Design of the FloBoat

A Floating Beach Wheelchair

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A thesis submitted for the degree of Master of Science in Engineering with Innovation and Entrepreneurship By

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I Miriam Salah Shaker Said, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Wheelchair users make up 1% of the global population. The increased social awareness of immobile individuals across the past century has driven engineers into creating the adaptable wheelchair design seen in the present day. Technology advances have brought about the increased integration of wheelchair users into society by providing support; in completing daily tasks and in participating in specific leisure activities, however, the majority of water activities remain inaccessible.

Therefore, a design opportunity was recognised which subsequently fuelled this study in creating the FloBoat, a wheelchair that provides support to individuals when in the water and on the beach. The FloBoat journeyed through a rigorous design approach, fulfilling the necessary design requirements to operate with maximum functionality and effectiveness. Throughout the design analysis, investigations were completed on design tasks such as material selection, hydrostatics and stability.

Finite Element Analysis alongside a material selection database, GRANTA EduPack, deduced component materials and a suitable fibre layup for the CFRP-based chair body. The FloBoat demonstrated the ability to float and achieved an average draft of 659mm at 26.4° from the base. Stability in water was additionally attained when the metacentric height of the final design was calculated to be 0.0014m indicating initial device stability. The final design was created as a Computer-Aided Design model.

Manufacturing and business plans were subsequently compiled to assess the financial feasibility of the FloBoat. The pricing model achieved a healthy gross margin averaging to 67.8% leading to 5-year projections that indicate a breakeven point in the first operating year after 146 sales.

This design study has fashioned an economical device that can effectively support immobile individuals in enjoying the water whilst maintaining health, safety and durability standards.

Acknowledgements

I would like to express my sincere gratitude to my project supervisor Professor Giles Thomas for his undeniable help and support throughout this project. I would also like to thank my family for their constant support when completing this project especially during the difficult times of this pandemic. Above all, I would like to give thanks to my Lord God for guiding me and showing constant compassion in trying times.

Contents

Nomenclature

A	Cross-Sectional Area
ACP	ANSYS Composite PrepPost
b	Box
c	Cylinder
CAD	Computer-Aided Design
CFRP	Carbon Fibre Reinforced Plastic
CoG	Centre of Gravity
CoM	Centre of Mass
F_b	Buoyant Force
FEA	Finite Element Analysis
g	Acceleration due to Gravity
GFRP	Glass Fibre Reinforced Plastic
GM	Metacentric Stability
h	Human Body
I_{xx}	Second Moment of Area of water plane about Heel Axis
KB	Vertical distance of Centre of Buoyancy
KG	Vertical distance of Centre of Gravity
m	Mass
T	Draft
V_s	Displaced Water Volume
θ	Angle Between the Centre of Buoyancy and the Centre of Mass.
ρ	Density
Φ	Angle of Inclination

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Introduction

Background

The wheelchair invention dates back to the 1600s when Stephan Farfler, a German clockmaker, designed the first self-propelled wheelchair for his mobility as a result of his long-term back injury. Throughout the centuries the wheelchair design has been advanced and perfected, significantly improving the quality of life of elderly and disabled people. Wheelchair users are becoming more integrated into society, completing normal day to day activities with ease and participating in leisure and sporting activities that accommodate wheelchair use. Nevertheless, several activities that cannot accommodate wheelchair use remain.

Design Opportunity

There are many mechanical devices that aid in improving the quality of life for the Elderly and Disabled, however, this is not the case within a water medium. Limited swimming or water leisure options are available to wheelchair users. Such options are often avoided, due to the difficulty that comes with pursuing them, such as the inability to swim without the necessary support. Currently, there are limited products on the market that accomplish these needs which, therefore, encourages this project in designing a mechanical device capable of operating in water whilst fulfilling specified requirements.

Aim and Objectives

The following aims and objectives are expected to be achieved throughout this design project:

- *A functional mechanical wheelchair design that can float and operate in water.*
- *A wheelchair comprising design qualities exhibited in standard wheelchairs in addition to flotation and stability capabilities.*
- *An economically feasible solution for the development of the final design.*

Thesis Structure

This thesis will first comprise a literature review which will encompass a brief background history of wheelchair designs, the wheelchair design, design considerations and current wheelchairs for beach use. Design requirements will then be outlined to further lead to the creation of multiple concepts deigns. The design analysis section will follow in presenting a unique design approach facilitating the development of the device from the concept design phase to the detailed design phase. A manufacturing and business plan will be composed for the final product outlining; parts lists, manufacturing procedures, supply chains and 5-year financial projections. Finally, a critical analysis and evaluation will evaluate the final product against the project aims.

Literature Review

Background and History of Wheelchairs

Early Discoveries

Wheeled devices such as wheelbarrows have existed for centuries from around 600 AD in Ancient China and Greece. The wheelchair invention later came into being in the late 1500s, where an unknown inventor was documented to have fashioned the first wheelchair for King Philip of Spain, who suffered from gout which negatively affected his walking capabilities. The chair required the assistance of a servant to move but essentially included many of the design features seen in today's wheelchairs such as armrests and footrests (Nias, 2019) (E. Rodrigo, V. Herrera and Diez, 2018).

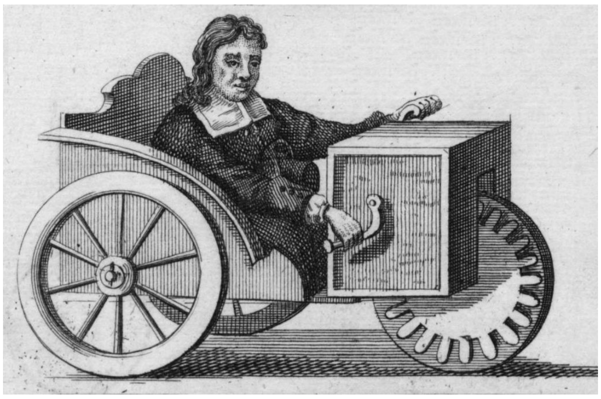


Figure 1 - Engraving of Steven Farfler using his vehicle (Nias, 2019)

Soon after in 1655, Steven Farfler, a 22-year-old German watchmaker, became the first known inventor. Farfler suffered from a broken back injury effecting his general mobility. In effect, his disability motivated him to create the first self-propelled wheelchair in history by mounting a chair onto a three-wheeled chassis. As detailed in Figure 1, the device used cranks and cogwheels to create a system that worked by the turning of handles that were attached to a geared front wheel. Farfler inspired many future inventions such as the hand-cranked chain-driven wheelchair built between1910 and1920 (Nias, 2019).

By 1783, another wheelchair design developed into the well-known "Bath Chair" (named after a well-known town in England at that time) by John Dawson. Bath was a spa town particularly known for its healing mineral waters and physical therapy attracting many sick and disabled people seeking comfort. The 'Bath Chair', displayed in Figure 2, was made to aid in the transportation of many of the visitors and residents wishing to use the facilities with ease of mobility. This chair comprised 3 wheels – two large wheels at the rear end and one small wheel at the front end. The chair also adopted a steering mechanism allowing the consumer to navigate the chair, nevertheless, secondary assistance was required for movement (Nias, 2019).

Figure 2 - 20th century developed "bath chair" (Nias, 2019).

Wheelchair Development

The Bath Chair gained popularity and soon after faced a competitor called the Sedan Chair. This wheelchair assumed a distinctive design of an enclosed box containing a seat attached to poles that were carried by two men. Both the Bath and Sedan Chair were considered a form of transportation for wealthy disabled people across Britain (Nias, 2019). However many problems arose with these designs including their heavyweight and lack of comfort experienced by consumers. These problems opened doors for other manufactures seeking to mitigate such issues throughout the nineteenth century (E. Rodrigo, V. Herrera and Diez, 2018).

Wheelchair designers began to prioritise manoeuvrability, comfort and independence. By 1869, the wheelchair design that is widely used today was established containing small front casters and rear push wheels. This challenged Farfler's design of a self-propelled device which contained propelling wheels at the front and the castors at the rear end. Farfler's design was best suited for indoor use allowing increased manoeuvrability in tight spaces however was deemed useless in outdoor settings where kerbs and obstacles were largely present. The castor at the rear end restricted the ability for the device to tip or balance when faced with such environments (Woods B, Watson N, 2004).

The development of the wheelchair later incorporated additional design features such as reclining backrests, adjustable footrests and movable arms (Nias, 2019) (E. Rodrigo, V. Herrera and Diez, 2018). Additionally, in 1932, Herbert Everest and Harry C. Jennings incorporated a folding mechanism into the wheelchair design by integrating a cross frame tubular design - this is now considered a standard wheelchair design (Figure 3). These folding frames were gaining popularity as they integrated well with other forms of transport such as motor vehicles and trains (Woods B, Watson N, 2004).


Figure 3 - Everest and Jennings Foldable Wheelchair (Foldawheel, 2019)

The Electric Wheelchair

Electric wheelchairs came to existence in the early 1900s where there were various designs introduced. These wheelchairs were desirable for persons who were unable to propel themselves or sought the option of independent function. The demand for these machines largely grew after the Second World War where many returning soldiers were left with severe disabilities. Before then, electric wheelchairs were not exclusively available to people with disabilities. George J Kline, a Canadian inventor designed the "Klein wheelchair" in 1953. The Klein wheelchair, seen in Figure 4, gained popularity and framed the future designs of electric wheelchairs (Woods B, Watson N, 2004) (E. Rodrigo, V. Herrera and Diez, 2018).

The Klein chair integrated batteries and motors to the standard wheelchair design. This design allowed the user to control movement from a joystick attached to the armrest. Klein polished his design to later include separate wheel drives and tighter turning systems (Bourgeois-Doyle, 2017). Over the decades, the electric wheelchair further embraced improvements in microprocessors, proportional controllers and facilitations to persons who are unable to operate the joystick by incorporating controllers operated by the head or chin (E. Rodrigo, V. Herrera and Diez, 2018). By 1956, Everest and Jennings became the first company to mass-produce electric wheelchairs (Foldawheel, 2019).

Figure 4 - George J Klein in Klein wheelchair (Woods B, Watson N, 2004).

Present State of The Art

Today the wheelchair is declared by the World Health Organisation (WHO) to be a fundamental human right to all disabled persons. They are chief contributors to assistive devices for disabled persons or individuals of limited mobility around the world (Nias, 2019). Wheelchairs have developed in all industries over the past century, for instance, they are widely used in sporting activities such as basketball and racing (Figure 5). Such wheelchairs embrace distinctive designs allowing them to operate with enhanced speed and agility (Nias, 2019).

Figure 5 – Bob Hall's three wheeled chair design for sprinting (Mandeville Legacy, 2014)

Latest developments include the introduction of Brain-Computer Interface (BCI) technology. This technology allows users to control movement through digital thought processing. Bioelectrical signals are released from brain activity caused by minor muscle movements or emotions. These signals are detected by a computer and converted into commands via software analysis. The commands are then transferred to an electric wheelchair to implement simple operations such as starting, stopping and moving in various directions (E. Rodrigo, V. Herrera and Diez, 2018). John Donoghue and Braingate manipulated this technology to create the BrainGate device which is implanted into a patient's brain whilst hooked to a computer (Bellis, 2020). Present research is directed to the improvement in the detection of the bioelectric signals and reduction in detection time. This is to increase efficiency by escalating the number of commands that control the wheelchair with amplified speed (E. Rodrigo, V. Herrera and Diez, 2018).

Wheelchair Design

The standard wheelchair design comprises necessary components to ensure optimal functionality. Components are chosen based on customer requirements and wheelchair use. These components are portrayed in Figure 6 below and additionally described below.

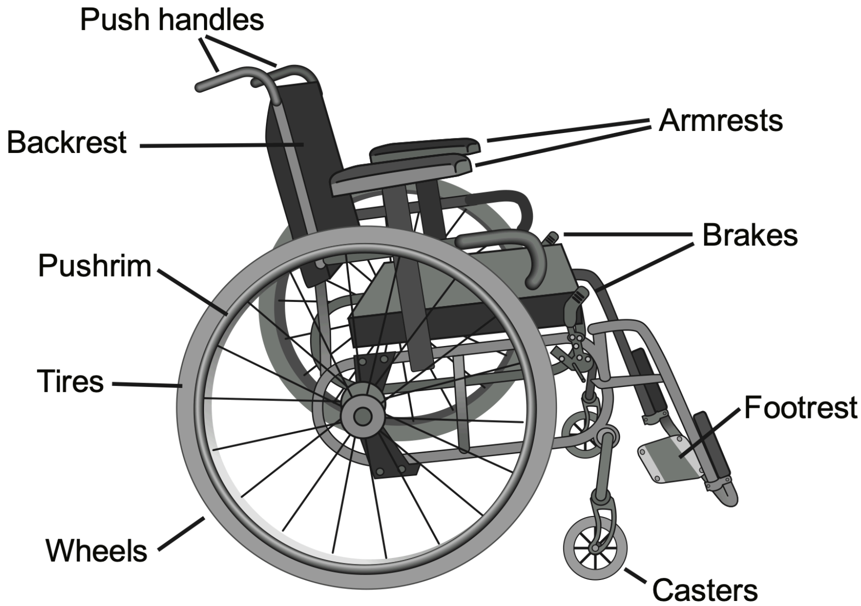


Figure 6 – Wheelchair Components (SCI Model Systems, 2011)

The *Frame* makes up the wheelchair base and shapes the seat where the user is positioned. It is generally made of aluminium tubes to ensure structural strength whilst producing a lightweight device. Frames can come in rigid or folding forms (Mobilitybasics, 2020).

The *Seat frame* is essentially the attachment of the seat to the backrest. Depending on the wheelchair style, backrests can be adjusted to recline or tilt. Backrests can be made of carbon fibre to reduce weight and ensure strength (Mobilitybasics, 2020).

Cushions are important components of the seat frame that come in different styles and materials for different user experiences. Common cushions embrace a firm and lightweight form to ensure user stability and avoid 'sliding' whilst the chair is in operation (SCI Model Systems, 2011).

The *Wheels* of a standard wheelchair are made up of a spoke/composite mag rim (light alloy magnesium based), tyre and hand rim. They are the chief components responsible for moving and manoeuvring the device.

Rims hold tyres in place and usually come in a composite mag or spoke form. Composite mag rims are the most common types of rims and are usually made of nylon/fibreglass-like material. Spoked rims are similar to the rims of a standard bicycle and were commonly used before the introduction of composite mag rims. (Wheelchair Components, 2012)

Tyres are in direct contact with the ground. Wheelchairs either support air-filled (pneumatic) or solid tyres. Air-filled tyres are most commonly used due to their lightweight nature. These tyres, conversely, require maintenance to check for punctures. Such tyres can also be filled with solid inserts to avoid punctures at the expense of weight. Solid tires require no maintenance and are low cost when compared to air-filled tyres. Solid tyres are conversely not recommended as they are not as shock absorbent as the pneumatic tyres, reducing comfort to the user when the wheelchair is operating (SCI Model Systems, 2011) (Mobilitybasics, 2020).

Hand rims are found in manual wheelchairs allowing the user to manually propel the wheelchair with their hands. They come in a variety of forms offering distinct friction coatings that allow improved propulsion whilst maintaining user comfort.

Footrests are positioned below the user's feet to provide support. The footrests can be manipulated to move into various positions. For example, they can be folded out to ensure a safe and clear passageway for the passenger whilst mounting onto the chair. Footrests are generally assembled from aluminium or a plastic composite material (Mobilitybasics, 2020).

Armrests are cushioned supports positioned underneath the user's arms for comfort. Comparable to footrests, the position of the armrests can also be personalised to the user. They are generally height adjustable or even removable.

Wheel locks are used to stabilise the wheelchair when the user wishes to remain in a specific spot or is transferring in or out of it (SCI Model Systems, 2011). Wheel locks come in different styles such as the push/pull-to-lock or scissor locks. The push/pull-to-lock is found in most standard wheelchairs whilst scissor locks are used in sports wheelchairs.

Casters are small wheels positioned at the front end of the wheelchair. They are used to stabilise the device whilst in motion. Similar to the rear wheels, castors can contain air-filled or solid tyres but are usually found to be solid tyres in standard wheelchairs (Mobilitybasics, 2020).

Additional features can be added to the wheelchair for extra comfort, safety and convenience, such features include push handles and grade-aids (Mobilitybasics, 2020).

Each wheelchair component has a function that contributes to the operation of the wheelchair. Different styles of these components can be chosen and combined to achieve different wheelchair types such as: economy, standard, lightweight, lightweight adjustable, rigid, reclining, tilting, paediatric and bariatric wheelchairs (Mobilitybasics, 2020).

Design Considerations of a Wheelchair

The wheelchair is designed to improve the user's quality of life by increasing comfort whilst enabling them to participate in ordinary day to day activities and maintain health and safety standards. To shape such a design, essential wheelchair standards are set and used to construct suitable design requirements. The International Organization for Standardization (ISO) has established international standards for wheelchairs, known as the ISO 7176 series which is adopted by most wheelchair manufactures (Production, 2008). The ISO 7176 series involves a set of terminology and testing methods for evaluating wheelchair performance, size, strength, durability and safety (Armstrong et al., 2008). The following terms summarise general considerations that apply to wheelchair design:

User Needs

Identifying the user needs by investigating the users; size, age, usability (temporary or long-term), postural requirements, independent function needs, home and geographical environment. Moreover, some users such as children have shifting needs as they are continually growing and require a device to accommodate these changes. Figure 7 shows varying wheelchair designs that cater to different user needs (Sullivan et al., 2018).

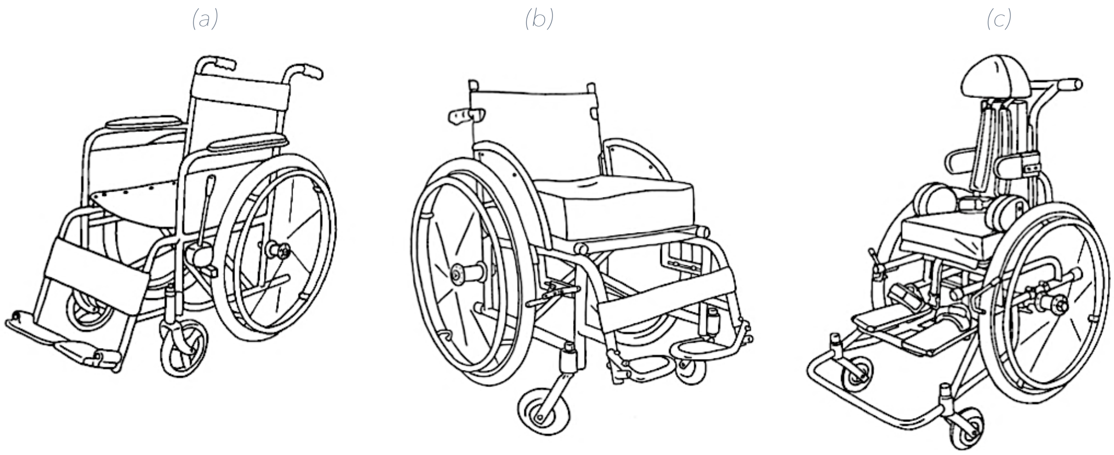


Figure 7 – Wheelchair designed for (a) temporary user (b) long-term user (c) user with postural support needs (Armstrong et al., 2008).

Durability and Strength

Wheelchairs are designed to operate in multiple environments, both indoor and outdoor. Such environments can cause a chair to face additional wear due to exerted loads form uneven paths and harsh weather (Production, 2008). A wheelchair must therefore be strong enough to resist the high impacts experienced in such environments, to avoid failure during operation. Furthermore, a suitable fatigue life must be achieved by the wheelchair to avoid repairs and replacements of wheelchair parts. The wheelchair design should comprise components that can be easily repaired and accessible if replacements are necessary (Armstrong et al., 2008).

The User's Health and Safety

User health and safety is the ultimate priority and is a vital and required consideration when designing any aid of mobility. The central goal in wheelchair design is to provide mobility support to wheelchair users without causing exceeded harm or injury to the user or their surroundings. For regular wheelchair users, pressure sores can and are likely to occur as a result of inadequate cushioning. Figure 8 depicts common pressure sensitive areas where wounds are likely to occur therefore outlining the locations of needed cushioning (Armstrong et al., 2008).

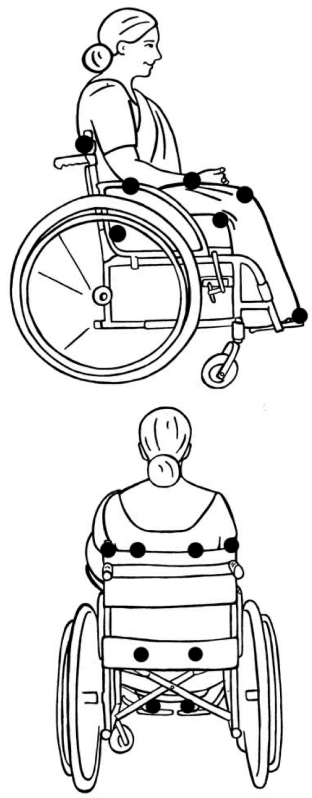


Figure 8 - Common pressure sensitive area's (Armstrong et al., 2008).

If a wheelchair lacks stability, tipping can occur and subsequently cause injury to the user or surrounding individuals. Figure 9 visualises an anti-tip device that can be incorporated into a wheelchair design to avoid tipping. Seat width and total mass of a wheelchair must not exceed a certain limit, to avoid shoulder injuries when self-propelling mechanisms are utilised (Production, 2008). Surface finishes must also be considered to avoid sharp edges that can cause wounds and potentially lead to infection. Finally, if the wheelchair lacks durability from the regular use, premature failure can occur and lead to unexpected harm to the user. (Production, 2008)

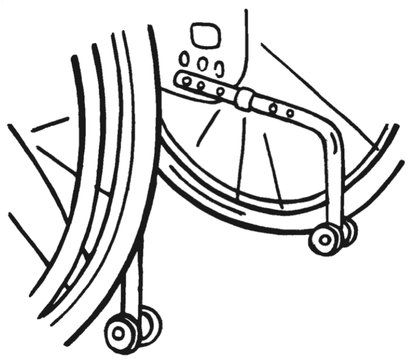


Figure 9 - Anti-Tip Device (Armstrong et al., 2008).

