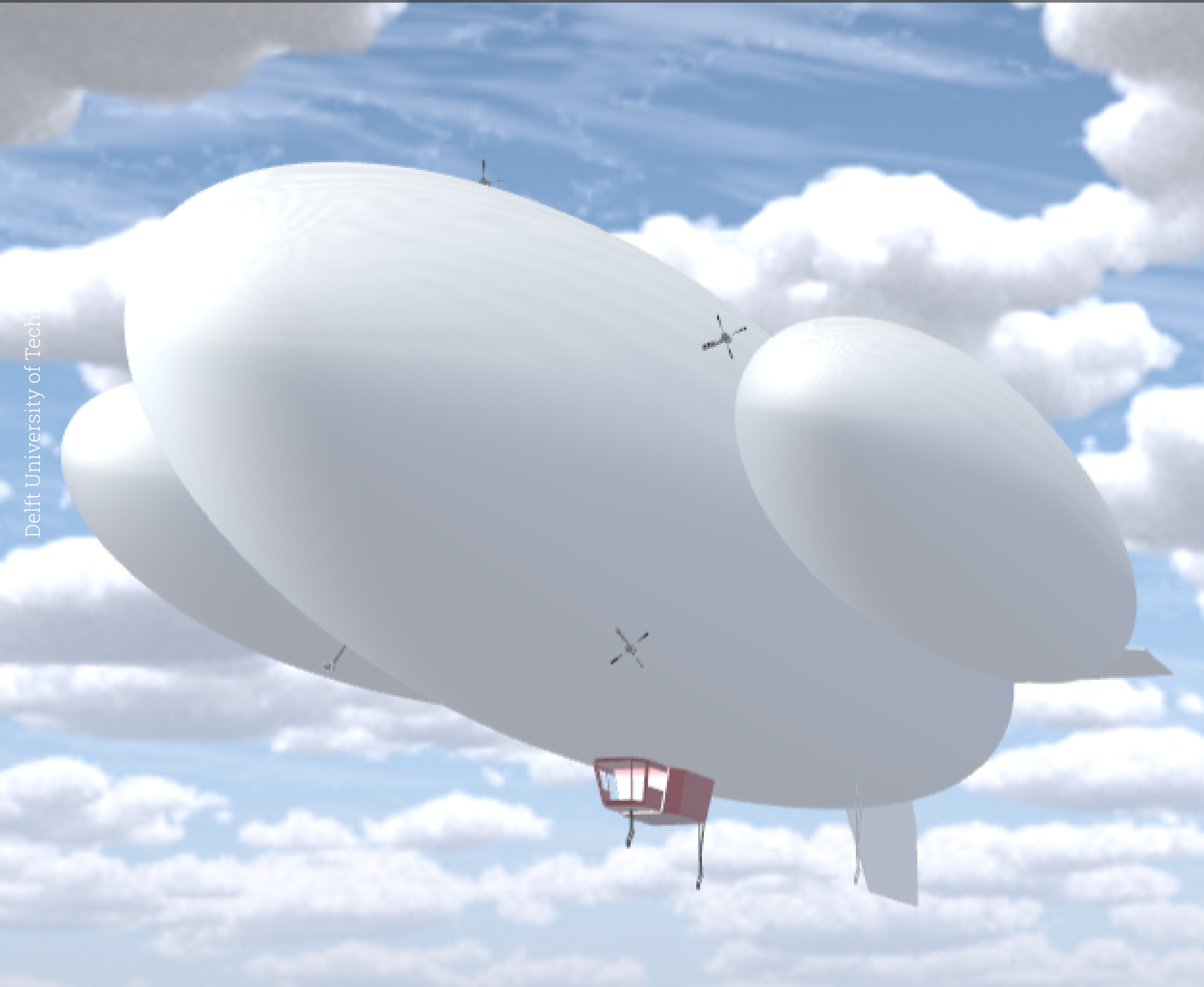
Transport Airship

Final Report

AE3200: Design Synthesis

Team 12



Delft University of Tech

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by

Team 12

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Executive Overview

In order to ease the transition to a sustainable and renewable energy economy it is necessary to identify and develop alternate fuels. The rise of hydrogen as an alternative to current fossil fuels offers a promising zero carbon alternative. However, transporting hydrogen is a major bottleneck which prevents large scale adoption of this fuel. After researching the need for hydrogen and setting up a business strategy, the mission need and subsequently the requirements were developed. The found mission need statement is: *"Provide transport of high-risk payload over intra-continental distances by 2040"*. The requirements were used as guidelines for the actual design of the airship, which went trough the conceptual and detailed design phase. Afterwards, a risk assessment of the new design was done. The operations and financial analysis of the airship were examined, followed by the verification and validation of the work done. Finally, the project design and development for the future were looked at, subsequently, recommendations for future research and design were set up.

Business Strategy

With the rise of hydrogen as a fuel for the future and its limitless potential in energy storage applications, it is necessary to overcome practical bottlenecks which could de-rail the transition from a non-renewable based market to a renewable one. The primary issue which arises when considering hydrogen as a fuel for the future is the transportation costs and dangers associated with it.

Existing methods of transportation have shown to have major deficiencies to them, either when it comes to operational efficiency, safety, transport time, or a combination of all three. Because of this, it is essential to develop a solution which does not burden existing infrastructure and is able to provide a safe, sustainable and efficient mode of transport without requiring construction of parallel infrastructure. The main competitor which was identified from these options were trucks, which had the least amount of downsides, but nevertheless were still is not a sustainable method of transportation.

In order to overcome these downsides, an airship is proposed as a solution to the transport of pure hydrogen from source points to the end-users. The airship offers numerous advantages over trucks which can be categorised as follows:

- The airship does not rely on existing overburdened infrastructure.
- The airship is faster than trucks due to it not having to do detours, and has improved operational capacity when it comes to routing.
- The airship is has less restrictions on the shape and volume of the payload.
- The airship transports the payload by air, circumventing heavily populated areas such as highways.

Additionally, the airship may provide a sustainable solution in comparison to its competitors seeing that a hydrogen carrying airship can rely on hydrogen for energy. This way, the airship can fly carbon emission-free, using less energy consumption.

However promising, the future of hydrogen as a market remains unpredictable. In order to mitigate the risk of over investing into a market with many unknowns, an alternative business model will also be pursued, which is the transport of payload other than hydrogen, such as sustainable air fuels. In order to get a better idea of the risk of the hydrogen demand and subsequently the hydrogen transport demand not being high enough to offer feasibility, the general trends and future predictions of hydrogen demands were studied, as can be seen in Figure 1.

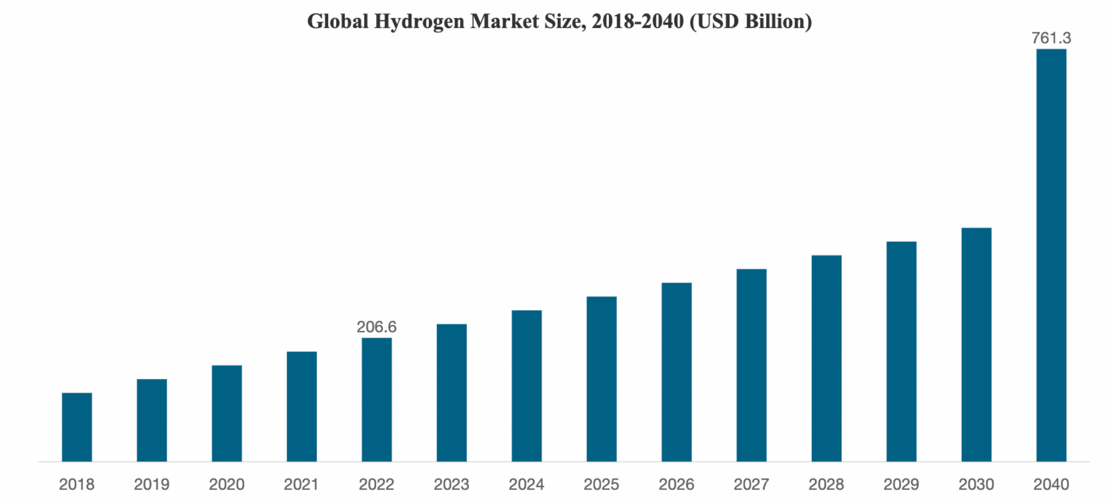


Figure 1: Graph shows the future projection of hydrogen market size in USD Billion [4].

In order to raise capital for the research and development of the airship it is not unreasonable to rely on venture capitalists and governments given the financial feasibility of the design and the projected rise in the demand for hydrogen.

Detailed Design

An overview of all the airship properties are shown in Table 1.

Table 1: Overview of all final parameters of the airship are shown in the table.

Parameter	Values
General	
Amount of hydrogen payload	800 kg
Length Airship	134 m
Width Airship	56 m
Volume Airship	66 724 m^3
Total Mass	69 023 kg
Tank Mass	12 282 kg
Structures	
Structures Mass	23 007 kg
Lightning Cage	2000 kg
Structures Material	CFRP
Envelope	
Envelope Material	Polyester
Coating Material	Polyurethane & Tedlar
Polyester Thickness	0.38 mm
Polyurethane Thickness	1.00 mm
Tedlar Thickness	0.10 mm
Cover Thickness	1.48 mm
Engines	
Engine	Siemens SP200D
Number of Engines	5
Number of Fuel Cells	4

The subsystems were designed and finalised following individual trade-offs on criteria which were deemed important for the functioning of the specific subsystem. For every subsystem various options were considered and the final options were determined by means of the trade-off. Sensitivity analyses were performed for each trade-off in order to determine how sensitive each trade-off result was to changes in certain criteria and generally the chosen materials retained their status for most changes in criteria weights.

The airship is a tri-lobed airship with the ability to carry 800 kg of hydrogen in multiple tanks. The option is left open to transport other (sustainable) goods, such as chemicals and Sustainable Aviation Fuel (SAF). The following paragraphs detail and justify the final design choices and parameters that were obtained.

Attached to the structure are five engines capable of propelling the airship forward at 100 km/h at 75% of the power for the entire duration of a 4000 km round-trip. The engine configuration provides differential thrust control about the yaw axis and has the potential to be used for roll and pitch control to smooth out any dynamic vibrations that may be encountered as part of normal operations. It is worth noting that the maximum operational range of the airship goes up rapidly with a lower cruise velocity, hence mission profiles may be adjusted if the target range is further.

Since the airship is aimed at aiding the transition to a sustainable energy economy, electric engines are chosen since they produce no carbon emissions. The engines are commercial-off-the-shelf (COTS) components which are powered by fuel cells that rely on hydrogen to produce power. The fuel cells have an efficiency of 61% and are capable of producing 300 kW of power each, four of these make up the primary power system for the airship. The airship features an onboard battery to ensure power to the flight computer and hydraulic systems for aerodynamic control in order to offer sufficient control to land in the event of a failure of the primary power system. This battery is charged in cruise with any excess power generated by the fuel cells being routed to the batteries.

The airship features both aerodynamic and differential thrust control, this means the airship is controllable even when stationary. The added control options also offer more options to overcome any unstable motions that may develop. The airship however, owing to its massive size is unlikely to experience any major instabilities since they would take a very long time to materialise into uncontrollable eigenmotions.

The internal load bearing structure of the airship is inspired by the Zeppelin NT, a modern semi-rigid airship which provides a good proxy for a modern airship structure. The structure is predominantly a large truss structure consisting of triangular sections. The best material for this structure was determined to be Carbon Fibre Reinforced Polymer (CFRP) owing to its exceptional unidirectional tensile strength and light weight. The structure was determined to be $23\,007$ kg when optimised, this includes required safety factors and a knockdown factor. The material choice results in an expensive structure however it is deemed necessary to use this material since it fulfils the requirements set out by the structure exceptionally.

The envelope material chosen for the airship is polyester. The main reason being the light and strong characteristics of the material. The cover is coated in polyurethane and tedlar mainly to protect the airship from the damaging UV light.

Below the structure, a gondola is attached for the two pilots. This is in addition to the completely autonomous operating capabilities of the airship. The gondola is designed to comfortably accommodate the pilots and flight computer.

Risk Management

It is easily identifiable that hydrogen will only combust when it is exposed to sufficient amounts of oxygen hence isolating the two gases is quintessential to the prevention of a catastrophic failure. However, in case of emergencies when venting or other methods are deployed it is crucial maintain hydrogen safety. Possible methods to increase the inertness of the hydrogen in the envelope are explored alongside methods to limit potential sources of ignition.

The handling of hydrogen can be made considerably safer when the right measures are taken. To avoid chemical reaction, every possible contact between hydrogen gas and oxygen gas should be avoided. Filling the airship with hydrogen should be proceeded by filling the lobes with nitrogen gas to expel the oxygen present in the lobes.

The envelope material shall be made inflammable in order to prevent catastrophic failure due to small leakages. Sensors can be deployed to detect small leaks across the envelope.

Operations

During the design phase, important operational problems have been identified and solved.
The weather has always been an issue for airships. The airship has been designed with certain weather limitations and is expected to remain within these limits. These limits include lightning, and wind gusts. More specifically, the airship will fly low and in Visual Flight Rules (VFR) conditions. This limits the operational availability of the airship, but guarantees the safe operation of the airship. The airship, when confronted with adverse weather conditions has the unique capability of orienting itself in the direction of any severe gusts meaning that the airship is merely put off course which does not significantly impede its operational capabilities since it is not limited in endurance the same way an airplane is. It will however ask more of the control surfaces, and may be slower in reacting to weather than aircraft.

Stormy weather should be avoided in particular, since the airship is a very large vehicle that will be particularly difficult to manoeuvre efficiently in adverse weather. Precautions must be taken to avoid lightning and other weather conditions that could severely impact the airship, this is done by avoiding patches of bad weather and deploying mitigation measures for lightning strikes. The mitigation measures for lightning strikes are designed to dissipate current across the airship without severely damaging vital subsystems or causing damage to the envelope. This is done by means of a wire mesh placed across the airship, concentrating on vital points such as the highest points, the nose and the aerodynamic control surfaces which are likely to be particularly susceptible to lightning strikes owing to their positioning on the ship.

The engines combined with the propellers can be loud, with a 130 dB peak noise level at 100% throttle 1 m away from the propulsion unit. This translates to a noise of 70 dB as perceived on the ground. The amount of noise that will reach the pilots at the gondola can be reduced with noise isolating material within the gondola. It is worth noting that sufficient noise mitigation strategies exist such that the real noise produced by the airship could be reduced by a noticeable degree. These include providing ducting for the engines and propellers, and employing the advantages of variable pitch.

Financial Analysis

The financial aspects of the airship is broken down into two groups: the airship manufacturer (THETA), and the airship operator (THETA's client).

THETA's airship is listed at 70 M€ based on airships currently on the market, and the costs associated. These costs consist of initial costs at 700 M€, and additional manufacturing cost at 45 M€ per airship. Therefore, THETA needs to sell 28 airships to break-even.

The hydrogen operator purchases the airship and will have yearly operational costs thereafter, which is estimated to be 0.74 M€ per year. Note that insurance cost is neglected due to the anticipated funding provided by the government. Revenue streams include the transportation of payload, as well as advertisements. Therefore with yearly operational profits of 3.24 M€, it would take the hydrogen operator 22 years to break-even and overcome the initial airship purchasing cost.

A business case can be made that the growth of the hydrogen market shows great promise and the sustainability that the THETA airship provides outweighs its profitability. THETA consumes less energy, uses green energy namely hydrogen, and creates zero emissions. This puts THETA and its clients in a good position for government funding and support.

Recommendations

The hydrogen market is currently a niche market which might not provide sufficient revenue, it is therefore preferred to create an additional revenue stream. Expanding to a recreational tourism market would provide a viable business case that has the potential of generating a large amount of revenue in the short term, thus also effectively financing any future development and designs. Further exploration of transporting very large payload is a potential untapped niche, for example transporting windmill blades which as of now is an arduous process that road infrastructure is ill-equipped for.

At the end of the design process, it became clear that a conventional, single lobed airship is a better option. The airship consumes less hydrogen for a marginal increase in total length and has a simpler structure requiring less cover material. The goal of the current design was however to investigate a more technologically advanced option which performed better on the primary trade-off performed. The design versatility of the multi-lobed airship however was not sufficient to overcome the increased drag and structural complexity.

Lifting surfaces could have possibly reduced the airship volume since they would reduce the dependancy of the airship on aerostatic lift alone. As a consequence the airship would require some horizontal velocity ideally combined with vectored thrust to maintain the neutral buoyancy. The advantage however is that such a vectored thrust system is already present in the current design iteration. A Computational Fluid Dynamics (CFD) analysis of the aerodynamic values is also warranted in future research since the empirical data is likely a heavy overestimate of the real drag value and is not representative of the real drag experienced by the airship.

