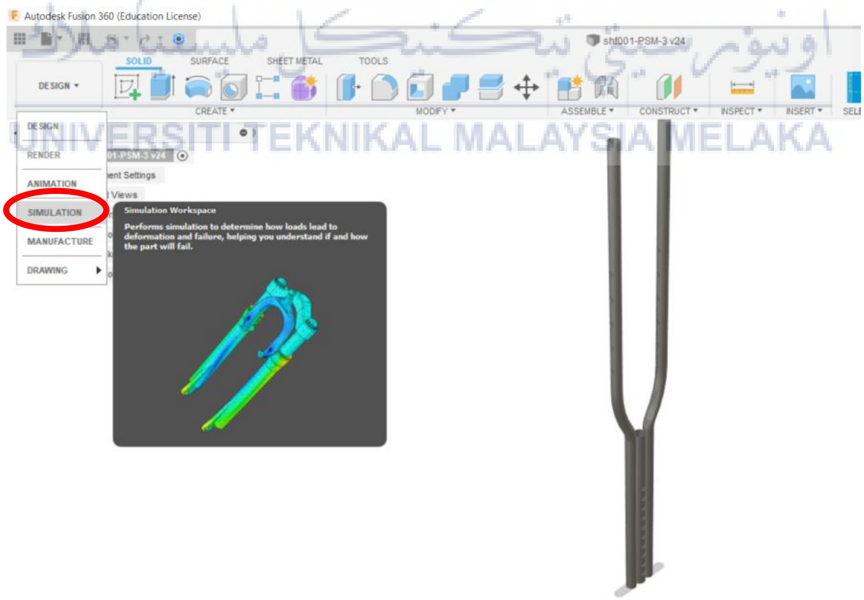



Figure 10: Changing workspace in Autodesk Fusion 360

Step 3 is to select the simulation study type to perform for the simulation. There are several of study types in Autodesk Fusion 360 such as static stress, model frequencies, thermal stress and other study type as shown in Figure 11. In this study, static stress study type has been chosen for the simulation analysis.

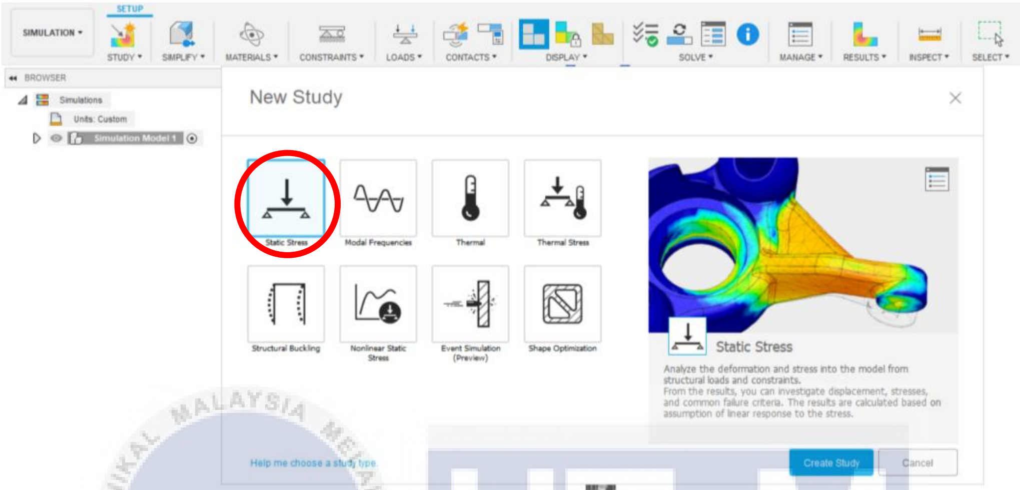



Figure 11: Simulation study type in Autodesk Fusion 360

Step 4 is to assign correct study material to the part as shown in Figure 12. This is important to simulate an accurate representation of the physical model.



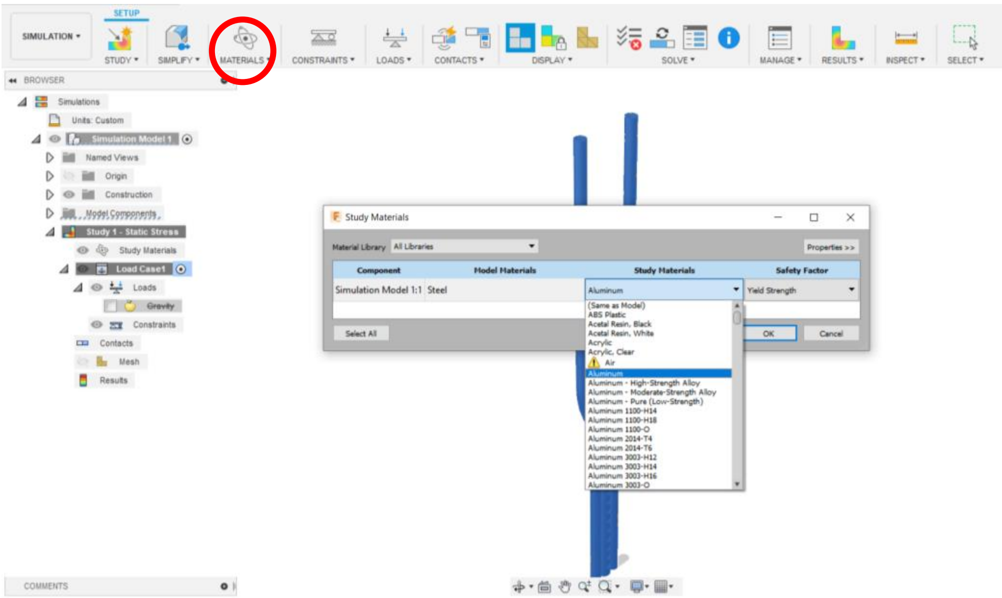



Figure 12: Study materials in Autodesk Fusion 360

Step 5 is to define structural constraints to the part at the selected geometry as shown in Figure 13. There are various type of structural constraints such fixed, pinned, frictionless and prescribed displacment. In this study, only fixed type of structural constraints is being selected.

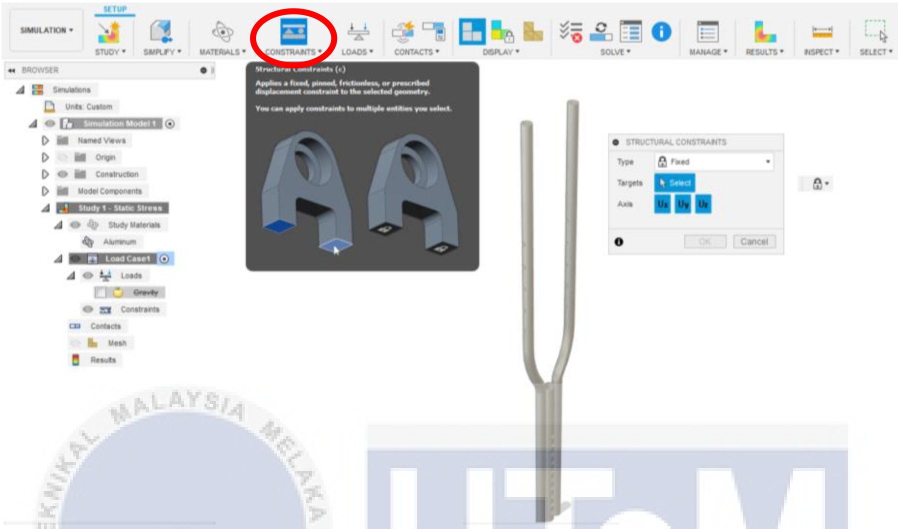


Figure 13: Structural constraints in Autodesk Fusion 360

Step 6 is to define structural load to the part at the selected geometry and define the magnitude value as shown in Figure 14. There are various type of structural load such force, pressure, moment, bearing load, remote force and hydrostatic pressure. In this study, only force type of structural load is being selected.

