UNIVERSITI TEKNIKAL MALAYSIA MELAKA

CONCEPTUALISATION OF MODULAR AIRLESS TYRE USING TRIZ AND PUGH METHOD

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

by

FOO CHER LIANG

FACULTY OF MANUFACTURING ENGINEERING

2022

DECLARATION

I hereby, declared this report entitled "Conceptualisation of Modular Airless Tyre Using TRIZ And Pugh Method" is the result of my own research except as cited in references.

Signature : ……………………………………
Author's Name : FOO CHER LIANG
Date : 25th January 2022

APPROVAL

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

PROFESSOR IR. TS. DR. SIVARAO SUBRAMONIAN
B.Eng.(Mech.)M.Eng.Sc.(Mech.)PhD.(Mech.)
Professional Engineer (Mech.), Professional Technologist (Mfg. & Industrial Design)
Faculty of Manufacturing Engineering
Universiti Teknikal Malaysia Melaka

……………………………………………………

(PROFESOR IR. DR. SIVARAO A/L SUBRAMONIAN)

ABSTRAK

Tayar ialah komponen bulat berbentuk cincin bagi kenderaan yang bersentuhan dengan tanah. Tayar berfungsi untuk memastikan kenderaan bersentuhan dengan tanah dengan memberikan daya tarikan yang diperlukan dan mengekalkan beban kenderaan. Tekanan inflasi mempunyai kesan pada cengkaman dan kemungkinan tayar pneumatik letupan dan menyebabkan ketidakstabilan kenderaan. Oleh itu, tayar tanpa udara sedang dibangunkan sebagai tindak balas kepada keperluan yang semakin meningkat untuk tayar yang lebih selamat untuk menangani masalah tayar pneumatik. Walau bagaimanapun, tayar tanpa udara sedia ada mengalami kesukaran untuk diubah suai selepas ia dikeluarkan, serta kekurangan kebolehsesuaian. Projek ini mempersembahkan konsep baharu pembangunan tayar tanpa udara modular kereta menggunakan penyepaduan teori penyelesaian masalah kreatif (TRIZ) dan kaedah Pugh. Analisis fungsional digunakan untuk mengenal pasti dan menganalisis interaksi komponen tayar tanpa udara. 39 parameter kejuruteraan, 40 matriks percanggahan prinsip inventif digunakan untuk menjana penyelesaian. Kemudian, 40 penyelesaian prinsip inventif yang dikenal pasti diperhalusi kepada strategi penyelesaian khusus yang digunakan untuk membina konsep tayar tanpa udara modular. Kekurangan kebolehlarasan tayar tanpa udara adalah disebabkan oleh interaksi yang tidak mencukupi antara jejari, hab dan cincin luar. 40 prinsip inventif, termasuk #1 Segmentasi, #6 Universality, #28 Ganti Sistem Mekanikal dan #34 Menolak dan Menjana Semula Bahagian, diperhalusi menjadi strategi penyelesaian khusus yang digunakan untuk menjana empat lakaran konsep inovatif baharu. Pemilihan konsep Pugh digunakan untuk menilai dan menentukan konsep akhir tayar tanpa udara modular. Keputusan menunjukkan bahawa konsep 2 menduduki tempat pertama dan mempunyai nilai kedudukan tertinggi antara 4 konsep yang dihasilkan.

ABSTRACT

Tyre is a circular, ring-shaped component of a vehicle that comes into contact with the ground. Tyre functions to keep the vehicle in contact with the ground by providing the required traction and to maintain the vehicle's load. Inflation pressure has an impact on grip and the likelihood of a pneumatic tyre blowout and induce vehicle instability. Thus, airless tyres are being developed in response to a growing need for safer tyres to address pneumatic tyre issues. However, existing airless tyre have difficulty to be modify after it has been manufactured, as well as its lack of adaptability. This project presents the new concept of car modular airless tyre develop using the integration of theory of creative problem solving (TRIZ) and Pugh methods. Functional analysis is used to identify and analyse the interactions of airless tyre components. The 39 engineering parameters, 40 inventive principles contradiction matrix are used to generate the solutions. Then, the identified 40 inventive principle solution are refined into specific solution strategy that is used to build the concept of modular airless tyre. The lack of adjustability of airless tyre is attributed to insufficient interaction between the spoke, hub, and outer ring. 40 inventive principles, including #1 Segmentation, #6 Universality, #28 Replace Mechanical System, and #34 Rejecting and Regenerating Parts, are refined into specific solution strategies that are used to generate four new innovative conceptual sketches. Pugh concept selection was used to evaluate and determine the final concept of modular airless tyre. The results shows that concept 2 ranked the first and has the highest-ranking value among the 4 concepts generated.

ABSTRACT

Tyre is a circular, ring-shaped component of a vehicle that comes into contact with the ground. Tyre functions to keep the vehicle in contact with the ground by providing the required traction and to maintain the vehicle's load. Inflation pressure has an impact on grip and the likelihood of a pneumatic tyre blowout and induce vehicle instability. Thus, airless tyres are being developed in response to a growing need for safer tyres to address pneumatic tyre issues. However, existing airless tyre have difficulty to be modify after it has been manufactured, as well as its lack of adaptability. This project presents the new concept of car modular airless tyre develop using the integration of theory of creative problem solving (TRIZ) and Pugh methods. Functional analysis is used to identify and analyse the interactions of airless tyre components. The 39 engineering parameters, 40 inventive principles contradiction matrix are used to generate the solutions. Then, the identified 40 inventive principle solution are refined into specific solution strategy that is used to build the concept of modular airless tyre. The lack of adjustability of airless tyre is attributed to insufficient interaction between the spoke, hub, and outer ring. 40 inventive principles, including #1 Segmentation, #6 Universality, #28 Replace Mechanical System, and #34 Rejecting and Regenerating Parts, are refined into specific solution strategies that are used to generate four new innovative conceptual sketches. Pugh concept selection was used to evaluate and determine the final concept of modular airless tyre. The results shows that concept 2 ranked the first and has the highest-ranking value among the 4 concepts generated.

DEDICATION

I dedicate my research work to my family, friends, supervisor and final year project panels for giving me assistance, continuous support and encouragement throughout the process. Thank you so much.

ACKNOWLEDGEMENT

A special thanks to my supervisor Professor Ir. Dr. Sivarao A/L Subramonian for the guidance given and supervision throughout the entire process. I would also like to thank my Final Year Project panels. I would like to acknowledge and thank UTeM for the provided assistance and allow me to conduct my research work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AHP	-	Analytic Hierarchy Process
ANP	-	Analytic Network Process
ARIZ	-	Algorithm of Inventive Problem Solving
3D	-	3 Dimensional
AL	-	Aluminium
CAD	-	Computer-Aided Design
CAGR	-	Compound Annual Growth Rate
CEC	-	Cause-And-Effect Chain
FAM	-	Functional Analysis Model
ME	-	Mechanical Elastic
PU	-	Polyurethane
PFD	-	Problem Formulation Diagram
QFD	-	Quality Function Deployment
RSM	-	Response Surface Methodology
TRIZ	-	Theory of Innovative Problem Solving

LIST OF SYMBOLS

°C	-	Degree Celsius
ρ	-	Rho
kg/m^3	-	Kilogram Per Cubic Metre
MPa	-	Mega Pascal
mm	-	Millimetre
kWh	-	Kilowatt-Hour

CHAPTER 1

INTRODUCTION

This chapter describe the introduction of modelling of a tyre suspending system for bachelor's degree project 1. This chapter go through the project's background of study, problem statement, objectives, scope, significant/important of study, organization of report as well as summary.

1.1 Background of Study

The comfort and safety of driving a vehicle are mostly determined by the components of the car suspension system's proper operating conditions and symbiosis. A shock absorber, a spring, and, most crucially, a tyre makes up a vehicle's suspension system. Drivers have been less mindful of the necessity of their tyres as vehicles have become more sturdy, reliable, and stylish. Tyres have come a long way in terms of safety, performance, and wear, however they still require more care than the majority of automobile components. (Sassi et al., 2016).

A tyre is an important component of any vehicle. Rubber members are used in tyres to provide cushioning as well as clearance for the vehicle. The rubber part is secured to the rim of the wheel. A tube is put inside a tube tyre, whereas a tubeless tyre does not have one. A tyre is a circular component that is installed on the rim of a wheel to transmit the vehicle's load from axle to rim (Abhishek & Kumar, 2020).

A vehicle's suspension system attaches the frame to the road. The primary aim of the suspension system is to increase a vehicle's overall performance as it rolls down the lane. The suspension system also assists in the absorption of road bumps, ensuring a healthy and enjoyable ride. Spring, shock absorbers, bars, linkages, and, most significantly, tyres make up the suspension system.

Tyres plays a variety of roles in a car's safety; they can both avoid and trigger accidents. If tyres are faulty or worn, they may play a significant role in car accidents. Faulty tyres are more skid on wet roads, increasing the risk of a punctured or blowout, which could result in a serious car accident.

Currently, tyre manufacturers are dealing with the increasing mountain of bald tyres that are defiling the landscape and come up with to recycle them or finding solutions for the tyre that long lasting and can be recycled. Airless tyres are currently being developed by companies including Michelin and Bridgestone, which means they are not pneumatic. Airless tyre strives for output standards beyond those possible with traditional pneumatic technology. Airless tyre has pneumatic-like load carrying capability ride comfort and will not fail due to a lack of air pressure because it does not have a pressurised air cavity inside the tyre.

Maintenance-free, strong impact resistance, the ability to function with a partially broken tyre, and use in harsh terrain are all advantages of airless tyre. In the case of an airless tyre, shaping the pressure and energy losses is limited to choosing the right support structure and material design. General airless tyre concept shown in Figure 1.1 have the following components: a tread, a shear beam (analogue to the carcass in a pneumatic tyre) or an elastic ring, a deformable supporting structure, and a rim. The rim and tread of the tyre serve the same purpose as those of traditional pneumatic tyres. The shear beam may have a core, solid or of a certain geometry) sandwiched between two low-deformation-modulus membranes (Hryciów et al., 2020).

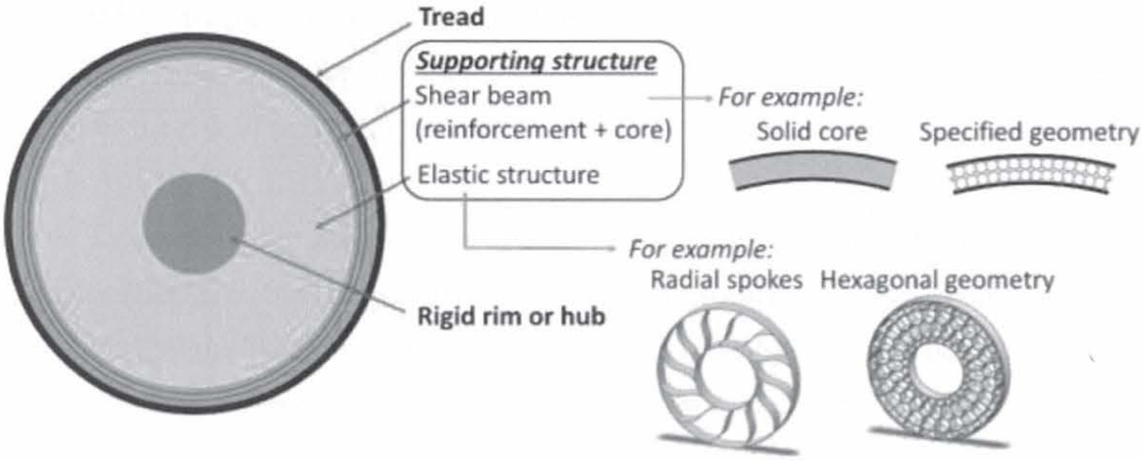


Figure 1.1: General concept of airless tyre (Hryciów et al., 2020)

1.2 Problem Statement

Numerous elements might cause or enhance the likelihood of a tyre failure (puncture or blowout). When a tyre's internal air pressure drops suddenly or gradually, such an unpleasant event can occur at any time. This pressure drop hinders the tyre from performing its primary function, which is to support the vehicle's weight. As a result, the driver is unable to maintain on a safe and straight path, that usually results in a dangerous car accident.

Pneumatic tyre has several flaws, the most significant of which being its vulnerability to air pressure fluctuations. Differences in air pressure have an influence on tyre performance and substantially alter passenger ride comfort. The chance of a blowout on the road is undeniably the most alarming of all the risks.

Inflation pressure affects both grip performance and the danger of tyre blowout failure. A large variance in inflation pressure diminishes grip and, because of the reduced rigidity, can cause vehicle instability even on dry roads. Tyre blowouts can happen as a result of heat generated by massive tyre deformations caused by severe underinflation (Jansen et al., 2016).

Attempts have been made to build flat proof that may provide the same mechanical qualities as the air trapped inside the tyre since the beginning of the twentieth century. There is no need for periodic maintenance to refill the tyres with air and maintain an acceptable internal pressure with the revolutionary technology of airless tyres. This technique minimises the risk of punctures and greatly improves the vehicle's safety.

To deal with the situation, the concept of flat-proof tyre was born out of a growing desire for safer tyres. Several tyre manufacturers company brought it back to the tyre market. Innovative designs like those proposed by Bridgestone and Michelin are popular because of their non-hazardous behaviour and high stability (Sassi et al., 2016).

As the source of hazard in pneumatic tyre is mainly due to their dependence on air, by introducing the concept of airless tyre such limitations can be avoided. This disadvantage of puncture can be removed by introducing airless tyre that have improved handling and increased surface traction. However, one of the most major disadvantages of the airless tyre is that once created, it cannot be changed and lack of adjustability. A new set of airless tyres would be required if the vehicle required a different quiet setting. When a car hits speeds of above 50 mph while creating a lot of noise, vibrations become pleasant (Kalahastimath, 2021).

1.3 Objectives

The primary objectives of this work are to:

i) Identify and analyse the interactions of the airless tyre system's core components

ii) Generate the concept of modular airless tyre employing TRIZ methodology

iii) Determine the final concept using Pugh concept selection

1.4 Scope

The scope of this project focused on the conceptualisation process where TRIZ approach is used as concept generation while Pugh method is used for concept selection. The interactions of car's airless tyre core components are identified and analysed using functional analysis. Then, the conflicts between good and bad feature of airless tyre components are matched using contradiction matrix. Later, based on the identified inventive principles, specific solution strategies are developed, which are used to construct the conceptual sketch of a modular airless tyre. Next, Pugh method is used to evaluate the concept generated where a final concept of modular airless tyre is made from the evaluation. This study does not involve system level design and detail design.

1.5 Significant/Important of Study

In terms of safety, durability, and wear, tyres have come a long way, but requires more attention than majority of the car components. Extreme under-inflation can cause increased tyre wall flexing and heat build-up within a tyre, which can lead to a disastrous tyre failure. Blowouts are caused by a combination of factors like vehicle speed, tyre pressure, and load. To improve vehicle protection, these factors necessitate both well-known design improvements and the quest for new wheeled mover design solutions, one of which is the use of wheels with airless tyre. Airless tyre has pneumatic characteristics with pneumatic tyre such as load carrying capacity and ride comfort, and it cannot be punctured because it does not have pressurised air cavity. This work looks forward to that new concept of modular airless tyre might be a benchmark study when developing modular airless tyre. The new concept hopes to solve lack of versatility issues of the current airless tyre.

1.6 Organization of The Report/Thesis

This section includes a summary of each chapter's material.

Chapter 1: Introduction

The topic of the project is introduced in this chapter, and the reader is given a brief overview of the study. The project's context, problem statement, goals, scope, significant/important findings, report organisation, and overview are all included in this chapter.

Chapter 2: Literature Review

This section includes a detailed and critical examination of the literature on the topic of the FYP report. It serves as the base for the experimental and theoretical parts of the paper.

Chapter 3: Methodology

This chapter go over the project's methodology, which includes the techniques and methodology used to develop airless tyre. It provides a description of concept development method and theoretical approaches used to achieve the study's goals.

Chapter 4: Result and Discussion

The findings and analysis from the concept of airless tyre are discussed in this chapter. This is a result interpretation based on engineering knowledge.

Chapter 5: Conclusion and Recommendations

This chapter summarised the study's overall importance and emphasises the results from which a conclusion was drawn to meet the objectives.

1.7 Summary

Work is conducted to formulate a new concept of modular airless tyre to solve the issue with the current airless tyre. Chapter 1: Introduction introduces the project's subject, background and gives the reader a brief overview of the study.

CHAPTER 2

LITERATURE REVIEW

In the literature review chapter, it discussed about the relevant information to the modelling of airless tyre. This includes the tyre anatomy, manufacturing process, concept of airless tyre. Besides, the concept development methods from previous studies are also discussed in this chapter.

2.1 Tyre Anatomy

In all tyre manufacturing enterprises, there is a common ground baseline for how all conventional car tyres are made. The tyres are designed to strike a balance between retaining proper road grip and providing a safe, predictable, and comfortable ride for the vehicle. Aside from that, the tyre might be designed to have specific features, such as long life, low rolling resistance, minimal noise emission, or maximum grip under specific conditions (Ludvigsen, 2017).

2.1.1 Tyre Components

The components of the tyre are illustrated in Figure 2.1 listed in the following subtitle.

Figure 2.1: Tyre structure (Rangdale et al., 2018)

2.1.1.1 Inner Liner

From the interior, the first substance is a synthetic rubber that provides an airtight layer to prevent air leakage, which would cause the tyre's pressure to drop (Ludvigsen, 2017).

2.1.1.2 Carcass

Carcass is constructed of solid textile fibre threads that are embedded in a rubber shell to keep the tyre's form under internal pressure. When inflating the tyre, this guarantees that it does not bulge out (Ludvigsen, 2017).

2.1.1.3 Beads

The section of the tyre that contacts the wheel rim is known as the bead. The bead, which is made of a high-strength, low-flexibility rubber, is frequently reinforced with steel wire. The bead is positioned snugly next to the two rims on the wheel to guarantee that a tubeless tyre holds air without leaking. The bead fits snugly to prevent the tyre from moving circumferentially while the wheel rotates. The width of the rim in relation to the tyre impacts the handling qualities of an automobile since it supports the tire's profile (Ali et al., 2016).

2.1.1.4 Sidewalls

The sidewall is the section of the tyre that connects the tread and the bead. The sidewall is mostly made of rubber, although it is reinforced with fabric or steel cables for tensile strength and flexibility. The sidewall holds air pressure and transmits torque from the drive axle to the tread to provide traction, although it only sustains a small portion of the vehicle's weight, as seen by the tire's complete collapse when pierced. Manufacturer-specific details, government-mandated warning labels, and other consumer information are moulded into the sidewalls (Ali et al., 2016).

2.1.1.5 Steel Belts

Multiple layers of angled rubber-coated thread made of textile, fibre glass, or brass-plated steel wrap around the tyre circumferentially to form the steel belts. The coat compound is usually made with good cord adhesion, stiffness, and tear and fatigue resistance in mind (U.S. Tire Manufacturing Association, 2018).

2.1.1.6 Cap Plies

Cap plies are strong fabric or steel wires implanted in the rubber that hold the tyre's form when it is inflated. The weight carrying capacity of the tyre and the inflation pressure that can be employed are both influenced by these plies (Das & Redrouthu, 2014).

2.1.1.7 Tread

As seen in Figure 2.1, the tread is the tire's outermost surface that makes contact with the road surface. Its purpose is to give strong traction while remaining durable. Tread also has grooves, lugs, voids, and sipe designs. In order to maintain proper contact with the road surface, the tread pattern's job is to expel any water that may occur between the road surface and the tyre (Das & Redrouthu, 2014).

2.1.2 Manufacturing Process of a Tyre

In most cases, the tyre is created in three stages by three distinct machines. The first prepares the rubber compound, the second instals the correct components in the right places, and the third defines the final shape and tread pattern before vulcanizing the rubber. The initial step in creating a tyre is to combine the various rubber varieties, which can range from 30 to 40 in number. Oil, pigments, and other chemical ingredients are subsequently added to the mixture. All of the components are mixed into a soft rubber compound in a big blender with high temperature and pressure.

To adhere each component to the tyre, a distinctive metal cylinder with a flexible inflated middle is used. Each layer of tyre component is rolled onto this drum starting from the inner components and working outwards. The components are applied in order, beginning with the airtight inner liner and ending with the sides. The centre of the drum, around which these materials are wrapped, expands. The tyre is roughly shaped to its final form, with a visible separating between the sidewall and contact region. The cap plies and steel belts layer might be applied before the tread material layer is finished.

Once all of the materials have been applied, the tyre is placed in the third machine, the curing mould. On the interior of the mould, the tread pattern and the legally required sidewall prints are engraved. The tyre is then filled with hot pressure water, which pushes the rubber into the grooves of the mould, producing the tyre. At a temperature of roughly 300 degrees, the rubber begins to cure and vulcanize as a result of the heat from steam and water. When rubber is vulcanised, it changes from a sticky plastic deformation state when distorted, the rubber stays in its new shape to an elastic deformation state when the rubber returns to its original form when the tension is removed (Ludvigsen, 2017).

2.1.3 Manufacturing Process of Airless Tyre

Airless tyres are made in three steps: shear band and tread creation, hub creation, and polyurethane spoke assembly. Tread is made in the first phase using a system similar to that used to make tyre treads. An airless tyre's tread is identical to that of a pneumatic tyre and is made in the identical approach. It's then linked to belt layers like pneumatic tyres. Manually rolling plies onto a drum to produce the desired diameter is still used today, so when airless tyre manufacture is completely automated, the same basic method which is used on tyres can be replicated. Rectangular sheets of rubber and steel cord are rolled onto a steel drum in this process, with the extra material from each sheet being eliminated. The extruded tread is rolled on top of the assembly, which is then vulcanised until the desired base thickness is achieved.

Steel hub casting or aluminium alloy casting is made in the second stage, which is identical to the ordinary casting method, in which molten metal is poured into the mould and solidified.

Hub and tread are aligned in the third stage, and while the entire assembly spins, polyurethane is injected into a spoke and shear band mould, ensuring that the mould is sufficiently filled in the radial direction. In comparison to the significant amount of energy necessary to heat and pressurise the ovens used to cure the shear band and then cure the entire assembly after the polyurethane has been filled, the shear band cures in a fraction of the time, the energy required to rotate the airless tyre assembly and polyurethane mould for only 5 minutes though the polyurethane is being filled is regarded as insignificant. Both surfaces that come into contact with the polyurethane are washed and coated with either an adhesive or a mould release for the spoke mould and shear band, correspondingly, before the filling process begins. Chemlok 7710, Ethyl acetate, Stoner M-804, and other adhesives were included. The polyurethane pre-polymers and curative are kept separate until this stage in the manufacturing process, when they are heated and mixed. The merging of heated pre polymers and curative may be explored in this Tweel manufacturing segment, but it is viewed as part of the raw material processing of polyurethane to coordinate the raw materials' impacts.

The whole Tweel tyre (spokes, shear band, and hub) is inserted into another oven after the polyurethane has been filled and the assembly has been allowed to stop rotating. This final curing takes place at 100°C for 4 hours in order to achieve the desired polyurethane properties to ensure that all of the components are tightly bonded together. To save energy, the curing procedure might be done at room temperature, but it would take a long time and be prone to being bumped and irreparably destroyed during that period. Tyre manufacturers have registered and studied the energy inputs for rubber curing presses, and the ordinary tyre curing process needs around 1.1 kWh of energy for a tyre weighing 10 kg, that means 0.11 kWh of energy is required to vulcanize 1 kg of rubber. Michelin used the same type of press that is used to cure radial tyres in the early stages of Tweel production, so it is believed in this study that curing 1 kg of rubber in a Tweel tyre would take the same amount of energy as curing 1 kg of rubber in a pneumatic tyre. Despite the fact that the rubber thickness of these two products is drastically different, the curing temperature and duration are sufficiently similar to conclude that the energy requirements per kg of rubber are the same. Thus, to cure the shear band in the Tweel, the necessary energy is approximately (6.35 kg) *(0.11 kWh/kg), which equals 0.7 kWh. The energy required to heat, combine, and cure the polyurethane is allotted to polyurethane raw material production, so this 0.7 kWh is required in the Tweel manufacturing inventory reported by (Abhishek & Kumar, 2020).

2.2 Tyre Safety Aspect

The main safety features of tyres are thought to be connected to the possibility of a sudden loss of inflation pressure, such as a tyre blowout. The likelihood of a tyre blowout is connected to insufficient inflation pressure and tyre deterioration (including ageing effects), both of which are significantly tied to tyre care. When a tyre blowout happens, debris is left on the road, the vehicle becomes unstable, or the vehicle comes to a halt in an unsafe position to change tyres. Inflation pressure affects both grip performance and the likelihood of a tyre blowout. Even on dry roads, a substantial variation in inflation pressure reduces grip and, due of the reduced stiffness, can induce vehicle instability. Tyre blowouts are caused by the heat produced by significant tyre deformations induced by severe underinflation (Jansen et al., 2016).

2.3 Type of Airless Tyre

Figure 2.2 depicts the components of each contemporary airless tyre construction. When loading an airless tyre with low stiffness spokes, the shear beam deformation in the contact region is compensated by stretching the higher spokes. The use of stiffer spokes prevents them from stretching, resulting in increased deformation (contact path length) in the contact region.

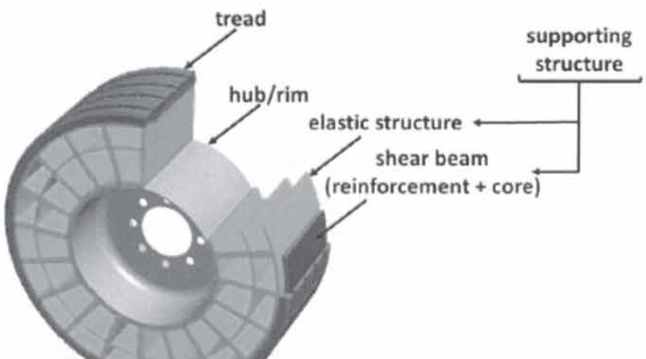


Figure 2.2: General construction of the airless tyre (Żmuda et al., 2019)

Solid elements or shell elements represent elastic structures in modern airless tyre models, while solid elements placed between shell elements or truss elements represent shear beam (reinforcement). The tread blocks' geometry is often ignored, and the tread layer is reduced to a smooth layer (ring) with fixed dimensions. The rim is often left out of models due to its extreme stiffness in comparison to the rest of the airless tyre (Żmuda et al., 2019).

2.3.1 Mechanical Elastic Wheel

Figure 2.3 depicts the Mechanical Elastic (ME)-basic wheel's structure. The construction of the ME-Wheel, as seen, is made up of many crucial components, such as assembly hinges-unit, suspension hub, combined elastic rings, and reset springs, which vary from those of a standard solid or pneumatic tyre. The elastic ring's skeleton structure, which acts as the stiffening material in ME-wheel is pre-embedded in the outer ring to limit the deformation of both rubber and cord ply of the wheel. The integrated elastic rings, which are made of multi-stranded steel wire, are held jointly by a locking mechanism. Combinatorial clips maintain the skeleton structure's elasticity. Elastic circles' outer surface. The carcass and tread are formed by covering the skeleton with rubber. The hinges-unit of the assembly acts as a connection that connects the suspension hub to the wheel's outer ring. There are twelve hinges-units in all, which are arranged in a grid pattern. The carcass and tread are formed by covering the skeleton of elastic rings with rubber. The assembly hinges-unit acts as a connection between the suspension hub and the wheel's outer ring. Twelve hinges-units are evenly spaced across the circumference of the elastic ring skeleton, with a 30 angle between them. It's worth noting that the mechanical properties of the ME-Wheel are heavily influenced by the groups of hinges-units under various operating conditions. The reset spring's critical purpose is to enable the deformable hinges-unit to return to its initial state. The whole wheel can be attached to the vehicle using the bolts literature review by (Zhao et al., 2018).