Further research into different means of propulsion or additional noise mitigation methods would ensure that the airship is more viable for operations at lower altitudes or near civilian areas which is currently not possible due to exorbitant noise emissions.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ADC	Airship Design Criteria
ASS	Assumptions
CC	Communication & Control
C.B.	Center of Buoyancy
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Polymers
C.G.	Center of Gravity
CON	Control
COTS	Commercial-Off-The-Shelf
CTS	Control & Stability
ELC	Electronics
EMER	Emergency
EOW	Empty Operational Weight
ESD	Electrostatic Discharg
FBD	Free Body Diagram
FL	Flight Level
FEA	Finite Element Analysis
FWD COMPT	Forward Compartment
GFRP	Glass Fibre Reinforced Polymers
HAND	Handling
HARM	Horizontal Arm
ISA	International Standard Atmosphere
LEMAC	Leading Edge of the Mean Aerodynamic Chord
MAT	Materials
MTOW	Maximum Take-Off Weight
NDT	Non Destructive Testing method
OEI	One Engine Inoperative
OEW	Operational Empty Weight
OPL	Operations & Logistics
OPR	Operational
PERF	Performance
PROP	Propulsion
PWT	Powertrain
R	Risk
R&D	Research and Development
RES	Rest (Miscellaneous)
REG	Regulations
ROI	Return On Investment
RPM	Rounds Per Minute
SAF	Sustainable Aviation Fuel
SDG	Sustainable Development Goal
STP	Standard Temperature and Pressure
STR	Structures
STRM	Structures & Materials
SUS	Sustainability

Abbreviation	Definition
SYS	System
TAR	Transportation
TVC	Thrust Vector Control
UD	Unidirectional
UN	United Nations
USD	United States Dollars
VEH	Vehicle
VFR	Visual Flight Rules
VTOL	Vertical Take-Off and Landing

Symbols

Symbol	Definition	Unit
r_{out}	Outer radius	[m]
R	Gas constant	$[J/mol \cdot K]$
n_{H_2}	Number of hydrogen particles	[-]
g	Gravity Constant	$[m/s^3]$
M	Mach Number	[-]
M	Molar mass	[-]
L	Lift	[N]
K	Effective length factor	[-]
l	Length	[m]
d	Diameter	[m]
D	Drag	[N]
d	Diameter	[m]
E	Young’s Modulus	[GPa]
S	Frontal Area or wing surface area	$[m^2]$
V or vol	Volume	$[m^3]$
v	Velocity	$[m/s]$
n	Amount of moles of gas	[-]
T	Temperature	[K]
r	Radius	[m]
t	Thickness	[m]
A	Surface Area	$[m^2]$
m	Mass	[kg]
p	Pressure	[Pa]
C_L	Lift Coefficient	[-]
C_D	Drag Coefficient	[-]
C_{Dp}	Prandtl shape coefficient	[-]
F_t	Thrust generated	[N]
T	Thrust	[N]
c	Chord length	[m]
c	Speed of sound	[m/s]
B	Buoyancy	[N]
B_{side}	Buoyancy side lobe	[N]
r_{side}	radius side lobe	[m]
B_{main}	Buoyancy main lobe	[N]
r_{main}	radius main lobe	[m]
W	Weight	[N]
w	outer width	[m]
$M_{a,b,c,p,g}$	Moments	[Nm]
Re	Reynolds number	[-]
$Ratio$	Ratio	[-]

Symbol	Definition	Unit
SFC	Specific Fuel Consumption	[J/kg/km]
R	Range	[km]
ROI	Return On Investment	[-]
SPL	Sound Pressure Level	[dB]
F	Fuel	[kg]
E	Energy	[J]
U	Energy Density	[J/m^3]
k_{mod}	Safety factor for multi-lobed	[-]
k_1	longitudinal stability coefficient	[-]
k_2	Transversal stability coefficient	[-]
I_{xx}	Mass moment of inertia around x-axis	[m^4]
I_{yy}	Mass moment of inertia around y-axis	[m^4]
I	Mass moment of inertia	[m^4]
$P_{critical}$	Critical buckling load	[N]
$P_{required}$	Power required	[Watt]
Cl_b	Lift coefficient of the body	[-]
S_B	Surface area of the body	[m^2]
SM	Safety Margin	[-]
SF	Safety Factor	[-]
ρ	Density	[kg/m^3]
η	Efficiency	[-]
η_p	Propeller rotational speed	[RPM]
d/d	Change rate in angle of attack	[-]
σ	Stress	[Pa]
σ_{yield}	Yield strength	[Pa]
σ_{hoop}	hoop stress	[Pa]
ϵ	Elongation	[%]
$q_{dynamic}$	Dynamic stability	[kg/ms^2]
S_h	Horizontal tail surface area	[m^2]
V_h	Airspeed at horizontal tail	[m/s]
l_h	Tail length	[m]

1 Introduction

With climate change setting the stage for the direction modern technology, takes a renewed focus on sustainable fuels is inevitable. One of these is the use of hydrogen, which is widely considered to be ”the fuel of the future” with expectations that extensive use of hydrogen would start from 2035 [6]. Owing to hydrogen's low density and flammable nature, the logistics of such a transition are a major bottleneck in facilitating the move to a hydrogen based renewable energy economy. Therefore, it is imperative to develop a sustainable and reliable way of transporting hydrogen from producers to consumers with minimal additional infrastructural commitments. Transporting hydrogen en mass on the road is difficult since transportation is subject to the many risks that come with operating on roads. Pipelines are a time-consuming and material-intensive option which are impractical to implement in the short term.

The aim of this report is to present a potential solution to this problem in the form of an airship which can be deployed for effective long range hydrogen transportation. This includes a design synthesis process exploring various design considerations, different ideas and many iterations, culminating in a final, optimised design: THETA. This *Tri-lobed Hydrogen Emission-free Transport Airship* is an airship consisting of three lobes with a large payload carrying capacity that may be used for transport of pure hydrogen or any other sustainable fuels. The airship presents itself as an option that addresses the shortcomings of conventional transport, notably diesel trucks. It is not a particularly intensive process requiring international co-operation like pipelines, neither is it a method which relies on already stressed road infrastructure. The airship is also expected to be emission free, which is crucial in order to facilitate the transition to a greener energy economy.

The report starts with a thorough examination of a potential business strategy, presented in chapter 2, followed by how the strategy pertains to sustainability in chapter 3. The strategy with sustainability considerations is then combined to a mission definition in chapter 4. Given the mission a conceptual design is chosen in chapter 5, after which the synthesis is expanded in more detail leading to the detailed design in chapter 6. The risk that the design has taken into account are explored in chapter 7, after which a sensitivity analysis on the detailed design is performed in chapter 8. Its operations are explained in chapter 9. The operations of the design are detailed in chapter 9, after which financial viability is explored in chapter 10. Verification and validation of the final design will be performed in chapter 11. Pen-ultimately the project phases and steps that were taken throughout the time span are discussed in chapter 12, followed by the recommendations to be tackled if the hydrogen transport airship is to be continued in chapter 13. Finally the conclusion obtained from the design process will be discussed in chapter 14.

2
Business Strategy

In the ideal world, the success of an engineering effort is merely judged by its engineering quality, but there is no good use to a product which does not sell. Too many projects start with an engineering-only mindset, creating a solution to a problem that does not exist, and only find out during deployment that there was never a need for their product to begin with. To prevent this, it was decided to first spend time analysing the need of the market, and the financial viability of the solution, before working out the solution in depth. In this chapter an explanation and justification is given of the proposed solution of an airship for the use of hydrogen transport.

2.1. Need for Hydrogen

The climate has been a hot topic for a long period of time. Governments and citizens worldwide have been focusing on an increasingly green future in order to deal with the threat of global warming. However, the energy consumption per capita is estimated to increase due to the living standards increasing. To make sure those living standards do not decrease, sustainable forms of energy have to be utilised. One of the large victims of these efforts have been fossil fuels. Due to their unsustainable nature and the toxic production and health effects, governments worldwide are realising that a sustainable future requires the use of sustainable fuels and other forms of energy. One of the biggest candidates to take up this role has been identified as hydrogen. Hydrogen can be created without any emission, and is extremely versatile in its application. Recent years have seen its adoption in electric cars, hydrogen engines and other use-cases.

Market Research

The hydrogen market as of today constitutes only a small percentage of the energy sector, however it is expected to only grow as other fuels decline. Figure 2.1 shows the market demand for hydrogen

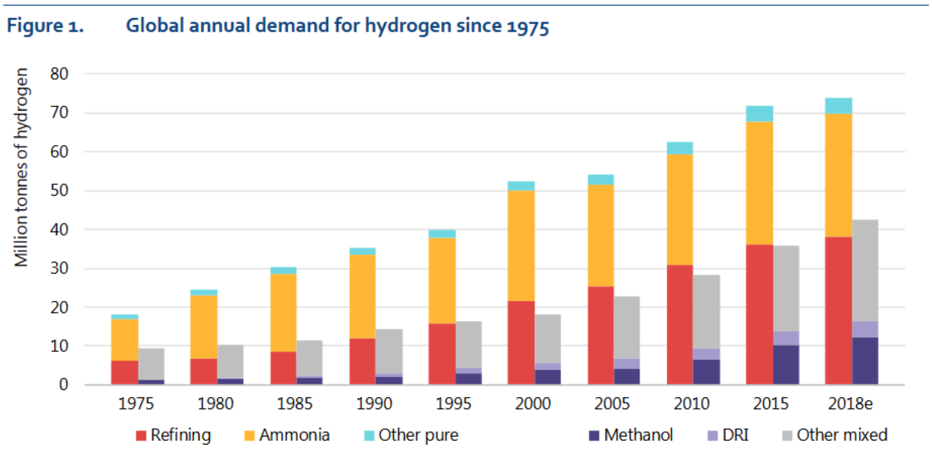


Figure 2.1: This figure shows the general Trends in Hydrogen market with breakdown of the use cases[13].

The annual demand for hydrogen has grown almost seven-fold compared to 1975. This growth has occurred across a time period when hydrogen was not necessarily viewed as the fuel to power the future, thus it is not unreasonable to not only expect further growth but further exponential growth. A projection of the growth of the hydrogen market size is illustrated in Figure 2.2.
The hydrogen tank and transport market has an estimated value of 174 M$ in 2022 and is expected to be valued at 4155 M$ in 2030[1].

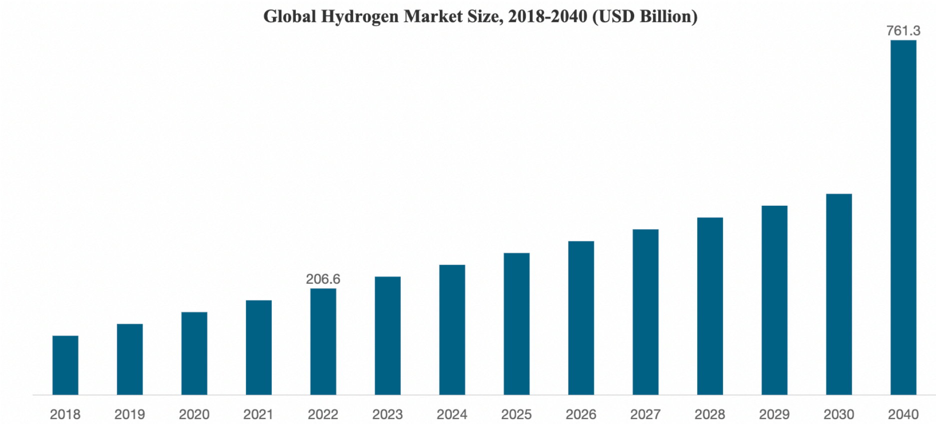


Figure 2.2: Figure shows the future projection of hydrogen market size in USD Billion [4].

Specific details on the transportation market are generally unavailable, however practical considerations regarding the transportation of hydrogen exist. Hydrogen has one of the lowest densities of any element, this makes transporting large quantities challenging. It is not necessary to transport vast amounts as the energy density of hydrogen is really quite high.

2.2. Current Situation

Hydrogen needs to be pressurised and transported by heavy tanks or through pipelines. Transporting hydrogen inland through trucks requires a very large number of trucks which would strain existing road infrastructure. In addition to this, since roads are not safe, the potential for any disaster affecting human life can not be understated.

[1] Research and Markets ltd. *Global Hydrogen Storage Tanks and Transportation Market by Modular Storage, Application, Tank Type, Pressure, and Region - Forecast to 2030*. URL: `https://www.researchandmarkets.com/reports/5716871/global-hydrogen-storage-tanks-and-transportation` (visited on 06/12/2023).

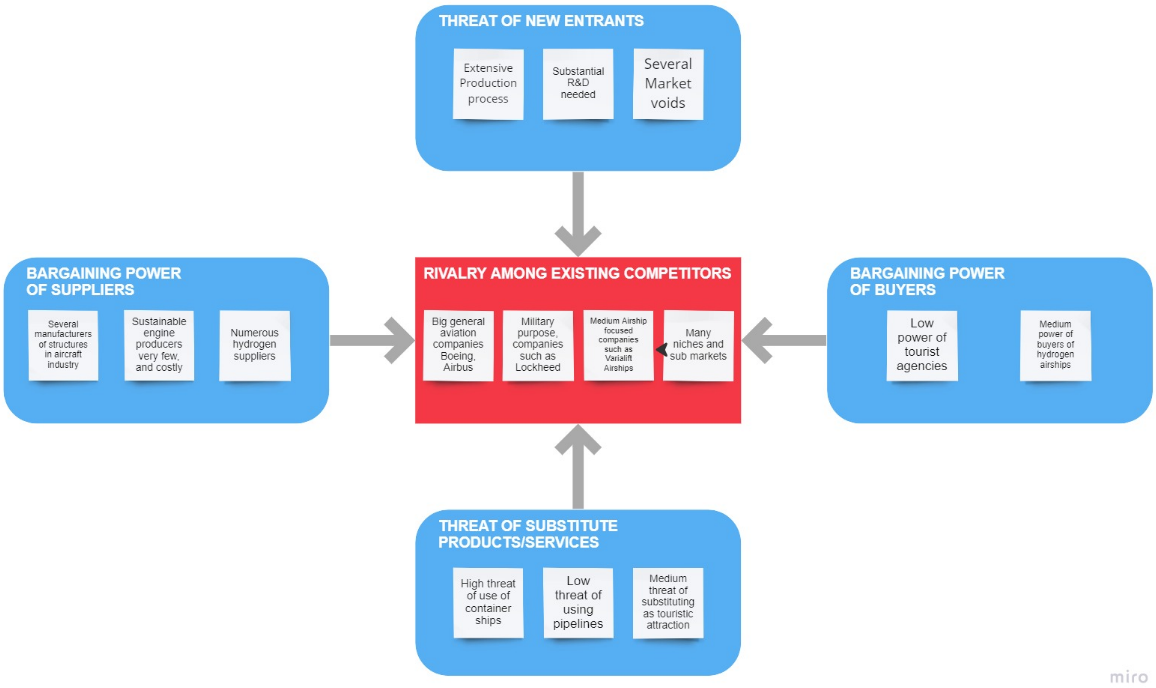


Figure 2.3: This figure shows main competitive forces of substitutes, new entrants and bargaining power.

As can be seen in the porters five forces analysis that is shown in Figure 2.3, trucks, container ships, trains and pipelines are the main competitors in terms of substitute products. Trucks are limited in their ability to reach remote places, as they depend on existing infrastructure. Furthermore, a truck carrying explosive hydrogen on the roads is undesirable. Next to that, trucks that run on fossil fuels are unsustainable, requiring hundreds of kilos of gasoline or other emission-inducing fuels to transport the emission-free hydrogen [2]. Cargo ships are able to carry significantly more hydrogen, however they are unsustainable as they dependent on local water infrastructure. On top of that they take a very long time to transport the hydrogen payload. Pipelines require international co-operation, require much maintenance, have a very long time-to-launch and have a low reliability due to possible leakage[2]. Trains share the similar downsides of the other methods in that it carries risk as it passes by populated train stations, and is heavily dependent on train infrastructure being present at the location, it is however a less polluting method of transportation compared to trucks and ships [2]. Finally, aircraft do not use sustainable fuel and transporting fuel by aircraft requires high costs and high risks, therefore, aircraft are not seen as a competitor.[3]

As follows from the previous analysis, the mission will be focused on transporting hydrogen in an emission-free and safe manner. This leads to the following Mission Need Statement (MNS):

”Provide sustainable transport of hydrogen payload over intra-continental distances by 2040”.

2.3. Solution to the Need

As opposed to all previously mentioned methods of transport, there is one transportation method which does not have any of the downsides of the aforementioned transport methods: the airship. There are several reasons why an airship was chosen as the solution. Airships are able to operate almost completely emission-free, when using hydrogen as a lifting gas and as fuel for the engines. Airships do not

[2]Energy.gov. *hydrogen pipelines*. URL: `https://www.energy.gov/eere/fuelcells/hydrogen-pipelines` (visited on 06/14/2023).

[3]Transport and Environment. *Airplane pollution*. 2022. URL: `https://www.transportenvironment.org/challenges/planes/airplane-pollution/` (visited on 06/11/2023).

require much local infrastructure as long as there is enough clearance, and they can fly between points in a straight line. Since there is less traffic in the air, this leads to a large increase in the operational efficiency. Finally, airships have enormous endurance and because the payload would be carried in the air it avoids heavily populated areas. Hence the airship offers a very attractive alternative as long as there is a financially viable return on investment.The comparison with trucks in order to draw a comparison with potential competitors within the field is detailed in section 9.6.

Even though the hydrogen market is expected to grow in the upcoming decades, it remains a risk to depend only on the adoption of hydrogen. For that reason the airship will not only transport hydrogen, but can also transport other payload that our target areas, airfields and industrial zones, need, such as sustainable aviation fuel (SAF) or chemicals.