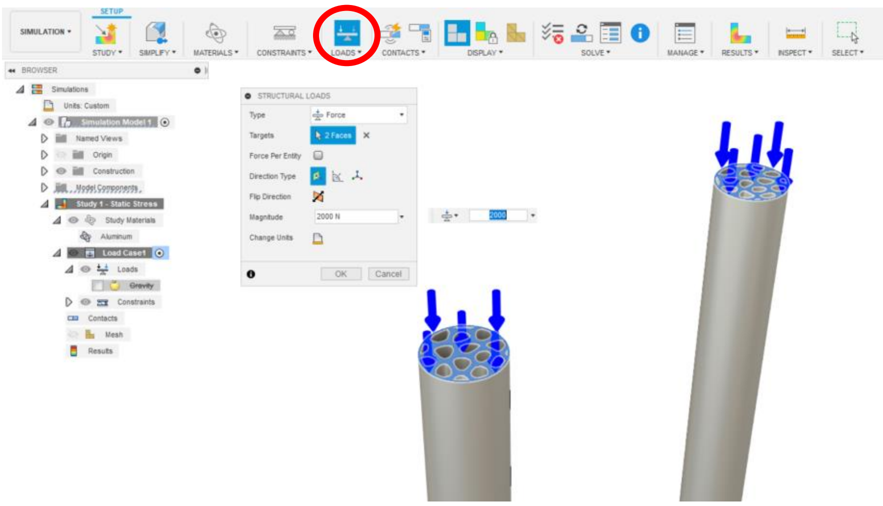


Figure 14: Structural load in Autodesk Fusion 360

Step 7 is to compute mesh to the part as shown in Figure 15. There are two types of mesh setting which are coarse and fine level. If the mesh setting is adjusted to the finest level, therefore the design model requires longer time to simulate.

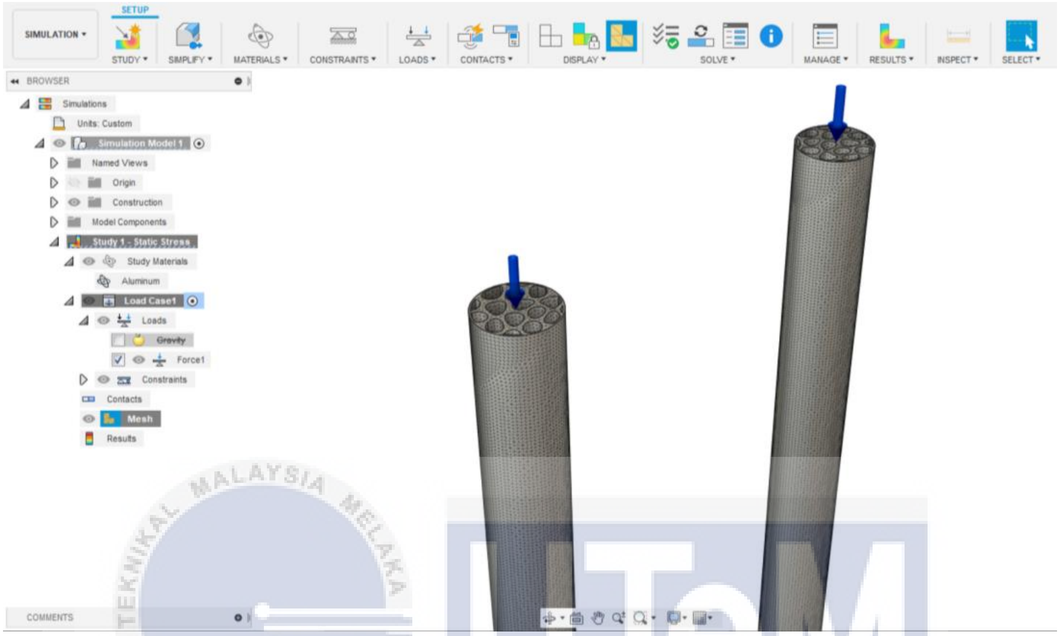



Figure 15: Compute mesh in Autodesk Fusion 360

Step 8 is pre-check to ensure that simulation study setup has all data or information required to solve the given study type as shown in Figure 16.



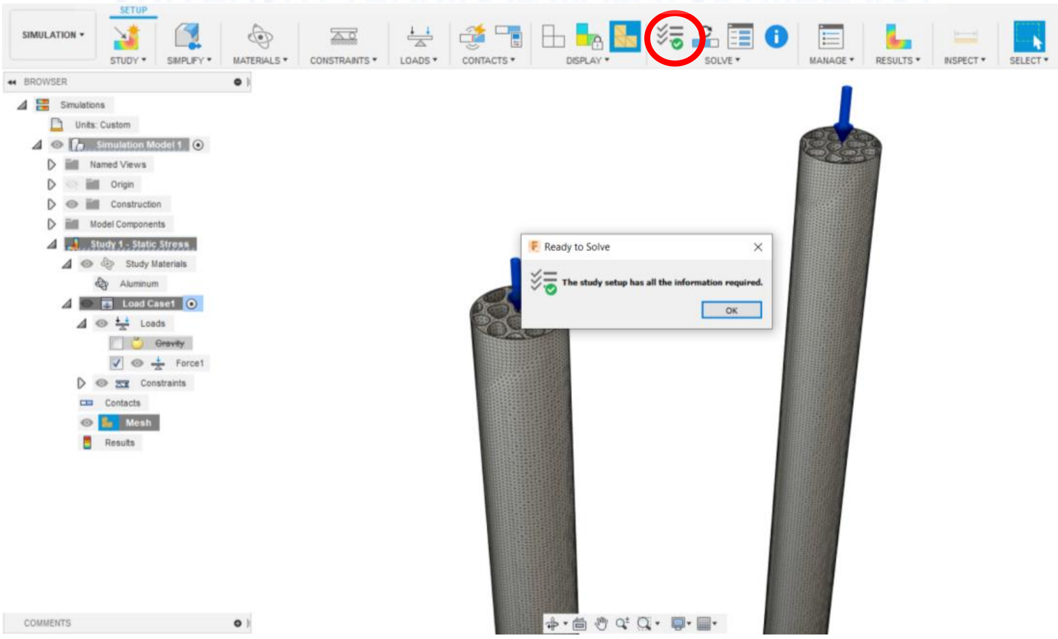



Figure 16: Pre-check of simulation study in Autodesk Fusion 360

Step 9 is to solve the simulation study as shown in Figure 17. There are two types of solve operation in Autodesk Fusion 360 which are on cloud and locally. Solve on cloud allows to solve multiple simulation studies at the same time however solve locally only allows to solve one simulation study at a time.

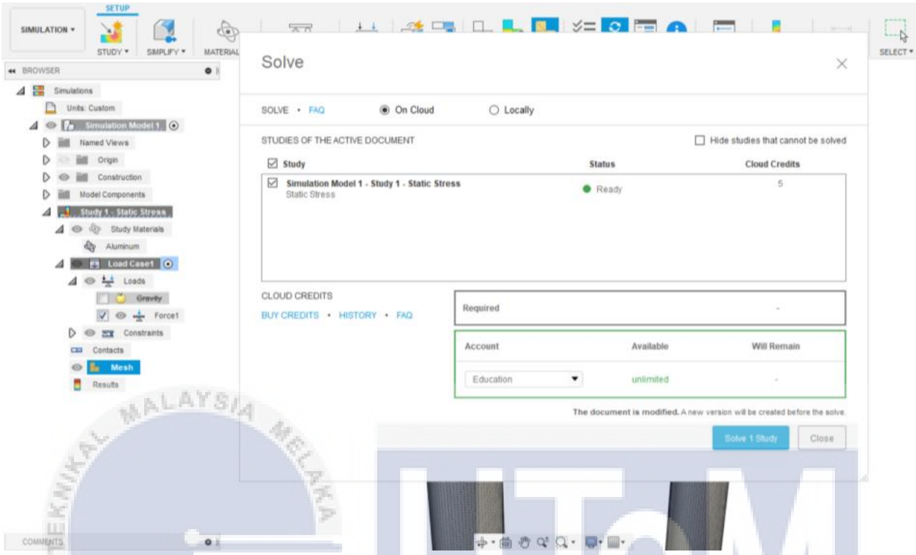



Figure 17: Solve simulation study in Autodesk Fusion 360

Step 10 is to analyze the result details of solved simulation study as shown in Figure 18. There are several of engineering criteria result details such as safety factor, stress, displacement, reaction force, strain and contact pressure can be obtained.