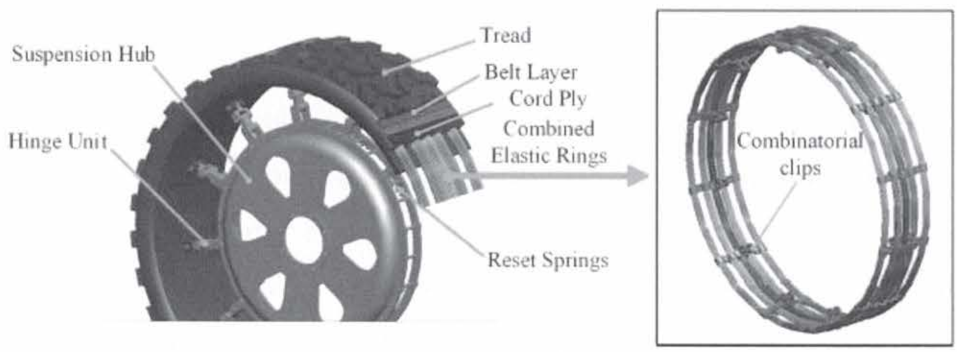


Figure 2.3: ME-Wheel geometric model (Zhao et al., 2018)

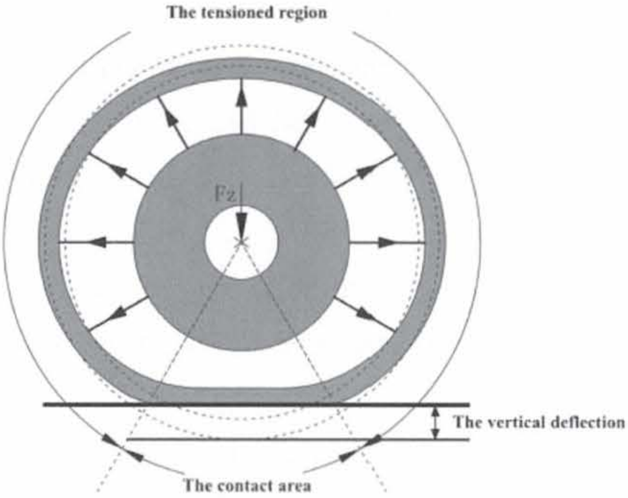


Figure 2.4: ME-Wheel load characteristic (Zhao et al., 2018)

2.3.2 Discrete and Continuous Spokes

The employment of an elastomer coating with strengthened rings and a unique spoke system, anchored to the inner surface of the tyre and equally disseminated across the rim, has been the most popular concept since the recent advent of newly designed airless tyres. The spokes support the vehicle's weight and deform to provide a cushioning effect similar to an air pressure tyre. airless tyre research has been active in order to enhance structural efficiency, such as contact pressure, flexible spoke design and structure, and rolling resistance. The air in pneumatic tyre was replaced in both solutions by a set of flexible polygon spokes that went through millions of tension–compression cycles while the tyre was spinning reported by (Sassi et al., 2016).

2.3.2.1 Discrete Spokes

One of the most popular airless tyre solutions has been to replace the trapped air within the toroidal volume around the rim with discrete spokes evenly distributed inside the circular plan between the inner and outer rings. In this layout, the spokes operate as elastic elements, deforming or bending in proportion to the amount of radial load applied, and therefore providing the necessary stiffness. The key issues with the majority of current solutions are the ride quality constraint (which is directly related to the number of spokes), the limited resistance to fatigue in stress concentration areas, the susceptibility to debris trapping, which can cause unbalance, and the risk of sound emission due to spoke vibrations and air circulation through the open lateral surfaces.

On various models of spokes-based airless tyres, a finite-elements analysis was performed using a commercial finite-elements code SolidWorks to examine the impact of discrete spokes on wheel results in Figure 2.5. The measurements of the airless tyre were chosen to be identical to those of a standard pneumatic tyre. For the sake of contrast with the literature, the spoke thickness was set to 5 mm in every versions reported by (Sassi et al., 2016).

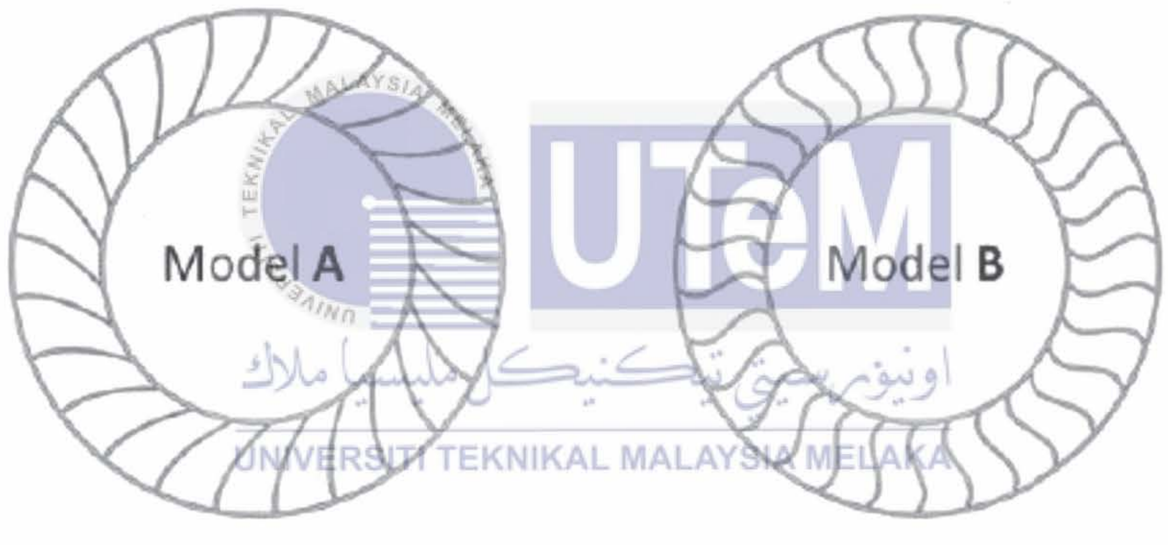


Figure 2.5: Different models of multi-spokes airless tyres (Sassi et al., 2016)

The wheel and tyre are combined in a single part in modern airless tyre designs. As shown in Figure 2.6, the airless tyre is made up of a rubber tread, shear band, flexible spokes, and rigid hub. In the case of a pneumatic tyre, the shear band and flexible spokes are the components that sustain the load operating on an airless tyre, such as air reported by (Mohan et al., 2017).

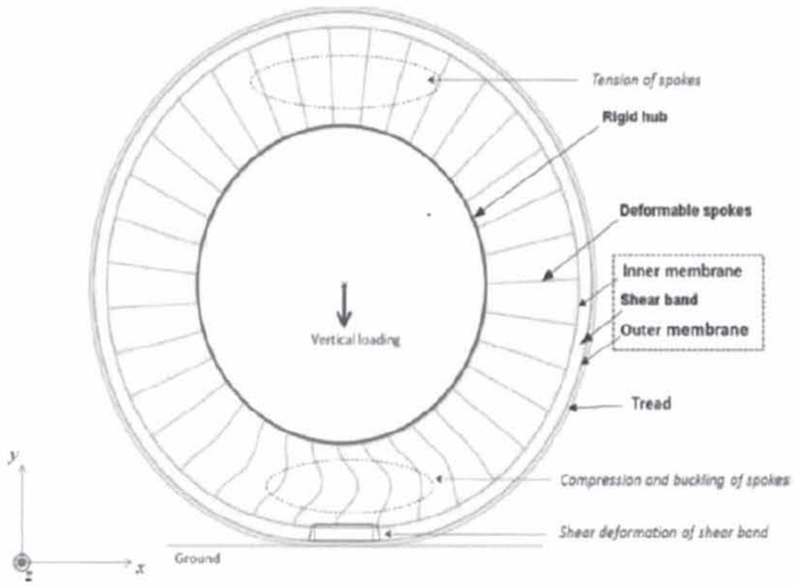


Figure 2.6: Schematic representation of an airless tyre (Mohan et al., 2017)

The shear beam is a composite ring with a low modulus material sandwiched between the reinforcements. The material between the reinforcements is subjected to shear loading during rolling and mainly deforms in pure shear.

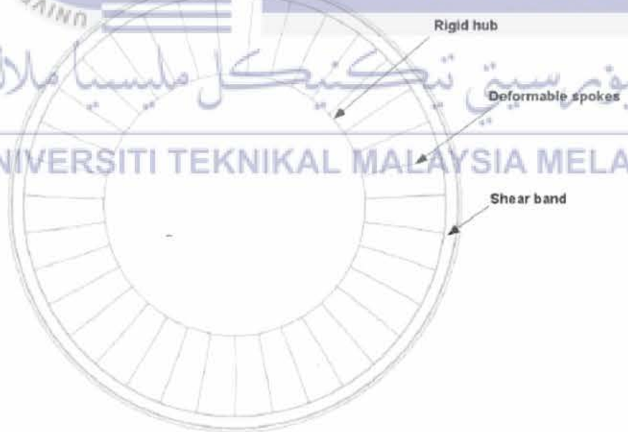


Figure 2.7: Airless tyre (Veeramurthy, 2011).

The shear beam and spokes are designed in such a way that they can achieve a reasonably uniform surface contact distribution with the ground when under load. The spokes and ring are cast in a mould that includes reinforcements. To provide traction, rubber tread is bonded to the outer ring. The use of PU for the spokes and shear band, which has a lower viscoelastic energy loss than rubber, can result in a low rolling resistance airless tyre design. Due to the shearing properties, hyperelastic materials like PU are critical because they contribute to damping, energy loss, flexibility, and pressure distribution between the airless tyre and the road.

The composite ring flattens in the contact region when the is loaded at the hub base, creating a contact patch. Because of the applied load, the deformable spokes buckle. The spokes that are not in contact with the contact region do not deform and stay in tension. The buckling of the airless tyre due to the application of static load is shown in Figure 2.8 adapted from (Veeramurthy, 2011).

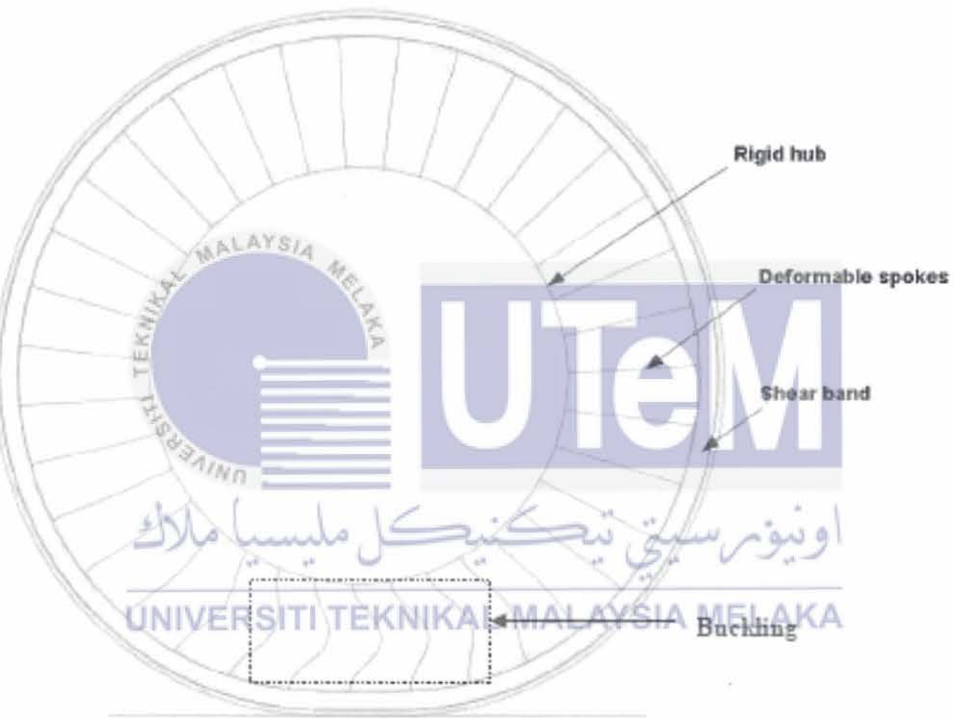


Figure 2.8: Deformed airless tyre due to the application of the load (Veeramurthy, 2011)

2.3.2.2 Continuous Spokes

The continuous stiffness nature is unaffected by the tyre's angle of rotation, which is the primary benefit that makes this type of tyre the most comfortable to ride on. Figure 2.9 illustrates the cross-chronological section's metamorphosis.

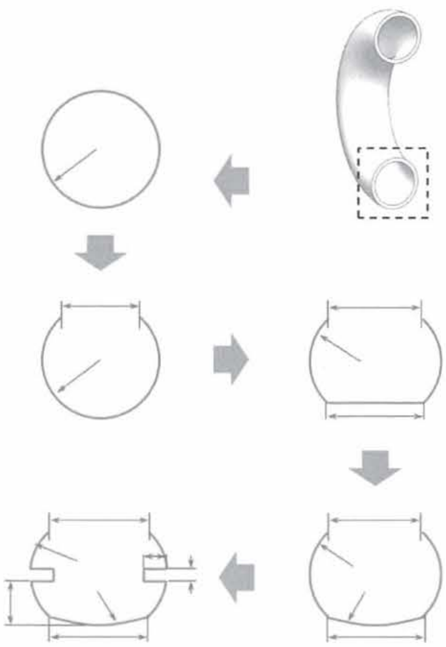


Figure 2.9: Various stages in the development of a new airless tyre (Sassi et al., 2016)

The design process began with a simple toroidal shell that looked like a blown-up donut. The cross-section shape was then changed several times, from a simple closed circle to an open circle (which was more practical for dismounting and mounting), and finally to a more complex contour with more design parameters, which could help with the later optimization/matching process between the mechanical properties of airless tyre and pneumatic tyre.

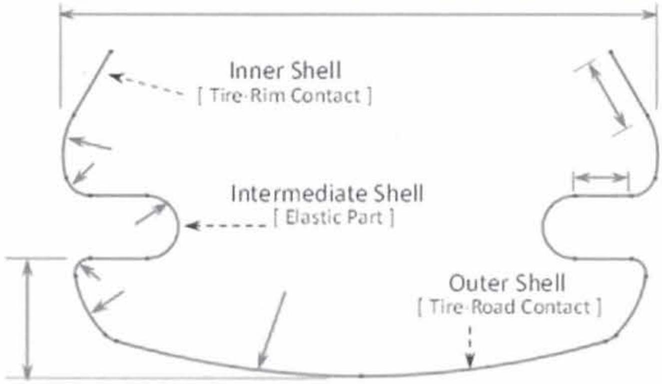


Figure 2.10: Cross-section properties of the new airless tyre design (Sassi et al., 2016)

The tyre shell is divided into three parts for the final design:

• The tyre's outer surface, which makes contact with the road.

• The inner shell, which provides tyre-rim touch

• The intermediate shell, which provides elasticity

All sharp angles have been curved to minimise tension concentration in intersecting curves, which could limit the highest deflections possible. Figure 2.11 shows the cross section in greater detail. When it comes to size and mechanical qualities, the new tyre should be constructed to be identical to the traditional pneumatic tyre (mainly radial stiffness). Figure 2.11 depicts the final version, which has a constant overall thickness of 7 mm reported by (Sassi et al., 2016).

Figure 2.11: Design of the new airless tyre (Sassi et al., 2016)

2.3.3 Honeycomb Spokes

The honeycomb structure is divided into cells during the design process. The entire structure is built by first creating a single cell and then mirroring it. Figure 2.12 depicts the dimensions of single cell notions.

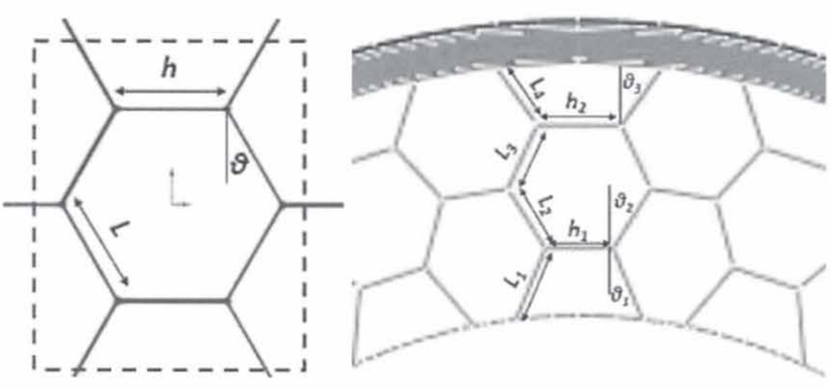


Figure 2.12: Geometric parameters of hexagonal honeycomb (Umesh & Amith Kumar, 2016)

Vertical cell length, h, cell wall thickness, t, inclined cell length, l, and cell angle, are all used to create hexagonal honeycombs. The honeycombs' effective stress–strain curves vary depending on the cellular geometry. Elevated cell angle causes cellular structures to lose flexibility under uniaxial packing. Lower local stresses can be seen in honeycomb spokes with a higher cell angle magnitude is ideal for fatigue-resistant spoke design literature review by (Umesh & Amith Kumar, 2016).

Figure 2.13: 3D model of honeycomb airless tyre (Umesh & Amith Kumar, 2016)

2.3.4 Tweel

Michelin unveiled an airless tyre that is appropriate for both extra-terrestrial and earth situations. Michelin believes that such compliant wheels can be used as a pneumatic tyre substitute, effortlessly replicating most pneumatic properties while perhaps outperforming others. TweelTM Tyre is the name of this flexible wheel.

According to Michelin's patents, there are two main nonpneumatic tyre designs, both of which are based on the same premise of having a compliant wheel without internal air pressure. A "structurally supported resilient tyre" is the first sort of design. As shown in Figure 2.14, it is constructed of a reinforced annular band, tread, and sidewall components identical to those seen in pneumatic tyres. When the wheel is pressed against the ground, the reinforced annular band is known as a shear band, and it deforms primarily in shear. A pneumatic-like near uniform contact pressure is produced if the shear band is built correctly.

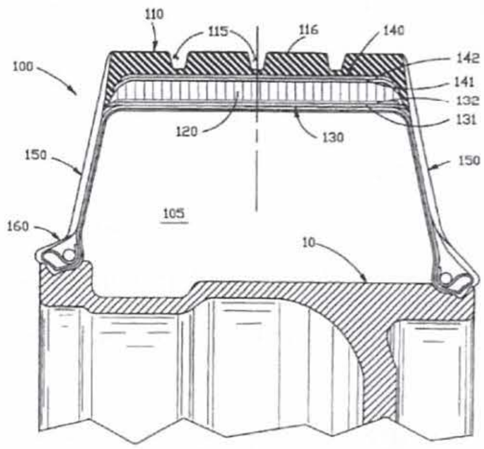


Figure 2.14: Schematic of airless wheel using sidewalls (Joseph et al., 2011)

The second sort of design, possibly the most well-known and also known as a TweelTM Tyre, is referred to as a "compliant wheel". It's made up of a tread, a strengthened annular band, and a slew of web spokes. As shown in Figure 2.14, the web of spokes provides load carrying by conveying the load of both the hub and compliant annular band via tension in the spokes, which are not connected to the ground contacting region of the wheel. As seen in Figure 2.15, this network of spokes can be arranged in a variety of ways. The spoke arrangement has a significant impact on the wheel's lateral and longitudinal rigidity properties.

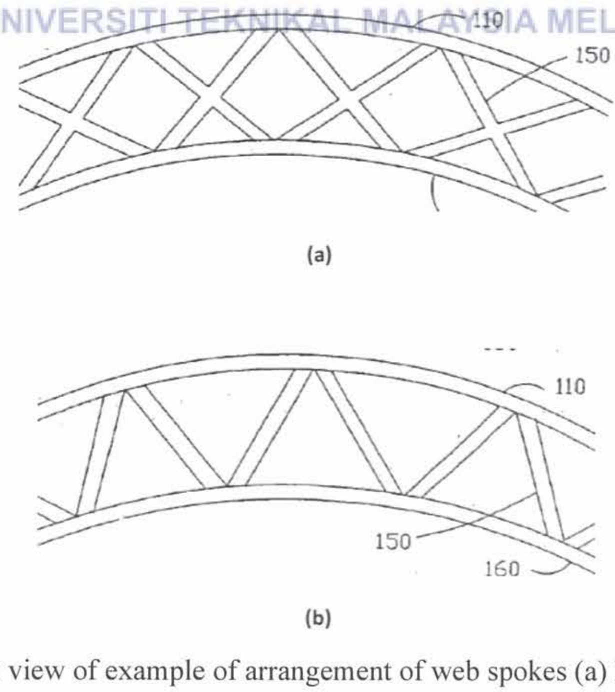


Figure 2.15: Section view of example of arrangement of web spokes (a) X pattern (b) V pattern (Joseph et al., 2011)

TweelTM Tyre is an integrated tyre and wheel that replaces the traditional tyre and wheel assembly. It is an airless compliant structural wheel. The Michelin TweelTM Tyre is shown in Figure 2.16. It's made out of a treaded composite reinforced ring that's linked to a hub by a network of thin, flexible spokes. The tyre has the same load bearing capacity, shock absorption, and ride comfort as pneumatic tyres, but it also has suspension-like features that assist handling. This nonpneumatic tyre has a number of advantages, including the fact that it does not require high pressure air (Joseph et al., 2011).

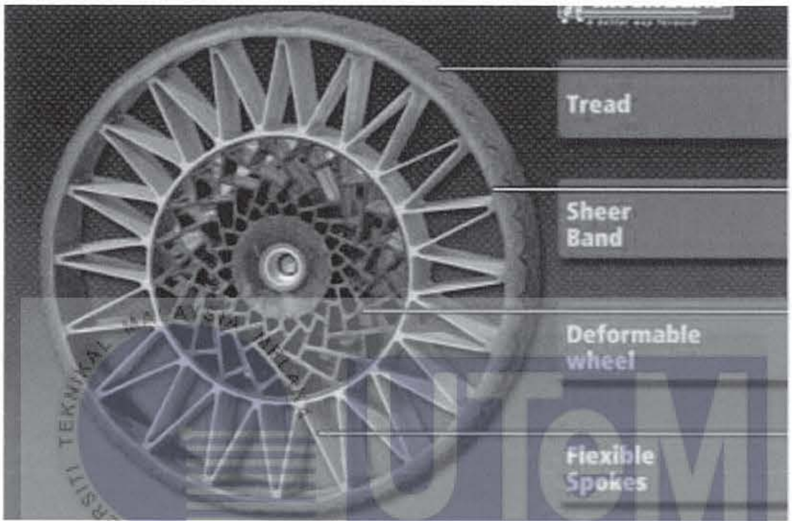


Figure 2.16: Automobile Tweel TM manufactured by Michelin (Joseph et al., 2011)

2.4 Material Properties

An airless tyre combines the wheel and tyre into a single structure, with various materials used for different sections of the airless tyre.

2.4.1 Material Properties Used in Airless Tyre

The materials properties assigned to these designs' components were identical. Aluminium alloy hubs for airless tyres are 10mm thick. Polyurethane honeycomb spokes that act as air in an airless tyre are attached to a stiff hub. An airless tyre's shear band is made of polyurethane and is protected by two 5mm thick high-strength steel shear rings. The shear rings are used to hold the tyre in place as it becomes deformed and shear band is used to create a uniform contact patch. The outermost portion of an airless tyre that comes into contact with the road surface has a tread similar to that of a pneumatic tyre, and the material used for construction tread is rubber (Mohan et al., 2017).

Table 2.1: Material properties (Abhishek & Kumar, 2020)

Part	Hub	Spokes	Outer Ring	Thread
Material	AL 7075- T6	Polyurethane	AISI 4340	Rubber
Density, ρ (Kg/m^3)	2800	1200	7800	1043
Youngs Modulus, E (Mpa)	72000	32	210000	11.9
Yield stress (Mpa)	500	140	470	16
Poissons Ratio, v	0.33	0.49	0.29	0.49

Aluminium alloy, polyurethane, steel, and syntactic rubber were used in this honeycomb tyre study. The key reason for choosing these materials is that they have a diverse set of mechanical properties, such as high durability, high stiffness and resilience, hyperelasticity, and high temperature tolerance, to name a few. Table 2.2 lists the properties of the chosen materials (Tarakaram & Varma, 2019).

Table 2.2: Material properties (Tarakaram & Varma, 2019)

Part	Hub	Spokes	Outer Ring	Shear Band
Material	UNS A97075	Polyurethane	AISI 4340	Synthetic Rubber
Yield Strength (Mpa)	503	140	470	16
Elastic Modulus, E (Mpa)	72000	32	210000	11.9
Poison's Ratio, v	0.33	0.49	0.29	0.49
Density, ρ (kg/m^3)	2180	120	7800	1043

Under load, a shear beam and spokes system can achieve a homogeneous surface contact distribution with the ground. The ring and spokes are cast in a mould with reinforcements built in. To create traction, a rubber tread is bonded to the outside ring. Because of their shearing qualities, hyperelastic materials such as PU are useful for energy loss, flexibility, dampening, and pressure distribution between the airless tyre and the road (Karthick et al., 2017).

An airless tyre's hub should provide a robust structure. The hub is made of AL 7075-T6 aluminium alloy. AL7075-T6's major alloying element is zinc. It's tough, with tensile strength like many steels, as well as good fatigue resistance and machinability.

Polyurethane is used as a constituent material in the honeycomb spokes. Polyurethane is a one-of-a-kind material that combines rubber's elasticity with metal's toughness and endurance.

The outer ring is made of AISI 4340 high-strength steel. This causes the thread rubber to distort when shear is applied. The edges of the spokes over the contact zone with the ground would buckle without the outer ring, causing an undesired nonlinear effect in the honeycombs.

Synthetic rubber is used for the thread component. Thread's purpose is to create required traction between the tyre and the road. On diverse terrains, the thread would have a decent grip. Any sort of artificial elastomer primarily synthesised from petroleum by products is known as synthetic rubber, which is invariably a polymer. An elastomer is a material that has the mechanical (or material) attribute of being able to bend far more elastically under stress than most materials while still returning to its original size without permanent distortion (Marattukalam et al., 2015).

Table 2.3: Properties of the constituent parts of airless tyre (Marattukalam et al., 2015)

Part	Hub	Spokes	Outer Ring	Thread
Material	AL 7075- T6	Polyurethane	AISI 4340	Rubber
Density ρ, (Kg/m^3)	2800	1200	7800	1043
Youngs Modulus, E (Mpa)	72000	32	210000	11.9
Poissons Ratio, v	0.33	0.49	0.29	0.49
Yield Strength (Mpa)	500	140	470	16

The rigid hub is formed by the inner ring, which is made of aluminium alloy. The IIEM and OIEM are built of high-strength steel with thicknesses of 1 and 0.75 mm, respectively. Without reinforcements, the spokes' edges will collapse across the ground's contact zone, resulting in an undesirable honeycomb non-linear impact. Polyurethane (PU) with a thickness of 10.2 mm is used for the spokes and shear layer. PU composite provides flexibility and rigidity at the same time. Due to their low modulus, PU materials can tolerate huge stresses with little stress. The tread is made up of rubber. The tread thickness has been chosen at 2mm, according to a review of the literature. The parts dimension and material properties are show in Figure 2.17. The material parameters used in the tyre are listed in Table 2.4. (Aboul-Yazid et al., 2015).