2.4. Funding

Due to the increasing worldwide push towards sustainable fuels, governments worldwide are pouring enormous amounts of government funds into the support of the entire hydrogen supply chain [13]. The United Kingdom has announced that it foresees that the setup of business models for hydrogen transport will require subsidy. The European Union has determined that it will set apart billions of euro's for the development of better hydrogen infrastructure, including the transport segment of the supply chain [13]. Therefore, this provides a great increase in the viability and financial attractiveness of the hydrogen-transporting airship. If a convincing business case can be set forth before the jury of the respective bodies which give out the subsidies, this could offer significant opportunities for the project. Therefore, extensive research was done on the historic availability of such grants and subsidies. An illustration of previous grants are given in Table 2.1:

Table 2.1: Table showing grants given out by the European Union to companies active in the hydrogen industry[13].

Project name	Industry	Amount
Zero Emission Valley	Electric vehicle use	€10,131,800 [1]
Green Hydrogen for Bremerhaven	Wind energy	€19,783,300 [2]
REFHYNE II	Hydrogen refinery	€32,431,618 [3]
GreenHyScale	Hydrogen suppliance	€30,000,000[3]

Though the magnitude and successful obtaining of government subsidies is not a given, and the priority which hydrogen will get from governments in the future is not predictable, the success in this area would provide a significant opportunity to significantly reduce the cost of an airship. Recent statements by several governments do give a promising picture for companies active in the hydrogen industry. The British government released a document in which it expressed its realisation of the need of government support for hydrogen transport utilities to be viable, which does provide optimism that governments will take it seriously [7]. Thereby, as mentioned in section 2.3, the transport of other payload, such as SAF and chemicals, can be used to fund the main hydrogen mission.

2.5. SWOT Analysis

Now that the business model has been discussed, the question is what the financial potential is of the business case. Before this is done however, first an internal analysis of the project is to be performed, which can be seen in Figure 2.4. The SWOT analysis analyses factors that affect the group which may be helpful or harmful to the functioning of the group with respect to the project. The SWOT analysis

[1]European Commission. *Connecting Europe Facility*. 2022. URL: `https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/connecting-europe-facility-transport_en` (visited on 05/04/2023)

[2]European Commission. *European Regional Development Fund*. 2022. URL: `https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/european-regional-development-cohesion-fund-react-eu_en` (visited on 05/04/2023)

[3]European Commission. *Horizon Europe*. 2022. URL: `https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/horizon-europe_en` (visited on 05/04/2023)

categorises these factors amongst strengths and weaknesses, after categorising these factors they are further developed into opportunities and threats which may be determined by extrapolating the potential ramifications of aforementioned factors.

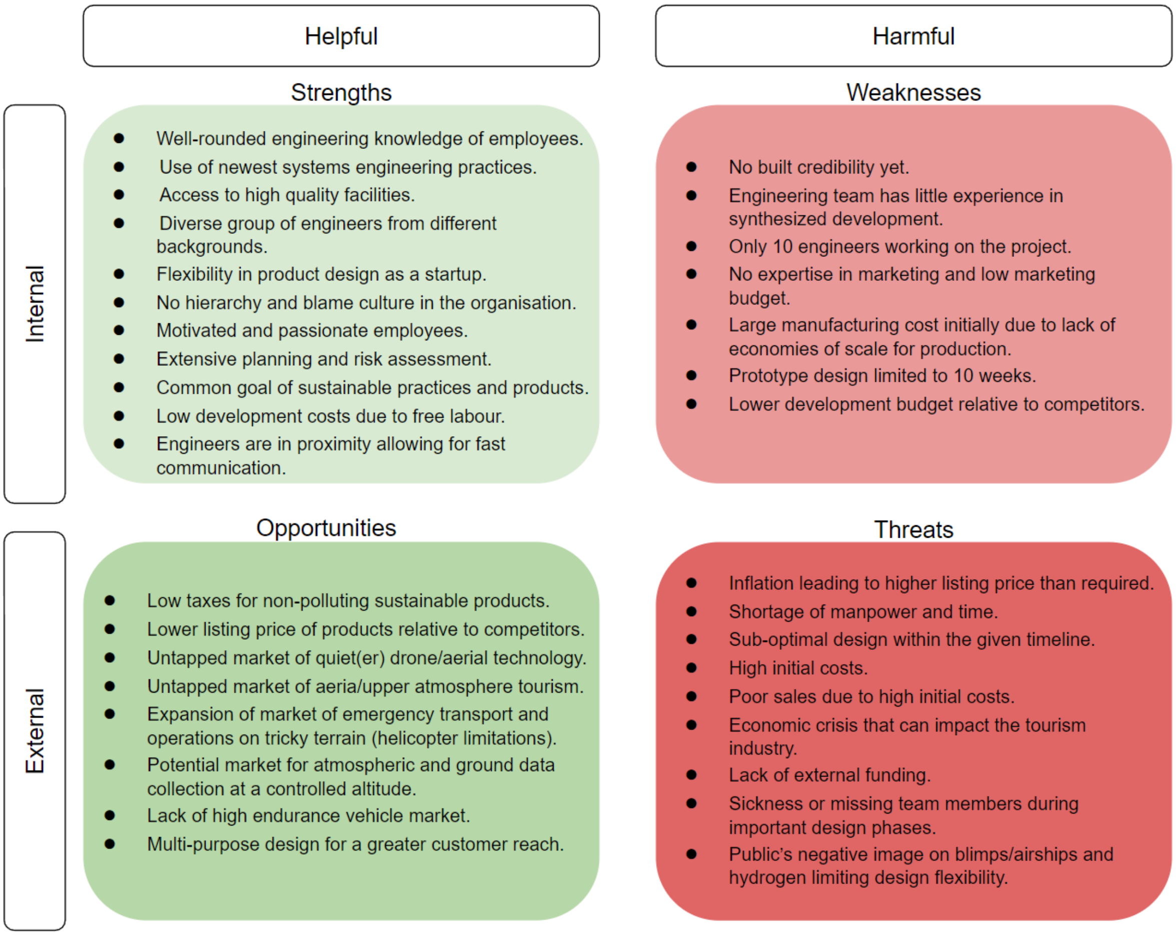


Figure 2.4: Figure shows the internal strengths, weakness, opportunity and threat evaluation of the business.

2.6. Conclusion

In conclusion, the business case for using an airship for the transport of hydrogen is feasible. In order to not enlarge the scope, a requirement will be made regarding the capabilities of the airship. The airship must be able to attain sufficient area coverage considering the locations of the hydrogen production plants and the industry areas which require the hydrogen. This can be seen in Figure 2.5. A range of 2000 km has been chosen as this provides sufficient coverage between industrial zones and major ports.

Figure 2.5: This figure shows some major ports and industrial zones in the world. The circles are indicative of the chosen range of 2000 km from these ports.

3 Sustainability

Now that the business model has been explained and the potential profitability of the project has grounds, the sustainability approach of the company remains to be investigated before jumping into the design. In this day and age, it is of the utmost importance to not only focus on the financial viability but to also take into account the non-financial effects of the airship. For this reason, a sustainable development strategy has been developed.

The long term vision and shorter term goals with respect to sustainability will be discussed. An in-depth coverage of how this sustainability strategy is implemented is covered in the detailed design phase in chapter 6.

3.1. Vision on Sustainability

The vision on sustainability of the project and the team, flows from the mission need statement in section 2.2. The primary focus is the technical and environmental aspects with a lower priority given to the social and economical aspects. Therefore, the sustainability aspects of this project will mostly focus on the design choices, production processes, material use and overall environmental impact of the airship.

Thereby, in terms of sustainability it is highly preferred to aim for a design that is as sustainable as possible. However, in terms of costs, materials, design or production process, the most sustainable design might not be the most efficient and possibly realistic design. During the design process, a balance must be found between all aspects mentioned above to find the optimal design.

3.2. Sustainability Goals and Implementation

Now that the vision on sustainability is clear, it is required to acquire a general outline and goals that should be followed during the design process. The United Nations, UN, provided similar guidelines that will be followed.

The UN established the Sustainable Development Goals (SDG), which is a collection of seventeen goals serving as a global guide for peace and prosperity for people and the planet, in the present and for the future. For this project, the SDG's reflecting the project vision are used as guidelines and requirements. These consist of SDG 7, 8 and 12. SDG 7 targets the universal share and accessibility of clean and affordable energy. SDG 8 is about sustainable, economic growth for all. SDG 12 aims for sustainable production and consumption patterns. In Table C.1 found in Appendix C, THETA–SYS–SUS–03 to 09 the definitions of each specific SDG can be found. The SDGs will provide guidance during the project process to make sustainable design choices, regarding materials, production, etc. Besides, following the SDGs will ensure the airship will contribute to a sustainable future [21].

With regards to the mission, sustainability goals arise regarding the environment. For the transport of hydrogen the airship will be mainly competing against trucks. Hence, the airship should at least emit less CO_2 gases than the truck, which emits $112\,\text{g/km}$[1]. The airship is aiming for a maximum pollution of $60\,\text{g}$ of CO_2 per km if any. Furthermore, sustainability goals aim to have a maximum noise level of $70\,\text{dB}$ during manoeuvring, take-off and landing received on the ground, $60\,\text{dB}$ of noise inside the cabin during cruise. These goals ensure lower noise levels and emissions than the direct competitors contributing to the SDGs and a more sustainable environment.

3.3. Sustainability of Hydrogen Production

Different types of hydrogen exist based on their production process, each classified by their environmental impact using a colour system. The classification is denoted by the colours green, blue, grey, black and brown. Nowadays, most of the hydrogen that is produced is grey, brown or black hydrogen, meaning it is produced using fossil fuels [13]. This makes hydrogen presently unsustainable.

In order to be the most sustainable and meet the sustainability goals, particularly SDG 7, the aim is to transport green. Only green hydrogen is produced in a clean climate-neutral manner.

With the development of renewable energy markets dominated by wind farms and solar fields, production of green hydrogen will only increase[2]. Green hydrogen can be used for energy storage for wind farms and solar fields. As they depend on the weather, they encounter high peaks and lows with generating energy and are limited by the energy storage system, which are currently limited to mainly batteries. They regularly exceed maximum storage capacity when weather conditions are particularly favourable to generate energy [13]. This excess energy can easily be stored by using it to electrolysis hydrogen. There will be an aim to only use green hydrogen as for the aspects mentioned above.

[1] evofenedex. *8 manieren om CO2 te besparen tijdens het transport van goederen*. 2021. URL: `https://www.evofenedex.nl/actualiteiten/8-manieren-om-co2-te-besparen-tijdens-het-transport-van-goederen` (visited on 05/04/2023).

[2] Rob Harvey. *Hydrogen-based wind-energy storage*. May 2019. URL: `https://www.windsystemsmag.com/hydrogen-based-wind-energy-storage/` (visited on 06/19/2023).

4

Mission Design

After the business model has been fleshed out and analysed in chapter 2, and preparations for the implementation of sustainability were made in chapter 3, the next step in the development was the design of the mission. The aim of this phase of the design was to get an accurate description of what the mission of the airship would be, so that the design process could be based upon this. During the whole mission, safety should always be prioritised, especially above profitability. Hydrogen is a very reactive substance that needs special handling procedures, depending on the phase of the mission. At this stage of the design process, the airship is assumed to remain in Visual Flight Rules (VFR) conditions.

Ground Operations

The ground phase is characterised by the airship not being airborne. It is expected that the airship has a base where the airship facilities such as a hangar for long term storage/maintenance are present. In chapter 2, three types of ground locations are identified. The first being the harbour where hydrogen arrives on large container ships. At the harbour the hydrogen is unloaded from the ship, where after the hydrogen is loaded into the tanks of the airship. The second ground location would be an airport, where the hydrogen can be delivered. The final ground location would be a factory. This factory could be producing the hydrogen which makes it a starting location, or the factory could require hydrogen, which would make the ground operation location a destination. On ground safety regulations and checks should be strict due to proximity to people and essential infrastructure.

Pre-Flight During the pre-flight, the airship is prepared for take off. In this process the airship systems are checked and the airship is prepared to take off. Special attention is payed to checklists and safety procedures. The airship might require to be movable on the ground in this phase.

Flight phase

The flight phase is defined as the phase when the airship is (going to be) airborne. To make things easier, the flight phase will be further broken up in different sub phases in which the most important aspects of a standard the mission are briefly discussed. Throughout the design description, additional possible contingencies during the flight will be treated.

Take-off When the pre-flight checks are performed and the crew & payload is ready, the airship can take off. The takeoff of the airship is chosen to be performed vertically. This is to increase the accessibility of the airship. The main reason for this is that taking of vertically requires less ground area/distance for takeoff and therefore the airship can operate on more locations.

Climb After a successful take off, the airship must climb to the desired flight altitude. This should be done while complying to the flight regulations and technical requirements. Special attention is paid to the route and climb performance of the airship.

Cruise The cruise phase is the phase at which the airship is expected to fly at a constant altitude and speed. As described in chapter 2, the airship is expected to have a range of 4000 km (2000 km up & down). Along this distance, the airship is encountering different flight conditions, which the airships is expected to withstand. The main threat to the airship is the weather, since changes in weather cause temperature, pressure and wind variations.

Descent Before starting the approach procedure, the airship should descend steadily and safely to the the approach altitude.

Approach/Landing During this phase, the manoeuvrability of the airship comes into play. The airship is expected to land vertically. In this phase the airship is expected to absorb the energy of the touchdown. During both the approach and the landing, the airship should be able to perform a go-around manoeuvre at any time.

Turnaround Phase

The turnaround phase is defined as the phase between two flights. In this phase, the airship is unloaded, cleaned, fuelled and loaded with payload again. When loading and unloading key is the buoyancy control, as the change in mass needs to be complemented for. Depending on which payload, different safety procedures need to be taken into account.

4.1. Functional Flow Diagram

Based on the mission design, a Functional Flow Diagram was made which can be found in Appendix A.

4.2. Functional Breakdown Structure

A Functional Breakdown Structure showing the different mission phases is shown in Appendix B.

5

Conceptual Phase

The conceptual phase characterises the top level concept of the airship and details the expected mission profiles and related concepts that determine the path future design phases take.

The general idea of the airship is that is able to carry payload. The main goal is to carry hydrogen in an efficient and sustainable way. The mission aims to make optimal use of all the capabilities of hydrogen.

From all the characteristics mentioned in chapter 4, the conceptual design phase can be commenced. Based on the mission and business strategy constraints and priorities have been identified, which led to an understanding in what is important regarding the concept and what is less so.

Keeping in mind the business strategy in chapter 2 and the mission design outlined in chapter 4, the conceptual design phase can be carried out. The constraints and requirements derived from these chapters are used to generate criteria for which the design concepts must fulfil.

Three main design options were identified, the conventional airship, a multi-lobed airship and a lifting body. The three concepts have unique characteristics and peculiarities resulting in different performances on the generated criteria presented in table Figure 5.1. The concepts are ranked on their relative ability to fulfil the requirements flowing from the mission need in order to perform a trade-off between them.

The criteria used for the trade-off are payload capacity, design complexity, safety, performance and accessibility. The criteria are scored between 1-5 depending on their relative importance with regards to the mission profile and the functioning of the airship. Safety and accessibility are deemed the most important criteria and hence scored a 5, payload capacity is slightly less important and hence scores a 4, the performance is graded a 3 and the complexity of the design is awarded a 1.

Once the criteria are established, the trade-off process can be started by scoring the different design options on each of these criteria. This scoring is done between 1-4 with 4 being the highest weight that can be achieved and 1 the lowest. The 1-4 scoring for the design options has been represented visually in the table by means of a colour scheme ranging from blue to green to yellow to red in descending order of points.

The scoring is illustrated by the following example: the conventional airship is graded yellow on payload. The payload design criteria itself is weighted 4 points (just below the highest grade of 5), yellow represents a score of 2 (out of 4 since this is the score the design is awarded on the colour scale) The two scores are multiplied in order to obtain 8, which is repeated for all other criteria and summed in order to create an overall score.

The results of the preliminary trade-off are summarised in Figure 5.1.

Table 5.1: The trade-off table gives a clear overview of the way the final design was chosen. The design criteria numbers as well as the colours correspond to certain weights and scores, leading to a final option with the highest score.

Options	Payload [4]	Design Complexity [1]	Safety [5]	Performance [3]	Accessibility [5]
Conventional	Only 800 kg hydrogen [yl]	Many comparable airships [bl]	Safe if helium is used [bl]	Low speed, low drag[gr]	Large size [yl]
Multi-lobed	Very high excess lift, can carry more payload [bl]	Some examples exist [gr]	Safe if helium is used [bl]	Low speed, high drag [yl]	Inflating/deflating might take long [yl]
Lifting Body	Very high excess lift, can carry more payload [bl]	No prior examples & complex stability [yl]	Requires a parachute, and flies at high speed [yl]	Low drag and high speed [bl]	Requires runway, eliminates off-shore operations [yl]

Table 5.2: The trade-off table indicating the scores given for each parameter, and the total scores of each design concept.

Options	Payload [4]	Design Complexity [1]	Safety [5]	Performance [3]	Accessibility [5]	Total Score
Conventional	2	4	4	3	2	51
Multi-lobed	4	3	4	2	2	55
Lifting Body	4	2	2	4	2	50

It is apparent that the multi-lobed option is the winner of the trade-off, hence the rest of this report revolves around the design choices which arise from choosing the multi-lobed airship.

Following the trade-off a complete list of user, mission and system requirements is generated for the airship, this is detailed in a compliance matrix which can be found in Appendix C.

6
Detailed Design

After choosing a tri-lobed airship in the conceptual design phase, the airship enters the next design phase resulting in a detailed design. In the following chapter the various subsystems that make up the airship and their associated design choices and parameters will be explored.

