RESEARCH AND PRODUCT DESIGN DEVELOPMENT OF HYBRID FURNITURE LOUDSPEAKER PRODUCT FOR HOME AUDIO CONSUMER

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Faculty of Mechanical and Manufacturing Engineering Technology

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A thesis submitted
in fulfillment of the requirements for the degree of
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DECLARATION

I declare that this project entitled “ Research And Product Design Development Of Hybrid Furniture Loudspeaker Product For Home Audio Consumer ” is the result of my own research except as cited in the references. The project report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : Syed Azhar Bin Seyed Abuthahir

Date : 1/1/2024

APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Manufacturing Engineering Technology (Product Design) with Honours.

Signature	:	
Supervisor Name	:	Ts. Dr. Syahibudil Ikhwan Bin Abdul Kudus
Date	:	1/1/2024

DEDICATION

I dedicate this research project report to my supervisor Ts. Dr. Syahibudil Ikhwan Bin Abdul Kudus and my peers. They have helped me in giving support, motivation, advice and guidance during the duration of the assignment.

ABSTRACT

This research and development project invents a new product and product category by combining two different products that were previously usually never put together into a single product to solve a modern-day problem involving the home environment. This product combines a furniture product and a loudspeaker product to save space and reduce room clutter as well avoid the trade-off of compromising the aesthetics of a room to achieve great sound quality in the home environment. The project goes through the entire process of research, design and fabrication of this product step by step following the normal design and development process by Ulrich. The user requirements for the product were acquired through secondary and tertiary sources. In the concept design phase, many different furniture and loudspeaker combinations were explored guided by a morphological chart but using Pugh's evaluation and weighted decision matrix, the concepts were narrowed down to one combination which was the coffee table and subwoofer. The coffee table subwoofer hybrid design was chosen due to the best balance of sound performance, practicality, and in-house location compatibility. The appropriate ergonomic considerations were made during the design of the cad model of the concept. The most compatible materials and parts were chosen before beginning the cad design process to aid and guide the final cad design and finally a computer analysis was performed on the final cad design model before proceeding to the prototype fabrication process. The computer analysis process is shown and explained in detail to relay the complexities and nuances in the designing process. The fabrication process is shown in brief and subsequently the finished prototype has acoustic optimizations performed on it before proceeding to the usability testing with actual users. 10 respondents were chosen to test and rate the product and the results were tabulated to give an idea of how well the product performed. The results show good to excellent results proving the project was a success as it hit the expectations set out in the research objective.

ABSTRAK

Projek penyelidikan dan pembangunan ini mencipta produk dan kategori produk baharu dengan menggabungkan dua produk berbeza yang sebelum ini biasanya tidak pernah digabungkan menjadi satu produk untuk menyelesaikan masalah moden yang melibatkan persekitaran rumah. Produk ini menggabungkan produk perabot dan produk pembesar suara untuk menjimatkan ruang dan mengurangkan kekusutan bilik serta mengelakkan pertukaran daripada menjejaskan estetika bilik untuk mencapai kualiti bunyi yang hebat dalam persekitaran rumah. Projek ini melalui keseluruhan proses penyelidikan, reka bentuk dan fabrikasi produk ini langkah demi langkah mengikut proses reka bentuk dan pembangunan biasa oleh Ulrich. Keperluan pengguna untuk produk diperoleh melalui sumber sekunder dan tertiari. Dalam fasa reka bentuk konsep, banyak gabungan perabot dan pembesar suara yang berbeza telah diterokai berpandukan carta morfologi tetapi menggunakan penilaian Pugh dan matriks keputusan berwajaran, konsep telah dikecilkan kepada satu kombinasi iaitu meja kopi dan subwufer. Reka bentuk hibrid subwufer meja kopi dipilih kerana keseimbangan terbaik prestasi bunyi, kepraktisan dan keserasian lokasi dalaman. Pertimbangan ergonomik yang sesuai telah dibuat semasa reka bentuk model cad konsep. Bahan dan bahagian yang paling serasi telah dipilih sebelum memulakan proses reka bentuk cad untuk membantu dan membimbing reka bentuk cad akhir dan akhirnya analisis komputer dilakukan pada model reka bentuk cad akhir sebelum meneruskan proses fabrikasi prototaip. Proses analisis komputer ditunjukkan dan dijelaskan secara terperinci untuk menyampaikan kerumitan dan nuansa dalam proses mereka bentuk. Proses fabrikasi ditunjukkan secara ringkas dan seterusnya prototaip siap mempunyai pengoptimuman akustik yang dilakukan padanya sebelum meneruskan ujian kebolehgunaan dengan pengguna sebenar. 10 orang responden telah dipilih untuk menguji dan menilai produk dan keputusan telah dijadualkan untuk memberi gambaran tentang prestasi produk tersebut. Keputusan menunjukkan keputusan yang baik hingga cemerlang membuktikan projek itu berjaya kerana ia mencapai jangkaan yang ditetapkan dalam objektif penyelidikan.

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In the Name of Allah, the Most Gracious, the Most Merciful

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LIST OF SYMBOLS AND ABBREVIATIONS

dB	-	Decibels
CAE	-	Computer Aided Engineering
FEA	-	Finite Element Analysis
CFD	-	Computational Fluid Dynamics
DSP	-	Digital Signal Processing
EQ	-	Equalizer
kHz	-	Kilo-hertz
DC	-	Direct Current
ft	-	feet
PC	-	Personal Computer

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Home audio systems began in the 1920s following the technological developments made in sound amplification during World War 1. The first home audio system began in the form of a radio that became the first major mass media outlet in the world that revolutionized the way humans were able to consume information (Hall, 2017).

High end home audio gear became popular in the 1950s due to technological advancements made in sound quality, but they consisted of extremely large speaker systems that consumed a lot of space yet were very inefficient and still had room to grow in terms of some aspects of sound quality. Since then, this technology has been continually improved in quality, complexity, and compactness till it eventually evolved into the stereo systems we know today. But the increased compactness of modern-day stereo systems wasn't without its share of trade-offs (Hall, 2017).

Modern day stereo systems have traded quality for convenience, often sacrificing important aspects of acoustic design to make loudspeakers smaller. This trend of downsizing speakers is driven by consumer demand where consumers prefer smaller audio systems due to a plethora of reasons, such not having the space to accommodate proper speakers in their homes or not willing to compromise on the aesthetics of their homes by installing larger clunky looking audio gear (Leopold, 2013).

1.2 Problem Statement

Traditionally, implementing high quality sound into any room or space has always been met with the trade-off of consuming extra space and compromising the elegance and aesthetics of a room. For example, implementing wall mounted surround speakers for a home theatre setup in a room would make the room look cluttered and busy due to the speaker's drawing attention to themselves, while the large subwoofer unit consumes a lot of space while also adding to the cluttered appearance of the room. To add to this, the speakers and the subwoofer need to be positioned in the room correctly to achieve the best sound quality but depending on the room this may be difficult or impossible due to the need to accommodate space for other furniture or simply living space to move around in the room freely.

1.3 Research Objective

This project seeks to solve the problem stated above by combining Speaker Design and Furniture Design using suitable materials and components to create a product that acts as both furniture and high-quality speakers to save space and reduce room clutter as well avoiding the trade-off of compromising the aesthetics of a room to achieve great sound quality. The specific objectives are as follows:

a) To determine ideal furniture and loudspeaker combination, components and acoustic chamber (loudspeaker cabinet) design.

b) To determine compatible furniture materials and internal structure design to achieve balance of furniture rigidity and vibration damping to minimize vibration transfer from loudspeaker.

c) To develop a detailed design of the Furniture Loudspeaker Hybrid product with CAD and evaluate and optimize using CAE Software.

1.4 Scope of Research

The scope of this research are as follows:

- Loudspeaker types, crossover components, amplifiers and acoustic chamber design including porting and passive radiators (bass reflex design)
- Furniture types, vibration damping methods, and structural design
- Design Evaluation and Optimization through CAE Analysis

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

When it comes to speaker design, one of the most exciting ideas is the idea that listeners have to be situated in a little sweet spot, which is created by meticulously triangulating a center line between our ears and the speaker's point source. For many audiophiles and music lovers, there is no other way to listen to their favorite music than in a specially constructed listening room (Loar, 2019). However, the "living room stereo" that the market formerly referred to is now mostly ignored.

For years, various brands experimented with integrated concepts that could be freely positioned in the never-ending quest to comprehend and translate people's lifestyles into their designs. Attempting to create a large stereo image from a single-source system was one of them, with the initial tube radios, TVs, and even the first portable stereo music systems in the 1950s serving as inspiration (Hall, 2017).

2.2 Sound System

By definition, a sound system is a collection of components, assembled for the purpose of taking an audio signal (acoustic, electrical, or digital, live, or pre-recorded), processing it, amplifying it, and reproducing it. Essentially, every sound system known to humans (including the humble rolled-up paper cone megaphone) is comprised of four fundamental parts: Inputs, Processing, Amplification and Output (Loar, 2019).

In an analogue sound system, the elements listed above (which we will go over in greater detail in a moment) may be the only elements present in the setup. The signal flow of the standard four analogue elements is depicted in Figure 2.2.1-1.

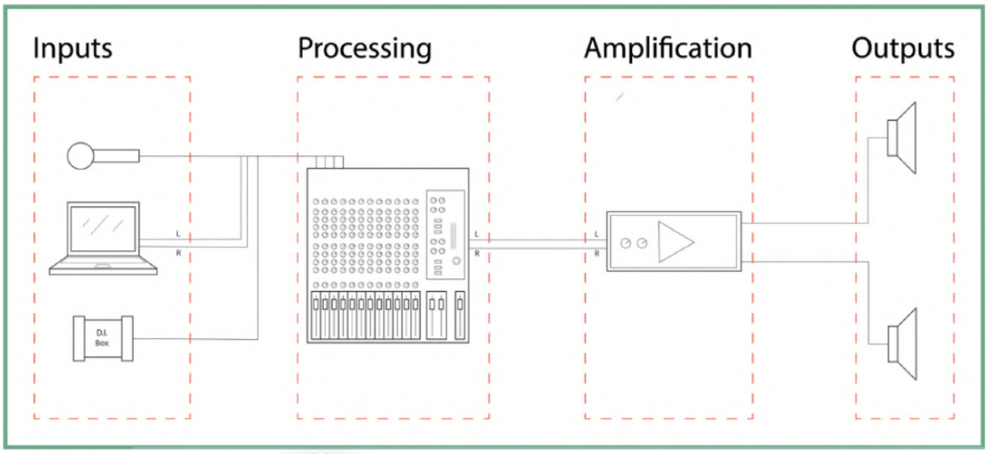


Figure 2-1 Signal Flow of Analogue Elements (Loar, 2019)

The input stage is the stage through which audio content enters a sound system of any type. It is then amplified (made louder) in its final form at the output stage after it has been processed (changed) in some way. Take, for example, the cone-shaped cardboard megaphone, which is perhaps the most rudimentary of all sound systems: the four elements are as follows:

The INPUT stage is represented by your voice, which enters the system through an acoustic path. The PROCESSING stage is represented by the narrow throat of the cone, which imparts specific acoustic changes to the incoming acoustic signal during the processing process. The AMPLIFICATION stage is defined as the distance between the narrow throat of the cone and the wide mouth of the cone (or vice versa). The cone serves as an acoustic resonator, among other things, and thus contributes to the overall loudness of your voice in a positive manner. The OUTPUT stage is represented by the wide mouth of the cone, which acts as a waveguide, spreading the sound out into the surrounding space (Loar, 2019).

2.2.1 Input Stage

The Input Stage is the first stage of the process. The input stage of a sound system always begins with the sound that we are attempting to amplify. However, while it will not be claimed that the singer herself is a component of the sound system, we are likely to have assembled all the equipment had it not been for her. As a result, whenever a sound system is designed, the very first thing to consider is: what sounds that are needed to be amplified? (Loar, 2019)

2.2.2 Processing Stage

A sound system's processing stage can take on an alarming variety of forms. When selecting processing stage equipment, we must consider the following: how many signals do we need to process? Which signal types do we need to process? How many destinations must the signal be routed to, and what type of destinations must they be (audience speakers, monitor speakers, etc.)? (Loar, 2019)

2.2.3 Amplification Stage

By definition an amplifier is a device used to increase the amplitude of electrical signals, especially in the context of sound reproduction. The amplification stage takes all of our processed electronic signals and increases their power, which results in a louder overall sound. In one sense, the process of amplification is very straightforward. We start with a signal, increase the power and volume of that signal, and then send it on its way to its destination. The specifics of how that works, on the other hand, are critical for a systems designer to understand. Because the choice of amplifier is primarily determined by the selection of speakers, we should select our speakers first, and then select amplifiers that will ensure that our speakers are properly powered (Loar, 2019).

2.2.4 Output Stage

The output stage is comprised of the devices that are responsible for actually producing the new, louder sound that is intended to be produced by the sound system. The vast majority of the time, the output device(s) will be some type of loudspeaker or speakers. We must first answer the following fundamental questions in order to determine what kind of output devices we require: Who needs to be able to hear the music? What is the minimum volume required for the sound? In terms of location, where can we reasonably place a device to generate that sound (and what are the spatial constraints of that location)? (Loar, 2019)

2.3 Loudspeakers

Loudspeakers (or "speakers" for those uninitiated with industry jargon) are often sophisticated devices comprised of multiple components. While we occasionally (most notably in theatre) employ so-called raw drivers as the speakers for a certain application, speakers are generally more complicated. By definition, a loudspeaker is a transducer that converts electronic signal to acoustic sound (Loar, 2019). Speakers are most typically made of the following:

2.3.1 Drivers

The cone, coil, and magnet assembly that vibrates and creates sound are referred to as speaker drivers. Many speakers feature more than one driver, generally of varying sizes, each of which is designed to create sound in a different frequency range from the other driver(s). Tweeters are often used to refer to high-frequency (HF) drivers in the audio industry. Low-frequency (LF) drivers, often known as woofers, are used to provide sound at low frequencies. As a general term, subwoofers are low-frequency speakers that are designed to reproduce just the lowest bass frequencies. Midrange drivers don't have a nice moniker, therefore they're often referred to as mids or midrange drivers instead (Loar, 2019). Drivers consist of the following:

Figure 2-2 Cross-section of Speaker Driver (Anderson B. E., 2004)

2.3.1.1 Cone

The vibrating membrane that is responsible for the generation of the acoustic pressure waves that we hear coming from the speakers (Loar, 2019).

Figure 2-3 Speaker Cone with Surround Attached (*Speaker Cone Paper,* n.d.)

2.3.1.2 Voice Coil

A wrapped copper coil, attached to the interior diameter of the speaker (through a shaping component, called the former, which prevents the coil from warping). This coil, when activated with electric signal, vibrates in and out of its magnetic home position, and so moves the cone, which makes sound (Loar, 2019).

Figure 2-4 Voice Coil (Uxcell, 2019)

2.3.1.3 Spider

An accordion-folded material that helps keep the cone and coil in lateral position while still allowing them to bend and move as required to make sound (Loar, 2019).

Figure 2-5 Spider (ASM, n.d.)

2.3.1.4 Magnet

The permanently charged magnet between the poles of which the voice coil floats is referred to as the magnet. In a dynamic microphone, a pole piece is passed through the centre of the coil (which is polarised in only one direction), and a ring magnet surrounds the coil (the opposite pole) (Loar, 2019).

Figure 2-6 Speaker Magnet (Ningbo IMANAFSA Magnetics Co., n.d.)

2.3.1.5 Basket

An aluminium or steel frame that keeps the whole driver assembly in place and enables it to be attached to an enclosure (Loar, 2019).

Figure 2-7 Speaker Basket (Drip Sound Store, n.d.)

2.3.1.6 Surround

The ring of connective material (often plastic or rubber) that secures the cone's large outer diameter to the basket; likewise flexible (as the spider), but not accordion-folded .

Figure 2-8 Surround (Densive, n.d.)

2.3.1.7 Dust Cap/ Phase Plug

The dust cap/phase plug is the centre cover that serves as a key barrier to dust and other particle material entering the driving assembly. In some speaker drivers, the central dust cap serves a dual purpose (and may be shaped specifically for the secondary purpose) of preventing particle entry and acting as a phase plug, which is a piece that helps direct waves (particularly high-frequency waves) out toward the listener rather than allowing them to cause destructive interference close to the driver before sound reaches the listener .

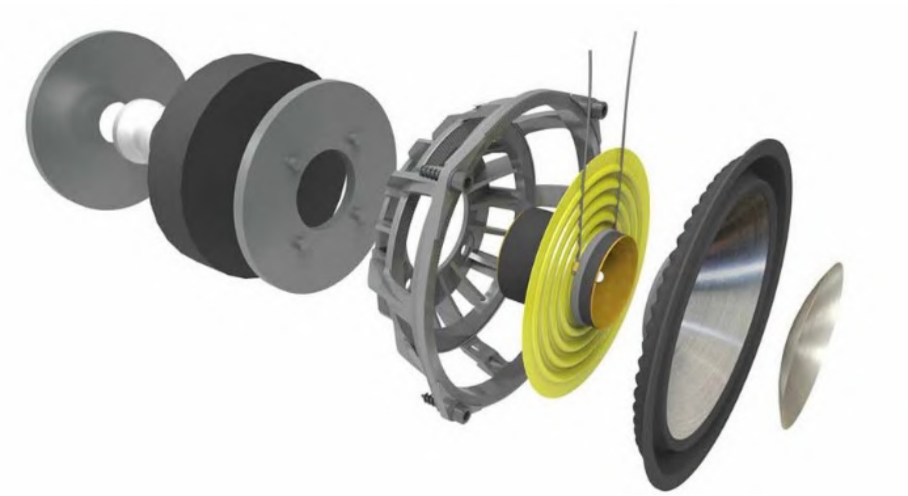


Figure 2-9 Speaker Driver Assembly Exploded View (Garmani, n.d.)

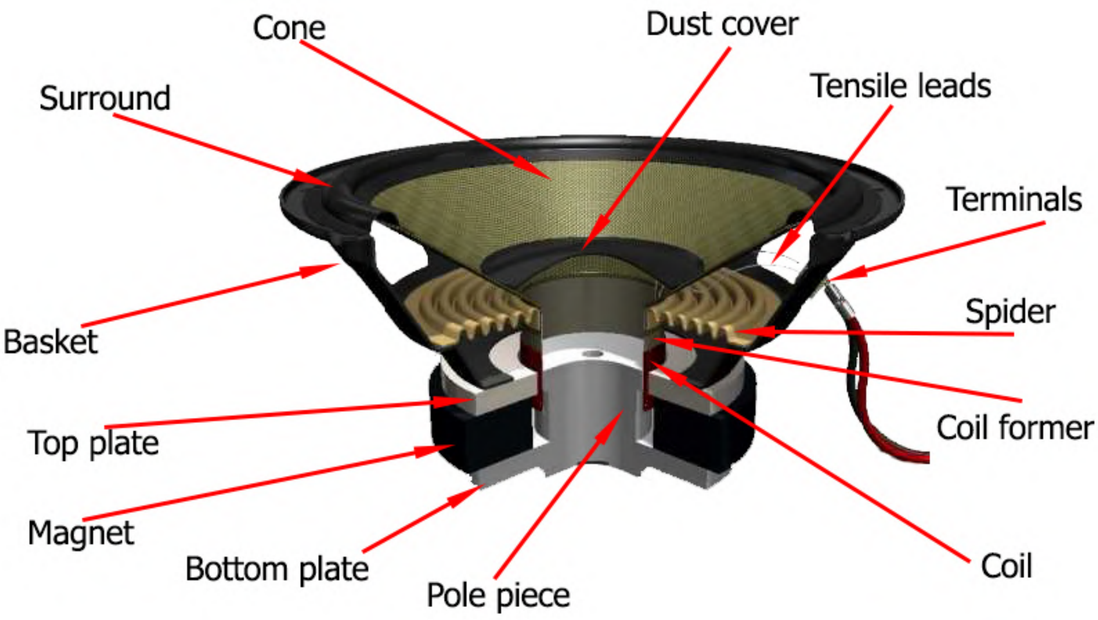


Figure 2-10Speaker Driver Diagram (With Parts Labeled)

(Standford Magnets, n.d.)

2.3.2 Enclosure

The "box" in which the drivers are housed is referred to as the enclosure. Baffles are a term used to describe the enclosures used to house speakers. By definition baffle is an object that is intended to limit the amount of sound that is carried through the air. They are designed to prevent out-of-phase signals created by the open back of drivers from merging with on-axis front sound and producing destructive interference to the speaker's signal path. Shapes, sizes, and materials of enclosures are available in a broad range of options (including absorption inside the cabinet). Some enclosures are intended to deaden the backflow of sound caused by the driver's backward motion, while others are tuned to improve bass response, and yet others are meant to fall somewhere in the middle. There are a very large variety of enclosures, but for the purposes of this project we will provide an overview of the most popular ones (Loar, 2019).

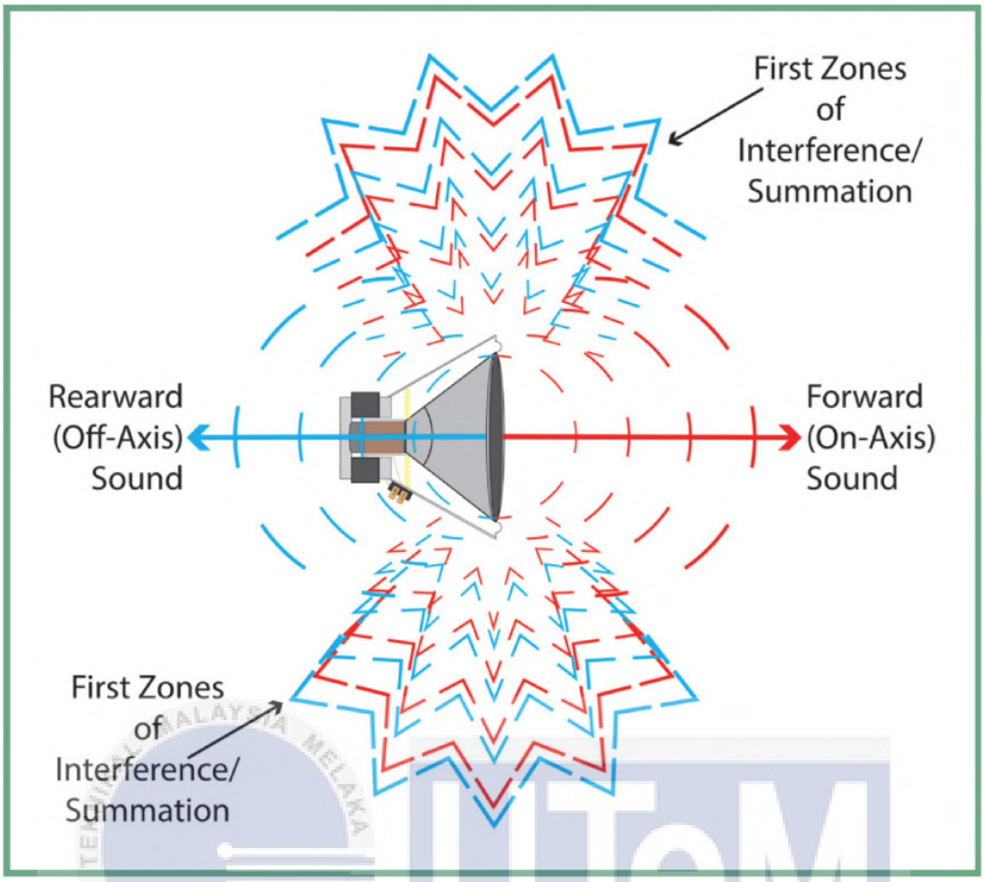


Figure 2-11 Raw Driver With Sound Waves Generated by Both Directions of Motion (Loar, 2019)

2.3.2.1 Sealed/Infinite Baffle

Sealed box/infinite baffle: A sealed box, also known as a "infinite baffle," is an enclosure that has no openings, ports, or vents that allow air to enter from the outside. This is the best design for preserving time coherence in a signal because the sound emitted by the rearward motion of the driver is typically absorbed before we (as listeners) can hear it outside the box when using this method. Consider the following scenario: a raw driver is left out in the open to demonstrate the benefits of a sealed box (Figure 2.3.2-2). Here, our in-phase sound is generated from the front of the driver, but when the first cycle of rarefaction occurs, the cone moves in the opposite direction and generates a half-cycle out-of-phase signal from the backside of the driver. As a result of this scenario, it is very easy for these two signals to combine in acoustic space, resulting in destructive interference and phase blurring between them. This is not desirable for high-performance audio, so we must surround the driver with a baffle, which is a barrier that prevents the sound emanating from the back of the driver from interfering with the sound emanating from the front. In a theoretical world, the perfect baffle would be an infinite wall, which is what we have here (Figure 2.3.2-2). Figure 2.3.2-2 depicts a wall in which the driver is positioned that extends in all directions into infinity. Thus, the waves generated by out-of-phase rarefaction motions can never recombine with the front waves, resulting in a clean and clear signal from the driver. It needs to be noted that this is predicated on the assumption that our infinite wall is acoustically dead and does not itself become a sympathetic vibrating membrane—which is a considerable assumption, given that the choice of baffle material will significantly influence the acoustics of the speaker's delivery. In any case, we want to avoid rear-facing interference, but the practicality of embedding a driver in an infinite wall is, of course, non-existent. So, what is the best way to get around this? As a result, we have a (usually) cuboid box with no openings and a driver (or multiple drivers) embedded into the face of our infinite baffle. Thus, this is referred to as either a sealed box or an infinite baffle enclosure, depending on your preference (Figure 2.3.2-3). When the interior absorption (which is used to prevent or reduce resonance and standing waves in the speaker box itself) is well-planned, these speakers can have extremely tight and controlled phase responses (Loar, 2019).

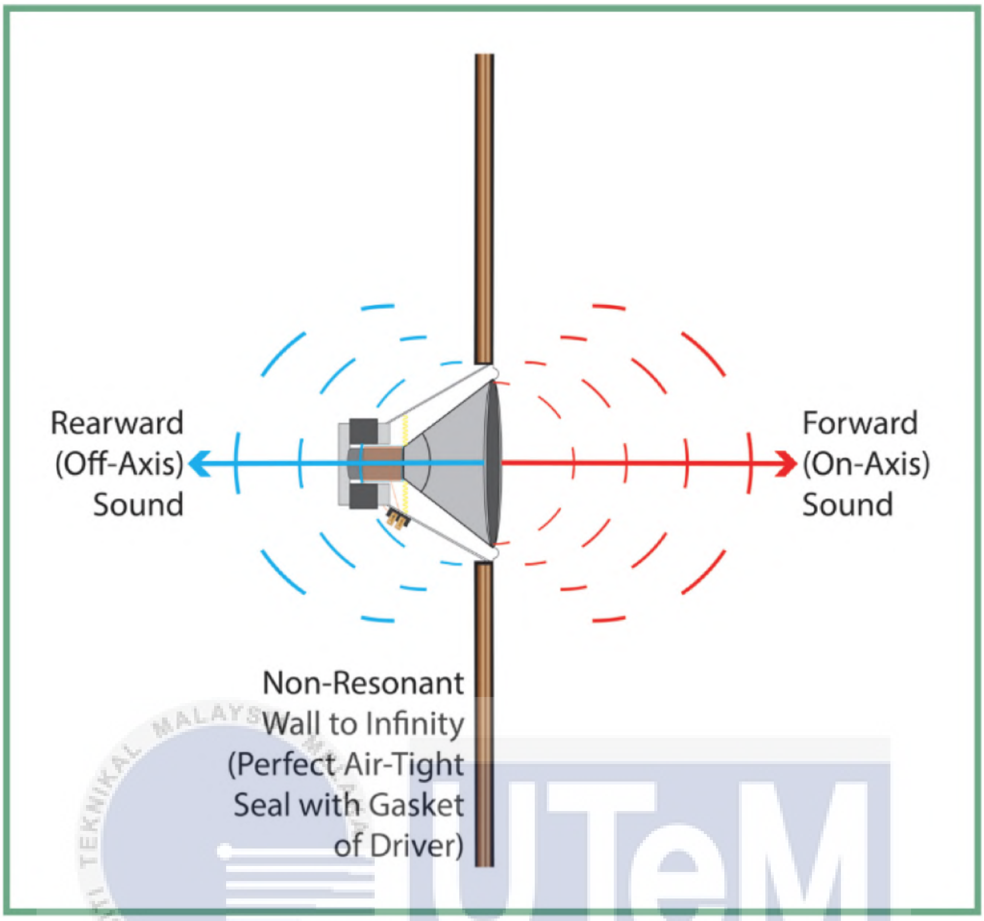


Figure 2-12Driver Set Into Infinite Wall (Loar, 2019)

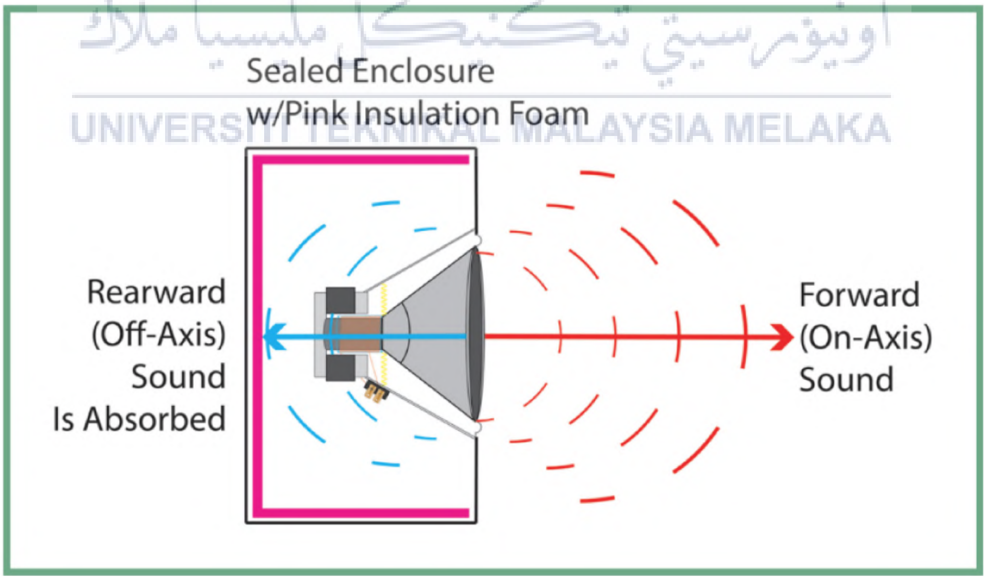


Figure 2-13An “Infinite Baffle” or Sealed Enclosure (Loar, 2019)

2.3.2.2 Ported/ Vented Enclosures

Ported/vented box (also known as "bass reflex" enclosures) are enclosures that have openings in them that allow sound to pass through. Since we've established that one of our primary goals in designing an enclosure is to prevent interference from the rear-facing side of our drivers, why would we then open our boxes back up, theoretically allowing such interference to take place? Generally speaking, the answer is improved bass quantity. The fact that ported or vented boxes are also referred to as "bass reflex" boxes, should clarify that the purpose of including a port or a vent in a speaker enclosure is to accentuate bass response by providing a tuned resonant opening that contributes to the overall sound. This is most commonly found in one of two speaker types: subwoofers, and in small enclosures that would otherwise have inadequate bass response if not for this technology (such as very small nearfield mixing monitors). A "ported" speaker is one with a round opening in the back, while a "vented" box has an opening in the shape of a slot. While the terms are sometimes used interchangeably, technically, they are not the same. Helmholtz resonance (the same principle that allows you to tune the note you hear when blowing across the open mouth of a Coke bottle by changing the amount of liquid inside the volume) is used to tune these openings so that they are resonant at frequencies that add to the speaker's performance in a controlled and desired way, according to the design specifications. There is a decrease in phase performance in open enclosures of this type, particularly at low frequencies where the ports/vents are intended to accentuate. But because the human hearing is less sensitive to phase issues in low frequencies than it is in high frequencies, the trade-off is frequently deemed worthwhile in exchange for the additional bass response provided (Loar, 2019).