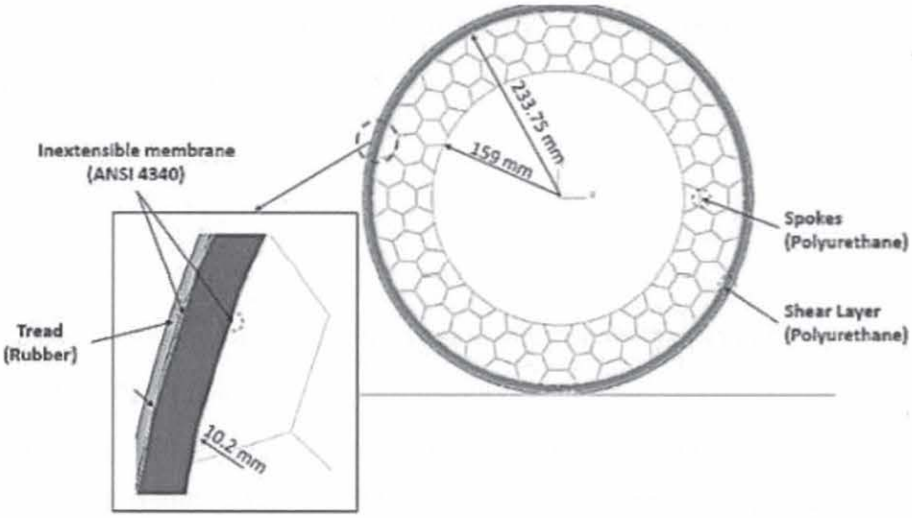


Figure 2.17: Different parts and dimensions of airless tyre (Aboul-Yazid et al., 2015)

Table 2.4: Material properties (Aboul-Yazid et al., 2015)

Material	Density, ρ (kg/m^3)	Young Modulus, E (MPa)	Poisson's ratio, ν	Shear Modulus, G (MPa)
Aluminium alloy	2800	$72x10^3$	0.33	-
PU	1200	32	0.49	10.8
ANSI 4340	7800	$210 x10^3$	0.29	-
Rubber	1043	11.9	0.49	4

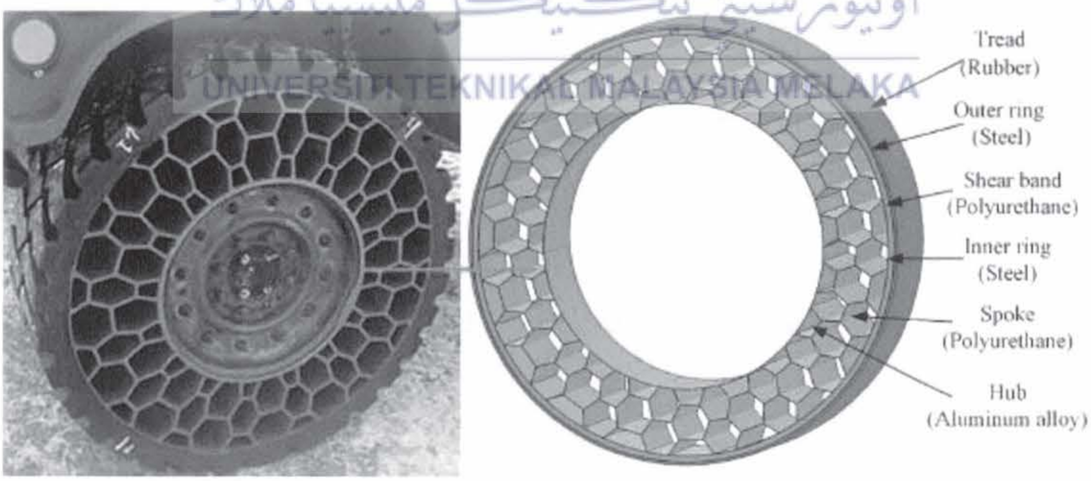


Figure 2.18: Honeycomb spokes on an airless tyre and a diagram of its components (Jin et al., 2018)

In simulations, the hub is believed to be made of aluminium alloy (AL 7075–T6), while the rings, which have an identical shape to airless tyre, are made of high-strength steel (ANSI 4340). Shear band and honeycomb spokes were made of polyurethane, while tread was made of synthetic rubber. Using Ogden theory, to model both hyperelastic materials, strain energy function can be interpreted as

$$w(\lambda^1,\lambda^2,\lambda^3) = \sum_{i=1}^{N} \frac{\mu}{\alpha_i}\left(\lambda^{1^{\alpha i}} + \lambda^{2^{\alpha i}} + \lambda^{3^{\alpha i}} - 3\right) \qquad \text{(Equation 2.1)}$$

where W represents the strain energy function, λ_i represents the deviatoric principal stretch, N represents a material parameter, and μ_i and α_i are represent temperature-dependent material parameters. The rolling energy loss of an airless tyre was also calculated using the viscoelastic characteristics of polyurethane and synthetic rubber. Using shear relaxation, the Prony series was utilised to create the generalised Maxwell model of viscoelastic behaviour, given by:

$$G_R(t) = G_0\left[\sum_{k=1}^{N} g_i\left(1 - e^{-\frac{t}{\tau_i}}\right)\right] \qquad \text{(Equation 2.2)}$$

The shear relaxation modulus G_R (t), the instantaneous shear modulus G_0, and the Prony relaxation time constants g_i and τ_i are used to match experimental results. The viscoelastic Prony series coefficients for polyurethane and rubber in ascending order of three terms (N=3). The cumulative viscoelastic energy loss (ALLCD in ABAQUS) per unit rolling distance was used to measure the rolling resistance of airless tyres.:

$$F_R = \frac{W_d}{D} \qquad \text{(Equation 2.3)}$$

The rolling resistance is calculated as above reported by (Jin et al., 2018).

Table 2.5: Material properties for airless tyre parts from literature review

Author	Airless Tyre Parts			
	Hub	**Spokes**	**Shear band**	**Outer Ring/Thread**
(Mohan et al., 2017)	Aluminium Alloy 7075- T6	Polyurethane	Polyurethane reinforced with high strength steel	Rubber
(Karthick et al., 2017)	Aluminium	Polyurethane	Polyurethane	Rubber Thread
(Abhishek & Kumar, 2020)	AL 7075-T6	Polyurethane	n/a	AISI 4340 And Rubber Thread
(Marattukalam et al., 2015)	AL 7075-T6	Polyurethane	n/a	AISI 4340 And Rubber Thread
(Umesh & Amith Kumar, 2016)	UNS A97075	Polyurethane	Synthetic Rubber	AISI 4140
(Jin et al., 2018)	Aluminium Alloy	Polyurethane	Polyurethane	Steel with thread
(Aboul-Yazid et al., 2015)	Aluminium Alloy	Polyurethane	Polyurethane	ANSI 4340 with Rubber thread

2.5 Airless Tyre Market Study

The market of airless tyre is predicted to increase at a CAGR of roughly 5.5 percent among 2020 and 2026, with a market value of USD 34.2 million in 2019. Continuous technological advances targeted at reducing tyre vibration and noise will boost the market.

The airless tyres have a higher load bearing capacity and better driving performance while also being environmentally beneficial. Consumers are becoming more interested in these tyres since they lessen the demand for spare tyres while also increasing productivity in industries such as manufacturing, farming, construction, and mining.

By lowering energy lost due to tyre rolling resistance, airless tyres have the potential to cut carbon emissions. Furthermore, market demand will be driven by the utilisation of recyclable materials combined with resource efficiency. Furthermore, the growing demand for tyres that do not require maintenance, specifically for utility, terrain, military, commercial vehicles, and motorcyclists will impact the airless tyres market.

The industry will be propelled forward by the product's high potential as a replacement for traditional pneumatic tyres. With such many cars requiring regular maintenance, fleet applications have a lot of room for expansion. Furthermore, the global shift in attention to the agricultural sector is pushing up demand for agricultural machinery, which will help to keep market demand stable.

The growing need for puncture-resistant tyres for vehicles that carry a lot of weight and operate in difficult environments will help market penetration. Furthermore, tyre companies like Goodyear and Michelin are focused their efforts on creating commercial vehicle tyres, resulting in increasing product growth. The Asia Pacific airless tyres market is predicted to develop at a CAGR rate of 6% throughout the projected period, thanks to the the manufacturers' presence such as Hankook, Bridgestone, and Sumitomo Rubber Industries throughout the area. As raw resources become more easily available and vehicle ownership rises, the industry landscape will see significant growth potential (Pulidindi & Mukherjee, 2020).

Figure 2.19: Airless tyre market global statistics (Pulidindi & Mukherjee, 2020)

2.6 Conceptualisation Methodology

The purpose of concept development is to come up with a design that maximises stakeholder value across the life of the system. Effective concept creation takes into account the interests of all stakeholders and establishes requirements that do not limit the design area needlessly. You could end up with systems that don't meet your needs or are poorly made if you don't. These efforts investigate a wide range of solutions in depth, yet effectively, through determining what solutions are available and how they will satisfy the demands.

The process of conceptualization is not new. Engineers use a range of procedures to help them find the greatest solutions. A range of models, mock-ups, simulations, and prototypes are used to better comprehend difficulties, produce candidate solutions, and validate their results. The type of challenge (e.g., latent, or explicit demand), the availability of resources and knowledge, and the development team's experience all influence them. Each instrument and procedure, like alternative solutions, has advantages and limitations (London, 2012).

2.6.1 Theory of Inventive Problem Solving (TRIZ)

The goal of TRIZ is to use practical tools and a methodical approach to solve issues and invent new technologies. The ARIZ algorithm is at the heart of TRIZ (Russian for Algorithm of Inventive Problem Solving). ARIZ is a multi-step technique for solving complex problems that employs pre-determined questions. Two more TRIZ problem-solving methodologies are the contradiction matrix and the 40 inventive principles.

The idea of finding concepts comes up when an innovator is trying to get from a problem to a solution. To tackle problems in product development, the trial-and-error method is commonly used, with less-than-optimal results. To arrive at a solution, a substantial number of attempts are required. B. S. Egorov, a Russian inventor who made around 300 variations of his initial winding machine. Even though none of the 300 efforts were successful, the amount of time wasted was considerable. An inventor's first thought for finding a solution is called a seeking concept. Figure 2.19 shows a graphic representation of issue solving using the trial-and-error method as well as search methods. If the difficulty is transporting merchandise from a continent to an island, an inventor would suggest using a boat. In most cases, the inventor's mind is now fixed on this original search concept, and other options, such as aeroplanes or hovercrafts, are dismissed. This is frequent in huge issues when it takes a long time to map all choices within a searching notion. Using a needle, however, was not an option this time because the machine's scale had to be reduced. Even yet, the idea of a needle was initially utilised since it looked to be the most obvious solution.

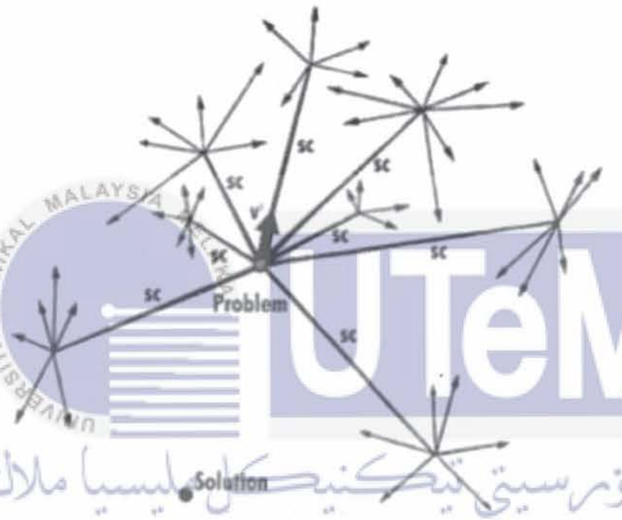


Figure 2.20 Exploring concepts usingtTrial-and-error method (Sairanen, 2017)

TRIZ divides challenges across five tiers based on their difficulty. Problems at levels one and two are common and can usually be solved in a hundred attempts or fewer. These are difficulties that every engineer should be able to address and seek solutions to. It can take a thousand tries to finish level three difficulties, while level five problems can take a million. There may be scenarios that are more difficult than level five and need an endless sequence of trials. A level five problem is the development of electro-discharge technology. Solving such a problem by trial and error would take far too long for a single inventor to accomplish in his lifetime. However, because successful innovators' work is usually built on top of that of unsuccessful inventors, such flaws can be rectified. Higher level challenges gradually degrade into lower-level difficulties because of repeated failed attempts. According to polls, several inventors believe that searching for patent information will impede their potential to develop. This is especially true for higher-level difficulties, as the existing patent that could help solve the problem could be in a whole different branch of science and technology (Sairanen, 2017).

2.6.1.1 Advantages of TRIZ

One of the TRIZ tools is a 39-by-39-quality matrix, where each cell represents a distinct conflict between two features. As solutions for settling the corresponding dispute in each cell of the matrix, up to four physical principles are proposed. One of the forty basic ideas is the concept of periodic activity such as replace a continuous action with a periodic action, like an impulse.

It's possible that the nailer team used TRIZ to come up with the idea of driving the nail with several little strokes. Detecting a design conflict and then figuring out how to address it looks to be a very beneficial problem-solving heuristic. This strategy can assist you produce concepts even if doesn't use the entire TRIZ process (Golder & Mitra, 2018).

The main advantage of utilising the TRIZ technique as a problem-solving tool is that it takes a systematic approach to problem-solving, as opposed to traditional alternatives, which are often haphazard and overly reliant on luck (Hassan et al., 2017).

2.6.1.2 TRIZ Steps to Problem Solution

The issue-solving process of the TRIZ methodology begins with the creation of a general description of the problem and the identification of inconsistencies that impede the "more desirable result" from being realised. The "superior prospective solution" is the finest option among the alternatives available. The second step in the resolution process is to pinpoint the source of the problem and devise a viable remedy, which necessitates a "correct formulation" of the technical inconsistency.

The issue must be framed in terms of technical inconsistency: with more specific description, then the solution will be more effective. The third part of the resolution process is to find a generic solution for each physical contradiction in the system. During this stage of the resolution process, Altshuller's TRIZ tools (such as contradiction matrix) will be immensely useful. The generic solution is transformed into a distinctive and inventive solution in the fourth and final step of the resolution process.

As a result, the resolution process is divided into four steps, which are depicted graphically in Figure 2.20 as the "TRIZ Problem Solution Steps." (Donnici et al., 2018)

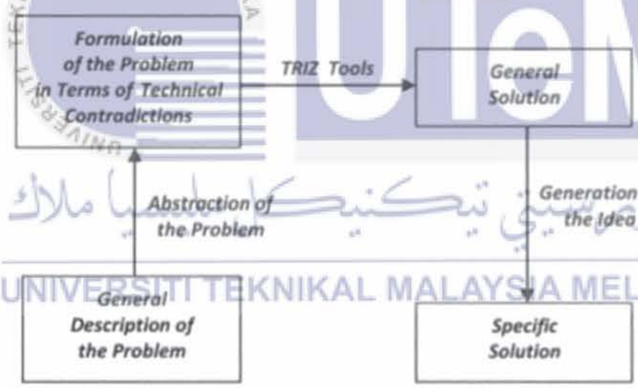


Figure 2.21: TRIZ problem solution steps (Donnici et al., 2018)

2.6.1.3 TRIZ Functional Analysis Model (FAM)

The method of finding problem and contradictions starts with an emphasis on the proper FAM, as displayed in Figure 2.21. The FAM uses component functions at three levels of system, as opposed to the SDA function structure, which stresses material, energy, and signal as they move over a component system boundary. The three categories of systems are system, subsystem, and super-system, with super-system referring to unconnected components which effect or affect the total system. (Kamarudin et al., 2015).

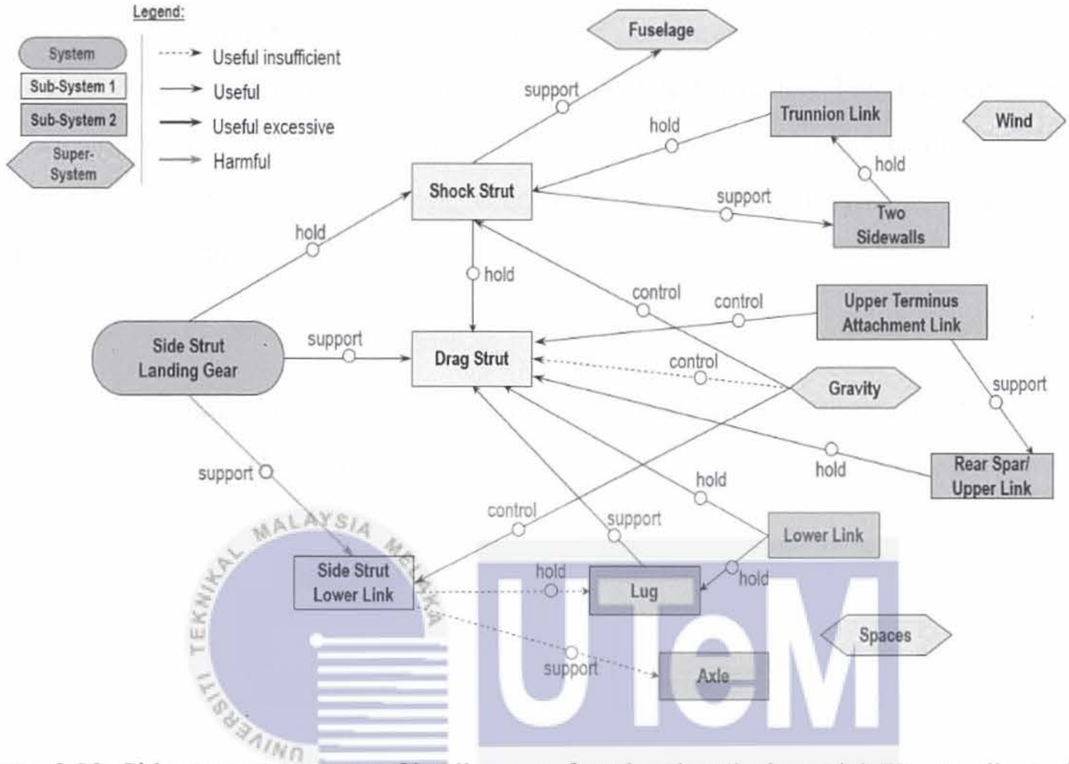


Figure 2.22: Side strut component of landing gear functional analysis model (Kamarudin et al., 2015)

2.6.1.4 TRIZ Contradiction

The notion of engineering contradiction underpins TRIZ. An engineering contradiction occurs when an attempt to improve one parameter of an engineering system causes another parameter to deteriorate. Engineering inconsistency is also known as "technical inconsistency." The Altshuller Matrix is a problem-solving tool that suggests creative solutions to technical issues.

In most technical arguments, he determined that 39 common factors are involved. Consider the length and weight of a stationary item, for example. In the majority cases, standard answers to standard contradictions appear to be effective. He dubbed these replies "Inventive Principles" once he generalised them. In TRIZ, there are 40 Inventive Principles (Ko et al., 2016).

2.6.1.5 TRIZ 39 Engineering Parameters

There are a total of 39 engineering parameters. The TRIZ theory defined engineering parameters and the expression of true problems in general. Altshuller summarised the 39 generic engineering qualities used to define general performance in engineering disciplines such as geometry, physical performance, and technical performance. The interplay between individual challenges and TRIZ theory is defined by these general technical variables. Increasing some technological factors, according to the Contradiction, will necessarily impair one or more other elements.

As a result, the requirements for improvement and degeneration create a technical paradox, with both opposites of oneness confined and dependent on one another. According to Altshuller's investigation, it could generate almost 1300 pairs of typical technical disputes, spanning virtually all technical content in projects and matching the 39 general engineering criteria pairwise.

While using TRIZ theory tools to solve practical problems, choose two of the 39 engineering parameters that correspond to the real problem to describe the system's technical contradiction—technical contradiction matrix, specifically, we should convert the contradictions that exist in the actual engineering design to standardised technical contradictions. It entails using the engineering parameter of the TRIZ theory to reflect real-world technical difficulties. Realize the standardised process of TRIZ, that puts the groundwork for the standardisation of creative theory, by combining contradiction and idealism in an organic way (Dong et al., 2017).

Table 2.6: TRIZ 39 engineering parameters (Lin & Wu, 2016)

No.	Engineering parameter	No.	Engineering parameter
1	Weight of M	21	Power
2	Weight of non-M	22	Waste of energy
3	Length of M	23	Waste of substance
4	Length of non-M	24	Loss of information
5	Area of M	25	Waste of time
6	Area of non-M	26	Amount of substance
7	Volume of M	27	Reliability
8	Volume of non-M	28	Accuracy of measurement
9	Speed	29	Accuracy of manufacture
10	Force	30	Harmful factors acting on object
11	Tension/pressure	31	Harmful side effects
12	Shape	32	Manufacturability
13	Stability of object	33	Convenience of use
14	Strength	34	Reparability
15	Durability of M	35	Adaptability
16	Durability of non-M	36	Complexity of device
17	Temperature	37	Complexity of control
18	Brightness	38	Level of automation
19	Energy spent by M	39	Productivity
20	Energy spent by non-M		

M: moving object.

2.6.1.6 TRIZ 40 Inventive Principles

To explain the unique circumstance, the first stage in the problem-solving algorithm is to define contradictions. The third stage, extraction, comprises using transformations from previously solved issues based on the 40 TRIZ principles to characterise the larger problem. Analogies to a general solution can be identified, and through employing a corresponding solution, a specific solution can be found. This innovation-seeking methodology has been successfully used by several major corporations (such as Samsung and IBM) as well as government research (Kretzschmar & Chekurov, 2018).

Table 2.7: Additive manufacturing examples in perspective of 40 TRIZ inventive principles (Kretzschmar & Chekurov, 2018)

#	TRIZ principle	AM example	Classification		
			DFAM	LAM	AMPC
1	Segmentation	Divide a component into smaller pieces in CAD		x	
2	Taking out	Take an essential part out of the component and apply AM		x	
3	Local quality	The use of lattice structures	x	x	
4	Asymmetry	A channel that changes its cross-sectional area	x	x	
5	Merging	A mechanism that works directly after printing without assembly	x	x	
6	Universality	Faster production times when objects are merged (e.g. air ducts)	x	x	
7	Nested doll	Designs that can be printed collapsed (e.g. chain)	x	x	
8	Anti-weight	Hollow (or lattice structure filled) components in airplanes	x	x	
9	Preliminary anti-action	3D-printable acoustic insulation (specific tower pattern)	x	x	
10	Preliminary action	Design object in a way that it can be post-processed easily		x	
11	Beforehand cushioning	Design holes to remove powder of inner functions after the print		x	x
12	Equipotentiality	Flexible objects produced with AM			x
13	The other way around	Comparison of SL and DLP build platform movement		x	x
14	Spheroidality - Curvature	Topology optimization	x	x	
15	Dynamics	Customization of design	x	x	
16	Partial or excessive actions	Design for steeper angles than instructed when possible	x	x	
17	Another dimension	Applying 4D Printing	x		x
18	Mechanical vibration	Support removal with vibration		x	x
19	Periodic action	Oxygen-permeable layer allows continuous printing with CLIP			x
20	Continuity of useful action	Adding new powder from both sides of the build chamber		x	x
21	Skipping	High laser speed to avoid melt pool spatter		x	x
22	Blessing in disguise	Benefit from rough surfaces (e.g. heat exchanger)	x	x	
23	Feedback	Closed loop for heat control in SLM		x	x
24	Intermediary	Removable build plate in SLM		x	x
25	Self-service	Re-use of metal powder		x	x
26	Copying	Prototyping	x	x	
27	Cheap short-living objects	Emergency spare parts / home appliance replacements		x	
28	Mechanics substitution	New ways of integrated identification of components (imprints)	x	x	
29	Pneumatics and hydraulics	Deformable grippers actuated with pneumatics		x	
30	Flexible shells and thin films	Basic printing mechanism of LOM			x
31	Porous materials	Lattice structures / porous lubrication	x	x	
32	Color changes	Photopolymer 3D printing	x		x
33	Homogeneity	LENS of turbine blades	x	x	x
34	Discarding and recovering	Support dissolving (e.g. FDM)			x
35	Parameter changes	Make solid parts from powder (m-PBF)		x	x
36	Phase transitions	Post-build sintering shrinkage (metal FDM)	x		x
37	Thermal expansion	Crucial process parameter to be controlled in m-PBF	x	x	x
38	Strong oxidants	As applied in the CLIP technology			x
39	Inert atmosphere	Needed in the SLM process		x	x
40	Composite materials	Carbon fiber composite applied in FDM			x

2.6.2 Quality Function Deployment

Quality functions deployment (QFD) were initially established in 1966 in Japan and made public in 1972 by Mitsubishi. Through multi-level deductive analysis, it effectively combines the user's product needs into quality management technologies for component characteristics, product design, process design, and production requirements. To put it another way, QFD refers to the functionality and technical specifications of the goods that will be built. It is a systematic process that considers client desires as well as product functionality and manufacturing criteria, and it extends beyond the concerns of traditional businesses.

QFD is used by several companies in the United States, including AT&T, HP, Ford, and GM. In the process of translating client demand into product quality design, it is critical to integrate and collaborate with key departments such as marketing, product development, quality design, production, and manufacturing. QFD can help with communication, engagement, and information sharing amongst departments. The House of Quality (HoQ) is the primary tool for QFD indicated in Figure 2.24.

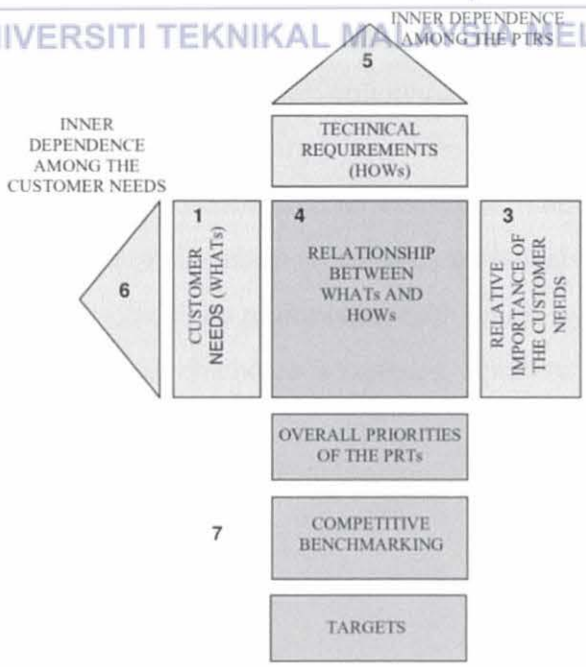


Figure 2.23: HoQ (Weijie, 2020)

User demand, user demand assessment, engineering demand (VOE), relationship matrix between user demand and engineering demand, engineering demand evaluation, engineering demand contradiction check, and selection of necessary quality features are among the processes involved in filling in the home of quality. The input of QFD is the user's needs, while the output is the results of the quality characteristic evaluation. The user demand is converted into engineering demand using the quality function deployment technique.

The key quality features are selected using the weighted importance weight of VOE calculated after evaluation and statistical analysis of correlation analysis, and then combined with the study of VOE contradiction at the top of the quality house. Thanks to the considerable weight achieved from user demand analysis, the accuracy and proximity of the generated essential quality attributes to the user's conceptions can be increased utilising this method (Weijie, 2020).

2.6.3 Pugh

The Pugh method is a numerical method for comparing and ranking decisions. It uses a basic matrix and specified criteria to compare options. This method compares alternatives to a baseline, which may be one of the alternatives or the existing product or service. The most relevant features are listed and compared to a baseline. The use of simple scores of worse (-1), equal (0), or better (+1) is common. Instead, statistical scales can be used (e.g., 2, 1, 0, -1, -2). The options are graded by multiplying each option by its weight. The relative scores are used to determine if a given choice is superior, equal, or inferior than the default (London, 2012)

Table 2.8: Pugh matrix with weighted criteria (Silverstein et al., 2011)

		Pugh Concept Selection Matrix	Wieght	Design Concepts: Electric 4-slot	Electric Conveyor	Gas Grill		
Selection Criteria	Good Toast Quality	Even Toasting	2	S	S	-		
		Good Taste	3	S	S	S		
		Repeatable	3	S	+	-		
		Quick	3	S	S	S		
	Capacity	Large Range of Bread Products	2	S	S	+		
		Multiple Slices/Units	4	S	+	+		
	Long Life	Reliable	1	S	-	S		
		Durable	3	S	S	S		
		Low Maintenance	3	S	-	S		
	Physical Attributes	Affordable	2	S	-	+		
		Attractive	5	S	-	-		
		Safe	3	S	-	- -		
		Good Size	4	S	-	-		
	Easy to Use	Easy to use Controls	5	S	S	+		
		Easy to Load	4	S	+	+		
		East to RemoveToast	4	S	+	-		
		Automated	4	S	S	- -		
		TOTAL +		0	4	4		
		TOTAL -		0	6	9		
		TOTAL SCORE		0	-2	-5		
		WEIGHTED TOTAL +		0	15	17		
		WEIGHTED TOTAL -		0	17	32		
		WEIGHTED SCORE		0	-2	-15		

2.6.4 Morphological Chart

Morphological approaches help frame the problem so that different components can be synthesised to attain the same goal. Having access to a component catalogue simplifies this method. However, it does not take on the role of designer cooperation. Teams are required for developing concepts, communicating with one another, and reaching an agreement. The optimal technique is for each participant to work for several hours on their own on a subset of the problem, for instance how to meet the demand indicated by a function. Morphological analysis aids a group in collecting separate study findings into a single structure that the entire group can process.