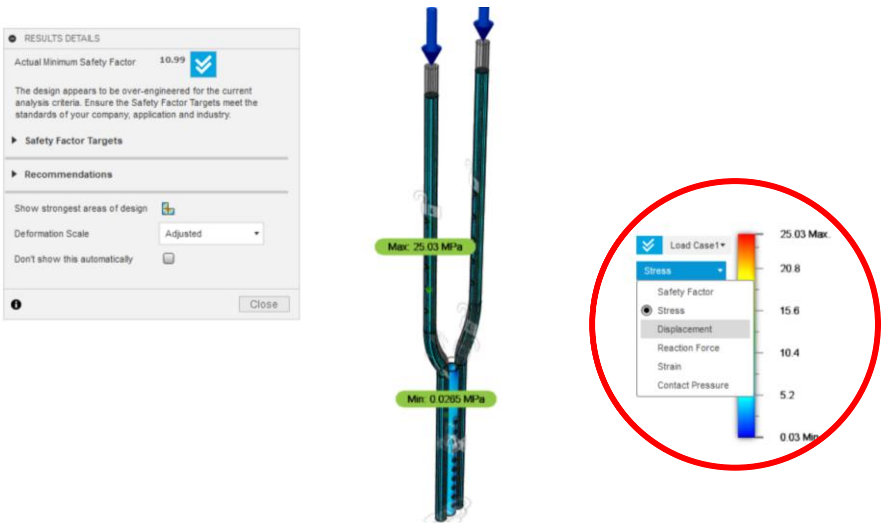



Figure 18: Result details of solved simulation study in Autodesk Fusion 360

Finally, collect and record all the simulation data and results of the design concepts and the final design concept selection will be made by using Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) one of the Multiple Criteria Decision Making (MCDM) method. In TOPSIS method, there are several steps needed to carry out as follows:

Step 1: Create a decision matrix consists of alternatives and criteria as shown in Figure 19. With the intersection of each alternative and criteria given as $X_{ij}$ . Then, estimate the value of weightage according the importance of criteria and identify types of beneficial for each criteria. Beneficial is meaning that the largest value consider as priority value of the selected criteria for the product, however for non-beneficial is the smallest value consider as priority value of the selected criteria for the product.

| | Benf. | Non Benf. | Non Benf. | Benf. |
|---|---|---|---|---|
| weightage | $W_1$ | $W_2$ | $W_3$ | $W_4$ |
| | Stress | Weight | Displacement | Safety Factor |
| DESIGN 1 | $X_{11}$ | $X_{12}$ | $X_{13}$ | $X_{14}$ |
| DESIGN 2 | $X_{21}$ | $X_{22}$ | $X_{23}$ | $X_{24}$ |
| DESIGN 3 | $X_{31}$ | $X_{32}$ | $X_{33}$ | $X_{34}$ |
| DESIGN 4 | $X_{41}$ | $X_{42}$ | $X_{43}$ | $X_{44}$ |
| DESIGN 5 | $X_{51}$ | $X_{52}$ | $X_{53}$ | $X_{54}$ |

Criteria

Alternatives

Figure 19: Example of decision matrix with alternatives and criteria

Step 2: Normalise the constructed decision matrix and transfer into normalised decision matrix by using the given formula below. Each data of decision matrix is divided by square root of total of square of column data according by criteria as shown in Figure 20. Each calculated value given as $\bar{X}_{ij}$.

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} {X_{ij}}^2}}$$

| | Stress | Weight | Displacement | Safety Factor |
|---|---|---|---|---|
| **Solving MCDM problem using TOPSIS Method** | | | | |
| | Benf. | Non Benf. | Non Benf. | Benf. |
| **Weightage** | 0.25 | 0.25 | 0.25 | 0.25 |
| | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| **DESIGN 1** | 29.1 | 0.54 | 0.0377 | 10.31 |
| **DESIGN 2** | 25.31 | 0.535 | 0.03643 | 11.85 |
| **DESIGN 3** | 44.49 | 0.469 | 0.04277 | 6.75 |
| **DESIGN 4** | 52.59 | 0.269 | 0.08211 | 5.7 |
| **DESIGN 5** | 26.77 | 0.711 | 0.02536 | 11.21 |
| | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| **DESIGN 1** | 0.349 | | =D6/((D6^2)+(D7^2)+(D8^2)+(D9^2)+(D10^2))^0.5 | |
| **DESIGN 2** | 0.3036 | 0.4561 | 0.3331 | 0.5583 |
| **DESIGN 3** | 0.5337 | 0.3999 | 0.3910 | 0.3180 |
| **DESIGN 4** | 0.6309 | 0.2293 | 0.7507 | 0.2686 |
| **DESIGN 5** | 0.3211 | 0.6062 | 0.2319 | 0.5282 |

Figure 20: Example of normalised matrix

Step 3: Calculate and construct weighted normalised decision matrix by multiplying the weightage value to each normalised data as shown in Figure 21.

$$V_{ij} = \bar{X}_{ij} \times W_j$$

| | Stress | Weight | Displacement | Safety Factor |
|---|---|---|---|---|
| **Solving MCDM problem using TOPS** | | | | |
| | Benf. | Non Benf. | Non Benf. | Benf. |
| **Weightage** | 0.25 | 0.25 | 0.25 | 0.25 |
| | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| **DESIGN 1** | 29.1 | 0.54 | 0.0377 | 10.31 |
| **DESIGN 2** | 25.31 | 0.535 | 0.03643 | 11.85 |
| **DESIGN 3** | 44.49 | 0.469 | 0.04277 | 6.75 |
| **DESIGN 4** | 52.59 | 0.269 | 0.08211 | 5.7 |
| **DESIGN 5** | 26.77 | 0.711 | 0.02536 | 11.21 |
| | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| **DESIGN 1** | 0.3491 | 0.4604 | 0.3447 | 0.4858 |
| **DESIGN 2** | 0.3036 | 0.4561 | 0.3331 | 0.5583 |
| **DESIGN 3** | 0.5337 | 0.3999 | 0.3910 | 0.3180 |
| **DESIGN 4** | 0.6309 | 0.2293 | 0.7507 | 0.2686 |
| **DESIGN 5** | 0.3211 | 0.6062 | 0.2319 | 0.5282 |
| | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| **DESIGN 1** | =B13*0.25 | 0.1151 | 0.0862 | 0.1214 |
| **DESIGN 2** | 0.0759 | 0.1140 | 0.0833 | 0.1396 |
| **DESIGN 3** | 0.1334 | 0.1000 | 0.0978 | 0.0795 |
| **DESIGN 4** | 0.1577 | 0.0573 | 0.1877 | 0.0671 |
| **DESIGN 5** | 0.0803 | 0.1515 | 0.0580 | 0.1320 |

Figure 21: Example of weighted normalised decision matrix

Step 4: Determine the ideal best ($V_j^+$) and ideal worst ($V_j^-$) value for each criteria as shown in Figure 22. However, it is not necessary that the larger value is the ideal best value as similar for ideal worst value. It depends on the criteria whether it is beneficial or non-beneficial to the product.