6.1. General Description

As mentioned, the airship is a multi-lobed consisting of three lobes, all filled with hydrogen as lift gas. The airship is optimised to fly at an altitude of 1000 m at a cruise speed of 100 km/h. The reason why 1000 m was chosen as flight altitude was because it limits the airship in size. The higher the airship flies, the bigger the volume of the airship. The airship is limited in speed to an airspeed of 100 km/h, as this limits the drag and power required. The speed is still within the speed range of a truck, which is the main competitor. The choice for a tri-lobed airship was made early in the design process because the estimated results were promising and it the goal initially was to store the hydrogen payload as gas in the side lobes, to later on compress it and deliver to the client. This idea was however too ambitious and deemed not efficient enough in terms of fuel usage. The multi-lobed concept did survive the design process however.

The three lobes have an identical shape consisting of two half ellipsoids. The front half has a semi-major axis that is four times the radius of the lobes, while the back half has a semi-major axis that measures six times the radius of the lobe. Although the three lobes have the same shape, they are not equal in volume. The middle lobe contains 75% of the airships lifting volume, while the side lobes contain 12.5% each. In chapter 13, details are given about whether this design choice was actually the best design. Note that for the structural analysis explained in section 6.3, an airship assuming $25\,000$ kg of structural weight was used. All other airship parameters given in this chapter are based on the actual structural weight, and all other subsystems are thus also sized for the actual structural weight.

Table 6.1: Table shows a general overview of the airship parameters.

Name	Value
Cruise altitude	1000 m
Cruise speed	100 km/h
MTOW	$69\,023$ kg
Length	134 m
Width	56 m
Height	28.8 m
C.G.	62.57 m
C.B.	63.50 m

6.2. Buoyancy Control

Buoyancy control is the primary mode of altitude control and lift generation. It is essential to devise a system that is reliable in order to have a functioning end-product. Airships typically rely on two lift gases because of their exceptionally low densities and high lift generation capabilities, these are hydrogen and helium. The choice was made to discard the options that used helium as buoyancy gas since reserves of helium occurring in nature are limited and unsustainable. On top of that, hydrogen uses around 8% less of volume for the same amount of lift. For that reason hydrogen is the most logical option considering that the ship is active in the hydrogen industry. The explosiveness and reactivity of the gas does entail dangers, although safe operations are possible when taking the right safety measures. These safety measures are further described in chapter 9.

The vertical velocity of the airship is controlled by means of compressing and releasing hydrogen gas in the lobes. The airship is designed for its MTOW, the volume of the airship is 1.02 times the required volume to maintain neutral buoyancy at its cruise speed. This allows the ship to accelerate vertically at a rate of 0.02 G. Table 6.2 describes the volumes of main and side lobes, together with the mass of hydrogen inside the lobes. These values support 1.02 times the weight of the airship and are based on the Law of Archimedes, Equation 6.1 [17]:

$$B = g \cdot V \cdot (\rho_{air} - \rho_{gas}) \tag{6.1}$$

Where B is the Buoyancy, g is the gravity constant and V is the volume. The density, ρ, at cruise altitude is used for sizing, which corresponds with $1.112\,\mathrm{kg/m^3}$. When analysing Equation 6.1, it is noticeable that the buoyancy force does not remain constant while in climb or descent. This means that altitude control acts like an acceleration controlled system and therefore the altitude control is an unstable system. This implies that whenever the system needs to level of, the magnitude of the buoyancy force should be lower/higher (depending on climb/descend respectively) than the magnitude of the gravity force on the airship before balancing out the same gravity force. This should in reality not be too disturbing for the pilots and/or buoyancy control system on board.

The envelope is pressurised by 5 millibar, this figure is determined by the maximum dynamic pressure on the airship. At a maximum cruise speed of $28\,\mathrm{ms^{-1}}$ the dynamic pressure is $\approx 436\,\mathrm{Pa}$. This is factored in along with a safety factor to give an envelope pressurisation of 5 millibar or $500\,\mathrm{Pa}$.

Table 6.2: Table shows the buoyancy parameters of the airship lobes.

	Main lobe	Side lobes	Total
Volume	$50\,043.2\,\mathrm{m^3}$	$16\,681.1\,\mathrm{m^3}$	$66\,724.3\,\mathrm{m^3}$
Pressure difference	$500\,\mathrm{Pa}$	$500\,\mathrm{Pa}$	-
Mass H_2	$3871.9\,\mathrm{kg}$	$1290.6\,\mathrm{kg}$	$5162.5\,\mathrm{kg}$
$F_{B_{H_2}}$	$507\,663.4\,\mathrm{N}$	$169\,221.1\,\mathrm{N}$	$676\,884.5\,\mathrm{N}$

As the ship ascends/descends, the hydrogen gas within the envelope is expanded/compressed. The ratio of this change in volume is dependant on the difference in altitude. Considering that the airship remains in the lower parts of the atmosphere, the difference in volume remains reasonably low. This change in volume of the gas causes the pressure to vary within the envelope, which is undesirable. To compensate for this pressure difference, inflatable ballonets are implemented in the lobes, to keep pressure constant. The ballonets are filled with atmospheric air and compensate for the difference in pressure by expending while the airship descends and deflating while the ship ascends. Table 6.3 describes the volume required of the ballonets for the airship.

Table 6.3: Table shows the ballonets sizing in the airship lobes.

	Main lobe	Side lobes	Total
Volume	$4631.8\,\mathrm{m}^3$	$1543.9\,\mathrm{m}^3$	$6175.7\,\mathrm{m}^3$

When the mass of the airship changes, for example due to propellant usage or water storage, the buoyancy need to change equally. This happens mainly during (un)loading the airship. To avoid venting of the airship, a compressor is going to be used to pump part of the hydrogen in the fuel tanks. This hydrogen could later on be recycled as propellant.

6.3. Structural Analysis

The structures subsystem is discussed in this section. This includes the sizing of the internal structure and its material choice. Furthermore, the envelope design, gondola and hydrogen payload tanks are discussed.

6.3.1. Internal Structure

For the internal structure inspiration was taken from the Zeppelin-NT[1]. It allows for more subsystems and envelope connections, which are needed for larger airships. The Zeppelin-NT structure contains truss-like elements that span along the envelope which are reinforced by triangular cross-sectional trusses. In addition, the structure is reinforced by pre-tensioned aramid cables that run diagonally between the triangular cross-sections. This structure is shown in Figure 6.1.

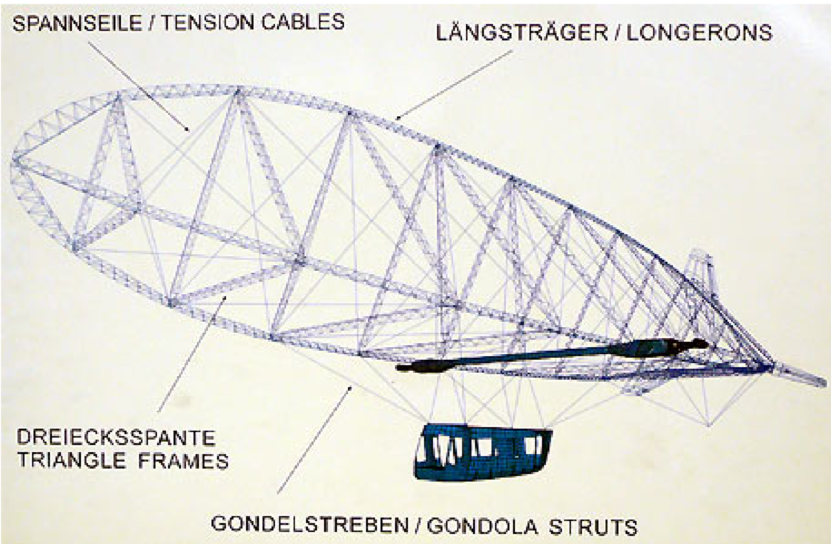


Figure 6.1: Internal structure of the Zeppelin NT is shown here[1].

Initially, a wingbox like keel structure was analysed using Python. However, it was concluded that this was not feasible due to the sheer size of the airship. Subsystems such as propulsion and empennage need to be attached to the airship at various places, and the envelope covers more volume than keel semi-rigid airships. It was therefore opted to go for the Zeppelin NT structure, that spans more of the airship allowing for more envelope connections and subsystem connections.

Model

Due to the complexity of analysis of the 3-dimensional structure, ANSYS Finite Element Analysis (FEA) was used. The Zeppelin NT structure is a truss-structure that allows for simplifications of the structural

[1] *Zeppelin NT*. 2008. URL: `https://www.wokipi-aerostation.com/zeppelin/Technical.html` (visited on 06/20/2023)

analysis, as its loading acts only in the axial direction of the members. Due to the still preliminary stage of the design, the structure was, however, implemented as a beam construction with point loads acting on the nodes connecting the elements. This approximates a truss like loading. The model is shown in Figure 6.2. Additional forces from subsystem sizing later in the report are also included in the table.

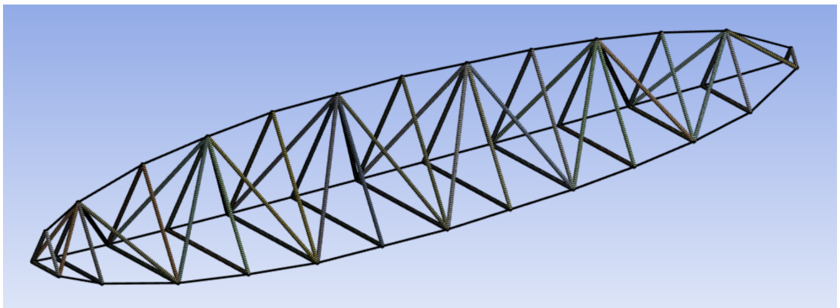


Figure 6.2: The model as implemented for FEA is shown here. The unproportionally large cross-bracings compared to the spars are explained further down the line.

The shape of the model has been determined by initially getting the coordinates of the ellipsoid envelope that the structure is designed for to determine the radius of the envelope in the length-wise direction. The location of the triangular cross-section elements are then selected at intervals of 10 m which was found to be the most efficient in terms of keeping the weight low such that buckling does not become an issue on the diagonal members. For each location, from the radius, the size of the triangle has been determined and then all members remaining are placed to connect the nodes. The distance between the leading edge and the second triangle is 5 m. This was designed to accommodate a nose-cone to prevent the aerodynamic loads acting on the envelope from denting inwards.

The algorithm used for sizing the airship and its subsystems assumes a structural mass of 25 tonnes. It is expected that the structural mass will be lower, therefore the airship parameters on which the structural analysis is performed is expected to be worse than reality. The 25 tonnes tonne assumed structural mass corresponds to the airship sizing in Table 6.4, which was obtained from a preliminary first sizing. The main difference with the newer sizing is only regarding the envelope weight which is neglected anyways, as is explained next, thus this outdated version is not an issue for the structural analysis.

Table 6.4: The table shows airship sizing assuming 25 tonne structural weight, with slightly outdated airship sizing due to an older iteration of the airship.

Name	**Value**
Length	126 m
Width	53 m
Buoyancy	$562\,320$ N
Structural Mass	$25\,000$ kg
Cover Mass	$17\,534$ kg
Drag	9797 N
Thrust per Engine	1959 N
Gondola + Assembly	$12\,700$ kg
Side Gust	$30\,000$ N
Vertical Tail Lift	$30\,000$ N
Horizontal Tail Lift	$15\,290$ N

Applied loads

The buoyancy that is loaded onto the structure is equally applied at every node of the three spars that span the airship. The buoyancy of the middle lobe acts more on the top lengthwise spar. However, the side lobes, that are roughly at the longitudinal centre of the envelope, will provide more loading on the the bottom spars. Therefore, the assumption of a third of the total buoyancy on each spar is valid. Furthermore, the buoyancy is distributed uniformly such that each node along the spars has the same buoyancy force on it. In reality the more central nodes are loaded more heavily compared to the outer nodes, thus the uniform assumption results in an overestimated of the bending moments and is thus conservative. Note that the buoyancy that the structure is loaded with is not the total buoyancy of the airship as shown in Table 6.4. The cover mass is subtracted as this is carried by the lift gas itself, and the load will not transfer through the structure. Furthermore, the structural mass is subtracted as the mass will sag the structure down, whereas the buoyancy will lift it back up resulting in almost net zero deflection and loads. This is a fine assumption to make to not over complicate the analysis.

The gondola and assembly weight which contains the payload act at 6 point loads on the lower side of the structure. This representation is realistic since these subsystems are suspended via cables and/or structural elements from the internal structure which carry them with tension.

The loads produced by the horizontal and vertical tail have been defined such that a reaction force at the point of selected boundary point is 0 N in all directions. This was done to simulate as realistic conditions as possible since the airship is in free flight while these loads are applied. In addition, if the system is not at equilibrium, there are unnecessary stresses on the elements that are attached to the boundary constraint. Therefore, the magnitude of the horizontal tail lift depended on the net difference between the weight of the whole airship and the buoyancy. The vertical tail lift magnitude depended on the gust magnitude since it is the only lateral force acting on the structure. Since the structure of the empennage have not been modelled yet due to time constraints, the vertical and horizontal tail lifts have been defined as point loads on roughly the aerodynamic centre of the lifting surface acting at a virtual distance away from nodes on the internal structure where the attachment of the lifting surfaces are likely to be made. Note that there is no moment equilibrium created around the boundary point. This was because a bending moment was created at the aerodynamic centres of the vertical and horizontal tail to create an equilibrium, but this resulted in unrealistic bending at the mid-length of the structure.

The location of fixed points were selected as the location where the gondola and the assembly weight applies at. This corresponds to 6 points. The reason for this choice was that at the location of the gondola and payload, the moment of inertia of the whole airship is greatest. This means in a non-fixed, free flight conditions, bending occurs around the location of the gondola in the longitudinal direction. Fixing there made the systems response as realistic as possible.

The drag acts mostly on the front of the airship. In reality the drag consists of both frontal shape drag as well as friction drag, where the frontal shape drag will have a parabolic distribution with the shape of the nose. The simplification is made that the drag simply acts uniformly on the first nine frontal nodes. This simplification will result in a conservative estimation in the front of the airship, with a non-conservative estimation in the rest of the airship. Overall this simplification is appropriate to make. At this time in the design the thrust is provided by five engines such that it mirrors the drag. Two engines are at the top of the structure, and three at the bottom. The loads are implemented in the FEA with virtual loads to simulate that they have a moment arm with the structure.

The loads and where they apply are shown in Figure 6.3. The coloured nodes show the points of application, and the arrows show the direction of the loads. The empennage and engine loads are displaced to where they would act in reality such that the moment arms are accounted for. This virtual position is shown where the node it is connected to is also shown.

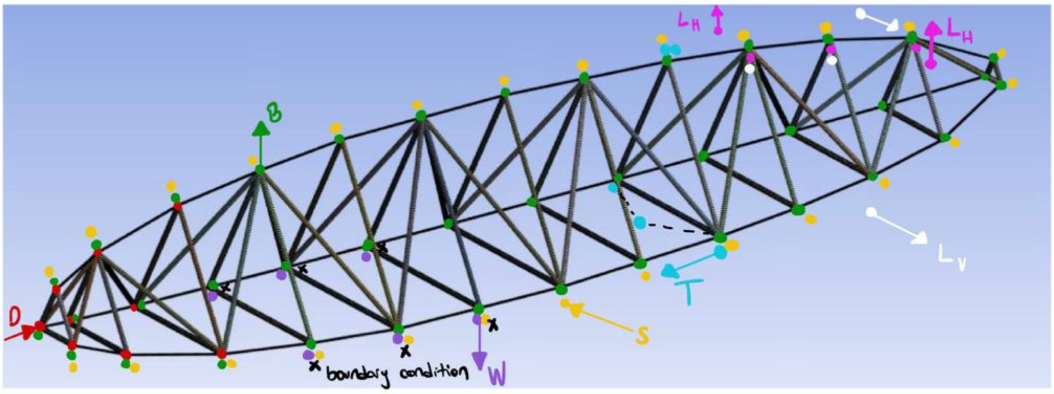


Figure 6.3: The loads and their nodes at where they apply are shown. The coloured nodes to show the load locations require coloured printing.

Member Sizing

Given these loads, it is clear that the top and bottom spars are primarily in bending. Whilst the cross-bracing, so both triangles and diagonals, are mostly in axial loads. Both the cross-bracing and spars have members that can be in heavy compression. Given the large lengths of the elements this results in buckling. For this reason the spacing of 10 m per triangle was found to be most efficient, since this is quite close together to limit buckling in the spars. Furthermore, the Zeppelin NT structure has the crosses implemented as cables. However, it was found that these carry significant compression in this case, thus they were kept as rigid members. Given the compression of the cross-bracing members, buckling is also an issue for these member with their large lengths of up to 22.5 m. Furthermore, the side gust loads and empennage loads cause significant lateral bending and some torsion.