The three steps below describe the morphological approach to design in general.

i) Dividing the main design problem into smaller subproblems is a good start.
ii) Formulate solutions for each subproblem.
iii) In a systematic approach, merge subproblem solutions into various complete solutions, then evaluate all combinations.

After the designer or team has adequately dissected the problem, morphological analysis can be performed. The first stage in the process is to make a morphological chart in Table 2.6. The chart is a table that organises the solutions to the subproblems. The names of the subproblems identified throughout the decomposition process are represented by the chart's column headings. The subproblem solutions are retained in the rows. The answer to each subproblem is displayed in each chart column using descriptive words or extremely basic images (Dieter & Schmidt, 2013).

Table 2.9: Shot-buddy basketball return system morphological chart (Dieter & Schmidt, 2013)

Solution Concepts for Subproblem				
Change Direction of Basketball	**Channel Moving Basketball**	**Guide Basketball to Return Device Inlet**	**Sense Shooter's Position**	**Rotate Return Device Outlet Toward Shooter**
Sheet of flexible material	Catch net	Funnel (net or solid material)	RFID tag worn by shooter	Ratchet device
Solid deflector panels	Plastic sheeting with wire ribs	Set of rails	Motion sensor	None (rely on ball's direction and gravity)
Shaped foam	Finger-like converging structure	Tube of netting	Optical sensor	Cam mechanism
Paddle arms	Tubing (partially open or closed)	Metal guide (moving or stationary)	Acoustic sensor	Geared shaft

2.7 TRIZ Integration with Other Methods

TRIZ has been a tremendous success/improvement/etc. in solving engineering challenges, and it is used frequently by designers and scholars. As evidenced by the fact that many designers and researchers have conducted and published studies on design selection for a variety of applications, many designers and researchers have conducted and published studies on design selection for a variety of applications to create a product using the TRIZ principle methodically. This project includes hybrid composite anti-roll bars for vehicles, kenaf composite car spoilers, automobile engine rubber composites, kenaf composite shoe shelves, transmission tower cross arm creep test rigs, and coupon scale flexural creep test rigs (Asyraf et al., 2020). This section explains on TRIZ integration with various of other methods when developing the concept of product. The details of the results are discussed in the subchapter.

2.7.1 TRIZ Integration with Morphological Chart-Analytic Network Process

An engine rubber mount is a car part that may be found in almost any moving vehicle with an internal combustion engine, whether it's in the air, on land, or at sea. Injection moulding is commonly used to create this product. The rubber/elastomers composite that works as an isolator or vibration absorber is the most important part of these engine rubber mounts. The most common engine mounting material is natural rubber, often known as natural polymer. Synthetic polymer composites, such as polyurethane (PU), are employed, although they are expensive and environmentally unfriendly. Automakers all around the world are transitioning to green products and materials for use in their components because of numerous environmental regulations modifications in the automobile sector. The researcher has been tasked with developing environmentally friendly green materials.

Natural rubber was mixed with thermoplastic polyurethane blends and kenaf fibres as a filler to create these uncommon engine rubber mounting composites. Experiments have proven that all three materials can be successfully mixed. Conversely, the goal of this study is to build a conceptual design for rubber composites for engine rubber attachment. For the early stage, four designs have been created, and the finest design will be chosen utilizing the TRIZ principal solution. After that, a morphological chart will be used in this paper and analytic network process (ANP) will be used to make the final design decision (Azammi et al., 2018).

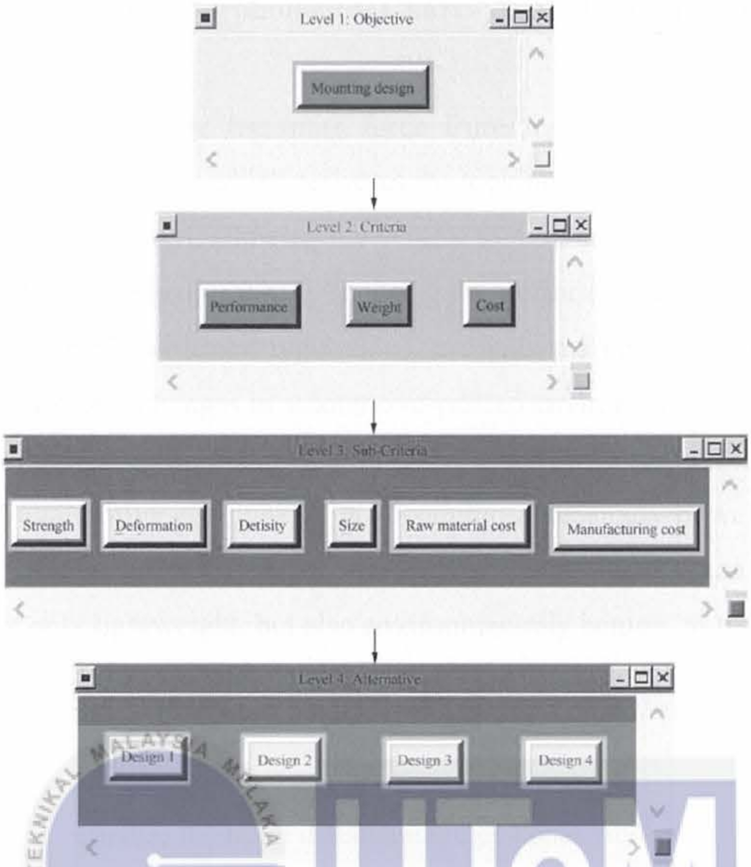


Figure 2.24: Kenaf fiber polymer composite engine rubber mounting ANP hierarchy framework (Azammi et al., 2018)

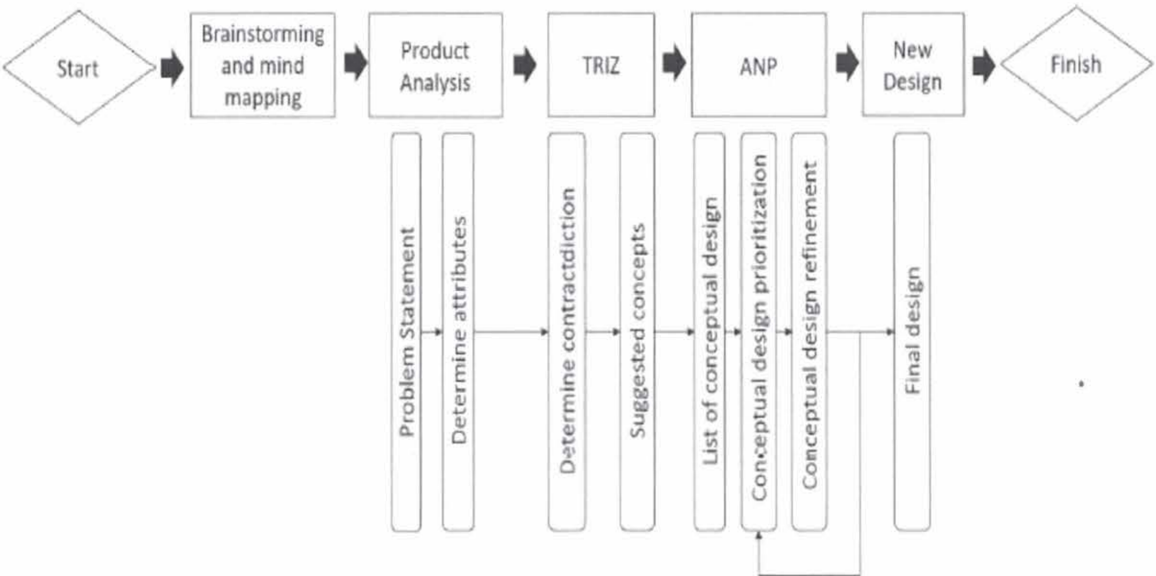


Figure 2.25: Conceptual design framework for TRIZ-morphological chart-ANP (Asyraf et al., 2020)

2.7.2 TRIZ Integration with Morphological Chart - Analytic Hierarchy Process

The parking brake lever transmits force from the driver's hand to the ratchet mechanism of the parking brake, which activates the locking and unlocking operation of the drum brake at the rear car wheel, allowing the vehicle to remain safely still whether stopped or idling. Manufacturers are progressively focusing their efforts on creating lighter vehicles and components to comply with new regulations, maintain market share, and assure future growth as a result of recent changes in automotive-related environmental legislation around the world. As a result, the use of kenaf fibre polymer composites as a substitute material in the production of automotive components is becoming increasingly prevalent; as a result, this research will focus on the parking brake lever component. Kenaf fibre polymer composites are not only lightweight, but also environmentally benign, as they are recyclable and made from renewable elements.

Despite these benefits, the main disadvantage of kenaf fibre polymer composites in the automotive industry is their inferior mechanical strength when compared to traditional engineering materials like steel, which limits their use to non-structural components. As a result, a new concurrent engineering method incorporating the TRIZ–Morphological Chart–Analytic Hierarchy Process (AHP) method is used to investigate suitable solutions for the issue during the conceptual design stage for the development of an automotive parking brake lever component made of kenaf fibre polymer composites. By combining TRIZ with the morphological chart approach, designers may swiftly translate common TRIZ responses into their own individual design elements utilising a systematic technique and sequence. A morphological chart allows designers to see concepts more clearly before merging them to create product conceptual designs.

In concept design development, the TRIZ technique was used as a solution tool for idea generation, and the morphological chart was used as an idea refinement tool based on the TRIZ supplied solutions. Finally, based on the car parking brake lever product design parameters, AHP technique was applied as a concept design selection tool as displayed in Figure 2.28 (Mansor et al., 2014).

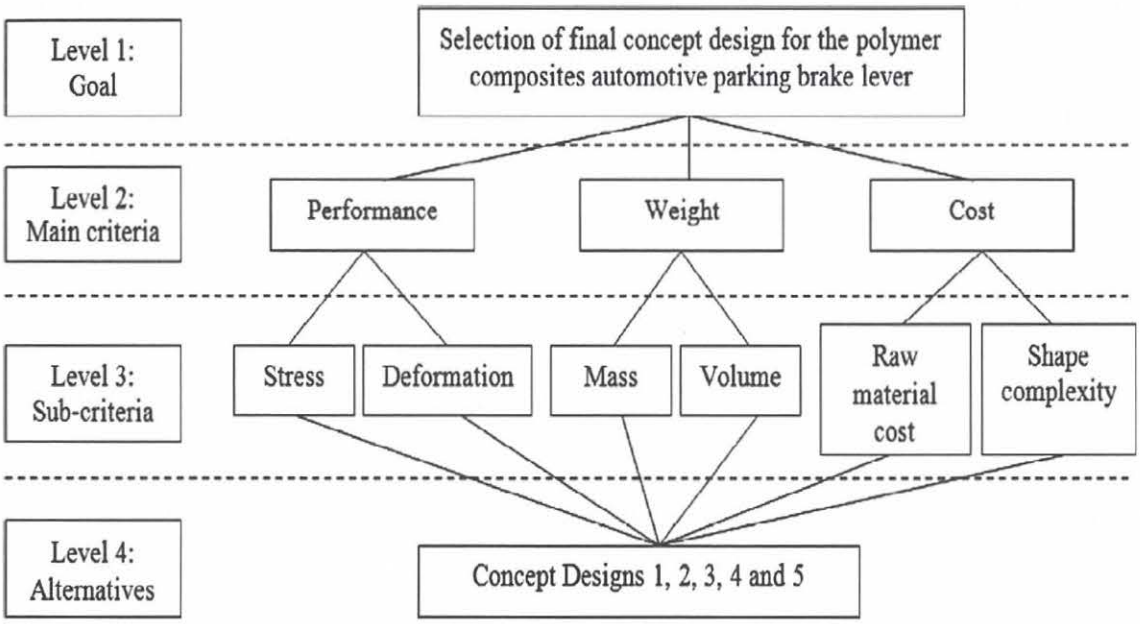


Figure 2.26: AHP hierarchy structure to choose a kenaf fibre polymer composite parking brake lever concept (Mansor et al., 2014)

2.7.3 TRIZ Integration with Pugh

Make statements that identify current problems using the Problem Formulation Diagram (PFD). PFD is separated into three categories based on the current system function, each of which contains different aspects of the process. It will further generate problem statements that there is a conflict based on the problems that have been found before utilising the problem formulation diagram. The problem statement will be used as an input in the construction of contradictions, with the parameters of each problem statement being recognised.

Using the Pugh technique, some previously established alternative concepts will be chosen. Prior to deciding on the Pugh approach, criteria were established to identify what material will be used to evaluate various conceptions. User demands, technical requirements, and operational needs of the tools specified by the researcher were among the criteria considered. Based on the concept of picking outcomes using the Pugh technique, three unique engine models have been chosen for future exploration. In this step, the selection matrix was used to go deeper into each alternative concept, giving each selection criterion a weight and assigning a scoring mechanism to each alternative concept on each criterion. (Meliandy et al., 2018).

2.7.4 TRIZ Integration with Concept Scoring

The main challenge is gaining a full awareness of the present research environment by reviewing previous papers. The next step is to pinpoint the source of the major issue. The TRIZ problem-solving tool is used in this stage. Cause-and-effect chain (CEC) analysis diagram is built using important results from previous research to assist in the identification of potential problem causes and the narrowing down of those causes to specific root causes. In TRIZ, the technique of building conflicts is crucial, and it is used in the next level. Engineering contradiction, physical contradiction, and substance-field analysis were the three methodologies used in this inquiry. These techniques are used to get to the bottom of a problem. Product development follows the generation of ideas. A way of refining and selecting from a pool of developed ideas is concept selection. An idea selection approach was used to the three created concepts. With minor modifications, the modified digital logic method was used in this study. In this experiment, it was difficult to see two features as equally important. As a result, neither of the two numerical scores was used in the selection process. This criterion, though, resulted in a huge numerical discrepancy between the most important and least significant attributes due to the difference between scores one and three. The least important received a one-point rating while the more important property received a two-point rating

The concept score matrix for the finger pinch enhancer for senior citizens is shown in Table 2.7. The ratings were based entirely on the main author's personal experience with and understanding of a variety of hand and finger assistive devices. The co-authors of this study agreed with the original author's grades and rankings in terms of the primary author's amazing design sense in the specialised domain of hand and finger assistive devices. Because no one notion was appropriate to serve as the reference in this example, each criterion's reference was chosen separately rather than as a single concept. Finally, idea 2 was chosen because of its benefits in terms of user comfort and ease of use, as well as the recommendation to use wires for flexible finger control (Wen et al., 2021).

Table 2.10: Concept scoring matrix for finger grip enhancer (Wen et al., 2021)

Selection criteria	**Weight**	**Concepts**					
		1		**2**		**3**	
		Rating	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**
Flexibility	0.133	3	0.399	4	0.532	2	0.266
Fulfils requirements	0.222	2	0.444	5	1.11	3	0.666
Realisable in principle	0.156	2	0.312	4	0.624	3	0.468
Cost	0.178	3	0.534	2	0.356	4	0.712
Safety	0.200	2	0.40	4	0.80	3	0.60
Preferred by PKN	0.111	2	0.222	3	0.333	4	0.444
Total score		2.311		3.755		3.156	
Rank		3		1		2	
Continue?		No		Develop		No	

2.8 Response Surface Methodology (RSM)

RSM is a set of statistical and mathematical methods that can be used to develop, optimise, and improve processes. It can be applied to the development of new products as well as the enhancement of existing ones. RSM is most typically employed in the industrial sector, especially when a product's or process's key point performance or quality feature is influenced by various input factors. The reaction is a metric of performance or a quality attribute. Even though attribute, rank, and sensory responses are prevalent, the response is essentially measured on a continuous scale. For the vast majority of RSM applications, multiple responses will be necessary. In general, the RSM approach can represent the observed response using a linear or second-order polynomial expression.

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X^2{}_i + \sum_{i=1}^{k-1} \beta_{ii} X_i X_j + \varepsilon \qquad \text{(Equation 2.4)}$$

where Y denotes the response variables utilised in the response surface design; k is number of factors; β_0 is the model constant; β_i (i = 1, 2,…, k) denotes the linear coefficient; β_{ii} (i = 1, 2,…, k; j = 1, 2, …, k) denotes the quadratic coefficient; X_i and X_j the coded independent variables and $\mathcal{E}$ is the statistical error (Kittidecha & Marasinghe, 2015).

2.9 Summary

As a summary, studies related to tyre structure, tyre components, material properties, safety aspect and engineering analysis method, concept development are discussed in literature review chapter. the core components of airless tyre are spoke, shear band, ring, thread and spoke. The material of airless tyre consists of aluminium alloy, polyurethane, high strength steel and rubber. Various type of concept method such as TRIZ, PUGH, QFD as well as integration of TRIZ with other methods when developing new product concept. The concept of airless tyre is explored to build a better understanding on conducting the project on the concept development of modular airless tyre.

CHAPTER 3

METHODOLOGY

This chapter explained about the methods and planned steps to achieve the project objective. The flow chart provides a guidance to conduct the project. This chapter is split into 4 subtopics and details of the subtopic are discussed.

3.1 Methodology Flow Chart

This process flow chart explains how to conduct this study project step by step and provides an overview of conducting the project. TRIZ methodology and Pugh method are used as the concept development method. TRIZ tools which include functional analysis, if-then-but, 39 engineering parameters and 40 inventive principles are used before producing the conceptual sketch. The first step TRIZ functional analysis is used to identify and analyse the interactions of components of existing airless tyre system. Second step is formulating the contradictions using TRIZ "If-Then-But" technique Then, using 39 engineering parameters contradiction are corresponded. TRIZ 40 inventive principle are identified using Contraction Matrix and general solutions obtained using 40 Inventive Principle. The solutions refined based on TRIZ 40 Inventive Principle into specific solution. The specific solutions are applied to generate the conceptual sketch. Several conceptual sketches are generated in this stage. Finally, Pugh concept selection method is used to determine the final concept.

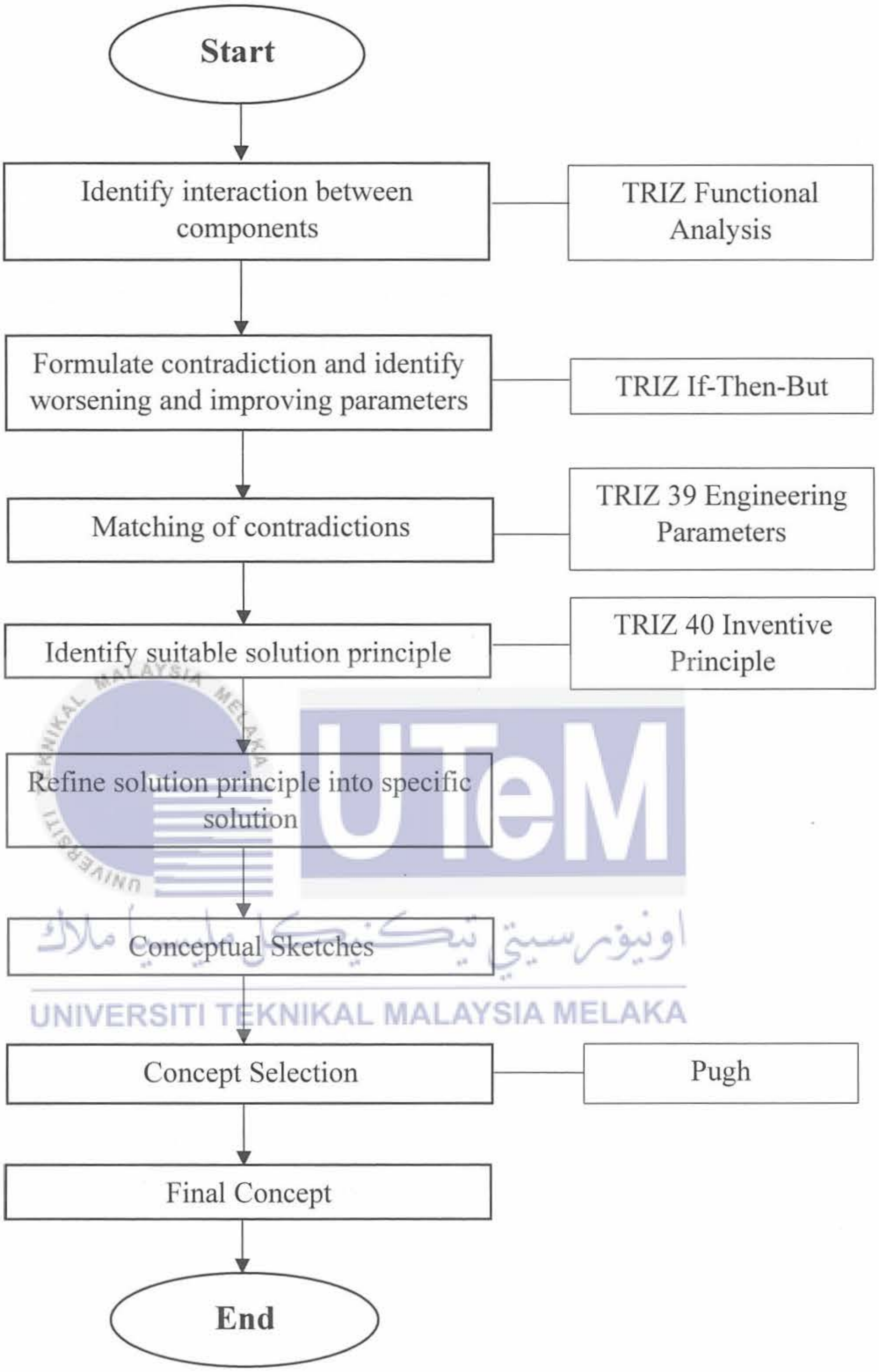


Figure 3.1: Methodology flow chart

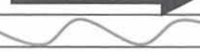
3.2 Concept Generation

An intuitive way to arrive at a viable design solution is to develop unique concepts. In engineering, however, producing a feasible conceptual design is not the same as coming up with one or two good concept ideas during a brainstorming session. Engineering systems are typically complicated, and their design entails numerous steps of methodical problem solving. TRIZ formalise and apply solution concepts learned from unique innovations to similar design issues, resulting in innovative solutions (Dieter & Schmidt, 2013).

3.2.1 Identify Interaction

TRIZ tool function model is a that shows the interplay of functions between the engineering system, its subsystems and supersystems graphically. Engineering system refers to the airless tyre in question, while the subsystem and supersystem, respectively, refer to the airless tyre's subcomponents and environmental aspects with which it interacts. This can determine the insufficient interaction between the components or subcomponents which the insufficient function can be used as reference for identifying problem solution. How does TRIZ function model depict all the functions performed by and for specific components as well as system elements? It connects all the factors to the positive and negative behaviours and results that correlate to airless tyre. This provides a solid understanding of how the airless tyre system operates and aids in identifying any functional concerns and fixing those issues so that the entire system or components of the system can be improved. The details of the functional analysis will be described in Chapter 4.

Table 3.1: Function type and line style

Function Type	Line Style
Useful (normal)	
Useful (insufficient)	
Useful (excessive)	
Harmful	

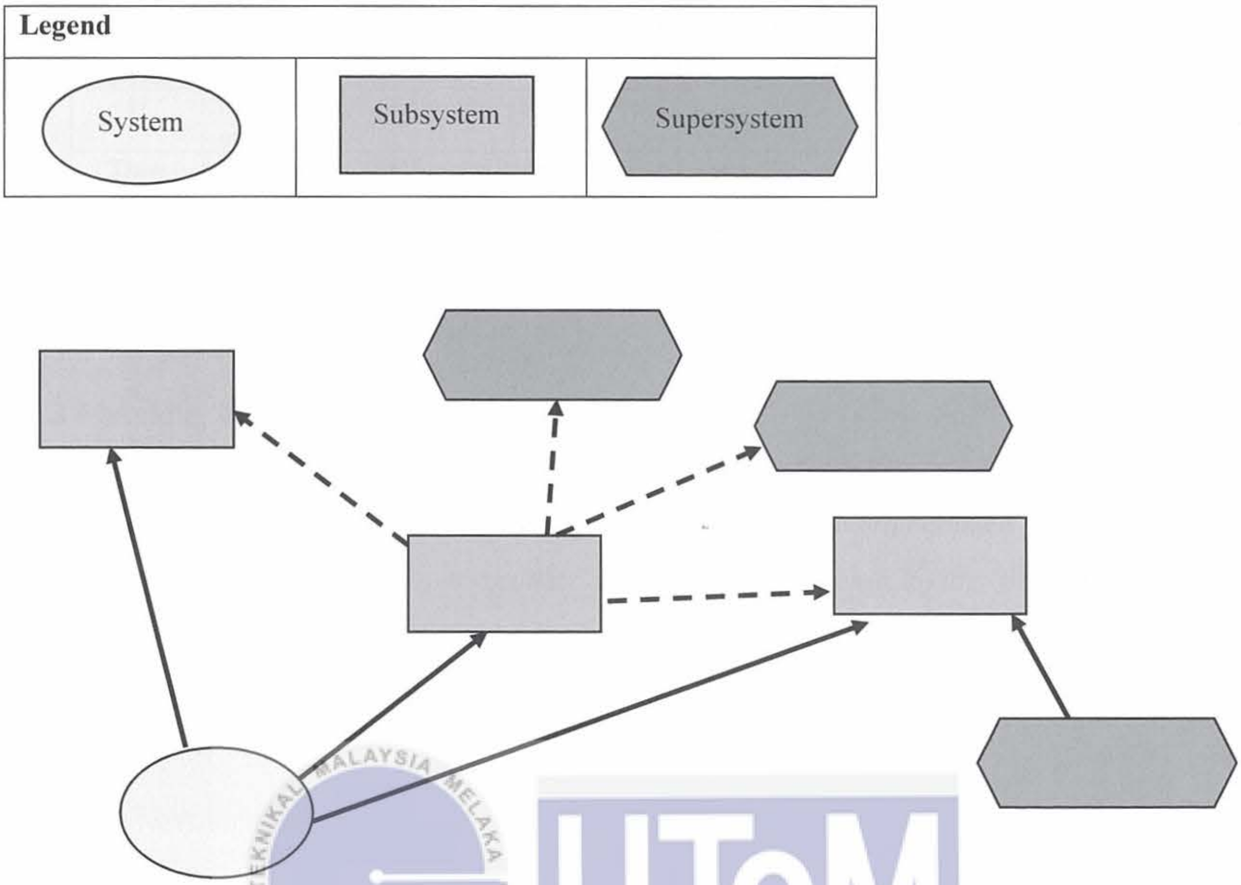


Figure 3.2: Function map diagram example

3.2.2 Formulate Contradiction

The TRIZ "IF-THEN-BUT" method is used to identify the technical contradiction problem. When there is a conflict, a contradiction exists: either opposites of the same thing exist, or one object improves while the other deteriorates. The "IF-THEN-BUT" method reduces the problem even further and makes it easier to discover the contradiction components of the airless tyre. The simplest way to look for conflicting criteria to identify worsening and improving parameters is to create a set of questions similar to this. What needs to be improved? What will be worsen?

Table 3.2: TRIZ if-then-but technique

Terms	Explanations	Conditions
If	A statement where the changes were made	If…
Then	A statement clarifies the future benefits gain from the expressed action	Then…
But	A statement explains the drawback from the expressed action	But...

3.2.3 Matching of Contradictions

The TRIZ system parameters are a collection of 39 keywords created to represent current technical parameters in a broader fashion. Many idea-thinking processes are inhibited by the usage of high-order technical vocabulary or jargons, thus can break the creative barrier by translating jargons into lower-order terms, allowing them to think more creatively and come up with more diverse and better solutions to the problem.

The TRIZ contradiction matrix is used to uncover creative principles for resolving the contradiction problem in the existing design. Every inconsistency may now be studied; while using the contradiction matrix, it's critical to consider both the characteristics that intensify and those that alleviate conflict. The Matrix can be used to find improving features and worsening features that can be used to solve the technological conundrum and come up with solutions or problem-solving ideas.