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | | | | | **Solving MCDM problem using TOPSI** |
| 2 | | | | | |
| 3 | | Benf. | Non Benf. | Non Benf. | Benf. |
| 4 | **Weightage** | 0.25 | 0.25 | 0.25 | 0.25 |
| 5 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| 6 | **DESIGN 1** | 29.1 | 0.54 | 0.0377 | 10.31 |
| 7 | **DESIGN 2** | 25.31 | 0.535 | 0.03643 | 11.85 |
| 8 | **DESIGN 3** | 44.49 | 0.469 | 0.04277 | 6.75 |
| 9 | **DESIGN 4** | 52.59 | 0.269 | 0.08211 | 5.7 |
| 10 | **DESIGN 5** | 26.77 | 0.711 | 0.02536 | 11.21 |
| 11 | | | | | |
| 12 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| 13 | **DESIGN 1** | 0.3491 | 0.4604 | 0.3447 | 0.4858 |
| 14 | **DESIGN 2** | 0.3036 | 0.4561 | 0.3331 | 0.5583 |
| 15 | **DESIGN 3** | 0.5337 | 0.3999 | 0.3910 | 0.3180 |
| 16 | **DESIGN 4** | 0.6309 | 0.2293 | 0.7507 | 0.2686 |
| 17 | **DESIGN 5** | 0.3211 | 0.6062 | 0.2319 | 0.5282 |
| 18 | | | | | |
| 19 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
| 20 | **DESIGN 1** | 0.0873 | 0.1151 | 0.0862 | 0.1214 |
| 21 | **DESIGN 2** | 0.0759 | 0.1140 | 0.0833 | 0.1396 |
| 22 | **DESIGN 3** | 0.1334 | 0.1000 | 0.0978 | 0.0795 |
| 23 | **DESIGN 4** | 0.1577 | 0.0573 | 0.1877 | 0.0671 |
| 24 | **DESIGN 5** | 0.0803 | 0.1515 | 0.0580 | 0.1320 |
| 25 | | | | | |
| 26 | V+ | 0.1577 | 0.0573 | 0.=MAX(E20:E24) | |
| 27 | V- | 0.0759 | 0.1515 | 0.1877 | 0.0671 |



Figure 22: Example of ideal best and ideal worst value

Step 5: Calculate the separation from the ideal best ($S_i^+$). By square root of sum of square of weighted normalised ($V_{ij}$) value subtract ideal best ($V_j^+$) value for each criteria and alternative as shown in Figure 23.

$$S_i^+ = \left[ \sum_{j=1}^{m} \left( V_{ij} - V_j^+ \right)^2 \right]^{0.5}$$

| | A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|---|
| 1 | **Solving MCDM problem using TOPSIS Method** | | | | | | | |
| 2 | | | | | | | | |
| 3 | | Benf. | Non Benf. | Non Benf. | Benf. | | | |
| 4 | **Weightage** | 0.25 | 0.25 | 0.25 | 0.25 | | | |
| 5 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** | | | |
| 6 | **DESIGN 1** | 29.1 | 0.54 | 0.0377 | 10.31 | | | |
| 7 | **DESIGN 2** | 25.31 | 0.535 | 0.03643 | 11.85 | | | |
| 8 | **DESIGN 3** | 44.49 | 0.469 | 0.04277 | 6.75 | | | |
| 9 | **DESIGN 4** | 52.59 | 0.269 | 0.08211 | 5.7 | | | |
| 10 | **DESIGN 5** | 26.77 | 0.711 | 0.02536 | 11.21 | | | |
| 11 | | | | | | | | |
| 12 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** | | | |
| 13 | **DESIGN 1** | 0.3491 | 0.4604 | 0.3447 | 0.4858 | | | |
| 14 | **DESIGN 2** | 0.3036 | 0.4561 | 0.3331 | 0.5583 | | | |
| 15 | **DESIGN 3** | 0.5337 | 0.3999 | 0.3910 | 0.3180 | | | |
| 16 | **DESIGN 4** | 0.6309 | 0.2293 | 0.7507 | 0.2686 | | | |
| 17 | **DESIGN 5** | 0.3211 | 0.6062 | 0.2319 | 0.5282 | | | |
| 18 | | | | | | | | |
| 19 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** | **Si+** | **Si-** | **Pi** |
| 20 | **DESIGN 1** | 0.0873 | 0.1151 | 0.0862 | 0.1214 | 0.09708 | 0.12129 | 0.55543 |
| 21 | **DESIGN 2** | 0.0759 | 0.1140 | =((B21-B26)^2+(C21-C26)^2+(D21-D26)^2+(E21-E26)^2)^0.5 | | | | |
| 22 | **DESIGN 3** | 0.1334 | 0.1000 | 0.0978 | 0.0795 | 0.08718 | 0.1192 | 0.57758 |
| 23 | **DESIGN 4** | 0.1577 | 0.0573 | 0.1877 | 0.0671 | 0.14857 | 0.12478 | 0.45647 |
| 24 | **DESIGN 5** | 0.0803 | 0.1515 | 0.0580 | 0.1320 | 0.12218 | 0.14511 | 0.54289 |
| 25 | | | | | | | | |
| 26 | V+ | 0.1577 | 0.0573 | 0.0580 | 0.1396 | | | |
| 27 | V- | 0.0759 | 0.1515 | 0.1877 | 0.0671 | | | |

Figure 23: Example of separation from ideal best ($S_i^{+}$) value

Step 6: Calculate the separation from the ideal worst ($S_i^{-}$). By square root of sum of square of weighted normalised ($V_{ij}$) value subtract ideal worst ($V_j^{-}$) value for each criteria and alternative as shown in Figure 24.

$$S_i^{-} = \left[\sum_{j=1}^{m} (V_{ij} - V_j^{-})^2\right]^{0.5}$$

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **Solving MCDM problem using TOPSIS Method** | | | | | | | | | |
| 2 | | | | | | | | | | |
| 3 | | Benf. | Non Benf. | Non Benf. | Benf. | | | | | |
| 4 | **Weightage** | 0.25 | 0.25 | 0.25 | 0.25 | | | | | |
| 5 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** | | | | | |
| 6 | **DESIGN 1** | 29.1 | 0.54 | 0.0377 | 10.31 | | | | | |
| 7 | **DESIGN 2** | 25.31 | 0.535 | 0.03643 | 11.85 | | | | | |
| 8 | **DESIGN 3** | 44.49 | 0.469 | 0.04277 | 6.75 | | | | | |
| 9 | **DESIGN 4** | 52.59 | 0.269 | 0.08211 | 5.7 | | | | | |
| 10 | **DESIGN 5** | 26.77 | 0.711 | 0.02536 | 11.21 | | | | | |
| 11 | | | | | | | | | | |
| 12 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** | | | | | |
| 13 | **DESIGN 1** | 0.3491 | 0.4604 | 0.3447 | 0.4858 | | | | | |
| 14 | **DESIGN 2** | 0.3036 | 0.4561 | 0.3331 | 0.5583 | | | | | |
| 15 | **DESIGN 3** | 0.5337 | 0.3999 | 0.3910 | 0.3180 | | | | | |
| 16 | **DESIGN 4** | 0.6309 | 0.2293 | 0.7507 | 0.2686 | | | | | |
| 17 | **DESIGN 5** | 0.3211 | 0.6062 | 0.2319 | 0.5282 | | | | | |
| 18 | | | | | | | | | | |
| 19 | | **Stress** | **Weight** | **Displacement** | **Safety Factor** | **Si+** | **Si-** | **Pi** | | **Rank** |
| 20 | **DESIGN 1** | 0.0873 | 0.1151 | 0.0862 | 0.1214 | 0.09708 | 0.12129 | 0.55543 | | **3** |
| 21 | **DESIGN 2** | 0.0759 | 0.1140 | 0.0833 | 0.1396 | 0.1027 | 0.1325 | 0.56335 | | **2** |
| 22 | **DESIGN 3** | 0.1334 | 0.1000 | 0.0978 | =((B22-B27)^2+(C22-C27)^2+(D22-D27)^2+(E22-E27)^2)^0.5 | | | | | |
| 23 | **DESIGN 4** | 0.1577 | 0.0573 | 0.1877 | 0.0671 | 0.14857 | 0.12478 | 0.45647 | | **5** |
| 24 | **DESIGN 5** | 0.0803 | 0.1515 | 0.0580 | 0.1320 | 0.12218 | 0.14511 | 0.54289 | | **4** |
| 25 | | | | | | | | | | |
| 26 | V+ | 0.1577 | 0.0573 | 0.0580 | 0.1396 | | | | | |
| 27 | V- | 0.0759 | 0.1515 | 0.1877 | 0.0671 | | | | | |