2.3.2.3 Passive Radiator

In a passive radiator enclosure, there is a primary active driver and a secondary passive driver that is not connected to the amplifier power and only exists to be vibrated by the pressure waves generated by the primary driver. Because of the 'array effect,' these enclosures can improve bass response while also avoiding the necessity of drilling a hole in the enclosure itself. In the right circumstances, this type of enclosure system can both alleviate (though not completely eliminate) the phase issues that are inherent in ported/vented designs, as well as avoid another problem that some poorly designed ported boxes experience, which is a kind of "whistling" of air through the opening at high sound pressure levels (also referred to as "port chuffing"). However, extensive calibration is required to ensure that the passive radiator resonates as desired, and the additional cost of the additional driver can be prohibitively expensive in some instances. Despite the fact that this is not a particularly common design type in live production speakers, it can still be found on occasion (Loar, 2019).

2.3.2.4 Dipole

Dipole enclosures don't actually close all the way. Fundamentally, the idea is to fit a driver into a small fascia, which reduces (though does not completely eliminate) front-back interference while also radiating sound both forward and backward. When it comes to theatrical sound effects systems, true dipoles are occasionally employed, particularly in smaller venues where space is limited and the ability to splash sound in two directions is desired. A natural dipole, most ribbon-driver speakers (as well as most ribbon microphones) are used in situations where a speaker needs to be concealed in a small amount of space. It is important to note that the majority of speakers sold as "dipoles" are not actually true dipoles, but rather dual-sided speakers designed for use as extremely wide-coverage cinema surrounds. A version of this type of "dipole" is depicted in Figure 2.3.2-4, which does not literally throw sound in two 180° opposed directions, but does have two main axes of coverage (Loar, 2019).

Figure 2-14Klipsch RP-250-S (Loar, 2019)

2.3.2.5 Horn Loaded

Horn-loaded (Figure 2.3.2-5): one of the most iconic images associated with sound production is that of speaker horns. A horn is a waveguide that is most frequently used with high-frequency drivers (though it is also found in specific shapes with low-frequency drivers). This is a physical object that directs acoustic sound along a predetermined path. The mechanism of the horn is quite simple to comprehend. The driver, which is frequently a dome-shaped tweeter, is housed in a compression chamber. This is generally equivalent to a sealed basket, but there are numerous variations. In any case, the chamber assists in directing the sound forward. The driver is connected to the horn's narrow end, referred to as the horn's throat. The throat contributes to the build-up of acoustic impedance. This means that, as a result of the narrow opening, there is a greater amount of air pressure in the throat than on either side (the throat itself being inflexible). As the driver forces sound into the throat, the impedance creates an obstacle that must be overcome with additional force. This additional force causes the sound to flare out along the waveguide's sides, spreading evenly before exiting the horn's wide mouth. By forcing sound through the obstacle, the lower pressure creates a void for the sound to fill, and because pressures seek equilibrium, sound naturally follows the shape of the horn. It is quite common for speakers to have one driver equipped with a horn (typically a high-frequency driver) and one or more without.

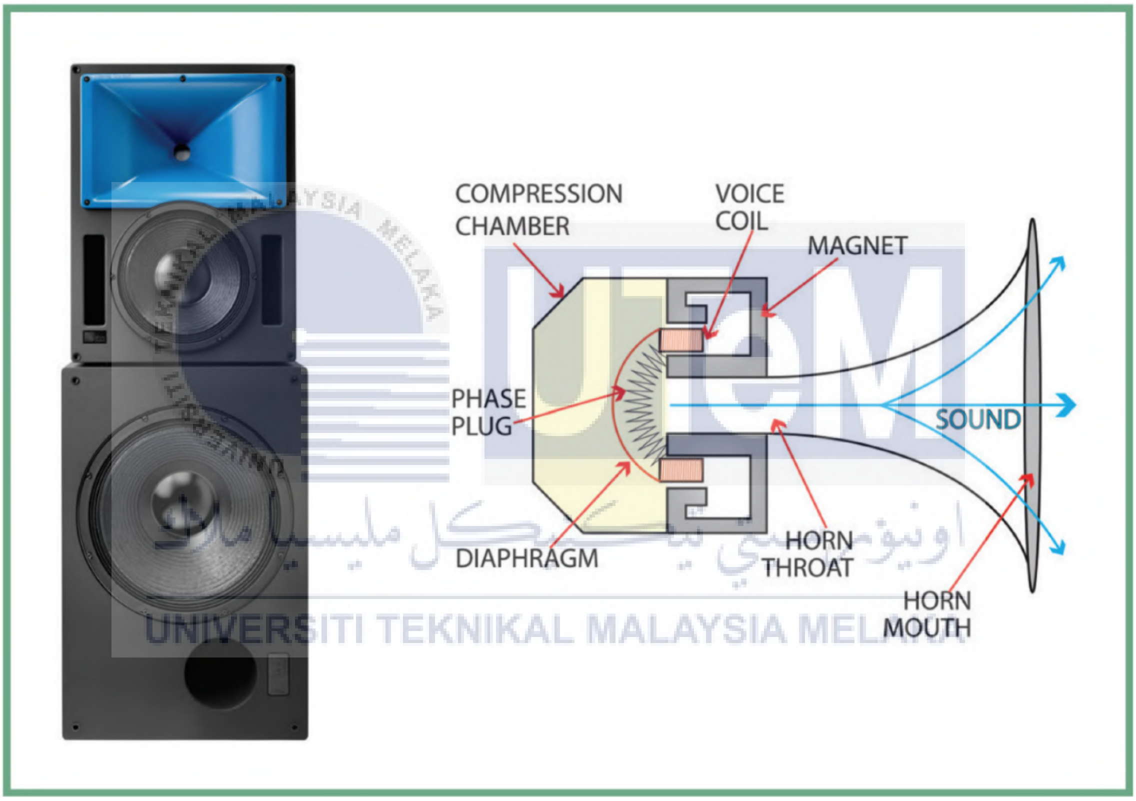


Figure 2-15(Left) Meyer Bluehorn System; (Right) Cross-section Diagram of Horn-Loaded Compression Driver with Parts Labelled (Loar, 2019)

2.3.2.6 Transmission Line

A transmission line enclosure is one that incorporates intricate maze-like chambers and an abundance of absorptive materials with the ultimate goal of completely absorbing rear-driver sound radiation. In a so-called perfect transmission line, the mazing behind the driver is infinite, which allows for complete attenuation of rear-facing sound (when sound energy is absorbed, it is mostly converted to heat/friction, which dissipates inaudibly in the air). As with the infinite baffle, the infinite transmission line is not a practical reality; therefore, enclosures are designed with a sufficient amount of line to significantly reduce noise. In these enclosures, care must be taken not to overfill the transmission line with absorptive material, as this can result in a higher pressure than the driver generates and actually induce acoustic backflow across the driver, resulting in phase/timing distortion.

2.3.3 Crossover

Crossover's are a type of electronic device that take a single audio signal and divide it into two or more output signals that are separated by frequency range and then sent to speakers or drivers that are designed to handle the specific frequency ranges.

As an example, crossovers can be found in speakers, where they are used to send a single signal divided into high and low-frequency bands to tweeters and woofers, as well as in digital signal processing (DSP), where they are used to send a single signal divided into high/mid frequencies and low frequencies to top speakers and subwoofers. In any speaker that features more than one driver, especially where those drivers are designed to handle different frequency ranges, it is common to find a crossover.

Speaker crossovers in passive speakers are designed to receive an amplified signal at the speaker level and divide it into two or more frequency bands, ensuring that no driver is exposed to frequencies it is not designed to handle. Speakers are frequently designed with two-way crossovers (separated into highs and lows), but they can be three-way or higher (some mastering studios, for example, use five-way speakers). A crossover's electronic design can have a significant effect on the sound of a speaker (Loar, 2019).

2.3.4 Frequency Response

The frequency response range of a speaker is a measurement of the wide range of sounds it can reproduce. The human ear can discern frequencies ranging from 20 to 20,000 Hz. The lower the number, the more lower the tone, and vice versa. The majority of speakers are capable of responding between 45 and 20,000 Hz. However, just because a speaker can cover a specified frequency range does not guarantee that it will deliver high-quality sound at every frequency (Hill, 2019).

The degree to which a speaker deviates from "flat" can be a useful indicator of its performance. This is specified as a "+/- x dB." The less variance there is, the more flat, or accurate, a speaker's response will be. Variances typically range between +/-.5 dB and +/- 3 dB, with the lower figure typically defining the frequency extremes. That is, a speaker with a published frequency response of 50-25 kHz, plus or minus 3 dB, will be -3 dB below "flat" at 50 Hz and 25 kHz. This is not to say that information below 50 Hz will not be audible; rather, it means that the drop-off after that point may be abrupt (Hill, 2019).

2.3.5 Resonance

Resonance is a system's or component's strong tendency to oscillate or continue vibrating at certain frequencies more than others. Depending on the enclosure type, it plays a critical role as it regularly establishes the low-frequency limits of the combined driver and enclosure. Most loudspeakers are inefficient machines, and a critical decision is to operate them in the mass-controlled range with a conventional cone (Hill, 2019).

2.3.6 Damping

The primary effect of damping in a loudspeaker is to reduce the SPL generated by the diaphragm moving due to its own inertia after the signal has ceased. The frequency of the sound produced by this movement will be the same as the moving system's resonant frequency. This is referred to as "overhang," and in severe cases, it can be translated as "one note bass."

There are two types of loudspeaker damping: mechanical and electrical. The loudspeaker's suspension and the air load on the diaphragm determines the amount of mechanical damping. This cannot be determined except by sophisticated measurements. Electrical damping is determined by the resistance load on the loudspeaker, which is the sum of the loudspeaker cable resistance and the amplifier output impedance. This can be determined by a simple calculation. Electrical damping or Damping Factor (DF) is calculated by dividing the loudspeaker's voice coil DC resistance by the sum of the loudspeaker cable resistance and amplifier output impedance (Hill, 2019).

2.3.7 Mass Loading

The moving mass of a speaker consists of the physical moving parts plus the air load on the diaphragm. For instance, mounting a driver on a horn allows the driver to effectively "grab" more nearby air more efficiently. Mass loading is also a key metric in cabinet design where choosing the dimensions and weight of a cabinet is influenced by the mass loading properties of a specific driver. A cabinet generally will need to be larger or heavier or both to compensate for a larger driver with a higher moving mass and mass load. The position of the driver relative to its cabinet is also influenced by the mass loading properties of a driver. A simple example where we can see this in action is in a 2 - way driver speaker that has a woofer and a tweeter. The woofer, being the larger speaker with higher mass loading is almost always positioned below the tweeter. This is to create more stability and reduce rocking motion that would cause unwanted vibration when a speaker is set up on a surface.

For further clarification, this happens because the center of gravity as well as the moving mass load of the speaker is lowered.

2.4 Furniture

The term "furniture" refers to movable objects that are designed to support a variety of human activities, including seating (e.g., stools, chairs, and sofas), eating (tables), storing items, eating and/or working with an item, and sleeping. Examples of furniture include stools, chairs, and sofas (e.g., beds and hammocks). As horizontal surfaces elevated off the ground, such as tables and desks, furniture can also be used to hold things at a height that is more conducive to work, and it can also be used to store things (e.g., cupboards, shelves, and drawers). It's possible to think of furniture as a form of decorative art and as a product of design at the same time. It is possible for certain pieces of furniture to have religious or symbolic significance in addition to their practical use. It is possible to construct it out of an extremely diverse range of materials, including wood, metal, and plastic. A wide variety of woodworking joints can be used to construct furniture, and these joints frequently reflect the cultural traditions of the region in which the piece is made (Hylton, 2010).

2.5 Furniture Design

Industrial design for volume and mass production is a primary focus of furniture design for the simple reason that nearly all furniture designers work in this field. Along with sound reasoning and creativity, designers require an understanding of materials and manufacturing parameters to communicate effectively with engineers and, ultimately, to produce designs that meet a client's brief and budget.

Design briefs and their supporting research fall somewhere between developing an innovative new paradigm and reinterpreting an established design standard, i.e., the development of an existing design or product type. The vast majority of design briefs requires a designer to strike a balance between creative freedom and well-defined functional, aesthetic, manufacturing, and cost constraints. While selecting a material or manufacturing process can be a rational and objective exercise, there are almost always multiple ways to achieve a desired form, structure, or aesthetic, as well as cost savings or improved interaction (Lawson, 2013).

2.5.1 Ergonomics

Ergonomics, also known as human factors, is the study and evaluation of usability and how people successfully or unsuccessfully interact with an environment or the objects within it. This usually refers to work, but any task or action is relevant to ergonomic research. Good ergonomic design aims to improve the physical experience of interacting with objects and environments by reducing the effort required, as well as the fatigue or injury caused by such interactions.

A variety of assessments are used to determine good ergonomics within environments, such as efficient working triangles in kitchens and the layout of office workspaces. Ergonomics can also refer to the comfort, adjustability, and appropriateness of a tasking chair, taking into account details such as air circulation through the backrest or the user's interaction with the adjustment control knobs(Lawson, 2013).

2.5.2 Concept Development

Taking a furniture concept from a sketch to a marketable concept poses significant challenges for both designers and the industry. Dynamic concept sketches and sophisticated renders must be accompanied by thoroughly researched manufacturing specifications and precise technical definition. To fulfill this often-complex role, designers must possess a wide range of skills as well as a wealth of detailed and peripheral knowledge.

Between the start and finish of any project, there is an intense process of optimization that can result in outcome-driven innovation. This rational development process also necessitates lateral thinking and compromise, putting even the most experienced designers to the test, because improving a design's function, aesthetics, ergonomics, or manufacturing rationale can undermine other previously well-thought-through attributes. The resulting machinations may result in a drawn-out process with more side steps than forward movement, but it is through such beneficial efforts that good design thrives (Lawson, 2013).

2.5.2.1 Concept Sketching

Free sketch drawings, which are a record of thoughts, potential, and a means of rationalising and furthering ideas, should be the designer's first recourse for concept origination and development. Initial sketches do not need to be to scale, have the correct perspective, or be very polished, but as the idea development process progresses, there is an exponential need for accuracy in these drawings in order for the potential of a concept to be assessed. (Lawson, 2013)

Drawings that are inaccurate can make the impossible appear possible, the mundane appear interesting, and the ugly appear beautiful. However, there is a catch: drawing is, by definition, interpretive and imprecise.

As a result, its inaccuracies can be usefully ambiguous to a designer, facilitating innovation by suggesting previously unthought-of constructions, materials, and aesthetics.

Although the line between concept sketches and presentation drawings is blurred, first sketches depict an idea, a note to oneself – possibly with annotations describing function, precise details, materials, or manufacturing processes. Drawings increasingly illustrate what is known as the idea is rationalised and turned into a concept, gradually becoming more accurate descriptions or presentations of a whole idea. However, as the saying goes, the devil is in the details, and what appears to unskilled observers to be a clear first concept at this stage is actually just the first step on the long journey of product development, resolution, and manufacture (Lawson, 2013).

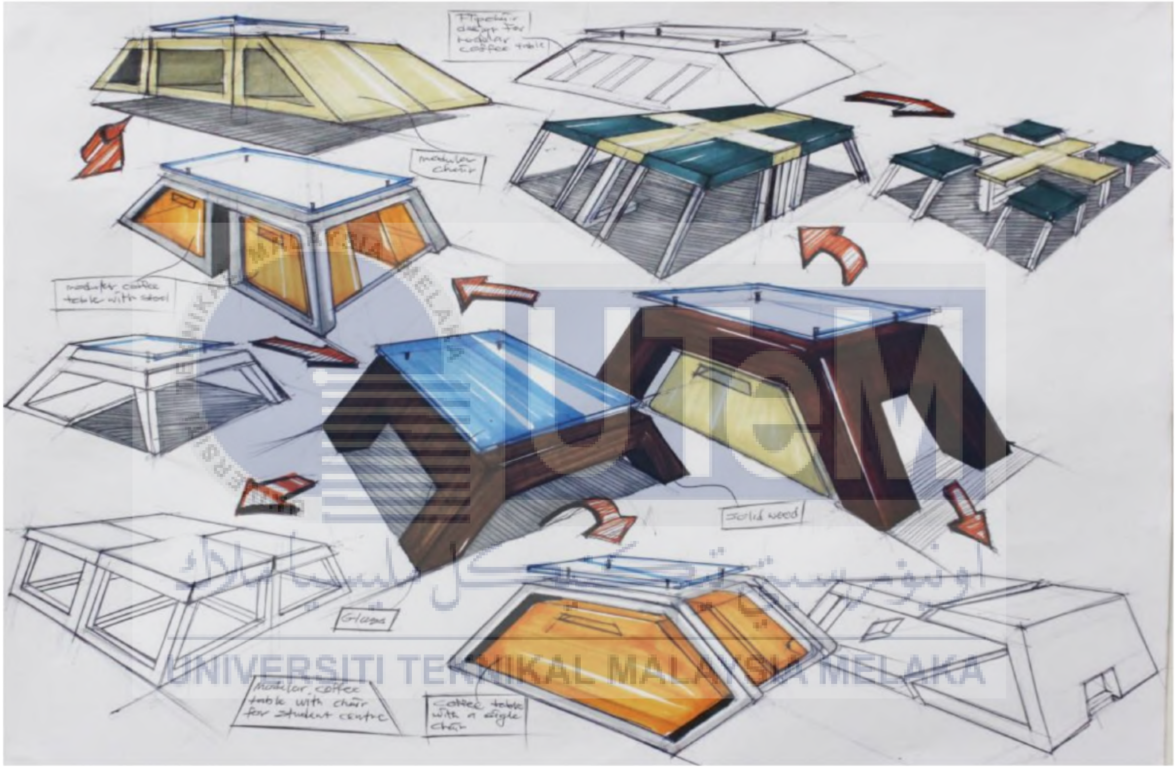


Figure 2-16Concept Sketches of Coffee Table (Fikri et al., 2018)

2.5.2.2 CAD-modelling software

Even though computer-aided design (CAD) drafting and 3-D modelling software provide designers with extremely powerful definition and presentation tools, they are not a complete solution. CAD tools work best when used in conjunction with other design tools, such as drawing, physical modelling, and prototyping. A large majority of 2-D and 3-D software can generate files for CNC (computer numerical control) routing, laser cutting, and other applications (Lawson, 2013).

2.5.2.3 Prototyping and Testing

Proofreading a concept can be accomplished through the use of test rigs, prototypes, visual models, and the subsequent detailed analysis of material and structural performance, as well as user interaction. Designers should expect to run into problems and even significant flaws during this type of rigorous investigation, and it would be foolish to consider a concept to be a finished design until it has been thoroughly tested and proven to be so. While it is true that a product designed by a designer who is familiar with a furniture type and the materials proposed should not require significant testing, any designer who is pushing the boundaries of their ability and knowledge, whether they are students or seasoned professionals, will be required to model and test their ideas before moving forward.

With the advent of rapid prototyping (RP), which includes both additive and subtractive processes, as well as accessible finite element analysis (FEA), the prototyping and testing of plastic and metal components has become significantly less difficult to accomplish. As a result of such opportunities, a world populated by furniture that performs exceptionally well should emerge. Unfortunately, as a result of the high costs of RP in relation to the size of the prototype built and the lack of quality control in the manufacturing process, there is a large amount of furniture available that is not fit for its intended use.

The potential of a concept can be communicated through sketching, but such drawings lack the definition necessary to be considered a "design." Additionally, computer-aided design (CAD) modelling can give the impression of a finished concept with little more detail defined than in a sketch. In order for a concept to be developed into a finished, manufacturing-ready design, its structure, ergonomics, and aesthetics must be tested and assessed using a series of related rigs, models, interactions, and software-based analysis; there is no single prototype that can be used to test and assess all of these aspects of the design (Ulrich et al., 2020).

2.6 Materials

A variety of material groups can be explored for furniture design such as metals, plastics, wood and other rare materials such as structural fabrics. This project requires a material suitable for both acoustic design and furniture design purposes. The only material that has wide compatibility with both designs is wood. Therefore, the scope of this project we will only focus on wood materials due to its balance of stiffness and damping as well as it being widely and primarily used in both furniture and speaker design.

2.6.1 Wood

When it comes to grain and colour, wood is unlike any other material. It is renewable, its strength-to-weight ratio can outperform steel, it has useful elastic properties, and it feels warm to the touch. Wood can be used in a variety of applications. Hardwood and softwood tree species exhibit a wide range of material properties; within each genus, each piece of wood exhibits distinct variations in performance and aesthetics, some of which are useful and desirable and others which are not so much. However, despite the fact that wood was the first furniture-making material used, wooden furniture does not have to be traditional in style. In fact, when sourced responsibly and used as a renewable resource, wood and wood fibre can play important roles in contemporary design and the development of a more sustainable future (Lawson, 2013).

2.6.2 Board Materials and Engineered Woods

In order to combat the inherent instability and inconsistency of solid timbers, man-made boards were developed, allowing much larger surface areas to be covered with a single stable component, rather than multiple unstable components. While the origins of plywood can be traced back to the ancient Egyptians, it was not until the Industrial Revolution that laminated materials began to be used in a wide variety of applications. The sophisticated production of plywood did not begin in earnest until the inter-war period, when advancements in glue technologies and forming processes made it possible to produce sheet materials and 3-D laminated forms in large quantities with consistency and repeatability.

Compared to solid wood, veneered man-made boards (substrates) account for a significant portion of the materials used by wooden furniture manufacturers. This is primarily due to the fact that they can be processed at a significantly lower cost in terms of both material and labour than solid wood. In addition, man-made boards are simple to store and dimension, and their standardisation within the construction industry allows for the systemization of construction processes to be achieved. The use of urea-formaldehyde glues in sheet-material manufacturing will eventually be phased out due to their contribution to volatile organic compound (VOC) emissions, which are harmful to both human and environmental health. Larger and smaller sheet sizes are available upon request for man-made boards, with the standard sheet size being 1220mm x 2440mm (48 x 96.1in).

2.6.2.1 Plywood

Plywood is a stable board that, while not as rigid as solid wood, does not split or warp significantly. It is made up of multiple layers of constructional veneers in a variety of thicknesses, which are most commonly laid perpendicular to each other. In order to balance the stresses within a board, the number of plies is usually an odd number (which means that the board is equally stiff in each direction); however, four and six plies are also used for structural applications where unequal rigidity in each direction is required, such as in bridge construction.

Manufacturers use a coding system to describe the quality and type of wood veneers used in their products, as well as whether the adhesives used to bond the plies are suitable for use in outdoor or damp interior applications, according to the manufacturer's specifications. The quality of a board's ply cores is graded by the manufacturer on a scale from A to D, with A being the highest quality. A grade is also assigned to each type of board to indicate the quality of its surface plies: A represents the best surface available; B represents minor defects; BB represents more defects; and WG and X represent increasing amounts of plugged knots and other surface defects. Such low-grade boards, on the other hand, are still used in the furniture manufacturing industry for the upholstery carcasses. Boards have either two exterior veneers of the same quality or one face that is superior to the other in terms of quality. As a result, surface grades for a single board can be different, for example, 'A–B' or 'B–BB', depending on the manufacturer.

Drawer-side plywood has all of its ply grains running in the same direction, producing a strength that is comparable to solid wood while also being more stable than solid wood. Drawer-side ply, as the name implies, is used in the construction of drawers and other applications where the majority of the strength is required in a single direction.

The use of flexible (bendy) plywood in furniture, joinery, and shop fitting allows for the creation of tight curves and flowing forms. It is possible to achieve extremely tight radii by using flexible ply because of the way it is constructed. However, while its flexibility can become a weakness in one direction, sheets are rigid in the opposite direction. 3, 5, 8, 12 and 16mm (0.1, 0.2, 0.3, 0.5, and 0.6in) are the most commonly available thicknesses, and the most commonly available sheet sizes are 2500 x 1220mm (98.4 x 48in), 3120 x 1850mm

(122.8 x 72.8in), and 2820 x 2070mm (2820mm by 2070mm) (111 x 81.5in). Depending on its width ('barrel wrap') or length ('column wrap'), this type of plywood can be wrapped either widthways or lengthways. A bending radius's tightness is dependent on the thickness of the sheet, but it is possible to bend a 5mm-thick (0.2in) sheet around a 5mm radius (0.2in) if the sheet is applied carefully and with proper support.

The most common type of multi-ply is made from birch plies that are 1mm thick (0.04in). In addition to its stability (it has an odd number of veneers) and the appearance of its edge grain, this high-priced, high-quality material was chosen because it is durable. For veneering or for clear finishing, it is best used in conjunction with an A- or B-grade surface or both.

Aero-ply is also a very high-quality birch ply that is made up of very thin plies and is manufactured from birch ply. Surface-finished boards are available in thicknesses ranging from 0.4mm to 12mm (0.02–0.5in) and are constructed from a minimum of three ultra-thin plies to achieve the desired thickness. Such plywoods are typically used for model-making, lighting, household products, and aircraft, but they can also be used to create thicker laminations (this is an expensive approach, but it can be justified in some cases for one-offs or low-volume production) (Lawson, 2013).

2.6.2.2 Blockboard and Laminboard (Lumberboard)

Although similar to plywood, they are constructed from a solid wood core with a plywood outer skin, rather than from successive layers of veneers as is the case with conventional plywood. This provides significantly greater rigidity and stability than plywood, making it particularly well suited for use as load-bearing surfaces such as shelving. However, because of their higher cost, they are less frequently used than MDF or plywood.

Blockboard's construction allows movement in the timber substrate to show through on a veneered surface, making it unsuitable for high-quality manufacturing. Laminboard, on the other hand, is more suitable for high-quality manufacturing. The core of a blockboard is made up of softwood or hardwood strips that are laid flat and oriented in the same direction as the board's thickness (typically twice the width of their thickness). Some of these timber strips are long enough to run the length of a board, but the majority are shorter lengths that have been butted together. In the core of a laminboard are a number of thin (typically softwood) strips of timber that are laid on their edges and all oriented in the same direction.

2.6.2.3 Fibreboard (MDF)

This is made from reconstituted wood fibre that has been either dry-mixed with adhesive (MDF) or wet-mixed without adhesive (MDF) and then pressed into sheets of various sizes.

Medium density fibreboard (MDF) was introduced in the 1970s and has since revolutionized the furniture and joinery construction industries, not least because of its superior stability and surface quality when compared to plywood. However, because of the lower density of MDF's core, sealing and finishing the machined edge surface is difficult and requires several more coats of sealant varnish, lacquer or paint than the board's surface. MDF can also be edge-molded. MDF is also an excellent substrate for wood veneers and surface laminates, and it is relatively inexpensive.

Hardboards have surface characteristics similar to MDF, but they are weaker due to the absence of adhesive resins in their manufacturing. Wood fibres and naturally occurring wood resins come together under the influence of heat and pressure to form sheet materials that have either one or two smooth surfaces on one or both surfaces (Lawson, 2013).

2.6.2.4 Particle board

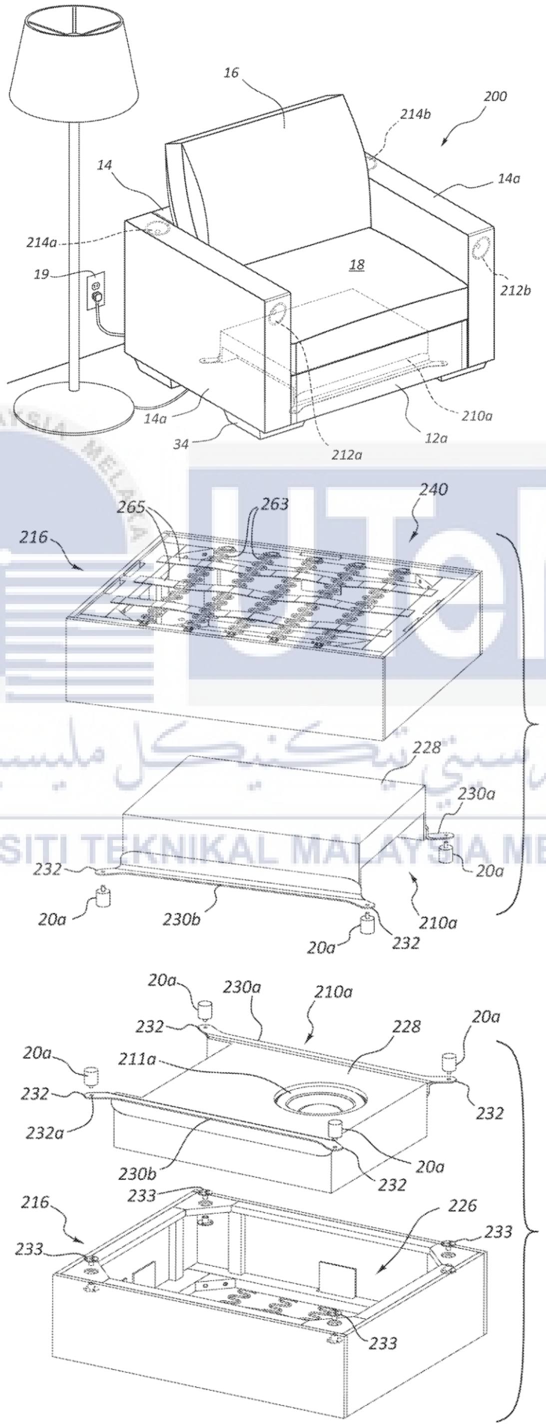
Particle boards are made by combining different grades of wood chips or flakes with adhesives and compressing the mixture. These products are made from softwoods and hardwoods. A growing amount of waste timber, both from factory waste and recycled timber product waste, is also used in their production. Compared to plywood, blockboard, and MDF (medium density fiberboard), particle boards are less expensive but also less durable. Because of their generally unappealing surface qualities, oriented strand board (OSB) and flakeboard are typically used concealed within construction, although they are increasingly being used exposed within architecture.

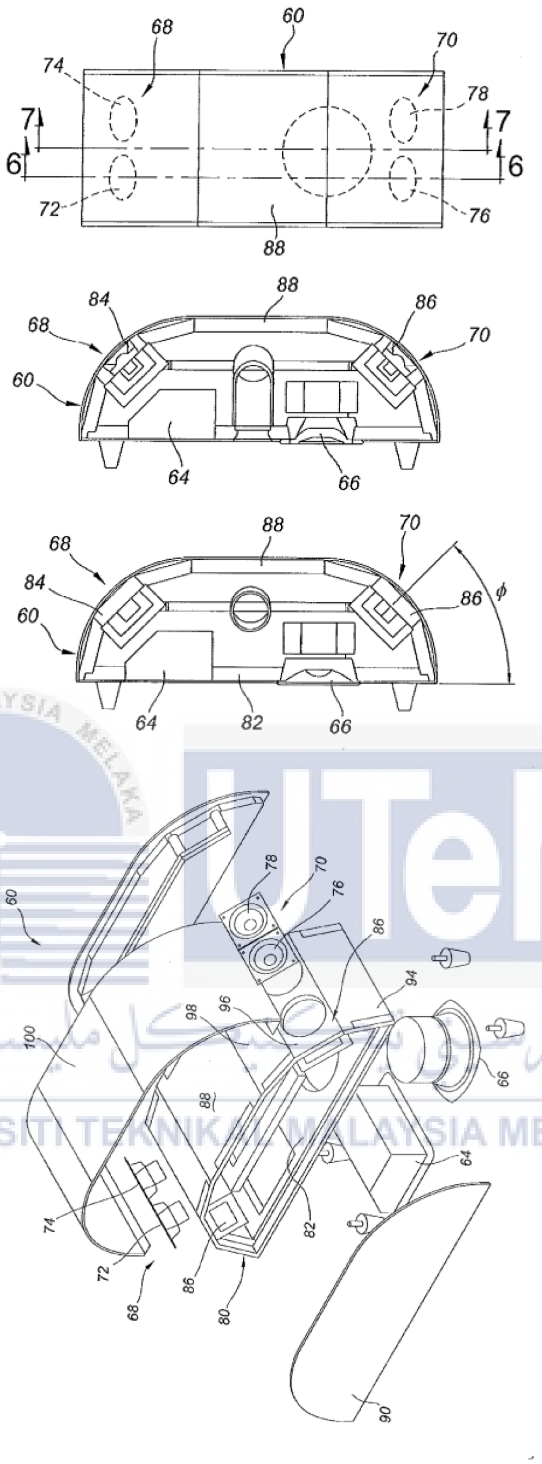
In terms of particle board types, chipboards are the most common, and they are available in a variety of qualities: standard quality single-layer chipboard has an even distribution of similarly sized wood chips throughout its thickness; higher quality three-layer chipboard is manufactured with a coarse-chipped core sandwiched between two layers of finely chipped particles; and composite particle boards are made of chipboard and particle board composites. Thin melamine foils applied as a veneer on three-layer chipboard are the most suitable for this application, whereas single-layer chipboard is the best choice for surfacing with thicker, high-pressure laminates.