Improve this one ↓ without making this one worse →

39 Technical Parameters

#	Parameter	1 Weight of moving object	2 Weight of Stationary Object	3 Length of moving object	4 Length of Stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force (intensity)	11 Stress or pressure	12 Shape	13 Stability of the object's composition	14 Strength
1	Weight of moving object		-	15 8 29 34	-	29 17 38 34	-	29 2 40 28	-	2 8 15 38	8 10 18 37	10 36 37 40	10 14 35 40	1 35 19 39	28 27 18 40
2	Weight of stationary object	-		-	10 1 29 35	-	35 30 13 2	-	5 35 14 2	-	8 10 19 35	13 29 10 18	13 10 29 14	26 39 1 40	28 2 10 27
3	Length of moving object	8 15 29 34	-		-	15 17 4	-	7 17 4 35	-	13 4 8	17 10 4	1 8 35	1 8 10 29	1 8 15 34	8 35 29 34
4	Length of stationary object		35 28 40 29	-		-	17 7 10 40	-	35 8 2 14	-	28 10	1 14 35	13 14 15 7	39 37 35	15 14 28 26
5	Area of moving object	2 17 29 4	-	14 15 18 4	-			7 14 17 4		29 30 4 34	19 30 35 2	10 15 36 28	5 34 29 4	11 2 13 39	3 15 40 14
6	Area of stationary object	-	30 2 14 18	-	26 7 9 39	-		-		-	1 18 35 36	10 15 36 37		2 38	40
7	Volume of moving object	2 26 29 40	-	1 7 4 35	-	1 7 4 17	-		-	29 4 38 34	15 35 36 37	6 35 36 37	1 15 29 4	28 10 1 39	9 14 15 7
8	Volume of stationary object	-	35 10 19 14	19 14	35 8 2 14	-		-		-	2 18 37	24 35	7 2 35	34 28 35 40	9 14 17 15
9	Speed	8 28 13 38	-	13 14 8	-	29 30 34	-	7 29 34	-		13 28 15 19	6 18 38 40	35 15 18 34	28 33 1 18	8 3 26 14
10	Force (Intensity)	8 1 37 18	18 13 1 28	17 19 9 36	28 10	19 10 15	1 18 36 37	15 9 12 37	2 36 18 37	13 28 15 12		18 21 11	10 35 40 34	35 10 21	35 10 14 27
11	Stress or pressure	10 36 37 40	13 29 10 18	35 10 36	35 1 14 16	10 15 36 28	10 15 36 37	6 35 10	35 24	6 35 36	36 35 21		35 4 15 10	35 33 2 40	9 18 3 40
12	Shape	8 10 29 40	15 10 26 3	29 34 5 4	13 14 10 7	5 34 4 10		14 4 15 22	7 2 35	35 15 34 18	35 10 37 40	34 15 10 14		33 1 18 4	30 14 10 40
13	Stability of the object's composition	21 35 2 39	26 39 1 40	13 15 1 28	37	2 11 13	39	28 10 19 39	34 28 35 40	33 15 28 18	10 35 21 16	2 35 40	22 1 18 4		17 9 15
14	Strength	1 8 40 15	40 26 27 1	1 15 8 35	15 14 28 26	3 34 40 29	9 40 28	10 15 14 7	9 14 17 15	8 13 26 14	10 18 3 14	10 3 18 40	10 30 35 40	13 17 35	

#	Parameter	15 Duration of action of a moving object	16 Duration of action of a stationary object	17 Temperature	18 Illumination Intensity	19 Use of energy by a moving object	20 Use of energy by a stationary object	21 Power	22 Loss of energy	23 Loss of substance	24 Loss of information	25 Loss of time	26 Quantity of substance	27 Reliability
1	Weight of moving object	5 34 31 35	-	6 29 4 38	19 1 32	35 12 34 31	-	12 36 18 31	6 2 34 19	5 35 3 31	10 24 35	10 35 20 28	3 26 18 31	3 11 1 27
2	Weight of stationary object	-	2 27 19 6	28 19 32 22	19 32 35	-	18 19 28 1	15 19 18	18 19 28 15	5 8 13 30	10 15 35	10 20 35 26	19 6 18 26	10 28 8 3
3	Length of moving object	19	-	10 15 19	32	8 35 24	-	1 35	7 2 35 39	4 29 23 10	1 24	15 2 29	29 35	10 14 29 40
4	Length of stationary object	-	1 40 35	3 35 39 18	3 25	-		12 8	6 28	10 28 24 35	24 26	30 29 14		15 29 28
5	Area of moving object	6 3	-	2 15 16	15 32 19 13	19 32	-	19 10 32 18	15 17 30 26	10 35 2 39	30 26	26 4	29 30 6 13	29 9
6	Area of stationary object	-	2 10 19 30	35 39 38		-		17 32	17 7 30	10 14 18 39	30 16	10 35 4 18	2 18 40 4	32 35 40 4
7	Volume of moving object	6 35 4	-	34 39 10 18	2 13 10	35	-	35 6 13 18	7 15 13 16	36 39 34 10	2 22	2 6 34 10	29 30 7	14 1 40 11
8	Volume of stationary object	-	35 34 38	35 6 4		-		30 6		10 39 35 34		35 16 32 18	35 3	2 35 16
9	Speed	3 19 35 5	-	28 30 36 2	10 13 19	8 15 35 38	-	19 35 38 2	14 20 19 35	10 13 28 38	13 26		10 19 29 38	11 35 27 28
10	Force (Intensity)	19 2		35 10 21	-	19 17 10	1 16 36 37	19 35 18 37	14 15	8 35 40 5		10 37 36	14 29 18 36	3 35 13 21
11	Stress or pressure	19 3 27		35 39 19 2	-	14 24 10 37		10 35 14	2 36 25	10 35 3 37		37 36 4	10 14 36	10 13 19 35
12	Shape	14 26 9 25		22 14 19 32	13 15 32	2 6 34 14		4 6 2	14	35 29 3 5		14 10 34 17	36 22	10 40 16
13	Stability of the object's composition	13 27 10 35	39 3 35 23	35 1 32	32 3 27 15	13 19	27 4 29 18	32 35 27 31	14 2 39 6	2 14 30 40		35 27	15 32 35	
14	Strength	27 3 26		30 10 40	35 19	19 35 10	35	10 26 35 28	35	35 28 31 40		29 3 28 10	29 10 27	11 3

Figure 3.3: TRIZ contradiction matrix

3.2.4 Identify Suitable Solution Principle

The TRIZ 40 solution model is used to select generic solutions. TRIZ's 40 principles can be used in various of situations. The proposed inventive thoughts served as a quick guide for users to generate fresh ideas or consider different approaches to solve the problem. The contradiction matrix is used to summarise the innovative principles.

Table 3.3: Innovative principles advocated summarised using contradiction matrix (Mansor et al., 2017)

No	Worsen Parameter	Improving Parameter	TRIZ 40 inventive Principle
1	No. 33: Ease of operation	No. 23: Quantity of substance	No.32: Colour changes a) change the colour of an object or its external environment. b) change the transparency of an object or its external environment
			No.28: Mechanics substitution a) replace a mechanical means with a sensory (optical, acoustic, taste or smell) means. b) use electric, magnetic and electromagnetic fields to interact with the object. c) change from static to movable field activated (e.g ferromagnetic) particles
			No.2: Taking out a) separate the interfering part or property from an object, or single out the only necessary part (or property) of an object
			No.24: Intermediary a) use an intermediary carrier article or intermediary process. b) merge one object temporarily with another (which can be easily removed)

3.2.5 Refine Solution Principle

There are numerous generic solutions to the contradiction that the TRIZ technique recommends. Each TRIZ 40 inventive principle from the contradiction matrix are analysed, and the most relevant 40 inventive principle solution related to the issue we want to solve are selected, then refine into specific solutions strategy.

Table 3.4: Specific solution strategy

No	40 Inventive Principle	40 Inventive Principle Solution Description	Specific Solution Strategy Description
1	# No..		
2	# No..		
3	# No..		
4	# No..		

3.2.6 Conceptual Sketches

A framework or graphical representation of the working structure is a common representation method. Hand or computer sketching is one sort of graphical representation. Sketches are one feature that should be employed when performing conceptual design. Diagrams or freehand sketches are the most effective means of expressing creativity and comprehending the working concept (Kamarudin, 2017). The conceptual sketch of the modular airless tyre is based on its geometric and shape. Based on the specific solution from TRIZ method, several conceptual sketches are generated in this section

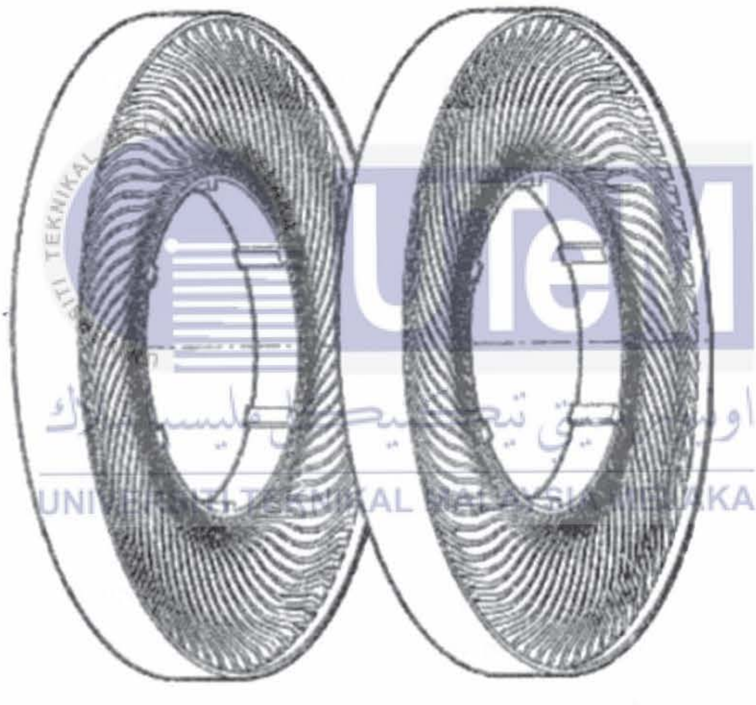


Figure 3.4: Airless tyre concept (Brell & Meng, n.d.)

3.3 Concept Selection

Using efficient information gathering and creative stimulation tools, as well as systematic TRIZ design approaches design concepts are created. Convergence concepts are re-evaluated against a set of criteria to assess if they are likely to be widely accepted.

3.3.1 Pugh Concept Selection Method

When making a decision, the Pugh Matrix is a straightforward way to take these various aspects into account. It is possible to make subjective thoughts about one alternative vs another more objective by utilising people's intrinsic capacity to make a pairwise comparison. Pugh Matrix provides some insight into the resilience of a given decision (Silverstein et al., 2011).

3.3.2 Concept Screening

Concept screening is used to choose among the concept and referring against a benchmark which the conceptual idea is evaluated with. The reference concept is known as datum. The datum is crucial as the proposed solution are evaluated against the datum. If no nearly identical thing exists, one of the new concepts can be chosen as the datum.

3.3.2.1 Selection Matrix

The selection matrix is made by choosing a physical medium that is appropriate for dealing with specific issues. A set of criteria is provided as a guideline for conducting the concept screening technique. The criteria and concept information are entered into the matrix. Details of selection criteria are described in chapter 4.

Because each criterion is weighted the same way it was during concept formation, redundant criteria are deleted and not recorded in the screening matrix. Aside from that, the outcome indicates the inaccurate consequences of disparities in ideas and concepts in terms of the most important criterion. Table 3.5 shows the concept screening selection matrix.

Table 3.5: Selection matrix

Selection Criteria	Conceptual Design		
	1	2	3
Criteria 1			
Criteria 2			
Criteria 3			
Criteria 4			
Sum +			
Sum –			
Sum 0			
Net score			
Rank			
Continue?			

3.3.2.2 Concept Rating

Each concept is given a relative score that is placed in each of the matrix boxes to demonstrate how the concepts compare to the baseline concept in relation to the specific criterion. The concept is compared by criteria by criteria.

Table 3.6: Rating used in concept screening stage (Silverstein et al., 2011)

Relative Performance	Rating
Better	+
Same as	0
Worse	-

3.3.2.3 Concept Ranking

The value of the "better", "same as, and " "worse", ratings were summed once the entire concept had been appraised, and the sums for each category were placed in the matrix's lowest row. Once the summing is complete, all summation is arranged in the order of the concepts using the evaluations of +1, 0, and -1. All the concept's requirements should be evaluated once the conceptual design has been graded and ranked to guarantee that the final result makes sense. Consider the following improvements and integration options for the concept “Is there a concept that is impacted negatively by a negative feature in general?” and “Is it possible to strengthen the overall concept while remaining different from others by making a modest change?

The revised concepts are then compared to the original concept in terms of rating and ranking on the matrix. The new concept was developed by combining several previous ideas, and it was used to exclude several members of the "worse" ranking system.

3.3.2.4 Concept Selection

The selected concepts are further improved and evaluated. As a result of the first steps, the most reliable concept has evolved. There are number of concepts that advance to the next stage of development. Before a final concept choice can be made, all issues related to the selected concepts are be investigated and explained for future investigation. It must also be decided whether a second round of screening be undertaken or if the concept be employed in the future.

3.3.3 Concepts Scoring

When a higher resolution is needed to distinguish between competing concepts, concept scoring is used. Concept scoring differs from concept screening in that it focuses more on the refinement of comparisons with respect to each criterion.

3.3.3.1 Selection Matrix

The choosing of the matrix is the first step in the concept scoring process. The difference between this step and the screening stage is that this stage contains more information that may be used to refine the selection criteria.

Table 3.7: Selection matrix of concept scoring

Selection Criteria	Weightage (%)	Conceptual Design					
		1		2		3	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
Criteria 1							
Criteria 2							
Criteria 3							
Criteria 4							
Sum +							
Sum –							
Sum 0							
Net score							
Rank							

3.3.3.2 Concept Rating

The entire concept can be graded at once because it is the simplest approach to focus the discourse. Furthermore, the concept is scored on a finer scale in order to distinguish between it with better precision.

Table 3.8: Relative performance

Relative Performance	Rating
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much Better than reference	5

3.3.3.3 Concept Ranking

The weighted scores are obtained by multiplying the criteria weights after all of the concepts have been appraised and the rating value for each concept has been recorded. The ultimate score for each notion is determined by the sum of the weightage ratings, and the complete concept is ranked.

Any changes that can improve the concept are essential, just as they were with the idea screening process. The strengths and weaknesses of the specific aspects of the product concepts are realised when some of the most innovative alterations and improvements are made during the concept selection process.

3.3.3.4 Concept Selection

Based on the results of the previous stage of the ranking and scoring procedure, one notion with the highest weighted value is picked. To determine the exact functionalities and specifications of items, the final concept is being identified.

3.4 Summary

In summary, the TRIZ methodology is used for concept generation, while TRIZ tools - Functional Analysis, If-Then-But, 39 Engineering Parameters, 40 Inventive Principles are applied. Then, conceptual sketches of modular airless tyre are being figured from the solution from TRIZ concept generations. The concept selection method use is Pugh concept selection to select the final concept. The methodology provides a guidance to obtain the results in chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 TRIZ Functional Analysis

Functional analysis tools are both useful at this point, especially for big or complicated systems, to aid understanding through describing each component clearly. The airless tyre interactions between each core component are identified through literature review and patent search (Appendix A), then the interactions between each core component are analysed.

4.1.1 Ideality Audit

Airless tyre technology relies on its unique structure to support a car's weight, effectively eliminating the need to regularly inflate the tyres. Airless tyre also absorbs road shocks, convey traction, braking forces, and torque to the road surface, and keep and change the car's travel direction. Examining benefits, wants, and requirements is an important element of issue solving, and because functions provide these benefits. The details of the ideality audit are described in Table 4.1.

$$\text{Ideality} = \frac{\text{Benefits}}{\text{Costs \& Harms}} = Function \qquad \text{(Equation 4.1)}$$

Table 4.1: Ideality audit

Ideality Audit – Modular Airless Tyre		
Ideal Outcome for Modular Airless Tyre = Have high adjustability and its parts can be easily replaceable.		
Ideality	SYSTEM we' ve got **Airless Tyre**	SYSTEM we want **Modular Airless Tyre**
Prime Benefit	• Eliminating flat tyre	• Have high modularity of tyre parts during maintenance/repair
Other Benefits	• Doesn't have loss of pressure	• Good ride comfort • Components and subcomponents easily replaceable or repaired • Attractive design
Prime Output / Function	• A tyre and hub that works in tension to support an applied weight and can be used as a replacement for pneumatic tyres or an improvement over other non-pneumatic tyre type.	• An airless tyre with modular parts which have damper to absorb the shock produce by the rotational movement of tyre and improvement over existing non pneumatic tyre
Acceptable costs / inputs	• Longer lasting compared to pneumatic tyre	• Reasonable to make - tyre design input, material and etc
Unacceptable costs / inputs	• If car require different kind of settings a new set of tyres is required.	• Frequent change of entire tyre when damage
Acceptable harms/problems	• Poor ride quality	• Need to repair when damage • Part destruction by wear and tear
Unacceptable harms/problems	• Issues with damping	• Very poor road condition damage to tyre
Citation	(Manesh, et al., 2012) (Raleigh, 2017) (Kongara & Madhusree, 2018)	

4.1.2 Component Diagram

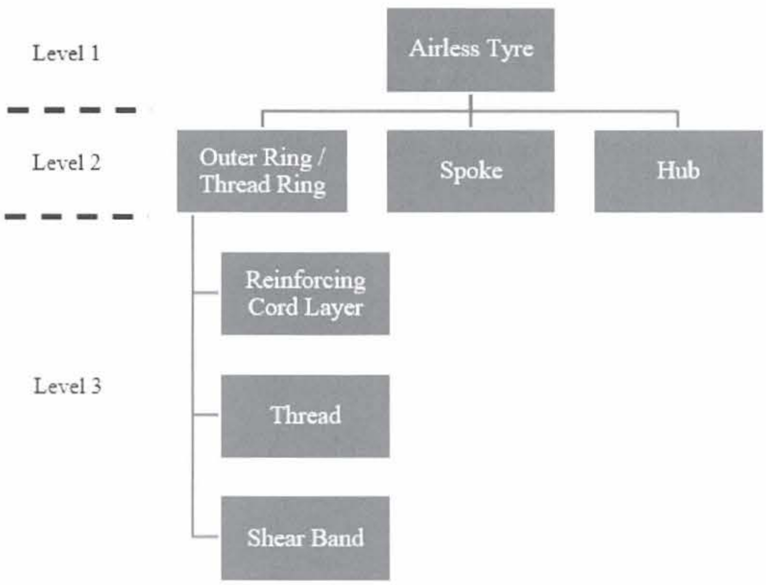


Figure 4.1: Airless tyre core components

From Figure 4.1, the general airless tyre consists of 3 main components which are outer ring or thread ring, spoke and hub. The outer ring/ thread ring consists of 3 subcomponents which are reinforcing cord layer, thread, and shear band. Each main components and its subcomponent function are explained in the function list below.

4.1.3 Function List

Function list is used to describe the functions associated with benefits. The purpose of an airless tyre is to support the car while enable the car to move in certain direction. Airless Tyre (subject) - Support (action) - Car (object) is a simple way that can assist figure out issues associated to it. Then we can consider why and how the airless tyre support the car.

If it's necessary or useful, each subject - action - object could be represented as a function declaration. It is simpler to remember what we want and any gaps between what we desire and what the system gives if we put benefits in this table.

Defining a simple system in terms of Subject - action - Object (S - a – Os) and the roles fulfil helps to comprehend how close to the 'ideality we seek' in table 4.1. Function list table as shown in table 4.2 is made by listing all the core components involved in the general airless tyre and then noting how and whether they interact with each other.

Table 4.2: Function list of airless tyre

Subject	Action	Object	Function	Outcome/Benefits
Airless Tyre	support	car	• Provides cushion between car and road and adequate traction with road surface	• Maintain the car direction of travel • Tyre do not run flat • Airless tyre can replace less frequently
Spoke	connect	hub and outer ring	• Support the pressure contact • Provide load carrying • Act as air and absorb road shock	• Improve riding comfortability
Hub	attach	front and back car axle and tyre	• Supporting the tyre and capable of attachment to the axis	• Keep wheel attached to the car
Thread	contact	road surface	• Provide sufficient grip when driving on road/ground surface	• Maintain good traction/contact with road surface
Outer Ring /Thread Ring	support	tyre and hub	• Support the load on the tyre and connected to the hub or wheel • Bond outer thread	• Reinforce the thread layer
Reinforcing Cord Layer	reinforce	tyre	• Keep the tyre in shape	• Enhance durability
Shear Band	attach	outer ring / thread ring	• Act as reinforcement to distribute load uniformly	• Act as load supporting member

4.1.4 Function Map

The function map diagram provides simple visual models, explanation, and a knowledge of the relationships between components and features such as outer ring, hub and etcetera. Through emphasising any damaging, redundant, or duplicated capabilities, this decreases the cause-effect links and explain the reasons for difficulties, failures, or flaws in a product, as well as identify solutions to address them.

Table 4.3: Function type and line style

Function Type	Line Style
Useful (normal)	⟶ (solid arrow)
Useful (insufficient)	– – – – – → (dashed arrow)

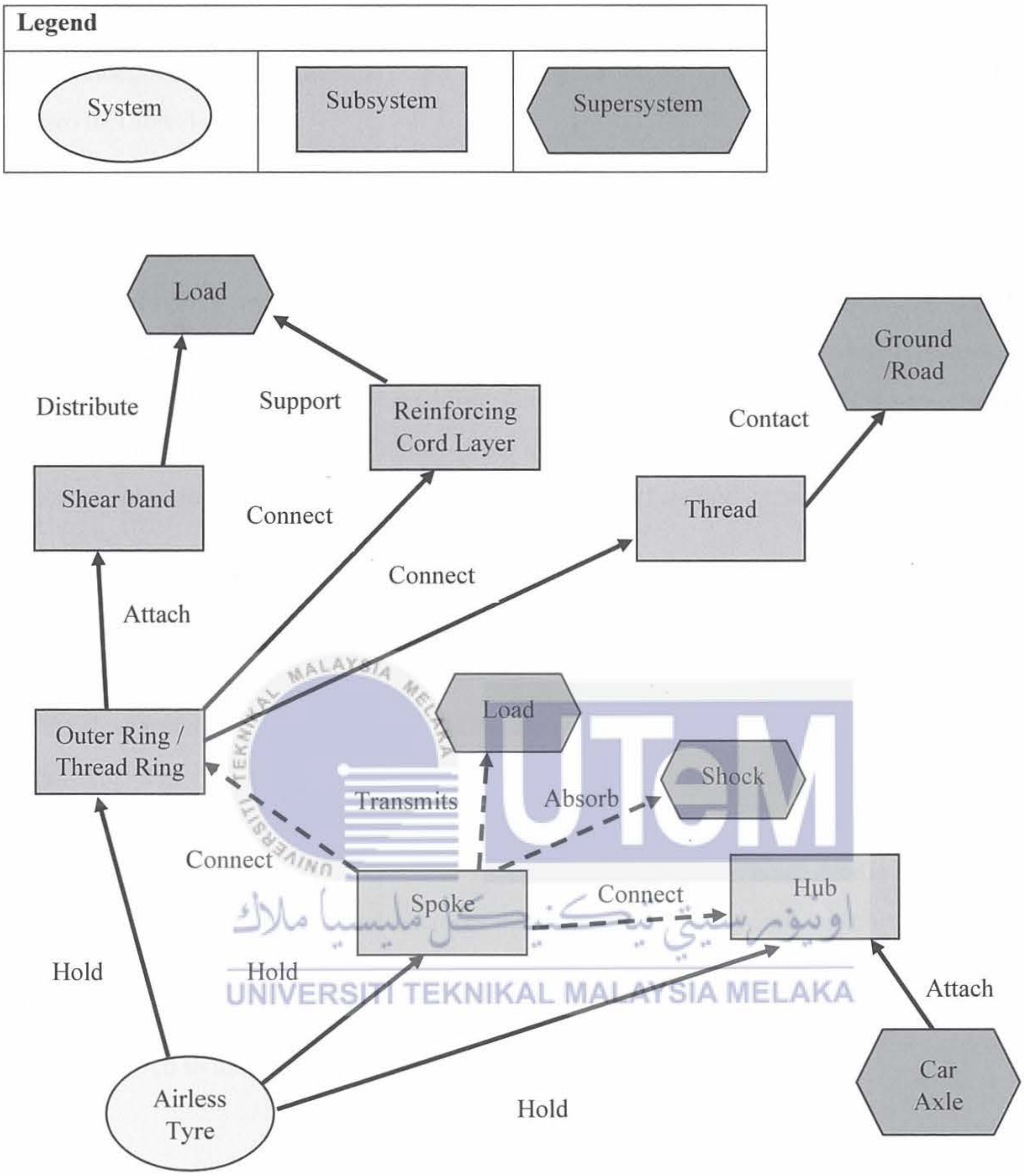


Figure 4.2: Function map for airless tyre

Function map is used to capture the functions associated with benefits. In this work, TRIZ functional map connects all the airless tyre components with their corresponding positive and negative behaviours while giving a clear picture of how the airless tyre system functions.

The functional map diagram is shown in Figure 4.2. The functional type is divided into 2 categories: useful (normal), and useful (insufficient) each indicated by the arrows shown in Table 4.3.

The engineering system refers to the airless tyre concept in issue, while the subsystem and supersystem, respectively, refer to the airless tyre's subcomponents and the environmental aspects with which it interacts with. The subsystem of the airless tyre consists of spoke, hub, thread, outer ring /thread ring, cord layer, and shear band. Airless tyre interacts with components/environment outside of the system which is known as supersystem. The supersystem in this case are shock, load, ground/road surface and car axle.

When the car is moving on the road or at a stationary at a position, the airless tyre will function to provide a cushion between the car and the road, as well as sufficient traction on the road surface/ground surface while the airless tyre hub is attached to the car front and back axle. The shock created during bumps of an uneven road surface or rotational movement of the car is helped by having the spokes connecting the outer ring and hub which act as air while having road shocks. The spokes also transmit the load. As the thread is the only contact point with the road surface, the tyre thread is required which the thread is connected to the outer ring. To keep the tyre in shape and provides the tyre with rigidity, reinforcing cord layer acts as the reinforcing component. Shear band attached to the outer ring is required to distribute the load uniformly around the tyre.

The root cause of the lack of adjustability of airless tyre is identified as insufficient interaction between the spoke, hub and outer ring that affect the versatility of the airless tyre. The insufficient interaction between will affects the repairability of the airless tyre when part or component of the tyre is encounters critical damage the entire airless tyre must be replaced. This insufficient interaction of airless tyre components may be use as reference for solution identification.

4.2 Contradictions Formulation and Identification

The technical contradiction problem is identified using TRIZ "IF-THEN-BUT" technique. When there is clash, a contradiction occurs: either opposites of the same thing or improve one item while making another worse. The technique located the 39 system parameters employed in the TRIZ contradiction matrix to choose the 40 Inventive Principles. Additionally, using "IF-THEN-BUT" technique simplifies the existing airless tyre problem and makes finding the contradiction of airless tyre components easier.

Table 4.4: TRIZ if-then-but technique contradiction 1

Terms	Explanations	Conditions
If	A statement where the changes were made	If breaking down the existing airless tyre into separate or independent modules
Then	A statement clarifies the future benefits gain from the expressed action	Then separation of the airless tyre components and subcomponents may improve its ease of fabrication with reduce shape complexity
But	A statement explains the drawback from the expressed action	But the airless tyre might have difficulty in in setting up different type of system and labour knowledge for maintenance when a part or subcomponent is damage

Based on the first contradiction in Table 4.4 above, the criteria are to separate the airless tyre components and subcomponents, then it will be easier to fabricate, and the shape complexity will be reduced but when a portion or subcomponent is damaged, the airless tyre may have problems setting up different types of systems and labour knowledge for maintenance. Therefore, the improving parameters is ease of fabrication and worsening parameters is component lack of correlation. As a result, from the matching of 39-system engineering parameter, the improving parameter is #32 Ease of manufacture whereas the worsening parameters is #37 Difficulty of detecting and measuring which is explain in Table 4.5.