The deflections that the loads create, in an older iteration of the structure, are very small in the upward direction of roughly 20 cm, yet significant in the sideways direction of roughly 2.4 m, although it is not necessarily an issue. The yield and ultimate stresses of the Carbon Fibre Reinforced Polymers (CFRP) are far from being reached. This highlights that the structure should be optimised for buckling and also keep the lateral bending in mind. For this reason the spar elements are made from a hollow square to resist bending loads in lateral and longitudinal directions. As well as provide equal moment of inertia's for both buckling directions, such that weight is kept minimal to carry the buckling. The Euler buckling formula was used for to compute the required moment of inertia as provided in Equation 6.2 [24].

$$P_{critical} = \frac{\pi^2 \cdot E \cdot I}{(Kl)^2} \tag{6.2}$$

Where E is the Young's modulus, I the mass moment of inertia , l the length and K the effective length order. In order to comply with the required safety factor of two for composites, it was assumed that K, thus the way the members are supported, equals one, corresponding to pinned supports. In reality the support is somewhere in between fixed and pinned. This corresponds to an effective length of 0.65 to 1 Equation 6.2. On top of this, the compressive stiffness of CFRP is roughly 80% of the tensile stiffness, as confirmed with materials expert D.M.J. Peeters. This results in an effective safety factor of 1.34, thus the moment of inertia still has to be multiplied by 1.5 to achieve a safety factor of 2.

Given the maximum compressive load of 148 kN in the spars with the largest length of 10 m of a member, the required moment of inertia from Equation 6.2 results in a hollow tube geometry of 12.6 cm wide with 2.8 cm thickness, obtained from Equation 6.3. The dimensions of this cross-section are shown in Figure 6.4.

$$I_{xx} = I_{yy} = \frac{1}{12}w^4 - \frac{1}{12}(w-2t)^4 \tag{6.3}$$

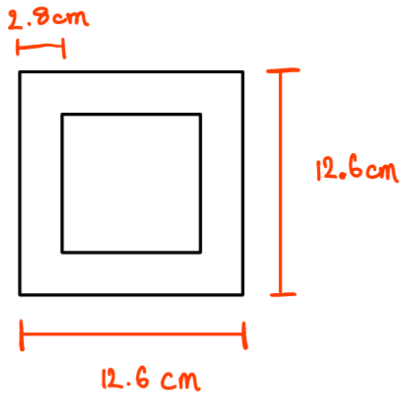


Figure 6.4: The square cross-sectional area with its dimensions used for the spars is shown.

For the rest of the structure, which includes the triangular cross-sections and the diagonal elements, the lengths of the elements is significantly larger. The maximum length of the triangles is 20 m, whereas the maximum length of the diagonals is 22.5 m. Given the maximum compressive loads of 57 kN and 100 kN on them, this proves a problem for regular beam elements. It was found that the beam elements will simply be too heavy to carry this compression. However, as the axial forces are the dominant loads for these members and bending is not an issue, these elements were replaced with a finer truss structure. This provides the benefit of having a significantly larger moment of inertia due to the hollow tubes being shifted away from the centre. On top of that the individual elements in the truss have a significantly smaller length, which reduces probability of buckling. Due to time constraints given the early phase of this design, it was chosen not to implement this truss-structure in the FEA software, but to resort to analytical solutions that replace the triangular and diagonal members. Note that the spars were kept as beams in the software, as their loading is primarily bending.

For the truss structure prone to buckling, one has to consider the whole member, thus the 20 m to 22.5 m member, and the smaller inner elements in the truss structure. Furthermore, for easy of use and cheaper manufacturing, the diagonals and triangles will be made from the same truss geometry. For the triangular sections, the maximum compression is 57 kN with a maximum length of 20 m, whereas for the diagonal sections, the maximum compression is 100 kN with a maximum length of 22.5 m. The diagonal is therefore the limiting case.

$$I_{yy} = \frac{\pi}{4}(r_{out}^4 - r^4) + \pi(R^2 - r^2)\frac{spacing^2}{2} \tag{6.4}$$

A truss structure with cross-section consisting of three hollow circular tubes with outer radius of 3.5 cm and inner radius of 2.5 cm with spacing between of 35 cm as shown in Figure 6.5 was chosen. The resulting moment of inertia in the weaker direction, thus I_{yy} using Equation 6.4, was found to be 1.18×10^{-4} m^4 which is greater than the required value of 6.36×10^{-5} m^4 found from Equation 6.2. The effective safety factor is therefore 3.71, which accounts for additional non-axial loads that are applied to the bracings.

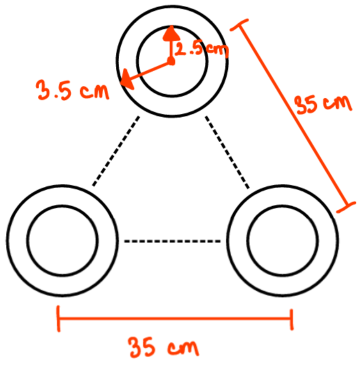
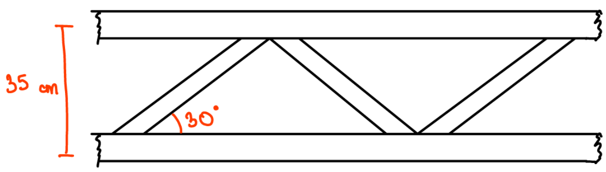


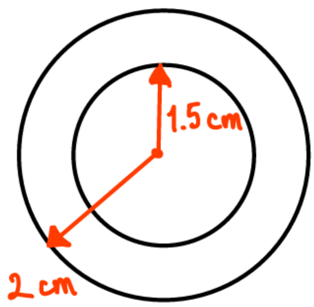
Figure 6.5: The truss cross-sectional area is shown with the dimensions that have been chosen.

The side view of the truss structure is shown in Figure 6.6a where inner tube elements are angled at $30\,°$ and the vertical spacing goes into the page since its a triangular cross-section. In this scenario, both the inner diagonal element as well as the straight element that span the inner diagonals need to carry the loads without buckling. For an inner tube cross-section, as shown in Figure 6.6b with inner radius of 1.5 cm and outer radius of 2 cm, the moment of inertia was found to be 8.6×10^{-8} m^4. This is greater than the required value of 6.15×10^{-8} m^4, which has been calculated as if the entire load of 100 kN runs through the diagonal inner element. This will not happen in real life and is considered a worst case scenario. For this case, the diagonal inner element has an effective safety factor of 2.8.

The inner straight element that spans the inner diagonals as shown in Figure 6.6a has a required moment of inertia of 1.85×10^{-7} m^4 when the entire load runs through it, whereas the element has a moment of inertia of 8.72×10^{-7} m^4. This provides an effective safety factor of 9.4, meaning that buckling for this element will not be an issue.



(a) The truss side view is shown with the dimensions that have been chosen.



(b) The inner tube truss elements cross-sectional area is shown with the dimensions that have been chosen.

The sizing of the cross-sections was based solely on column buckling which is the dominant loading since it was discovered that the truss already satisfies the compressive yield stress requirement with a safety factor of 2 at the maximum axial stress location. The same truss structure is used in all cross-sectional triangles and diagonals after it is sized for the location of maximum compressive force and buckling probability. This likely means the structure is over-engineered for other locations where the loads will never be as high, however, this design choice has been made to reduce the total structural costs by using the same components to compensate for the high costs of using CFRP.

When the airship is on the ground and the lift gas has been removed for maintenance, the buoyancy will not apply anymore. In this case the structure needs to be able to carry itself and the subsystems. In comparison to flight loads the upper spar will now be in tension, whereas the lower spars will be in compression. It was found that this ground loading compression and flight loading compression are very similar, resulting in the same hollow square cross-section and dimensions for both upper and bottom spars.

During flight in which buoyant loads are applied, the upper spar is under compression and lower spars are in tension. However, during maintenance operations when the buoyancy gas is removed, the structure rests on its own weight causing tension in the upper spar and copmpression in the lower spars. This was simulated in the FEA and found that the compressive forces on the lower spars were similar to compressive forces in the upper spar with buoyancy. Therefore, the same cross-sectional area has been used without optimising upper and lower spars to reduce the costs of production.

Deflections and stresses

After sizing all members it has to be confirmed that stresses will also not cause issues. It was found that the maximum stress occurring in the spars is 13.6 MPa in compression and the maximum stress occurring in the trusses is 182 MPa in compression in the small inner diagonal when the entire loads runs through it, which is a worst case scenario. The compressive strength of uni-directional CFRP is 1.08 GPa. The material property is provided by the ANSYS software[2].

For analyses of the deflections, the team has resorted back to the FEA. Given that the trusses were not modelled in the FEA, a hollow tube was created that matches both the cross-sectional area of the truss, as well as the smaller moment of inertia, I_{yy}, of the truss. Given this is the smaller two of the moment of inertia's, the deflections will be worse than in reality.

With the selected geometry and dimensions, it was found through FEA that in the worst case scenario where all loads are maximal and are acting at the same time, the maximum deflection in the structure is 106 cm laterally at the trailing edge of the envelope. This deflection was deemed acceptable due to it being relatively very small to the length of the airship and having no impact on the empennages and other subsystem's performance. When the sideloads had been removed, the dominant external force becomes the buoyancy which causes a vertical deflection of 12 cm at the tail. Since the structure does not fail with this flex and the horizontal tail only experiences an increased angle of attack of roughly 0.14 °, this was determined as an acceptable deviation. It was found that adding extra reinforcement thus increasing the weight has diminishing returns on reducing the deflection at the tail. The maximum stresses and deflections with and without lateral loading are shown below in Figure 6.7, and Figure 6.8.

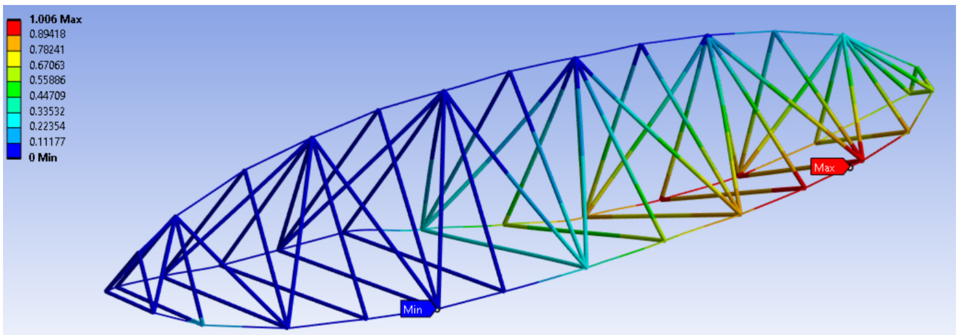


Figure 6.7: The extreme case deformations on the structure with lateral loads applied on it are shown.

[2]ANSYS. *Ansys Mechanical Finite Element Analysis (FEA) Software for Structural Engineering*. 2022. URL: `https://www.ansys.com/products/structures/ansys-mechanical` (visited on 06/20/2023).

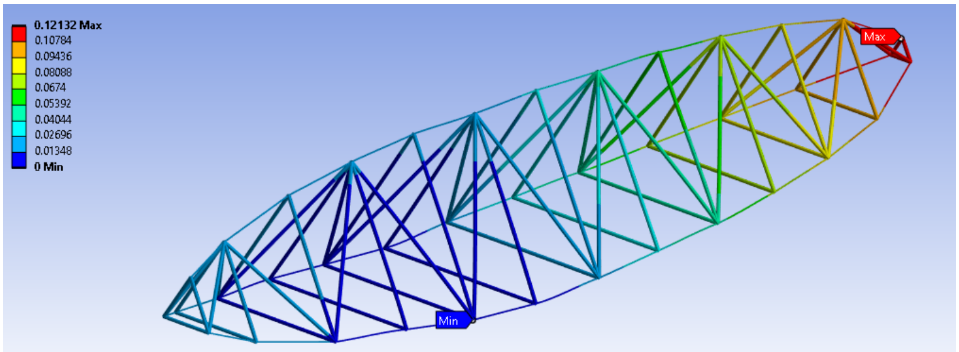


Figure 6.8: The extreme case deformations on the structure with no lateral loads applied on it are shown.

Conclusion

Since CFRP and other composites are not as efficient as metals at transferring loads between discrete elements such as those used in a truss and joining methods are far less flexible. Aluminium rings at the joints for improving load transfer have to be used. This increase the structural weight and increase the costs but it is deemed worth it compared to using a full aluminium alloy structure to reduce the complexity because of the weight penalty that it brings. On top of this, additional structural weight is to be added for attachment of the subsystems. These are the attachment of the engines, sidelobes, empennage and gondola with payload. Furthermore, weight is to be added for the nose shield that prevent caving in of the nose of the airship. For this reason, the structure mass concluded by the analysis is to be increased by 35%.

The mass of the entire structure as sized in the previous subsections is $17\,042$ kg. Adding the knock-down factor of 35% needed to account for the neglected loads is equivalent to adding 5965 kg, landing at a total structural weight of $23\,007$ kg. As the assumed structural weight for which the airship was sized is $25\,000$ kg, the actual structural weight is slightly lower. This structural mass is considered to still be worst case, given the loads that were considered and assumptions that were made. On top of this further optimisation to significantly reduce structural weight is possible. Consider this $23\,007$ kg to be an upper bound of the structural weight. In chapter 13 recommendations on how to improve the structural design in the future are discussed.

6.3.2. Material Selection

The material selection of the entire airship consists of five main categories being, the material of the rigid structure, the envelope, the coating, gondola material and material of the control surfaces. The materials considered were based on airship and material research, examining materials that have been used in past missions in the aerospace industry. Besides sustainability and cost being a significant factor in all material decisions, there are material properties to consider depending on the structure and its function, of which the most important ones will be discussed in this section. All material properties that were taken into account for the materials analysed can be found in Appendix D.

For the rigid structure the most important properties are the density, the specific strength and the Young's modulus. Since the structure needs to be as light as possible, the density and specific strength are crucial. The latter needs to be as high as possible to ensure that the structure is able to carry loads without failing. Its stiffness, expressed by the Young's modulus, shall also be high to avoid buckling.

The envelope material must be able to withstand loads without ripping, thus requiring a high tensile strength and stiffness. It shall also be as light as possible, meaning the specific strength and density are important.

Since the coating and film function as the protective layer between the airship and the environment, they have some additional properties that are relevant such as its abrasion resistance, resistance to UV light and weatherability, which must be as good as possible to avoid having to reapply the coating often. Permeability is crucial for the coating as hydrogen exiting the lobes shall be limited since hydrogen is the airship's lifting gas. Due to hydrogen being highly explosive, flammability of the coating is an additional aspect to consider. The envelope with 3 of its layers have been visualized in Figure 6.9.

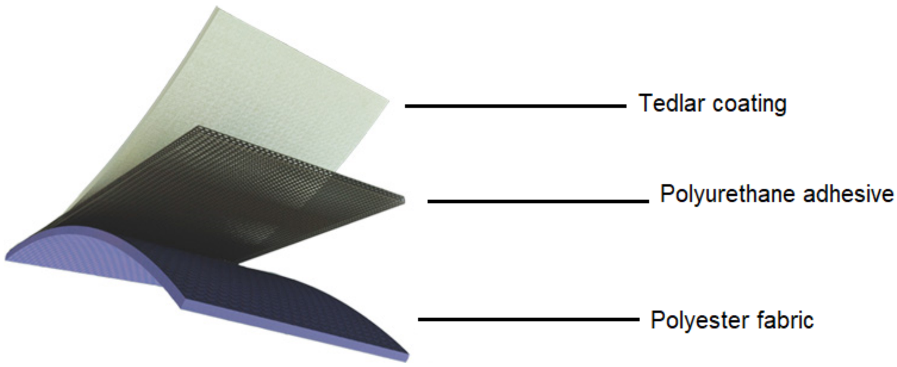


Figure 6.9: The 3 layers of envelope shown with the corresponding material chosen.

Rigid structure

The rigid structure will be made out of CFRP since it has a relatively low density, a high tensile strength, a high stiffness and is sustainable. Glass fibre Reinforce Polymers (GFRP) have a density that is not much higher, but is much cheaper. However, it cannot be chosen due to the fact that the stiffness of the material is crucial for the structure explained in section 6.3, where CFRP greatly exceeds GFRP. The choice for CFRP results in nine times higher material costs, which is undesirable, but since the stiffness is critical for the structure, CFRP is still chosen.

Envelope

The envelope is a laminate that consists of an environmental/weathering protection layer, a gas retention layer and a woven load bearing layer, where all are connected with adhesives. Out of the potential load bearing components, polyester HT and kevlar have the best properties since they have a fairly low density, a high tensile strength and high elastic modulus. Kevlar excels polyester with its much higher tensile strength and excellent sustainability, but polyester is considered strong enough and is much cheaper. This results in polyester being chosen as the envelope material.

The thickness of the envelope is determined by using Equation 6.5.

$$t = \frac{pr}{\sigma_{yield}} \cdot \text{SF} \tag{6.5}$$

where p is the pressure difference between the outside and inside of the balloon in of 500 Pa or 5 mbar, given in Table 6.2, r is the radius of the envelope in m, given in Table 6.1, SF is a safety factor of 4 required by regulation, as shown in Appendix C, and σ_{yield}, the yield stress of the envelope material, being polyester, given in Appendix D. This leads to a thickness of 0.38 mm.

As for the coating, multiple (modern) materials are both gas retention components as well as effective weathering components [17]. This means a coating by itself could be enough, but sometimes a layer of film is added as well. For the tri-lobed airship, Tedlar will be used due to its excellent performance regarding permeability, resistance to UV light and sustainability. Besides that, it only has to be reapplied every 15-20 years. It is more expensive than polyurethane, which also has good strength and stiffness properties, but it is non-flammable, whereas polyurethane is. For Tedlar a coating thickness of about 0.1 mm is required [9].

Tedlar is, however, poor in adhesion to fabrics. Since polyurethane has good properties as well (low permeability, weatherability, relatively high strength, low density and sustainability), is not very expensive and, unlike Tedlar, has excellent adhesion to fabrics, it is used as an adhesive between the polyester envelope and the Tedlar film. A polyurethane layer with a thickness of about 1 mm is used[3].