Oriented strand board (OSB) and flakeboard are wood products that are intended for use in the construction industry and architectural interiors rather than in the production of furniture. However, when sanded, stained, or finished, their grain structure creates a distinct and interesting visual aesthetic that is worth noting (Lawson, 2013).

2.7 Patents

Table 2-1 Related Patents

No	Patent Number, Title, Date, Hyperlink	Image/ Structure	Similar	Difference
1	US20220060829A1, Electronic Furniture Assembly with Intergrated Internal Speaker System Inlcuding Downward Oriented Speaker Patent, 24/2/2022, https://www.patentguru.com/US2022060829A1. (S. Nelson et al., 2022)		The product combines a type of furniture with loudspeakers	The design does not focus on acoustic quality rather only seeks to implement loudspeakers as a means to hide them in a room.

2	US20120121092A1, Single Enclosure Surround Sound Loudspeaker System and Method, 17/5/2012, https://patents.google.com/patent/US20120121092. (Starobin, 2012)		Attempts to save space in a room by producing a solution that combines multiple loudspeakers that are usually spread out in surround setup into a single unit that appears like furniture	Does not involve combining loudspeakers with any known type of functional furniture

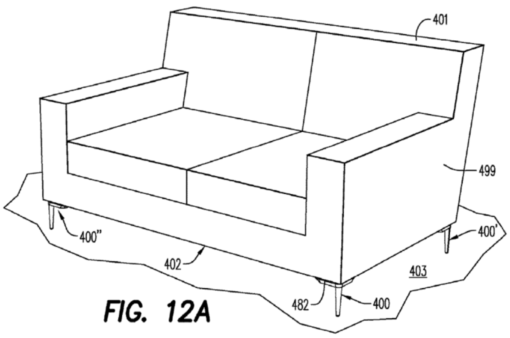
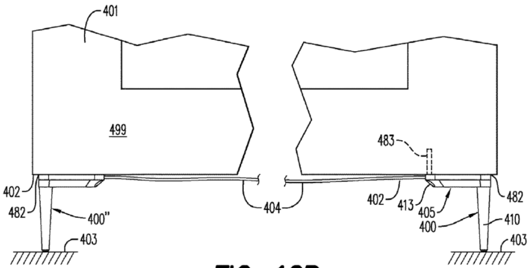
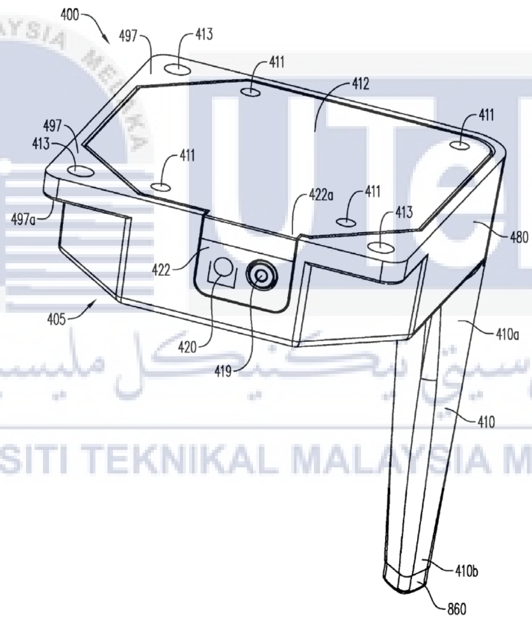
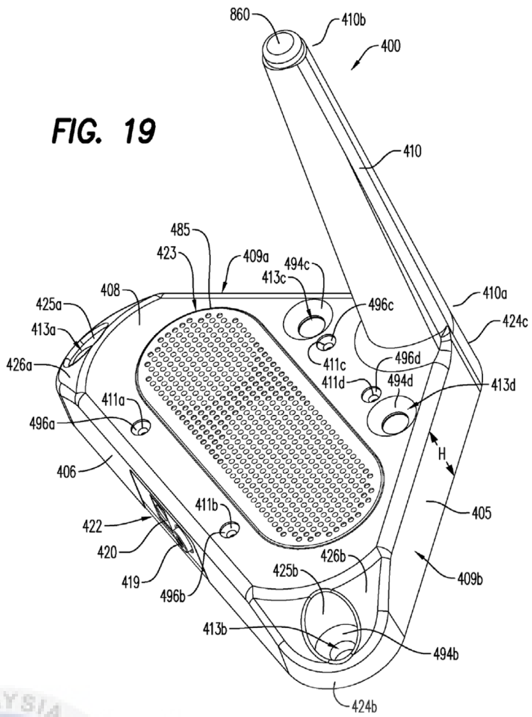
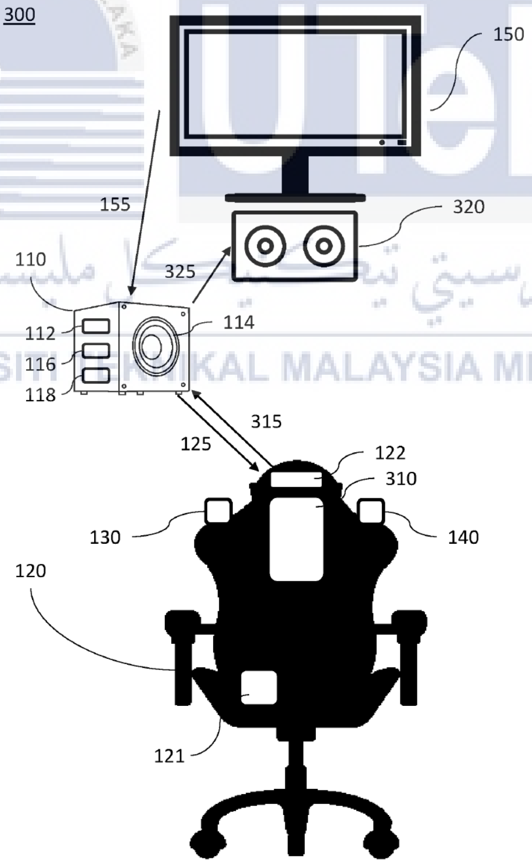
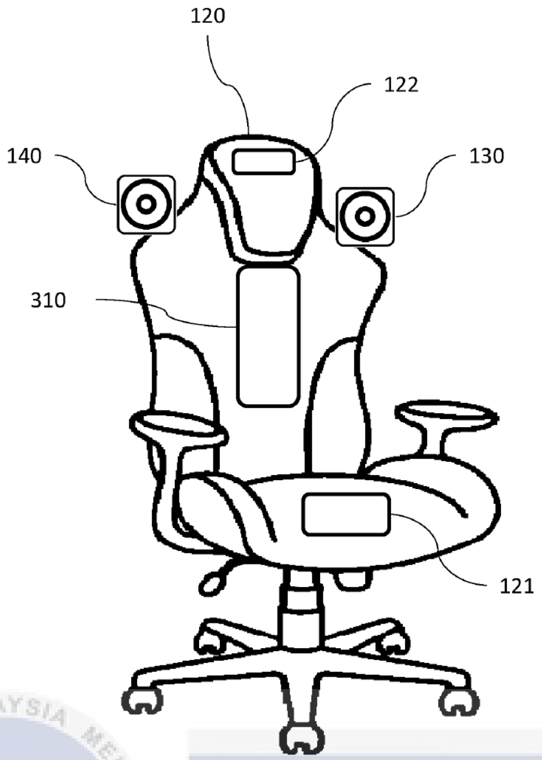
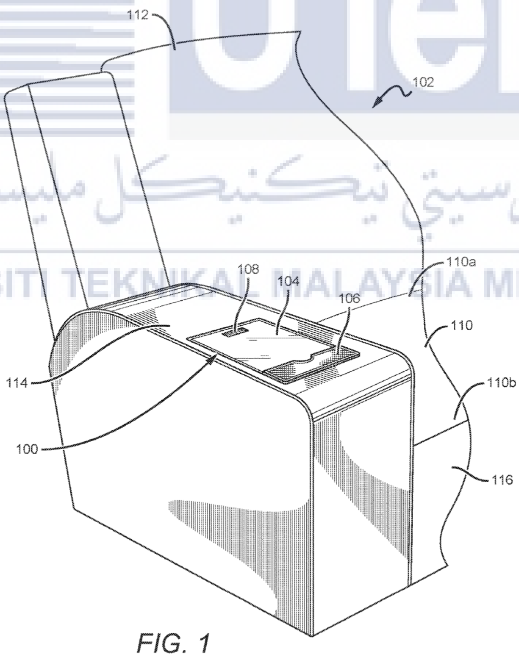
3	US11631405B2, Supporting Audio Element With Voice Recognition For A Furniture Item, 18/4/2023, <u>https://www.patentguru.com/US11631405B2</u>. (Tang, 2023)	 FIG. 12A  FIG. 12B  FIG. 13	Implements a loudspeaker into a furniture.	The implementation does not concern itself with sound quality and is only used to provide speech feedback to the user.

		FIG. 19 		
4	US11641945B2, Chair system with an untethered chair with speakers, 9/5/2023, <u>Chair system with an untethered chair with speakers - US11641945B2 | PatentGuru</u>. (Sim, 2023)	 FIGURE 3	Implements multiple loudspeakers into a functional furniture.	The implementation does not focus on sound quality or vibration control. The aim of this patent is simply exploring new ways of innovating computer chairs.

		 FIGURE 4		
5	US11779116B2, Control panel for furniture and home entertainment system, 10/10/2023, <u>Control panel for furniture and home entertainment system - US11779116B2 | PatentGuru</u>. (Rafieha, 2023)	 FIG. 1	Implements a speaker on a functional furniture.	Aims to expand the function of a sofa by adding an entertainment console and does not focus on sound quality or hiding loudspeakers in furniture.

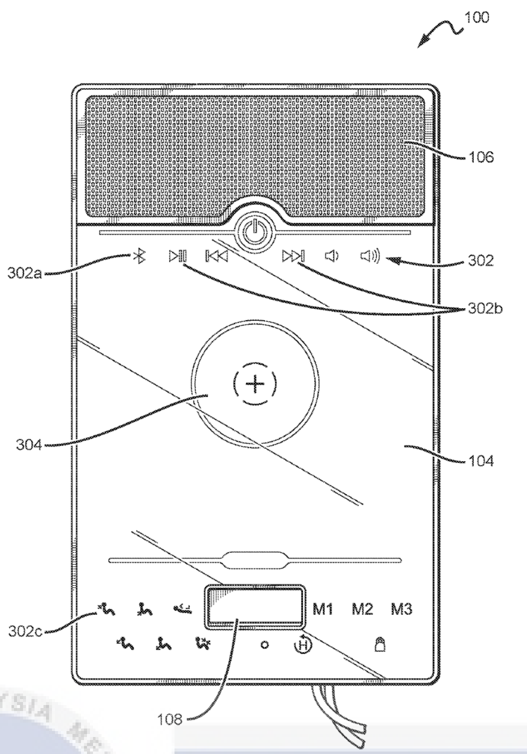
<table>
<tr><td></td><td></td><td>

FIG. 4</td><td></td><td></td></tr>
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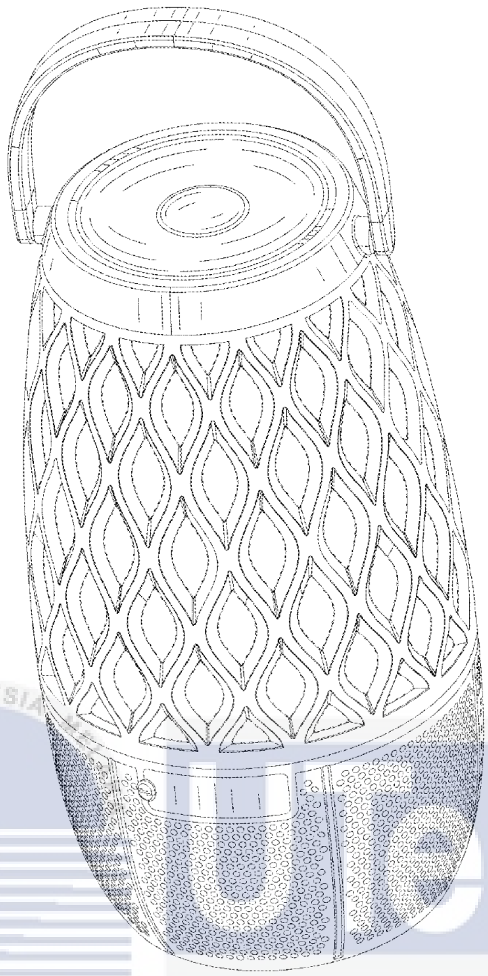
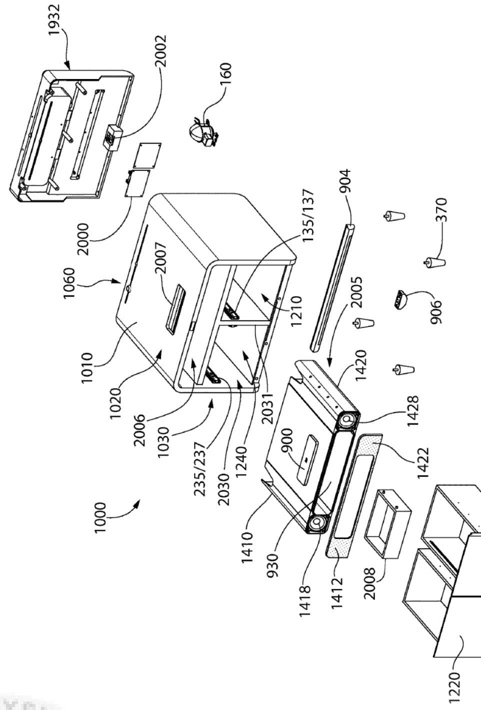
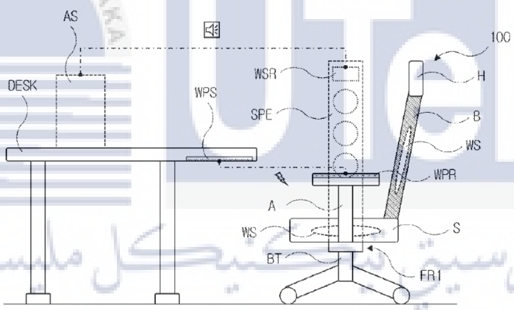
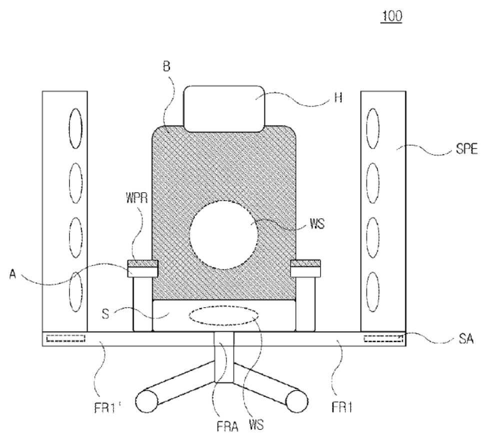
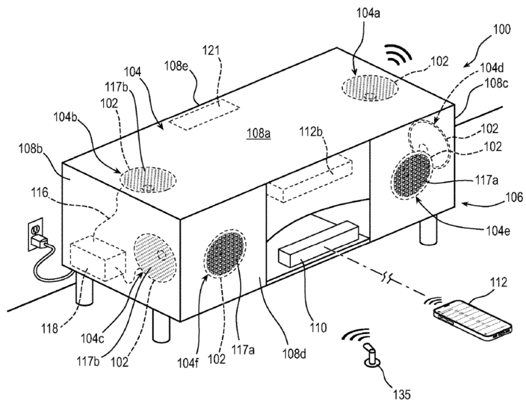
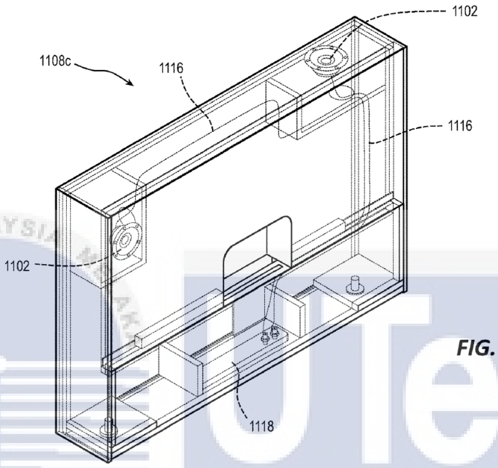
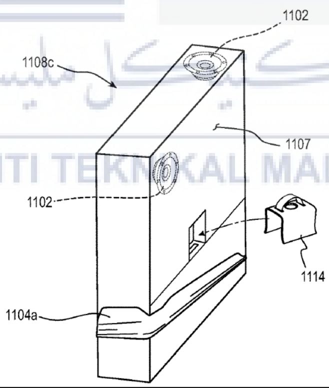
6	USD0997411S1, Speaker lamp, 29/8/2023, Speaker lamp - USD0997411S1 | PatentGuru. (Zhong, 2023)	 FIG. 1	Implements a loudspeaker into a furniture product.	Is not concerned with sound quality or acoustic positioning within a room.

7	US20230090125A1, Multi-Function Table, 23/3/2023, [MULTI-FUNCTION TABLE - US20230090125A1 | PatentGuru](). (Dash, 2023)	 FIG. 16	Implements a loudspeaker into a furniture product.	The loudspeaker is treated as an afterthought and only serves to add functionality. The quality of the implementation is completely ignored.
8	US20230179918A1, Wireless Speaker Chair, 8/6/2023, [WIRELESS SPEAKER CHAIR - US20230179918A1 | PatentGuru](). (Park, 2023)	FIG. 1  FIG. 2 	Implements a loudspeaker into a furniture product.	The implementation does not focus on sound quality or vibration control. The aim of this patent is simply exploring new ways of innovating on computer chairs.

9	US20230209263A1, Systems And Methods For Correcting Sound Loss Through Partially Acoustically Transparent Materials, 29/6/2023, <u>US20230209263A1Patents | PatentGuru</u>. (S. U. D. K. B. G. C. Nelson, 2023)	 FIG. 1  FIG. 5C  FIG. 5D	Implements speakers into a furniture product. Focuses on sound quality and quality of implementation as well as positioning and materials.	Focuses entirely on implementation of acoustics in a furniture without consideration of any aspects of aesthetics or furniture design.

CHAPTER 3

METHODOLOGY

3.1 Product Development Process

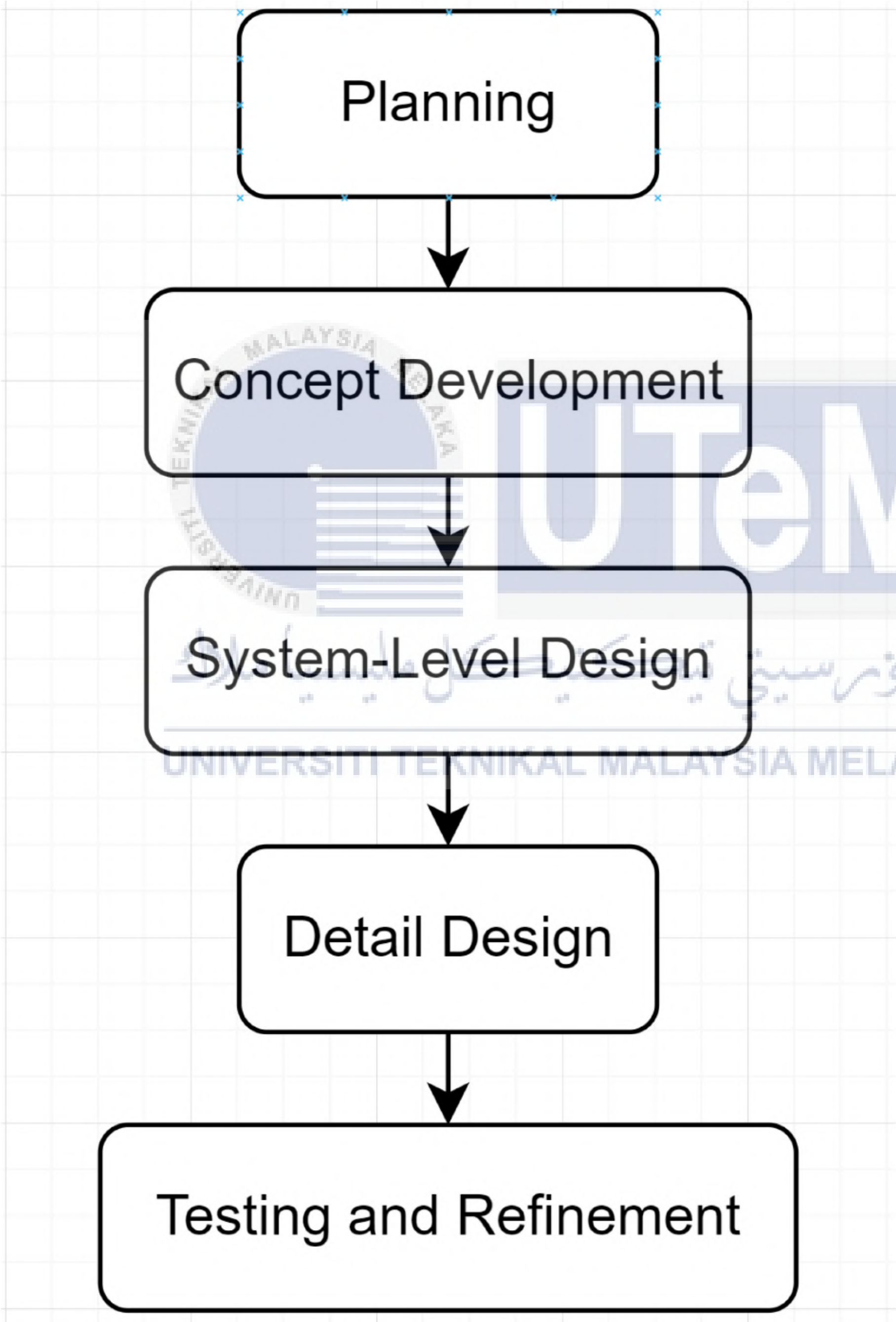


Figure 3-1 General Product Development Process

3.1.1 Planning

In this project the planning phase process involves selecting the type of furniture and loudspeaker that would be an ideal combination and will detail the reasoning behind the decision process and behind the choices made during this phase. Following the combination selection process, the design and acoustic performance requirements will be determined based on the Quality Function Deployment (QFD) process.

3.1.1.1 Quality Function Deployment (QFD)

A method for creating products that focus on the needs of the consumer is called Quality Function Deployment (QFD). The QFD planning process helps the company identify every problem by assisting in the right adoption of various technical support tools. The QFD method is a way to increase the quality of goods and services by figuring out what consumers want and then matching those demands with the technical requirements to produce goods or services at each stage of the production process (Ginting et al., 2020).

Quality Function Deployment is also a process that detects customer expectations and converts them into technical characteristics that can be understood and enhanced at all organizational and functional levels (Ginting et al., 2020). One of the central tools of the QFD process is called House of Quality (HOQ).

3.1.1.2 House of Quality (HOQ)

The House of Quality is a central tool of QFD, it translates customer requirements, market research and benchmarking data into prioritized engineering targets to be met by a new product design. A HOQ typically contains information on ‘‘what to do’’ (CRs), ‘‘how to do’’ (ECs), and relation measures between CRs and ECs (Kwong et. al, 2007). (CR) equates to a clear list of functions and subfunctions on important needs of the customer while (EC) equates to list of quantitative performance parameters and associated units.

House Of Quality (HOQ) consists of nine (9) types of rooms which include Customer Needs, Importance Rating, Competitive Analysis, Technical characteristics, Relationship Matrix, Importance Rating, Target Value, Engineering Analysis, and lastly Correlation Matrix.

3.1.2 Concept Development

This phase will involve experimental sketches intended to allow a free flow of ideas to be explored and create a few promising concepts that will be evaluated. The conceptual design phase lacks whole info and involves many uncertainties. Thus, a designer's perceptual decision must be made based on uncertain beliefs. For the concept selection process, the "weighted decision matrix method" will be employed (Ulrich et al., 2020).

3.1.2.1 Weighted Decision Matrix

The weighted decision matrix is an effective quantitative tool. It compares a set of options (such as ideas or projects) to a set of criteria that must be considered. It is also referred to as the "prioritisation matrix" and the "weighted scoring model." The method proceeds as follows:

1. List different choices

   All decision choices will be listed in rows. These rows form the foundation of the decision matrix.

2. Determine Influencing Criteria

   Criterias that will affect the decicion choices will be indentified, such as, acoustic performance, aesthetics, function and so on.

3. Rate the criteria

   The crieteria will be rated in the columns using a number (weight) to assess their importance and impact on the decision. A clear and consistent rating scale will be established for each one. This helps to calculate the relative importance of each criterion.

4. Rate each choice for each criterion

   Different choices will be evaluated againts the criteria. Each criterion will be rated, while using the same rating system.

5. Calculated weighted scores

6. Calculate total scores

7. Make decision

   Make a decision based on the concept with the highest score.

3.1.3 System – Level Design

In this phase, material choices for the furniture and parts for the loudspeaker system will be determined as well as necessary anthropometric data will be acquired for ergonomic design uses (Lawson, 2013). The decisions made in this level are informed choices from the understanding of the interplay of our chosen loudspeaker system parts and furniture materials with our chosen concept design and acoustic performance requirements as well ergonomic dimensional limits. For example, we cannot choose a driver that is too large and heavy for a smaller furniture type as we will run into problems with structural strength and vibration (Colloms & Darlington, 2018).

3.1.4 Detail Design

A CAD model will be developed with the use of CAE to further optimize the design. The CAD design process involves dimensioning and tolerancing which will be heavily aided by CAE where the ideal thickness of a given material and necessary structural design in the right places to achieve ideal strength and stiffness to weight ratio will be acquired through analysis of CAE results. The CAE software will also aid in determining ideal mass loading weight and position to combat the vibration from the loudspeaker driver as well as predict the primary resonance frequency of the design. This can be used to make necessary design changes to push any unwanted resonances below the audible frequency region. A back-and-forth trial and error process may occur between CAD design and CAE testing to finally arrive at an optimized design.

3.1.4.1 Computer Aided Engineering (CAE)

Computer-aided engineering relies heavily on computer-aided design (CAD) software, also known as CAE tools. Component and assembly robustness and performance are evaluated using CAE tools. CAE tools include simulation, validation, and optimization of manufacturing tools and products. CAE systems aim to be major information providers that aid design teams in making decisions. (Saracoglu & Gozlu, 2006)

3.1.5 Testing and Refinement

The refinement for this project will be done via performing a frequency sweep and observing unwanted vibrations on the furniture as well as listening for harsh peaks of loudness in specific frequencies and correcting both problems via DSP. The equipment used will include a PC and Equalizer APO Software with Fab Filter Pro Q2 plugin. The last software in the given equipment description above is a DSP used to develop a frequency response compensation EQ file that will correct excess vibrations caused by the speaker system of our product. Finally, a usability test will be done via a modified SUS (System Usability Scale) survey.

3.1.6 Expected Planning to Prototype Detailed Flow Chart

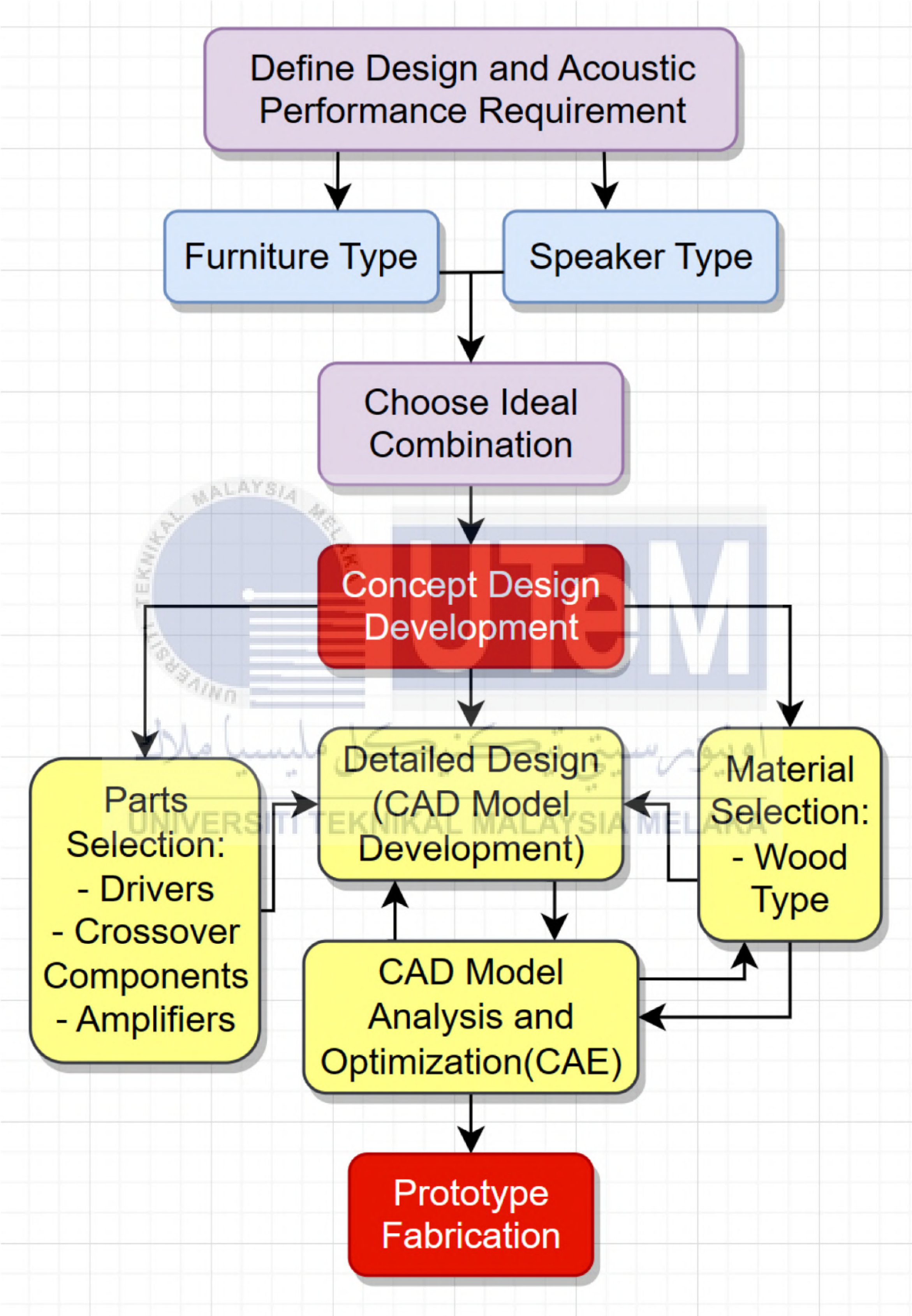


Figure 3-2 Planning to Prototype Flowchart

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter will be showing the process of deriving the type of furniture and loudspeaker type combination, design specifications, parts and material choices, prototype design and design optimization through the use of CAD and CAE as well as prototype fabrication and final performance tuning.