Table 4.5: 39 engineering parameters identification contradiction 1

Parameters	Simplified Conditions	39 Engineering Parameters	Explanation
Improving	Ease of fabrication	#32 Ease of manufacture	The degree of facility, comfort or effortlessness in manufacturing or fabricating the object/system.
Worsening	Component lack of correlation	#37 Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labour to set up and use, or that have complex relationships between components or components that interfere with each other all demonstrate 'difficulty of detecting and measuring.' Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring.

Table 4.6: TRIZ if-then-but technique contradiction 2

Terms	Explanations	Conditions
If	A statement where the changes were made	If the existing components and subcomponents of the airless tyre are separated with improved repairability
Then	A statement clarifies the future benefits gain from the expressed action	Then the airless tyre's subsystems are then separated into smaller sections that can each execute a specific function independently to achieve overall system functionality.
But	A statement explains the drawback from the expressed action	But the essential components of an airless tyre may be lacking, resulting in the loss of existing subcomponents.

According to the first contradiction in Table 4.6, the criteria divide the airless tyre into smaller sections that may each perform a specific function independently, resulting in an overall system functioning. However, an airless tyre's essential components may be lacking, resulting in the loss of existing subcomponents. Therefore, the improving parameter is functional operations of parts and worsening parameter is components may be lacking. Consequently, from the matching of 39-system engineering parameter, the improving parameter is #31 Object - generated harmful factors whereas #23 Loss of substance is the worsening parameters. The improving and worsening parameters are described in Table 4.7.

Table 4.7: 39 engineering parameters identification contradiction 2

Parameters	**Simplified Conditions**	**39 Engineering Parameters**	**Explanation**
Improving	Functional operations of parts	#31 Object - generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These harmful effects are generated by the object or system, as part of its operation.
Worsening	Components may be lacking	#23 Loss of substance	Partial or complete, permanent or temporary, loss of some of a system 's materials, substances, parts or subsystems.

Following the detection of contradictions, the contradiction matrix is used to analyse the design problem and rectify contradictions of the airless tyre. The contradiction matrix is used to derive the associated inventive principles. From the TRIZ 39 system parameters and 40 inventive principles, there are 3 solutions identified from the contradiction matrix which are #1 Segmentation, #10 Prior Action, and #34 Discarding and Recovering for contradiction 1 where the improving parameter is #32 Ease of manufacture, and the worsening parameter is #37 Difficulty of detecting and measuring. Whereas, for contradiction 2 where the improving parameter is #31 Object - generated harmful factors and worsening parameter is #23 Loss of substance, 4 solutions are identified from the contradiction matrix which are #1 Segmentation, #6 Universality, #11 Cushion in Advance and #28 Replace Mechanical System as shown in Table 4.8.

Table 4.8: Extraction of contradiction matrix

	Improving Parameters \ Worsening Parameters	Loss of energy	Loss of substance	Loss of information	…	Device complexity	Difficulty of detecting and measuring	Extent of automation
		22	**23**	**24**	**....**	**36**	**37**	**38**
25	**Loss of time**	10 5 18 32	35 18 10 39	24 26 28 32	....	6 29	18 28 32 10	24 28 35 30
26	**Quantity of substance**	7 18 25	6 3 10 24	24 28 35	....	3 13 27 10	3 27 29 18	8 35
27	**Reliability**	10 11 35	10 35 29 39	10 28	....	8 35	27 40 28	11 13 27
28	**Measurement accuracy**	26 32 27	10 16 31 28		....	27 35 10 34	26 24 32 28	28 2 10 34
29	**Manufacturing precision**	13 32 2	35 31 10 24		....	26 2 18		26 28 18 23
30	**Object affected harmful factors**	21 22 35 2	33 22 19 40	22 10 2	....	22 19 29 40	22 19 29 40	33 3 34
31	**Object-generated harmful factors**	21 35 2 22	10 1 34	10 21 29	....	19 1 31	2 21 27 1	2
32	**Ease of manufacture**	19 35	15 34 33	32 24 18 16	....	27 26 1	6 28 11 1	8 28 1
33	**Convenience of use**	2 19 13	28 32 2 24	4 10 27 22	....	32 26 12 17		1 34 12 3
34	**Ease of repair**	15 1 32 19	2 35 34 2		....	35 1 13 11		34 35 7 13
35	**Adaptability or versatility**	18 15 1	15 10 2 13		....	15 29 37 28	1	27 34 35
36	**Device complexity**	10 35 13 2	35 10 28 29		....		15 10 37 28	15 1 24
37	**Difficulty of detecting and measuring**	35 3 15 19	1 18 10 24	35 33 27 22	....	15 10 37 28		34 21
38	**Extent of automation**	23 28	35 10 18 5	35 33	....	15 24 10	34 27 25	
39	**Productivity**	28 10 29 35	28 10 35 23	13 15 23	....	12 17 28 24	35 18 27 2	5 12 35 2

4.2.1 Formulations Summary

The TRIZ engineering contradiction 1 and 2 formulations, improving and worsening parameters, and the inventive principle from the engineering contradiction formulation are summarised in Figure 4.3 below.

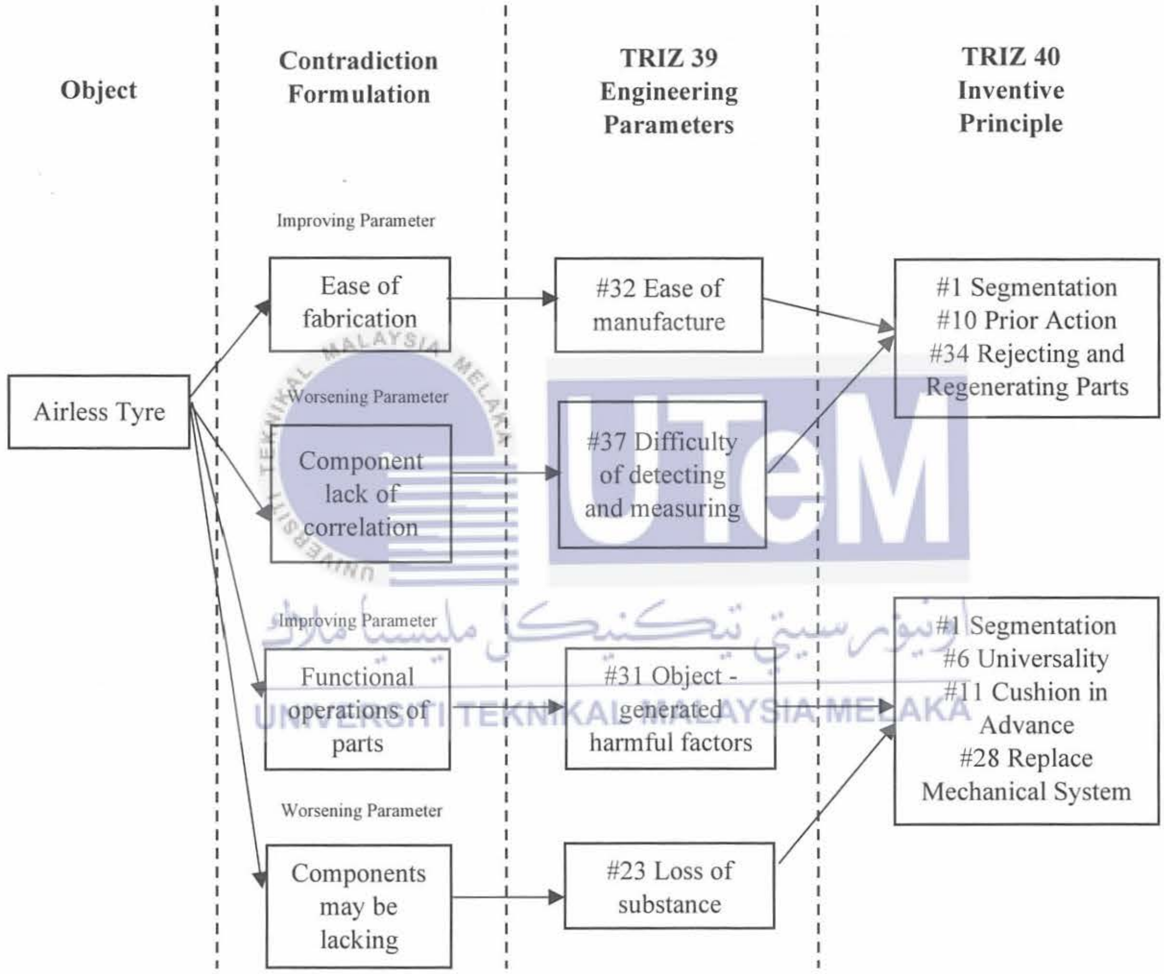


Figure 4.3: Formulations of TRIZ 39 system parameters and 40 inventive principles summary

4.3 Selection of 40 Inventive Principle

This section describes on the selection of TRIZ 40 inventive principles before proceeding to on a specific solution strategy.

Table 4.9: TRIZ 40 inventive principle description

Contradiction	40 Inventive Principle	Solution Description
1,2	#1 Segmentation	• Divide an object into independent parts. • Make an object sectional (for easy assembly or disassembly). • Increase the degree of an object's segmentation.
2	#6 Universality	• An object can perform several different functions; therefore, other elements can be removed.
1	#10 Prior Action	• Perform required changes to an object completely or partially in advance. • Place objects in advance so that they can go into action immediately from the most convenient location
2	#11 Cushion in Advance	• Compensate for the relatively low reliability of an object with emergency measures prepared in advance.
2	#28 Replace Mechanical System	• Replace a mechanical system with an optical, acoustical, thermal or olfactory system. • Use an electric, magnetic or electromagnetic field to interact with an object • Replace fields that are: o Stationary with mobile o Fixed with changing in time o Random with structured • Use fields in conjunction with ferromagnetic
1	#34 Rejecting and Regenerating Parts	• After completing its function, or becoming useless, an element of an object is rejected (discarded, dissolved, evaporated, etc.) or modified during its work process. • Used-up parts of an object should be restored during its work.

After reviewing the TRIZ 40 inventive principle and extracting it to Table 4.9 with its solution description, as a practical and effective instrument for issue solving. As the goal was to develop the concept of modular airless tyre with a wide range of flexibility and easily interchangeable components each solution is examined with the best solutions focusing on the conflicts being #1 Segmentation, #6 Universality, #28 Replace Mechanical System, and #34 Rejecting and Regenerating Parts. #10 Prior Action and #11 Cushion in Advance are not included as their associated design for modularity are still in proposals.

4.4 Specific Solution Strategy

To arrive at a specific solution strategy, the TRIZ 40 inventive principle is used to look at #1 Segmentation, #6 Universality, #28 Replace Mechanical System, and #34 Rejecting and Regenerating Parts. The specific solution strategy and its detail solutions are presented in table 4.10 below.

Table 4.10: TRIZ 40 inventive principle and specific solution strategy

40 Inventive Principle	Specific Solution Strategy
#1 Segmentation	• The airless tyre item is segmented by making it sectional, making it easier to disassemble and reassemble. • What components are segmented or increase in its segmentation degree? o To increase component modularity, divide the outer ring/thread ring, spoke, and hub into distinct elements along the perimeter of the airless tyre. The hub, outer ring, and spoke are the three main separated components, and each of them has multiple 90-degree rotatable hinges with a bolt and nut-like system that holds the assembly together, as opposed to the current airless tyre system, which uses a polymerisation process to connect all the parts together.
#6 Universality	• What components have multiple functions? o Each spoke serve as a link between the hub and the outside ring. o Each spoke is equipped with a damper that absorbs stress and vibration via an integrated rubber damper or a spring linked to the spoke. o While the airless tyre is coupled to the car axle system, each spoke is able to handle the car's load.
#28 Replace Mechanical System	• Which components are replacing its current mechanical system? o The domain magnetic flux is formed when an iron component is made up of tiny domains with circular currents running through them. Initially, all domain fluxes were unorganised, but when an external magnetic flux, such as from a solenoid, was applied, all domains or parts of them aligned with the external flux, resulting in the magnetization of the iron piece (Mikerov, 2014). Hence, by applying the principle of electromagnetism, the hub of the airless tyre acts as the solenoid which have magnetism characteristics and magnetise the inner circumference of the spoke hub. When the solenoid is demagnetised, the airless tyre can be disassembled.
#34 Rejecting and Regenerating Parts	• What components are rejected and regenerated? o Instead of using a single universal spoke (hexagonal/discrete/continuous/honeycomb and other shapes) between the hub and outer ring, which requires the replacement of the entire airless tyre if the spoke is badly damaged, a radial spoke is used. The new type of spoke made from a rubber damper or spring shock absorbing devices. o Distinct entities, such as 8/10/12 individual parts throughout the circle of the airless tyre, should be separated from the outer ring that is now linked to the spoke.

	o The existing hub of the airless tyre is replaced with an interlocking hub which works like a locking mechanism that locks the multiple spokes onto the hub. o Along the perimeter of the hub, new interlocking mounting parts incorporated in the outer ring will connect the airless tyre reinforcing cord layer, shear band, and tyre thread. The interlocking mounting parts link the interlocking hub using unique bolts and nuts that match the interlocking hub's layout. o The rubber damper secures the spoke with a bracket.

From the 4 solutions principles which are #1 Segmentation, #6 Universality, #28 Replace Mechanical System, and #34 Rejecting and Regenerating Parts described in Table 4.10, the specific solution strategy is used to develop the conceptual sketch of modular airless tyre.

4.5 Conceptual Sketch

The utilisation of geometrical effects in sketching stimulates the idea generation process, leading to even more innovative solutions. Figure 4.4 to Figure 4.7 shows a range of concept illustrate through sketches that highlight ideas and discussions about the modular airless tyre.

4.5.1 Concept 1

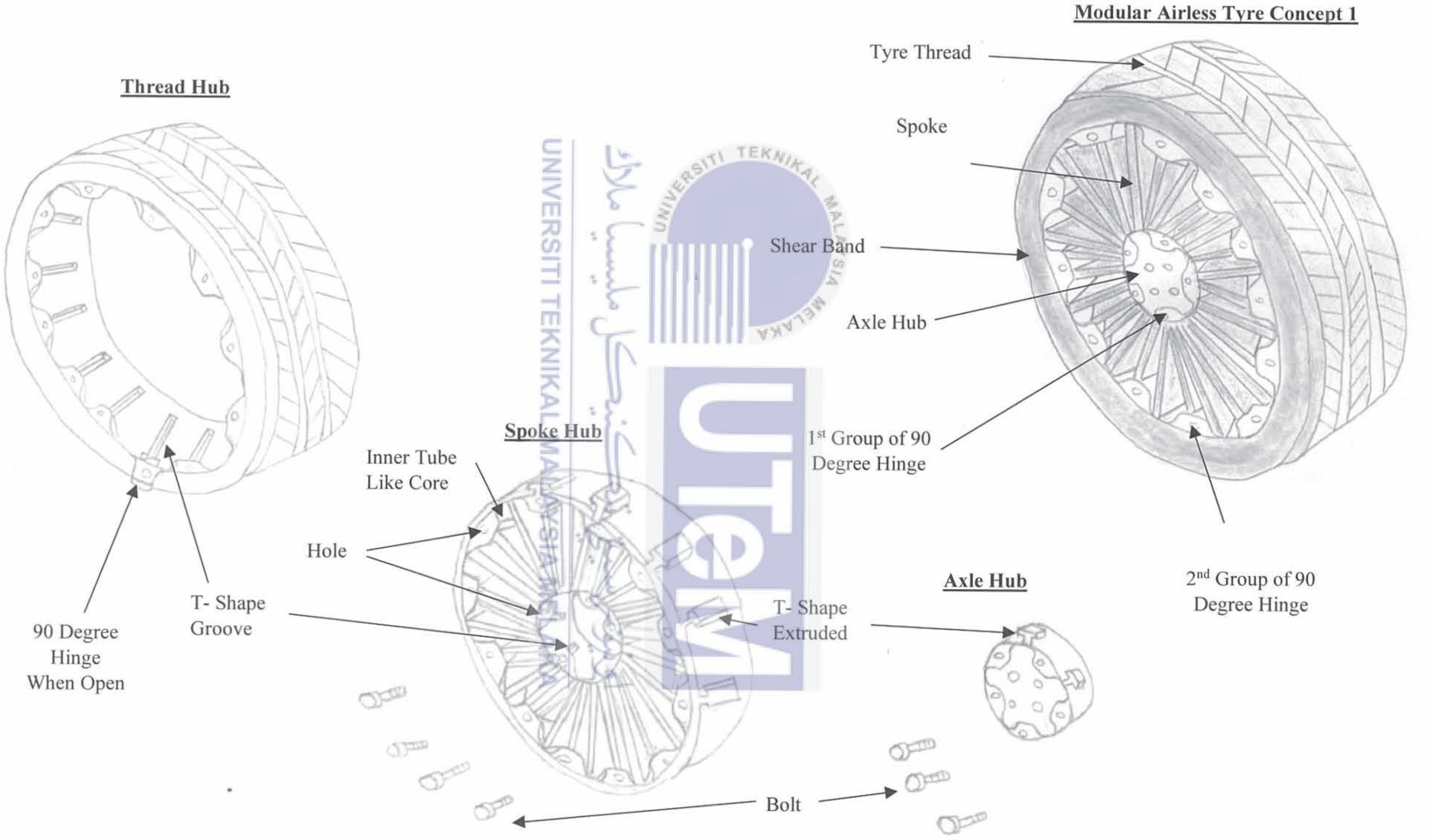


Figure 4.4: Concept 1

4.5.2 Concept 2

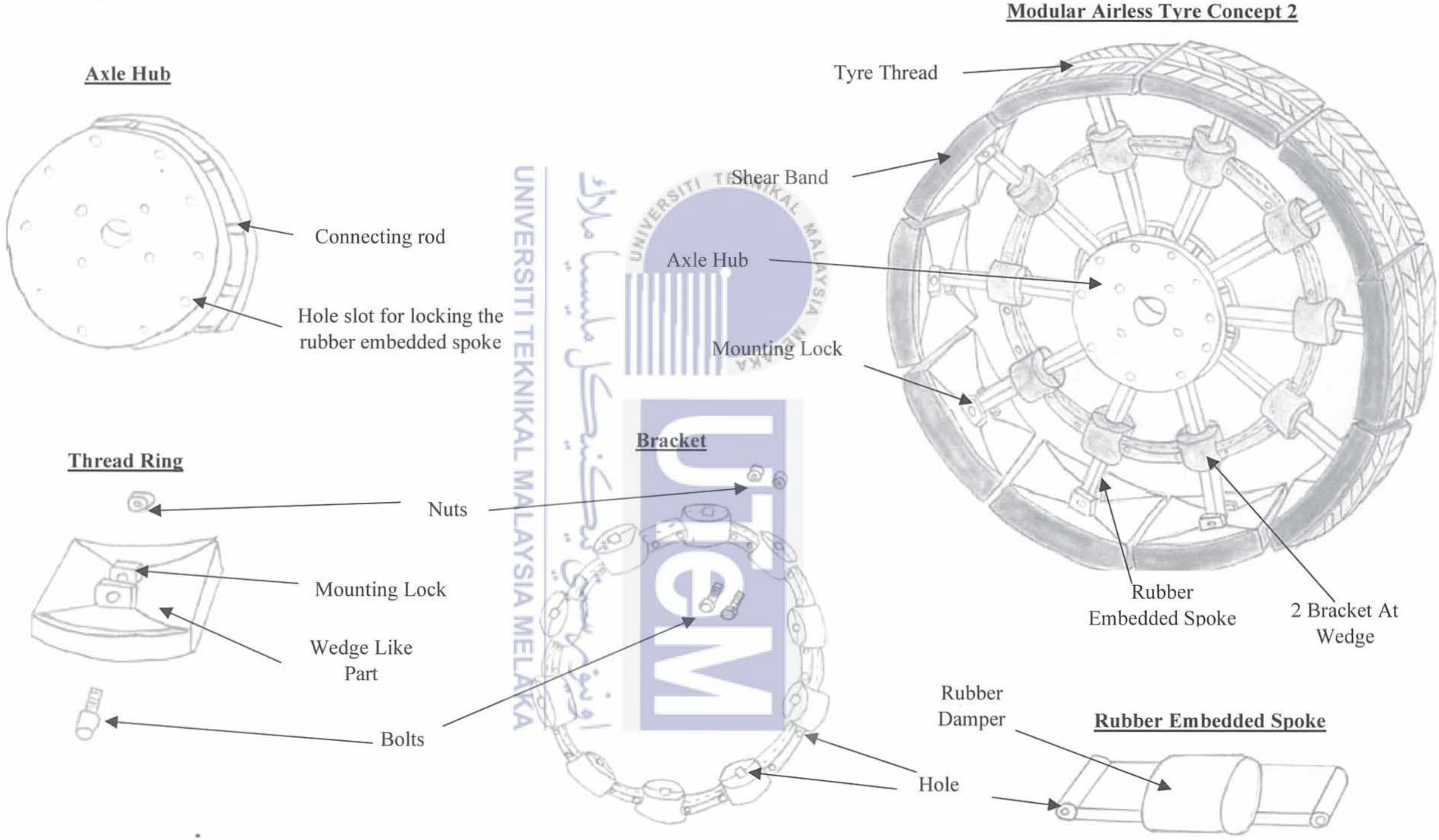


Figure 4.5: Concept 2

4.5.3 Concept 3

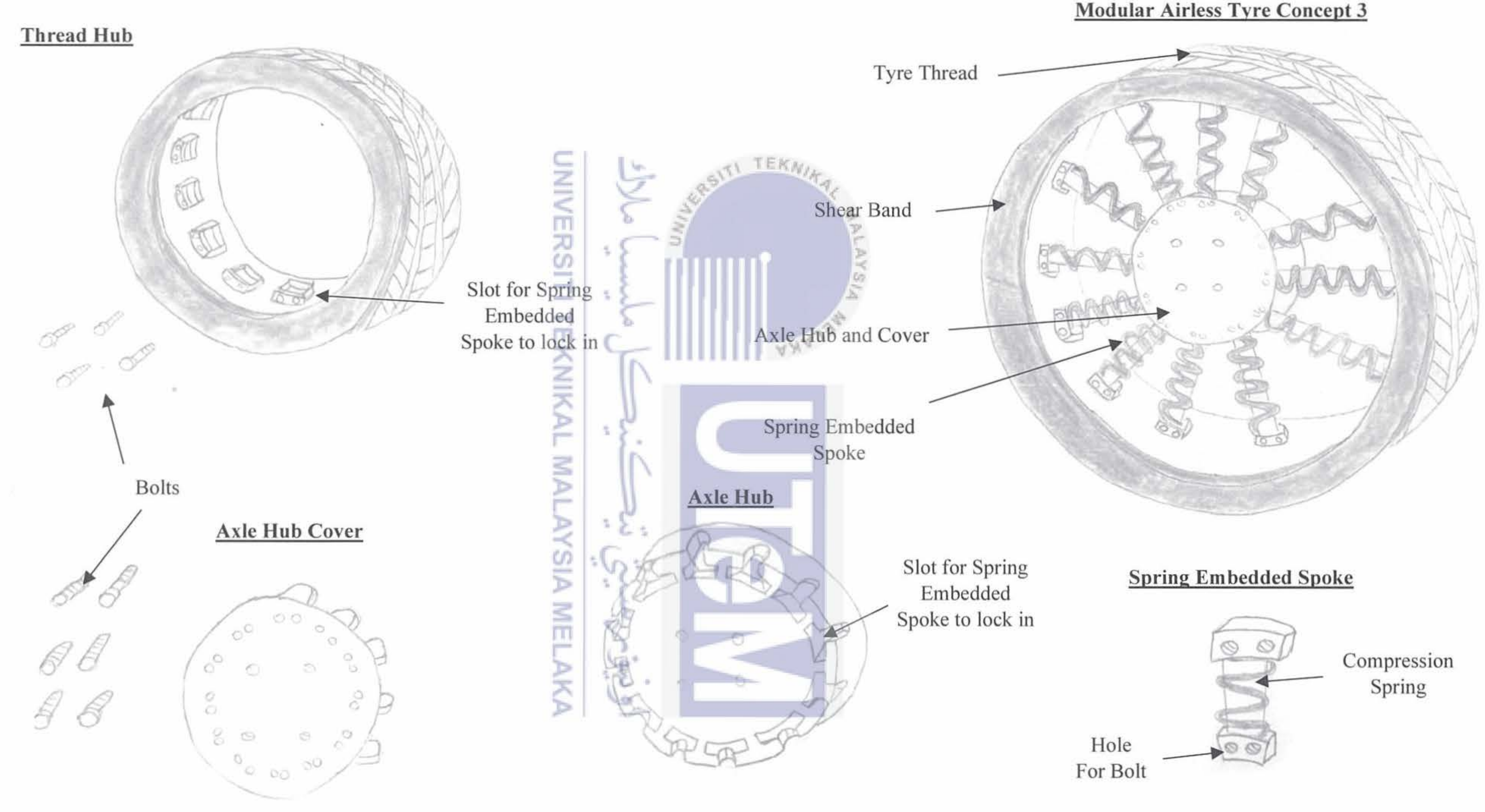


Figure 4.6: Concept 3

4.5.4 Concept 4

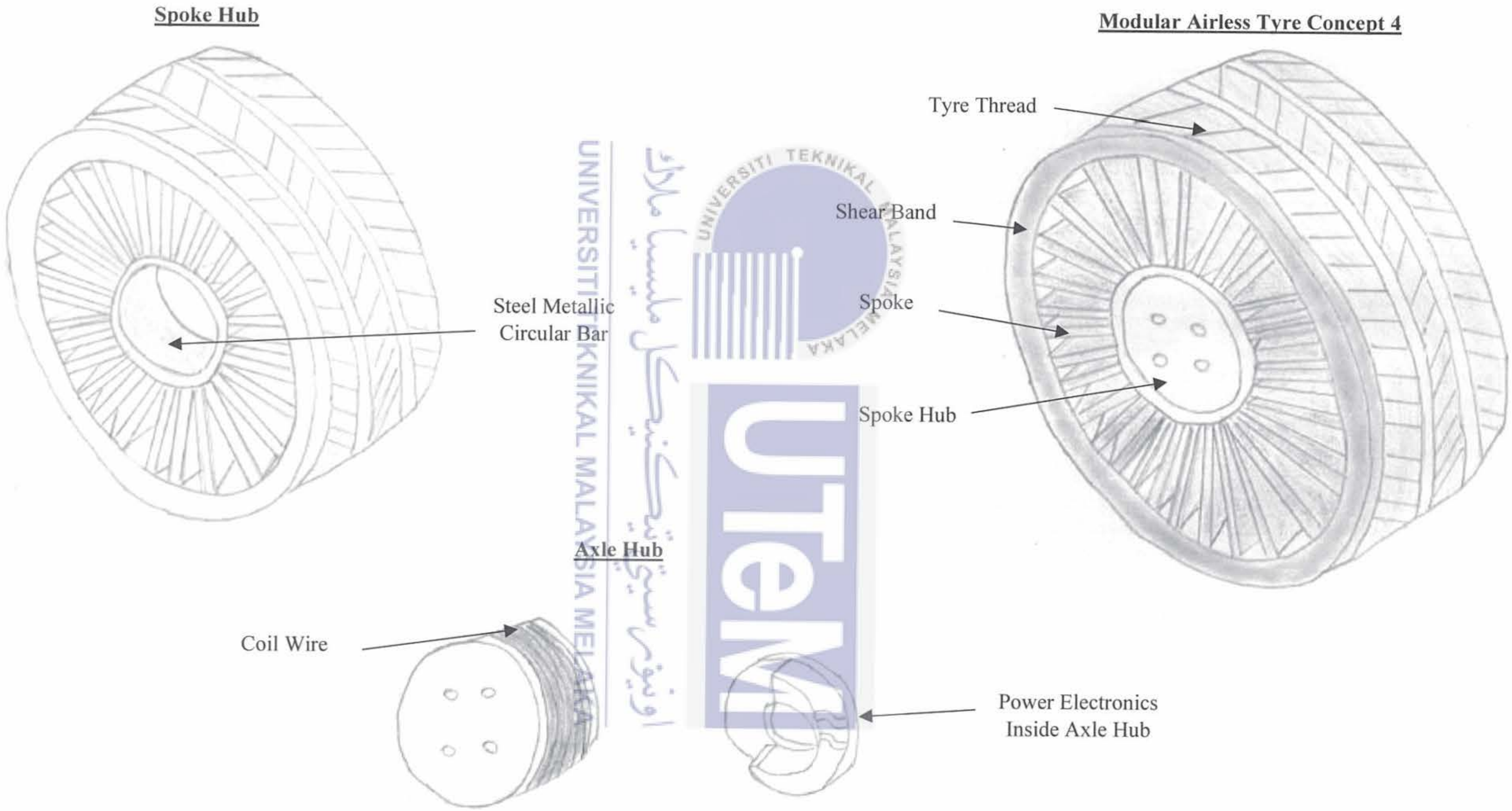


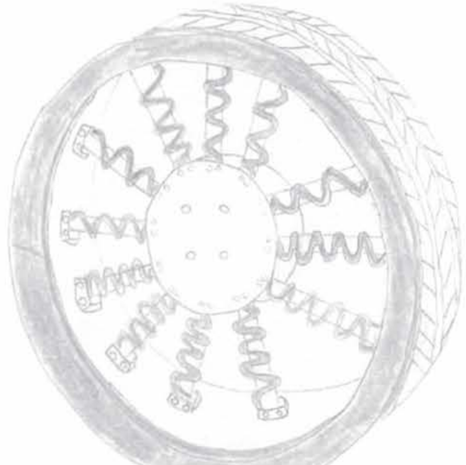
Figure 4.7: Concept 4

4.5.5 Concept Description

This section explains the detail for each of the concepts that were generated.