Figure 24: Example of separation from ideal worst ($\boldsymbol{S_i}^-$) value

Step 7: Calculate performance score ($P_i$) for determine relative closeness to ideal solution. Each of the ideal worst ($S_i^-$) value is divided by sum of ideal best value ($S_i^+$) and ideal worst ($S_i^-$) value according each row of alternative.



$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

Step 8: Ranking the alternative based on value of performance score from larger to smaller value. The alternative that ranked as first will be considered as the best ideal solution.

# CHAPTER 4

# RESULTS AND DISCUSSION

In this study, method 2 as explained in section 3.2 was implemented by using function keyword of Biomimicry Taxonomy to find the biological strategies in AskNature.org. Biomimicry Taxonomy consists of 8 groups and 30 sub-groups that contain more than 160 functions where user can look function keyword and search in AskNature.org and read the ideas of biological strategies that are listed. Table 1 shows the numbers of biological strategies search by function based on Biomimicry Taxonomy that features one group, two sub-groups and three functions that related to the project.

Table 1: Numbers of biological strategies search by function using Biomimicry Taxonomy

| Group | Protect from Physical Harm | | |
|---|---|---|---|
| Sub-Group | Prevent Structural Failure | Manage Structural Forces | |
| Function | Buckling | Impact | Compression |
| Biological Strategies | 18 | 61 | 70 |



By reading through the ideas of biological strategies that are listed in the database according to the function keyword and read through the references such as journal article and web page that given in each biological strategies, the biological strategies that have potential in solving the problems and met the design constraints and requirements were listed in Table 2.

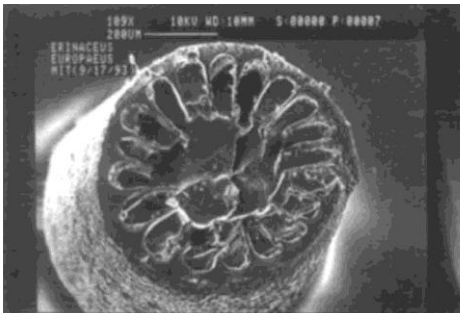
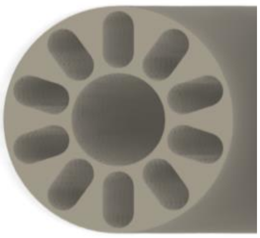
Table 2: Potential solutions of biomimetics

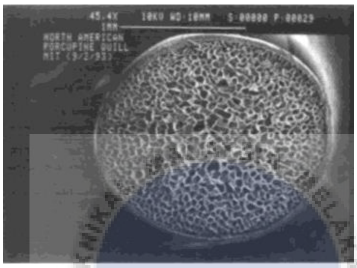
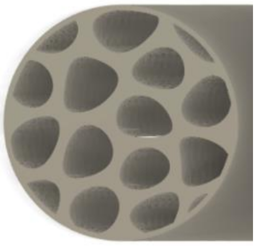
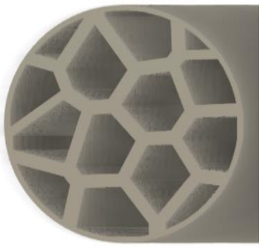
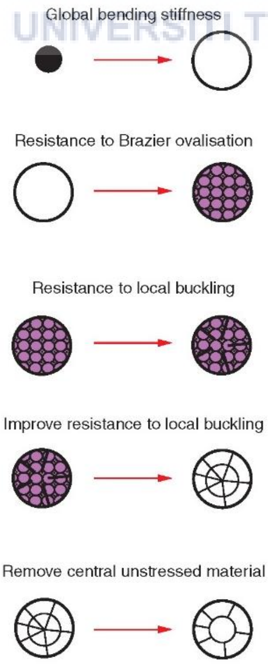
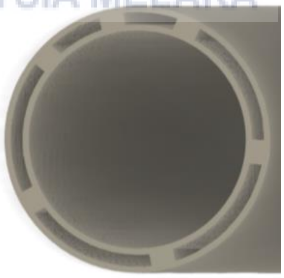
| **Nature** | **Biological Strategies** | **References** |
|---|---|---|
| West European hedgehog | Spines work as shock absorbers | (AskNatureTeam, 2016c) |
| North American Porcupine | Quills resist buckling | (AskNatureTeam, 2016b) |

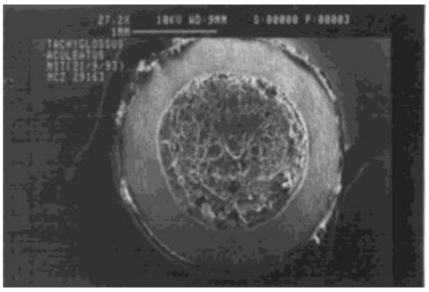
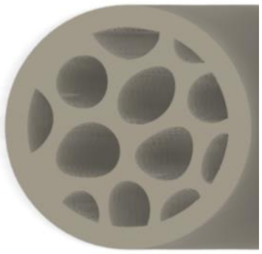
There are several biomimicry cases have been identified through journal article of Karam and Gibson (1994) and Vincent (2002) that given in the biological strategies references section and there are five design concepts have been developed as shown in Table 3. Porcupine quill function as protect porcupine from predators meanwhile hedgehog spine act as shock absorber that protect hedgehog when falling down from high place. Both researches stated that hedgehog spine and porcupine quill consists of foam-like structure that filling inside the hollow tube structure as a function to support the outer cylindrical wall against ovalization and buckling which allows the structure to bend further without fail. Therefore, the structure design of the spine and quill can be as reference model for engineering and technology as it able to withstand high compression and impact energy to prevent buckling.



Table 3: Biomimicry Case and Design Concept

| Biomimicry Case | Design Concept |
|---|---|
| Hedgehog (Erinaceus Europaeus) spine   |  DESIGN CONCEPT 1 |

<table>
<tr>
<td>North American porcupine<br>(Erethizon Dorsatum) quill<br><br></td>
<td><br>DESIGN CONCEPT 2<br><br>DESIGN CONCEPT 3</td>
</tr>
<tr>
<td>Characteristics of ‘foam’ filling of hedgehog spines – a tentative evolution. Each pair of cross-sections of the spine represents the next stage in optimization of the structure.<br><br></td>
<td><br>DESIGN CONCEPT 4</td>
</tr>
</table>

| | |
|---|---|
| Echidna (Tachyglossus Aculeatus) quill    |  DESIGN CONCEPT 5 |

During the finite element analysis (FEA), the study force that applied is 2000N which is equivalent to 203.94kg and the meshing size that applied is 1mm. Besides that, the study materials that applied are aluminium, magnesium, carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP). Therefore, Table 4 shows the generated finite element analysis (FEA) results based on static stress study by using Autodesk Fusion 360.