4.2 User Requirements

This project seeks to innovate a new product category and explore a new need/market that is unknown to the user base. This type of project relates to "Horizon 3 Opportunities" (Ulrich et al., 2020).

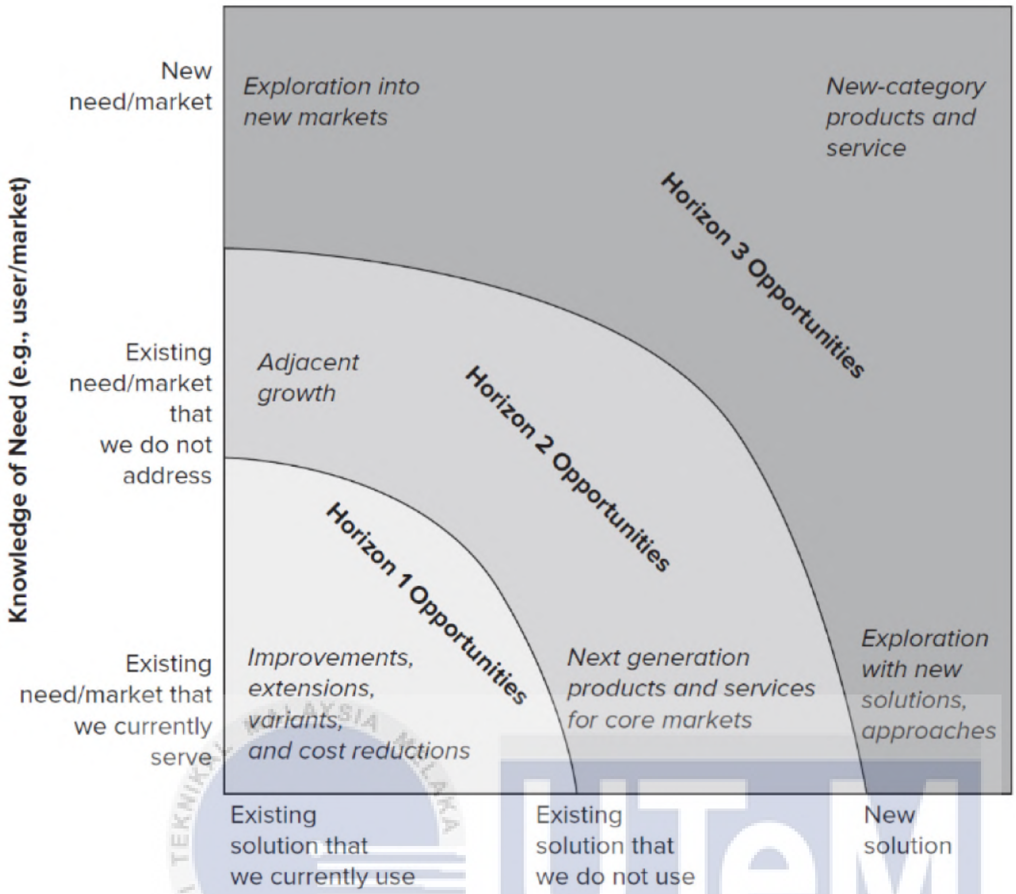


Figure 4-1 Knowledge of Solution (Ulrich et al., 2020)

Collecting user requirements data through survey method for a product category that is unknown is difficult. This is because, in order to use the survey method for this project, it requires a high degree of educating on the nuances of the project concept to survey responders which will reduce the number of survey participants and in turn will yield low quality statistical data. Compounding that, due to the need to educate a new concept to survey participants, this introduces the likelihood of the participants misunderstanding the concept which will further reduce the quality of the collected data. Designing based on low quality statistical data will harm the overall project rather than improve it.

Due to those reasons, the user requirement data is not derived through statistical methods and is derived through a combination of self-observation and literature review of the general expected user requirements of both a furniture product and a loudspeaker product (*Design Requirements for Amps and Speakers, Part One: Form Factors and Coverage Patterns – HARMAN Professional Solutions Insights*, n.d.; *Loudspeakers and Their Specifications - TOA Electronics*, n.d.).

The general expected user or performance requirement for a loudspeaker is simple and intuitive which is high sound quality. A loudspeaker is a single function product therefore there are no other requirements that are related to its function. Requirements that are related to other than its function will be disregarded in this case because it will be wrapped in another product which is a furniture. For a furniture product the general expected user requirements in order of priority would be its function, quality and aesthetics (*Furniture Regulations in the European Union: A Complete Guide*, n.d.; *Quality Control for Furniture – What Do Importers Need to Know? - HQTS*, n.d.).

As we are designing a product which is a hybrid or combination of both products, the primary challenge would be combining the key requirements of both types of products, which is their function. Therefore, the highest importance will be the compatibility of function of both products. Secondly, would be their individual functions which would be sound quality for the loudspeaker while for the furniture it will depend on the type of furniture that will be chosen. Following that in order of importance would be usability, reliability which relates to quality and finally aesthetics and unique quality.

House of Quality (HOQ)

		Technical Characteristics					
Improvement Direction		N/A	N/A	↓	N/A	N/A	N/A
User Requirement	Importance Rating	Type of furniture	Material Selection	Vibration Damping	Speaker Driver Type	Enclosure and Porting	Speaker Electronics (Crossover/Amplifier)
Compatibility of function (Product intended use, location in house and performance)	0.3	9	1	3	9	1	
Furniture function	0.2	9		3	3	3	
High sound quality	0.2	3	1	3	9	9	3
Usability	0.1	9	3		3		
Reliability	0.1		9	9			
Aesthetics	0.05	9	9				
Unique	0.05	1	1		1		
Total	1	6.5	2.2	3	5.45	2.7	0.6
Relative Weight %		31.78	10.76	14.67	26.65	13.20	2.93
Rank Order		1	5	3	2	4	6
Strong(9)		Medium(3)			Weak(1)		
Maximize (↑)		Minimize(↓)			Target not applicable (N/A)		

Table 4-1 House of Quality (HOQ) Table

Based on the HOQ analysis, the highest priority technical specification is the type of furniture and secondly the type of loudspeaker that it will be paired with. This is because both of them have the highest correlation in regard to compatibility of function and many of the customer requirements. The third highest priority belongs to the vibration damping as it supports the function of both the furniture and loudspeaker parts of the design. It's also seen that sound quality is affected at least to a moderate degree by almost every technical specification but mostly affected by the type of speaker driver and enclosure. Furniture function is mostly affected by the type of furniture that will be chosen but is moderately affected by vibration damping, speaker driver type and enclosure. We also see the reliability of the product has a strong correlation to material selection and vibration damping. The same can be said for aesthetics and its correlation with the type of furniture and material selection.

Based on the analysis above, our product specification should be focused on choosing the best furniture and loudspeaker combination that can maximize the function of both the furniture and loudspeaker part of the design. Secondly a good solution should be developed for vibration damping to aid in the functions of the furniture and loudspeaker. The enclosure design should reflect the same sentiment to vibration damping. The material selection should prioritize reliability and aesthetics. Due to the target market being a home consumer, the aesthetic design should be minimal and unassuming.

4.3 Conceptual Design

In the conceptual design stage, the preliminary concepts will show an ideation process, creating concept designs that lead to the final realistic portrayal of the end product. The ideation process begins with the morphological chart. The concept design creation is guided by the morphological chart. Figure 4-2 shows the morphological chart used in this conceptual design process.

Figure 4-2 Morphological Chart

4.3.1 Preliminary Concepts

The preliminary concepts will physically look different to the final developed concepts that are more realistic due to them being after considering costs and manufacturability. The final developed concepts will still retain the core design and general idea of the preliminary ones. Figure 4-3 shows the preliminary concepts.

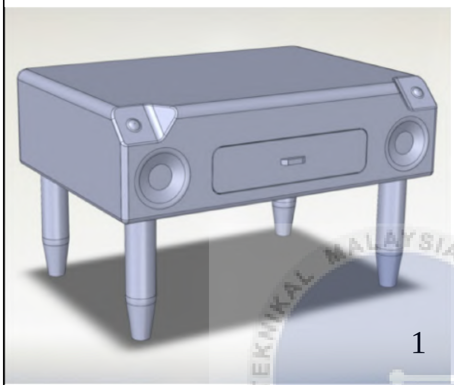
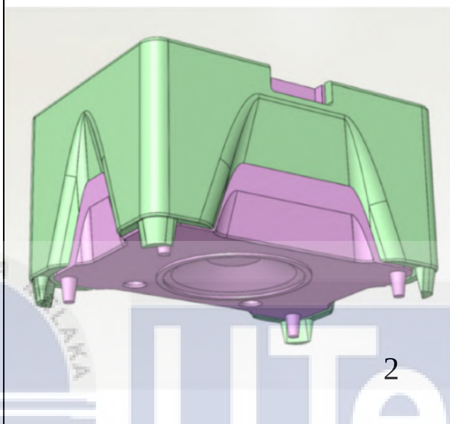
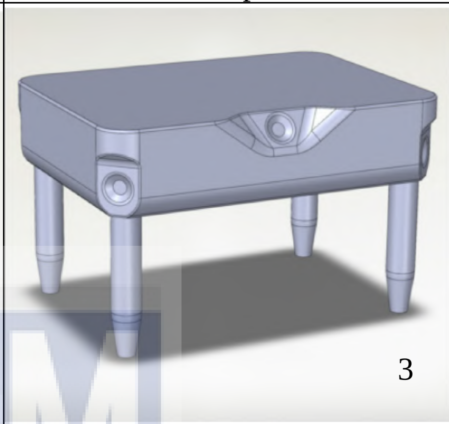
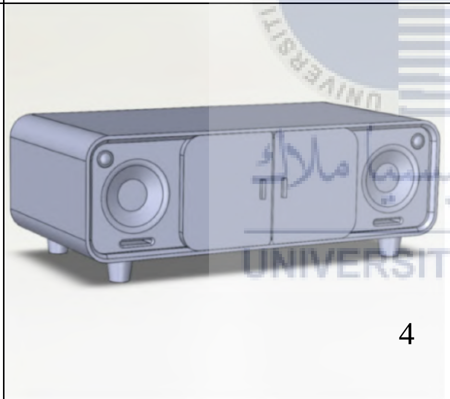
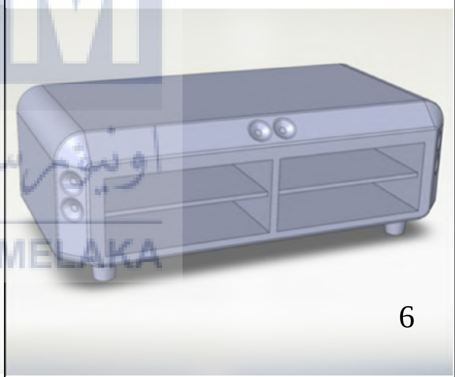
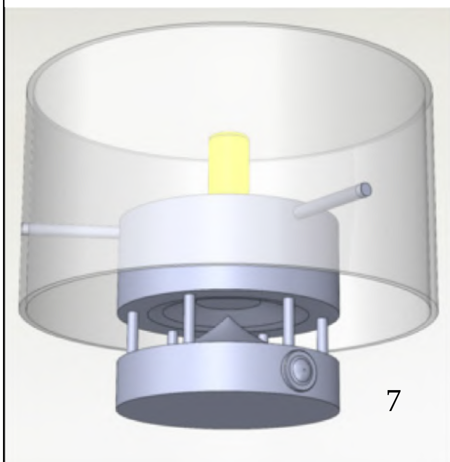
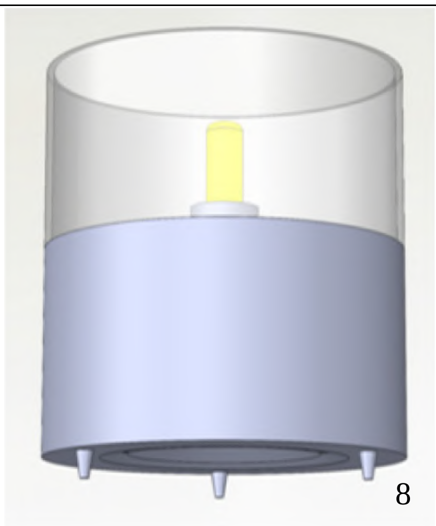
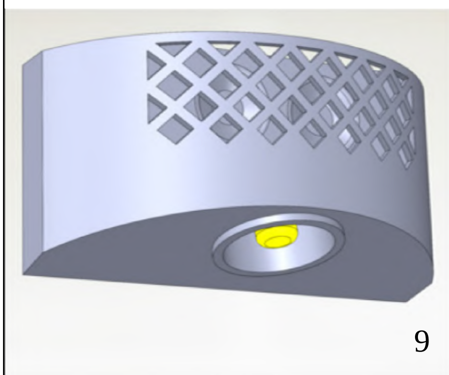
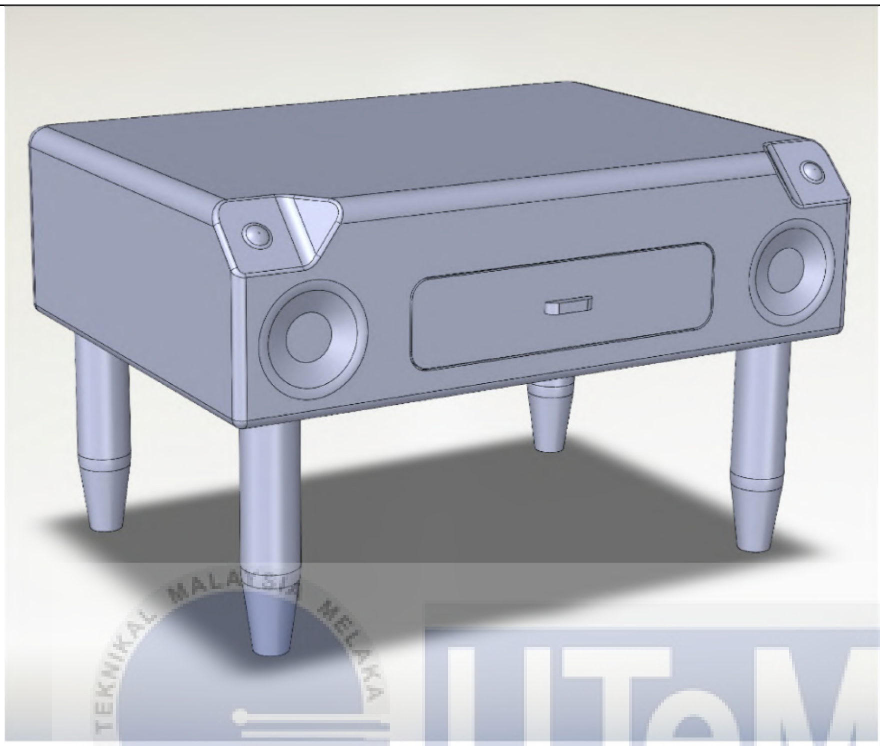
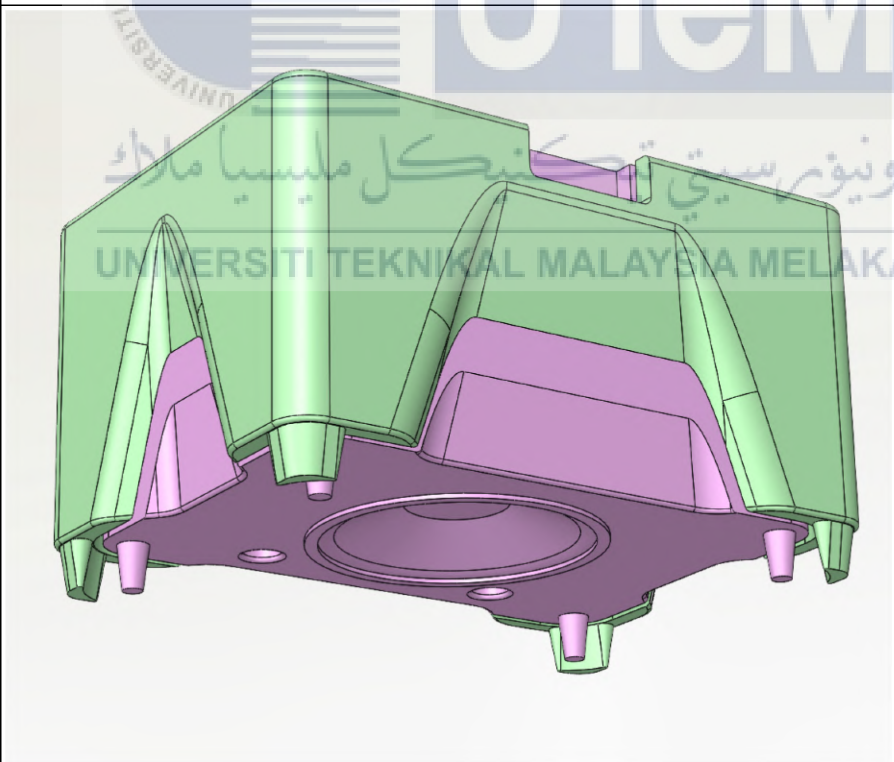
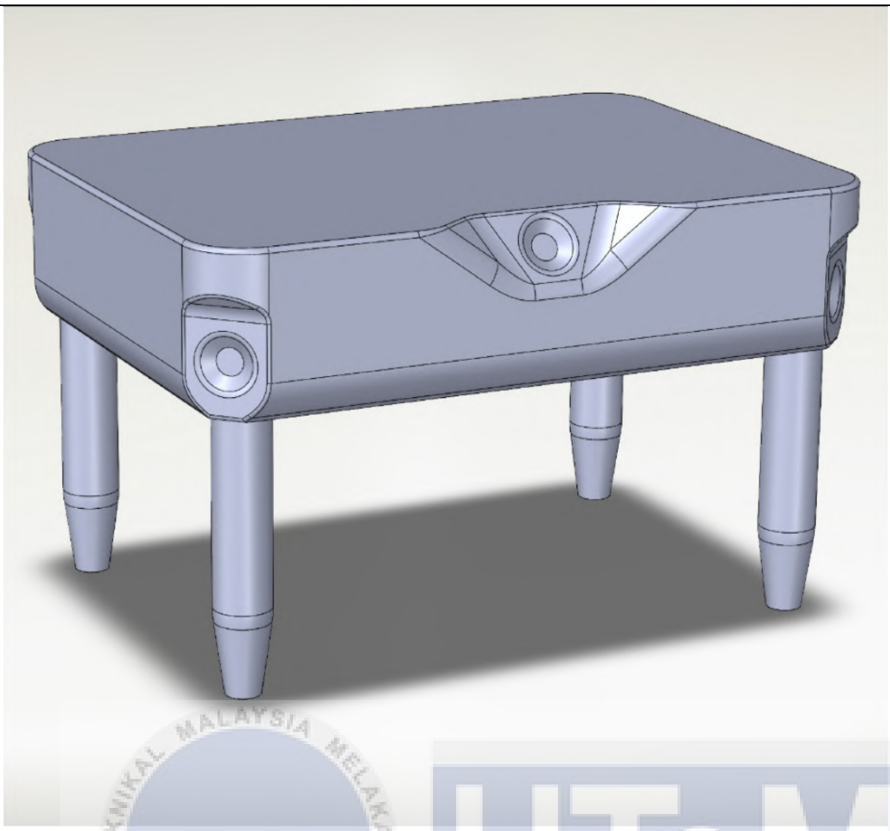
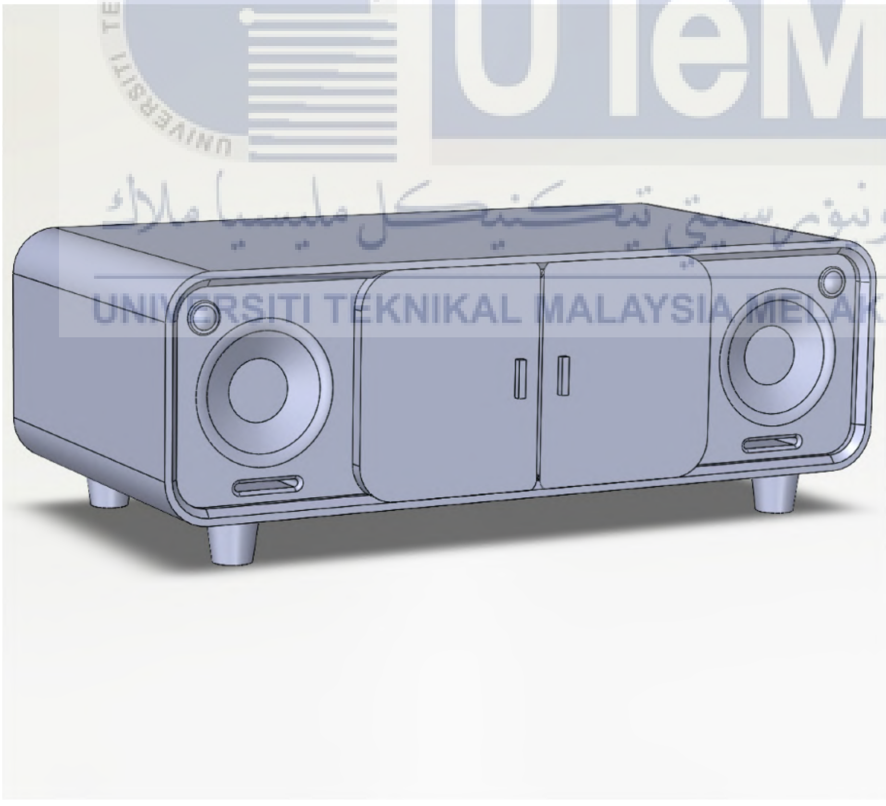
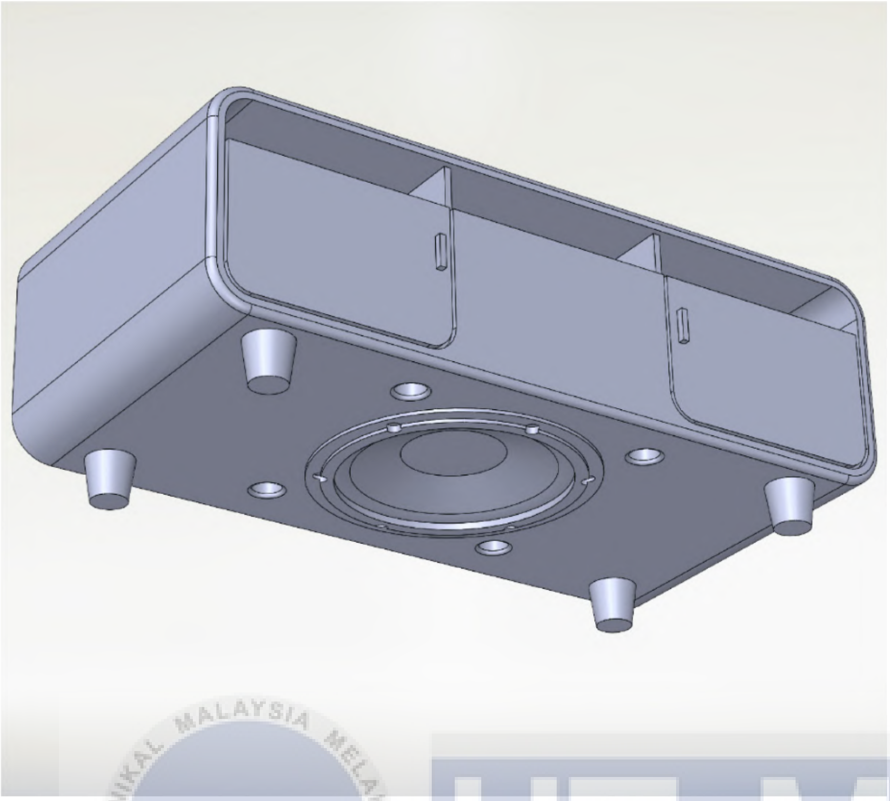
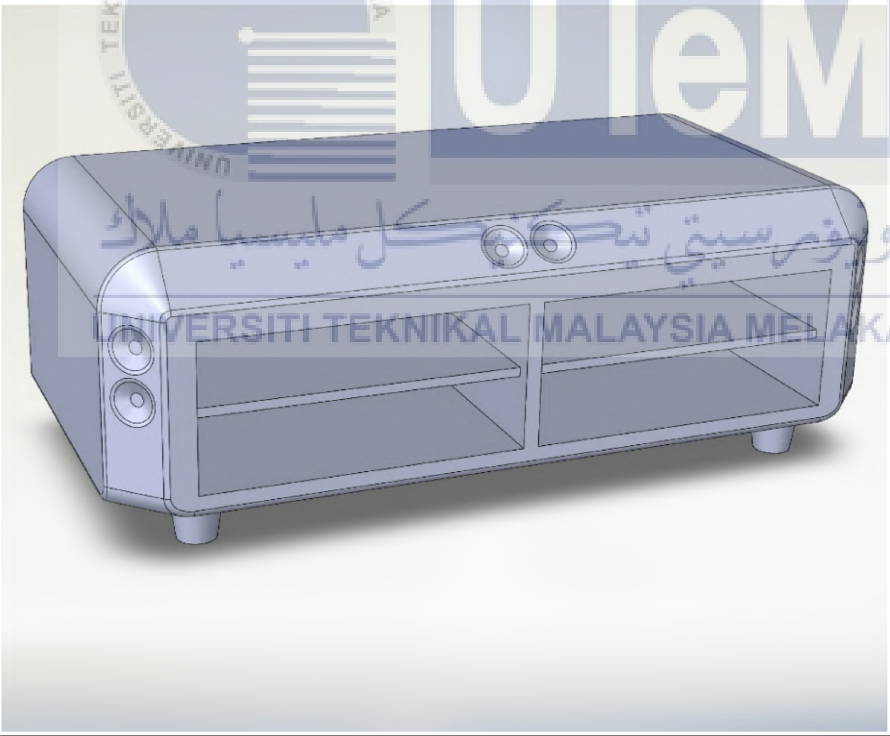
	Stereo Speaker	Subwoofer	Satellite speakers
Coffee Table	 1	 2	 3
TV Table	 4	 5	 6
Lamp	 7	 8	 9

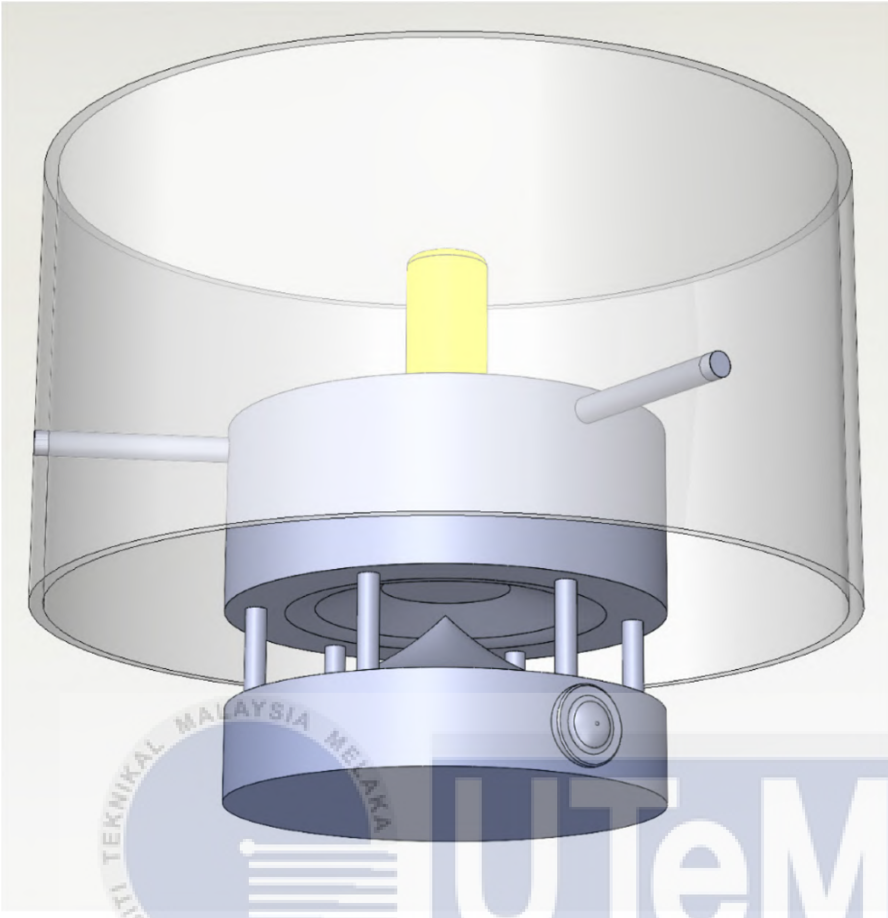
Figure 4-3 Hybrid Concept Types Design Exploration

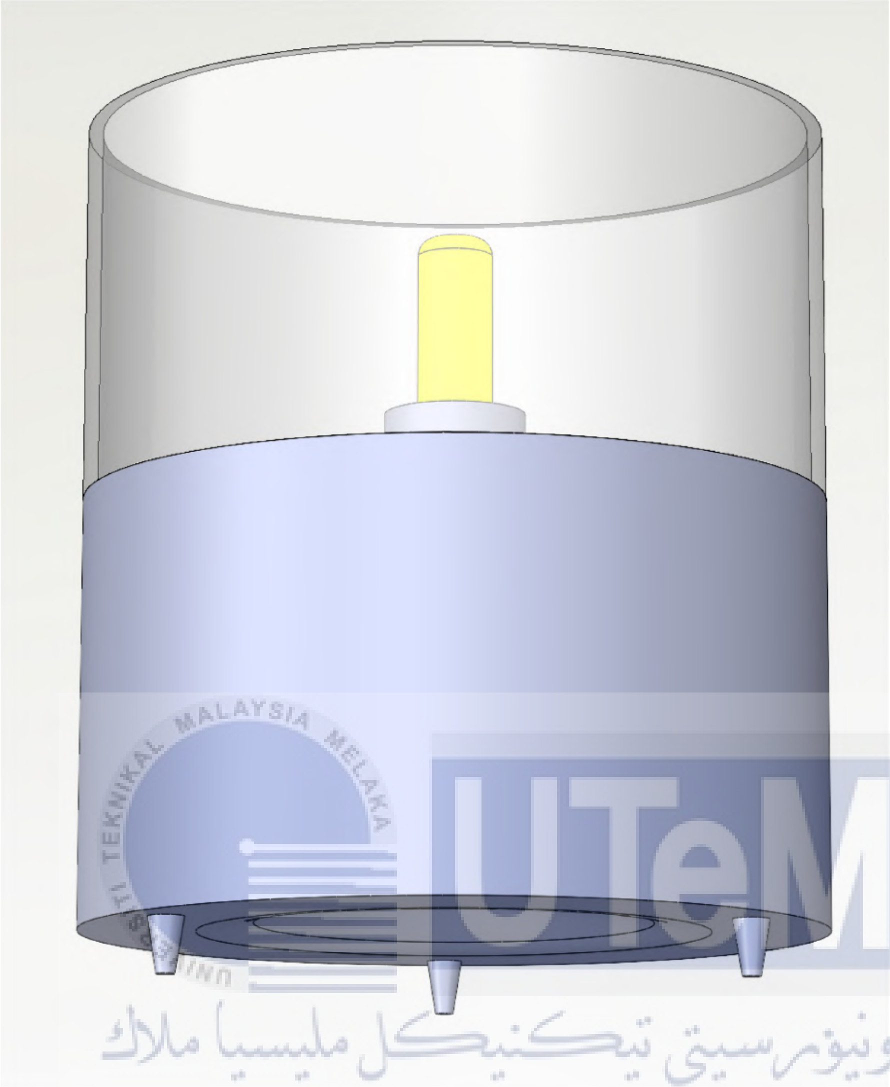
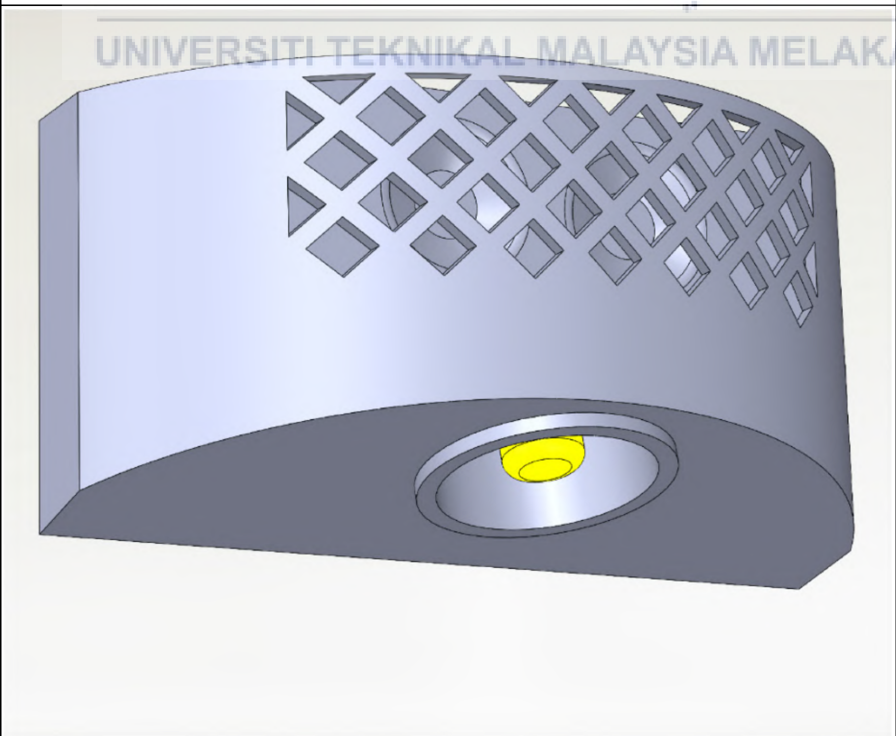
Table 4-2 Hybrid Concepts Design Description

No	Concepts	Description
1		Coffee table and stereo speaker combination with a sealed enclosure type. Front firing speaker design with internal bracing for sound damping. Powered and driven by an internal amplifier and crossover.
2		Coffee table and subwoofer combination with a dual ported enclosure type. Downward firing speaker design with **mechanical isolation** for sound damping. Powered and driven by an external amplifier and crossover.