Control Surfaces

The control surfaces will be made out of GFRP due to its fairly high strength over weight ratio and its high stiffness. These are important criteria for control surfaces as there will be exposed directly to the environment and responsible for stability and control of the airship. Besides, it is much cheaper than some other potential, stiff and strong materials, such as CFRP.

6.3.3. Gondola Design

The gondola will be used by two pilots. Assuming a person needs about 1 m in length and 1 m in width, and taking into account that the pilots need a resting place and a lavatory, a gondola of about 2.5 x 4.0 x 2. m is required. It will be made out of aluminium, which is often used for airship gondolas as it is fairly light, has a high strength/weight ratio, a high stiffness and is relatively cheap. CFRP and GFRP would be fairly good options, even better in density, strength/weight and stiffness, but they are more expensive. Besides, the impact on aluminium is easier to calculate. Since this is much harder for newer material, such as GFRP and CFRP, structures using these materials are often overdesigned in reality. Assuming a thickness of 2 mm, the structure mass will be about 400 kg. After adding 200 kg of avionics, a gondola mass of about 600 kg is obtained. This is an overestimation that will be used for structural analysis. The gondola will be attached to the airship using steel cables, which is commonly used for airships[17]. The cockpit design is presented in more detail in Appendix E.

6.3.4. Hydrogen Tanks

The airship will be equipped with two types of hydrogen tanks. The most important tank being the hydrogen tank filled with the propellant hydrogen. The required hydrogen for the trip will be carried by CFRP tanks. CFRP is an industry standard for hydrogen propellant tanks. Equation 6.6 shows an estimate for the propellant tank characteristics that eventually result in Table 6.5. The mass of the tanks is not dependant on the actual dimensions of the tank. It is obvious that the higher the pressure at which the propellant is stored the smaller the volume of the tank. The propellant tank will be positioned above the gondola, within the airship's envelope, with an access point to refill the tank.

$$m_{H_2} + m_{tank} = n_{H_2} \cdot M_{H_2} + SF \cdot \frac{3 n_{H_2} R T}{2 \cdot \sigma_{hoop}} \cdot \rho_{tank} \tag{6.6}$$

in which m is mass, M is molar mass, SF is the safety factor of 2.25 as required by regulation, R is the gas constant, T is the temperature, σ_{hoop} is the hoop stress and ρ the density.

Table 6.5: Table shows the propellant tank parameters.

Name	Value
Material	CFRP
Storage pressure	700 bar
Volume	5.6 m^3
Thickness	0.1 kg
Mass tank	1802.6 kg
Mass H_2	340 kg
Total mass	2142.6 kg

The tanks used to transport the 800 kg of hydrogen transport are off-the-shelf available tanks. The hydrogen will be stored in an intelligent way to make optimal use of the available payload space behind the gondola containing the pilots. The hydrogen is divided over different tanks for security reasons that will be further elaborated in section 9.4

[3] Marlin Steel. *What is the Average Thickness for Urethane Coating?* 2013. URL: `https://www.marlinwire.com/blog/what-is-the-average-thickness-for-urethane-coating` (visited on 05/25/2023).

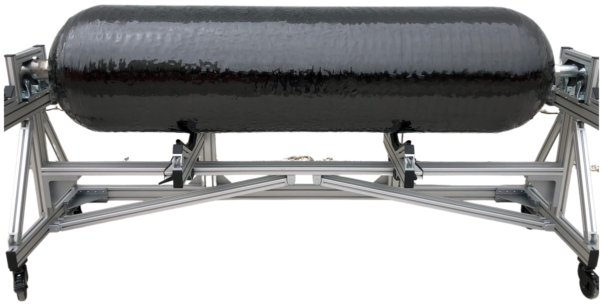


Figure 6.10: A picture of the off the shelf hydrogen tank that is going to be used[4].

Table 6.6: The table shows the payload tank parameters[4].

Name	Value
Material	CFRP
Storage pressure	700 bar
Volume	0.35 m^3
Number	60
Mass tank	190 kg
Mass H_2	15 kg
Total payload mass	12282.0 kg

Sustainability Analysis

Finally, the sustainability of the chosen materials and their production process needs to be taken in consideration to be able to analyse if they meet our sustainability goals. All selected materials are sustainable regarding their recyclability.

For the rigid structural parts the material is either CFRP or GFRP. Both materials are considered sustainable looking at not only the recyclability but also their long life span. However, producing CFRP or GFRP takes much energy and when using fossil fuels the CO_2-emissions are significant. The environmental impact can be reduced by using more renewable energy sources and using different techniques such as such as microwave heating when producing the fibres. [12]

For the envelope polyester is chosen. The raw material of which polyester is made is a non-renewable resource oil and the production process requires a lot of water and energy[5]. However, polyester is the best material for the airship given its price, ease of use and strength.

After this brief analysis the chosen materials do not seem to be so sustainable, but when looking at the bigger picture the decisions make more sense. The overall performance of the airship is of high importance as well. Besides the sustainability of all selected materials they improve the performance, for example by making the airship lighter and being light is very crucial. So as the chosen materials have some down sides, for the overall picture they are beneficial and add to the sustainability of our product as a whole and our sustainability goals, such as SDG 12, are still met.

[4]Hyfindr. *carbon4tank hydrogen vessel 700 bar 350 l*. 2023. URL: `https://hyfindr.com/marketplace/components/hydrogen-tanks/gaseous-hydrogen-tanks/carbon4tank-hydrogen-vessel-700-bar-350-l/` (visited on 06/20/2023)

[5]CFDA. *Material index polyester*. 2019. URL: `https://cfda.com/resources/materials/detail/polyester` (visited on 06/19/2023).

6.4. Aerodynamic Analysis

An aerodynamic analysis is necessary for any flying object, however since the airship is such a large body the drag estimation takes precedence in driving design parameters. In addition to this since the overwhelming majority of lift of the airship is generated by means of aerostatic lift an aerodynamic analysis for the lift produced by the body is deemed unnecessary. The lift generated by the envelope is extremely low at low angles of attack and flying at higher angles of attack is impractical owing to the increased lift induced drag. Any lift produced aerodynamically by the envelope and side lobes is hence negated.

Drag Analysis

In order to estimate the drag, empirical methods were used from multiple studies and reports. Owing to the relative lack of popularity of airships, some of the sources may be considered dated. It is however worth noting that even these older sources add value to the analysis from a statistical viewpoint since combining the largest number of sources results in a more complete and valid analysis. The studies generally used different estimation methods for the C_d or drag, this increased variety of sources adds credibility to the estimation.

US Marshall Study

A method to estimate the drag of the multi-lobed design is by using an empirical relation that can be seen in Equation 6.7 [1].

$$D_R = C_{Dp}\rho(V)^{\frac{2}{3}}v^{1.86} \tag{6.7}$$

Here D_R is the air resistance or drag of the airship in N, C_{Dp} is the dimensionless Prandtl shape coefficient, ρ the air density, v the cruise speed and V is the volume of the airship.

The Prandtl shape coefficient for multiple airships are given in a table in the book and the coefficient is based on the prismatic coefficient which is based on the volume, length and maximum area. THETA's coefficient is determined by the previous mentioned parameters and an extrapolation is made from the table in the book to determine THETA's shape coefficient.

Multi-lobed Airship Report

The drag estimation in the report relies predominantly on an empirical formula used for the drag estimation. This is shown in Equation 6.8

$$C_d = \frac{0.18(l/d)^{0.3} + 0.27(l/d)^{-1.2} + 1.08(l/d)^{-2.7}}{(k_{mod} \cdot Re)^{1/6}} \tag{6.8}$$

The drag estimates for this method have been validated by means of CFD data compiled from various other research papers [19]. The report concluded that the estimated drag and the computed drag did not vary significantly from the drag produced by the formula for a conventional single hull airship. The drag for the multi-lobed design however was 44% off the equivalent CFD analysis, this is attributed to the increased skin area in a multi-lobed design and hence a factor of 1.5 is applied to the equivalent conventional airship drag estimation to compute the final drag estimation.

The limitations of this report however are that only one multi-lobed airship was used in order to perform the estimation for the multi-lobed airship specifically. The CFD data was used to validate the equation specifically for single hull conventional airships, when applied for a multi-lobed airship a 44% deviation in the C_d is noticed. While this has been overcome by means of a safety factor in the report, it is a limitation that needs to be addressed during the validation procedure.

The drag coefficient varies between 0.026-0.033, this is a reasonable range considering the variety of studies that have been used and the power values obtained from other airships in the past. The reference area used for these calculations is the area perpendicular to the incoming flow, resulting in a final drag value of approximately $11\,000$ kN.

6.5. Propulsion Analysis

For propulsion jet engines are simply not viable. They are used for high velocities and high altitudes which are not appropriate for THETA. Ion thrust on the other hand provides too low thrust. This leaves electric propulsion and combustion engines. Given the better sustainability and lower noise of electric engines, this is the way to go.

For the right engine choice, the most important criteria are the engine's power to mass ratio, the amount of engines needed and the total mass of these engines. The power to mass ratio shall be as high as possible to ensure that the airship is able to overcome the drag, while being as light as possible. Due to its low weight and high performance, providing 4.16 $\frac{kW}{kg}$, the Siemens SP200D engine was chosen. The other main engine options are shown in Appendix F.

Table 6.7: Siemens SP200D engine parameters are shown in the table. This is the engine chosen for the final airship design [27].

Name	Value
Type	Siemens SP200D
Number	5
Mass	49 kg
RPM	1400
Efficiency	0.8
Power available	163200.0 W
Total price	1860000.0 €

With this engine there is a significant amount of excess power, which is the difference between the power required and the power available. Here, the power required is the power needed to overcome the drag, which is calculated using Equation 6.9.

$$P_{required} = D \cdot v \tag{6.9}$$

where D is the drag in N, determined in section 6.4 and v the velocity of 100 km/h as shown in Table 6.1.

The power available, $P_{available}$ is a material property of the engine, shown in Table 6.7.
From Figure 6.11 it can be seen that there is a significant amount of excess power at all times. Overcoming drag is however not the only function of the engines. The five engines allow the design to be redundant: in the case of failure of one of the engines, the other can compensate for the lost thrust.

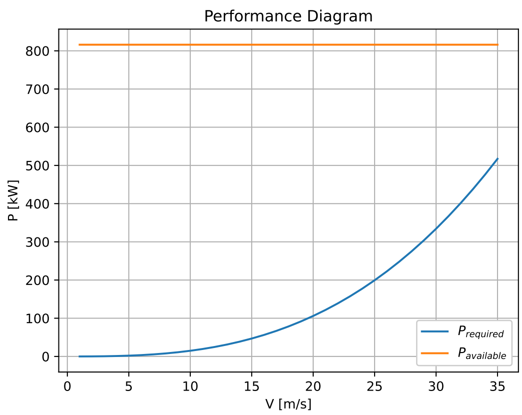


Figure 6.11: The performance diagram shows that with the use of the Siemens SP200D electric propeller engine there is a lot of excess power.

Propeller Sizing and Rotation Speed

The propeller sizing is performed using the thrust, propeller diameter, outlet velocity of the propeller and rotation speed of the engines as variables.

There is a desired propeller diameter and required thrust around which the other parameters are calculated. These requirements are considered driving since they have the greatest impact on other subsystems in the airship, namely structures and the entire power train.

The thrust per engine is calculated by dividing the final drag value over the total number of engines, given in Table 6.7, (assuming a One Engine Inoperative (OEI) condition). This results in a required thrust of approximately 2750 N per engine.

The thrust generated by the engine is given by Equation 6.10.

$$F_t = \rho \cdot \pi \cdot r^2 \cdot v^2 \tag{6.10}$$

Where ρ is $1.112 kg/m^3$, r is the propeller radius in m and v is the outlet velocity in m/s.
A diameter around 2 m is desired for the propellers since this allows for optimum mounting of the motors. The propellers must be designed such that they do not have supersonic tip speeds since that would result in a heavy loss in efficiency.

The outlet velocity is determined using Equation 6.11 [30].

$$v = 0.175(n) + 0.014 \tag{6.11}$$

This allows for a comprehensive sizing of the propeller and determination of the required rotation speed. In order to have a diameter of 2 m a rotation speed of 9600 RPM is required. This is well into the supersonic regime and hence the design needs to be analysed in much further detail. This is out of the scope of what is reasonably possible within the given time constraints, however based on the diameter and existing propellers on the market it is not unreasonable to assume that a propeller this size can produce the required net thrust given the right gearing ratios. This is further elaborated on in chapter 13.

Sustainability Analysis

Looking at the sustainability of the propulsion system, it is not only sustainable due to the electric engine. When taking into account the other criteria as well, $\frac{power}{mass}$ ratio, total mass, etc., it improves the overall performance of the airship and hence increasing the overall sustainability of the airship. also, opting for an electric engine complies with SDG 8, promoting and supporting sustainable economic growth.

6.6. Power Analysis

In the following section the power analysis will be discussed. The use of a compressor and fuel cells will be explained.

6.6.1. Electric Scheme

The airship is powered electrically, with all systems deriving power from the fuel cell. A sized lithium battery is placed on board to ensure power to all flight control systems and the flight computer, this is a redundancy measure which ensures static control even when there is a failure in all the fuel cells.

The electronics of the airship are structured as follows, the fuel cell supplies the compressor and the engines directly (with the necessary intermediate power delivery and speed control systems). The fuel cell simultaneously funnels any excess power into a battery, which is connected to the flight computer and hydraulic control systems as well as any other non-power intensive systems.

Since the airship is expected to offer completely autonomous flights, remote controlled flights and manually piloted flights a more specific block diagram can be drawn up for the airship from the aforementioned top level diagram. This is shown in Figure 6.12

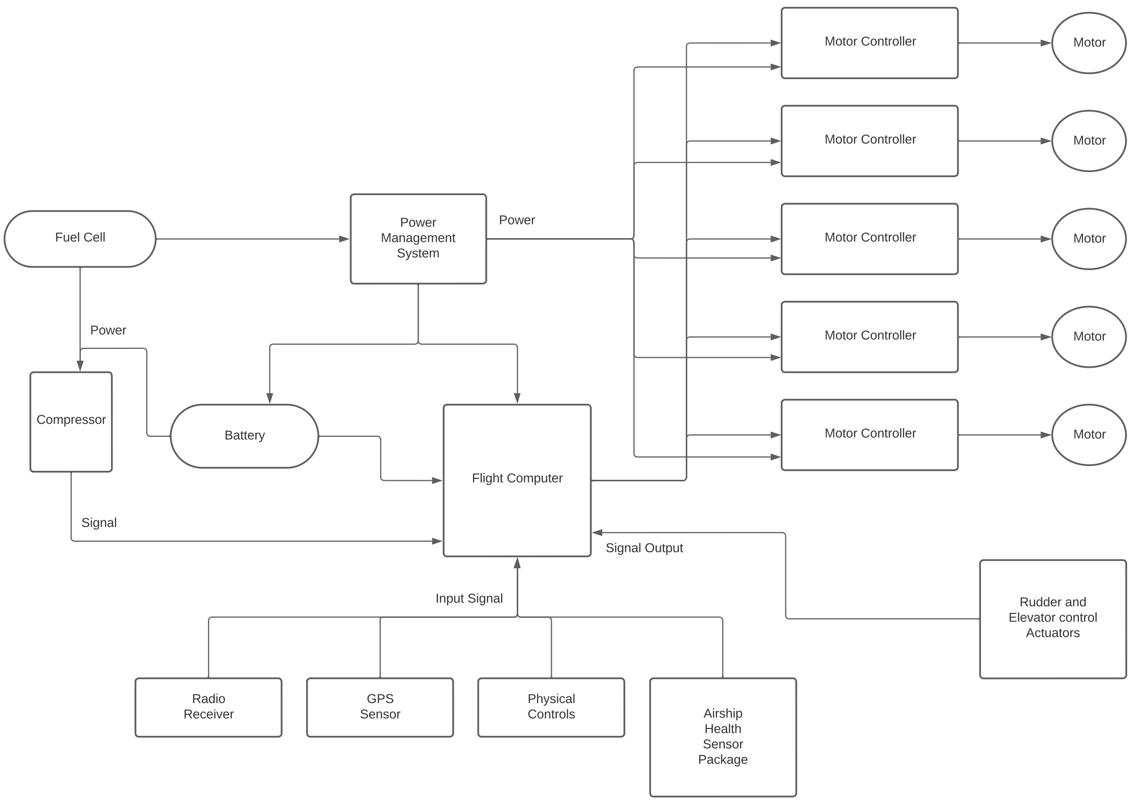


Figure 6.12: Figure shows a detailed breakdown of the electronics.

6.6.2. Compressor

The compressor is used to achieve altitude control of the airship as the airship is controlled by means of pumping lift gas into or out of the envelope. A compressor is therefore an integral element of the airship and it needs to be powerful enough to pressurise the lift gas sufficiently in order to inflate or deflate the envelope. The compressor is located between the main lobe and the propellant tank. There is no of the shelf compressor available at this point, so a custom compressor is expected to be designed based on Table 6.8.

Table 6.8: Table shows the compressor parameters

Name	Value
Type	Custom made compressor
Number	1
Mass	100 kg
Price	23250 €

6.6.3. Battery

The battery must have sufficient capacity and discharge rate to satisfy both the power and the energy requirements of the airship. In order to do this estimates need to be made with regards to how much the flight computer and hydraulic control systems would consume over the flight duration or over the duration of an emergency landing process.