Table 4: Decision matrix (Step 1)

| | *Benf. | **Non Benf. | Non Benf. | Benf. |
|---|---|---|---|---|
| **Weightage** | 0.25 | 0.25 | 0.25 | 0.25 |
| **Criteria / Design Variable** | **Stress (MPa)** | **Weight (kg)** | **Displacement (mm)** | **Safety Factor** |
| **ALU-D1** | 27.95 | 1.020 | 0.07639 | 9.84 |
| **ALU-D2** | 25.03 | 1.011 | 0.07526 | 10.99 |
| **ALU-D3** | 44.47 | 0.886 | 0.08791 | 6.18 |
| **ALU-D4** | 53.78 | 0.509 | 0.16420 | 5.11 |
| **ALU-D5** | 24.19 | 1.342 | 0.05349 | 11.37 |
| **MAG-D1** | 28.32 | 0.657 | 0.11790 | 4.06 |
| **MAG-D2** | 25.11 | 0.651 | 0.11550 | 4.58 |
| **MAG-D3** | 44.48 | 0.571 | 0.13510 | 2.59 |
| **MAG-D4** | 53.13 | 0.328 | 0.25440 | 2.16 |
| **MAG-D5** | 25.01 | 0.865 | 0.08157 | 4.60 |
| **CFRP-D1** | 29.10 | 0.540 | 0.03770 | 10.31 |
| **CFRP-D2** | 25.31 | 0.535 | 0.03643 | 11.85 |
| **CFRP-D3** | 44.49 | 0.469 | 0.04277 | 6.75 |
| **CFRP-D4** | 52.59 | 0.269 | 0.08211 | 5.70 |
| **CFRP-D5** | 26.77 | 0.711 | 0.02536 | 11.21 |
| **GFRP-D1** | 29.10 | 0.661 | 0.36080 | 2.00 |
| **GFRP-D2** | 25.31 | 0.655 | 0.34860 | 2.30 |
| **GFRP-D3** | 44.49 | 0.574 | 0.40920 | 1.31 |
| **GFRP-D4** | 52.59 | 0.330 | 0.78560 | 1.10 |
| **GFRP-D5** | 26.77 | 0.870 | 0.24270 | 2.17 |
| **Note: *Benf: Beneficial, **Non Benf: Non Beneficial** | | | | |

Table 5 to Table 8 shows the calculation data and calculated value based on generated finite element analysis (FEA) results that listed in decision matrix (Table 4) by using TOPSIS method.

Table 5: Normalised matrix (Step 2)

| Criteria / Design Variable | Stress | Weight | Displacement | Safety Factor |
|---|---|---|---|---|
| **ALU-D1** | 0.1682 | 0.3166 | 0.0677 | 0.3195 |
| **ALU-D2** | 0.1506 | 0.3138 | 0.0667 | 0.3568 |
| **ALU-D3** | 0.2676 | 0.2750 | 0.0779 | 0.2007 |
| **ALU-D4** | 0.3236 | 0.1580 | 0.1455 | 0.1659 |
| **ALU-D5** | 0.1456 | 0.4165 | 0.0474 | 0.3692 |
| **MAG-D1** | 0.1704 | 0.2039 | 0.1045 | 0.1318 |
| **MAG-D2** | 0.1511 | 0.2020 | 0.1024 | 0.1487 |
| **MAG-D3** | 0.2676 | 0.1772 | 0.1197 | 0.0841 |
| **MAG-D4** | 0.3197 | 0.1018 | 0.2255 | 0.0701 |
| **MAG-D5** | 0.1505 | 0.2685 | 0.0723 | 0.1494 |
| **CFRP-D1** | 0.1751 | 0.1676 | 0.0334 | 0.3348 |
| **CFRP-D2** | 0.1523 | 0.1660 | 0.0323 | 0.3848 |
| **CFRP-D3** | 0.2677 | 0.1456 | 0.0379 | 0.2192 |
| **CFRP-D4** | 0.3164 | 0.0835 | 0.0728 | 0.1851 |
| **CFRP-D5** | 0.1611 | 0.2207 | 0.0225 | 0.3640 |
| **GFRP-D1** | 0.1751 | 0.2051 | 0.3198 | 0.0649 |
| **GFRP-D2** | 0.1523 | 0.2033 | 0.3090 | 0.0747 |
| **GFRP-D3** | 0.2677 | 0.1781 | 0.3627 | 0.0425 |
| **GFRP-D4** | 0.3164 | 0.1024 | 0.6963 | 0.0357 |
| **GFRP-D5** | 0.1611 | 0.2700 | 0.2151 | 0.0705 |

Table 6: Weighted normalised decision matrix (Step 3)

| Criteria / Design Variable | Stress | Weight | Displacement | Safety Factor |
|---|---|---|---|---|
| **ALU-D1** | 0.0420 | 0.0791 | 0.0169 | 0.0799 |
| **ALU-D2** | 0.0377 | 0.0784 | 0.0167 | 0.0892 |
| **ALU-D3** | 0.0669 | 0.0687 | 0.0195 | 0.0502 |
| **ALU-D4** | 0.0809 | 0.0395 | 0.0364 | 0.0415 |
| **ALU-D5** | 0.0364 | 0.1041 | 0.0119 | 0.0923 |
| **MAG-D1** | 0.0426 | 0.0510 | 0.0261 | 0.0330 |
| **MAG-D2** | 0.0378 | 0.0505 | 0.0256 | 0.0372 |
| **MAG-D3** | 0.0669 | 0.0443 | 0.0299 | 0.0210 |
| **MAG-D4** | 0.0799 | 0.0254 | 0.0564 | 0.0175 |
| **MAG-D5** | 0.0376 | 0.0671 | 0.0181 | 0.0373 |
| **CFRP-D1** | 0.0438 | 0.0419 | 0.0084 | 0.0837 |
| **CFRP-D2** | 0.0381 | 0.0415 | 0.0081 | 0.0962 |
| **CFRP-D3** | 0.0669 | 0.0364 | 0.0095 | 0.0548 |
| **CFRP-D4** | 0.0791 | 0.0209 | 0.0182 | 0.0463 |
| **CFRP-D5** | 0.0403 | 0.0552 | 0.0056 | 0.0910 |
| **GFRP-D1** | 0.0438 | 0.0513 | 0.0799 | 0.0162 |
| **GFRP-D2** | 0.0381 | 0.0508 | 0.0772 | 0.0187 |
| **GFRP-D3** | 0.0669 | 0.0445 | 0.0907 | 0.0106 |
| **GFRP-D4** | 0.0791 | 0.0256 | 0.1741 | 0.0089 |
| **GFRP-D5** | 0.0403 | 0.0675 | 0.0538 | 0.0176 |



Table 7: Ideal best and ideal worst value (Step 4)

| Criteria / Value | Stress | Weight | Displacement | Safety Factor |
|---|---|---|---|---|
| $V_j^+$ | 0.0809 | 0.0209 | 0.0056 | 0.0962 |
| $V_j^-$ | 0.0364 | 0.1041 | 0.1741 | 0.0089 |

Table 8: Separation from the ideal best and ideal worst, performance score and ranking (Step 5-8)

| Design Variable | $S_i^+$ | $S_i^-$ | $P_i$ | Rank |
|---|---|---|---|---|
| **ALU-D1** | 0.0728 | 0.1743 | 0.7054 | **9** |
| **ALU-D2** | 0.0732 | 0.1785 | 0.7093 | **7** |
| **ALU-D3** | 0.0693 | 0.1667 | 0.7064 | **8** |
| **ALU-D4** | 0.0655 | 0.1618 | 0.7119 | **6** |
| **ALU-D5** | 0.0947 | 0.1824 | 0.6582 | **12** |
| **MAG-D1** | 0.0824 | 0.1591 | 0.6588 | **11** |
| **MAG-D2** | 0.0814 | 0.1604 | 0.6634 | **10** |
| **MAG-D3** | 0.0836 | 0.1595 | 0.6561 | **13** |
| **MAG-D4** | 0.0937 | 0.1484 | 0.6129 | **15** |
| **MAG-D5** | 0.0873 | 0.1628 | 0.6508 | **14** |
| **CFRP-D1** | 0.0445 | 0.1923 | 0.8119 | **1** |
| **CFRP-D2** | 0.0476 | 0.1977 | 0.8060 | **2** |
| **CFRP-D3** | 0.0465 | 0.1863 | 0.8002 | **3** |
| **CFRP-D4** | 0.0515 | 0.1856 | 0.7828 | **5** |
| **CFRP-D5** | 0.0534 | 0.1937 | 0.7838 | **4** |
| **GFRP-D1** | 0.1192 | 0.1084 | 0.4763 | **18** |
| **GFRP-D2** | 0.1178 | 0.1110 | 0.4851 | **17** |
| **GFRP-D3** | 0.1237 | 0.1070 | 0.4637 | **19** |
| **GFRP-D4** | 0.1898 | 0.0894 | 0.3202 | **20** |
| **GFRP-D5** | 0.1110 | 0.1261 | 0.5319 | **16** |