Wheelchair Environment

Knowledge of the wheelchair environment is crucial before initiating the design process. The final design of a wheelchair made for indoor usage varies significantly in comparison to a design made for outdoor usage. The same applies to diverse terrains; snowy, rocky or sandy terrains necessitate a different design outlook than for that of urban or concrete roads. The wheelchair role should also be considered so that certain features can adapt to the need. For example, some wheelchair may be required to travel over kerbs and ramps daily whilst others face additional exposure to moisture. These factors must be considered so the final design achieves maximum effectiveness and productivity (Production, 2008).

Current Wheelchairs for Beach Use

Wheelchairs are currently used by low-mobility users in essential activities. Enabling wheelchair users to participate in additional activities, such as leisure, can contribute to the enhancement of their quality of life. Accessibility to exclusive beach activities for wheelchair users is currently low, due to the difficulty that accompanies pursuing such activities. However, few manufactures have recognised this problem and developed select solutions which are described in the following section.

AccessRec® - WaterWheels®

WaterWheels® is a floating beach wheelchair produced by AccessRec®, a manufacturer of high-quality beach wheelchairs and beach accessibility mat systems. AccessRec® has developed a variety of products including the AccessDeck™ and the AccessMat®. These products are compliant with the Americans with Disabilities Act of 1990 (ADA) and focus on easily transporting people of all abilities across the sandy terrain closer to the seafront. In addition to this, TerraWheels®, another product developed

Figure 10 - WaterWheels® Beach Chair in Use

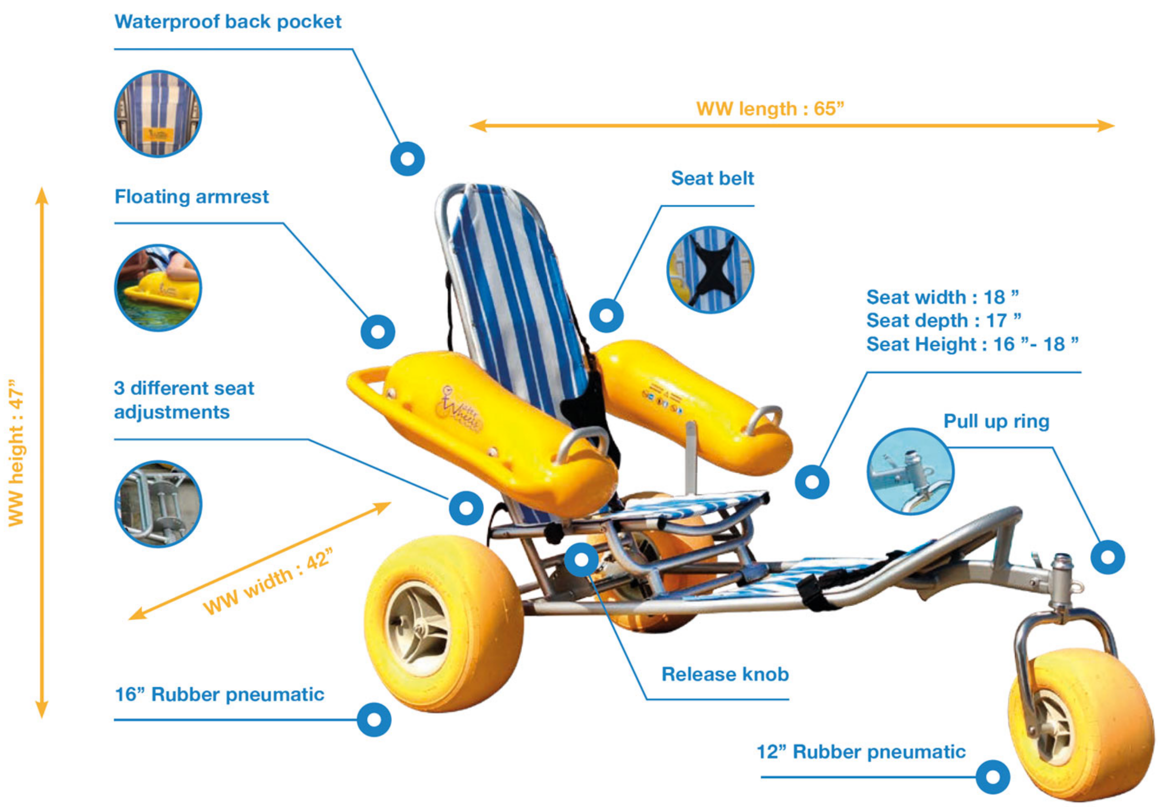


Figure 11 - WaterWheels® Component Breakdown

by AccessRec®, is an all-terrain wheelchair enabling users to roam on the sand and other forms of uneven terrains. WaterWheels® builds upon the TerraWheels design to additionally allow the user to enjoy the water using its unique floatable armrests and tires (AccessRec, 2019). The device incorporates all the necessary components allowing it to function, such as the rubber pneumatic wheels, floating armrests and required safety belt. Detailed components are portrayed in Figure 10 and 11.

Sand Rider

Figure 12 - The Sand Rider

The Sand Rider is another wheelchair capable of roaming on beach surfaces as seen in Figure 12. The sand rider comprises a lightweight rigid frame with large tires allowing an individual to manoeuvre over sand and large obstacles. The 22kg chair has a weight limit of 160kg and includes additional features such as a headrest, cup holder, seat belt, parking brake and travel bag. (Sand Rider, 2019).

Trackmaster

The Trackmaster chair, shown in Figure 13, delivers creative mobility solutions through its unique track-based design that can roam on all terrains. The chair essentially comprises an electric-powered chair and specialised tracks allowing the user to independently man the device on terrains of sand, snow, rocks, mud and many more. Currently, there are two track master deigns, Trackmaster MK-1 & MK-1X, where the latter offers extra terrain manoeuvring capabilities (TrackMaster, 2020).

Figure 13 - The Trackmaster

The Omeo

Figure 14 - The Omeo

The Omeo (Figure 14) is an electric wheelchair that comprises an Active Seat Control (ASC) system allowing an individual to control the direction, speed and braking through body movements. In addition to the ASC, a joystick is available as an additional movement method. The Omeo includes an 'Off-Road Kit' allowing it roam on a wider range of surfaces such as rocky ground and mud. The overall weight and load capacity of the Omeo is 75kg and 110kg respectively (Omeo Technology, 2020).

Hippocampe - VIPAMAT

The Hippocampe is a wheelchair that allows disabled users to enjoy pool/beach activities and participate in activities such as disabled swimming as presented in Figure 15. Its stainless-steel structure allows it to operate in water whilst resisting corrosion. The Hippocampe adopts a three-wheeled design allowing it to easily manoeuvre within a space. The double wheeled design for the all-terrain Hippocampe allows the chair to manoeuvre on sandy beaches. The chair weighs 17 kg and has a maximum load constraint of 130kg (Vipamat, 2020).

Figure 15 - The Hippocampe

AQUATREK2 AQ-1000 Beach Wheelchair

Figure 16 - The Aquatrek2 AQ-1000

The AQ-1000 Beach wheelchair can operate on sand terrains in beaches and parks. The wheelchair is assembled from a PVC frame, reinforced with aluminium pipe to provide integrity and strength (Figure16). In addition to this, balloon wheels are utilised throughout the wheelchair with aluminium forks operating the rear wheels for ease of movement on the specified terrains. The wheelchair has a weight capacity of 160kg and includes additional features such as: a footrest, brakes, seat cushions, a seat belt and a shoulder harness (Aquatrek2, 2020).

Grit Freedom Chair

The Grit Freedom Chair is an all-terrain and independent mobility wheelchair. The wheelchair features a patented lever-drive system allowing users to propel the wheelchair with increased ease in comparison to the standard wheelchair system. The chair comprises high surface area mountain bike wheels allowing it to roam on diverse grounds as depicted by the sandy terrain seen in Figure 17. Parking brakes, adjustable footrests and push handles are also included in the Grit freedom chair design (GRIT Freedom Chair, 2020).

Figure 17 - Grit Freedom Chair

Competitor Assessment

Table 1 visualises the comparison between the mentioned beach wheelchairs presenting the different features of each device. The Trackmaster and the Omeo use electrical propulsion to provide independent function to the user however their increased weight and cost weaken their competitive advantage. The Sand Rider and Git Freedom Chair exhibit light weight properties and feature folding mechanisms making them desirable to consumers in terms of ease of transportation. The AQUATREK2 AQ-1000 features the lowest cost at the expense of an increased weight and desirable features exhibited in the other wheelchairs. It can be seen that all wheelchairs are able to manoeuvre on sandy terrain however the WaterWheels® and Hippocampe wheelchairs are considered key competitors as they can operate in water. The Hippocampe is seen to additionally accommodate for independent function giving it a competitive advantage over WaterWheels®.

Table 1 - Comparison of Current Wheelchairs for Beach Use

		WaterWheels®	Sand Rider	Trackmaster	The Omeo	Hippocampe - VIPAMAT	AQUATREK2 AQ-1000	Grit Freedom Chair
Can this device manoeuvre on sandy terrains		X	X	X	X	X	X	X
Can This device operate in water?		X				X		
Weight Range	<25kg							X
	25-60kg	X	X			X		
	>60kg			X	X		X	
Load Capacity Range	<110kg				X			
	110-130kg					X		
	>130kg	X	X	X			X	X
Cost Range	<£2000						X	
	£2000-5000	X	X			X		X
	>£5000			X	X			
Does this device have independent function?				X	X	X		X
Is this device electrical?				X	X			
Is this device foldable or capable of becoming condensed		X	X			X		X

Design Approach

To pursue this research opportunity a solution-based approach was defined to dictate the design methodology of this project. The design spiral was used as a basis for the design approach of the floating wheelchair. It is a widely accepted method used by naval architects that outlines a systematic approach to tackle specific design problems. The spiral comprises chosen design tasks required to yield the design outcome. For this project these tasks include design requirements, sizing estimate, weight estimate, hydrostatics, stability, materials, aesthetics, manoeuvrability, structure and cost estimate. Whilst undertaking these tasks, solutions become increasingly specific with the narrowing of options and calculations (Vossen and Randi Hjørungnes, 2013). This strategy gradually shifts the design from the concept to the preliminary to the final detailed design stage.

The concept design stage will focus on multiple concepts formed in the first cycle of the design spiral. The second cycle will narrow down and yield a preliminary design which will be further studied and perfected in the third cycle to produce a detailed design. Figure 18 visualises the design spiral containing the design stages framed with the specified design tasks.

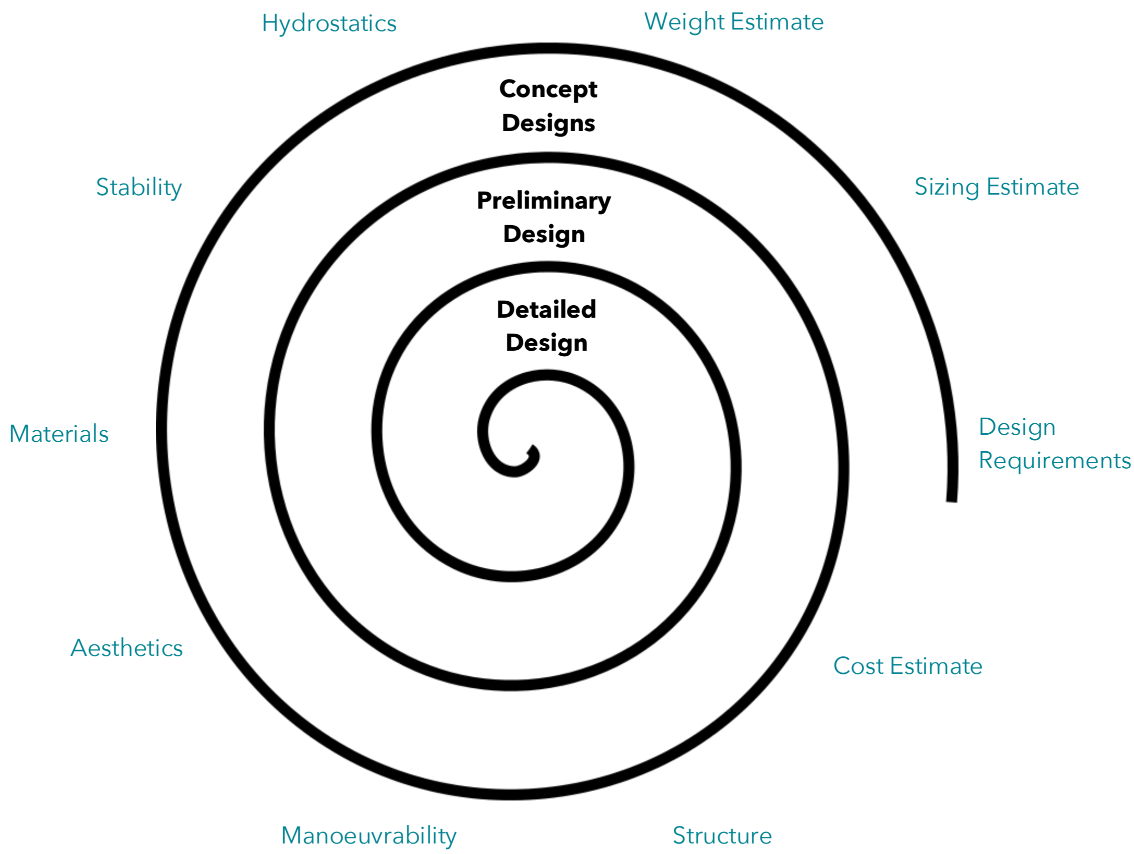


Figure 18 - Design Spiral

Design Requirements

The first stage of the design process is outlining the design requirements for this project. Design requirements were derived from desires and necessities of consumers that utilise both standard wheelchairs and marine products such as boats, ships and marine leisure devices. Table 2 describes specified design requirements alongside determined thresholds for this project. These thresholds were established with the comparison and study of a standard wheelchair and a competitor on the market - WaterWheels®.

Table 2 - Design Requirements

Design Requirements	Description	Thresholds			How will Target Requirements be assessed?
		Normal Wheelchair	Competitor - WaterWheels®	This Product	
Total mass	The combined mass of all components that make up the device	3.5 - 14kg	27kg	10 -30kg	Data of total mass and volume will be collected in Excel spreadsheet throughout phases
Volume	The combined volume of all components	0.5 m^3	2.07 m^3	2 m^3	
Max Load	Maximum applied load before fracture or inability to float	136kg	115kg	110 - 120kg	Finite Element Analysis and flotation calculations to determine max load
Material	Materials used for different components of the wheelchair	Stainless steel, aluminium, titanium, chrome and other lightweight materials	Aluminium, Stainless Steel, PVC, Rubber	Aluminium, Stainless Steel, PVC, Other lightweight non-corrosive materials	Material selection research and software will assess the materials and narrow down selection
Water Resistance	Is the device resistant to water (including any electronic parts)	Yes	Yes	Yes	Constraint will be applied in material selection software to ensure chosen materials are water/corrosion resistant
Corrosion Resistance	Is the device resistant to corrosivity (in this case saltwater)	No	Seawater Resistant	Seawater Resistant	

Health and Safety	Does this device concur with safe and healthy regulations	Yes	Yes, includes a safety belt	Yes, includes a safety belt	On the fulfilment of the following safety related requirements inclusion of safety components
Foldable	Is the device foldable?	Yes	Yes	Yes	Determine practicality through concept and preliminary design phases
No. of parts	How many parts make up the device	1	6	Less the better	
Seat Positions	Possible seating positions	1	3	2-3	
Independ-ent function	Can the wheelchair function/driven by the individual	Yes	No	Preferably Yes	Evaluate feasibility of this feature via wheelchair components and project management
Electric	Does the wheelchair operate electronically	Some	No	Preferably Yes	
Cost	Price of wheelchair	£50 - £1000	£3000	£1000-3000	Data will be collected in Excel spreadsheet throughout phases
Manoeuv-rability	Is the wheelchair easily manoeuvred?	Yes	No	Yes	Wheel types will be explored to fulfil terrain and manoeuvrability requirements and deduce a suitable wheel size
Wheel Size	Diameter sizes of wheels	24 inches	16 inches	16-24 inches	
Terrain	Surfaces device can roam on	Road	Road, Sand	Road, Sand	
Flotation	Can the device float in water	No	Yes	Preferably Yes	Use of Archimedes principal to calculate draft of wheelchair
Adjustable buoyancy	Does the wheelchair have the ability to adjust its draft when in the water?	No	No	Preferably Yes	Evaluate floating components in design to understand if this mechanism is feasible
Floating Stability	Stability of device when in water	No	Yes	Yes	Calculation of metacentric height and Evaluation of position of Centre of Gravity of user throughout all phases
Free Stand Stability	Stability of device when on ground	Yes	Yes	Yes	

Concept Designs

The first cycle of the design approach was completed with the finalising of multiple concept designs illustrated in this section. The design tasks in this stage will be further explained in the Design Analysis section.

Initial Design Sketches

The following section illustrates the initial design sketches and their corresponding features.

- Boat shaped exterior- greater surface area for buoyancy
- Armrests
- 3 wheels for manoeuvrability

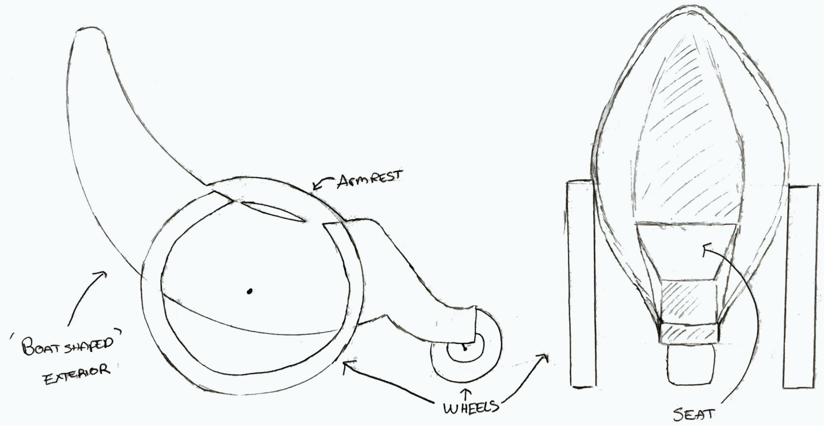
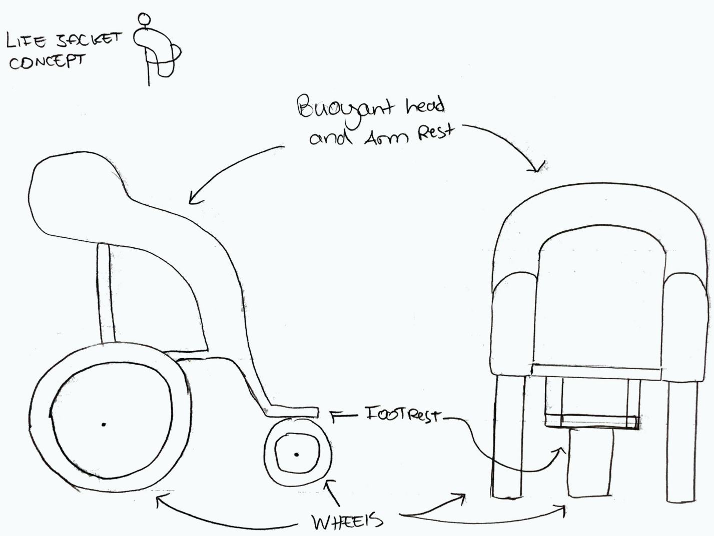


Figure 19 - Concept 1



- Standard wheelchair frame
- Life-jacket concept – buoyant head and armrests
- 3 wheels for manoeuvrability

Figure 20 - Concept 2

- Two-foot positions for choice of comfort
- Extended front wheel
- Buoyant armrests

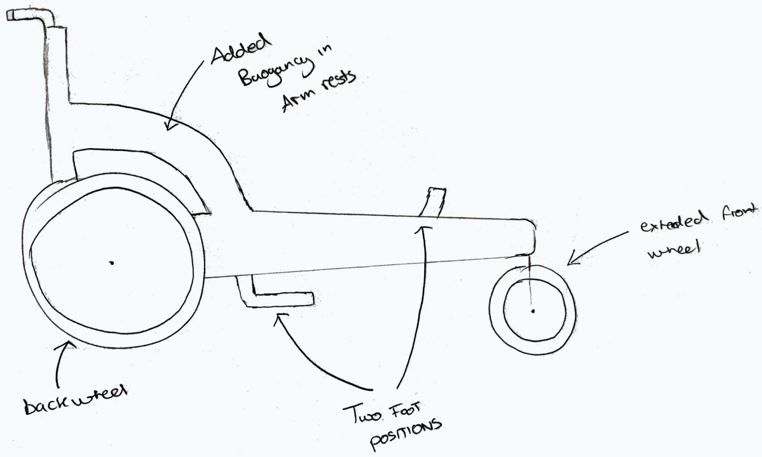


Figure 21 - Concept 3

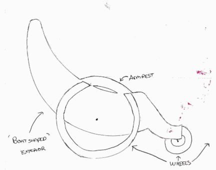
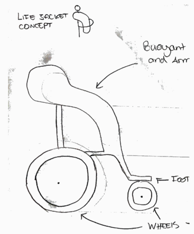
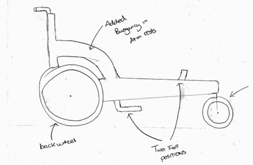
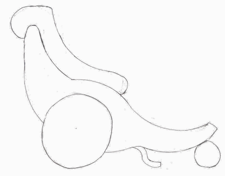
Concept Design Selection

The concept designs are chosen based on the functional requirements displayed in Table 3. These requirements are first weighted on their relative importance. The full weighting matrix is displayed in Table 22 in Appendix 1. The Pugh Matrix, which is a criteria-based decision matrix, was used to assess the different concepts displayed above. Table 4 visualises this process and concludes that all three concepts have unique advantages. A fourth concept design was thus created combining the unique features of the 3 concepts. This Design is portrayed in Figure 22. As seen in the Pugh Matrix, Concept 4 holds the greatest total score when compared to the other concept designs.