The batteries that shall be used will be lithium based since this has the highest energy density of any battery that is available nowadays. It is worth noting that lithium batteries are not particularly stable and hence flame retardant measures will need to be deployed along with a sophisticated battery management system.

Table 6.9: Table shows the battery parameters[6].

Name	Value
Type	Tesla Home Battery
Number	1
Usable energy	13.5 kWh
Mass	100 kg
Price	13020 €

6.6.4. Fuel Cell

The fuel cell is the primary power supply for the airship. The fuel cell supplies the flight computer, the hydraulic systems, the engines and the compressor at all times during conventional operations. The power available from the fuel cell is dominated by the power required by the engines. The currently chosen fuel cell is still in an experimental phase. The market value at the moment is 1000 euro per kilowatt, but this is expected to decrease in the coming years. The fuel cell is expected to be certified for aviation by 2028.[7]

Table 6.10: Table shows the fuel cell parameters[8].

Name	Value
Type	INOCEL Z300
Number	4
Mass	100 kg
Power available	300000 W
Total price	300000 €

The fuel cells are expected to produce heat, which will be dissipated using active cooling attached to radiators that are hanging at the outside of the gondola. The heat should remain as far away as possible from the airship, since it can cause a potentially hazardous situation. This is further described in section 7.1.

6.6.5. Power Balance

Considering that the airship is transporting hydrogen, an energy calculation is done to map the changes in energy levels throughout the mission. Table 6.11 shows an approximate overview of the amount of pressurised hydrogen present in the ship.

To transport 800 kg of hydrogen a distance of 2000 km (so transporting to a point at 2000 km and going back with empty payload tanks), around 390 kg of hydrogen is required. 340 kg is stored in the propellant tank and around 55 kg is "recycled". This means that around 55 kg of hydrogen mass is taken from the lobes and compressed, this compensates for the excess lift created after having delivered the payload hydrogen. This amount of hydrogen needs to be added in the lobes again once the airship is loaded with a new payload.

[6]TESLA. *POWERWALL*. 2023. URL: `https://digitalassets.tesla.com/tesla-contents/image/upload/powerwall-2-ac-datasheet-en-na_001` (visited on 06/20/2023)

[8]INOCEL. *300 kw high power hydrogen fuel cell*. 2023. URL: `https://inocel.com/product/` (visited on 06/20/2023)

Table 6.11: An overview of the power analysis on the airship is shown in the table.

Name	Value
Loading	
H_2 payload	800 kg
H_2 tank	340 kg
Flight	
H_2 trip fuel (onward)	182.9 kg
H_2 buoyancy control	8.4 kg
H_2 hydrogen compression	2.2 kg
Unloading	
H_2 buoyancy compensation	54 kg
Return flight	
H_2 trip fuel (return)	128.9 kg
H_2 buoyancy control	8.4 kg
Total	800 kg

Sustainability Analysis

Using hydrogen as fuel is essential to meet our sustainability goals and comply with SDG 7 and 12, as hydrogen is a renewable source with no green house gas emissions. However, it is also important to look at the bigger picture and find out if the power system as a whole meets our goals. When fuel cells are used an electrical engine is needed as well to convert the energy in hydrogen to a motion meaning more energy losses, but when you compare them with the average combustion engine they are still more efficient [23]. Thereby, using hydrogen as a lifting gas, fuel and possible payload combines different systems, such as the fuel tank and the tank where the compressed hydrogen is stored, making the overall design lighter and hence more efficient. Thus, it can be said that the power system satisfies our sustainable goals sufficiently.

6.7. Control Analysis

In order to have complete control over the airship at all times control mechanisms need to be developed. The control mechanisms include differential thrust based controls and aerodynamic control surfaces. Sizing and positioning these control surfaces and engines is essential to develop a fully controllable airship. The following sections analyse the various control measures and their contributing factors.

6.7.1. Empennage Sizing

The empennage sizing is integral to ensure sufficient controllability of the airship. It is worth noting that the empennage surfaces predominantly control the airship by means of aerodynamic forces and hence can not be used to control the airship when stationary. Both the vertical and the horizontal stabiliser are sized appropriately in order to ensure stability and controllability of the airship. The chosen configuration is a plus sign at the back of the airship. This was chosen because of its symmetry and simplicity. The following subsections detail the method by which the sizing for both stabilisers was performed.

Vertical Stabiliser and Rudder

The vertical stabiliser surface and the rudder were sized by examining the limit cases for airship control. Generally, the limiting case for the sizing of a multi-engine aircraft is the net moment resulting from gusts combined with a multiple engine inoperative condition resulting in a strong differential thrust component.

The sizing was done for the worst case of a multiple engine inoperative condition combined with a gust load resulting in the largest moment about the yaw axis. In order to perform the sizing, firstly an airfoil needs to be chosen, this airfoil is ideally symmetrical and generates no lift at 0 angle of attack (AoA) (to prevent a yawing moment in steady straight flight). A NACA0015 symmetric airfoil was picked. The maximal rudder deflection was capped at $25°$ and a model of this deflected surface is generated in order to estimate the aerodynamic characteristics of the surface. The model was generated and simulated in Xfoil. Xfoil tends to overestimate lift values and under-estimate drag values, these quirks were accounted for by reducing the resultant C_l value by approximately 20%.

Once the C_l values have been determined for the maximally deflected control surface, a moment equivalence can be set up to determine the area of the control surface. A further safety factor of 3 is included in the sizing of the control surface. This might seem excessive at first glance, however since the control surface is likely to be in very turbulent air, it is unreasonable to expect optimal performance from the control surface. The vertical stabiliser for other airships were visually estimated and checked in order to validate the assumptions made regarding the safety factors. In addition to this, the amount of material added by assumption of the safety factor is not significant enough to warrant any major downsizing since the gust loads that act on the control surface are relatively small and do not add any major design complexity with regards to structures.

Horizontal Stabiliser and Elevator

To estimate the horizontal tail sizing, firstly a simple approximation was done to determine the required surface area. The moment generated by the tail should be able to counter the moment generated by the buoyancy force. This results in the Equation 6.12 that needs to be satisfied.

$$Cl_B S_B \cdot (x_B - x_{cg}) = Cl_{Ht} S_{Ht} \cdot (x_{Ht} - x_{cg}) \tag{6.12}$$

The left hand side is for the airship body while the right hand side is for the horizontal tail. This leads to a required horizontal tail area of $148.9\,\mathrm{m}^2$. The geometry is taken to be a trapezoid, this can be seen in Figure 6.13. After this approximation a more in depth study was performed, which can be seen in chapter 13.

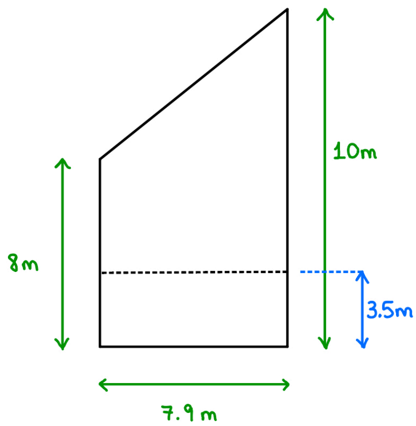


Figure 6.13: Geometry of the horizontal tail, with the elevator indicated by the black dashed line (not to scale).

Empennage Structure

Accounting for aero-elastic flutter of the tail surfaces is necessary to ensure that the airship control surfaces do not fail by this mode. The airship control surfaces are not large relative to the airship and the plus configuration of the empennage is one that is not inherently conducive to the development of major flutter. However, since the areas are large in absolute terms, 4 stiffening cables/rods are laid across the empennage to provide stability in case any adverse oscillations do develop this is shown in Figure 6.14.

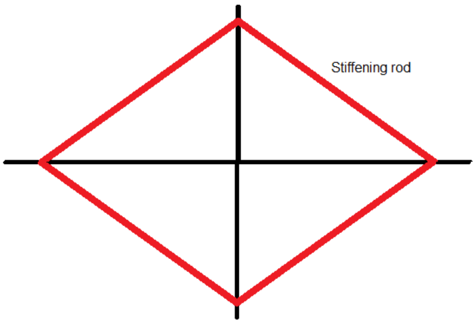


Figure 6.14: Figure shows the lay-out of the stiffening rods about the tail surface (figure not to scale).

The rods need to carry a maximum axial load of approximately $10\,\text{kN}$ each, hence a cross sectional area of $\approx 10\,\text{mm}^2$ should be sufficient to mitigate any flutter that may occur otherwise. These measures are purely precautionary since it is highly unlikely that flutter will develop at the low speeds the airship is expected to fly at and with the chosen geometry of the control surfaces. Nonetheless, since it does not add a considerable amount of weight and improves the safety of the design they are included.

6.7.2. Engine Positioning

The airship is going to require multiple engines. This offers flexibility with regards to motor placement and by extension control characteristics. The motor sizing must take into account controllability, added burden on structures and practical aerodynamic aspects. From a controllability perspective it is ideal to have the motors as far out as possible from the centre of gravity, however this adds to the structural complexity significantly. The motor positioning must hence be optimised to have the minimum impact on structures while being sufficiently far out to have differential thrust based control, this must also take into account aerodynamic effects that may be induced from being close to the envelope. The engine selection is shown in Figure 6.19, and will be elaborated upon in section 6.8.

The gust loads acting on the side of the airship induce a moment about the centre of gravity, this moment is estimated by checking the force induced by the dynamic pressure acting over the body. This force can be modelled as a point load acting at the centroid of the body and this creates a moment. The moment can, upon calculation, be used to check the moment that must be created by control surfaces to prevent rotation about the C.G. The model used is shown in Figure 6.15

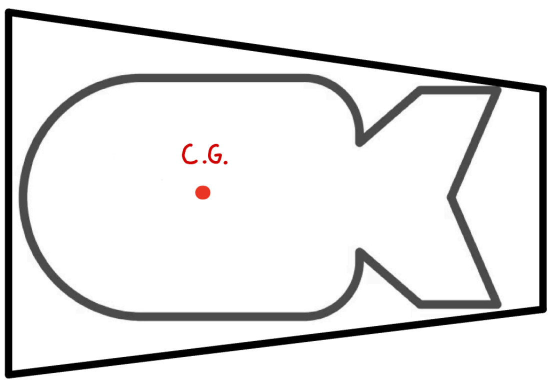


Figure 6.15: Approximate profile used for approximation of moments about the airship. (not to scale)

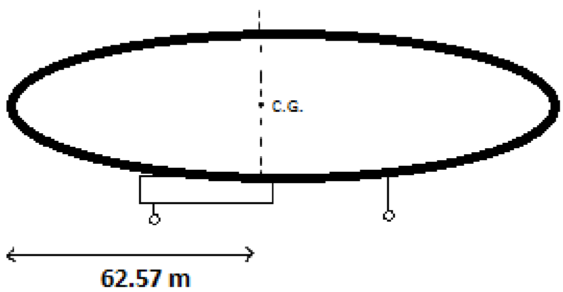
In order to simplify the moment calculation, the airship was approximated by a trapezoid with the vertical stabiliser acting as a point area (hence creating a point load) at the rear end of the airship. The resultant moment for this was checked with the moment that could be produced by the engines about the C.G. by means of a combination of differential thrust and aerodynamic control surfaces.

What results from this calculation is a C.G. range within which differential thrust control is possible, this centre of gravity range is used for future calculation used to determine positions of other subsystems.

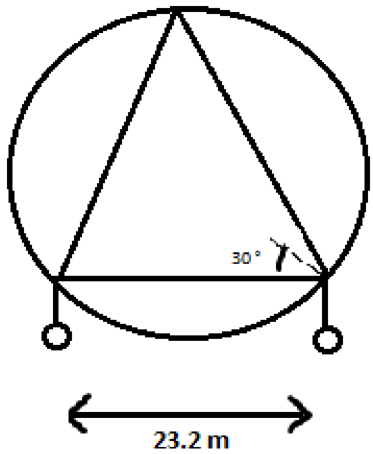
6.7.3. Landing Gear Positioning

From the empirical data shown in Appendix G and the fact that the maximum wind speed with which an airship is allowed to fly is $35\,\mathrm{km/h}$, it follows that the aft landing gear shall be at least $9.1\,\mathrm{m}$ from the centre of gravity of the airship[9]. The lateral distance between the aft landing gear shall be equivalent to the maximum cross-sectional width of the structure at this longitudinal point. From the analysis of the inner structure, explained in section 6.3, it follows that this width is $23.2\,\mathrm{m}$. This is illustrated in Figure 6.16b. This way the landing gear is supported by the primary load-bearing structure and does not require an additional point of connection since it can be connected to the mainframe itself.

The main landing gear shall be positioned such that tip back and tip over are avoided. From Figure 6.16a it can been seen that this is accomplished when the main landing gear is positioned at the front of the gondola. Its position is not critical since the normal force exerted on the landing gear is not high enough to warrant any major structural redesign. After all, this force is the difference between the buoyancy force and the total weight, which will rarely be significant during normal operation. The landing gear position ensures that even if a shift in the centre of gravity occurs, the airship shall still not tip over any axis. An airship filled with hydrogen is lighter than air and thus this buoyancy force will largely compensate for the weight of the airship.



(a) Sketch shows the longitudinal landing gear position, where the C.G. from Table 6.1 is implemented.



(b) Sketch shows the lateral landing gear position.

Figure 6.16: Sketch of the landing gear positioning. Tip back and tip over shall be avoided.

During exceptional cases, i.e. situations where lift gas is not present in the envelope, the landing gear will have to support the full weight of the airship. The landing gear will therefore be designed to support these forces since they present the limit case for the design.

[9] ZeppelinNT. *Frequently asked questions about the flights*. 2023. URL: `https://zeppelinflug.de/en/faqs` (visited on 06/15/2023).

6.8. Stability Analysis

In this section the stability analysis of the airship will be performed. Both static stability as well as dynamic stability will be discussed.

6.8.1. Static Longitudinal Stability

The static longitudinal stability of the airship needs to be determined to ensure that sufficient controllability of the airship can be maintained even in the face of adverse weather conditions and other operational limit cases.

Figure 6.17 shows a free body diagram of the airship during cruise.

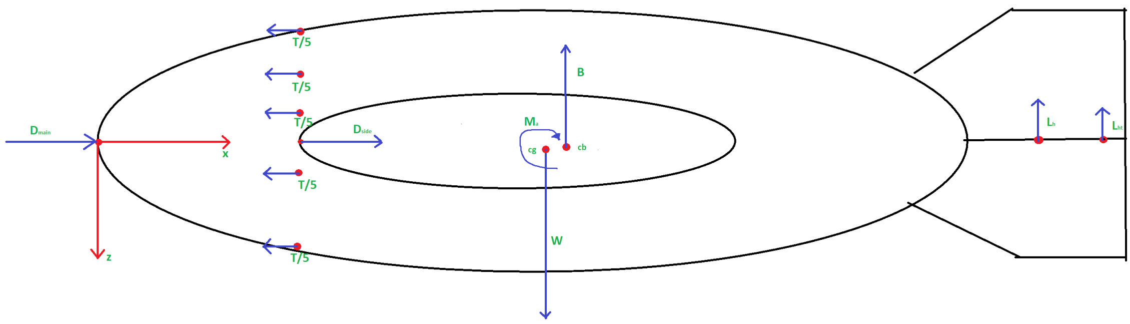


Figure 6.17: The free body diagram of an airship showing all forces.

Several assumptions apply for this longitudinal static stability analysis:

1. Steady flight
2. Straight flight
3. Horizontal flight
4. Symmetric flight

These assumptions are common assumptions that apply during cruise conditions. Their effects are well known and shall not be explained further here. Positive forces are to the right and downwards for horizontal and vertical forces respectively.

The shape of an airship is inherently unstable [17]. This is due to the asymmetric tear drop shape causing an aerodynamic moment around the C.G. [5].

$$M_a = V \cdot q_{dyn} \cdot (k_2 - k_1) \cdot \sin 2 \cdot \theta \tag{6.13}$$

Next to that, the buoyancy forces cause a moment around the centre of gravity as the centre of buoyancy is not in the same position of the C.G. [17].

$$M_b = B_{side} \times r_{side} + B_{main} \times r_{main} \tag{6.14}$$

Furthermore a propulsion moment is created by both drag and thrust. The five engines placed around the main lobe cause several moments, which can be both clockwise and counter-clockwise depending on if the engines are placed above or below the C.G. respectively. The drag is mainly acting through the noses of the lobes causing yaw moments, where the main lobe causes more drag since it is larger in cross section [17].

$$M_p = \sum T_i \times r_i + \sum D_i \times r_i \tag{6.15}$$

Additionally, the moment created by the control surfaces should be taken into account as well. Although the force created might be small compared to the buoyancy, the moment arm will be largest as it is placed in the back of the airship [17].

$$M_c = L_h \times r_h \tag{6.16}$$

Finally the gravity causes no moments since the weight acts through the C.G. which is the point where the moments are taken around. Then all moments are added with the use of 6.17.

$$M_{tot} = M_a + M_b + M_p + M_c \tag{6.17}$$

To trim the aircraft during cruise, the elevator at the back part of the tail of the airship can be deflected. This creates more positive or negative camber on the airfoil thereby creating more positive or negative lift respectively. The elevator has to deflect a precise amount to trim the aircraft. It requires the sum of moments around the airship to be zero. This requires a certain force that acts over a predefined surface, at a predefined distance, with a predefined airfoil shape. This makes for a certain deflection that acts as a certain angle of attack of the elevator surface. The force does not have to be that large such that it needs a large elevator surface, since the moment arm of the force is long. The horizontal tail is over designed in terms of size such that it does not need a large elevator deflection, which may require a strong, stiff, and thereby possibly a heavy structure.