Table 9: Ranking for the results

| Design Variable | $S_i^+$ | $S_i^-$ | $P_i$ | Rank |
|---|---|---|---|---|
| **CFRP-D1** | 0.0445 | 0.1923 | 0.8119 | **1** |
| **CFRP-D2** | 0.0476 | 0.1977 | 0.8060 | **2** |
| **CFRP-D3** | 0.0465 | 0.1863 | 0.8002 | **3** |
| **CFRP-D5** | 0.0534 | 0.1937 | 0.7838 | **4** |
| **CFRP-D4** | 0.0515 | 0.1856 | 0.7828 | **5** |
| **ALU-D4** | 0.0655 | 0.1618 | 0.7119 | **6** |
| **ALU-D2** | 0.0732 | 0.1785 | 0.7093 | **7** |
| **ALU-D3** | 0.0693 | 0.1667 | 0.7064 | **8** |
| **ALU-D1** | 0.0728 | 0.1743 | 0.7054 | **9** |
| **MAG-D2** | 0.0814 | 0.1604 | 0.6634 | **10** |
| **MAG-D1** | 0.0824 | 0.1591 | 0.6588 | **11** |
| **ALU-D5** | 0.0947 | 0.1824 | 0.6582 | **12** |
| **MAG-D3** | 0.0836 | 0.1595 | 0.6561 | **13** |
| **MAG-D5** | 0.0873 | 0.1628 | 0.6508 | **14** |
| **MAG-D4** | 0.0937 | 0.1484 | 0.6129 | **15** |
| **GFRP-D5** | 0.1110 | 0.1261 | 0.5319 | **16** |
| **GFRP-D2** | 0.1178 | 0.1110 | 0.4851 | **17** |
| **GFRP-D1** | 0.1192 | 0.1084 | 0.4763 | **18** |
| **GFRP-D3** | 0.1237 | 0.1070 | 0.4637 | **19** |
| **GFRP-D4** | 0.1898 | 0.0894 | 0.3202 | **20** |

As a result, according to the ranking shown in Table 9, the ideal best material is carbon fiber reinforced polymer (CFRP). All the design concepts with CFRP material are in top five ranking. However, the ideal worst material is glass fiber reinforced polymer (GFRP) and all the design concepts with GFRP material are in last top five ranking. This is because the value of safety factor of CFRP material is the highest compare to other materials according design concept and the value of weight and displacement of CFRP material is lowest compare to the other materials according design concept. This means that CFRP material able to withstand high structural load with minimum elongation and provides lightweight properties.

Table 10: First ranking for each material

| MATERIAL / DESIGN | ALUMINIUM | MAGNESIUM | CFRP | GFRP |
|---|---|---|---|---|
| **DESIGN 1** | 4 | 2 | 1 | 3 |
| **DESIGN 2** | 2 | 1 | 2 | 2 |
| **DESIGN 3** | 3 | 3 | 3 | 4 |
| **DESIGN 4** | 1 | 5 | 5 | 5 |
| **DESIGN 5** | 5 | 4 | 4 | 1 |

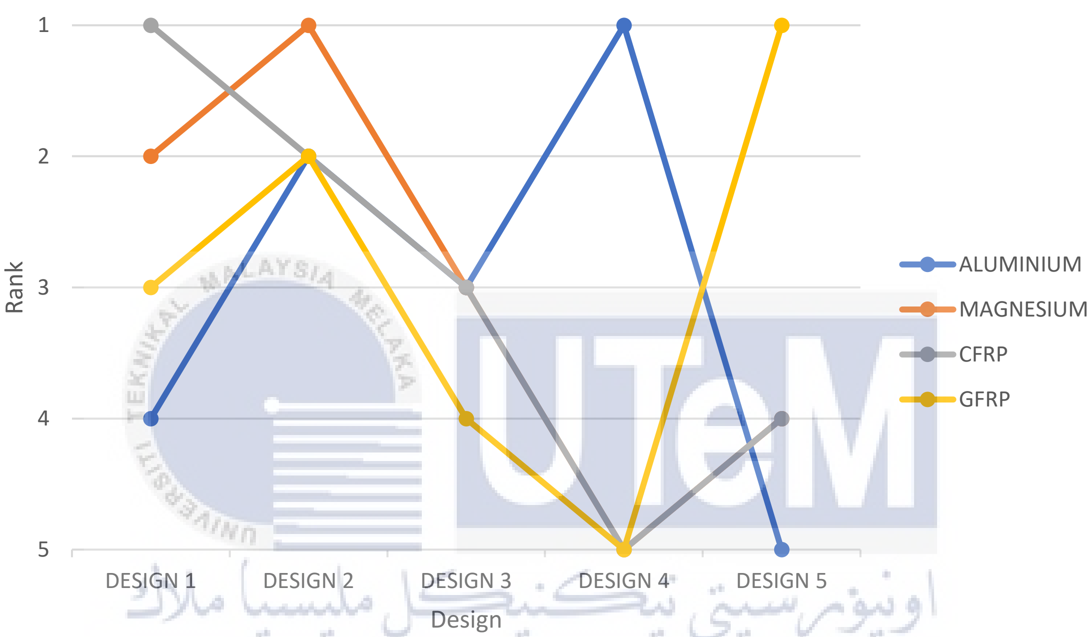
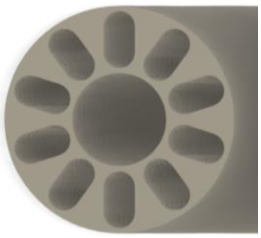
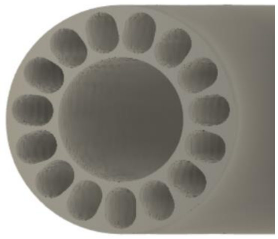



Figure 25: Graph of ranking for each material

Table 10 and Figure 25 show that first ranking of each material. As a result based on the table and figure, each of the material has different on first ranking according to the design concepts. For instance, the first ranking for the aluminium material is design concept 4. Nevertheless, the first ranking for the magnesium, CFRP and GFRP materials are design concept 2, design concept 1 and design concept 5 respectively. Besides that, from the table and graph also show that the design concepts do not give big influence to the ranking. For instance, the design concept 5 has low ranking for aluminium, magnesium and CFRP materials but it ranked as first for GFRP material. Therefore, materials that applied play as a main role in determine the best or optimul solution rather than the design concepts.