Table 3 - Weighting Matrix

Functional Requirements Weightings	Total	Weight
Cost	4	3%
Aesthetics	7	5%
Manoeuvrability	11	7%
Total mass	9	6%
Max Load	9	6%
Volume	7	5%
Water Resistance	15	10%
Corrosion/Oxidation Resistance	12	8%
Health and Safety	15	10%
Seat Positions	3	2%
Flotation	17	11%
Adjustable buoyancy	5	3%
Floating Stability	15	10%
Free-stand Stability	13	8%
Storage volume	1	1%
Manufacturing Ease	2	1%
User Friendliness	7	5%
Ease of Repair	1	1%

Table 4 - Selection Matrix

Direction of Improvement	Selection Criteria	Weight	Concept 1		Concept 2		Concept 3		Concept 4	
										
			Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score
-	Cost	3%	2	0.052	5	0.131	4	0.105	2	0.052
+	Aesthetics	5%	5	0.229	2	0.092	1	0.046	5	0.229
+	Manoeuvrability	7%	4	0.288	4	0.288	2	0.144	4	0.288
-	Total mass	6%	4	0.235	5	0.294	4	0.235	4	0.235
+	Max Load	6%	5	0.294	5	0.294	5	0.294	5	0.294
-	Volume	5%	3	0.137	3	0.137	3	0.137	4	0.183
+	Water Resistance	10%	5	0.490	4	0.392	4	0.392	5	0.490
+	Corrosion/Oxidation Resistance	8%	5	0.392	4	0.314	4	0.314	5	0.392
+	Health and Safety	10%	5	0.490	5	0.490	5	0.490	5	0.490
+	Seat Positions	2%	3	0.059	3	0.059	5	0.098	5	0.098
+	Flotation	11%	5	0.556	4	0.444	4	0.444	5	0.556
+	Adjustable buoyancy	3%	3	0.098	4	0.131	4	0.131	4	0.131
+	Floating Stability	10%	5	0.490	3	0.294	4	0.392	5	0.490
+	Free-stand Stability	8%	4	0.340	4	0.340	4	0.340	5	0.425
+	Storage volume	1%	2	0.013	2	0.013	2	0.013	2	0.013
+	Manufacturing Ease	1%	3	0.039	5	0.065	4	0.052	4	0.052
+	User Friendliness	5%	5	0.229	4	0.183	3	0.137	5	0.229
+	Ease of Repair	1%	4	0.026	4	0.026	4	0.026	4	0.026
		Total	4.46		3.99		3.79		**4.67**	

Updated Concept Design

- Boat shaped exterior
- 3 wheels for manoeuvrability
- Two-foot positions
- Extended front wheel
- Life-jacket concept – buoyant head and armrests

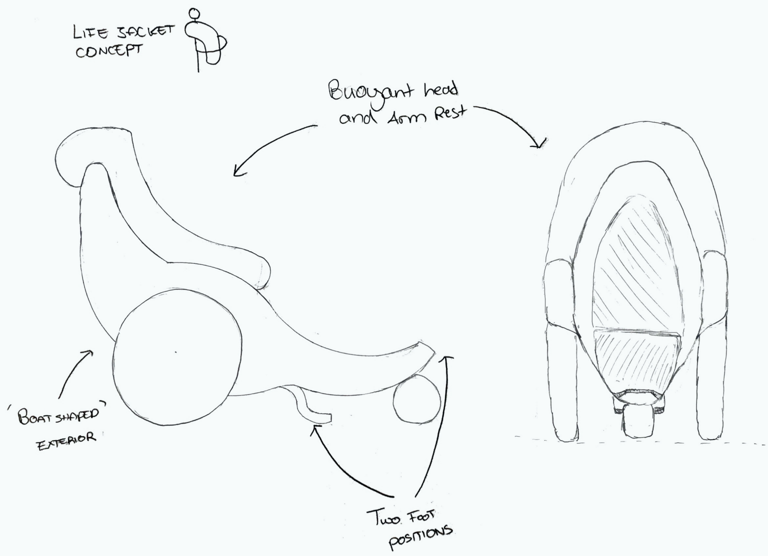


Figure 22 – Combined Concept 4

Design Modelling and Analysis

Sizing Estimate

The conceptual designs were based on a simple sizing estimate of a standard wheelchair which has an approximate length of 107 cm, a height of 92 cm and a width of 64 cm as seen in Figure 23. These sizings were initially chosen to fulfil general sizing requirements of a wheelchair allowing them to be used and stored in a variety of environments. Continuing to the preliminary design, sizings were increased to make allowances for accessories that provide extra buoyancy, for example, the extended footrest and buoyant armrests. The preliminary design size estimates were deduced to be:

Length: 100cm -200cm

Height: 100cm – 175cm

Width: 75cm – 125cm

The final detailed design refined the estimates stated in the preliminary design too; a length of 178.3cm, a height of 111.7cm and a width of 104.3cm.

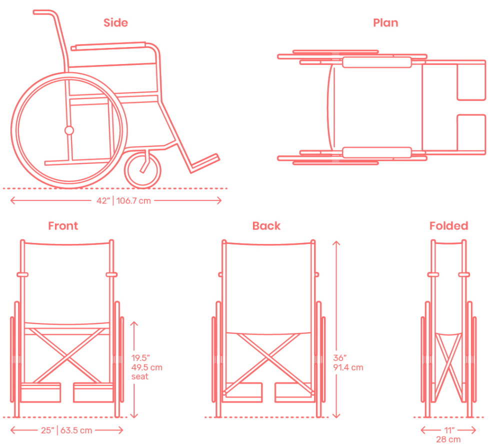


Figure 23 – General Wheelchair Sizings (Wheelchairs Dimensions & Drawings | Dimensions.com, 2020)

Weight Estimate

Throughout the design phases, the weight of the device was estimated. Initially, a weight estimate was taken from that of a standard wheelchair which was between 10-25kg corresponding to wheelchair type. This, therefore, led to a weight estimate for the concept designs of around 17-31kg. The increased weight estimate allowed for considerations such as increased tyre and structure weights in contrast to standard wheelchairs. This value was later refined in the preliminary design when other factors were considered such as the increased sizing's which inevitably lead to an increased weight estimate of 20.5-39.5kg. The final weight seen in the detailed design was 25.6kg, which fell in the range of predicted weight of the previous stages. The weight estimates were calculated by determining upper and lower bounds of each wheelchair component that resulted in total estimated weight for each stage. Figure 24 below visualises the weight estimate of each stage of the process.

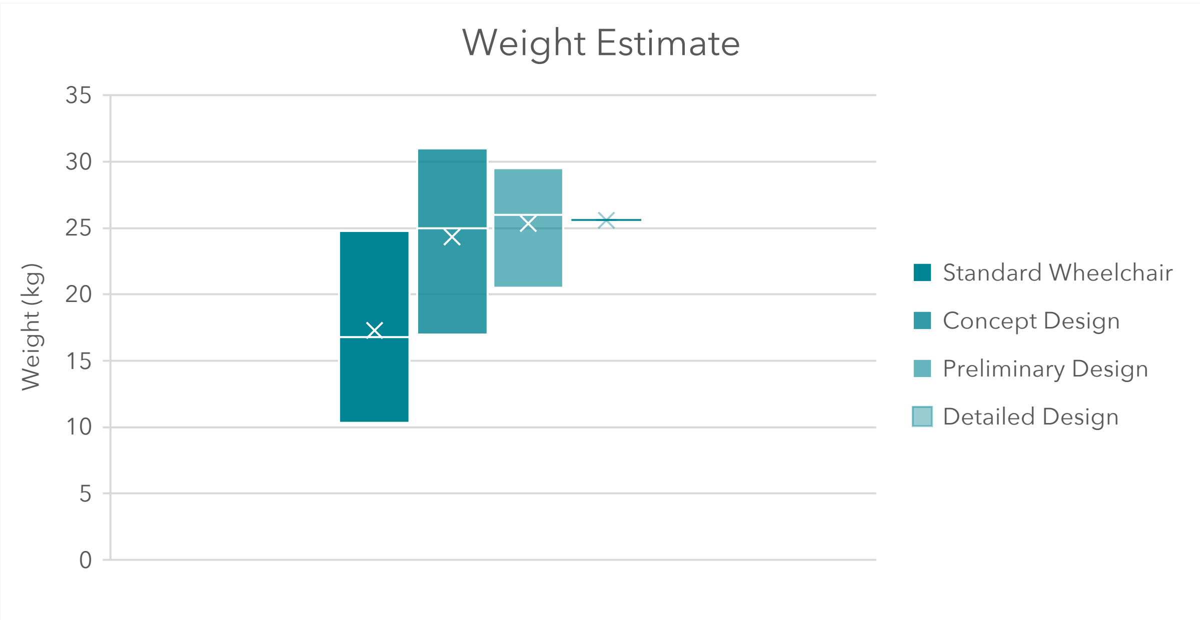


Figure 24 - Weight Estimate

Hydrostatics

In the initial conceptual design phase of the project, basic calculations were conducted to understand the hydrostatics forces acting on a human body and a wheeled device in water. Archimedes principle of buoyancy was used to assess the overall draft (T) of different models. Achieving an appropriate draft value is an important outcome in this investigation as it affects both the safety and comfort of the user. Archimedes principle clarifies a relationship between the weight of an object and the Buoyant force (F_b) resulting from the displaced volume of water when the object is immersed. F_b is defined in Equation 1.

$$F_b = V_s \cdot \rho \cdot g \qquad (1)$$

Where V_s is the displaced volume of water.

For a floating object, the Buoyant force is greater than or equal to the weight of the object, therefore the following equation for Draft can be deduced:

$$F_b = V_s\, \rho\, g = mg$$

$$\rightarrow A\, T\, \rho\, g = mg$$

$$\rightarrow T = \frac{m\, \rho}{A} \qquad (2)$$

Initially, the human body was investigated using the following assumptions:

- The human body has a height 1.65m and is modelled using six cylinders
- The mass of the body is 75 kg

The body was split into 3 levels as visualised in Figure 25. A draft value for each level was calculated to then contribute to an overall draft value of 1.489m. This process is visualised in table 5

Table 5 - Draft Calculation for Human Body

Level	Body	Radius (m)	Height (m)	Area (m^2)	Total Area (m^2)	Total Volume (m^3)	Mass (kg)	Density of saltwater (kg/m^3)	Draft T (m)	Overall T (m)
1	1	0.05	0.75	0.008	0.016	0.012	17.50	1025	1.087	1.489
	2	0.05	0.75	0.008						
2	3	0.05	0.75	0.008	0.212	0.159	42.50	1025	0.196	
	4	0.25	0.75	0.196						
	5	0.05	0.75	0.008						
3	6	0.15	0.15	0.071	0.071	0.011	15	1025	0.207	

Further to this, the human body using the wheeled device was modelled as 6 cylinders mounted on a box-shaped object as shown in Figure 25. Calculations were carried out on varying box dimensions. Independent variables, such as length (L) and width (W) were altered to evaluate the overall draft of the model with varying box shapes. The weight of the device was a fixed variable at 15kg. Figure 26 displays a plot of the different sizes of boxes and their corresponding drafts. The first calculation was carried out on the cylinder without a box to determine the approximate draft of an ordinary person. Subsequent calculations were made with the additional boxes of chosen dimensions. These calculations were verified with manual hand calculations.

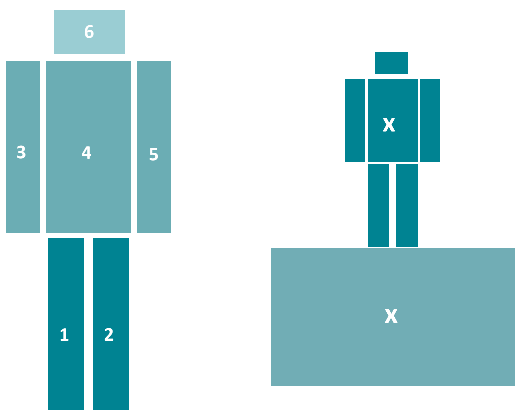


Figure 25 - Human Body and Wheeled Device Model

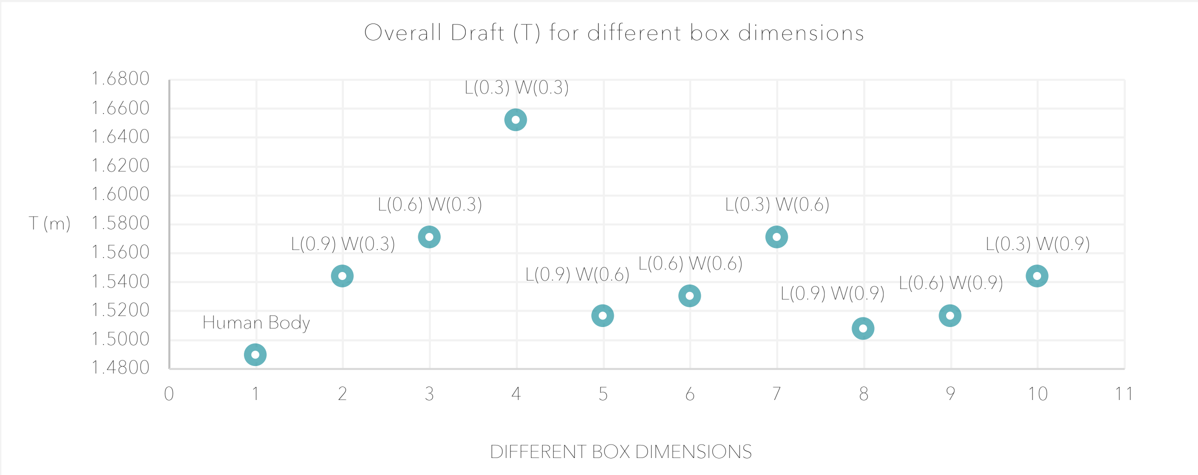


Figure 26 - Plot of Draft with Varying Box Dimensions

This investigation provided an understanding of how different shapes affected draft values and was consequently used to shape the conceptual designs.

SolidWorks Design Study

In the preliminary design phase, the draft of the design was similarly calculated. To conduct this investigation a physical Computer-Aided Design (CAD) model was created using SolidWorks. Two configurations of the model were defined; a physical model and a water model. The physical model assembled all the wheelchair components with their corresponding material. The water model likewise integrated all the wheelchair components with an assigned material of water for all components. The water model additionally suppressed all commands that allowed parts to have hollow features in the physical model, so an ideal displaced water volume could be modelled. These models are pictured in Figure 27. Once the model was set up (Figure 28), the longitudinal angle of inclination and the draft were simultaneously measured. The following method was used:

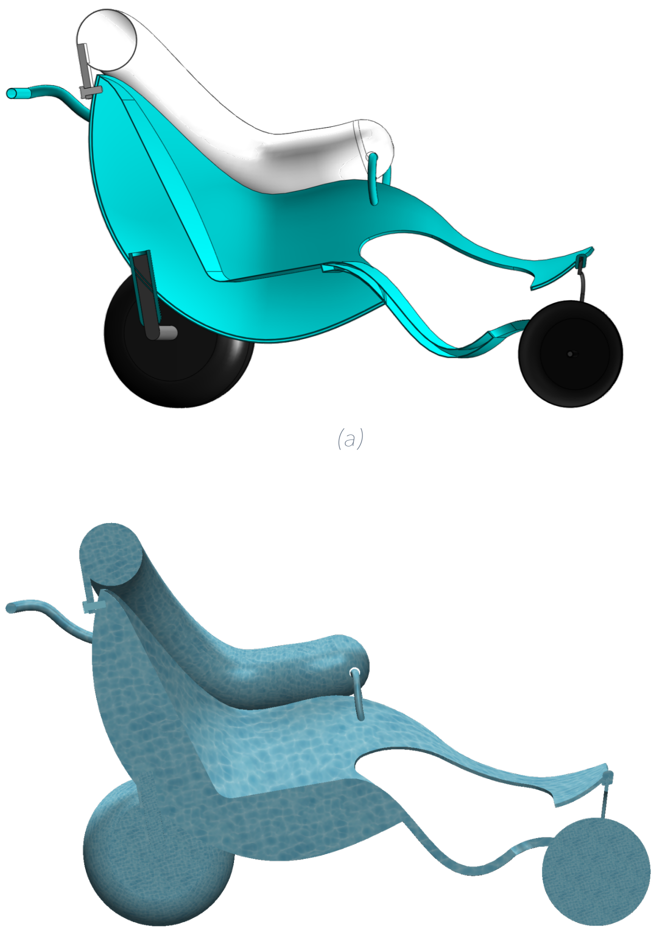


Figure 27- (a) Physical Model (b) Water Model

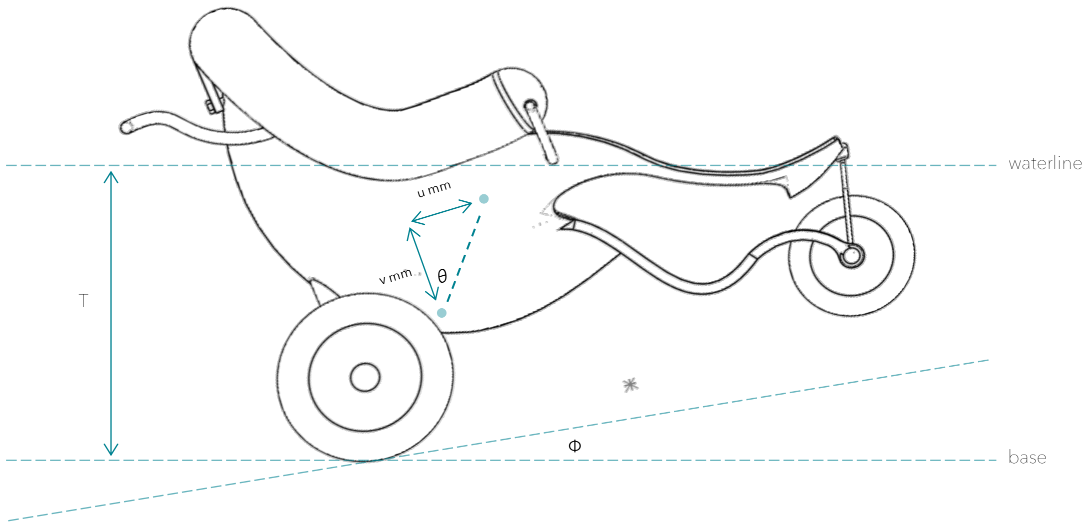


Figure 28 - Hydrostatic Variables

- Use moments to determine the combined *centre of mass* of the physical wheelchair and an ideal human body.
- Assume waterline on wheelchair water model and subtract any material above the waterline
- Use SolidWorks design study to determine appropriate draft dimension (T) where the mass of displaced water is equivalent to the mass of wheelchair and the human body.
- Once dimension T is determined, collect data detailing the centre of gravity of the altered water model to determine the *centre of buoyancy*.
- Calculate angle θ between the *centre of buoyancy* and the *centre of mass*.
- If θ is not equal to 0, repeat method whilst changing angle Φ and dimension T until angle θ is equal to 0 (so *centre of buoyancy* and the *combined centre of mass are* vertically aligned and equilibrium is achieved)

Appendix 1 Figure 47 portrays the results of the above process. The draft of the final detailed design was calculated to be 659mm at an angle of 26.4° from the base. Figure 29 below shows the final position of the wheelchair when placed in seawater detailing the vertical alignment of the centre of buoyancy and combined centre of mass.

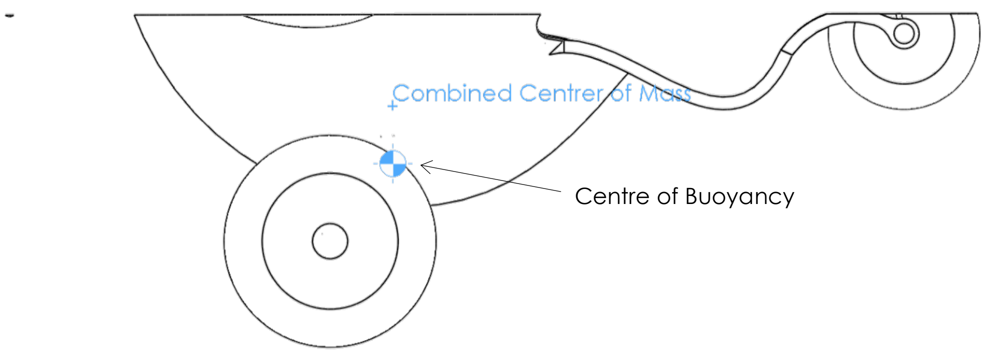


Figure 29 – Final Position of Wheelchair in Water - Centre of Mass and Centre of Buoyancy Aligned

Stability

Stability is a vital design criterion and is investigated whilst the device is in the water and on land. Each category will be expanded on in the following section.