3		Coffee table and satellite speaker combination with a sealed enclosure type. Front firing speaker design with internal bracing for sound damping. Powered and driven by an internal amplifier and crossover.
4		TV table and stereo speaker combination with a ported enclosure type. Front firing speaker design with internal bracing for sound damping. Powered and driven by an external amplifier and internal crossover.

5		TV Table and Subwoofer combination with a quad ported enclosure type. Downward firing speaker design with internal bracing for sound damping. Powered and driven by an external amplifier and crossover.
6		TV Table and satellite speaker combination with a sealed enclosure type. Front firing speaker design with internal bracing for sound damping. Powered and driven by an external amplifier and internal crossover.

7		Lamp and stereo speaker combination with a sealed enclosure type. **Front firing and Downward Firing** speaker design with internal bracing for sound damping. Powered and driven by an internal amplifier and crossover.

8		Lamps and Subwoofer combination with a sealed enclosure type. Downward firing speaker design with internal bracing for sound damping. Powered and driven by an internal amplifier and crossover.
9		Lamp and satellite speaker combination with a sealed enclosure type. Front firing speaker design with internal bracing for sound damping. Powered and driven by an internal amplifier and crossover.

4.3.2 Concept Screening with Pugh's Evaluation Matrix

A Pugh matrix is a tool for evaluating and prioritizing a list of options based on a set of criteria. It involves comparing each option to a reference option and rating it as better (+1), same (0), or worse (-1) for each criterion. The ratings are then summed up to rank the options. Table 4-3 below shows Pugh's matrix used to decide which preliminary concepts will be further developed.

Selection Criteria	Hybrid Concept Combinations								
	1	2	3	4	5	6	7	8	9
Compatibility of function (Product intended use, location in house and performance)	=	+	=	+	+		+	-	+
Furniture function	=	+	-	+	+		=	=	+
High sound quality	=	+	=	+	+	DATUM	-	+	=
Practical	=	+	=	+	+		-	-	+
Reliable	+	+	=	+	+		-	=	-
Aesthetics	=	=	=	=	=		+	+	+
Unique	=	=	=	=	=		=	=	=
Quantity +	1	5	0	5	5		2	2	4
Quantity -	0	0	1	0	0		3	2	1
Quantity =	6	2	6	2	2		2	3	2
Final Score	1	5	-1	5	5		-1	0	3
Develop?	No	**Yes**	No	**Yes**	**Yes**		No	No	No

Table 4-3 Pugh's Evaluation Matrix

4.3.3 Developed Concepts

Developed concepts are concepts that are more realistic due to them being after considering costs and manufacturability. The final developed concepts will still retain the core design and general idea of the preliminary ones. The figures below show the fully developed concepts that were chosen from the preliminary concepts through Pugh's evaluation matrix.

Hybrid 2

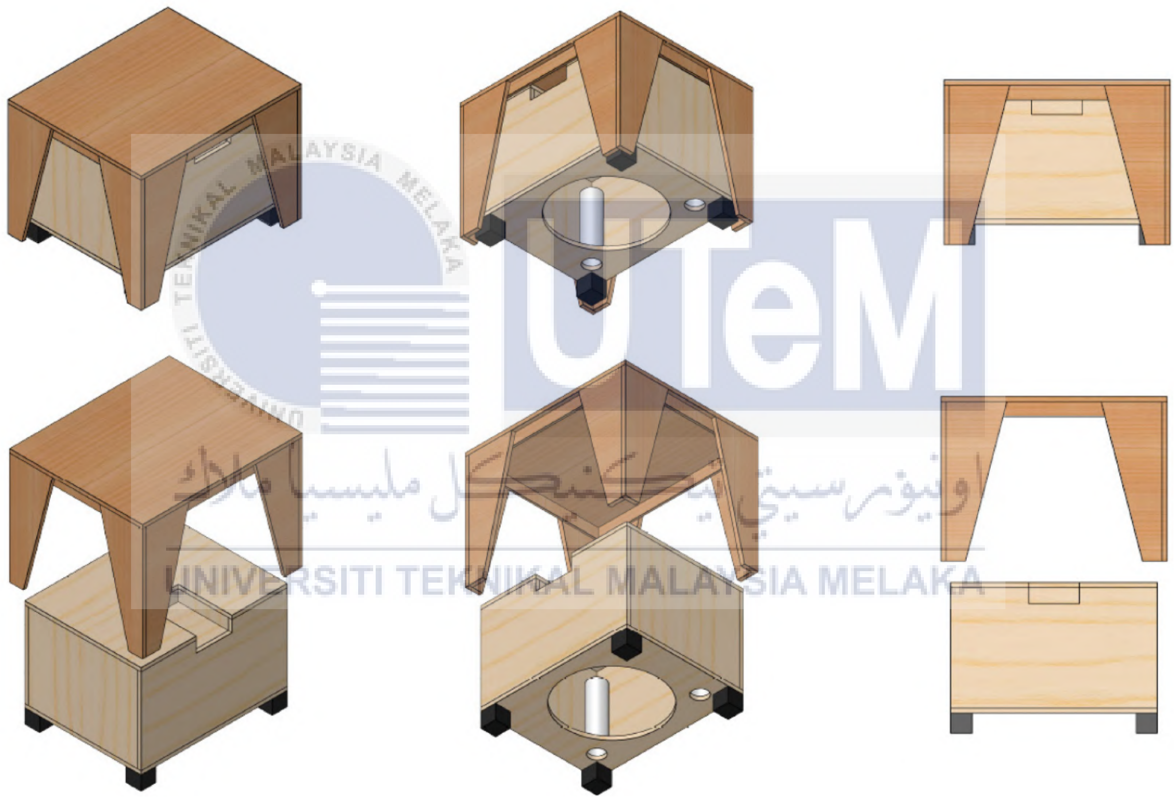


Figure 4-4 Hybrid 2 Concept

Hybrid 2 is a Coffee Table Subwoofer Hybrid. It is a 2-part design that separates subwoofer housing from table structure to remove direct vibration transfer (mechanical isolation). This in turn removes the need for internal bracing within the subwoofer housing. The lack of internal bracing then increases woofer air volume in the housing which improves bass response. Large rubber feet are put on the subwoofer housing to further isolate vibration transfer via floor or carpet. There's a small space on top of the woofer housing that is meant for an external amplifier-crossover combo. Using an external electronic unit allows easy access for volume control, replaceability and upgradability. This increases reliability, practicality and potential for sound quality upgrades.

Hybrid 4

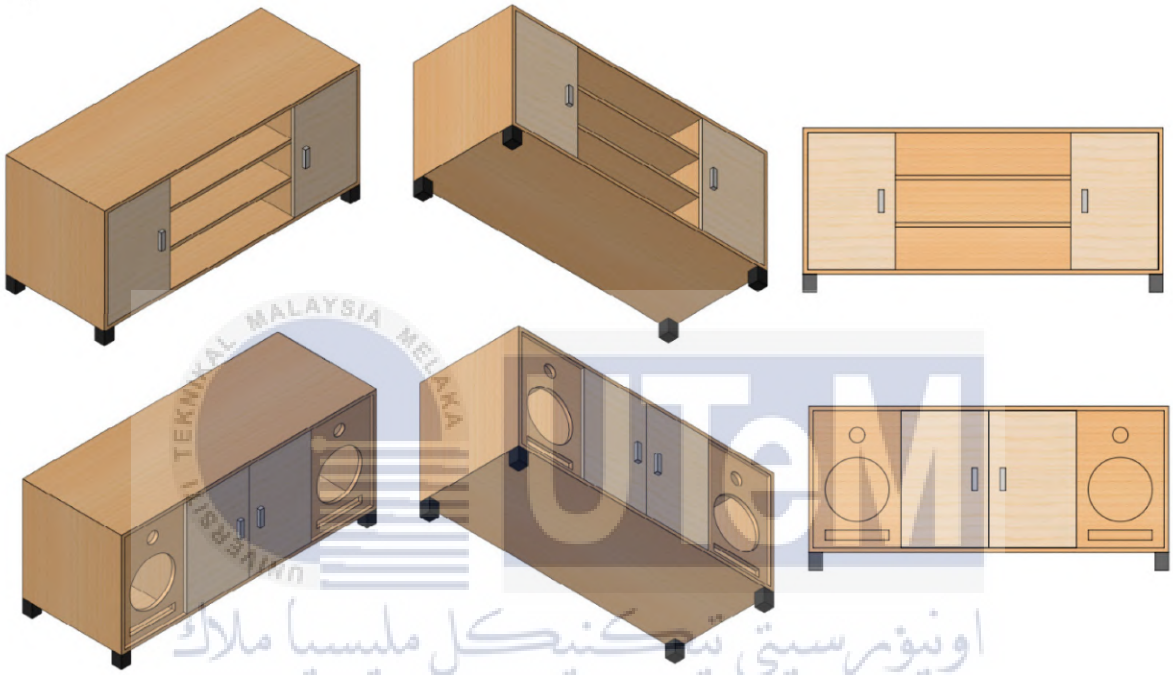


Figure 4-5 Hybrid 4 Concept

Hybrid 4 is a 2-way Stereo Speaker TV Table Hybrid. This design has sliding doors that can be moved to expose the storage space in the middle of the furniture while hiding the speaker system and vice versa. This design can transform its appearance to hide its function and look like normal furniture that won't attract attention. While the speakers can be exposed when its function is needed. This design requires a moderate degree of internal bracing to reduce vibration transfer. Part of the electronics will be placed in the easily accessible storage space for the same reasons as Hybrid 2. This would be the amplifier while the crossover would be inside the speaker housing.

Hybrid 5

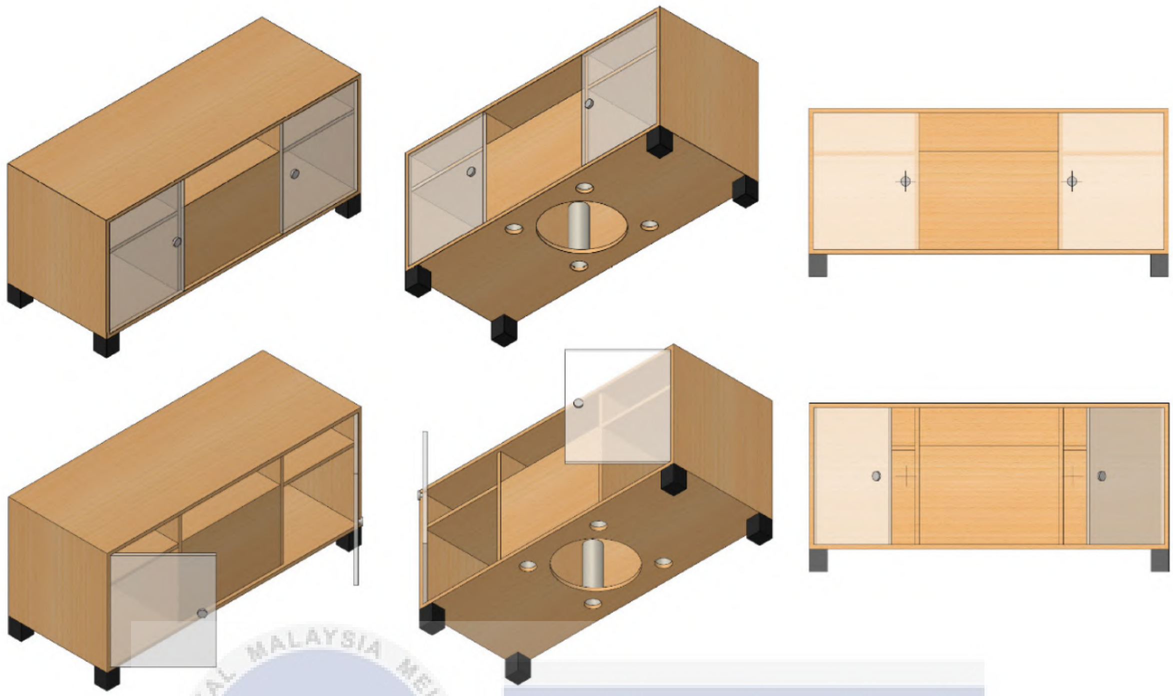


Figure 4-6 Hybrid 5 Concept

Hybrid 5 is a TV Table Subwoofer Hybrid. This design is made to look and function close to a regular furniture as much as possible while accommodating space and internal volume for the subwoofer system. It features glass doors with circular nobs which follows an old school furniture design aesthetic to conceal its modern functions. This design requires a high degree of internal bracing to reduce vibration transfer. Due to the internal bracing consuming some woofer air volume, there will be some loss in bass response which affects sound quality. The electronics will be packaged the same way as Hybrid 2, featuring an external amplifier-crossover combo that will be placed in the top middle storage space above the subwoofer housing.

4.3.4 Concept Selection with Weighted Decision Matrix

		Hybrid Variations					
		Coffee Table + Subwoofer		TV Table + Stereo Speaker		TV Table + Subwoofer	
Criteria	Importance weight (%)	Rating	Weighted rating	Rating	Weighted rating	Rating	Weighted rating
Compatibility	30	4	1.2	3	0.9	3	0.9
Furniture function	20	4	0.8	4	0.8	3	0.6
Sound quality potential	20	4	0.8	4	0.8	3	0.6
Practicality	10	3	0.3	4	0.4	4	0.4
Reliability	10	4	0.4	3	0.3	4	0.4
Aesthetics	5	3	0.15	3	0.15	2	0.1
Unique	5	4	0.2	3	0.15	2	0.1
	100	0	**3.85**	0	3.5	0	3.1

Rating	Value
Unsatisfactory	0
Tolerable	1
Adequate	2
Good	3
Very Good	4

Table 4-4 Weighted Decision Matrix

4.4 Detail Design

In this section, we will create a 3D CAD model of the coffee table furniture based on our subwoofer, crossover amp combo part selection and material selection of the furniture. We will need to select the appropriate parts and know their dimensions first, before we will be able to design the main structure in order to make sure everything fits perfectly during assembly. We will also need to know the frequency response, and woofer cone size specs of the subwoofer to calculate the right port quantity, size and length to extract the best sound out of the system. The material selection will affect the thickness of material needed to achieve acceptable vibration characteristics and structural rigidity. Therefore, the material also needs to be selected before the 3D CAD modelling process can begin.

4.4.1 Part Selection

4.4.1.1 Subwoofer Selection

Figure 4-7 Bosoko 12" Subwoofer

For the subwoofer loudspeaker part, a 12 inch (30cm) Bosoko Subwoofer was chosen. The reason for choosing this part in particular is due to its frequency response specifications that show it has bass extension down to 30HZ. This is also the reason for its very large dimensions. Its cone size is 27.5cm therefore the hole cut out on the 3D Model needs to be slightly larger than that for mounting purposes.

Subwoofers of this size are on the upper end of the scale in terms of size range and while they have very good frequency response, they come with some drawbacks. Due to its large cone (diaphragm) size, the subwoofer has a high mass loading capacity and therefore will have a high amount of vibration transfer without vibration damping or a heavy box. Fortunately, this will be less of an issue in our design due to the nature of the design separating the subwoofer box from the functional elements of the coffee table furniture.

4.4.1.2 Amplifier and Crossover Combo Selection

Figure 4-8 Aiyima A1001 Amplifier

This is the Aiyima 100w at 4-ohm amplifier with tunable subwoofer frequency dial. This subwoofer amplifier was chosen because it matches our subwoofer selection's impedance and has a tunable crossover that lets us adapt the subwoofer to any stereo loudspeaker setup. It has enough power to push the subwoofer to adequate levels of loudness but is well within the max wattage threshold of the subwoofer which is 400 watts.

4.4.2 Material Selection

The chosen material for the construction of this design was MDF (Medium-Density Fiberboard). The primary reasons this material was chosen is because of its ease of workability, smooth surface, dimensional stability, and cost.

MDF is easy to work with and can be cut and carved into different designs. Aside from that, MDF's smooth surface and uniform composition make it an excellent choice for interior trim, cabinetry, and furniture. Unlike plywood, MDF doesn't have knots, ensuring a uniform appearance. The consistency of MDF extends to its edges as well, which are smooth and can be easily shaped into decorative designs with a router.

MDF also offers dimensional stability, meaning it retains its shape for a long time. This stability refers to the ability of MDF to retain its shape and size over time, even when exposed to changes in humidity and temperature.

Lastly, MDF is generally less expensive than other engineered woods. The cost of MDF can vary based on factors such as the thickness, grade of the material, and the region but despite that it generally remains lower compared to any solid wood and plywood.

4.4.3 CAD Design

The figures below show the details and dimensions of the developed 3D CAD model of the Hybrid 3 Concept and the calculations made for the port tuning.