Table 4.11: Concept description

Concept No.	Conceptual Sketch	Description
Concept 1		• In concept A, it has 3 separate entities which are axle hub, spoke hub and thread hub. • The type of spoke use is discrete spoke. The discrete spoke is generally connected along both end of the surface of hub. The type of spoke can be emulated with other type of existing airless tyre spoke such as hexagonal, honeycomb, discrete continuous and other shape. • The T-shaped grooves runs along the circumference of both the spoke and thread hubs, reaching to the front end (parallel to the car door). The inner circumference of the thread hub has one group of T shaped grooves, whereas the inner circumference of the spoke hub has the other group of T shaped grooves. By sliding the T-shaped extruded portion into the T-shaped groove, the T-shaped groove and the T-shaped extruded section joins. • The 90-degree rotatable hinge worked like a cover securing the spoke hub and axle hub in place by fastening the 90-degree rotatable hinge components and inner tube-like core segments together where the inner tube-like segments, with the inner tube-like core attached to the spoke hub's inner circumference. • The bolts fastened when the holes at the 90-degree rotatable hinge parts and inner tube-like core segments coincide with each other. The thread hub joins the spoke hub, and the mating of the 2nd group of 90-degree rotatable hinge. The spoke hub connected to the axle hub, and the 1st group of 90-degree rotatable hinges mated. • In an outward-facing radial arrangement, the thread hub has a tyre reinforcing cord layer and tyre thread on the exterior surface. The shear band stretches transversely across and outward from the tyre thread.

Concept 2		• Concept B has components such as tyre thread, shear band, axle hub, rubber embedded spoke and bracket • The thread ring which is attached to the spoke is divided into 10 individual sections each with individual tyre thread running around the circumference of the airless tyre. If any section of the outer ring is damaged only the selected section of the outer ring need to be replaced. The spoke section is works in the same way with the thread ring. • A mounting lock is attached to the thread ring wedge-like element that is flat on top of it. • The bracket is divided into two sections: one half holds the vulcanised rubber damper in place at the front, while the other half holds the rubber damper in place on the opposite side. Both halves of the bracket are fastened together with bolts and nuts through a group of mating holes along with the bracket. • The rubber damper is incorporated in the spoke and functions as a shock absorbing device or cushioning, absorbing energy as the tyre compresses. • The axle hub consists of hole slot that allows the spoke to secure to the axle hub in place by fastening the bolts. A semi-circular liner is put between the hub and slightly below the x-axis direction (from the car axle) of the hole slot for locking the rubber embedded spoke to align it in the axle hub. • Each thread ring has a tyre reinforcement cord layer and tyre thread on the outside surface in an outward-facing radial pattern. The shear band runs transversely over the tyre thread and outward.
Concept 3		• The thread hub, axle hub, axle hub cover, spring embedded spoke bolt, and other components make up the modular airless tyre in concept C. The axle hub and the thread hub are connected by 12 spring embedded spokes. • The axle hub cover contains holes which is align with the hole in the spoke. The unique group of slot part spaced apart equally with each other along the circumference of the axle hub allows the spring embedded spoke to slide in the slot in the axle hub part. • In each of the spring embedded spoke there are 2 holes on top and bottom part of the spoke for the bolt to fastened. • The function of the set of compression springs embedded in the spoke are to absorb shock or vibration created by road contact with car tyre. • To secure the spoke with the axle hub, insert the 12-spring embedded spoke into the axle hub's spoke slot, then fastened the bolt through the circular sets of holes in the axle hub cover and the hole in the spring embedded spoke. • There is another set of slots on the thread hub's inner circle for spring-loaded spokes to be fastened in. • The thread hub outer circumference surface features tyre reinforcing cord layer and tyre thread. The shear band extends in a transverse direction from the tyre thread.

Concept 4		• In concept D, there are 2 main components, axle hub and spoke hub with tyre thread. • The axle hub functions as an electromagnet (solenoid) connected to the car's motor. The magnet coil wire is positioned on the axle hub's outer circumference, while the steel metallic circular bar is located on the spoke hub's inner circumference. • When current passes through the wire's embedded coil, a magnetic field forms around it, and the coiled wire becomes an electromagnet, attracting the metal segment of the spoke hub's inner circumference. • This would be organised and arranged in such a way that when the solenoid is demagnetized, their opposite faces lose their magnetism. • There are tyre reinforcing cord layer and tyre thread on the outer surface of the spoke hub in an outward-facing radial configuration. From the tyre thread, the shear band extends transversely across and outward.
Reference Concept (Michelin Tweel Airless Radial Tyre)		• Michelin Tweel airless radial tyre is a single unit that has Zero-degree belts (below the tread) which give excellent lateral stiffness while preventing damage and cushioning impacts. • The Comp10 CableTM from Michelin generates a semi-rigid "shear beam" that allows the weight to hang from the top. • Steel hub with a heavy gauge that fits a variety of vehicles. • High-strength poly-resin spokes support the weight and absorb impacts, as well as smooth the ride and provide a unique energy transmission that reduces pneumatic bounce.

4.6 Pugh Concept Selection

From the TRIZ concept generation stage there are four concepts of modular airless tyre generated. To develop the best concept, Pugh concept selection has been used to analyse and choose from a variety of design options.

4.6.1 Selection Criteria for Concept Selection

After collecting data from books, journals, and previous research and fulfilling the design requirement goals, a set of criteria is used to choose the best conceptual design for a modular airless tyre system from a pool of concepts. A set of criteria are utilised as a concept selection tool to choose the best idea from a pool of submitted concepts and its reference concept (datum). There are 8 selection criteria, which are ease of maintenance, modularity in design, low part complexity/ simplicity, easy to manufacture parts/ manufacturability, safety, ease to setup/ ease of assemble, reliability and appearance. The selection criteria description is described in Table 4.12.

Table 4.12: Selection criteria

Selection Criteria	Selection Criteria Description
Ease of maintenance	• If a component of a modular airless tyre is broken, it may be repaired or replaced with minimal or easy maintenance.
Modularity in design	• The airless tyre may be dismantled or broken down into smaller, simpler components that can be manufactured and assembled individually. The final product is constructed from each of these distinct components. Increased modularity can help the product's long-term viability while also reducing tyre waste.
Low part complexity/ Simplicity	• The modular airless tyre's components or parts are made up of low-complexity parts.
Easy to manufacture parts/ Manufacturability	• The modular airless tyre's components are easy to be manufactured
Safety	• The product's ability to be safe for the application it was designed for. Safety is important for a car if the tyre form is not safe and doesn't fit for the purpose of it, it increases the risk of accidents.
Ease to setup/ Ease of assemble	• All the components of the modular airless tyre are easy to assemble. The
Reliability	• The likelihood that the idea concept will execute the intended function without failure during the estimated life of the product.
Appearance	• The appearance of the product is attractive.

4.6.2 Concept Screening

Table 4.13: Concept screening

	CONCEPT VARIANTS				
SELECTION CRITERIA	**1**	**2**	**3**	**4**	**REF.**
Ease of maintenance	+	+	+	0	DATUM
Modularity in design	+	+	+	+	
Low part complexity/ Simplicity	+	+	-	-	
Easy to manufacture parts/ Manufacturability	0	+	+	-	
Safety	+	0	0	0	
Ease to setup/ Ease of assemble	0	+	0	-	
Reliability	0	+	+	-	
Appearance	0	-	0	0	
Sum +	4	6	4	1	
Sum 0	4	1	3	3	
Sum –	0	1	1	4	
Net score	4	5	3	-3	
Rank	2	1	3	4	
Continue?	**Yes**	**Yes**	**Yes**	**No**	

Table 4.14: Rating used in concept screening stage

Relative Performance	**Rating**
Better	+
Same as	0
Worse	-

The concept screening is shown in Table 4.13, in which all four concepts were compared to the reference concept or datum. Each concept is rated based on its relative performance. The ratings of "+", "0" and "-" denote "better", "same as", and "worse", respectively. When a criterion is improved upon in a new concept, the symbol "+" is used. If the quality is similar to the reference, "0" is utilised. If it is worse than the reference, "-" is used.

There is no existing modular airless tyre in the market, hence Michelin Tweel airless radial tyre is chosen as the reference concept. Michelin Tweel airless radial tyre is a single unit that replaces the existing pneumatic tyre and wheel combination. No complicated mounting equipment and requirement to maintain air pressure after they are fastened on.

Concept 2 has the highest rating of the 4 concepts, with a net score of 5, and its selection criteria, such as modularity in design, easy to manufacture parts/ manufacturability, and others, is better than reference. Concept 1, with a net score of 4, is the second highest, followed by concept 3, with a net score of 3 and lastly concept 4 with a net score of -3.

Due to criteria such as low part complexity/simplicity and parts that are difficult to manufacture/manufacturability. Based on the concept screening results, Concept 4 can be eliminated. Furthermore, concept 4 is less reliable than the reference concept since it relies on the current passing through the wire's integrated coil to lock the airless tyre to the car.

Concept 1, concept 2, and concept 3 have the top three highest rank scores from the concept screening, indicating that they meet most of the criteria such as ease of maintenance ease to setup/ ease of assemble, reliability and so forth. For the concept scoring phase, concept 1, concept 2 and concept 3 were picked.

4.6.3 Concept Scoring

Table 4.15: Concept scoring

SELECTION CRITERIA	Weightage (%)	CONCEPT VARIANTS						
		1		2		3		REF.
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	
Ease of maintenance	15	3	0.45	5	0.75	4	0.60	DATUM
Modularity in design	15	4	0.60	5	0.75	4	0.60	
Low part complexity/ Simplicity	10	2	0.20	3	0.30	2	0.20	
Easy to manufacture parts/ Manufacturability	13	3	0.39	4	0.52	4	0.52	
Safety	15	4	0.60	3	0.45	3	0.45	
Ease to setup/ Ease of assemble	12	3	0.36	4	0.48	4	0.48	
Reliability	12	4	0.48	3	0.36	4	0.48	
Appearance	8	4	0.32	3	0.24	3	0.24	
Total Score	100	3.4		3.85		3.57		
Rank		3		1		2		
Continue?		**No**		**Yes**		**No**		

Table 4.16: Rating used in concept scoring stage

Relative Performance	Rating
Much worse than	1
Worse than	2
Same as	3
Better than	4
Much Better than	5

Table 4.15 shows the concept scoring. Each selection criteria were given a distinct weightage, the total weighted score of each concept was computed by taking into consideration the separate weightage.

From the concept scoring, the selection criteria such as ease of maintenance, modularity in design and safety has the highest weightage (15%) compared to other criteria. Modularity in design selection criteria has a (15%) weightage because the fundamental goal of the modular airless tyre concept is to increase modularity, which increases the product's long-term viability while reducing tyre waste, resulting in sustainable development. The percentage weightage of the selection criteria is then followed by easy to manufacture parts/ manufacturability (13%), ease to setup/ ease of assemble (12%), reliability (12%) low part complexity/ simplicity (10%), and appearance (8%). The ratings of "1", "2", "3", "4", and "5" denote "much worse than", "worse than", "same as", "better than", and "much better than", respectively.

Concept 2 has the highest total score of 3.85 and fulfils most of the criteria such as ease of maintenance, modularity in design, ease of assemble and so on. Concept 2 has a higher ranking in terms of modularity in design than reference because it has a segmented spoke-attached thread ring with each tyre thread extending around the circle of the airless tyre. If a section of the outer ring or a spoke is damaged, only that section of the outer ring needs to be replaced.

Concept 3 scored the second highest score of 3.57 as is appeared to be easy to manufacture parts/ manufacturability and modularity in design. However, it flaws are lack in simplicity and appearance. While concept 1 has the lowest ranking compared to concept 2 and 3 with a total score of 3.39. Concept 1 also doesn't fulfil majority of the criteria such as low part complexity/ simplicity and easy to manufacture parts/ manufacturability.

From the concept scoring results, as Concept 2 has the greatest scoring in Pugh concept selection, it has been selected and is the finalised concept of modular airless tyre. Besides, in terms of ease of maintenance, concept 2 has the advantage compared to other concepts as concept 2 as each spoke and thread ring have 10 individual entities, for example when the thread in the thread ring is damaged only the selected part is required to be taken out to be replaced and not replacing all the other thread ring.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This chapter concludes the complete research study. This chapter also includes recommendations for future work and findings of work on sustainable design and development.

5.1 Conclusion

Using TRIZ and the Pugh approach, this study presents the conceptualisation framework that was utilised to develop the concept of a modular airless tyre. The concept for a modular airless tyre was then finalised. Before formulating the engineering contradiction, TRIZ functional analysis is performed, which connects the airless tyre components with their associated positive and negative behaviours, providing a clear image of how the airless tyre system works. To develop concepts, the TRIZ 40 inventive principles was used in conjunction with TRIZ 39 engineering parameters. The specific solution was made possible at the conceptual stage by employing the TRIZ technique, which is derived on TRIZ 40 inventive principles, which include #1 segmentation, #6 universality, #28 mechanical system replacement, and #34 rejecting and regenerating parts.

4 new concepts were generated. The concepts are ranked using the Pugh method after being reviewed for each criterion. Concept 2 was chosen as the finalised concept for product

development as it has the greatest ranking value in Pugh concept selection compared to the other concept alternatives. TRIZ–Pugh approach demonstrated its ability to collaborate in the creation of proposals, ideas, conceptual designs, and concept selection procedures, and has a comprehensive approach to obtaining the intended result, particularly in the development of a modular airless tyre concept.

5.2 Recommendation for Future Work

Even though the concepts of modular airless tyre were established in a systematic manner, more research with industry experts and tyre manufacturers is anticipated to see how well the proposed developed concept stand up in various circumstances. As a result, current work has limitations that need to be taken into account when interpreting the findings.

5.3 Sustainable Design and Development

The environmental impact of tyre waste has long been a topic of concern when contemplating the concept of sustainable development in the context of broader development discussions. The concept of modular airless tyre can reduce disposed tyre mass by developing longer-lasting tyres, may reduce the amount of material introduced into the sustainability cycle, because the new concept of modular airless tyre's structure makes it easier to replace individual parts of the airless tyre throughout its service life.

REFERENCES

A.Manesh, Tercha, M., O. Ayodeji, B., & Anderson, B. Meliska, F. C. (2012). *Tension-Based Non-Pneumatic Tire* (Patent No. US 8,104,524 B2). United States Patent and Trademark Office.

Abhishek, R., & Kumar, A. (2020). Non Pneumatic Tyre design with Honeycomb spoke structure. *International Journal of Innovative Science, Engineering & Technology*, *7*(6), 86–91.

Aboul-Yazid, A. M., Emam, M. A. A., Shaaban, S., & El-Nashar, M. A. (2015). Effect Of Spokes Structures On Characteristics Performance Of Non-Pneumatic Tires. *International Journal of Automotive and Mechanical Engineering*, *11*, 2212–2223. https://doi.org/10.15282/ijame.11.2015.4.0185

Ali, N., Seng, C. H., Mohammad, M. S., & A. I. Din, A. H. (2016). Design and Development Of The Mechanism For Run Flat Tyre Part 1'' for group member 1. In *2nd Integrated Design Project Conference (IDPC) 2015, Faculty of Mechanical Engineering, Universiti Malaysia Pahang* (Issue January).

Asper, R. (2016). *Airless Tire Construction Having Multiple Layers* (Patent No. US 2016/0200145 A1). United States Patent and Trademark Office.

Asyraf, M. R. M., Rafidah, M., Ishak, M. R., Sapuan, S. M., Yidris, N., Ilyas, R. A., & Razman, M. R. (2020). Integration of TRIZ, morphological chart and ANP method for development of FRP composite portable fire extinguisher. *Polymer Composites*, *41*(7), 2917–2932. https://doi.org/10.1002/pc.25587

Azammi, A. M. N., Sapuan, S. M., Ishak, M. R., & Sultan, M. T. H. (2018). Conceptual design of automobile engine rubber mounting composite using TRIZ-Morphological chart-analytic network process technique. *Defence Technology*, *14*(4), 268–277. https://doi.org/10.1016/j.dt.2018.05.009

Brell, E., & Meng, B. (n.d.). *Can Airless Tyres Eliminate Caravan Fishtailing?* 1–17.

Choi, S. J., Joo, H., Ko, K. J., & Kang, K. H. (2016). *Non-Pneumatic Tire For Vehicle* (Patent

No. US 9,290,053 B2). United States Patent and Trademark Office.

Choi, S. J., Kim, H. J., Kim, M. S., Ko, K. J., & Kang, K. H. (2016). *Non-Pneumatic tire With Reinforcing Member Having Plate Wire structure* (Patent No. US 9,333,799 B2).

Das, S., & Redrouthu, B. (2014). *Tyre modelling for rolling resistance*.

Dieter, G. E., & Schmidt, L. C. (2013). *Engineering Design 5th Edition* (Vol. 5).

Dong, W., Dai, X., Huang, J., & Zhou, Y. (2017). *Preliminary Study on Furniture Innovative Design Based on the Technical Contradiction Matrix of TRIZ*. *112*(Icreet 2016), 500–504. https://doi.org/10.2991/icreet-16.2017.83

Donnici, G., Frizziero, L., Francia, D., Liverani, A., & Caligiana, G. (2018). TRIZ method for innovation applied to an hoverboard. *Cogent Engineering*, *5*(1), 1–24. https://doi.org/10.1080/23311916.2018.1524537

Gadd, K. (2011). *TRIZ for Engineers: Enabling Inventive Problem Solving* (1st Editio). John Wiley & Sons, Ltd. https://doi.org/DOI:10.1002/9780470684320

Golder, P., & Mitra, D. (2018). Product Design and Development. In *Handbook of Research on New Product Development*. https://doi.org/10.4337/9781784718152.00017

Hassan, S. Bin, Ghani, J. A., Haron, C. H. C., & Dali, M. N. A. B. M. (2017). Development of dynamic assisted tooling using TRIZ approach for dimple structure fabrication in milling process. *Journal of Mechanical Engineering*, *SI 3*(1), 23–32.

Hryciów, Z., Jackowski, J., & Żmuda, M. (2020). The Influence of Non-Pneumatic Tyre Structure on its Operational Properties. *International Journal of Automotive and Mechanical Engineering*, *17*(3), 8168–8178. https://doi.org/10.15282/IJAME.17.3.2020.10.0614

Jansen, T. N. O. S., Schmeitz, A., & Maas, S. (2016). Study on some safety-related aspects of tyre use. In *TNO innovation for life* (Issue 2). https://doi.org/10.2832/67191

Jin, X., Hou, C., Fan, X., Sun, Y., Lv, J., & Lu, C. (2018). Investigation on the static and dynamic behaviors of non-pneumatic tires with honeycomb spokes. *Composite Structures*, *187*, 27–35. https://doi.org/10.1016/j.compstruct.2017.12.044

Joseph, P. F., Fadel, G. M., & Biggers, S. B. (2011). *On the Modeling of Contact Problems for Curved and Straight Elastic Thin Continuums with Application to Non-Pneumatic*

Tires A Dissertation Presented to the Graduate School of Clemson University In the Partial Fulfillment of the Requirements for the Degree (Issue August).

Kalahastimath, A. K. A. (2021). Review on Airless Tyre. *International Research Journal of Engineering and Technology*, 980–986.

Kamarudin, K. M. (2017). *Development Of Integrated Systematic Approach Conceptual Design And TRIZ Using Safety Principles In Embodiment Design For Complex Products* (Issue February). Universiti Putra Malaysia.

Kamarudin, K. M., Ridgway, K., & Hassan, M. R. (2015). Modelling the conceptual design process with hybridization of TRIZ methodology and systematic design approach. *Procedia Engineering*, *131*, 1064–1072. https://doi.org/10.1016/j.proeng.2015.12.424

Karthick, S., Surendhar, R., & Rose, V. R. (2017). Design and Analysis of Non – Pneumatic Tyre by using Composite Materials. *International Journal for Scientific Research & Development*, *5*(10), 424–431.

Kittidecha, C., & Marasinghe, A. C. (2015). Application of Kansei Engineering and Box – Behnken response surface methodology for shape parameter design : A case study of wine glass. *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, *9*(5), 1–12. https://doi.org/10.1299/jamdsm.2015jamdsm00

Ko, Y. T., Lu, C. C., & Lee, L. H. (2016). A Contradiction-Based Approach for Innovative Product Design. *MATEC Web of Conferences*, *68*, 6–10. https://doi.org/10.1051/matecconf/20166805001

Kongara, M., & Madhusree, D. (2018). Modelling And Analysis of Honeycumb Airless Tire. *IJSART*, *4*(12), 268–278.

Kretzschmar, N., & Chekurov, S. (2018). The applicability of the 40 TRIZ principles in design for additive manufacturing. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, *29*(1), 888–893. https://doi.org/10.2507/29th.daaam.proceedings.128

Lin, S. Y., & Wu, C. T. (2016). Application of TRIZ inventive principles to innovate recycling machine. *Advances in Mechanical Engineering*, *8*(49), 1–8. https://doi.org/10.1177/1687814016647303

London, B. N. (2012). *A Model-Based Systems Engineering Framework for Concept*

Development. Massachusetts Institute of Technology.

Ludvigsen, S. (2017). *Improving Mechanical Grip on Winter Tyres*.

Mansor, M. R., Sapuan, S. M., Zainudin, E. S., Nuraini, A. A., & Hambali, A. (2014). Conceptual design of kenaf fiber polymer composite automotive parking brake lever using integrated TRIZ-Morphological Chart-Analytic Hierarchy Process method. *Materials and Design*, *54*(August 2013), 473–482. https://doi.org/10.1016/j.matdes.2013.08.064

Mansor, M. R., Shaharuzaman, M. A., Tahir, M. M., Akop, M. Z., Salim, M. A., & Zainudin, A. Z. (2017). Product design improvement Of water dispenser tap using TRIZ method. *Journal of Advanced Manufacturing Technology*, *11*(1 Special Issue), 101–111.

Marattukalam, K. J., Varghese, S. Z., Samuel, S., & Sreekumar, S. (2015). Modeling and analysis of non-pneumatic tyres with hexagonal honeycomb spokes. *International Journal on Recent Technologies in Mechanical and Electrical Engineering*, *2*(3), 19–24.

Matsuda, J., & Hashimura, Y. (2011). *Non-pneumatic tire and method of manufacturing same* (Patent No. US 2011/024.0193 A1). United States Patent and Trademark Office.

Meliandy, F., Ruslan, W., & Sukwadi, R. (2018). *Design of Mixer Machine for Powder with Triz Method (Case Study : Mixing Powder Process in PT . X). 13*(20), 14627–14632.

Mikerov, A. G. (2014). From history of electrical engineering III: Electromagnetism discovery and its fundamental laws in the first half of 19-th century. *Proceedings of the 2014 IEEE North West Russia Young Researchers in Electrical and Electronic Engineering Conference, ElConRusNW 2014*, 1–7. https://doi.org/10.1109/ElConRusNW.2014.6839186

Mohan, A., Johny, C. A., Tamilarasu, A., Bhasker, J. P., & Ravi, K. (2017). Design and analysis of non-pneumatic tyre. *IOP Conference Series: Materials Science and Engineering*, *263*, 062061. https://doi.org/10.1088/1757-899X/263/6/062061

Mun, D. Y., Kim, H. J., & Choi, S. J. (2015). *Airless Tire* (Patent No. US 9,120,351 B2). United States Patent and Trademark Office.

P.Raleigh. (2017). *Conti exec skeptical of airless tires for passenger cars*. European Rubber Journal. https://www.rubbernews.com/article/20170627/NEWS/170629948/conti-exec-skeptical-of-airless-tires-for-passenger-cars

Pulidindi, K., & Mukherjee, S. (2020). *Airless Tires Market Size By Product (Radial, Bias), By Vehicle (Military Vehicles, Passenger & Commercial Vehicles, Terrain Vehicles, Utility Vehicles, Two-wheelers), By Material (Rubber, Plastic), By Sales Channel (OEM, Aftermarket), Industry Analysis R*.

Rangdale, P. A., Chandak, K. R., & Bagade, P. G. M. (2018). Non pneumatic tyre. *Intenational Journal of Engineering Sciences & Research Technology*, *7*(2), 61–68.

Rhyne, T. B., Thompson, R. H., Cron, S. M., & Demino, K. W. (2010). *Non-Pneumatic Tire Having Web Spokes* (Patent No. US 7,650,919 B2). United States Patent and Trademark Office.

RRL. (2013). *40 Principles*. Technical Innovation Center, Inc. https://www.triz.org/triz/principles

Sairanen, J. (2017). *Methods for New Product Concept Development* (Issue December). Tampere University of Technology.

Sassi, S., Ebrahemi, M., Mozien, M., & Hadary, Y. (2016). New Design of Flat-Proof Non-Pneumatic Tire. *International Journal of Mechanical Systems Engineering*, *2*(1). https://doi.org/10.15344/2455-7412/2016/114

Silverstein, D., Samuel, P., & Decarlo, N. (2011). Pugh Matrix. *The Innovator's Toolkit*, 212–216. https://doi.org/10.1002/9781118258316.ch36

Tarakaram, K., & Varma, D. P. (2019). *Modeling and Analysis of Non-Pneumatic Tyres With Different Design Structures*. *4*(1), 49–64.

Thompson, R. H. . (2016). *Non-Pneumatic Tire And Other Annular Devices* (Patent No. WO 2016/126983 Al). World Intellectual Property Organization.

Thompson, R. H. . (2017). *Annular Ring And Non - Pneumatic Tire* (Patent No. US 9 , 751 , 270 B2). United States Patent and Trademark Office.

U.S. Tire Manufacturing Association. (2018). *Sustainability: Driving the U.S. Tire Manufacturing Industry*.

Umesh, G. C., & Amith Kumar, S. N. (2016). Design and Analysis of Non-Pneumatic Tyre (NPT) With Honeycomb Spokes Structure. *International Journal of Engineering*

Science and Computing, *6*(9), 2136–2140.

Veeramurthy, M. (2011). *Modeling , finite element analysis , and optimization of Non-Pneumatic Tire (NPT) for the minimization of rolling resistance*.

W.Asper, R. (2016). *Airless Tire Construction Having Varable Stiffness* (Patent No. US 9,321,312 B2). United States Patent and Trademark Office.

Wako, I., & Makoto, S. (2016a). *Airless Tire And Method For Manufacturing Same* (Patent No. EP 3 000 619 A1). European Patent Office.

Wako, I., & Makoto, S. (2016b). *Airless Tire And Method For Manufacturing Same* (Patent No. US 2016/0089935 A1). United States Patent and Trademark Office.

Wako, I., & Makoto, S. (2017a). *Airless Tire* (Patent No. EP 3 159 184 A1). European Patent Office.

Wako, I., & Makoto, S. (2017b). *Non-Pneumatic Tire* (Patent No. EP 3 254 869 A1). European Patent Office.