Stability in Water

Stability is the ability of a vessel to remain upright and to additionally return to its initial position when an exerted force has diminished. Metacentric height (GM) was used as a key measure to assess the stability of the device in water. A vessel's initial stability can

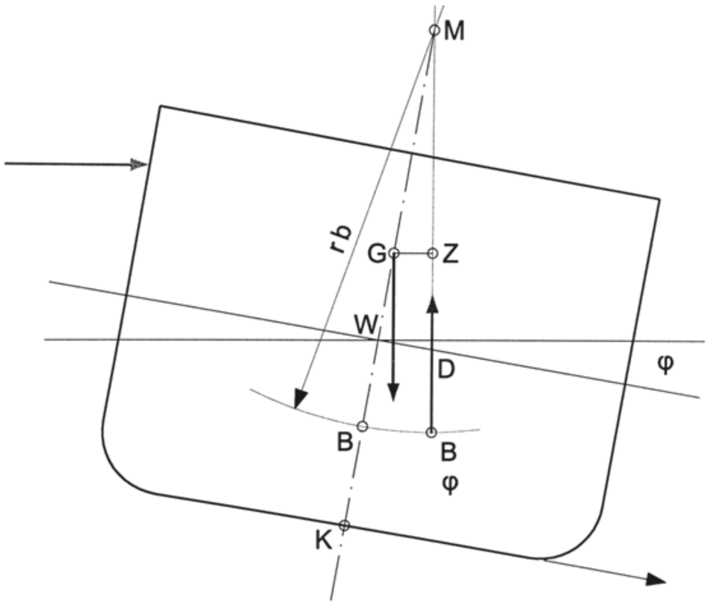


Figure 30 - Metacentric Stability Diagram (Babicz, 2015)

be determined from the metacentric height which is the distance between the centre of gravity (G) and the initial metacentre (M). These variables are depicted in Figure 30. The values of GM can define the stability of the device. If GM is positive the device is generally considered stable. If GM is equal to zero the device is considered neutrally stable, however if GM is negative the device is considered unstable (Babicz, 2015).

GM is calculated using the following formula:

$$\mathbf{GM = Vertical\ Centre\ of\ Buoyancy\ (KB) + BM - Vertical\ Centre\ of\ Gravity\ (KG)} \quad \textbf{(3)}$$

$$\text{Where } \boldsymbol{BM} = \left(\frac{\textit{Second moment of area of waterplane about heel axis } (I_{xx})}{\textit{Volumetric Displacement of object } (\nabla)} \right) \quad \textbf{(4)}$$

Stability was explored to gain an understanding of the suitable shapes for the conceptual designs. Similar to the initial hydrostatics calculations, metacentric height was found for the various sized boxes outlined in the hydrostatics section and is displayed in Figure 31.

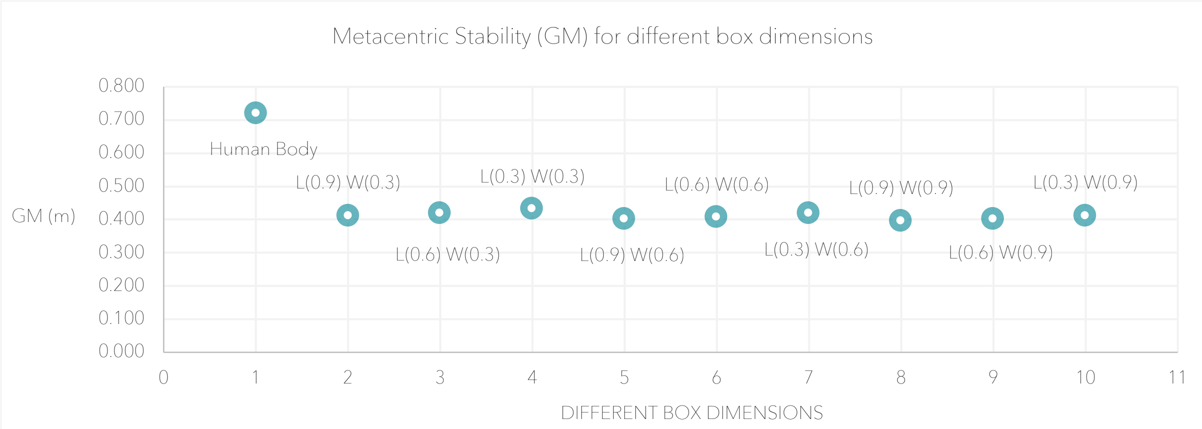


Figure 31 - Metacentric Stability (GM) for different box dimensions

In the preliminary and design phase, stability was determined for the CAD model, following the determination of Draft. Data was obtained from SolidWorks to complete the metacentric height calculation. Throughout the preliminary design phase, the model was continuously altered to achieve a sensible metacentric height. Initially, a negative metacentric height was exhibited prompting a change in the wheelchair design. The seat height was decreased to achieve a lower vertical centre of gravity. The final calculations for this design are detailed in Table 6, 7 & 8 and Figure 32. Within the calculations, the density of the human body was assumed to be 985 kg/m^3. GM of the detailed design was calculated to be 0.0014m implying that the wheelchair will exhibit initial stability.

Table 6 - Human Body Volume Calculation

Human Body Volume		
Mass	80	kg
Density	985	kg/m^3
Volume	0.08	m^3

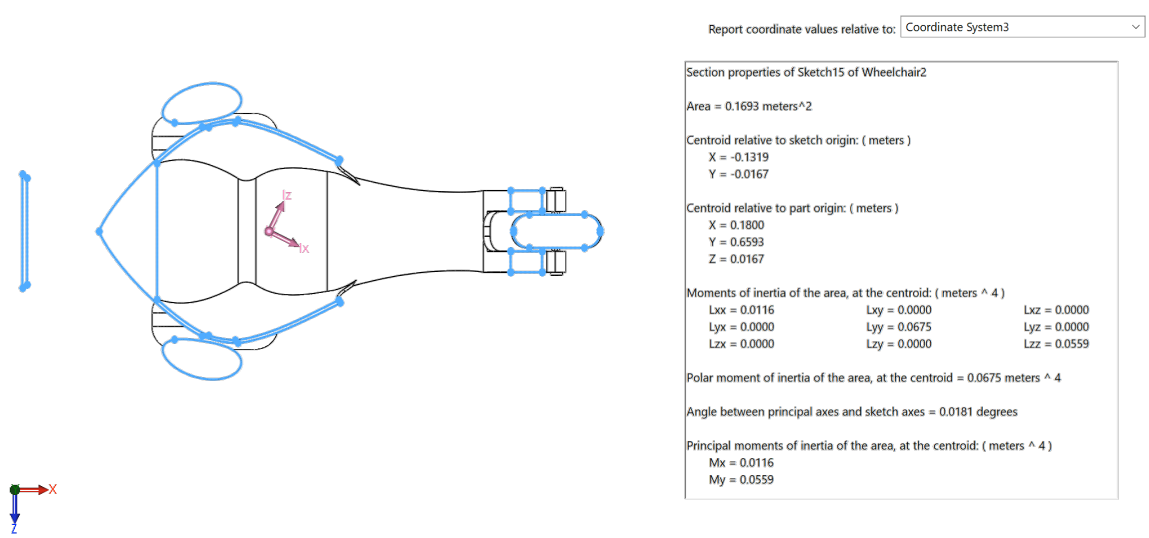


Figure 32 – Water Plane and Moments of Inertia of Waterplane Data

Table 7 - Overall Volumetric Displacement

Volumetric Displacement		
Volume of chair	0.01770	m^3
Volume of Human	0.08122	m^3

Table 8 – Metacentric Height Calculation

Vertical Centre of Gravity (KG)	0.4789	m
Vertical Centre of Buoyancy (KB)	0.3630	m
Second Moment of Area of water plane about Heel Axis (I_{xx})	0.0116	m^4
Volumetric Displacement	0.0989	m^3
BM	0.1173	m
GM	0.0014	m

Stability on Land

Stability of the device on land is an essential quality that must be present for the operation of the wheelchair. To prevent directional and lateral tipping, the Centre of Gravity (CoG) of the user must be located in an optimal position. This optimal position is found by determining and connecting the contact points of each tire with the ground, to form a triangle. A line from the midpoints of each triangle edge is connected to the opposing vertices. The Optimal position of the CoG is essentially the point at which all lines intersect as seen in Figure 33. In addition to this, increased stability of the device is achieved when the CoG is closer to the ground. Therefore in each stage of the project, the chair was modelled so that the centre of gravity of the user was located in the optimal position to avoid tipping.

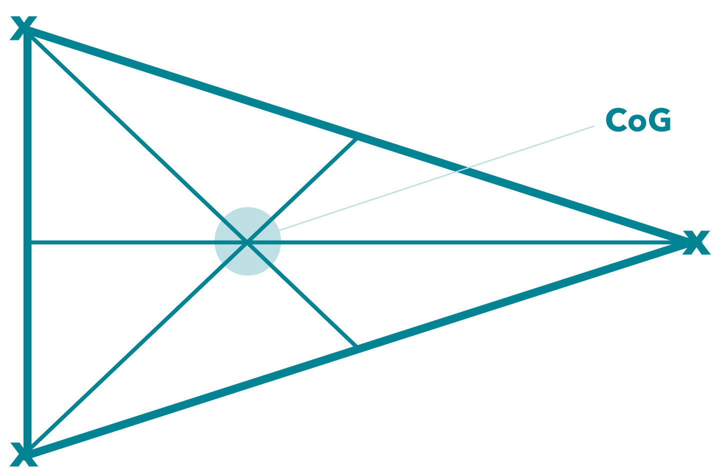


Figure 33 - Optimal CoG position

Materials

Material selection is a vital process within an engineering design project. Throughout the design stages of the project, materials were chosen to satisfy the defined design requirements. Materials for this device should exhibit appropriate structural and water/corrosion-resistant material properties. Initially, general materials used within the manufacture of structural and marine devices were explored and highlighted in Table 9 alongside their corresponding advantages and disadvantages.

Table 9 - Advantages and Disadvantages of Materials

Material	Advantages	Disadvantages
Steel	– Hard and strong – Can tolerate high loads – Cheap	– Exceedingly Heavy – Corrosive
Aluminium	– Easily shaped – Lightweight – Non-corrosive – Cheaper than other materials (excluding steel)	– Not as hard or as strong as steel
Stainless Steel	– Non-Corrosive – Strong and Hard	– Very Heavy – Expensive
Polyethylene	– Robust	– Sensitive to Ultraviolet (UV) radiation – Heavier than GFRP and CFRP
Glass Fibre Reinforced Plastic (GFRP)	– Lightweight but heavier than CFRP – Strong	– Not as Stiff as CFRP – Cheaper than CFRP
Carbon Fibre Reinforced Plastic (CFRP)	– Lightweight – Strong and Stiff	– Expensive in comparison to other materials

In the later stages of the design process, materials were explored in depth with the GRANTA EduPack software. This software offers teaching resources that support Materials Education across Engineering, Design, Science and Sustainable Development (What is GRANTA EduPack? | GRANTA Design, 2020). GRANTA EduPack can be used to narrow down materials for design optimisation projects and was subsequently used to choose appropriate materials for each wheelchair component. Material requirements were formerly set before the analysis. The fixed constraints were:

1. A minimum Tensile and Yield strength of 100MPa
2. *Excellent* resistance to freshwater
3. *Excellent* resistance to saltwater water

Excellent is a category created by GRANTA EduPack that represents no degradation in material performance after long term exposure to either freshwater or saltwater.

Once these constraints were established, results were collected and summarized in the following charts. Figure 34 shows a Level 3 (a database containing detailed information of 4000 materials) analysis of cost per unit strength vs mass per unit strength of a panel in bending. It can be seen that the majority of materials found in Table 9 are located on this graph.

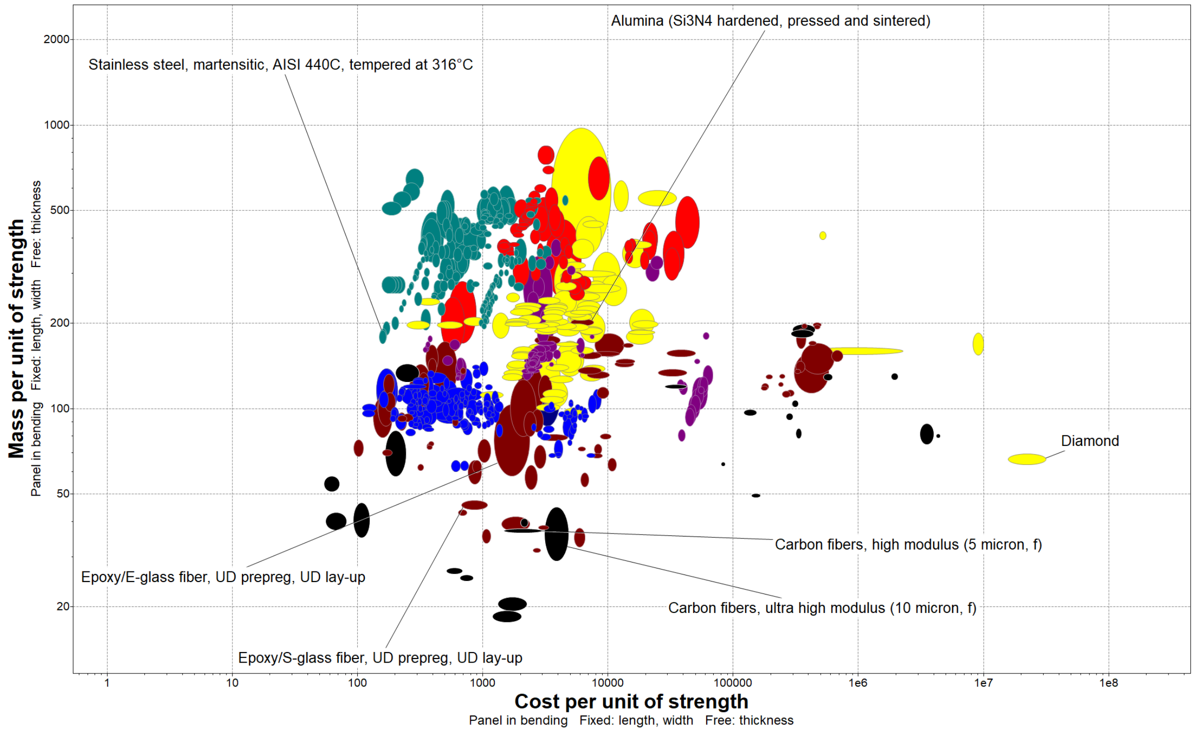
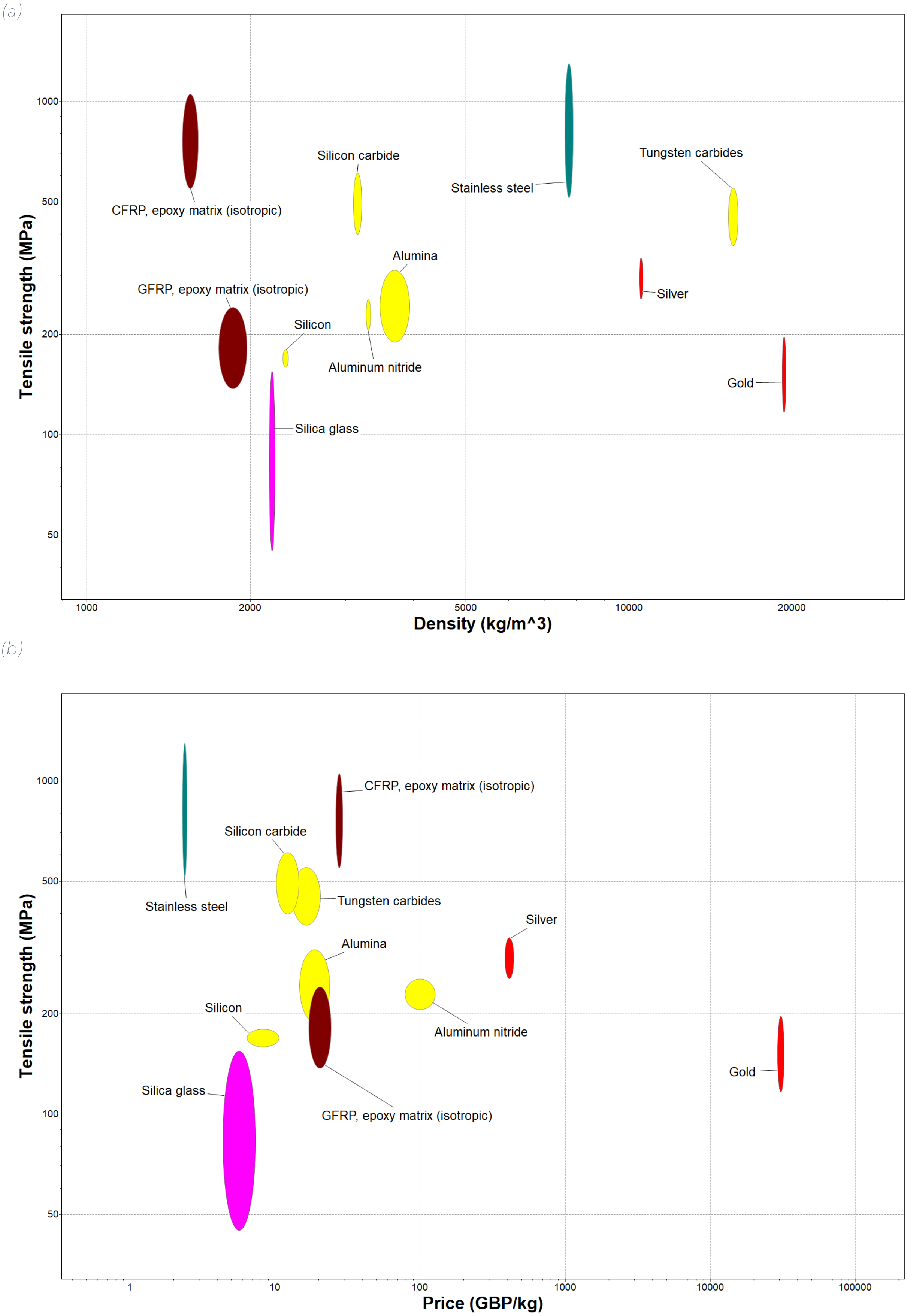


Figure 34 - Level 3 Cost vs Mass per Unit Strength

Table 10 - Material Properties of Selected Materials

	Stainless Steel	GFRP	CFRP
Density (kg/m^3)	7.61×10^3 - 7.87×10^3	1.75×10^3 - 1.97×10^3	1.50×10^3 - 1.60×10^3
Price (GBP/kg)	2.3 - 2.47	17.1 – 24.2	26.3 - 29.2
Young's modulus (GPa)	190 - 210	15 - 28	69 - 150
Yield strength (elastic limit) (MPa)	257 - 1.14×10^3	110 - 192	550 - 1.05×10^3
Tensile strength (MPa)	515 - 1.3×10^3	138 - 241	550 – 1.05×10^3
Elongation (% strain)	10 - 49	0.85 – 0.95	0.32 – 0.35
Hardness – Vickers (HV)	170 - 438	10.8 – 21.5	10.8 – 21.5
Fatigue strength at 10^7 cycles (MPa)	256 - 542	55 - 96	150 - 300
Fracture toughness (MPa.m^0.5)	57 - 137	7 - 23	6.12 - 20

(a)



(b)

Figure 35 - Bubble chart of Tensile Strength against (a) Density (kg/m^3) (b) Price (GBP/kg)

Figure 35 displays a simplified analysis comparing tensile strength with material density and price. The chief materials of comparison in this analysis are Stainless Steel, GFRP and CFRP. Whilst stainless steel appears to have high tensile strength and decreased Price, its density is significantly high when compared to CFRP and GFRP. CFRP and GFRP can be seen to almost match the tensile strength of stainless steel at the expense of greater cost. This design project concluded higher importance of a decreased total mass over total cost, as previously clarified in the weighting matrix shown in Table 3. Stainless steel, therefore, did not qualify and CFRP and GFRP were further investigated.

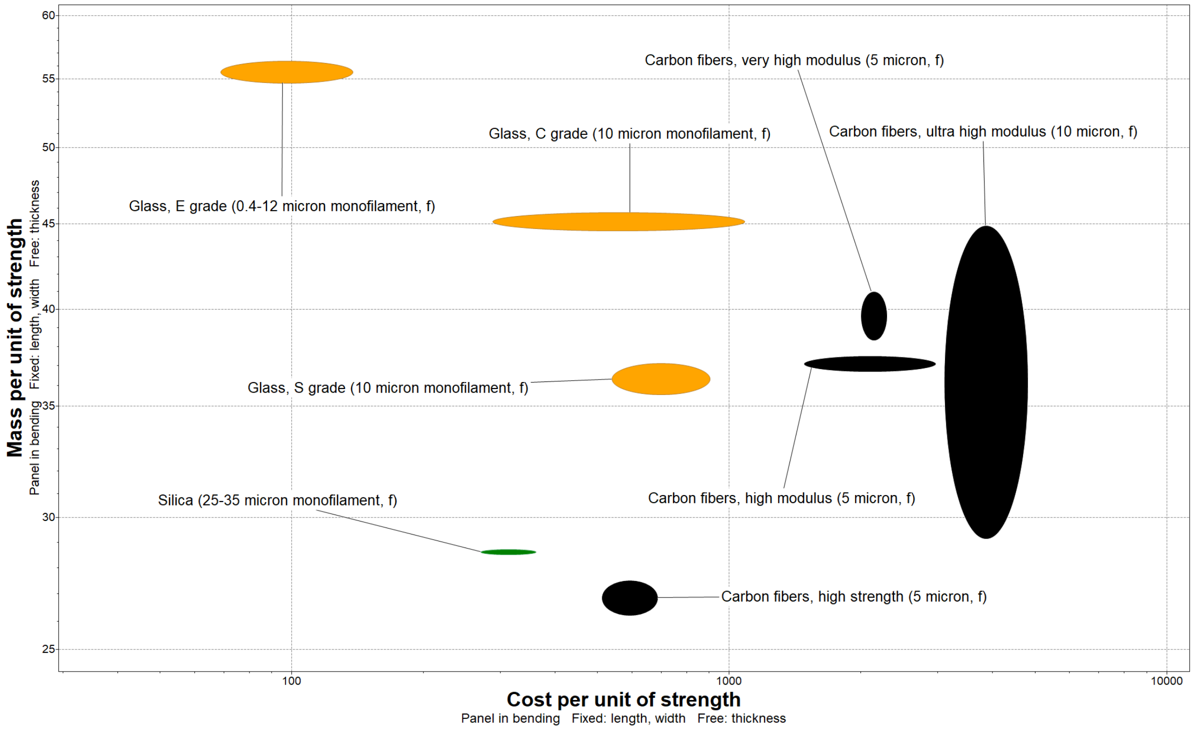


Figure 36 - Cost vs Mass per Unit Strength of Carbon and Oxide Fibres

Figure 36 visualises an additional cost versus mass per unit strength analysis of Carbon and Oxide fibres, showing increased detail on specific reinforced plastic grades. It can be deduced that the E-glass GFRP exhibits the lowest cost per unit strength and also the highest mass per unit strength when compared to the other materials. The CFRP demonstrates a decreased mass per unit strength however its cost is significantly elevated when compared to GFRP.