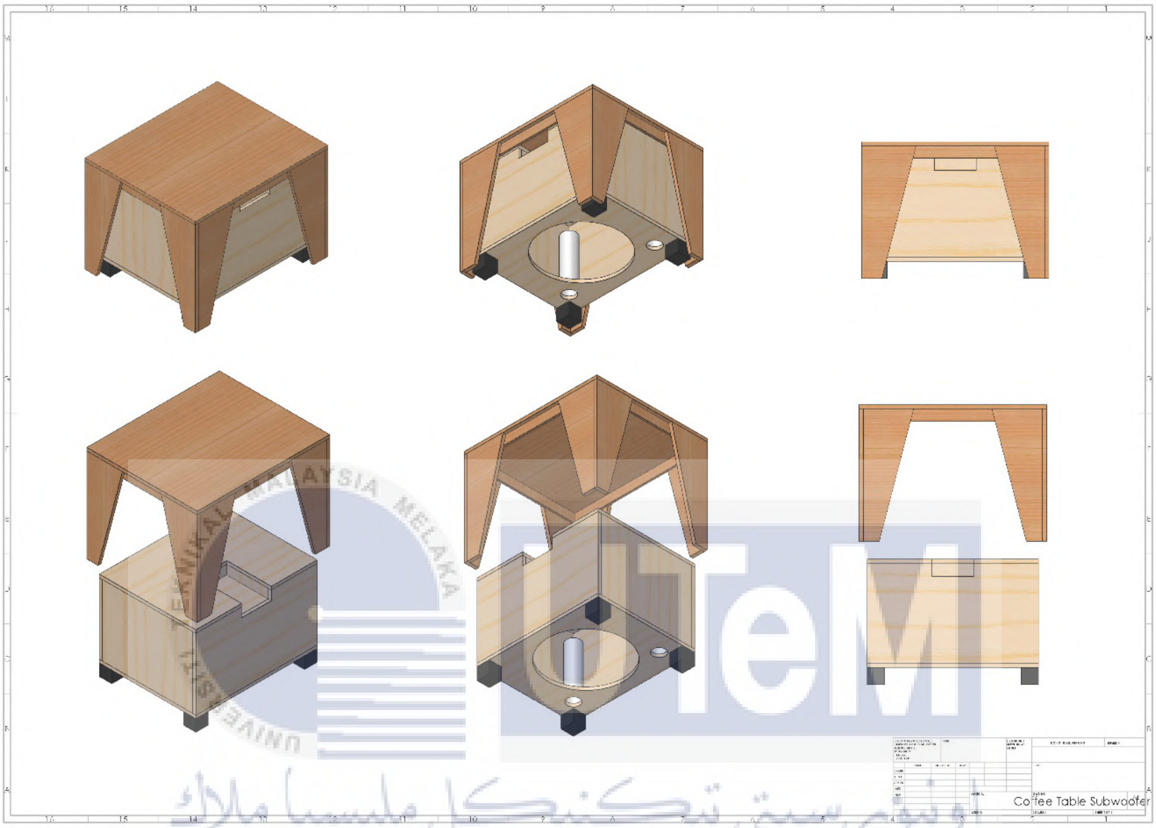


Figure 4-9 Coffee Table Subwoofer Detail Design

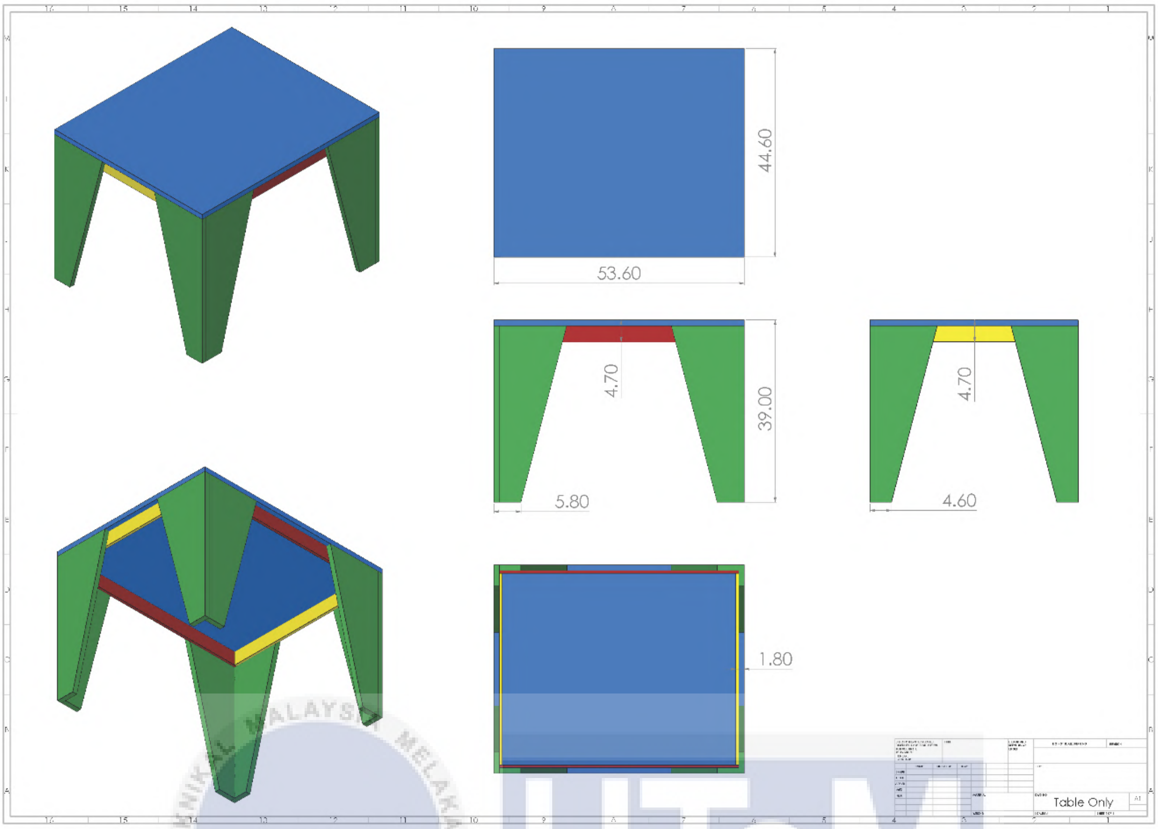


Figure 4-10 Table Section Detail Design

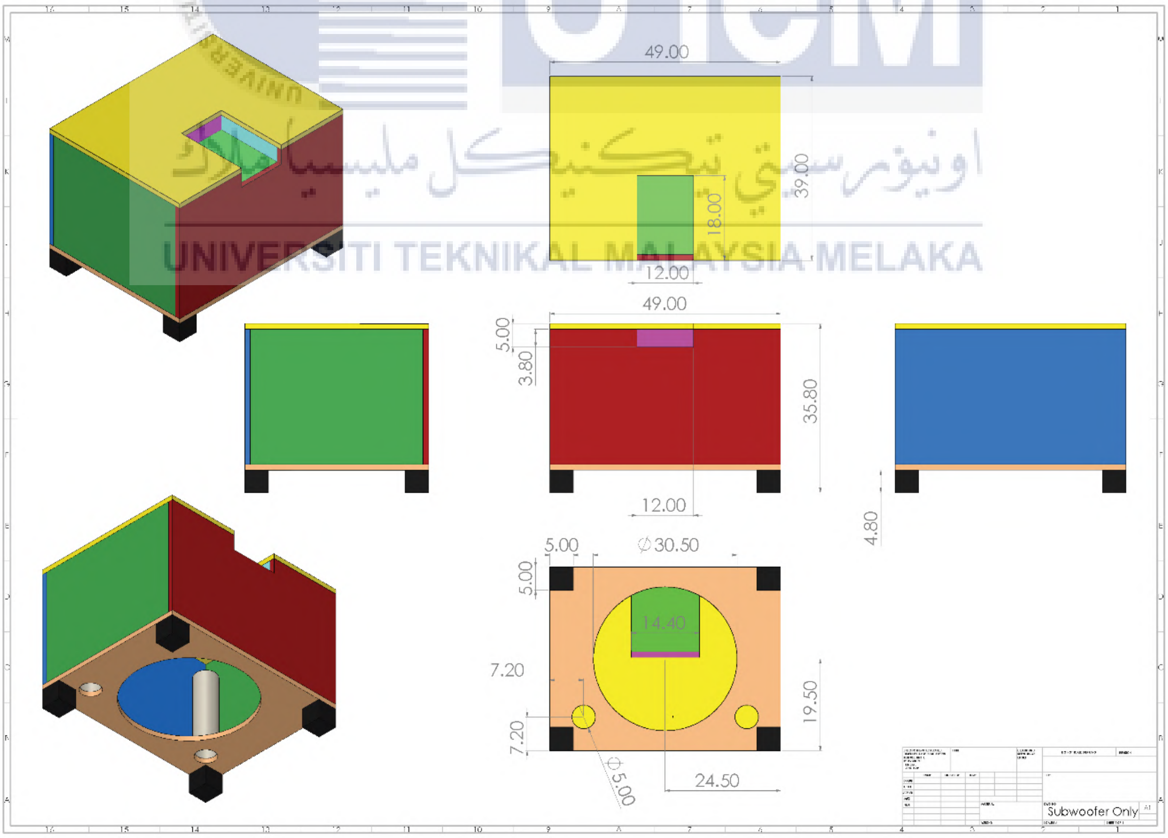


Figure 4-11 Subwoofer Section Detail Design

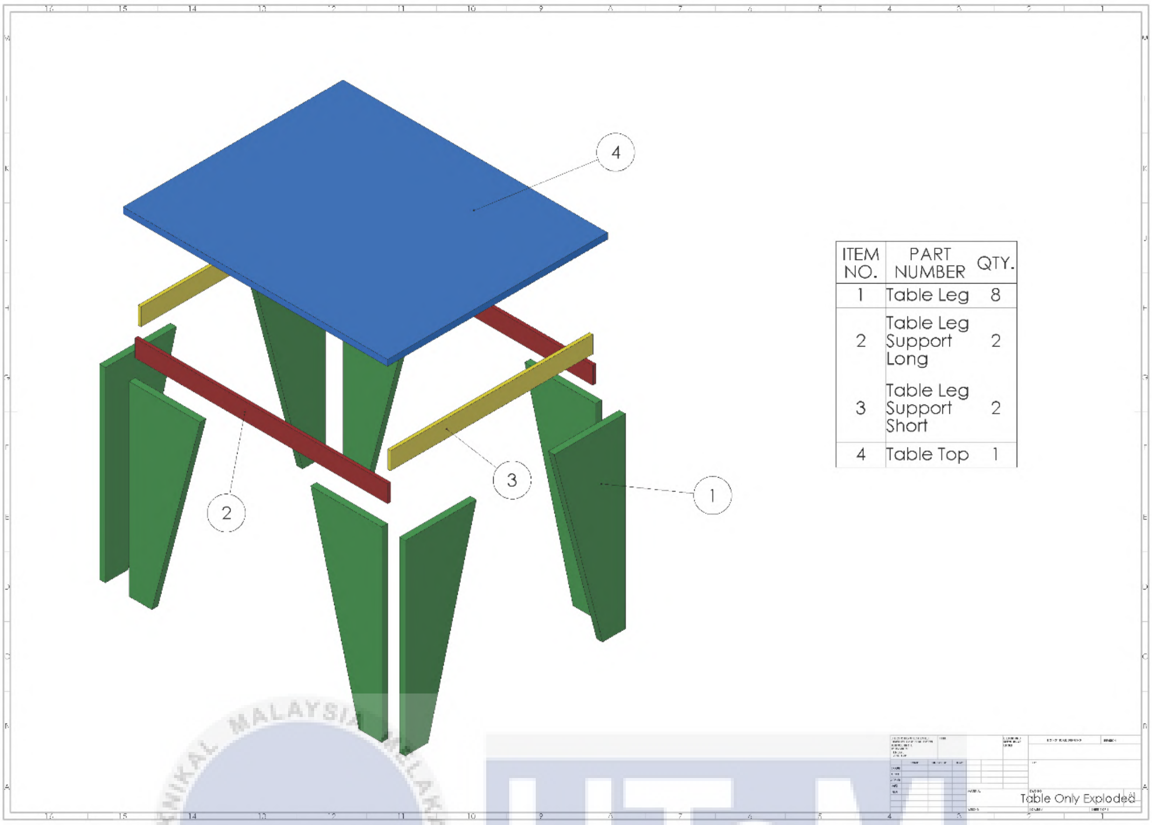


Figure 4-12 Table Section Exploded View

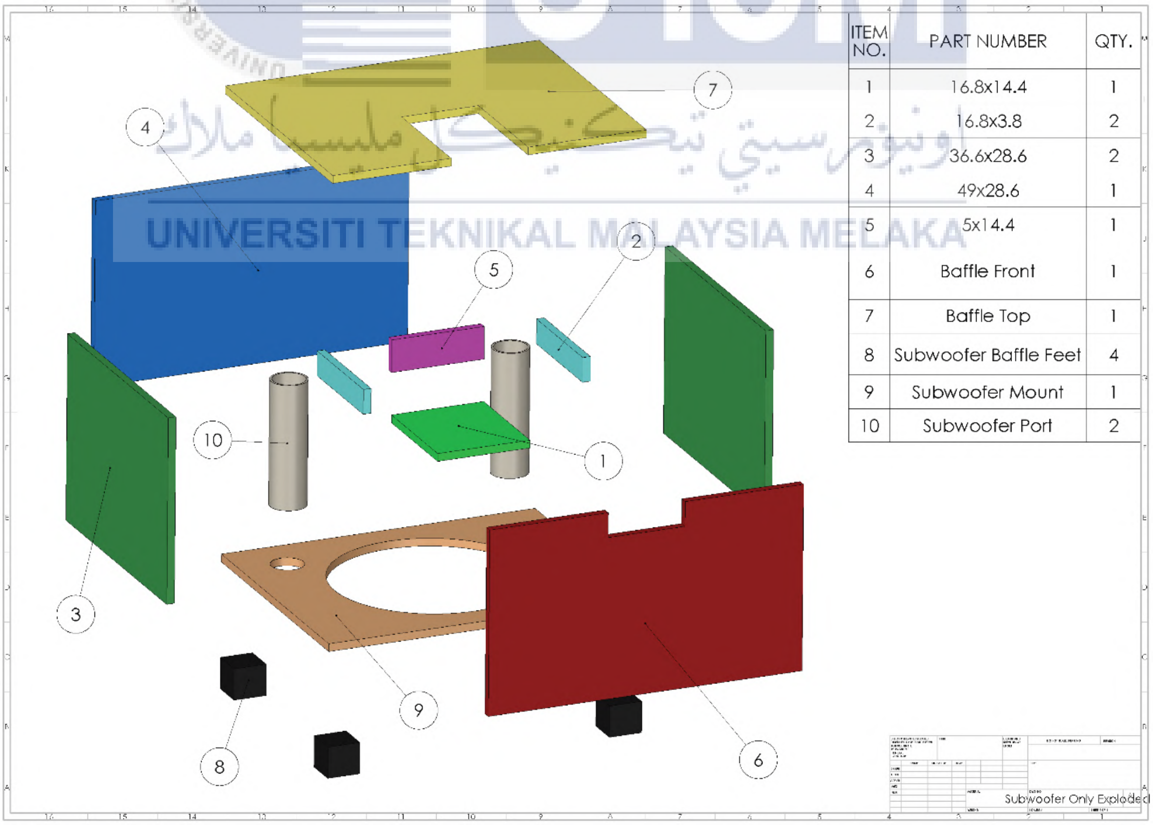


Figure 4-13 Subwoofer Section Exploded View

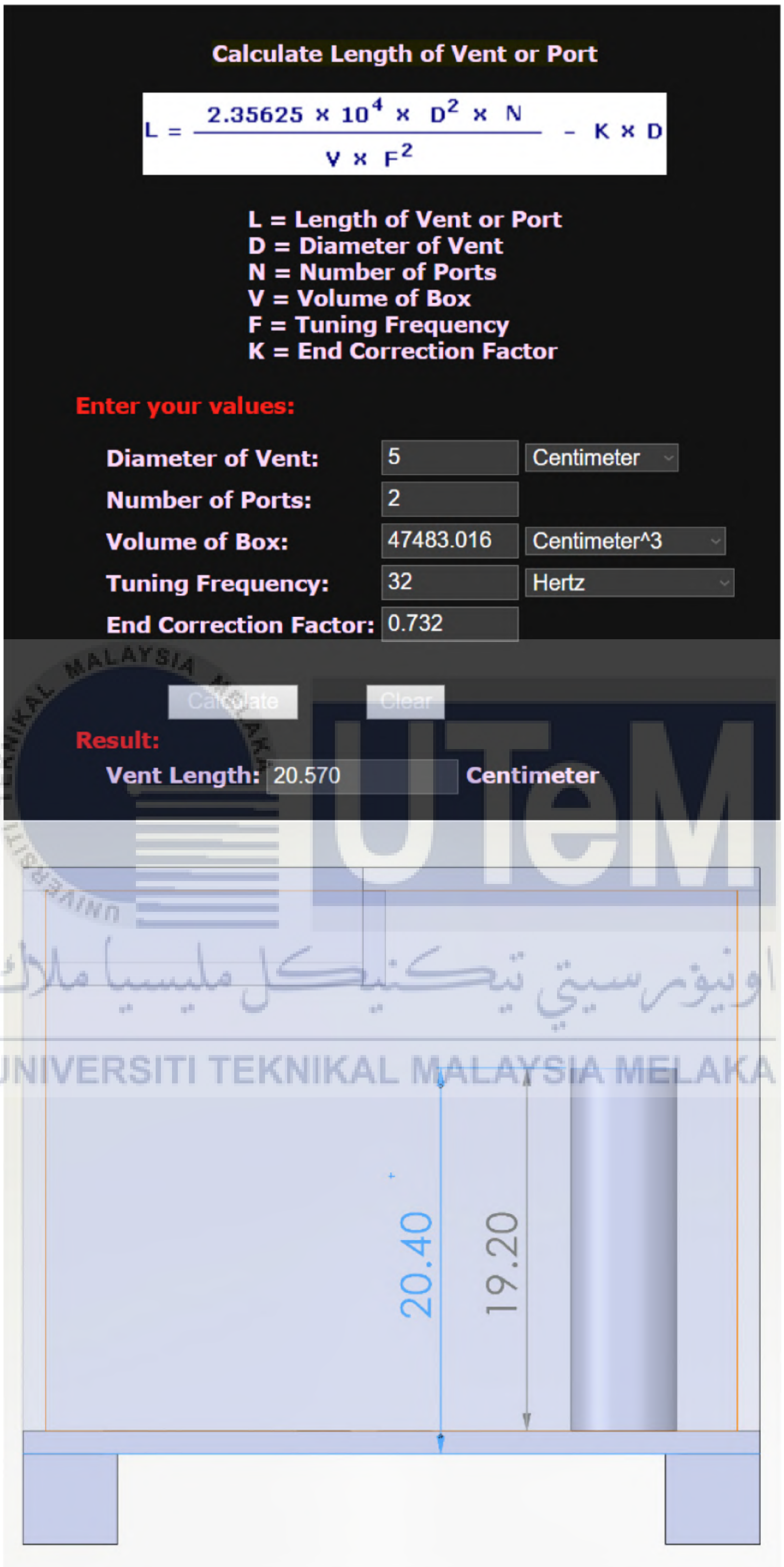


Figure 4-14 Port Tuning Calculation and Design

4.4.4 CAE Analysis

We will be using SolidWorks Simulation (FEA) and SolidWorks Flow Simulation (CFD) to perform the analysis. The FEA will be done on the table section to test rigidity and general load capacity while the CFD will be done on the subwoofer section to analyse the effects of low frequency pressure oscillation in the subwoofer enclosure.

4.4.4.1 Table Section FEA

In regards to the FEA analysis, SolidWorks Material Library does not include MDF Wood material, therefore a custom material file needs to be created. Creating a material file for MDF (Medium-Density Fiberboard) in SolidWorks involves defining the mechanical properties of MDF in the SolidWorks material database.

MDF does not contain knots or rings, making it more uniform than natural woods during cutting and in service. However, MDF is not entirely isotropic since the fibres are pressed tightly together through the sheet. The mechanical properties of MDF can vary depending on the direction due to its composition and manufacturing process. For instance, a study on MDF derived from two Malaysian wood species found differences in tensile and flexural strengths, indicating that the material's properties can change based on the direction (Ahmad et al., 2011).

In the field of material science, materials like MDF are often categorized as orthotropic or anisotropic. Orthotropic materials, such as wood or cubic single crystals, are characterized by nine nonzero constants, while fully anisotropic materials are characterized by 21 constants.

So, while MDF can be well modelled using the linear elastic model, it does not belong to the linear elastic isotropic group due to its directional-dependent properties. Instead, it would be more accurate to categorize MDF as a **linear elastic orthotropic** material. This means that its mechanical properties (such as strength and stiffness) vary along different directions.

The mechanical properties also can vary depending on the exact density of the MDF. We will be assuming the density of MDF that is commonly available for purchase which is 750kg per meter cube. The mechanical properties for this density of MDF Wood material is taken from a material properties database website (*Medium Density Fiberboard (MDF) :: MakeItFrom.Com*, n.d.). The mechanical properties given were general and is not defined for every direction. Therefore, we will assume the mechanical properties for every direction is the same for the sake of simplicity and the restricted boundaries of the scope this project that does not aim to venture deep into material science territory. Figure 4-12 shows the custom material file that was made.

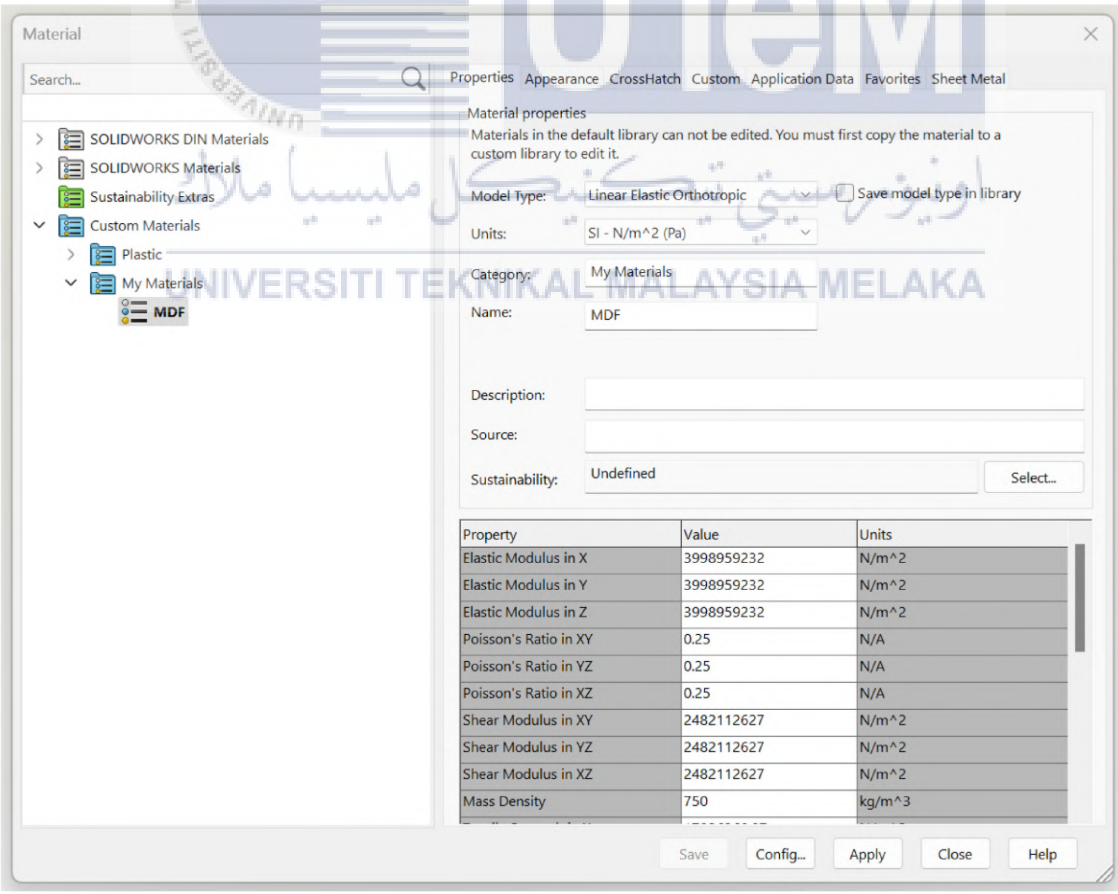
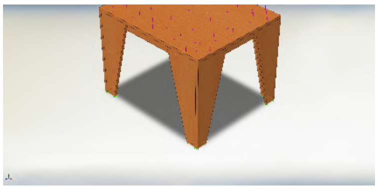


Figure 4-15 Adding MDF Material to Database

4.4.4.2 FEA of Table Section Setup Information and Results

The figures and tables below show the setup information for the simulation involving the table section of the design and the results of stress, strain, displacement and safe factor map of the table.

Fixture name	Fixture Image	Fixture Details
Roller/Slider		**Entities:** **8 face(s)** **Type:** **Roller/ Slider**

Resultant Forces

Components	X	Y	Z	Resultant
Reaction force(N)	0	1,000	0	1,000
Reaction Moment(N.m)	0	0	0	0

Load name	Load Image	Load Details
Force		**Entities:** **1 face(s)** **Type:** **Apply normal force** **Value:** **1,000 N**

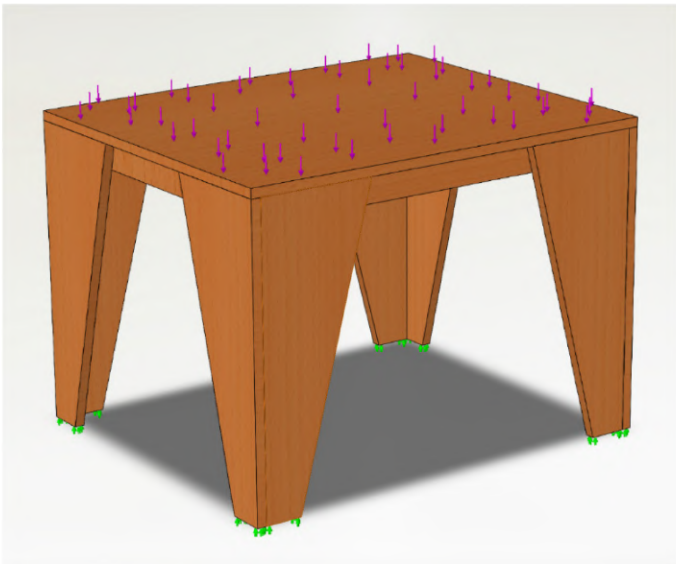


Figure 4-16 Load and Fixture Locations

Name	Type	Min	Max
Stress	VON: von Mises Stress	3.028e+04N/m^2 Node: 12487	3.272e+06N/m^2 Node: 6930

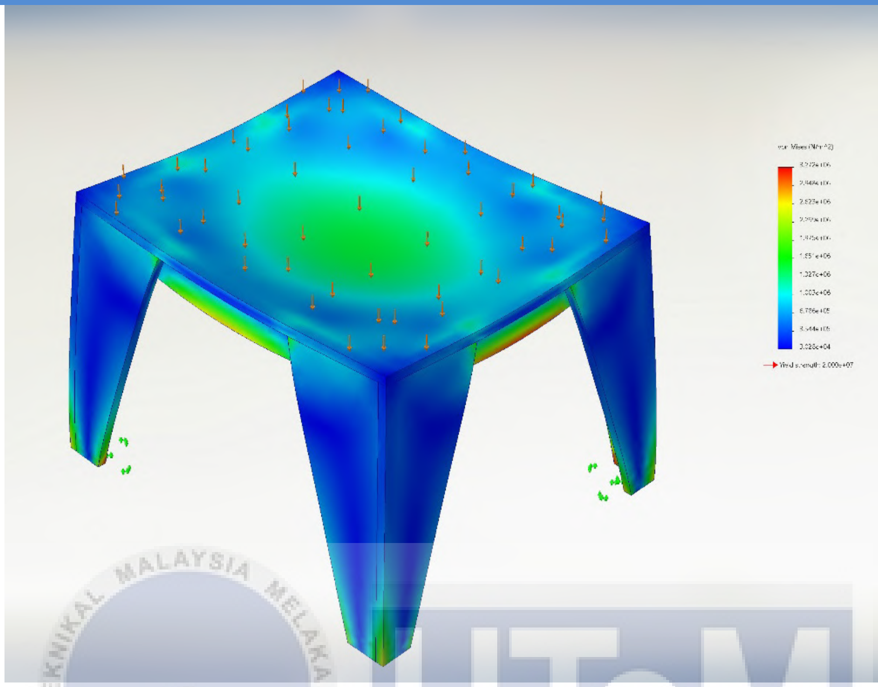


Table Only-Table Load Test-Stress-Stress

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	1.579e-02mm Node: 14975	1.220e+00mm Node: 15583

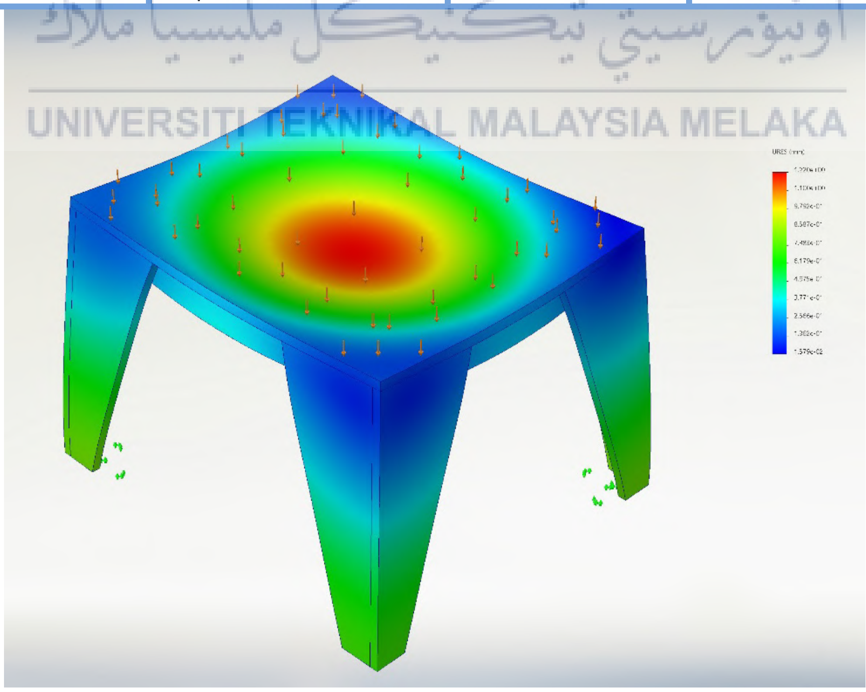


Table Only-Table Load Test-Displacement-Displacement

Name	Type	Min	Max
Strain	ESTRN: Equivalent Strain	4.507e-06 Element: 6127	5.605e-04 Element: 635

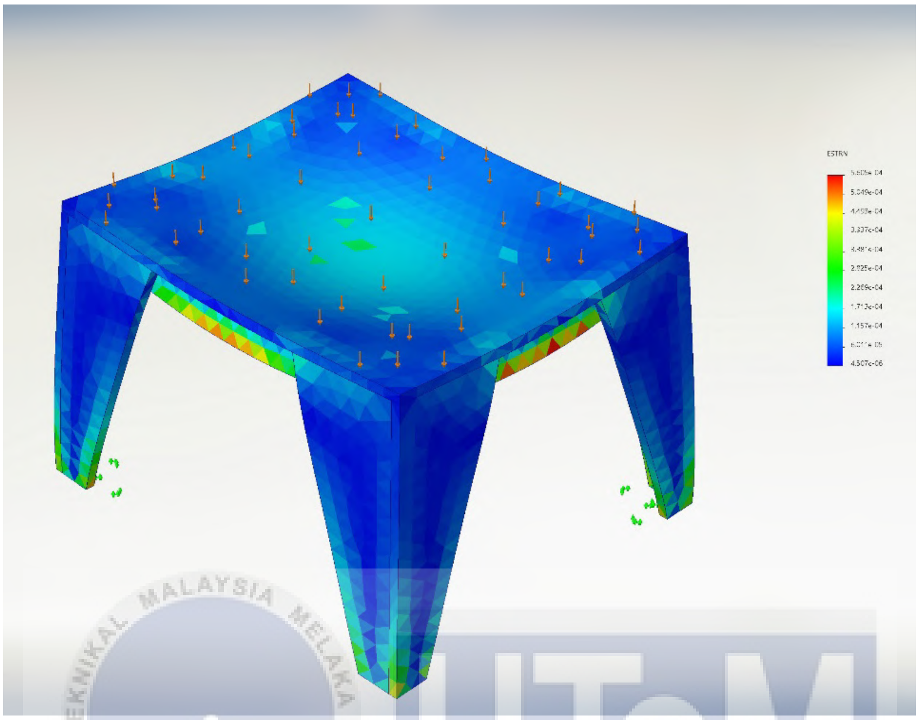


Table Only-Table Load Test-Strain-Strain

Name	Type
Displacement	Deformed shape

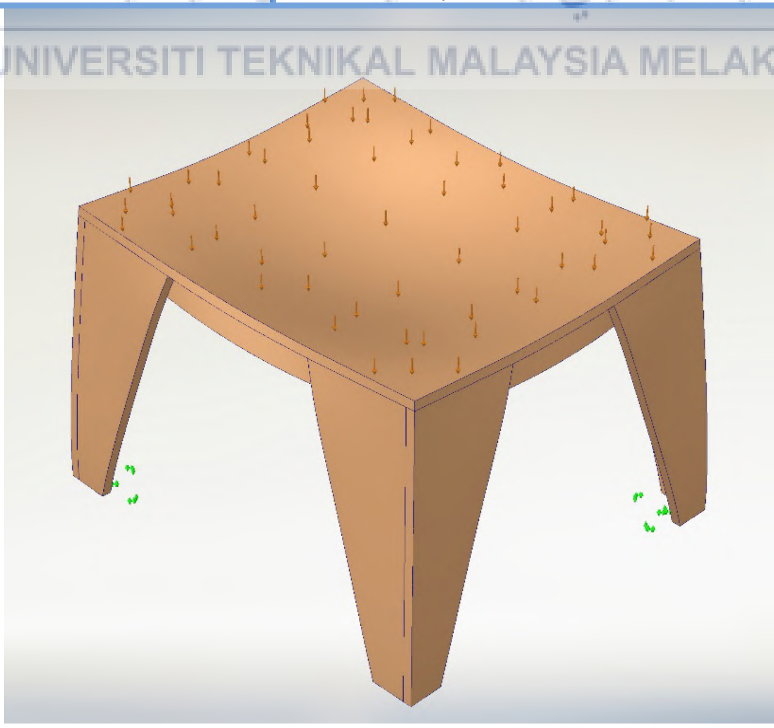


Table Only-Table Load Test-Displacement-Displacement1{1}

Name	Type	Min	Max
Factor of Safety	Automatic	6.113e+00 Node: 6930	6.605e+02 Node: 12487

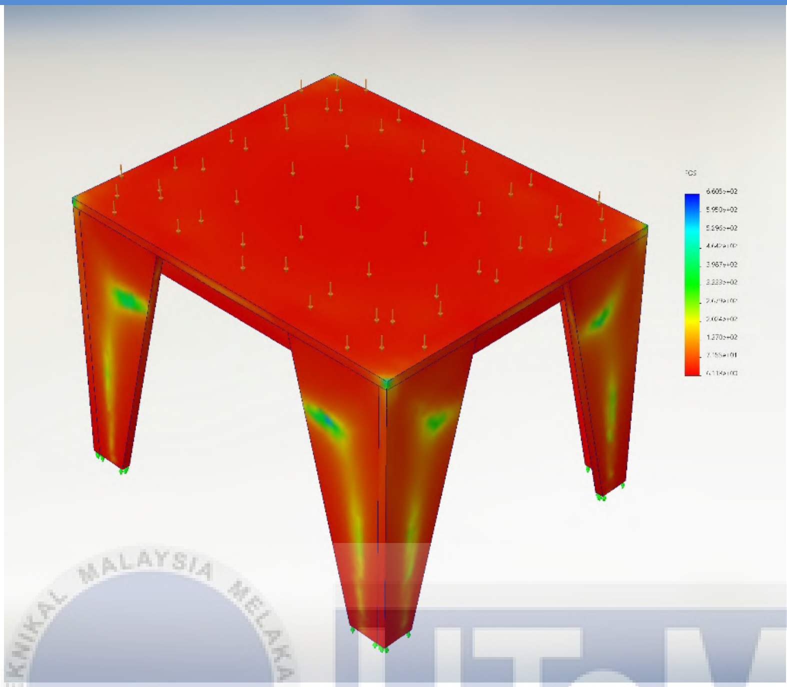


Table Only-Table Load Test-Factor of Safety-Factor of Safety

Observing the simulation results we can understand that the weakest point of the table structure is in the middle of the table surface as seen in in the strain and displacement plot. We can also see in the stress and strain map that the table support elements are exercising their purpose as the colors are skewing towards closer to red on the lower edge of the support beams. This indicates they are meaningfully contributing to the overall stable structure's strength and rigidity. The factor of safety map indicates that overall the structure is more than rigid enough to be used for its intended purpose. Based what we have understood, a recommendation can be made to add support structures in the middle of the table to improve the weak points.

4.4.4.3 Subwoofer Enclosure CFD

In regards to the CFD simulation of the subwoofer enclosure, the aim is to simulate and observe the effects of pressure fluctuations caused by the subwoofer playing bass frequencies. Because bass frequencies are fluctuating pressure waves over time, the time-dependent check box will be ticked. The analysis type will be defined as internal, the fluid as air and the appropriate flow type which will be left default for this simulation. Figure 4-17 &18 shows the analysis setup.

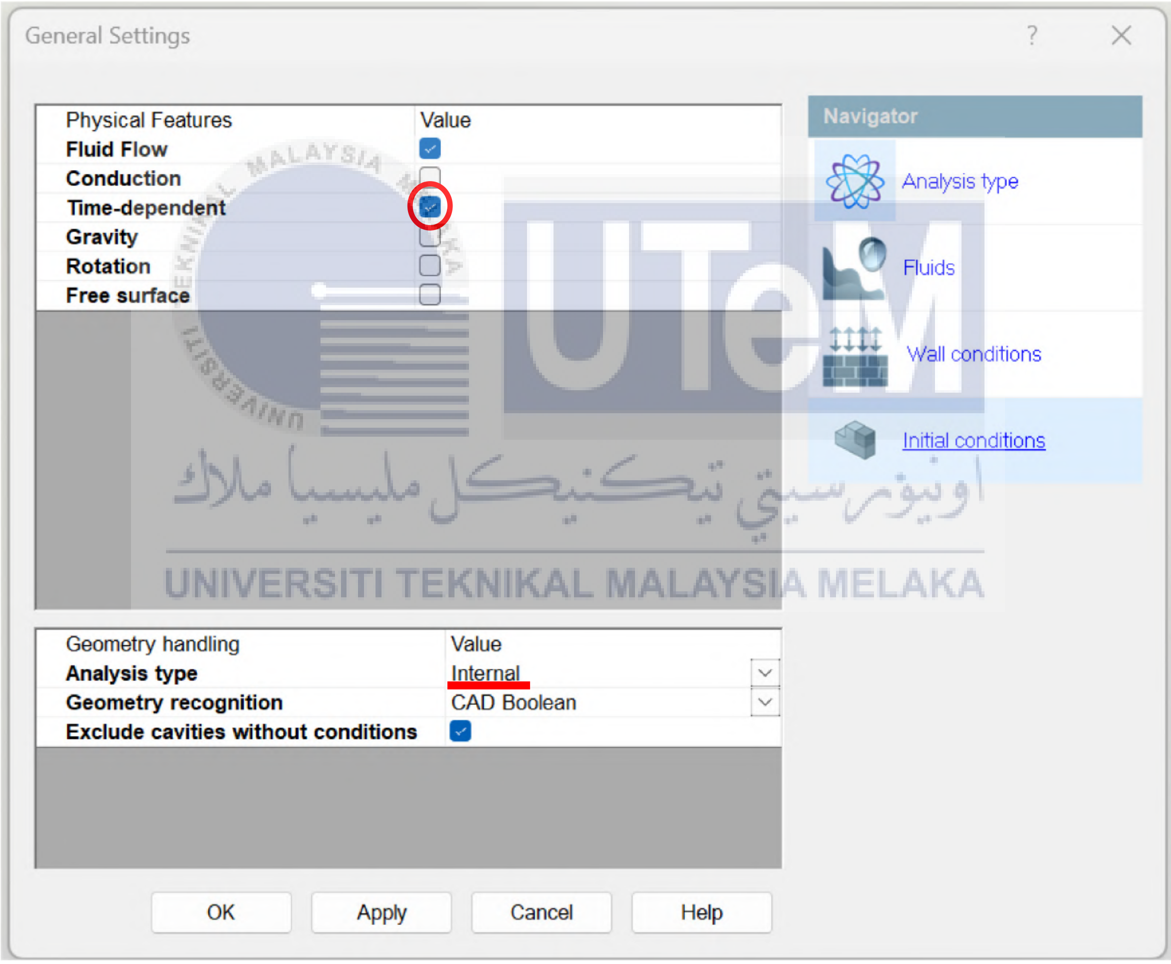


Figure 4-17 CFD Setup 1

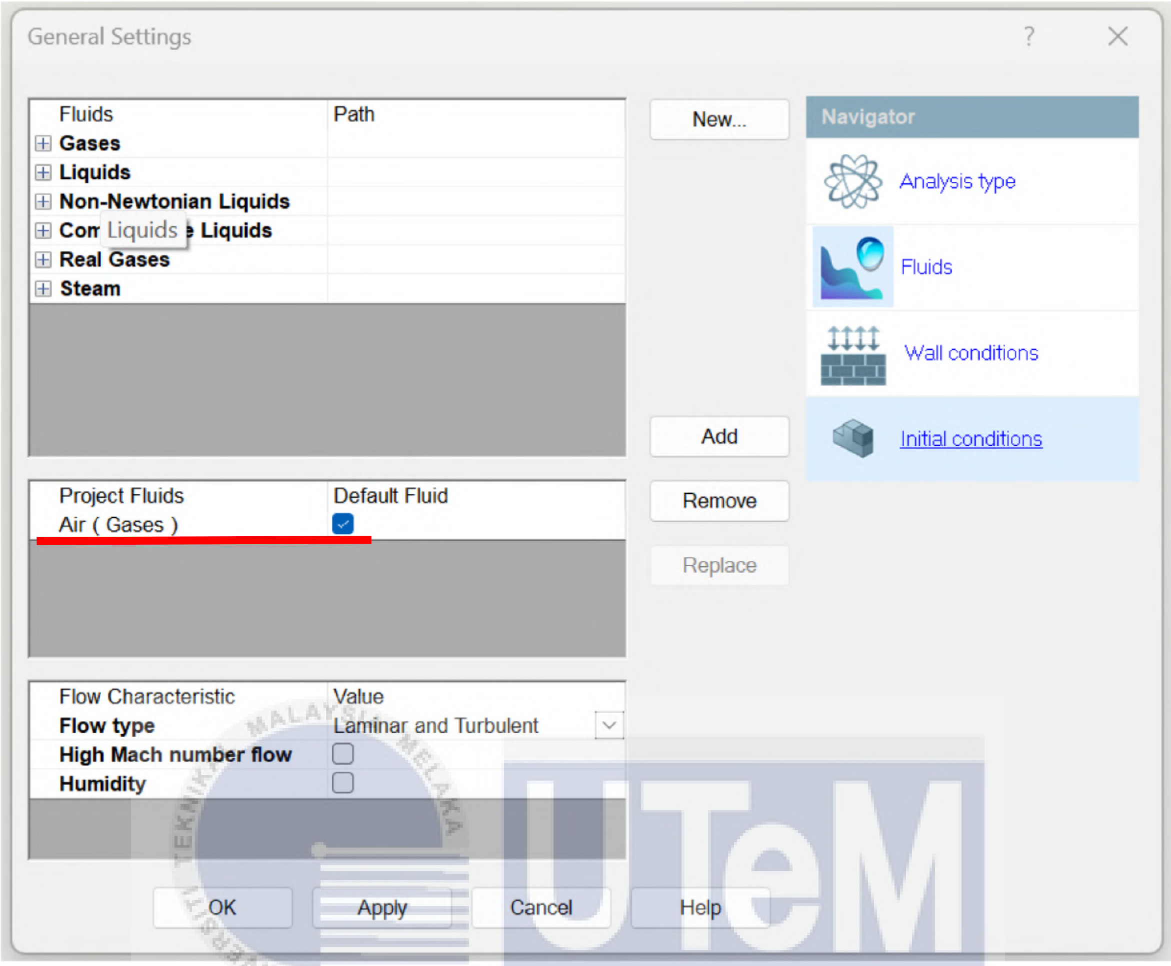


Figure 4-18 CFD Setup 2

In the calculation control options, we will set the physical time to 1s for ease of calculation during the later stages of the simulation setup. This is because frequency in (Hz) is defined as oscillations over time in seconds. Figure 4-19 shows the setup mentioned.