Weijie, J. (2020). Research and Application of Mechanical Product Design Process Based on QFD and TRIZ Integration Research and Application of Mechanical Product Design Process Based on QFD and TRIZ Integration. *Journal of Physics: Conference Series*. https://doi.org/10.1088/1742-6596/1544/1/012088

Wen, D., Tan, H., Ng, P. K., Efzan, E., & Noor, M. (2021). A TRIZ-driven conceptualisation of finger grip enhancer designs for the elderly [version 1; peer review: 2 approved, 1 approved with reservations]. *F1000Research 2021*, 1–35. https://doi.org/https://doi.org/10.12688/f1000research.51705.1

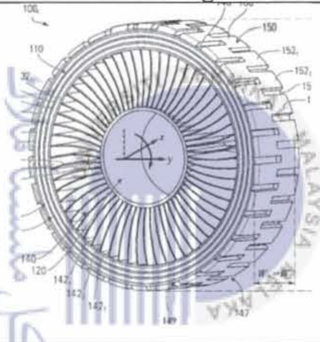
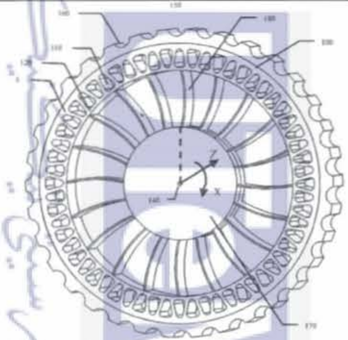
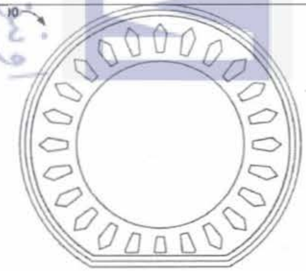
Yokoyama, Y., Sugimoto, M., Iwamura, W., & Sugiya, M. (2019). *Rubber Compound For Tires , Pneumatic Tire , And An Airless Tire* (Patent No. US 10,507,692 B2). United States Patent and Trademark Office.

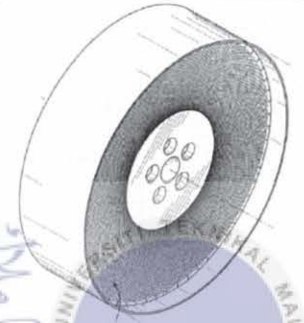
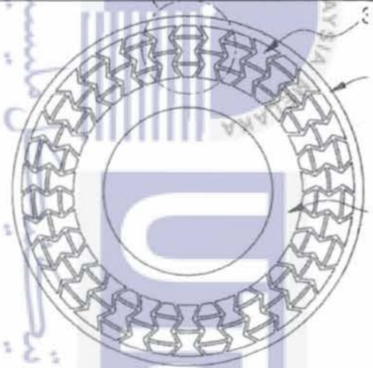
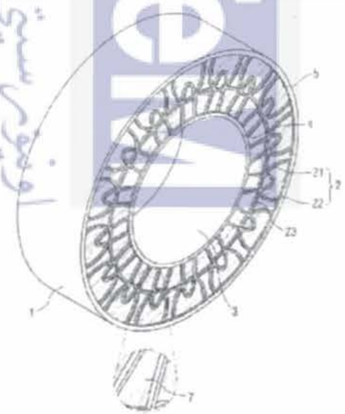
Zhao, Y., Zhu, M., Lin, F., Xiao, Z., Li, H., & Deng, Y. (2018). Thermal modal analysis of novel non-pneumatic mechanical elastic wheel based on FEM and EMA. *AIP Advances*, *8*(1), 015229. https://doi.org/10.1063/1.5018488

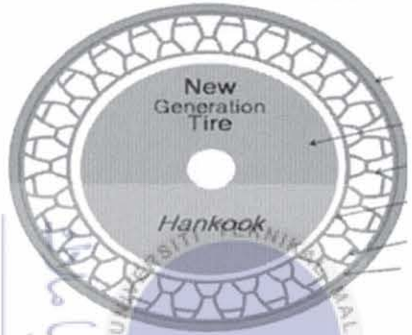
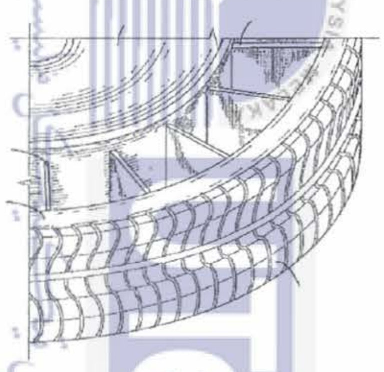
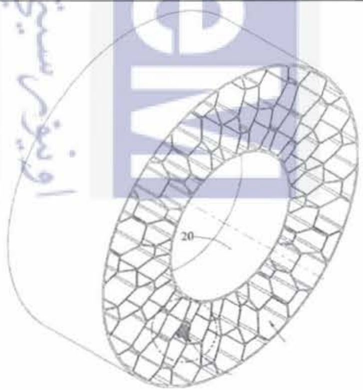
Żmuda, M., Jackowski, J., & Hryciów, Z. (2019). *Numerical research of selected features of the non-pneumatic tire*. 020027. https://doi.org/10.1063/1.5092030

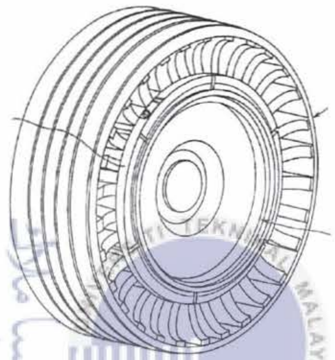
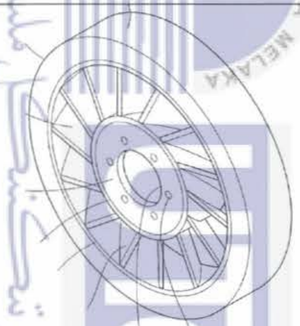
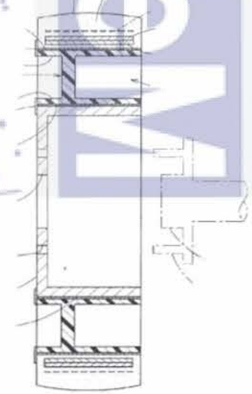
APPENDIX A

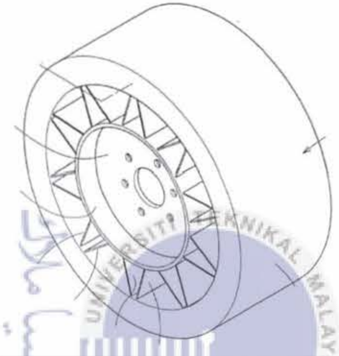
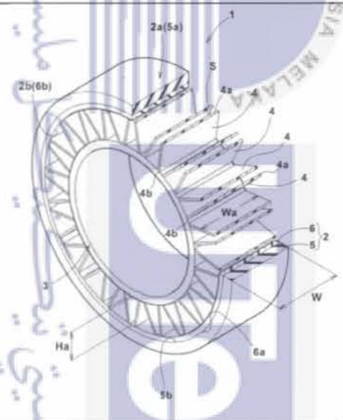
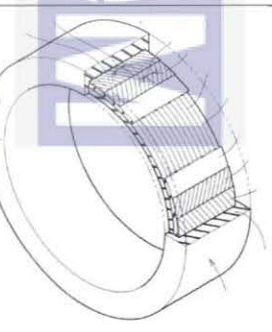
Patent Search

Assignee/Applicant	Citation	Patent Title	Relevant Figures	Take Away Points
Advancing Mobility, LLC.	(Thompson, 2016)	Non-Pneumatic Tire And Other Annular Devices		• An annular beam may be used in a non-pneumatic tyre. The annular beam may be made up of many layers of various elastomeric materials. • The annular beam may be devoid of a considerably inextensible reinforcing layer that runs circumferentially around the non-pneumatic tyre. • The annular beam may have several apertures spread around the circumference of the non-pneumatic tyre.
	(Thompson, 2017)	Annular Ring And Non - Pneumatic Tire		• The annular beam, a ground contacting component, a central wheel, and a number of web spokes that link the wheel and beam comprise the non - pneumatic tyre. • Tension in the web spokes transmits load from the beam to the hub.
Bridgestone Americas Tire Operations	(Asper, 2016)	Airless Tire Construction Having Multiple Layers		• The spoke rings may be coupled to a hub that, when loaded, tensions the spokes above the hub and compresses the spokes below the hub, with the tensile and compression pressures being equal in magnitude.

Bridgestone Americas, Inc	(W.Asper, 2016)	Airless Tire Construction Having Variable Stiffness		• An airless tyre has a wheel segment and webbing that extends from the wheel part to the axis of rotation of the airless tyre. • The webbing stiffness of an airless tyre varies along its axial direction.
Hankook Tire Co., Ltd.,	(Mun et al., 2015)	Airless Tire		• The airless tyre consists of a circular tread that contacts the ground, an axle fixing section with a smaller circle than the tread and arranged in the tread, and an auxetic spoke buffer linking the tread and the axle fixing part.
	(Choi, Joo, et al., 2016)	Non-Pneumatic Tire For Vehicle		• The non-pneumatic tyre is made up of a tread that contacts with road surface, a rim component, inner and outside annular bands, a spoke member, and two protective layers. • The rim section of a vehicle is attached to the axle. The inside and outer annular bands are coaxially spaced apart and are located between the tread and the rim section. • The spoke member is made up of supports arranged in a certain pattern and designed to link the inner and outside annular bands, as well as holes formed by the supports.

	(Choi, Kim, et al., 2016)	Non-Pneumatic Tire With Reinforcing Member Having Plate Wire Structure		• The non-pneumatic tyre consists of a tread part that contacts the ground, a rim part that is connected to an axle, an outer annular band part that interfaces with the tread part's inner surface, an inner annular band part that interfaces with the rim part, a spoke part that is locate between the inner annular band part and outer annular band part, which functions as a support, and a connector that connects spokes.
Michelin Recherche of Technique S.A.,	(Rhyne et al., 2010)	Non-Pneumatic Tire Having Web Spokes		• A structurally supported, non-pneumatic tyre contains a reinforced annular band that supports the load on the tyre and a multiplicity of web spokes transmit tension load forces between the annular band and a wheel or hub.
Resillient Technologies LLC	(A.Manesh et al., 2012)	Tension-Based Non-Pneumatic Tire		• The elements in a deformed area of the tyre between the hub and a footprint region where the tyre touches a surface may assume a much-reduced percentage of the load by buckling. • Web components in other parts of the interconnected web must work in tension to sustain the load.

The Yokohama Rubber Co., Ltd.	(Matsuda & Hashimura, 2011)	Non-Pneumatic Tire And Method Of Manufacturing Same		• When a non-pneumatic tyre is attached and fixed to a wheel as an assembly, there is difficulty that when the tyre is worn or damaged, the operation of detaching the tyre from the wheel and installing a new tyre is extremely difficult.
Sumitomo Rubber Industries, Ltd.	(Wako & Makoto, 2016a)	Airless Tire And Method For Manufacturing Same		• An airless tyre comprising hub, tread ring, and spoke. • The spoke has an outer annular portion with an outer peripheral surface bonded to the inner peripheral surface of the tread ring via a first adhesion layer, an inner annular portion with an inner peripheral surface bonded to the outer peripheral surface of the hub via a second adhesion layer, and a spoke portion that connects the inner and outer annular portions.
	(Wako & Makoto, 2016b)	Airless Tire And Method For Manufacturing Same		• The moulding process is to set the hub and tread ring in a casting mould with the adhesive compound to generate space between the hub and tread ring that corresponds to the spoke.

	(Wako & Makoto, 2017a)	Airless Tire		• A cylindrical tread ring with a ground contact surface, a hub portion placed on a circumferential direction inner side of the tread ring and fastened to an axle, and a spoke connecting the tread ring and the hub part are all included in an airless tyre. There is a strengthening body in the tread ring.
	(Wako & Makoto, 2017b)	Non-Pneumatic Tire		• A radially inner ring linked to a wheel, a radially outer ring having an electrically conductive radially outermost annular tread section and a radially innermost second portion, and radial link portions connecting the radially outer and inner rings make up a non-pneumatic tyre.
	(Yokoyama et al., 2019)	Rubber Compound For Tires, Pneumatic Tire, And An Airless Tire		• Airless tyre containing a cylindrical tread ring with a ground contacting surface, a hub disposed radially inside the tread ring and secure to a vehicle axle, and a spoke connecting the tread ring and the hub, characterised in the tread ring comprises a tread rubber forming the ground contacting surface, an outer reinforcing cord layer disposed closest to the tread rubber, and a spoke connecting the hub and tread ring.

APPENDIX B

39 Engineering Parameters Contradiction Matrix (Gadd, 2011)

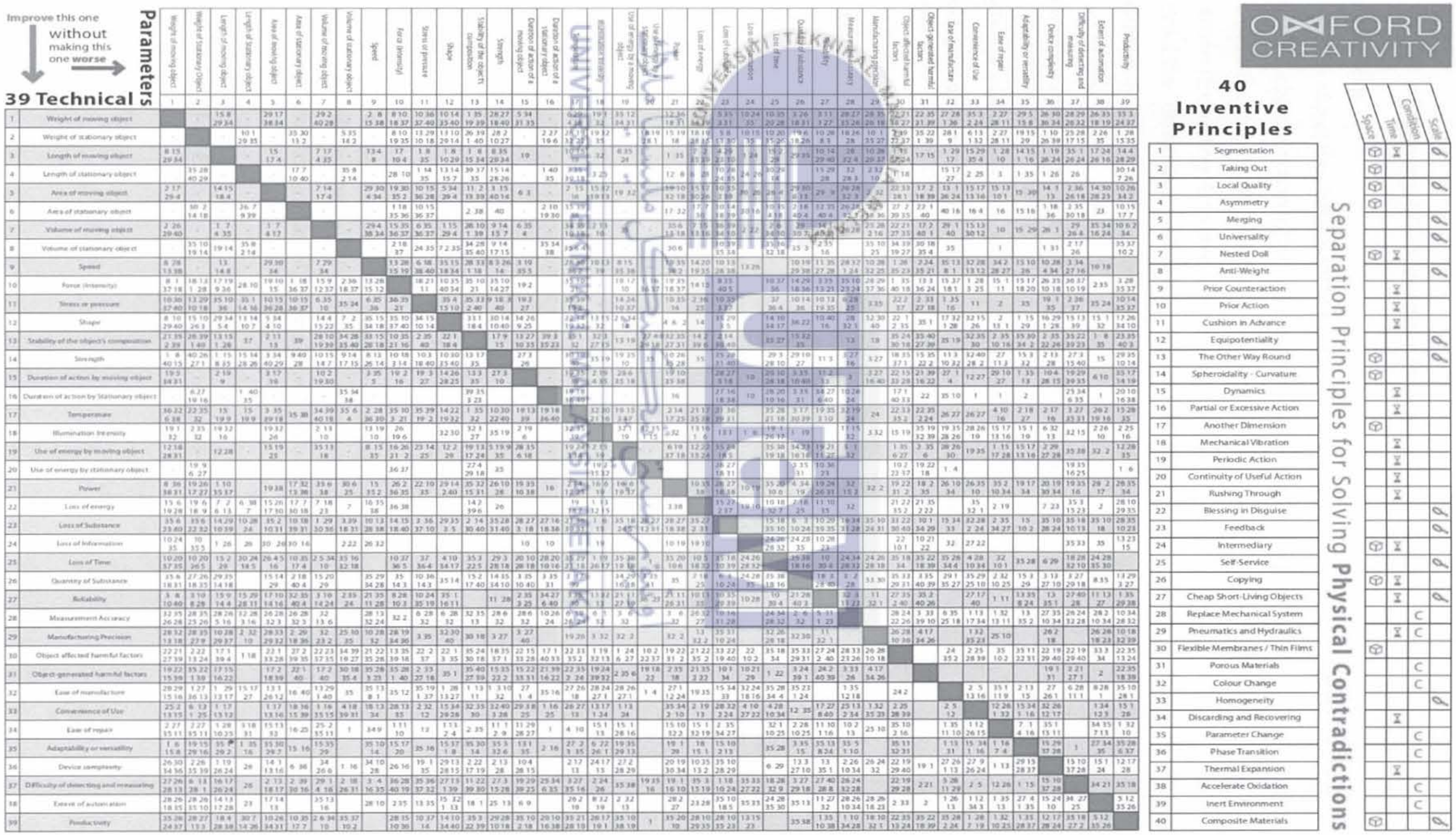
No.	Title	Explanation
	Moving objects	Objects which can easily change position in space, either on their own, or as a result of external forces. Vehicles and objects designed to be portable are the basic members of this class.
	Stationary objects	Objects which do not change position in space, either on their own, or as a result of external forces. Consider the conditions under which the object is being used.
1	Weight of moving object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension.
2	Weight of stationary object	The mass of the object, in a gravitational field. The force that the body exerts on its support or suspension, or on the surface on which it rests.
3	Length of moving object	Any one linear dimension, not necessarily the longest, is considered a length.
4	Length of stationary object	Same.
5	Area of moving object	A geometrical characteristic described by the part of a plane enclosed by a line. The part of a surface occupied by the object. OR the square measure of the surface, either internal or external, of an object.
6	Area of stationary object	Same.
7	Volume of moving object	The cubic measure of space occupied by the object. Length x width x height for a rectangular object, height x area for a cylinder, etc.

No.	Title	Explanation
8	Volume of stationary object	Same.
9	Speed	The velocity of an object; the rate of a process or action in time.
10	Force	Force measures the interaction between systems. In Newtonian physics, force = mass x acceleration. In TRIZ, force is any interaction that is intended to change an object's condition.
11	Stress or pressure	Force per unit area. Also, tension.
12	Shape	The external contours, appearance of a system.
13	Stability of the object's composition	The wholeness or integrity of the system; the relationship of the system's constituent elements. Wear, chemical decomposition, and disassembly are all decreases in stability. Increasing entropy is decreasing stability.
14	Strength	The extent to which the object is able to resist changing in response to force. Resistance to breaking.
15	Duration of action by a moving object	The time that the object can perform the action. Service life. Mean time between failure is a measure of the duration of action. Also, durability.
16	Duration of action by a stationary object	Same.
17	Temperature	The thermal condition of the object or system. Loosely includes other thermal parameters, such as heat capacity, that affect the rate of change of temperature.
18	Illumination intensity	Light flux per unit area, also any other illumination characteristics of the system such as brightness, light quality, etc.
19	Use of energy by moving object	The measure of the object's capacity for doing work. In classical mechanics, Energy is the product of force x distance. This includes the use of energy provided by the super-system (such as electrical energy or heat.) Energy required to do a particular job.
20	Use of energy by stationary object	Same.
21	Power	The time rate at which work is performed. The rate of use of energy.
22	Loss of Energy	Use of energy that does not contribute to the job being done. See 19. Reducing the loss of energy sometimes requires different techniques from improving the use of energy, which is why this is a separate category.
23	Loss of substance	Partial or complete, permanent or temporary, loss of some of a system's materials, substances, parts or subsystems.
24	Loss of Information	Partial or complete, permanent or temporary, loss of data or access to data in or by a system. Frequently includes sensory data such as aroma, texture, etc.
25	Loss of Time	Time is the duration of an activity. Improving the loss of time means reducing the time taken for the activity. 'Cycle time reduction' is a common term.

No.	Title	Explanation
26	Quantity of substance/the matter	The number or amount of a system's materials, substances, parts or subsystems which might be changed fully or partially, permanently or temporarily.
27	Reliability	A system's ability to perform its intended functions in predictable ways and conditions.
28	Measurement accuracy	The closeness of the measured value to the actual value of a property of a system. Reducing the error in a measurement increases the accuracy of the measurement.
29	Manufacturing precision	The extent to which the actual characteristics of the system or object match the specified or required characteristics.
30	External harm affects the object	Susceptibility of a system to externally generated (harmful) effects.
31	Object-generated harmful factors	A harmful effect is one that reduces the efficiency or quality of the functioning of the object or system. These harmful effects are generated by the object or system, as part of its operation.
32	Ease of manufacture	The degree of facility, comfort or effortlessness in manufacturing or fabricating the object/system.
33	Ease of operation	Simplicity: The process is not easy if it requires a large number of people, large number of steps in the operation, needs special tools, etc. 'Hard' processes have low yield and 'easy' process have high yield; they are easy to do right.
34	Ease of repair	Quality characteristics such as convenience, comfort, simplicity, and time to repair faults, failures or defects in a system.
35	Adaptability or versatility	The extent to which a system/object positively responds to external changes. Also, a system that can be used in multiple ways for under a variety of circumstances.
36	Device complexity	The number and diversity of elements and element interrelationships within a system. The user may be an element of the system that increases the complexity. The difficulty of mastering the system is a measure of its complexity.
37	Difficulty of detecting and measuring	Measuring or monitoring systems that are complex, costly, require much time and labour to set up and use, or that have complex relationships between components or components that interfere with each other all demonstrate 'difficulty of detecting and measuring.' Increasing cost of measuring to a satisfactory error is also a sign of increased difficulty of measuring.
38	Extent of automation	The extent to which a system or object performs its functions without human interface. The lowest level of automation is the use of a manually operated tool. For intermediate levels, humans program the tool, observe its operation, and interrupt or re-program as needed. For the highest level, the machine senses the operation needed, programs itself and monitors its own operations.
39	Productivity	The number of functions or operations performed by a system per unit time. The time for a unit function or operation. The output per unit time, or the cost per unit output.

APPENDIX C

Contradiction Matrix (Gadd, 2011)



APPENDIX D

Summary of 40 Inventive Principals (RRL, 2013)

1. Segmentation

   a. Divide an object into independent parts.

   b. Make an object sectional (for easy assembly or disassembly).

   c. Increase the degree of an object's segmentation.

2. Extraction (Extracting, Retrieving, Removing)

   a. Extract the "disturbing" part or property from an object.

   b. Extract only the necessary part or property from an object.

3. Local Quality

   a. Transition from homogeneous to heterogeneous structure of an object or outside environment (action).

   b. Different parts of an object should carry out different functions.

   c. Each part of an object should be placed under conditions that are most favorable for its operation.

4. Asymmetry

   a. Replace symmetrical forms with asymmetrical forms.

   b. If an object is already asymmetrical, increase its degree of asymmetry.

5. Consolidation

   a. Consolidate in space homogeneous objects, or objects destined for contiguous operations.

   b. Consolidate in time homogeneous or contiguous operations.

6. Universality

   a. An object can perform several different functions; therefore, other elements can be removed.

7. Nesting (Matrioshka)

   a. One object is placed inside another. That object is placed inside a third one and so on...

   b. An object passes through a cavity in another object.

8. Counterweight

   a. Compensate for the weight of an object by combining it with another object that provides a lifting force.

   b. Compensate for the weight of an object with aerodynamic or hydrodynamic forces influenced by the outside environment.

9. Prior Counteraction

   a. Preload countertension to an object to compensate excessive and undesirable stress.

10. Prior Action

a. Perform required changes to an object completely or partially in advance.

b. Place objects in advance so that they can go into action immediately from the most convenient location.

11. Cushon in Advance

a. Compensate for the relatively low reliability of an object with emergency measures prepared in advance.

12. Equipotentiality

a. Change the condition of the work in such a way that it will not require lifting or lowering an object.

13. Do It in Reverse

a. Instead of the direct action dictated by a problem, implement an opposite action (i.e., cooling instead of heating).

b. Make the movable part of an object, or outside environment, stationary — and stationary part moveable.

c. Turn an object upside-down.

14. Spheroidality

a. Replace linear parts with curved parts, flat surfaces with spherical surfaces, and cube shapes with ball shapes.

b. Use rollers, balls, spirals.

c. Replace linear motion with rotational motion; utilize centrifugal force.

15. Dynamicity

a. Characteristics of an object or outside environment, must be altered to provide optimal performance at each stage of an operation.

b. If an object is immobile, make it mobile. Make it interchangeable.

c. Divide an object into elements capable of changing their position relative to each other.

16. Partial or Excessive Action

a. If it is difficult to obtain 100% of a desired effect, achieve more or less of the desired effect.

17. Transition Into a New Dimension

a. Transition one-dimensional movement, or placement, of objects into two-dimensional; two-dimensional to three-dimensional, etc.

b. Utilize multi-level composition of objects.

c. Incline an object, or place it on its side.

d. Utilize the opposite side of a given surface.

e. Project optical lines onto neighboring areas, or onto the reverse side, of an object.

18. Mechanical Vibration

a. Utilize oscillation.

b. If oscillation exists, increase its frequency to ultrasonic.

c. Use the frequency of resonance.

d. Replace mechanical vibrations with piezovibrations.

e. Use ultrasonic vibrations in conjunction with an electromagnetic field.

19. Periodic Action

a. Replace a continuous action with a periodic one (impulse).

b. If the action is already periodic, change its frequency.

c. Use pauses between impulses to provide additional action.

20. Continuity of Useful Action

a. Carry out an action without a break. All parts of the object should constantly operate at full capacity.

b. Remove idle and intermediate motion.

c. Replace "back-and-forth" motion with a rotating one.

21. Rushing Through

a. Perform harmful and hazardous operations at a very high speed.

22. Convert Harm Into Benefit

a. Utilize harmful factors — especially environmental — to obtain a positive effect.

b. Remove one harmful factor by combining it with another harmful factor.

c. Increase the degree of harmful action to such an extent that it ceases to be harmful.

23. Feedback

a. Introduce feedback.

b. If feedback already exists, change it.

24. Mediator

a. Use an intermediary object to transfer or carry out an action.

b. Temporarily connect the original object to one that is easily removed.

25. Self-service

a. An object must service itself and carry out supplementary and repair operations.

b. Make use of waste material and energy.

26. Copying

a. A simplified and inexpensive copy should be used in place of a fragile original or an object that is inconvenient to operate.

b. If a visible optical copy is used, replace it with an infrared or ultraviolet copies.

c. Replace an object (or system of objects) with their optical image. The image can then be reduced or enlarged.

27. Dispose

a. Replace an expensive object with a cheap one, compromising other properties (i.e., longevity).

28. Replacement of Mechanical System

a. Replace a mechanical system with an optical, acoustical, thermal or olfactory system.

b. Use an electric, magnetic or electromagnetic field to interact with an object.

c. Replace fields that are:

1. Stationary with mobile
2. Fixed with changing in time
3. Random with structured

d. Use fields in conjunction with ferromagnetic

29. Pneumatic or Hydraulic Constructions

a. Replace solid parts of an object with a gas or liquid. These parts can now use air or water for inflation, or use pneumatic or hydrostatic cushions.

30. Flexible Membranes or Thin Films

a. Replace customary constructions with flexible membranes or thin film.

b. Isolate an object from its outside environment with flexible membranes or thin films.

31. Porous Material

a. Make an object porous, or use supplementary porous elements (inserts, covers, etc.).

b. If an object is already porous, fill pores in advance with some substance.

32. Changing the Color

a. Change the color of an object or its environment.

b. Change the degree of translucency of an object or its environment.

c. Use color additives to observe an object, or process which is difficult to see.

d. If such additives are already used, employ luminescent traces or trace atoms.

33. Homogeneity

a. Objects interacting with the main object should be made out of the same material (or material with similar properties) as the main object.

34. Rejecting and Regenerating Parts

a. After completing its function, or becoming useless, an element of an object is rejected (discarded, dissolved, evaporated, etc.) or modified during its work process.

b. Used-up parts of an object should be restored during its work.

35. Transformation of Properties

a. Change the physical state of the system.

b. Change the concentration or density.

c. Change the degree of flexibility.

d. Change the temperature or volume.

36. Phase Transition

a. Using the phenomena of phase change (i.e., a change in volume, the liberation or absorption of heat, etc.).

37. Thermal Expansion

a. Use expansion or contraction of material by changing its temperature.

b. Use various materials with different coefficients of thermal expansion.

38. Accelerated Oxidation

a. Make transition from one level of oxidation to the next higher level:

1. Ambient air to oxygenated
2. Oxygenated to oxygen
3. Oxygen to ionized oxygen
4. Ionized oxygen to ozoned oxygen
5. Ozoned oxygen to ozone
6. Ozone to singlet oxygen

39. Inert Environment

a. Replace a normal environment with an inert one.

b. Introduce a neutral substance or additives into an object.

c. Carry out the process in a vacuum.

40. Composite Materials

a. Replace homogeneous materials with composite ones.