To aid in the material selection process, finite element analysis was used to deduce a suitable material. *See the corresponding section on Page 35 for detailed investigation.* The analysis concluded that CFRP is the most suitable material for the exterior frame in terms of mass and cost for this project.

The materials of the wheels and the armrests were chosen to be Polyurethane rubber as it is widely used by wheel and buoy manufacturers. CFRP was additionally chosen for the manufacture of the front fork, rear axle and front axle for its structural, non-corrosive and lightweight properties. Table 11 summarises the final component materials.

Table 11 - Component Materials

Component	Material
Exterior	CFRP
Buoyant armrests	Polyurethane Rubber
Wheels	Polyurethane Rubber
Front Fork	CFRP
Rear Axle and Front Axle	CFRP

Aesthetics

This task in the design analysis focuses on the appearance of the device and its appeal to users in terms of beauty. To achieve an aesthetic design a sleek 'boat design' approach was adopted throughout the design phases.

Colours

The colour scheme of the device was additionally considered to attain an appealing design. The main body colour was chosen to be ocean green as it familiarises with the operating environment. In addition to this, a colour scheme generator, Coolors.com (Coolors, 2020), was used to determine harmonising colours for the wheels and armrests. The final colour scheme, seen in the detailed design section in Figure 38, included Ocean green, Alice blue, Davys grey and Gunmetal.

Manoeuvrability

Manoeuvrability is the ability for a device to move or be directed somewhere. As detailed in the weighting matrix in Table 3, manoeuvrability was deduced to have a weighting of 7%, which is above average. In the concept design phase, standard wheelchairs were analysed to assess manoeuvrability. It was found that most wheelchairs comprise 2 rear wheels and 2 front caster wheels allowing them to easily move in direct motions. However, the four-wheeled arrangement was found to decrease ease of turning due to its large turning circle. To combat this, a 3 wheeled arrangement was implemented in the preliminary and detailed design phase to allow a user to turn in swifter motions while operating the chair.

Tyre Selection

A critical design requirement for this device was the ability for it to roam on sandy terrain. To fulfil this requirement, tyres, which are the central components in direct contact with the ground, were explored. The types of tyres to be evaluated included the Balloon (Pneumatic) tyre, the Mountain Bike tyre, the Bicycle Road Tyre and the Go Kart tyre. Each tyre type embraces specific qualities, making it suitable for different applications. The Pugh matrix seen in Table 12 assesses each tyre against specific criteria chosen to identify a suitable tyre for the application of this device. The corresponding weighting matrix is found in Appendix 1 Table 23. The Balloon

Tyre accumulated the highest score and concluded to be most suitable for this application. This tyre is, moreover, incorporated in the majority devices used on sandy terrains concurring with this investigation.

Table 12 - Tyre Pugh Matrix

Selection Criteria	Weight (%)	Tyre 1		Tyre 2		Tyre 3		Tyre 4	
		Balloon (Pneumatic) Tyre		Mountain Bike Tyre		Bicycle Road Tyre		Go Kart Wheel Tyre	
		Score	Weighted score	Score	Weighted score	Score	Weighted score	Score	Weighted score
Cost	2	3	0.055	3	0.055	1	0.018	3	0.055
Ease of Roaming on Sand Terrain	18	5	0.909	2	0.364	0	0.000	2	0.364
Durability	13	3	0.382	4	0.509	3	0.382	3	0.382
Manoeuvrability	16	3	0.491	4	0.655	4	0.655	3	0.491
Total mass	9	5	0.455	2	0.182	5	0.455	3	0.273
Max Load	11	4	0.436	4	0.436	3	0.327	3	0.327
Water Resistance	15	5	0.727	5	0.727	5	0.727	5	0.727
Corrosion Resistance	5	5	0.273	2	0.109	2	0.109	2	0.109
Flotation	7	5	0.364	2	0.145	2	0.145	2	0.145
Assembly Time	2	4	0.073	5	0.091	5	0.091	3	0.055
Tyre Size	2	4	0.073	4	0.073	4	0.073	4	0.073
Total		**4.24**		3.35		2.98		3.00	

Structure

The structure of the wheelchair was similarly considered throughout the design phases of this project. Initially, the structure of a standard wheelchair was investigated and was found to comprise a frame, a seat, wheels, armrests, footrests push handles and wheel locks. The majority of these parts were inherited in the preliminary and detailed design phase. To adapt to the beach environment, specific components such as the tyres were considered and selected. The main parts that made up the final wheelchair were a seat, a chair body, rear axle, rear wheels, front wheel and front fork and push handles. The final structure is visualised in Figure 38 in the detailed design section. The seat and chair body were combined to make one part manufactured from CFRP alongside the axles and front fork.

Cost Estimate

Similar to the sizing and weight estimates, the cost estimate for this wheelchair was based on the average cost of a standard wheelchair. The cost at each phase was likewise calculated by evaluating upper and lower cost bounds at each phase. The average cost of a standard wheelchair lies within the range of £70-£1000 dependant on wheelchair function. Considering the cost range of standard wheelchairs, allowances were made for the cost of materials and sizings. The cost estimate at the concept design phase was £1500. The preliminary design further considered the material cost, as the dominant material was CFRP, which increased the cost estimate to £2500. The final detailed design was deduced to be £2750. This value was suitable as it yielded an appropriate profit margin as depicted in the financial model in Table 21. The final cost fell in the range estimated in the preliminary design stage as seen in Figure 37.

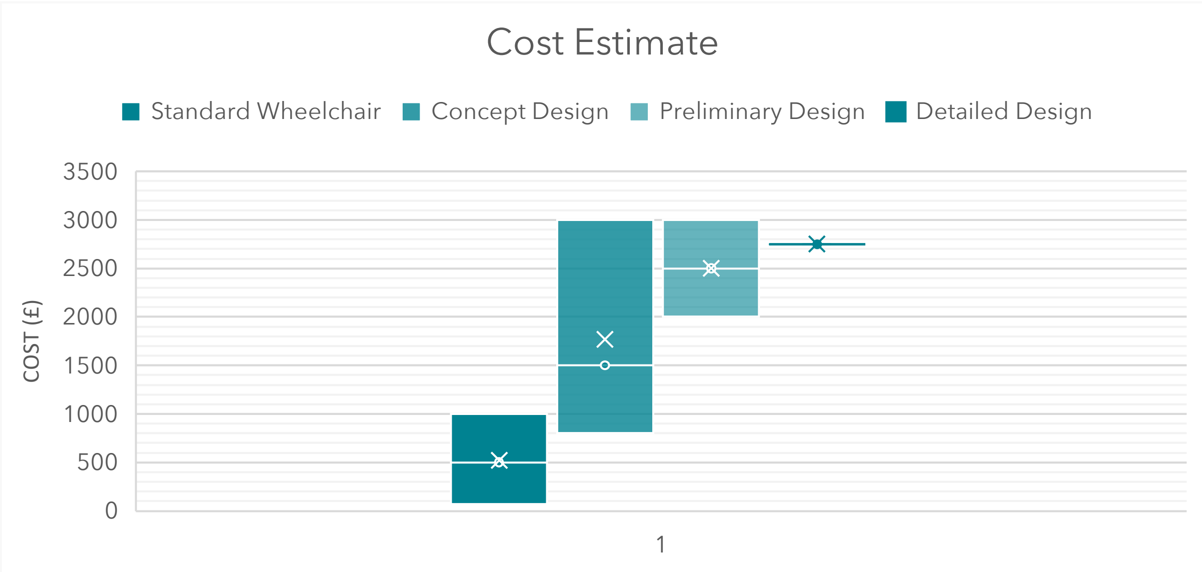


Figure 37 - Cost Estimate

Technical Specifications

The full technical specifications for the detailed design are visualised in Table 13.

Table 13 - Technical Specifications

Total Length	178.3cm
Total Width	104.3 cm
Total Height	111.7cm
Total Weight	25.6 kg
Front Wheel Diameter	30 cm
Rear Wheels Diameter	42 cm
Maximum Weight Capacity (approx.)	115 kg
Seat height (from the ground)	36cm
Seat width	45cm

Detailed Design

The final design was composed, after the completed design analysis, using SolidWorks, a Computer-Aided Design (CAD) software. Figure 38 displays the final render of the detailed design including the following components:

1. Chair exterior
2. Seat
3. Two footrests
4. Pneumatic armrests
5. Rear Balloon Wheels
6. Rear Axle
7. Front Fork
8. Front Axle
9. Front Balloon Wheel
10. Push handles

The CAD model comprises the general components listed above however the tangible model will incorporate the following additional features:

- Seat Cushions
- Seat Belt
- Front Suspension
- Rear Brakes

Detailed component and Assembly drawings are attached in Appendix 2.

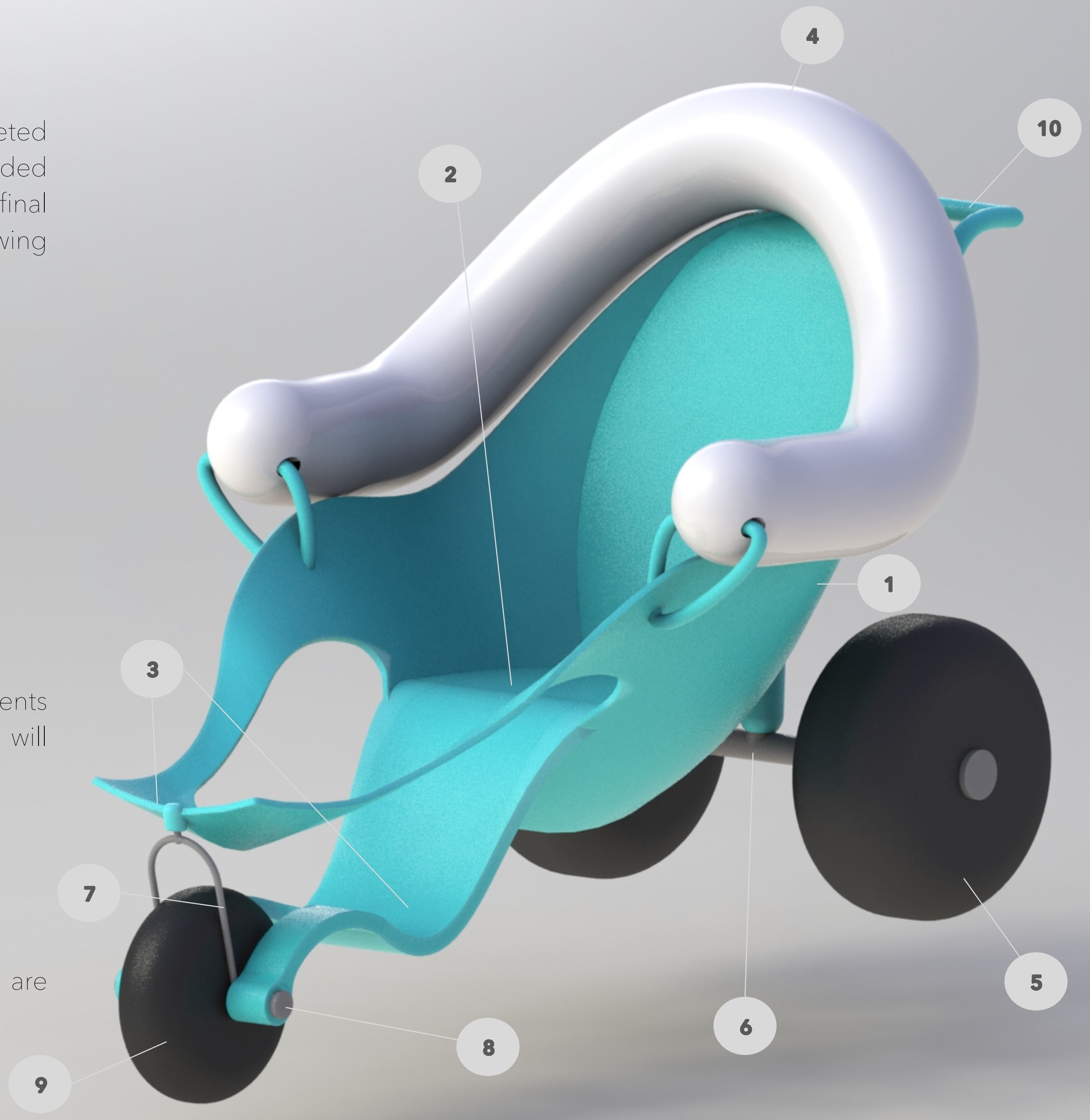


Figure 38 – Detailed Design

Finite Element Analysis

Once the detailed design was complete, Finite Element Analysis (FEA) was used to analyse the device's structural capabilities whilst deducing appropriate material thickness for the main body of the wheelchair. ANSYS was the chosen software used to simulate the model. Due to the nature of the selected materials, CFRP and GFRP, a composite analysis was undertaken using Ansys Composite PrepPost (ACP). ACP is used to analyse layered composites and was subsequently used to model the ply lay-ups in the chair body. To begin the analysis, the material fabrics were initialised as woven epoxy carbon and woven epoxy glass fibre. These materials were then stacked up in perpendicular directions as displayed in Figure 39. Layup and stacking directions were then set to achieve the final composite model. ACP (pre) used the imputed data to deduce material thicknesses and the total weight of the model as portrayed in Figure 40.

Fabric	Angle
Fibre glass	0.0
Fibre glass	90.0
Fibre glass	0.0
Fibre glass	90.0
Fibre glass	0.0
Fibre glass	90.0

Figure 39 - Example Lay-Up of Woven Epoxy Glass Fibre Fabric

This model was then transferred into a static structural analysis, which determined magnitudes and locations of Total deformation and Equivalent (Von Mises) Stress as a result of applied loads onto the model. The Equivalent (Von Mises) Stress is a single positive stress value that embodies any arbitrary three-dimensional stress state (Sharcnet, 2020). Loads that mimic a person's weight were applied evenly across the model on the seat, the armrests, leg rests and the push handles.

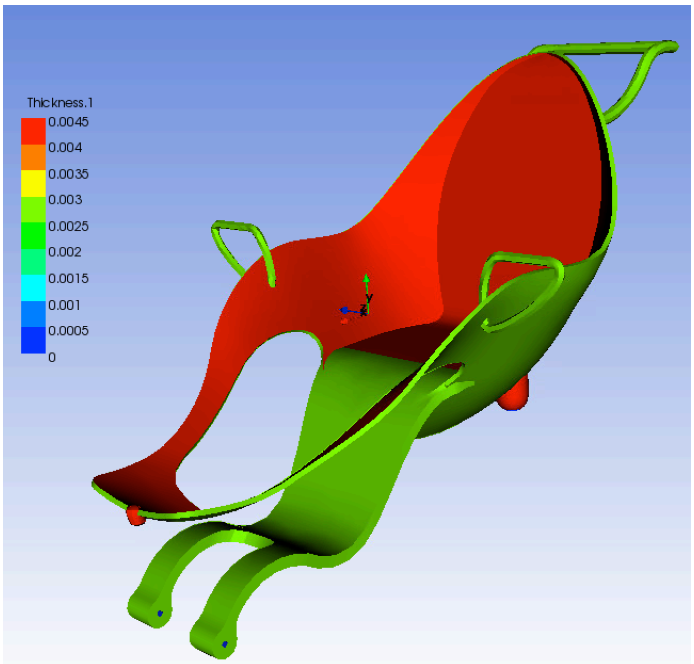


Figure 40 - Material Thickness Plot of Carbon Fibre Layup

This process was completed on both CFRP and GFRP for two different ply-layups visualised in Table 14.

Table 14 – Ply Angles of Layups

Chair Body Section	Ply Angle (°) Layup 1	Ply Angle (°) Layup 2
Seat and interior	0	0
	90	45
	0	0
		45
Exterior, Footrests and Handles	0	0
	90	45
		0

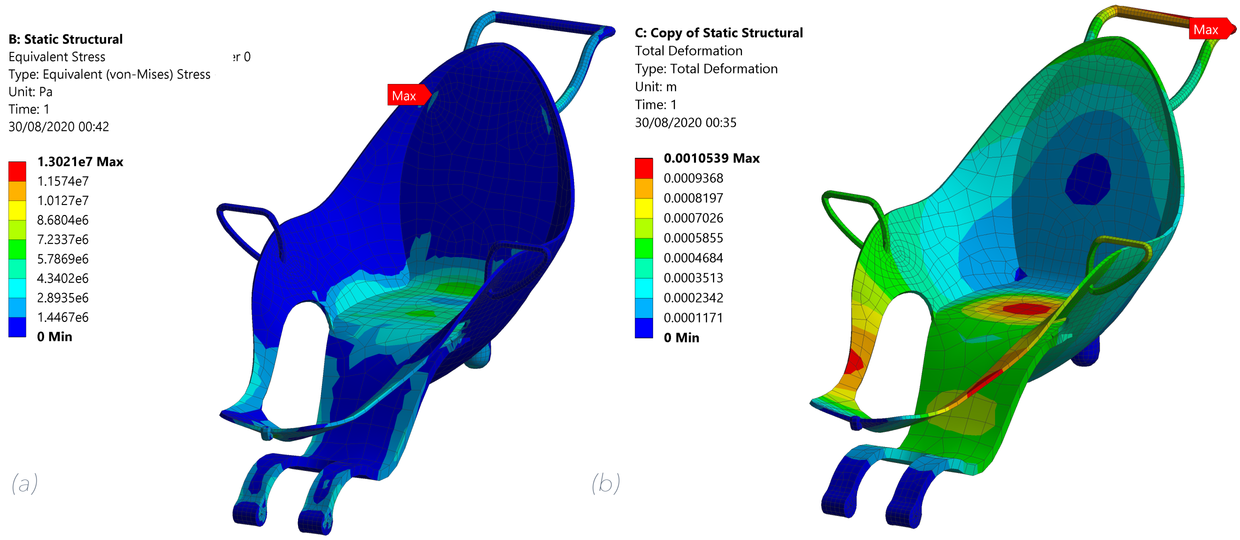
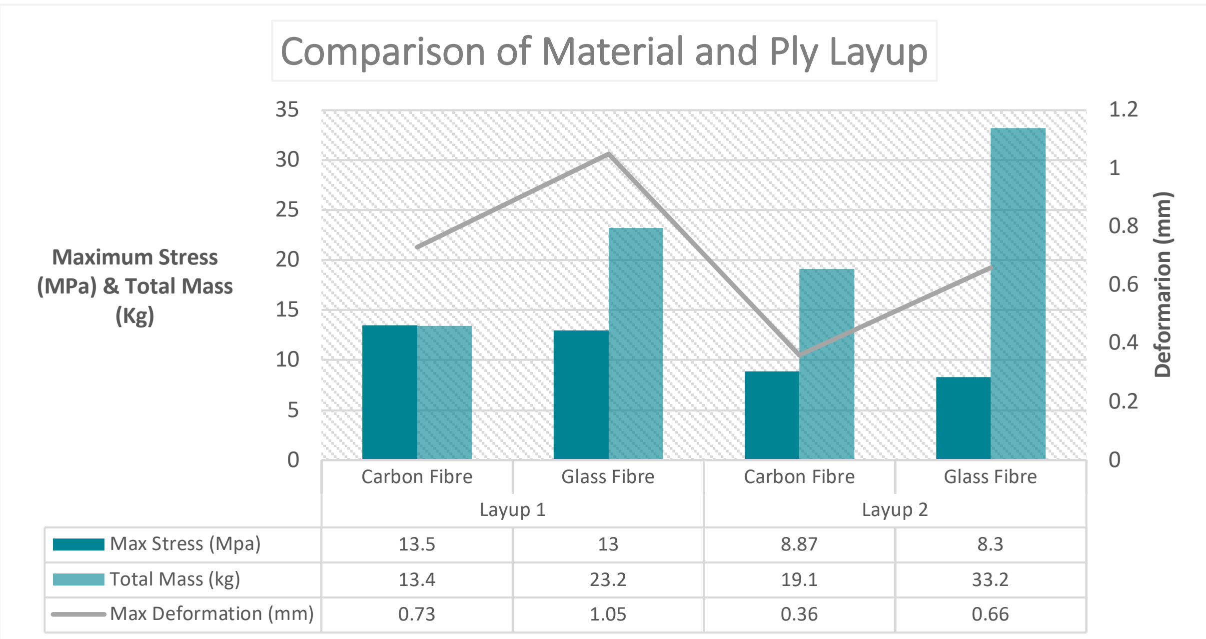


Figure 41 – Plots of (a) Equivalent (Von Mises) Stress of CFRP Model (b) Total deformation of GFRP Model

Results for the two layup arrangements and the two materials were collected and compared. A visualisation of this comparison is seen in Figures 41 & 42. It can be deduced that the CFRP model experienced decreased deformation and equivalent stress with both layup arrangements in comparison to the GFRP model. In addition to this, the CFRP model was 42% less in total mass, with a minimum mass of 13.4kg. The GFRP model also experienced deformation in undesired parts of the chair, such as the upper leg rest, unlike the CFRP model which embraced greater resistance.