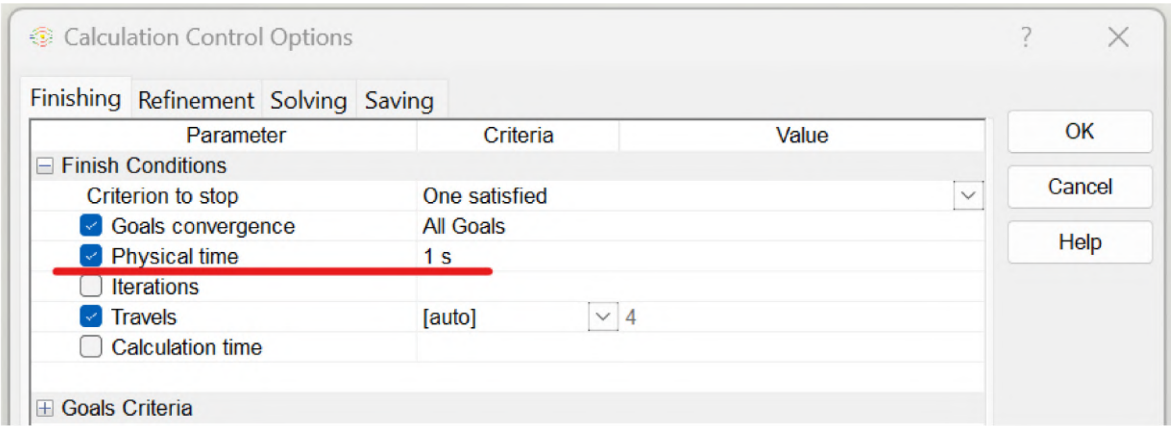


Figure 4-19 CFD Setup 3

Openings in the internal volume of the enclosure needs to be closed with the LID feature and subsequently the computational domain of the simulation will be automatically calculated by the software. After that, boundary conditions as shown below will be used for the ports and subwoofer driver mounting hole. Figure 4-20 shows the lids closing openings that allow the internal boundary of the simulation to be defined.

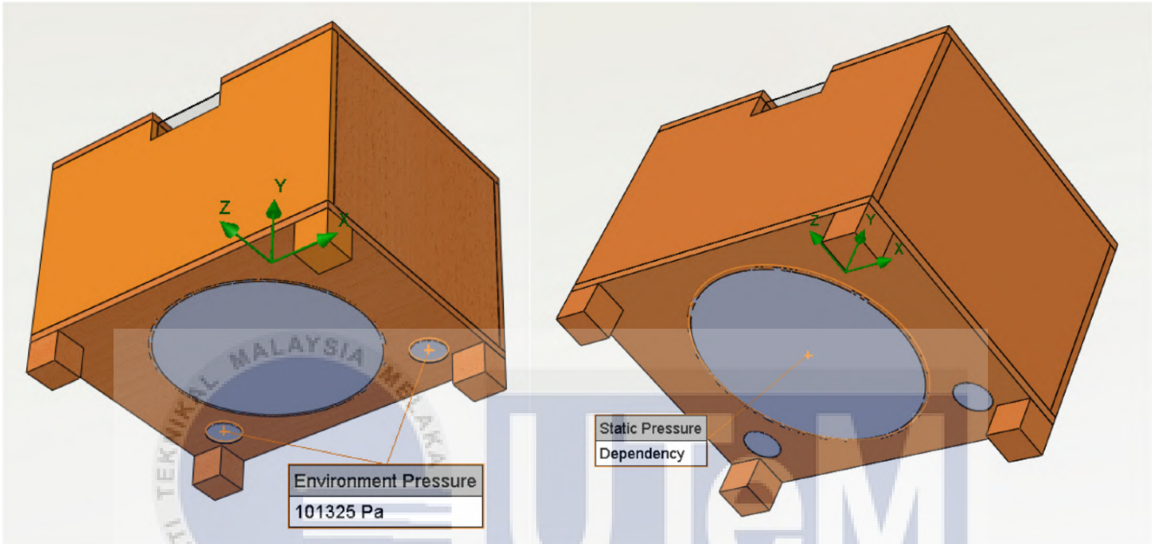


Figure 4-20 CFD Setup 4

In this simulation we are testing the targeted port tuning frequency of 32Hz and assuming a cone excursion of 1inch (2.54cm) which is slightly above normal volume for the subwoofer driver unit we have chosen. The pressure at the subwoofer mounting hole is fluctuating over time due to the cone excursions and this needs to be manually calculated and entered into the simulation software. The data that needs to be entered into the simulation software is the pressure value at every 1/32 second interval to simulate the 32Hz driver frequency as in figure 4-21 shown below.

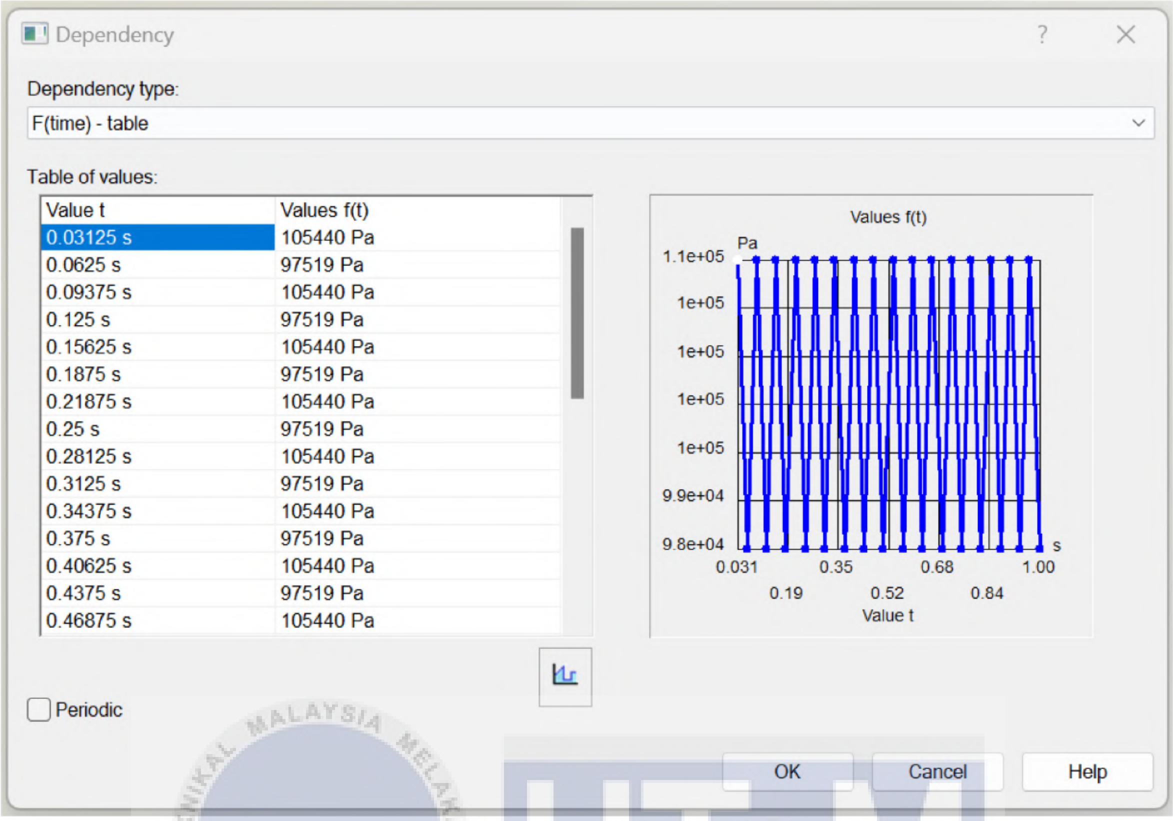


Figure 4-21 CFD Setup 5

To find the pressure value during the push and pull excursion of the subwoofer cone, we will be using Boyle's law calculator (*Boyle's Law Calculator*, n.d.). We will be able determine the pressure by adding or subtracting the volumetric displacement of the subwoofer during its push and pull excursions at 1inch (2.54cm) from the volume of the subwoofer enclosure. This volumetric displacement of the subwoofer is calculated by multiplying the cone area of the subwoofer with its excursion which is 1inch in this case. The calculated volumetric displacement for our chosen subwoofer unit is 1,853.33 cm cube at 1inch. The volume of the subwoofer enclosure is 47,483.016 cm cube. The initial pressure before push or pull excursion will be atmospheric pressure. These are the values used to enter into the Boyle's law calculator as seen in figure 4-22 below.

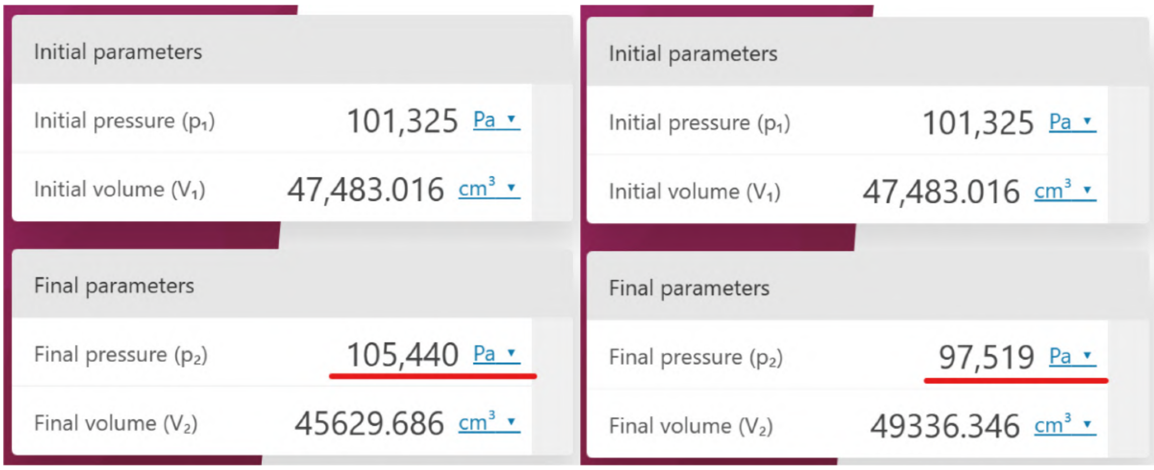
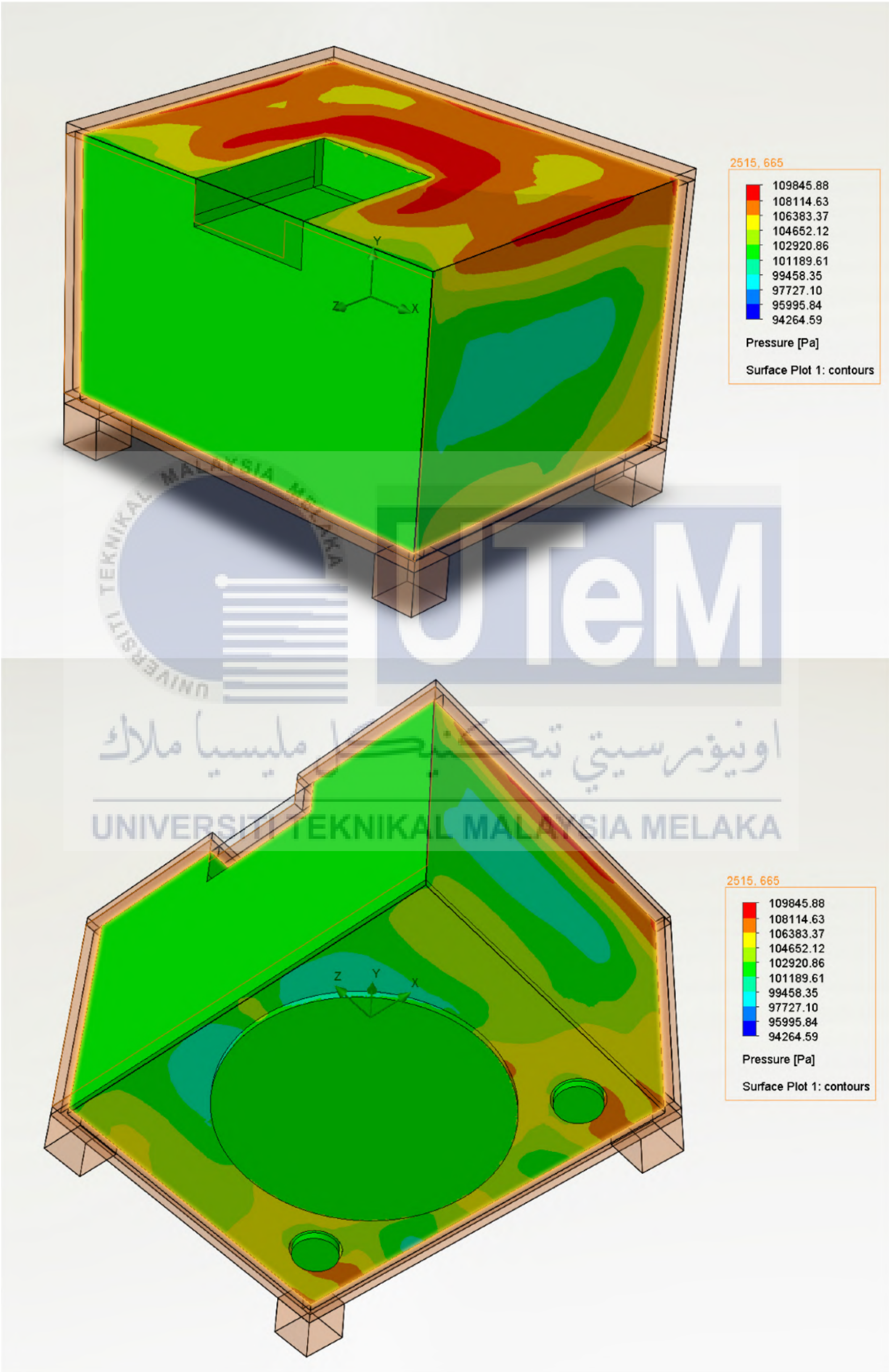


Figure 4-22 Boyle's law calculator

4.4.4.4 CFD of Subwoofer Enclosure Results

Figure 4-23 shows the visualization of the results of our simulation.



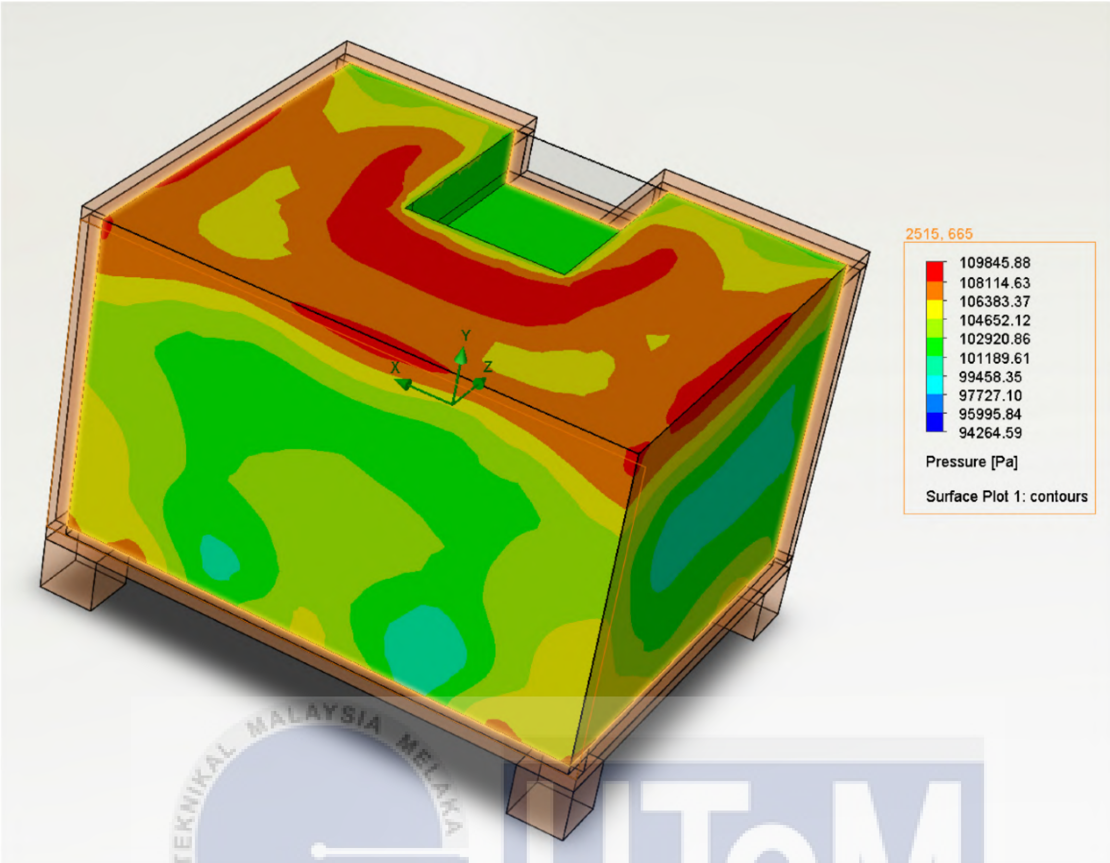


Figure 4-23 CFD Results

Observing the simulation results, we see that the top surface of the enclosure experiences the highest pressures and the sides of the enclosure experiences the least pressures. Because the enclosure is an acoustic chamber, any surface that deviates the furthest from atmospheric pressure whether it be higher or lower pressure is considered a weak result and can be resonant. The green color shows the ideal surface pressures and anything closer to red or blue is considered less ideal. According to the results, if any improvements in the design were to be made, they should be done to reinforce the top and side surface structures to reduce the subwoofer enclosure chamber resonance.

4.4.5 Photorealistic Rendering

The figures below show the photorealistic rendering made of the chosen colors and surface finish intended for the final prototype.

Figure 4-24 Render 1

Figure 4-25 Render 2

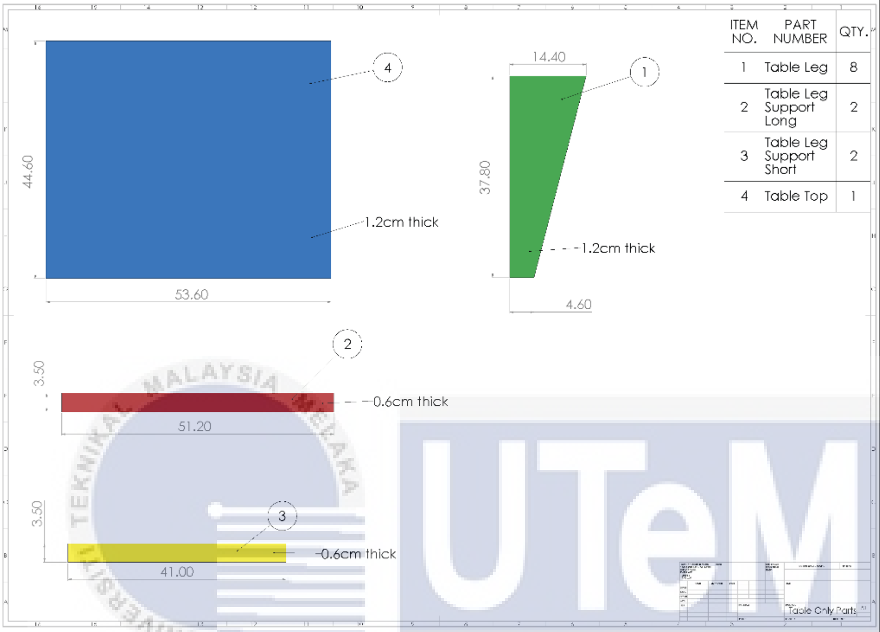
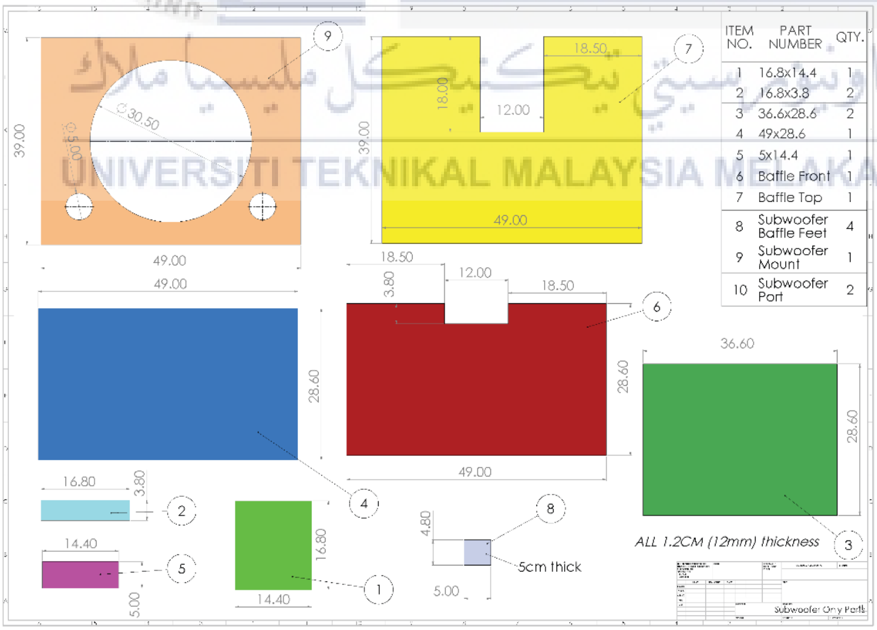
Figure 4-26 Render 3

Figure 4-27 Render 4

4.5 Prototype Fabrication

The table below shows the process of fabricating the prototype from start to finish.

Table 4-5 Fabrication Process

No	Process	Description
1	Purchase Parts, Wiring and MDF Wood Boards and PVC Pipe	-
2		A drawing that includes dimensions of each piece MDF wood piece with quantity is prepared.

3		Each piece is cut out from the MDF wood boards based on the drawing made and the PVC pipe is also cut to length.

4	  	The MDF boards are assembled and fixed together using nails and glue.

5	 	Fitment testing is performed to ensure all the parts fit together as intended.

		
5		The remainder of the build is completed.

6		The furniture is painted with a primer.

7	 	Final layer of paint is applied with colors matching the 3D render.

8		The subwoofer is reinstalled and the wiring is soldered to the subwoofer and speaker terminal. The speaker terminal is also installed.

9	 	The build of the prototype is completed

4.6 Acoustic Refinement

The acoustic refinement is done by performing a frequency sweep and observing unwanted vibrations on the furniture as well as listening for harsh peaks of loudness in specific frequencies and correcting both problems via DSP. The equipment used include a PC and Equalizer APO Software with Fab Filter Pro Q2 plugin. The last software in the given equipment description above is a DSP used to develop a frequency response compensation EQ file that will correct excess vibrations caused by the speaker system of our product. The figure below shows our custom developed EQ graph made to compensate for the non-linear acoustic response of our subwoofer. Figure 4-28 shows the frequency response graph that was created.

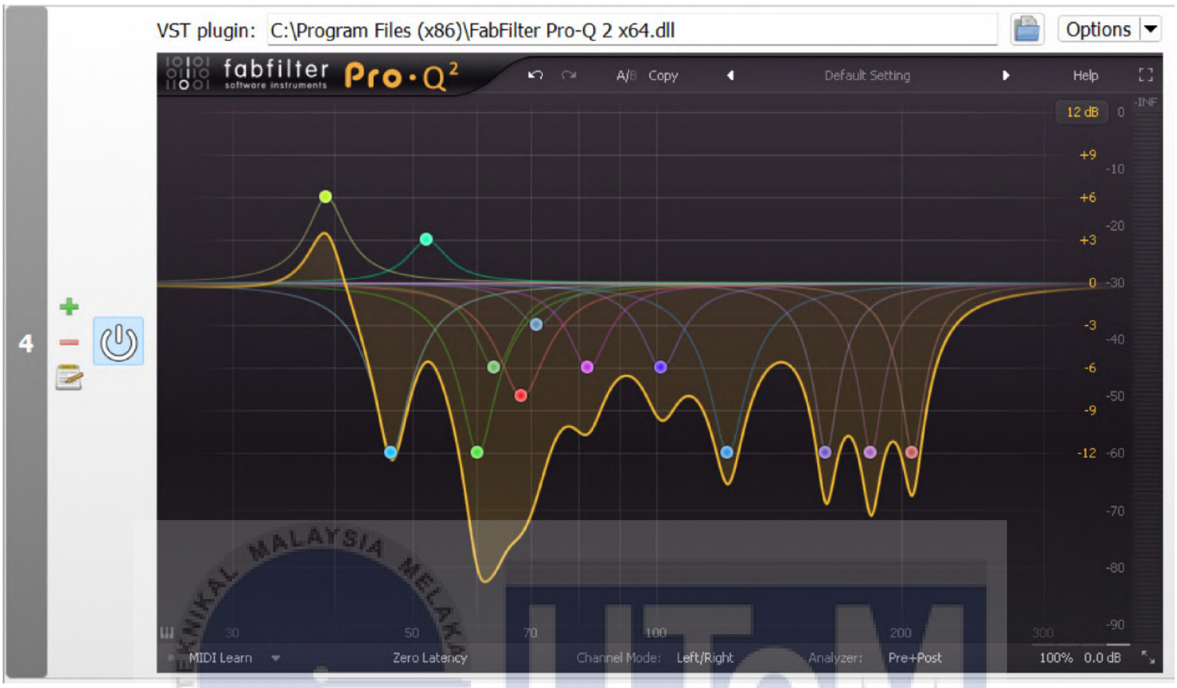


Figure 4-28 Developed frequency response compensation graph.

4.7 Usability Test

To assess the usability of this product, a survey will be carried out using a modified SUS (System Usability Scale) questionnaire. The modification is only done via a custom set of statements instead of using the standardized ones. A system usability test uses real users' interactions to assess how user-friendly and satisfying a product or service is. It can assist in locating design defects, usability problems, user preferences, and user satisfaction levels. A typical System Usability Test involves giving users a set of tasks to complete using the product or service while researchers gather information about their actions, comments, and feelings. (Sauro, 2011)

The SUS is a standardized set of ten questions with five-point Likert scales from Strongly Agree to Strongly Disagree on each item. Based on the subjective opinions of users, the SUS can offer a fast and accurate usability score for a product or service. To compute the SUS score, multiply the total by 2.5 after converting each response to a new number. Converting each response to a new number depends on the nature of the statements. A positive statement takes the value and subtracts 1 from it while a negative statement takes the value and subtracts from 5. The SUS score is not a percentage; rather, it is a number between 0 and 100. One can interpret the SUS score by normalizing it to a percentile ranking or by comparing it to the average score of 68. (Sauro, 2011)

	The System Usability Scale Standard Version	Strongly Disagree 1	2	3	4	Strongly Agree 5
1	I think that I would like to use this system frequently.	O	O	O	O	O
2	I found the system unnecessarily complex.	O	O	O	O	O
3	I thought the system was easy to use.	O	O	O	O	O
4	I think that I would need the support of a technical person to be able to use this system.	O	O	O	O	O
5	I found the various functions in this system were well integrated.	O	O	O	O	O
6	I thought there was too much inconsistency in this system.	O	O	O	O	O
7	I would imagine that most people would learn to use this system very quickly.	O	O	O	O	O
8	I found the system very awkward to use.	O	O	O	O	O
9	I felt very confident using the system.	O	O	O	O	O
10	I needed to learn a lot of things before I could get going with this system.	O	O	O	O	O

Table 4-6 Standardized Questions of SUS (Sauro, 2011)

QUESTIONS	Responses	Deviation	SUS
Q1	5	-1	4
Q2	1	-5	4
Q3	4	-1	3
Q4	1	-5	4
Q5	5	-1	4
Q6	4	-5	1
Q7	3	-1	2
Q8	2	-5	3
Q9	5	-1	4
Q10	1	-5	4
SUM OF SUS:			33
MULTIPLY BY 2.5			82.5

The example above is only for 1 participant. You should have at least five.

1. Odd numbered question deviation: Response – 1 = SUS
   Even numbered question deviation: 5 – Response = SUS
2. Total the SUS for all 10 questions.
3. Multiply the total from step two by 2.5.
4. Repeat steps 1 through 3 for all participants.
5. Total the SUS for all participants & divide the total by the number of participants to get the average.

Table 4-7 SUS Calculation Method (Sauro, 2011)

4.7.1 Questionnaire

The table below shows the questionnaire used in our survey.

Table 4-8 Questionnaire

System Usability Scale						
No.	Statements	Strongly Disagree				Strongly Agree
1	The product has good sound quality	1	2	3	4	5
2	The product functions well as a coffee table	1	2	3	4	5
3	The product's appearance is pleasing	1	2	3	4	5
4	The product fits well in a home space	1	2	3	4	5
5	The product is easy to set up	1	2	3	4	5
6	The sound system of the product does not interfere with the use of the coffee table	1	2	3	4	5
7	The product's build quality feels sturdy	1	2	3	4	5
8	The product is practical to use	1	2	3	4	5
9	The product's size and dimensions are appropriate	1	2	3	4	5
10	The product can be easily maintained or repaired	1	2	3	4	5

4.7.2 Questionnaire Results

The table below shows the results of our survey.

Table 4-9 Questionnaire Results

No.	Statements	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Average
1	The product has good sound quality	4	4	4	4	4	4	4	4	4	4	
2	The product functions well as a coffee table	5	5	4	5	5	5	4	5	4	5	
3	The product's appearance is pleasing	5	4	5	5	4	5	5	5	4	5	
4	The product fits well in a home space	5	4	4	5	5	5	4	5	4	5	
5	The product is easy to set up	3	3	3	4	3	4	2	4	2	4	
6	The sound system of the product does not interfere with the use of the coffee table	5	5	4	5	4	4	4	5	4	5	
7	The product's build quality feels sturdy	4	4	4	5	5	5	4	5	4	5	
8	The product is practical to use	4	5	4	4	4	4	4	4	4	5	
9	The product's size and dimensions are appropriate	5	5	5	5	5	5	4	5	4	5	
10	The product can be easily maintained or repaired	4	3	4	5	4	4	4	5	3	5	
Raw Score		34	32	31	37	33	35	29	37	27	38	33
Final Score		85	80	78	93	83	88	73	93	68	95	**83**

The respondents' backgrounds are university students and white-collar workers. The results show generally a high score on average on most statements except for ease of set up which scores average across the respondents. Overall, the average final score was 83.