Table 11: Optimization of Design Concept 1 (CFRP material)

| Old | | New |
|---|---|---|
|  | Optimization of Design Concept 1<br>Material: CFRP |  |
| | | |
| 29.10 | Stress (MPa) | 66.33 |
| 0.540 | Weight (kg) | 0.385 |
| 0.03770 | Displacement (mm) | 0.05310 |
| 10.31 | Safefy Factor | 4.52 |

In order to get more optimum result, the design concept 1 with CFRP material which ranked first in Table 9 has been selected to be optimize its design. The optimization of design concept 1 for CFRP material has been carried out and the FEA also has been carried out in order to get the static stress simulation result data for the optimized design concept 1. The comparison of old and new design concept 1 for CFRP material data has listed and shows in Table 11. As the result from Table 11, even though the displacement value for the new design concept 1 is slightly increased but it able to withstand high value of stress compare to old design concept 1. Apart from that, the weight of new design concept 1 has been reduced about 28% which is more lighter than the old design concept 1 and the safety factor also has been decreased from 10.31 which the design is over-engineered to 4.52 which the design is well-engineered.



Apart from that, Table 12 is the FEA result data which including the optimized design concept 1 and non-optimized design concepts with CFRP material only. From Table 13 to Table 16 are the calculation data and calculated value based on generated finite element analysis (FEA) results that listed in Table 12 by using TOPSIS method.

Table 12: Decision matrix (optimized) (Step 1)

| | Benf. | Non Benf. | Non Benf. | Benf. |
|---|---|---|---|---|
| **Weightage** | 0.25 | 0.25 | 0.25 | 0.25 |
| **Criteria / Design Variable** | **Stress (MPa)** | **Weight (kg)** | **Displacement (mm)** | **Safety Factor** |
| **CFRP-D1** | 29.10 | 0.540 | 0.03770 | 10.31 |
| **CFRP-D2** | 25.31 | 0.535 | 0.03643 | 11.85 |
| **CFRP-D3** | 44.49 | 0.469 | 0.04277 | 6.75 |
| **CFRP-D4** | 52.59 | 0.269 | 0.08211 | 5.70 |
| **CFRP-D5** | 26.77 | 0.711 | 0.02536 | 11.21 |
| **CFRP-D1 (NEW)** | 66.33 | 0.385 | 0.05310 | 4.52 |

Table 13: Normalised matrix (optimized) (Step 2)

| **Criteria / Design Variable** | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
|---|---|---|---|---|
| **CFRP-D1** | 0.2732 | 0.4374 | 0.3101 | 0.4751 |
| **CFRP-D2** | 0.2376 | 0.4334 | 0.2996 | 0.5461 |
| **CFRP-D3** | 0.4176 | 0.3799 | 0.3518 | 0.3111 |
| **CFRP-D4** | 0.4937 | 0.2179 | 0.6753 | 0.2627 |
| **CFRP-D5** | 0.2513 | 0.5760 | 0.2086 | 0.5166 |
| **CFRP-D1 (NEW)** | 0.6226 | 0.3119 | 0.4367 | 0.2083 |



Table 14: Weighted normalised decision matrix (optimized) (Step 3)

| **Criteria / Design Variable** | **Stress** | **Weight** | **Displacement** | **Safety Factor** |
|---|---|---|---|---|
| **CFRP-D1** | 0.0683 | 0.1094 | 0.0775 | 0.1188 |
| **CFRP-D2** | 0.0594 | 0.1083 | 0.0749 | 0.1365 |
| **CFRP-D3** | 0.1044 | 0.0950 | 0.0879 | 0.0778 |
| **CFRP-D4** | 0.1234 | 0.0545 | 0.1688 | 0.0657 |
| **CFRP-D5** | 0.0628 | 0.1440 | 0.0521 | 0.1292 |
| **CFRP-D1 (NEW)** | 0.1557 | 0.0780 | 0.1092 | 0.0521 |

Table 15: Ideal best and ideal worst value (optimized) (Step 4)

| Criteria / Value | Stress | Weight | Displacement | Safety Factor |
|---|---|---|---|---|
| **$V_j^+$** | 0.1557 | 0.0545 | 0.0521 | 0.1365 |
| **$V_j^-$** | 0.0594 | 0.1440 | 0.1688 | 0.0521 |

Table 16: Separation from the ideal best and ideal worst, performance score and ranking (optimized) (Step 5-8)

| Design Variable | $S_i^+$ | $S_i^-$ | $P_i$ | Rank |
|---|---|---|---|---|
| **CFRP-D1** | 0.1077 | 0.1186 | 0.5240 | **4** |
| **CFRP-D2** | 0.1126 | 0.1312 | 0.5381 | **2** |
| **CFRP-D3** | 0.0949 | 0.1078 | 0.5320 | **3** |
| **CFRP-D4** | 0.1403 | 0.1109 | 0.4415 | **6** |
| **CFRP-D5** | 0.1292 | 0.1399 | 0.5199 | **5** |
| **CFRP-D1 (NEW)** | 0.1046 | 0.1311 | 0.5562 | **1** |

Table 17: Ranking for the results (optimized)

| Design Variable | $S_i^+$ | $S_i^-$ | $P_i$ | Rank |
|---|---|---|---|---|
| **CFRP-D1 (NEW)** | 0.1046 | 0.1311 | 0.5562 | **1** |
| **CFRP-D2** | 0.1126 | 0.1312 | 0.5381 | **2** |
| **CFRP-D3** | 0.0949 | 0.1078 | 0.5320 | **3** |
| **CFRP-D1** | 0.1077 | 0.1186 | 0.5240 | **4** |
| **CFRP-D5** | 0.1292 | 0.1399 | 0.5199 | **5** |
| **CFRP-D4** | 0.1403 | 0.1109 | 0.4415 | **6** |

As a result, according to the ranking shown in Table 17, the ideal best design concept among 6 design variable is the optimized design concept 1. This is because the value of safety factor of optimized design concept 1 is not over-engineered and it can withstand high value of stress with lightweight characteristic. Therefore, optimized design concept is better than non-optimed design concepts.

# CHAPTER 5

## CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

In conclusions, TRIZ (FOS) – Biomimetics with TOPSIS method has been implemented successfully for the conceptual design phase in this project. Referring back to the objectives, the design concepts for the crutches using TRIZ (FOS) – Biomimetics method has been developed which consists of five design concepts. Those design concepts are imitate from the identified biological cases such as hedgehog (Erinaceus Europaeus) spine, North American porcupine (Erethizon Dorsatum) and echidna (Tachyglossus Aculeatus) quill and characteristics of 'foam' filling of hedgehog spines which optimized. Besides that, the performance of the design concepts has been studied through finite element analysis (FEA) using Autodesk Fusion 360 software. Overall there are 20 design variables which includes four types of materials which is aluminium, magnesium, CFRP and GFRP with five design concepts has been performed their static stress study through FEA by using Autodesk Fusion 360.



Apart from that, TOPSIS method has been implemented for selection of the ideal best design concept of the crutch among the 20 design variables with four types of design criteria such as stress, weight, displacement and safety factor. As a result of TOPSIS, the ideal best design concept is design concept 1 with CFRP material. Nonetheless, optimization of design concept 1 with CFRP material has been carried out in order to get more optimum result. The result of optimized design concept 1 is more impressive compare to the non-optimized design concept 1 such as the weight has been reduced about 28%, the stress value has been increased about 128% and the safety factor has been adjusted from over-engineered to well-engineered value. After that, TOPSIS method carry out once again in order to determine the ideal best design concept within the optimized design concept 1 and the other five non-optimized design concepts with CFRP material only. As a result, the optimized design concept 1 ranked as first rank and it is the ideal best design concept among 6 design variables. Finally, TRIZ (FOS) – Biomimetics with TOPSIS method has successfully in determine and develop the ideal best design concepts in new for crutches.

Nevertheless, the recommendation for the future research of this project is utilization of different software or standalone engineering simulation software such as ANSYS or ABAQUS to perform finite element analysis (FEA) in order to compare the results with present criteria data. Besides that, other MCDM method can be applied such as AHP or VIKOR method or combination with TOPSIS method in order to do the comparative study for this analysis. Finally, the crutches could be fabricate in the scale of 1:1 model to identify the reliability, advantages and limitations of the design concept for the crutches through physical testing in the lab.

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