	Layup 1		Layup 2	
	Carbon Fibre	Glass Fibre	Carbon Fibre	Glass Fibre
Max Stress (Mpa)	13.5	13	8.87	8.3
Total Mass (kg)	13.4	23.2	19.1	33.2
Max Deformation (mm)	0.73	1.05	0.36	0.66

Figure 42 – Comparison of The Two Layup Arrangements and The Two Materials

This investigation, therefore, concluded a body material of woven CFRP assuming the composite layup 1 arrangement. The thickness was hence deduced to be between 2 - 4.5mm throughout the chair body as seen in Figure 40.

Manufacturing Plan

Materials list

Deduced component materials were used to calculate material quantity and sizes and are summarized in Table 15.

Table 15 – CFRP Fabric Size of Particular Components

Material	Component	Required Fabric Size	Quantity	Total	
CFRP	Chair Exterior	2.70m^2	3	8.1m^2	8.61m^2
	Front Fork	0.02m^2	3	0.06m^2	
	Axles	0.150m^2	3	0.45m^2	

Product Parts List

A complete parts list is pictured in Table 16, showing each part alongside supplier descriptions and total cost. Components and materials will be brought in bulk directly from manufacturers allowing for the assumption of an applied 10% discount on all purchases. The complete part list can assume a total cost of £625.71 per wheelchair.

Table 16 – Parts list

Part	Component/ Raw Material	Quantity	Price (£)	Total (£)	Supplier
Front Wheel	30 cm PU Beach Wheel	1	63.71	63.71	Wheeleez™
Rear Wheels	42 cm PU Beach Wheel	2	97.56	195.12	Wheeleez™
Armrests	Xencast PX60 Medium Flexible Polyurethane Rubber - 4kg Kit	1	59.00	59.00	Easy Composites
Chair Exterior	XPREG XC110 210g 3K 2x2 Twill Prepreg Carbon (1250mm) 5m Roll	1	225.35	225.35	Easy Composites
Front Axle Rear Axle Front Fork	XPREG XC110 210g 3K 2x2 Twill Prepreg Carbon (1250mm) 2m Roll	1	98.34	98.34	Easy Composites
Chair Exterior	Cerakote Aztec Teal Basecoat Paint 1.15 litres	1	48.34	48.34	Cerakote ©
Cost Per Wheelchair		£625.71			

Manufacturing Procedure

The manufacturing technique that was chosen to make the chair exterior, axles and front fork is vacuum bag resin infusion. This technique will be used to cure the prepreg carbon fibre. The recommended cure cycle is approximately 8 hours as seen in Figure 43. Hence the total production time of one unit has been estimated to be 2.5 working days with the consideration of the fibre layup period, body painting and final assembly.

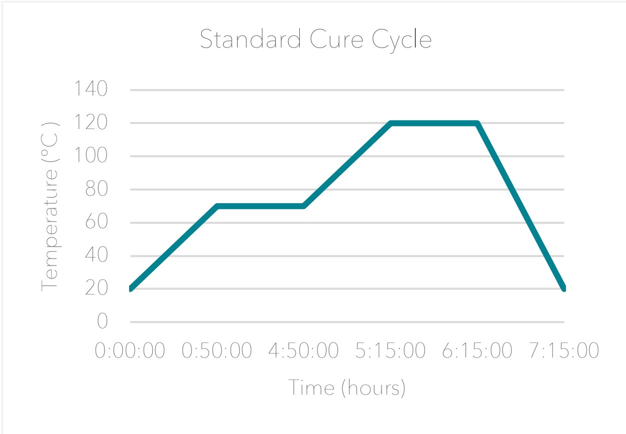


Figure 43 - Standard Cure Cycle of Prepreg Carbon Fibre

Manufacturing Location

To ensure the optimal manufacturing location is chosen, selection criteria were chosen to evaluate different countries such as the UK, the US and China. Table 17 shows this process outlining the main selection categories: manufacturing requirements, logistic requirements, Government policy & political climate and additional requirements.

Table 17 – Manufacturing Location Comparison

Selection Criteria			UK	US	China
Manufacturing Requirements	Hourly Labor Costs/ per employee (£) (Grünig and Morschett, 2012)		20.40	21.08	2.07
	Real Estate Costs	Purchase £ per square meter (Boyle, 2020)	4304	2017	5229
		Rent $ per square meter (Cushman & Wakefield, 2008)	55.47 - 170.09	37.03 -124.00	65.76 - 78.72
	Utility Costs – Electricity $ per kilowatt-hour (Statista, 2018)		0.22	0.13	0.08
Logistics Requirement	Proximity to The Market		High	High	Low
	Proximity to Material Source		High	High	Low

	Infrastructure Facilities Available	Mid	High	High
Governmental Policy & Political Climate	Trade Agreements (Lloyd et al., 2017)	Long Term Supplier Declaration (LTSD)	North America Free Trade Agreement (NAFTA), U.S.-Mexico-Canada Agreement (USMCA)	APAC trade agreements
	Corporate Tax Rates (Asen, 2020)	19%	25.9%	25%
	Financial Incentives	Patent Box	CARES Act, Work Opportunity Tax Credit,	High and New Technology Enterprises (HNTEs)
Additional Requirements	Safety Requirements	The Health and Safety at Work Act 1974 (the HSWA), CE marking	OSH Act of 1970	PRC Production Safety Law
	Environmental legislation	Environmental Permitting Regime (EPR)	The Clean Air Act (CAA)	Environmental Protection Law of the People's Republic of China (2014 Revision)

Although China displayed low manufacturing costs, its distance from the market can lead to logistical implications. The UK is seen to exhibit the lowest corporation tax, with an additional reduction to 10% if the Patent Box financial incentive is utilised. With the consideration of all the above manufacturing criteria, the manufacturing location was chosen to be based in the UK. The manufacturing warehouse will be based in Cardiff and rented for around £22,000 a year.

Geographic target market

According to the WHO, 15.3% of the world's population live with a moderate or severe disability (Albrecht et al., 2011). These statistics show that there are potential consumers around the world, however for this particular product the geographic target market will likely be based in locations that contain beaches, coasts and financially able buyers. Therefore it was concluded that the target market will initially be geographically located in the UK and the US.

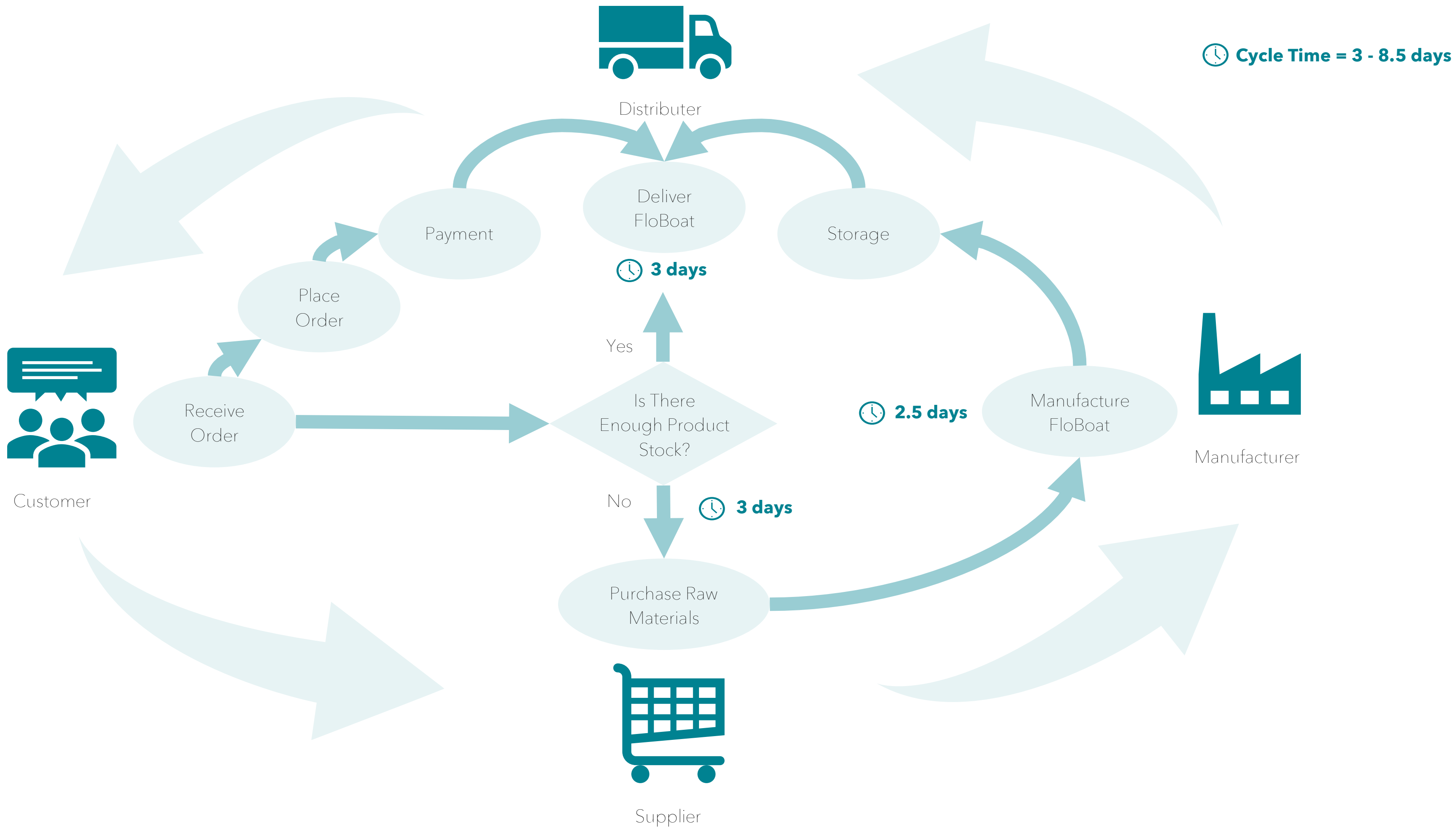


Figure 44 - Supply Chain and Production Plan

Supply Chain

The detailed supply chain is depicted in Figure 44. Initially, the customer will use the unique online system to place an order. Suppliers will deliver raw materials to the warehouse which will manufacture and assemble the FloBoat to then be distributed to consumers. The production plan is also visualised in Figure 44, depicting the critical tasks and periods leading to a cycle time of 3-8.5 days.

Business Plan

Product

The FloBoat is a floating beach wheelchair for wheelchair users. It can roam on sandy terrains and effectively float in water. FloBoat is designed to improve the quality of life of individuals with limited mobility, by allowing them to participate in water activities whilst providing the necessary support.

Market Research

Before deducing a specific market, research was conducted to identify the market opportunities for the FloBoat. The PEST analysis framework (Figure 45) was used to understand the Political, Economic, Sociological and Technological factors that highlight the external environment of this product. The analysis concluded a clear market opportunity for the FloBoat when all factors were considered.

Political	Economical
Section 20 of the Equality Act 2010 (EA 2010) enforces all organisations in making necessary adjustments to ensure availability of all inclusive and accessible services for disabled people (Tomlinson, 2019). U.S. Administration on Aging (AoA) maintains Elder Rights Protection, Health Prevention and Wellness, Special Projects and more (Voit and Vickers, 2012).	Global wheelchair market was $4.73 billion in 2018 and is estimated to reach $8.09 billion by 2026. (Fortune Business Insights, 2020) Fall in consumer confidence and rise in global inflation rates subsequent to COVID-19 pandemic. (Jones, Palumbo and Brown, 2020)
Social	**Technological**
There are around 3.3 million wheelchair users in the US and 1.2 million in the UK. 1.825 million of those users in the US are aged 65 and older. Wheelchair users expected to increase by 2 Million every year in the US. Rising participation of disabled persons in sporting activities such as the paralympic games.	Increasing technolgies are becoming available in the wheelchair industry from electric propulsion to brain-computer interface (BCI) technology Floating technology in wheelchairs is negligible and only available from main competitor WaterWheels ©.

Figure 45 - PEST Analysis

Sales and Marketing

Market Size

It was assumed that 20% of wheelchair users in the UK and US would be potential customers for FloBoat. This value was assumed from the increased predictability of using the device in coastal locations; with coastal towns making up around 5% and 29% of the population in the UK and US respectively. Additionally, target buyers such as hotels were included in the estimation. Table 18 shows the market size estimation with a final market volume of 797,777 people and market value of £2,193,887,641.

Table 18 - Market Size Estimation

Population in the UK	67,886,011 people
Population in the US	331,002,651 people
Total	398,888,662 people
Average percentage of people in need of a wheelchair	1%
Estimated Population of people in need of a wheelchair	3,988,887 people
Penetration rate - Assumed percentage of customers	20%
Market volume - Assumed population of FloBoat customers	797,777 people
Market value	£2,193,887,641

Marketing Strategy

FloBoat will primarily target hotels, country clubs and other leisure providers who will likely buy larger volumes. Brochures will be distributed to such providers in addition to coastal care homes and beach fronts. The primary marketing strategy for FloBoat will be via online publicity. This will increase product awareness by reaching all target market locations through the internet and social media. FloBoat will be marketed on most social media platforms such as: Facebook, Instagram, Twitter, LinkedIn, and more. Influencers will additionally be hired to promote the device on social media.

Pricing Model

The 5-year pricing model per unit is seen in Table 19. The main component costs of the wheelchair are deduced to be, raw materials, labor and shipping costs. These costs are seen to decrease over the years due to the increase in material purchase and employees. The pricing model deduced a healthy gross margin averaging to 67.8%.

Table 19 - Pricing Model Per FloBoat/Unit

	2021	2022	2023	2024	2025
Selling Price (inc VAT)	£3,300	£3,300	£3,300	£3,300	£3,300
VAT	£550	£550	£550	£550	£550
Selling Price (exc VAT)	£2,750	£2,750	£2,750	£2,750	£2,750
Component Costs					
Component 1 - Raw Material Costs	£626	£601	£577	£554	£531
Component 2 - Labor costs	£300	£297	£294	£291	£288
Component 3 - Shipping Costs	£15	£15	£15	£15	£15
Total Costs	£941	£913	£886	£860	£835
Gross Profit	£1,809	£1,837	£1,864	£1,890	£1,915
Gross Margin	65.79%	66.81%	67.79%	68.74%	69.65%

Financing Plan

FloBoat will be financed through a variety of methods. In addition to bank loans, crowdfunding platforms will be used to advance sales before manufacturing initiates. Table 20 details the presumed funding rounds over a 5-year period. Crowdfunding platforms such as Kickstarter, Angel investors and Venture Capitalists will contribute to the rounds of funding outlined below. By 2025 around £3.9 million is expected to be raised.

Table 20 - Presumed Funding Rounds

Round of Funding	Amount Raised in Round	Date of Funding Round
Pre-Seed	£150,000	March 2021
Seed	£1,500,000	January 2023
Seed	£2,250,000	February 2025
Total	*£3,900,000*	

Five-Year Projections

Sales

An estimated sales forecast is visualised in Figure 46 showing an increase in sales in each year. It was initially estimated that 200 units will be sold in 2021, with a 20% increase in sales in the following year. A further 25%, 40% and 50% increase in sales is seen in the remaining years. The summation of sales seen in this 5-year projection is seen to make up 0.22% of the market value which is typical in an early stage start-up business.

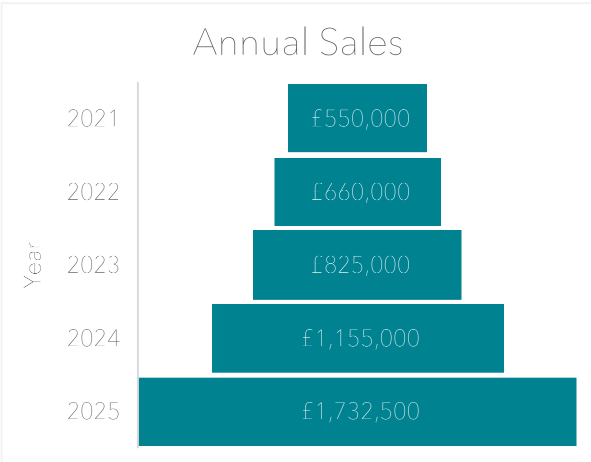


Figure 46 - Annual Sales

Financial model

The complete FloBoat financial model is detailed in Table 21. The model contains the chief overheads that contribute to fixed costs of the company including warehouse and office lease, utilities, total salaries, online bank charges, legal & insurance, marketing & advertising and other costs (maintenance etc.). Annual loan interest resultant of a 5-year bank loan of £100,000 at a fixed annual rate of 6% is also included in the financial model. Depreciation on machines (curing ovens, spray painting etc), equipment, computer systems and personal cars are additionally taken into consideration within the model. Total Operating Expenses, EBITDA, Operating Profit, Profit Before Tax, Profit After Tax and Break-Even Point is subsequently calculated for each year. In the monthly forecast seen in Figure 47, It can be estimated that the company will break even in the first quarter of 2021. Due to seasonal demand, sales will fluctuate throughout the years, with increased sales exhibited in the hotter seasons.

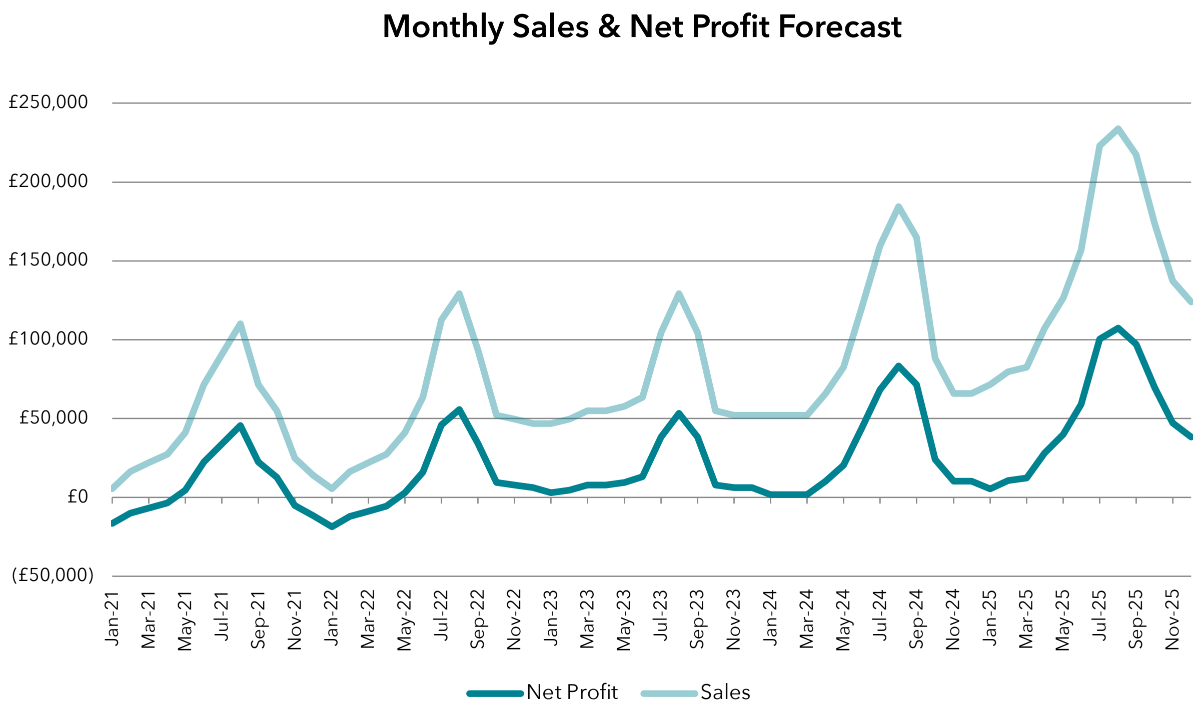


Figure 47 - Monthly Sales Vs Net Profit

Table 21 - Financial Model

	2021	2022	2023	2024	2025
Sales Volume	200	240	300	420	630
Sales	£550,000	£660,000	£825,000	£1,155,000	£1,732,500
Cost of Sales	£188,142	£219,044	£265,705	£361,065	£525,813
Gross Profit	£361,858	£440,956	£559,295	£793,935	£1,206,687
Overheads					
Warehouse and Office lease	£29,000	£29,580	£35,000	£35,700	£36,414
Utilities	£20,000	£20,400	£23,000	£23,460	£23,929
Total Salaries	£185,000	£212,750	£255,300	£319,125	£430,819
Online Bank Charges	£2,500	£2,500	£2,500	£2,500	£2,500
Legal & Insurance	£3,200	£3,200	£3,200	£3,200	£3,200
Marketing & Advertising	£8,000	£8,150	£7,335	£6,602	£5,941
Other Costs (Maintenance etc.)	£4,000	£4,800	£6,000	£8,400	£12,600
Total Operating Expenses	£251,700	£281,380	£332,335	£398,987	£515,403
EBITDA	£110,158	£159,576	£226,960	£394,949	£691,284
Depreciation	£6,250	£6,250	£6,250	£6,250	£6,250
Operating Profit	£103,908	£153,326	£220,710	£388,699	£685,034
Loan Interest	£6,000	£5,640	£5,302	£4,984	£4,684
Profit Before Tax	£97,908	£147,686	£215,408	£383,715	£680,349
Corporation tax (10%)	£9,791	£14,769	£21,541	£38,372	£68,035
Profit After Tax	£88,117	£132,918	£193,867	£345,344	£612,314
Break-Even Point (Sales)	£401,186	£438,951	£507,258	£596,779	£755,689
Break-Even Point (No. Customers/yr)	146	160	185	218	275
Break-Even Point (No. Customers/mon)	13	14	16	19	23

Critical Analysis and Evaluation

Design Requirements

The following section evaluates the final design against the design requirements outlined in Table 2. In terms of mass properties, FloBoat fulfilled all the requirements exhibiting a total mass of 25.6 kg and a maximum load of 115kg. These values, however, lie in the upper division of the defined requirement range allowing future improvement on the mass properties. The materials chosen to manufacture the FloBoat accomplished excellent resistance to water and corrosion. The FEA analysis additionally demonstrated high durability and strength of the FloBoat.