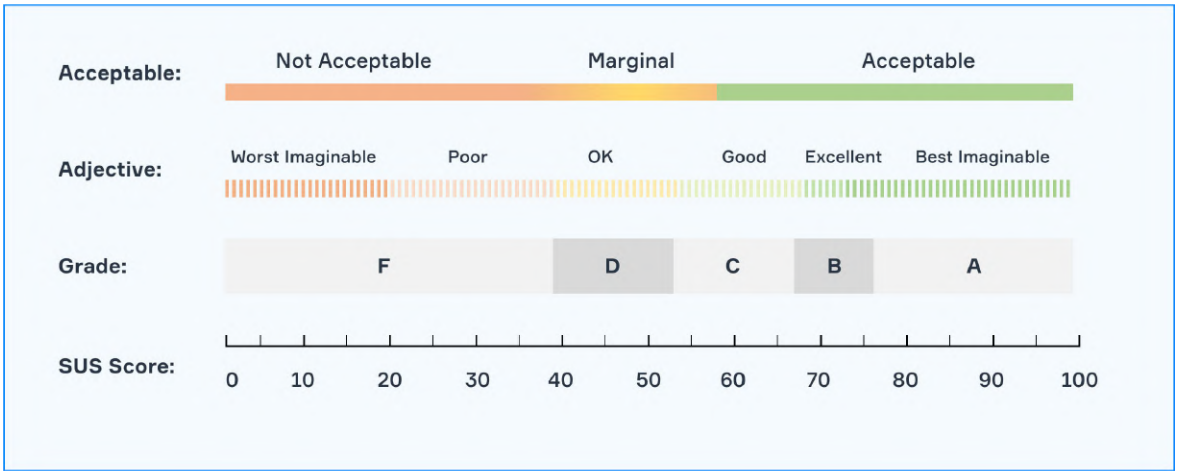


Figure 4-29 SUS Scoring Guide (*What Is System Usability Scale (SUS)? | FlowMapp Design Blog*, n.d.)

Based on the SUS scoring guides our product receives an excellent rating and an A grade for the usability test. This score is not the final determining factor on the products competence nor is it fully encompassing result. There are still many improvements that can be made to the design and fabrication process in the many iterations to come. This result serves to prove that the concept of this project is viable to be developed further and deserves time and research to make it into a new product category that becomes something common in the marketplace.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, the ideal furniture and loudspeaker combination, components and acoustic chamber (loudspeaker cabinet) design was determined from the concept design process that is guided by the design specifications derived from the QFD process. The most compatible furniture material for the chosen concept design was derived by researching and comparing different materials and their properties to achieve the best furniture rigidity and manufacturability. The internal structure design that was chosen was based on which method fits the concept design the most as well as which does the best vibration damping to minimize vibration transfer from the loudspeaker used. A detailed design of the chosen Furniture Loudspeaker Hybrid concept was made with CAD Software and evaluated and optimized using CAE Software.

5.2 Recommendation

There are still many improvements that can be made to the design and fabrication process. One of my recommendations for future design improvements is to add extra internal bracing to minimize the effects of the high-pressure zone (red) seen in the CFD simulation results in Chapter 4.4.4.4. Other than that, the usability test evaluation method should be improved to include subjective comments from respondents so there can be more valuable information that can be derived from the testing and evaluation process.

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APPENDICES

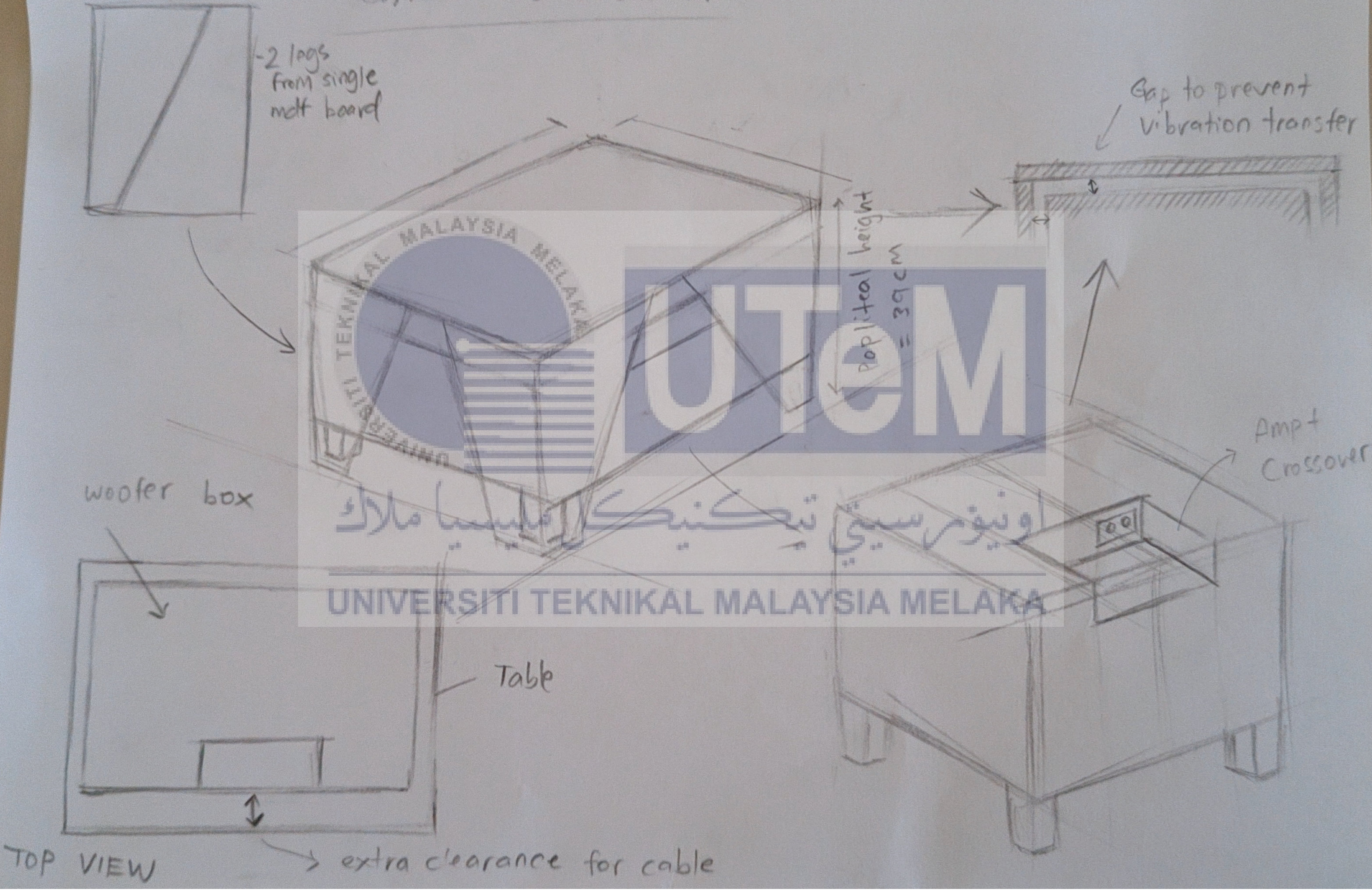
APPENDIX A PSM 1 Gantt chart

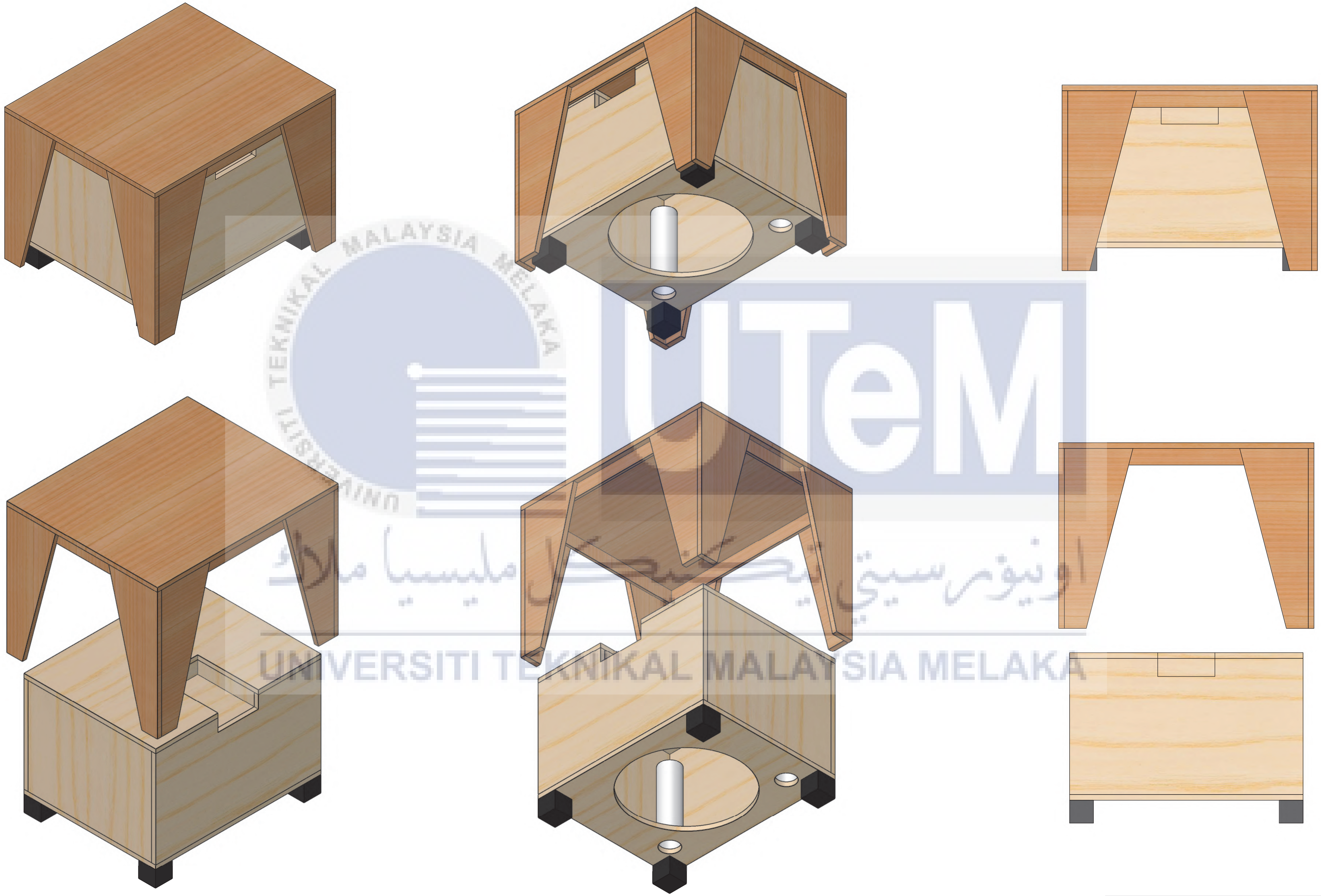
A.PROJECT PLANNING														
2022														
Project Activity	March		April				May				June			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PSM 1														
PSM briefing by course coordinator														
Meeting with supervisor														
Literature Review Material Collection														
Problem statement and objectives identification														
Furniture Design Reasearch														
Acoustic Tuning Research														
Prototype Fabrication Method Search														
Components and Material Research														
Realistic Project Flow Planning														
Patent Search														
Thesis Writing														
Thesis writing on report chapter 1														
Thesis writing on report chapter 2														
Thesis writing on report chapter 3														
Evaluation														
Draft submission														
Thesis submission														
Presentation														

PSM 2 Gantt chart

PROJECT PLANNING														
2024														
Project Activity	October			November				December				January		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PSM 2														
PSM briefing by course coordinator														
Meeting with supervisor														
Deriving User Requirements														
House of Quality (QFD)														
Morphological Chart														
Preliminary Concept Design and Concept Selection														
Developed Concept Design and Final Concept Selection														
Parts and material selection and CAD design														
Design Analysis, FEA and CFD														
Prototype Fabrication														
Acoustic Tuning via DSP and Usability Testing														
Report Writing														
Presenting														

Coffee Table Subwoofer





UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

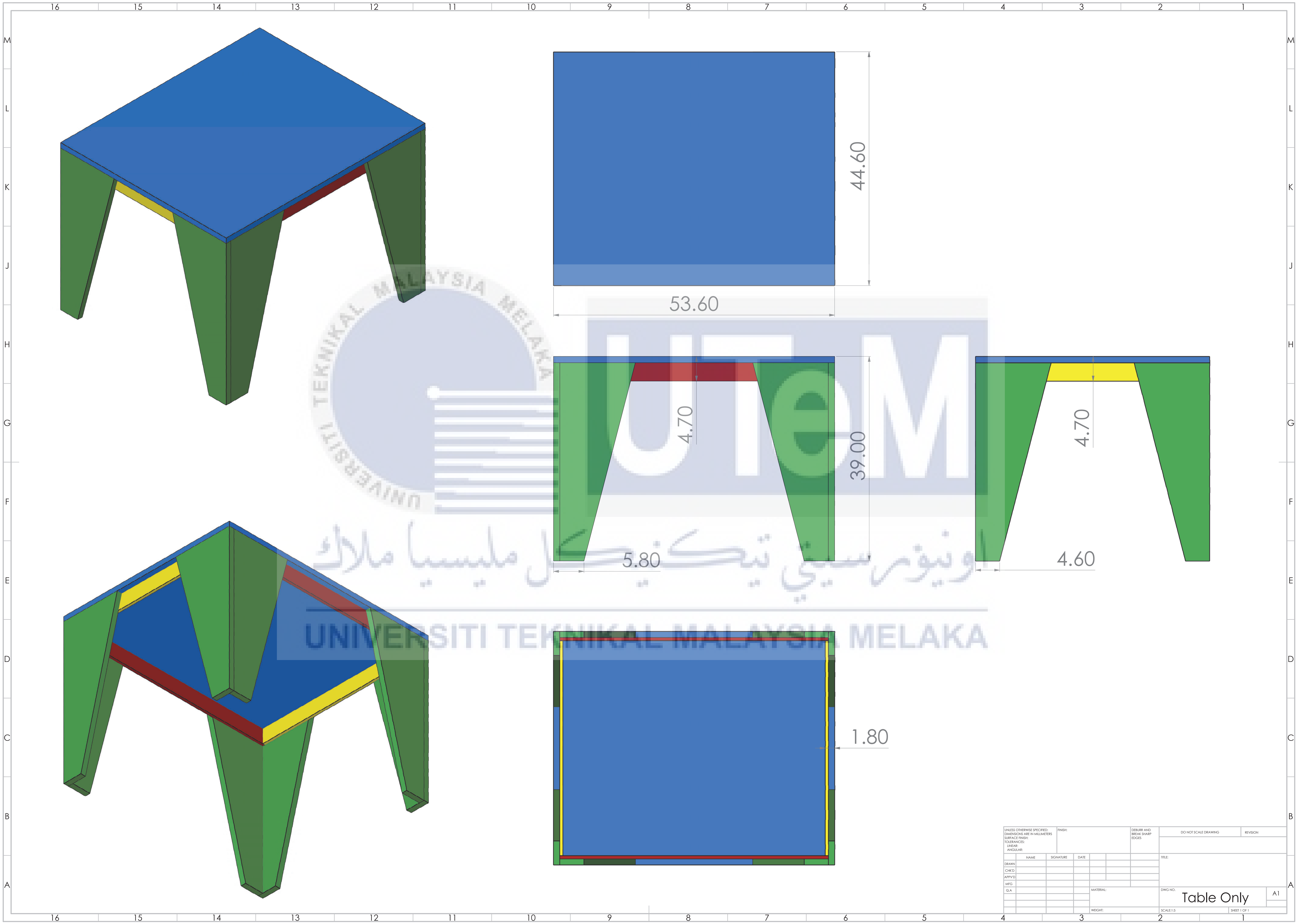
Coffee Table Subwoofer

A1

WEIGHT:

SCALE:1:5

SHEET 1 OF 1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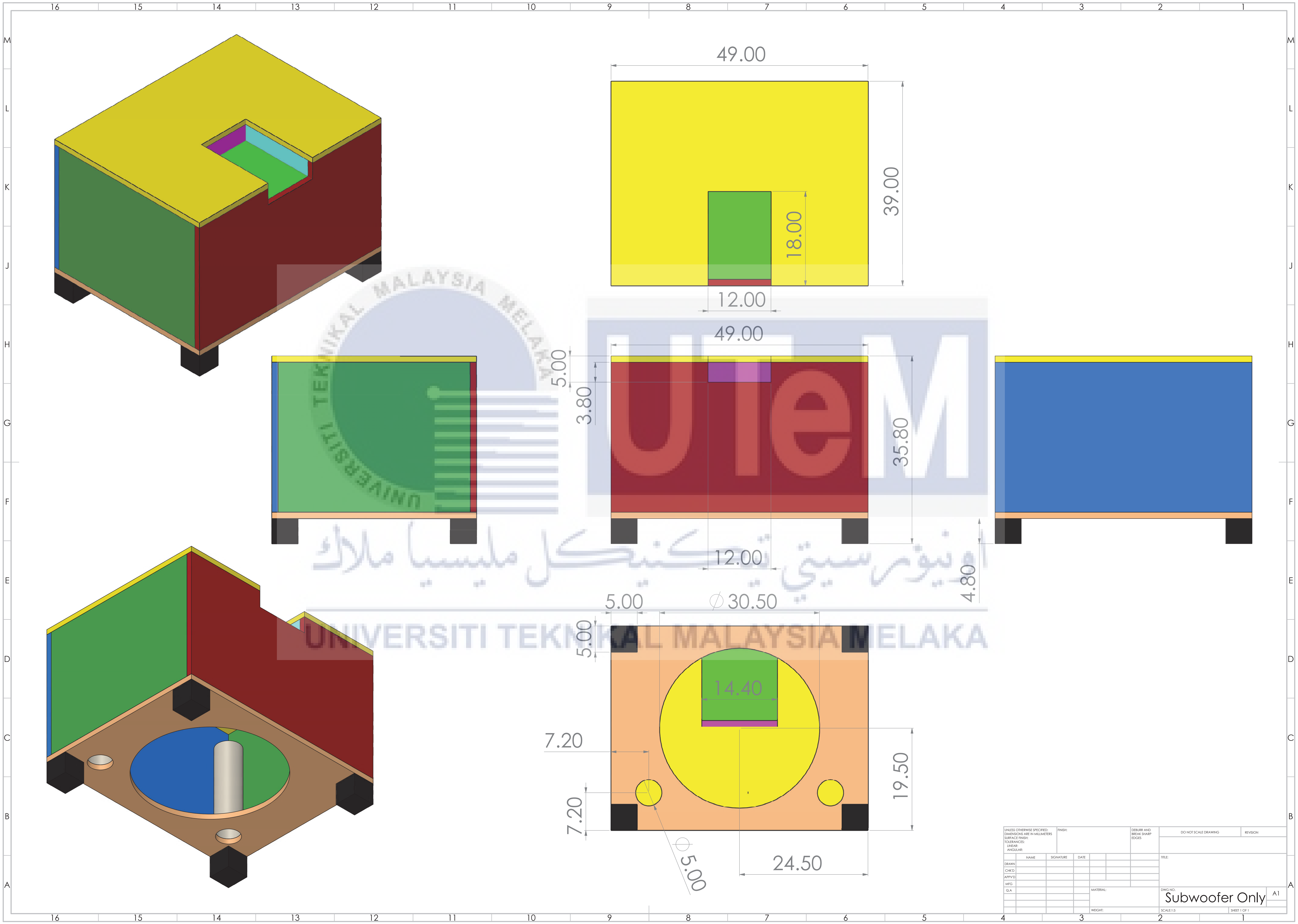
4.70
4.60
1.80
Table Only
A1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39.00
18.00
12.00
49.00
5.00
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35.80
12.00
4.80
5.00
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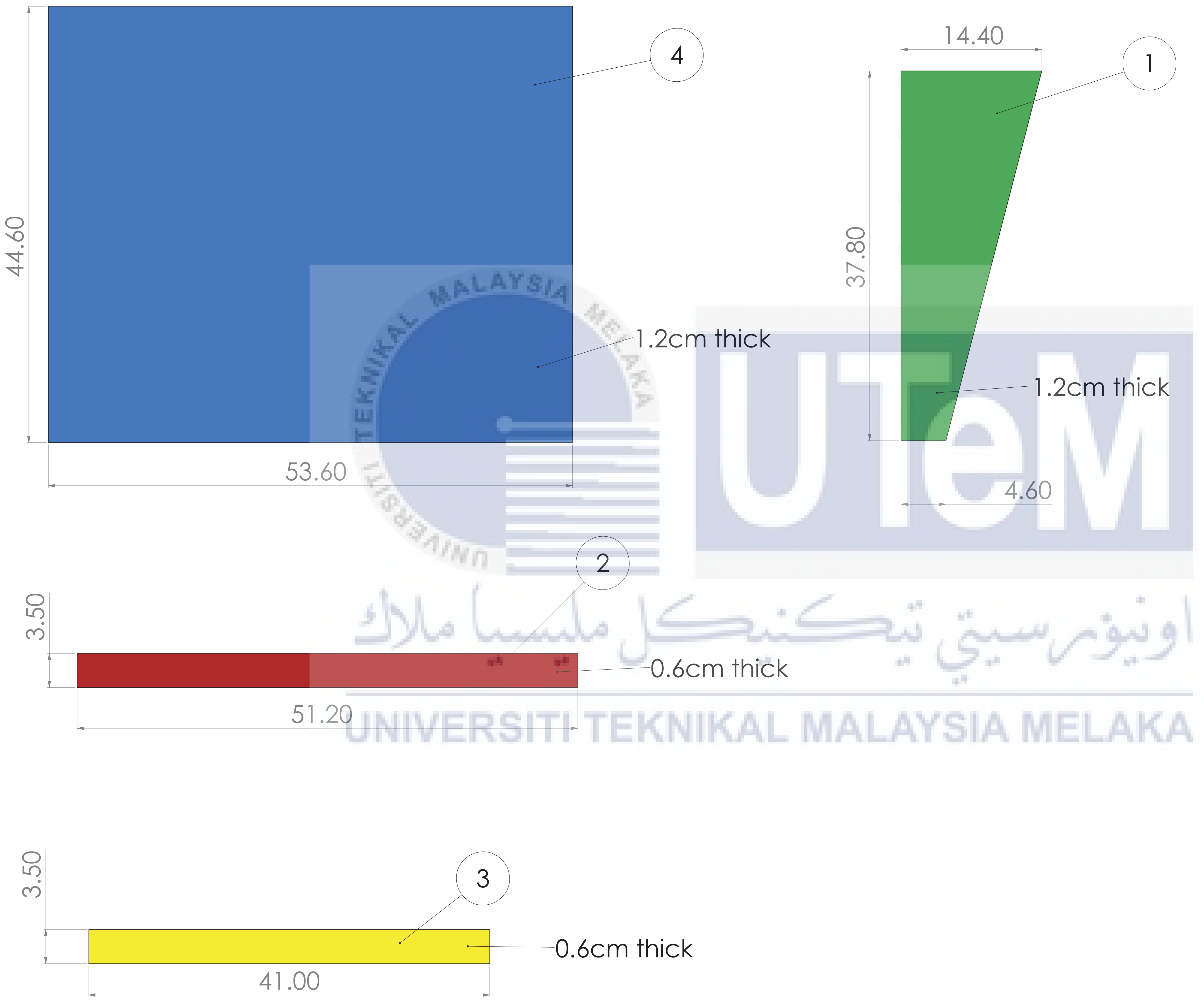
5.00
14.40
7.20
7.20
19.50
⌀5.00
24.50
DO NOT SCALE DRAWING
REVISION
Subwoofer Only
A1

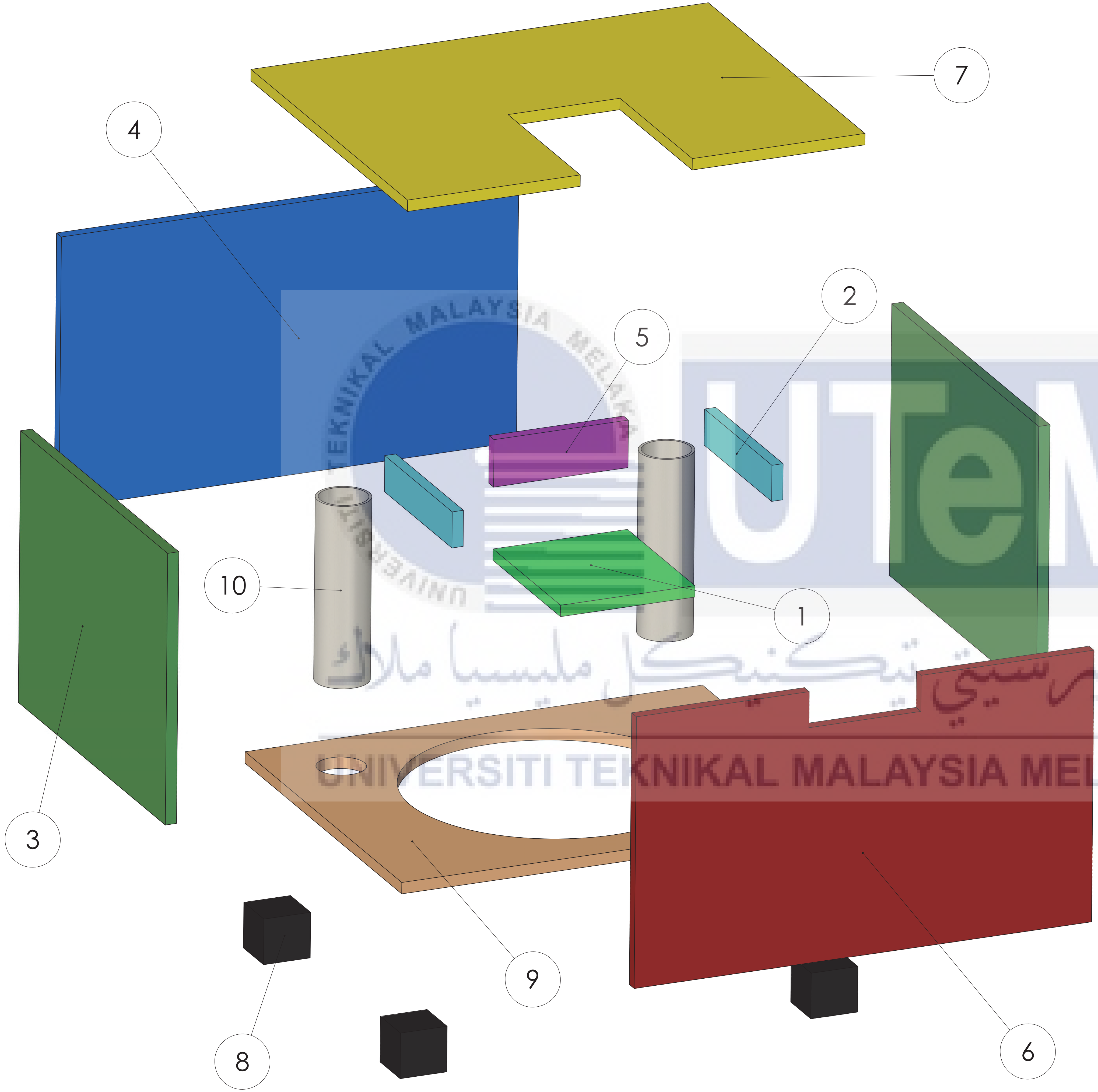
ITEM NO.	PART NUMBER	QTY.
1	Table Leg	8
2	Table Leg Support Long	2
3	Table Leg Support Short	2
4	Table Top	1

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:	DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE:
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A			MATERIAL:	DWG NO. Table Only Exploded A1
			WEIGHT:	SCALE:1:5 SHEET 1 OF 1



ITEM NO.	PART NUMBER	QTY.
1	Table Leg	8
2	Table Leg Support Long	2
3	Table Leg Support Short	2
4	Table Top	1

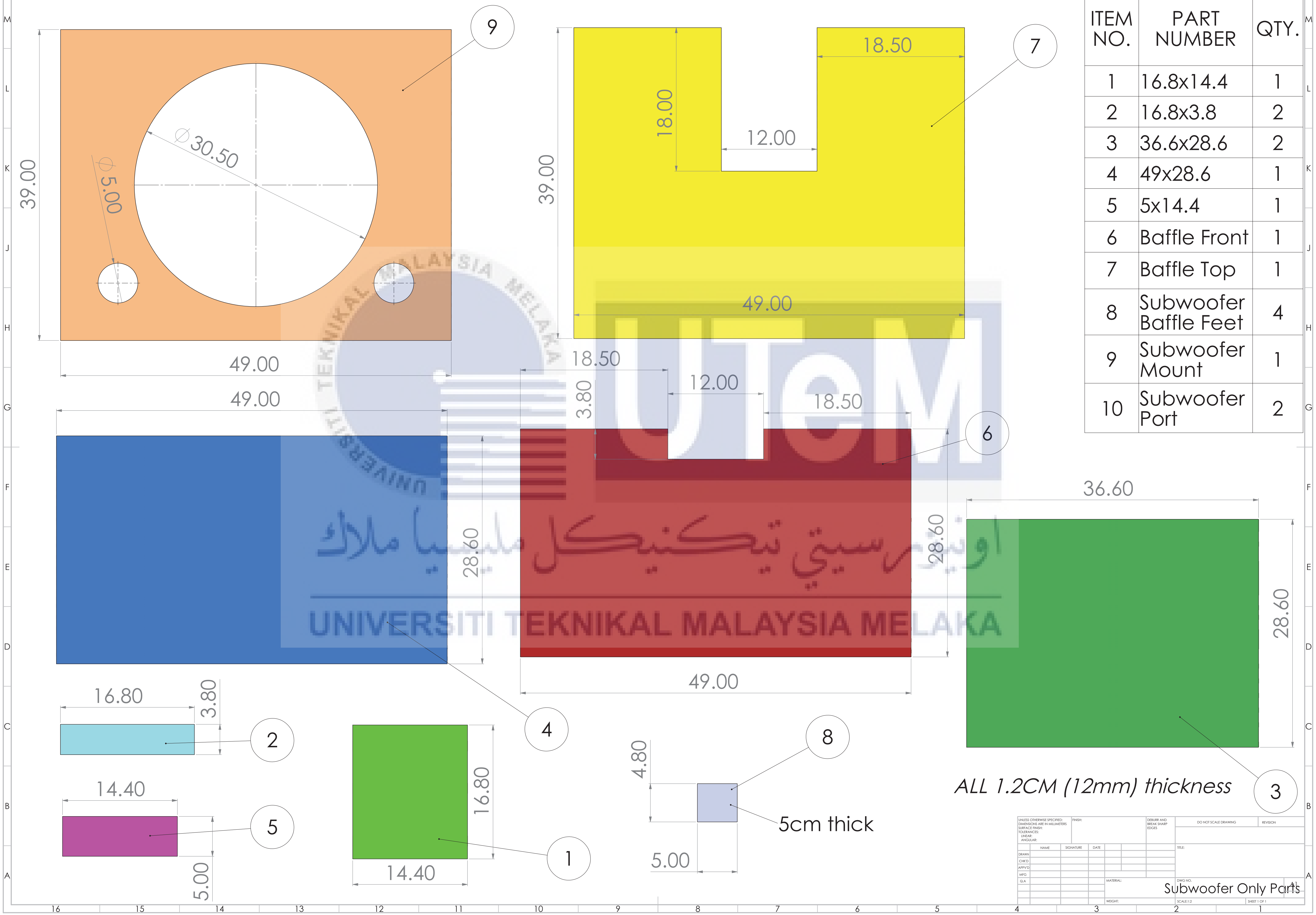
Table Only Parts A1



ITEM NO.	PART NUMBER	QTY.
1	16.8x14.4	1
2	16.8x3.8	2
3	36.6x28.6	2
4	49x28.6	1
5	5x14.4	1
6	Baffle Front	1
7	Baffle Top	1
8	Subwoofer Baffle Feet	4
9	Subwoofer Mount	1
10	Subwoofer Port	2

Subwoofer Only Exploded

ITEM NO.	PART NUMBER	QTY.
1	16.8x14.4	1
2	16.8x3.8	2
3	36.6x28.6	2
4	49x28.6	1
5	5x14.4	1
6	Baffle Front	1
7	Baffle Top	1
8	Subwoofer Baffle Feet	4
9	Subwoofer Mount	1
10	Subwoofer Port	2



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