The wheelchair structure was composed of seven parts that built a rigid structure preventing the inclusion of a folding mechanism. In addition to a folding mechanism, an independent electric propulsion and adjustable buoyancy function was not explored due to the limited timescale of the project. However, these design requirements were considered supplementary and can be pursued in future designs. Two seat positions were comprised into the final design allowing users to embrace a choice when operating the wheelchair.

FloBoat demonstrated the ability to float and exhibited a draft of 659mm at an angle of 26.4° from the base when an 80kg load was applied. The floating ability of the wheelchair was constrained by the maximum load of the user which was deduced to be around 115kg. Future design alterations are therefore necessary as the deduced maximum load can limit a certain segment of the customer pool. Moreover, the wheelchair was considered stable as inferred from the positive metacentric height of 0.0014m. Nevertheless, this metacentric height value is perceived to be minute thus upcoming design phases should aim to increase this value to ensure stability. Free standing stability was also achieved in framing the design around the correct placement of the users centre of gravity.

A product price in the range of £1000-£3000 was first outlined in the design requirements and a final price of £2750 was assumed for the FloBoat. Although this product price is high, it is considered reasonable as the cost of manufacture is also high while a sensible gross margin must be established.

The final set of design requirements focussed on the wheelchairs ability to manoeuvre. Balloon wheels were used as they feature a larger surface area that allows for ease of movement on sandy terrain. Furthermore, a small front wheel was integrated into the design to ensure a smaller turning circle. Overall, it can be deduced that the device presented an ability to manoeuvre with ease on multiple terrains.

The above design requirements collectively fulfil the utmost requirements of Health and Safety. Alongside these requirements, necessary components such as a safety belt and seat cushions were included in the FloBoat to ensure the user's health and safety.

Design Process

The design of the FloBoat followed a thorough design procedure inherited by naval architects, the design spiral. This process enabled the design to grow from the concept design stage to the detailed design whilst fulfilling and refining necessary tasks defined in the design requirements. The tasks outlined in the spiral were based on previous design projects and research completed on the nature of this project. It can be seen that the procedure was fitting for this design task as it allowed the refinement of each task whilst allowing space for improvement in each stage.

Financial Evaluation

Cohering with the financial model outlined in Table 21, the deployment of the FloBoat is considered to be economically and financially feasible. FloBoat is expected to breakeven in the first projected year of operation after selling around 146 units. Furthermore, the financial state of the company is considered to be better than depicted in the model as other funding streams, including grants crowdfunding and investments, are excluded from the financial model. The chief drawback threatening financial feasibility is the economic state of the country. Due to the COVID-19 pandemic, the UK has entered into a recession. These unforeseeable circumstances will lead to a rise in inflation rates and a decrease in consumer confidence which can negatively impact the FloBoat and potentially lead to a delay in product release.

Conclusion

This design project commenced on the idea of creating a device for wheelchair users that allows them to participate in beach and water activities whilst maintaining health and safety standards. The FloBoat has demonstrated an ability to fulfil this gap in the market by providing a social solution towards the increased integration of wheelchair users. It can be concluded that the design of the FloBoat currently fulfils the specified design requirements and is considered to be economically feasible. However, additional research and simulation are required to perfect the final design in ensuring utmost confidence to the users in terms of health, safety and durability.

Future Work

Next steps that can be explored in this project include the following points:

- *Prototype* – A physical prototype will be built and tested in a seawater environment. This will allow for greater understanding of the product in terms of flotation, stability and other design requirements that require further investigating before production.
- *Further analysis* – Investigation on how the chair will be affected by waves and tides.
- *Foldable mechanism* – A foldable design can be of increased interest to consumers when considering transportation and can be integrated into future designs.
- *Electric Propulsion* – This will provide Independent function to the wheelchair, which has an increased market and competitive advantage.

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Appendices

Appendix 1 – Data

Table 22 – Selection Criteria Weighting Matrix

	Cost	Aesthetics	Manoeuvrability	Total mass	Max Load	Volume	Water Resistance	Corrosion/Oxidation	Health and Safety	Seat Positions	Flotation	Adjustable buoyancy	Floating Stability	Free Stand Stability	Storage volume	Manufacturing Ease	User Friendliness	Ease of Repair	Total	Weight
Cost	x	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	1	4	3%
Aesthetics	1	x	0	0	1	1	0	0	0	1	0	0	0	0	1	1	0	1	7	5%
Manoeuvrability	1	1	x	1	1	1	0	0	0	1	0	1	0	0	1	1	1	1	11	7%
Total mass	1	1	0	x	0	1	0	0	0	1	0	1	0	0	1	1	1	1	9	6%
Max Load	1	0	0	1	x	1	0	0	0	1	0	1	0	0	1	1	1	1	9	6%
Volume	1	0	0	0	0	x	0	0	0	1	0	1	0	0	1	1	1	1	7	5%
Water Resistance	1	1	1	1	1	1	x	1	0	1	0	1	1	1	1	1	1	1	15	10%
Corrosion/Oxidation Resistance	1	1	1	1	1	1	0	x	0	1	0	1	0	0	1	1	1	1	12	8%
Health and Safety	1	1	1	1	1	1	1	1	x	1	0	1	0	1	1	1	1	1	15	10%
Seat Positions	0	0	0	0	0	0	0	0	0	x	0	0	0	0	1	1	0	1	3	2%
Flotation	1	1	1	1	1	1	1	1	1	1	x	1	1	1	1	1	1	1	17	11%
Adjustable buoyancy	0	1	0	0	0	0	0	0	0	1	0	x	0	0	1	1	0	1	5	3%
Floating Stability	1	1	1	1	1	1	0	1	1	1	0	1	x	1	1	1	1	1	15	10%
Free-stand Stability	1	1	1	1	1	1	0	1	0	1	0	1	0	x	1	1	1	1	13	8%
Storage volume	1	0	0	0	0	0	0	0	0	0	0	0	0	0	x	0	0	0	1	1%
Manufacturing Ease	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	x	0	1	2	1%
User Friendliness	1	1	0	0	0	0	0	0	0	1	0	1	0	0	1	1	x	1	7	5%
Ease of Repair	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	x	1	1%

Table 23 - Weighting Matrix for Tyre Selection

	Cost	Ease of Roaming on Sand Terrain	Durability	Manoeuvrability	Total mass	Max Load	Water Resistance	Corrosion/Oxidation Resistance	Flotation	Tyre Size	Assembly Time	Total	Weight
Cost	x	0	0	0	0	0	0	0	0	0	1	1	2%
Ease of Roaming on Sand Terrain	1	x	1	1	1	1	1	1	1	1	1	10	18%
Durability	1	0	x	0	1	1	0	1	1	1	1	7	13%
Manoeuvrability	1	0	1	x	1	1	1	1	1	1	1	9	16%
Total mass	1	0	0	0	x	0	0	1	1	1	1	5	9%
Max Load	1	0	0	0	1	x	0	1	1	1	1	6	11%
Water Resistance	1	0	1	0	1	1	x	1	1	1	1	8	15%
Corrosion/Oxidation Resistance	1	0	0	0	0	0	0	x	0	1	1	3	5%
Flotation	1	0	0	0	0	0	0	1	x	1	1	4	7%
Tyre Size	1	0	0	0	0	0	0	0	0	x	0	1	2%
Assembly Time	0	0	0	0	0	0	0	0	0	1	x	1	2%

Table 24 - Draft Calculations for Varying Box Dimensions

Device Shape	Length (m)	Width (m)	Height (m)	Area (m^2)	Volume (m^3)	Mass (kg)	Density (kg/m^3)	Device Draft (m)	Combined (m)
No Box	0	0	0	0.000	0.000	15	1025	0	1.4895
L (0.9) W (0.3)	0.9	0.3	0.6	0.270	0.162	15	1025	0.054	1.5437
L (0.6) W (0.3)	0.6	0.3	0.6	0.180	0.108	15	1025	0.081	1.5708
L (0.3) W (0.3)	0.3	0.3	0.6	0.090	0.054	15	1025	0.163	1.6521
L (0.9) W (0.6)	0.9	0.6	0.6	0.540	0.324	15	1025	0.027	1.5166
L (0.6) W (0.6)	0.6	0.6	0.6	0.360	0.216	15	1025	0.041	1.5301
L (0.3) W (0.6)	0.3	0.6	0.6	0.180	0.108	15	1025	0.081	1.5708
L (0.9) W (0.9)	0.9	0.9	0.6	0.810	0.486	15	1025	0.018	1.5075
L (0.6) W (0.9)	0.6	0.9	0.6	0.540	0.324	15	1025	0.027	1.5166
L (0.3) W (0.9)	0.3	0.9	0.6	0.270	0.162	15	1025	0.054	1.5437

Table 25 – Metacentric Height Calculations for Varying Box Dimensions

	d	T	KB_b	KB_h	KB	Ixx	∇	BM	KG_b	KG_h	KG	GM
No Box	0.5	1.489	-	1.442	1.442	0.009	0.181	0.048	0.0	0.924	0.770	0.720
L (0.9) W (0.3)	0.5	0.054	0.027	2.042	1.706	0.009	0.343	0.025	0.3	1.524	1.320	0.411
L (0.6) W (0.3)	0.5	0.081	0.041	2.042	1.708	0.009	0.289	0.030	0.3	1.524	1.320	0.418
L (0.3) W (0.3)	0.5	0.163	0.081	2.042	1.715	0.009	0.235	0.037	0.3	1.524	1.320	0.432
L (0.9) W (0.6)	0.5	0.027	0.014	2.042	1.704	0.009	0.505	0.017	0.3	1.524	1.320	0.401
L (0.6) W (0.6)	0.5	0.041	0.020	2.042	1.705	0.009	0.397	0.022	0.3	1.524	1.320	0.407
L (0.3) W (0.6)	0.5	0.081	0.041	2.042	1.708	0.009	0.289	0.030	0.3	1.524	1.320	0.418
L (0.9) W (0.9)	0.5	0.018	0.009	2.042	1.703	0.009	0.667	0.013	0.3	1.524	1.320	0.396
L (0.6) W (0.9)	0.5	0.027	0.014	2.042	1.704	0.009	0.505	0.017	0.3	1.524	1.320	0.401
L (0.3) W (0.9)	0.5	0.054	0.027	2.042	1.706	0.009	0.343	0.025	0.3	1.524	1.320	0.411

Key

Φ		
B	M	Dimension
x	x	u
y	y	v
θ		

0 dp

20		
B	M	Dimension
154.8155	75.8986	-78.9169
416.1582	545.3012	129.1430
-31.42833092		

25		
B	M	Dimension
96.5026	75.8986	-20.604
427.3523	545.3012	117.949
-9.909		

25.5		
B	M	Dimension
89.488	75.8986	-13.589
428.1661	545.3012	117.135
-6.618		

26		
B	M	Dimension
82.584	75.8986	-6.685
428.8906	545.3012	116.411
-3.287		

27		
B	M	Dimension
65.1008	75.8986	10.798
430.2084	545.3012	115.093
5.360		

30		
B	M	Dimension
9.6582	75.8986	66.240
432.132	545.3012	113.169
30.341		

1 dp

26.3		
B	M	Dimension
77.494	75.9	-1.594
429.3314	545.3	115.969
-0.787		

26.4		
B	M	Dimension
75.8152	75.9	0.085
429.464	545.3	115.836
0.042		

26.5		
B	M	Dimension
74.0993	75.9	1.801
429.5989	545.3	115.701
0.892		

2 dp

26.39		
B	M	Dimension
75.9856	75.9	-0.086
429.454	545.3	115.846
-0.042		

3 dp

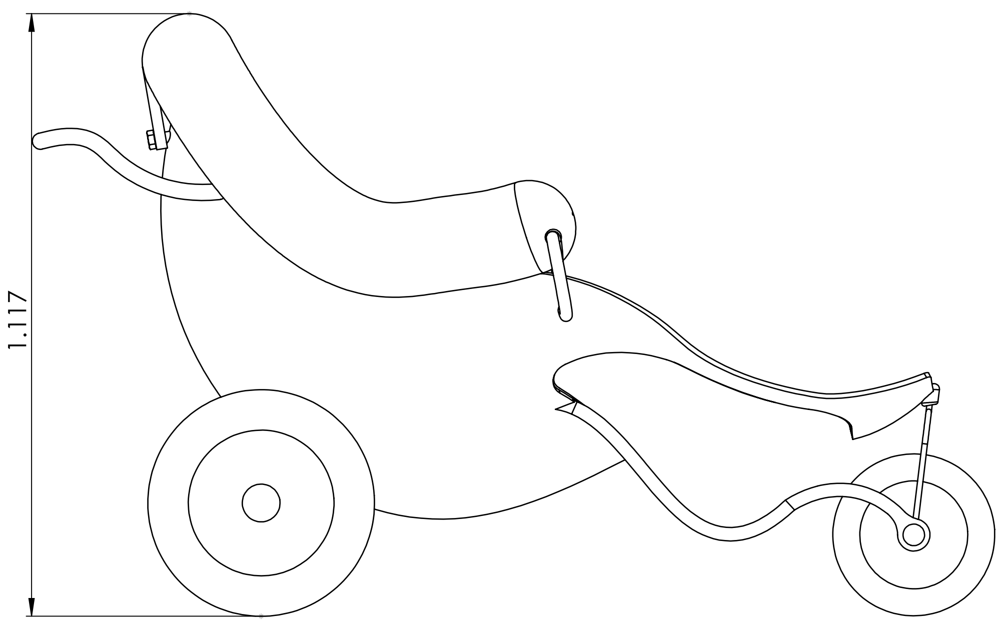
26.395		
B	M	Dimension
75.9002	75.9	0.000
429.4578	545.3	115.842
0.000		

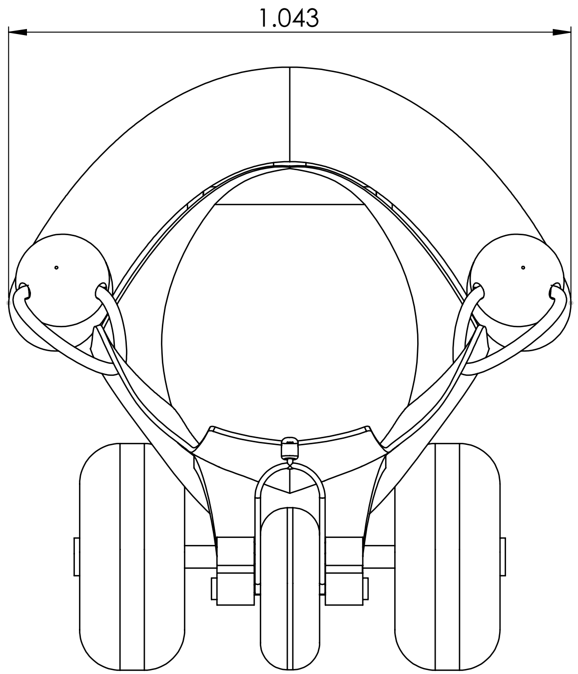
Φ
26.395

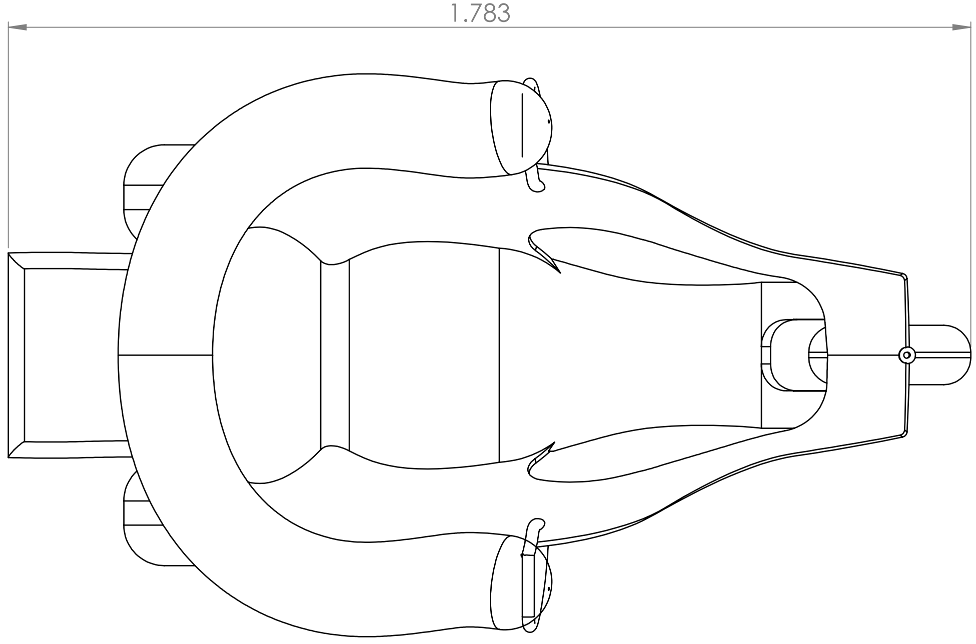
θ
0.000

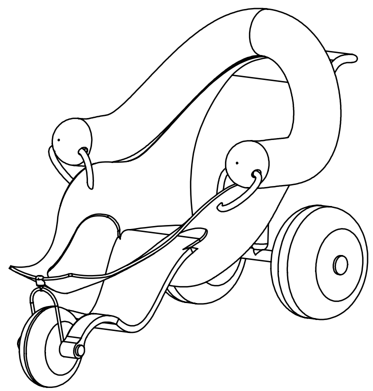
Figure 48 - Angle of Inclination Calculation

Appendix 2 – CAD Drawings

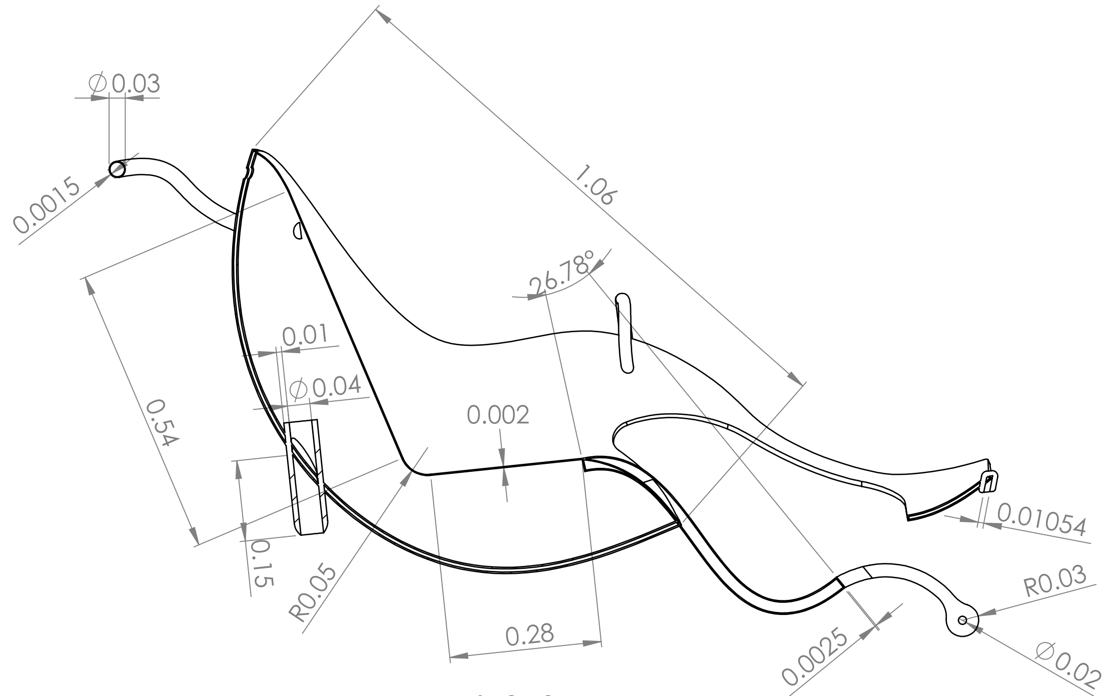




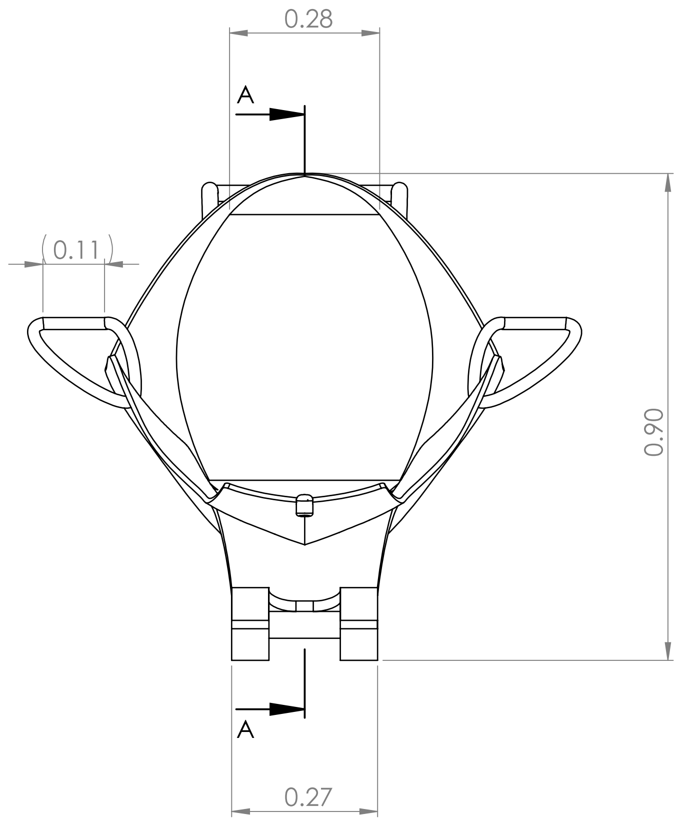


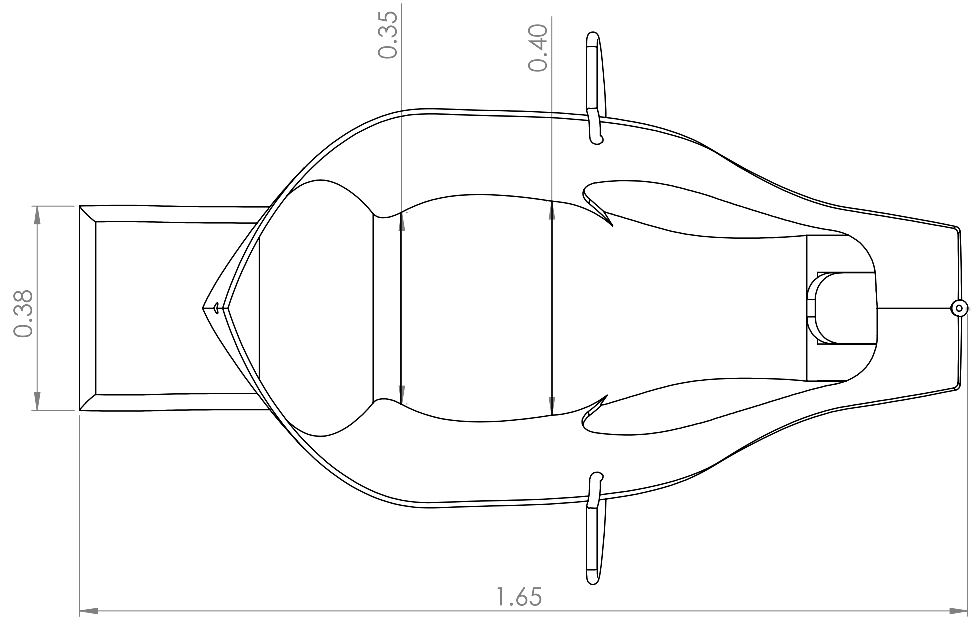


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE: Full Assembly		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: Multiple	DWG NO. Wheelchair	A3	
			WEIGHT: 25.6 kg	SCALE:1:20	SHEET 1 OF 1	

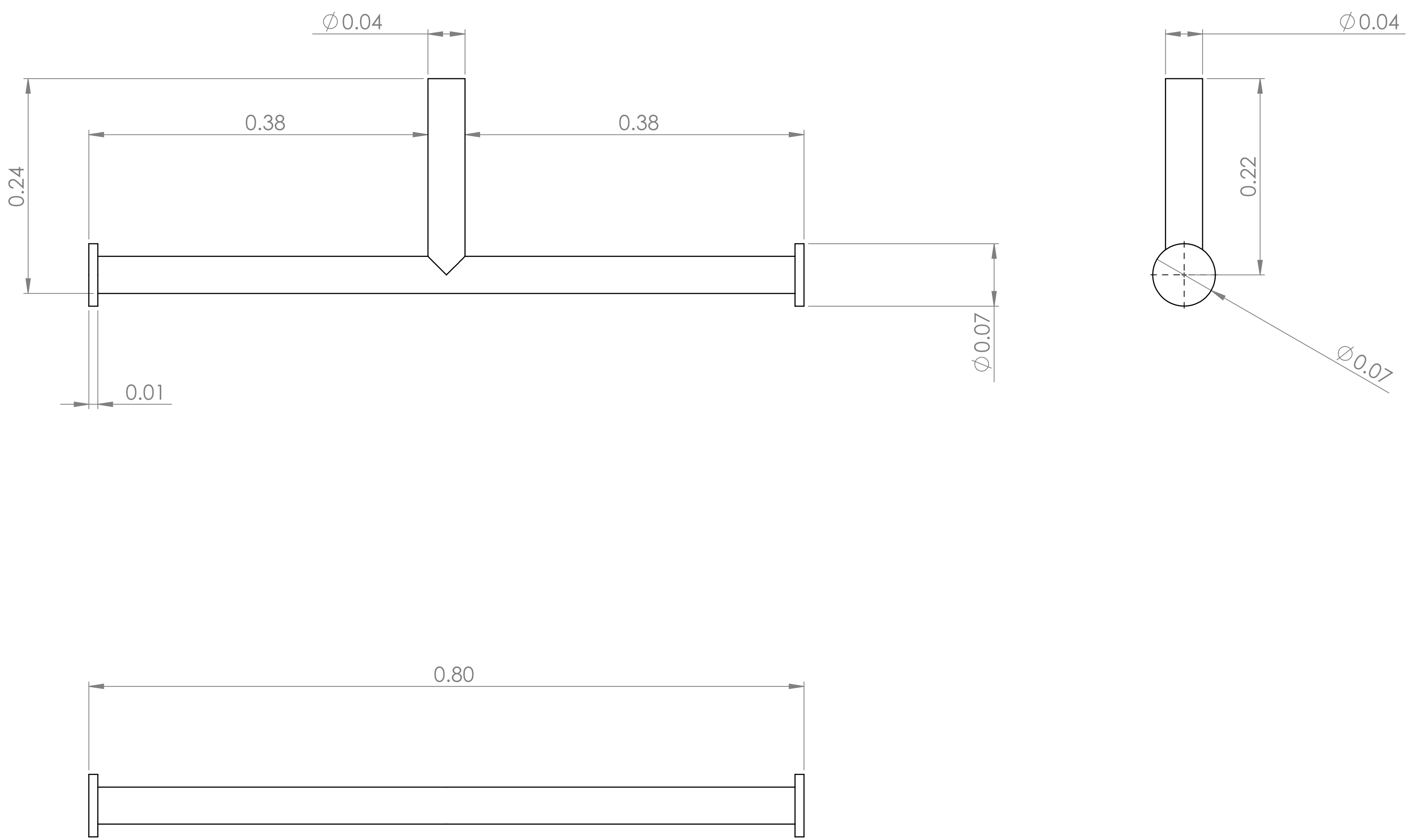


SECTION A-A
SCALE 1 : 10

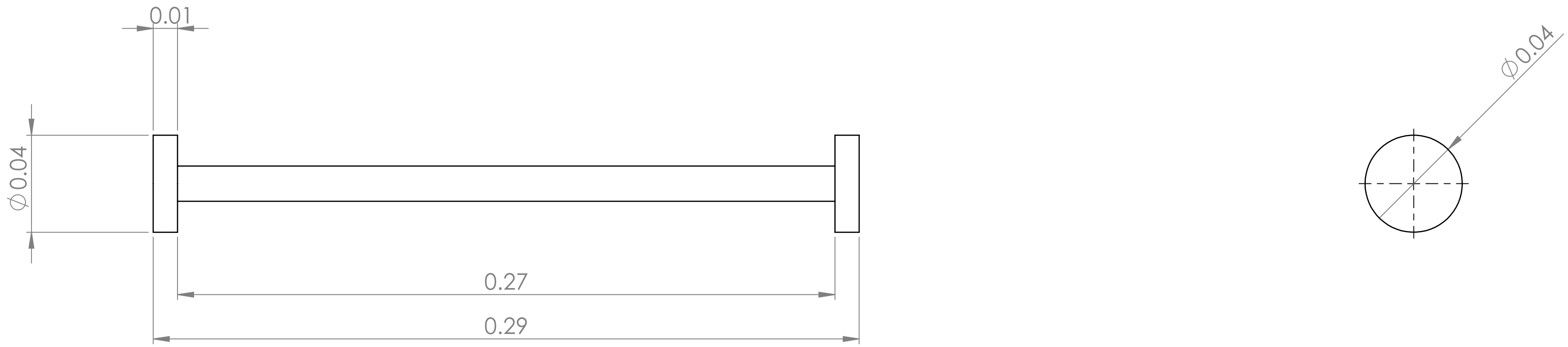




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES		DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE			TITLE:	
DRAWN						Main Body	
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: CFRP		DWG NO. exterior	A3
				WEIGHT: 13.38 kg		SCALE:1:20	SHEET 1 OF 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: Rear Axle
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: CFRP		DWG NO. rear axle	A3
			WEIGHT: 2.098 kg		SCALE:1:10	SHEET 1 OF 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
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Front Axle

MATERIAL: CFRP

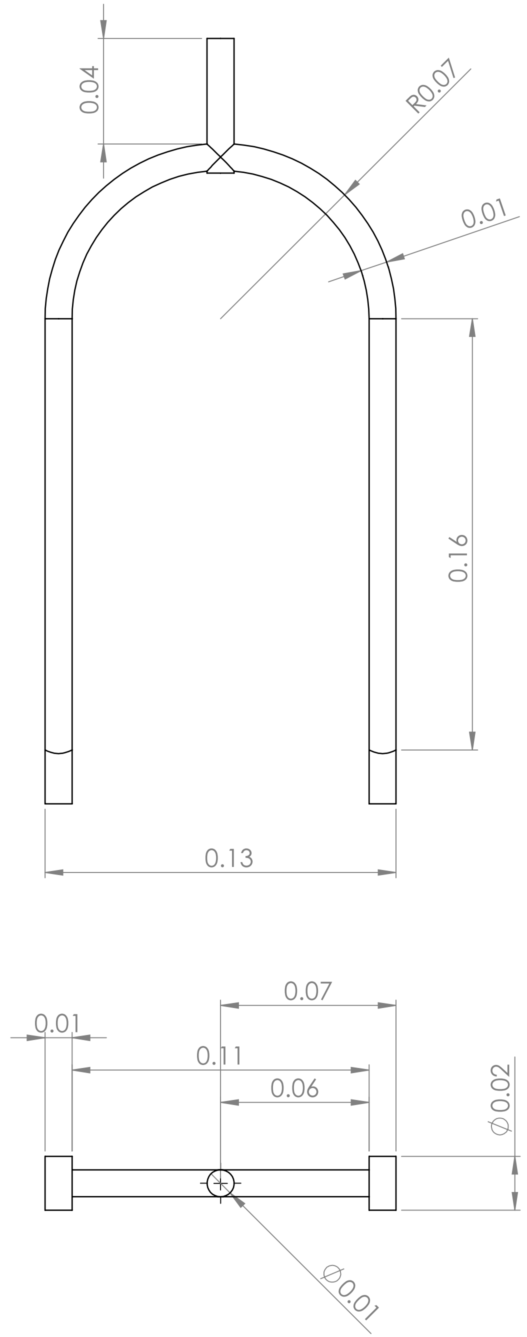
DWG NO. front axle

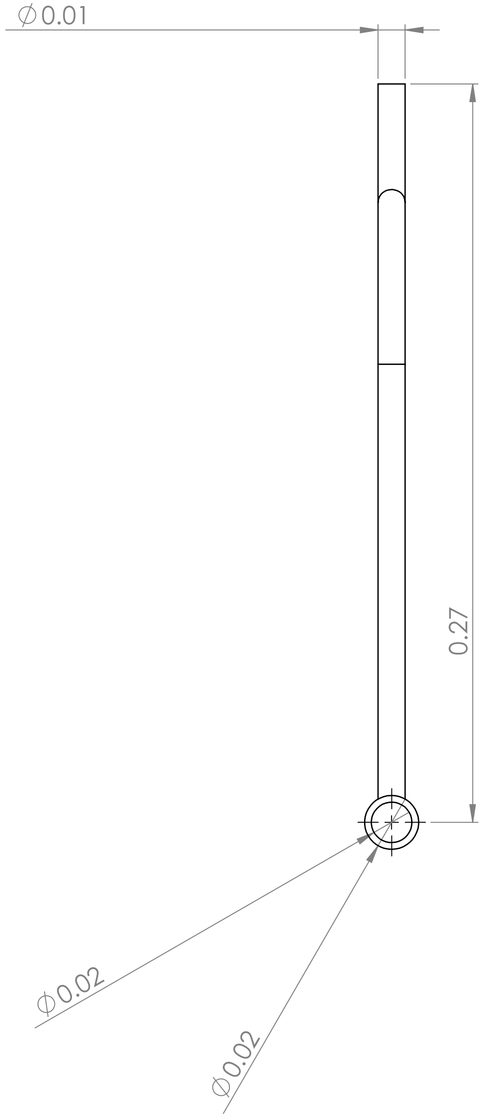
A3

WEIGHT: 0.112 kg

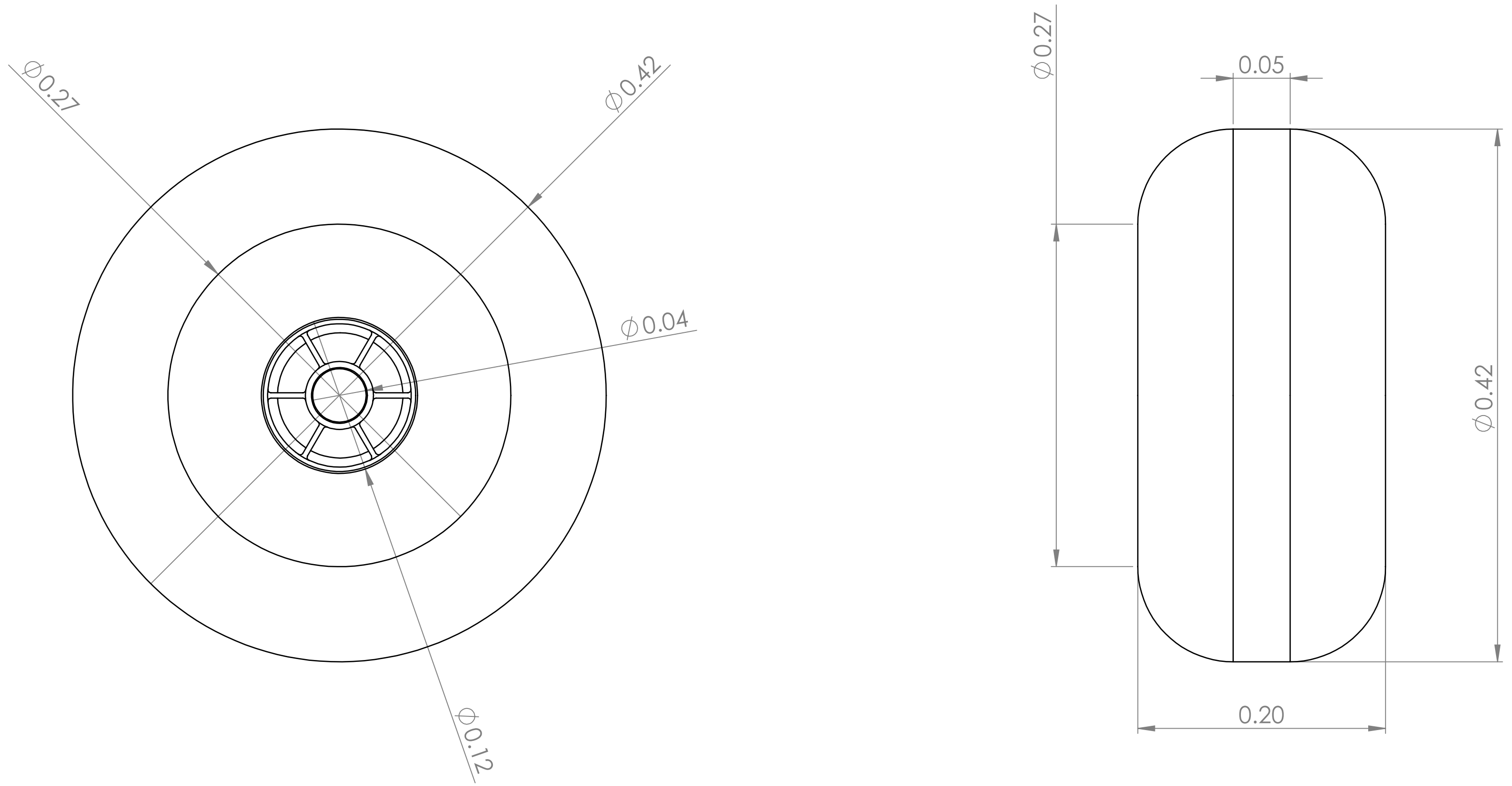
SCALE:1:5

SHEET 1 OF 1

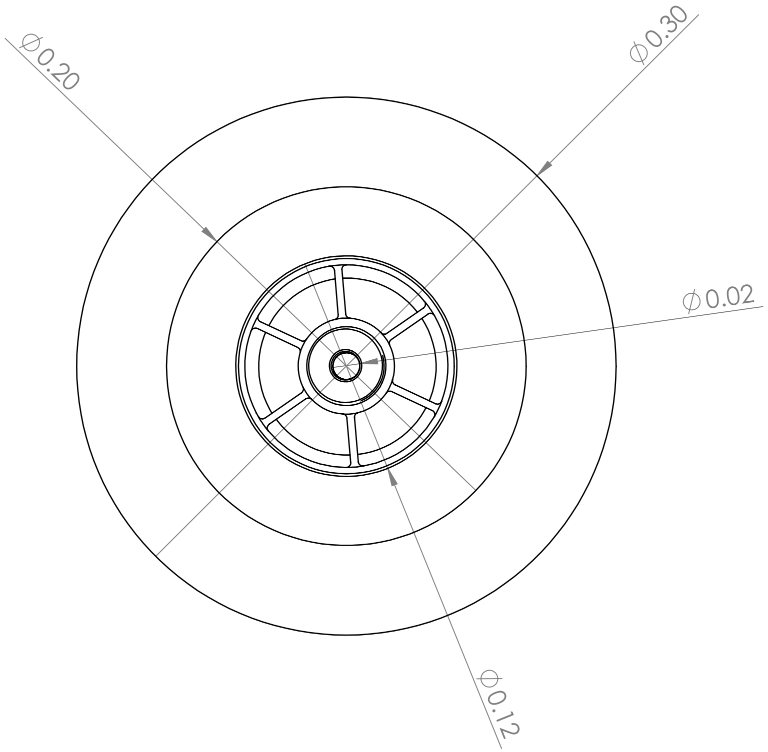


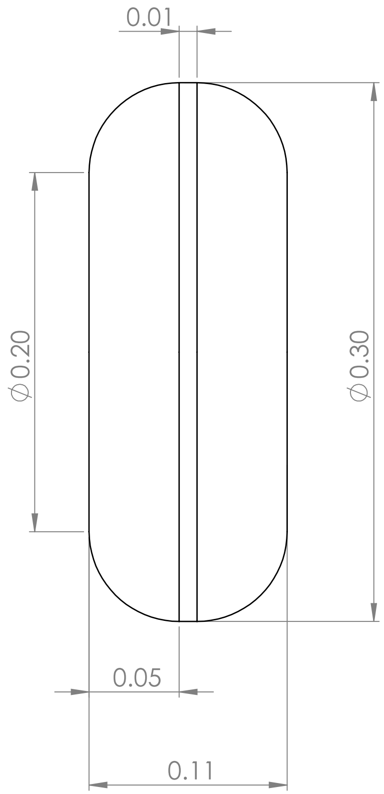


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:			DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE		TITLE: Front Fork	
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: CFRP		DWG NO. Front Fork	A3
			WEIGHT: 0.074 kg		SCALE:1:2	SHEET 1 OF 1

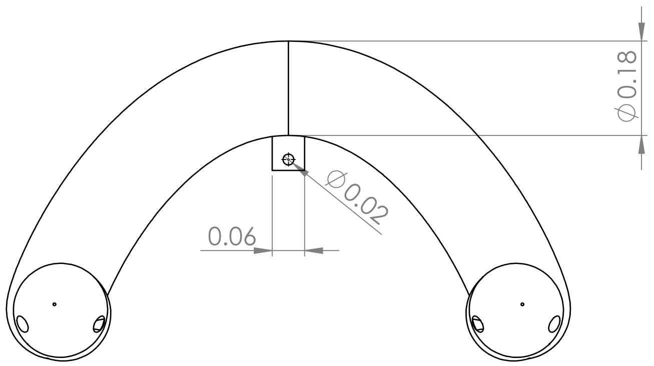


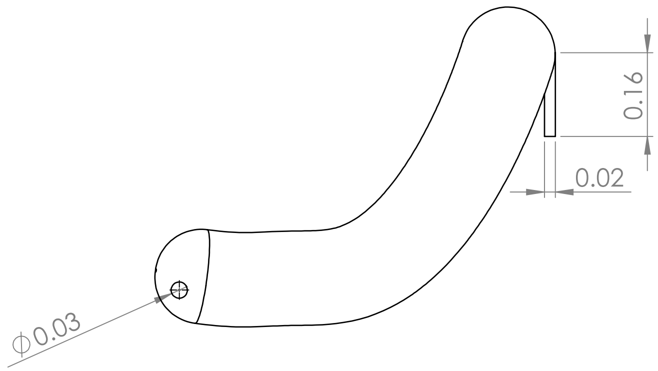
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN				Rear Wheel		
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: Polyurethane Rubber	DWG NO. back wheel		A3
			WEIGHT: 2.5 kg	SCALE:1:5	SHEET 1 OF 1	

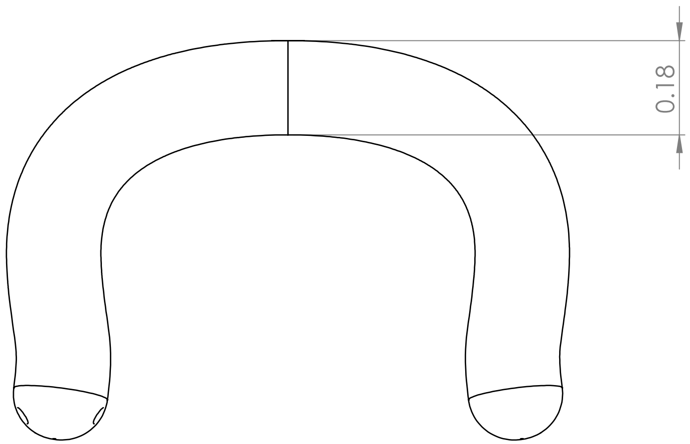




UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBURR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE	TITLE: Front Wheel		
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: Polyurethane Rubber	DWG NO. front wheel	A3	
			WEIGHT: 0.7 kg	SCALE:1:5	SHEET 1 OF 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					Armrests	
CHK'D						
APPV'D						
MFG						
Q.A				MATERIAL: Polyurethane Rubber	DWG NO. armrests	A3
				WEIGHT: 5.079 kg	SCALE:1:20	SHEET 1 OF 1