The engine placement is also determined by the longitudinal static stability. As in the case of this airship configuration 6.17, the horizontal tail causes a counter clockwise pitch down moment if the force is negative (upwards). Same applies to the main lobe buoyancy which is behind the centre of gravity. The buoyancy force of the side lobes cause the same moment as the side lobes as their centres of buoyancies align with the main lobes centre of buoyancy. The drag acts through the nose and the centre of gravity is located slightly below the nose height, or in the case of the axis system used, is located with a z value higher than that of the nose. This causes a minor pitch up moment, which could have been neglected as the moment arm is very low, about 3.21 m. The aerodynamic moment is clockwise as can be seen in figure 6.17. The engine placement is decided such that when each engine uses the same throttle settings creating the same magnitude of thrust, while its directional pointing being assumed to be horizontal (which is the case during cruise), the engines cause a counter moment $M_p - M_d$ to the already existing moments of aerodynamic, aerostatic, and drag effects, or M_a, M_b, and M_d respectively. This requires at least two engines to be placed below the airships C.G.

When doing the trim calculations to find out how much the elevator needs to be deflected, it was found that $64\,°$ would be required to trim the airship. This is considered to be too much, as it will require a strong and therefore heavy and complicated hinge. Next to the fact that fluttering and vibrations caused by aerodynamics will require a lot of maintenance. Therefore the horizontal tail size is doubled and the new dimensions of the horizontal tail can be seen in Figure 6.18.

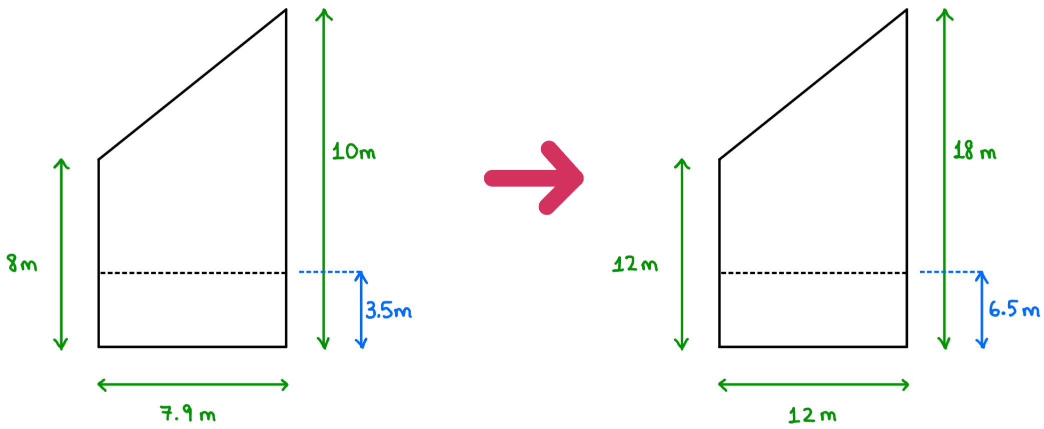


Figure 6.18: The new sizing of the horizontal tail after static stability analysis.

Considering all of the prior information, the deflection of the elevators to trim the aircraft is calculated to be only $29\,°$, which is downwards thereby creating a positive force. Additionally the engine position has been decided, as it influences the moment arm from the C.G. to the engine. The engine placement is placed at x $=25$ m based on the axis system used in Figure 6.17. The engines are placed at an angle that is calculated with Equation 6.18.

$$\angle engine = \frac{360}{N_{engines}} \tag{6.18}$$

Where the amount of engines are 5 as written in Table 6.7, and the first is placed on top of the airship, whereafter each other engine is rotated around the main lobe. The following figure, Figure 6.19, shows the engine placement.

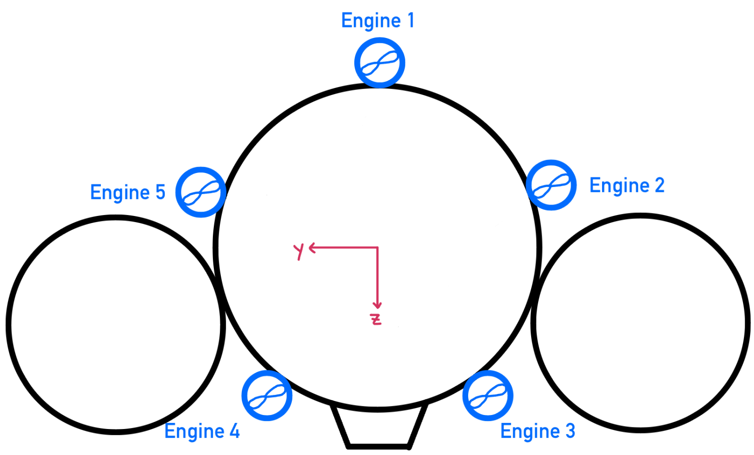


Figure 6.19: The engine placement around the main lobe, shown as a front view, including the axis for reference.

6.8.2. Static Directional Stability

Now that the longitudinal stability has been analysed, and some trim calculations have been done, the next step is to look at other rotational stabilities. Since an airship could hypothetically roll, this is nearly impossible in practise. Unless a very large fin is placed on the airship or if thrust vectoring is used, the airship is not able to roll due to its large moments of inertia, and heavy elements, such as structure, tanks and gondola being placed at the bottom of the airship not allowing it to roll around its longitudinal axis.

This only leaves static stability analysis of yaw and pitch during each part of the mission including, take-off, climb, cruise, descent, and landing. The airship can be trimmed in several ways. However the preferred way is to deflect certain control surfaces, which in the case of the airship is the elevators for pitch stability, and rudder for yaw stability. Static longitudinal stability is the most important form of stability for aircraft since if that is unstable, the rest of the aircraft dynamic stability is highly likely to be unstable as well. The same principle applies to airships as well.
The longitudinal stability is the limiting factor in the airship case due to the following reasons:

- The forces in the longitudinal plane are greater compared to the forces causing directional or yawing moments.
- The length of the airship is greater than the width, causing smaller moment arms of directional yawing moments.
- The control surfaces are the same size, both vertical and horizontal fins have about the dimensions.

Since the longitudinal trim stability required an elevator deflection of $29\,°$, the rudder deflection will be less, as the proportion of the force of the control surface will be more compared to the longitudinal case, next to the aspects stated above. Furthermore, there are other options to trim the airship in the yaw direction, such as altering the magnitudes of thrust of the individual engines.

6.8.3. Dynamic Stability Analysis

The next step in the stability analysis is the dynamic analysis. Little is known about the dynamic behaviour of an airship and the eigenmotions of airships. Regardless of this, an attempt has been made to approximate the airship model as a state-space model, inspired by an aircraft model, using flight parameters of an aircraft where the values are multiplied with a factor of about 2.2 to account for the fact that an airship reacts slower to sudden changes. Additionally, rolling motion of an airship is not taken into account since the airship cannot roll.

This is however not the optimal method of approximating the airship dynamics. The very under-damped results of the system are a proof of this statement's validity. The state variables of planes used, are not comparable to actual airship values, considering an airship reacts significantly slower than an aircraft, and airships do not posses any eigenmotions such as aeroplanes. Thus, dynamic analysis of the airship can only be done with experimental data of an actual airship.

The dynamic stability of the airship is largely determined by the neutral stability of the airship itself. However, a poorly tuned control algorithm could force the airship into an unstable or unfavourable motion, which can reduce ride quality, increase pilot workload or even lead to a dangerous situation. Hence, a PID controller is implemented and tuned. Further tuning is expected after experimental flights during the testing phase of the airship. This will prevent the active stabilisation from functioning erroneously during operations once the airship is released to the market.

7 Technical Risk Assessment

After conclusion of the conceptual design phase, following the subsystem trade-off, it was apparent that certain risks were insufficiently mitigated. These risks are denoted by the following identifiers and are as follows:

- R-PSU.01 : Gas Leak- Possible risk of ignition and fuel leak results in dangerous conditions and loss of operating range
- R-PSU.02 : Ignition of stored Hydrogen- Ignition of hydrogen leads to large fires and very high temperatures resulting in catastrophic failure
- R-PSU.03 : Excessive Heating of Fuel tank- Results in weakening of the fuel tank and potential ignition of fuel
- R-PPU.03 : Propeller Detachment- Detached propeller may fly off and damage the airship, also results in loss of power from one engine
- R-STR.03 : Exceeding mass budget would warrant a complete redesign of most airship systems potentially resulting in being unable to deliver the project prior to the deadline
- R-MAT.09 : Difference in static electricity potential between the airship and the environment- Only dangerous if there is a rupture or gas leak

Of these risks, R-STR.03 is not longer a risk since the design has not exceeded the mass budget and is hence excluded from the risk assessment for this phase (in order to avoid confusion, what was previously R-STR.04 is now R-STR.03). In addition to this, the risks involving the folding of the side lobes was also negated due to the change in mission profiles over the two phases.

What the other risks have in common is that they are all related to uncontrolled combustion of hydrogen as a consequence of the event occurring. Since the common theme between the risks is identified as hydrogen, a comprehensive research is performed on this element, its characteristics, the risks it induces, the mechanisms of these risks, and possible mitigation measures now that a great deal is known about hydrogen.

It is worth noting that since the design itself has undergone very few conceptual changes with regards to the risk, the risk table determined previously still generally holds true and is merely updated with newer better mitigation measures to make the design safer.

7.1. Hydrogen Risk Assessment

In section 7.1, the properties of hydrogen are explored in detail. Then in Table 7.1, the ignition sources of hydrogen have been identified with corresponding measures that may be taken to eliminate these risks during operations and sufficiently mitigate the previously identified risks when possible.

Hydrogen Properties

Table 7.1: This table shows the properties of Gaseous Hydrogen at Standard Temperature and Pressure (STP) Conditions[1][3].

Property	Value/Description	Comments/Definition
Molecular Weight	2.02 g/mol	14 times lighter than air, gets stuck in higher places due to buoyancy
Colour/Odour	None	Difficult detection
Flame Colour	Pale Blue/Near Invisible	Difficult detection
Lower Flammability Limit	4.00 %volumetric	Minimum hydrogen concentration needed in air to sustain a flame
Upper Flammability Limit	75.00 %volumetric	Maximum hydrogen concentration needed in air to sustain a flame
Lower Explosion Limit	18.30 %volumetric	Minimum hydrogen concentration needed in air to sustain an explosion
Upper Explosion Limit	59.00 %volumetric	Maximum hydrogen concentration needed in air to sustain an explosion
Auto-ignition Temperature	585.00 °C	Lowest temperature for hydrogen to ignite by itself
Flame Temperature	2045.00 °C	Approximate temperature of hydrogen flame with air as oxidizer
Heat of Combustion	144 MJ/kg	Total heat released when a kilogram of hydrogen undergoes combustion at STP conditions (0 °C, 1 atm)
Corrosivity	None	Does not pose problems for hydrogen containing systems
Ignition Energy	0.019 mJ	Minimum energy required to ignite hydrogen
Absolute Viscosity	0.01 centipose	Low viscosity means that hydrogen can escape from leaks easily

Potential Hazards

Hydrogen is a highly flammable gas. The minimum flammability volume limit of hydrogen is 4% of concentration in air. The minimum ignition energy is 0.019 mJ. This energy is extremely low equivalent to energy produced from using a roller to apply tape. This means that if the hydrogen concentration is above 4% in air and 0.019 mJ of energy is produce by anything within this region, a flame is produced. This flame is at 2045 °C in air, hence extremely high. Therefore, many safety procedures have to be designed to prevent any form of leakage as even the smallest amount of hydrogen in the air is still flammable.

Another hazard is that hydrogen is completely odourless and colourless. For humans, it is impossible to detect a leakage. Special hydrogen sensors are required to ensure that any potential leakages or invisible fires are detected. In addition to this, the hydrogen could be mixed with chemicals in order to give it odor, hence making any leaks detectable by smell.

[1] PubChem. *PubChem Hydgoren*. 2021. URL: `https://pubchem.ncbi.nlm.nih.gov/compound/783` (visited on 06/17/2023)

Hydrogen has a very low molecular weight and size which could lead to high leak rates or brittleness in the material of the container(in case the container is metal). This problem can be solved by choosing suitable materials and designing the ventilation and leak detection systems appropriately. Due to it being light, during a leak it is important to also analyse the spread of hydrogen above the source of the leak. Since hydrogen is very small in size, it can easily permeate fabrics. As the envelope that contains the hydrogen is a fabric, it is required that an air-tight coating surface shall be applied and preferably re-applied at regular intervals as determined by inspection since coatings can become ineffective over time.

In order for the hydrogen to combust, a sufficient amount of oxygen must be present. Within the envelope it is unlikely that large amounts of oxygen would be present since the envelope is isolated from external air. Venting gas is however an inevitability and an essential safety feature for emergency landing or altitude control of the airship. When venting, preventing the hydrogen from mixing with the air is inevitable and owing to the very low ignition energy needed to set off combustion merely reducing the likelihood of ignition is deemed insufficient as a measure to prevent catastrophic failure.

Ignition Sources and Measures

Hydrogen has the ability to ignite by reacting with oxygen in air given the following conditions are met[2].

- It is subjected to energy higher than its minimum ignition energy of 0.019 mJ.
- It is incident on a surface of temperature greater than the auto-ignition temperature of 585 °C [3].

Hot surfaces

The odds of a hot surface to causing ignition depends on the temperature of the surface or the surface area the hydrogen is in contact with which both cases proportionally impact the likelihood. The auto-ignition temperature of the hydrogen depends on pressure of the explosive gas and the material that is hot. The greater the pressure of hydrogen, the larger the auto-ignition temperature is. Certain material surfaces such as platinum can act as a catalyst and reduce the auto-ignition temperature to 70 °C which is dangerously low. There is also a risk of ignition at temperatures around 300 °C at pressures lower than atmospheric pressure for prolonged periods of time [25].

Measures:

- A physical separation between hydrogen lobes and sources of heat such as fuel cells and electric motors have been implemented.
- Cooling of the fuel cell is done via a thermal management system to prevent high temperatures.
- Tank pressure and temperature must be monitored during refilling.

Flames and hot gases

The products of flames include hot gases and other molecules that may ignite in an explosive environment. This makes flames and hot gases one of the most effective ignition sources and the primary source which affects the risks identified in the beginning of the chapter.

When an explosive environment results in ignition either inside or outside an installation, component, or its adjacent components, the flame can spread to other places through openings such as ventilation ducts. Preventing flame propagation requires special protective measures.

Since the airship will not use combustion, flames or hot gasses will not be present in standard conditions. During accidents however, the spread of flames should be minimised.

Measures:

- Check for sources of flames and hot gases coming from the airship by means of a well defined pre-flight operation and maintenance checklist.

[2] NEN. *NEN-EN 1127-1:2019 en*. Aug. 2019. URL: `https://www.nen.nl/en/nen-en-1127-1-2019-en-262504` (visited on 06/17/2023).

- Ban the use of cigarettes, matches and sources of flames/hot gases on-board and in proximity to the airship.
- Make sure that the air-flow over the fuel-cell is sufficient to prevent build-up of hydrogen if there is leakage.
- Prevent the forming of hot gases by battery ignition or explosion. Therefore the batteries should not be stored with a high state of charge. Make sure the batteries are not in direct sunlight or near other sources of heat. Monitor battery temperature. Make sure the batteries are not overcharged for longer amounts of time.

Mechanical ignition sources

Friction, impact and abrasion processes such as grinding could cause particles to separate from the surface of the material and could become hot enough to get over the auto-ignition temperature of hydrogen due to the energy from the process that caused it to separate. If these particles consist of oxidisable substances such as steel and iron, they undergo oxidation which further increases the temperature. Sparks can initiate ignition of hydrogen and other random molecules[3].

Foreign materials upon impact with surfaces such as stones can cause sparks as well. Rubbing between two components which are similarly ferrous or ceramics can generate sparks as well(similar to grinding[3]). A surface that does not generate sparks but is under constant friction can pass the auto-ignition temperature over time leading to a hot surface.

Metal fractures due to stresses can produce sparks and emit energy to heat hydrogen particles above their auto-ignition temperature. Mechanical vibrations/repeated flexing can transfer their energy involved in vibration to thermal energy by friction and lead to the same risks [3]. These risks are important for consideration due to extremely low ignition energy of hydrogen.

Measures:

- Make sure that there is a physical separation between the electric motor and the hydrogen system.
- Make sure that there is a physical separation between the propeller and the hydrogen system.
- Make sure that the pre-flight checklist includes an assessment regarding all metal components or belts that create friction have proper electrical insulation and/or have been lubricated properly.

Adiabatic compression and shock waves

Adiabatic, near-adiabatic compression and shock waves can create such high temperatures that it could ignite an explosive atmosphere (or deposited dust). The temperature increase depends on the ratio between the pressures before and after the compression[6]. Potential sources of adiabatic compression and shock waves are sudden venting of high-pressure gasses into the atmosphere, sudden pressure losses due to leakage or valve failure.

During sudden venting in case of an emergency, due to high pressure ratio between the internal system containing hydrogen and the external atmosphere, shockwaves that propagate faster than speed of sound may be produced. These shockwaves can exert immense forces on piping/valves/connection flanges to blow them up. On bends in the piping, the shockwaves may heat up the internals to dangerous temperatures which could ignite the hydrogen that is being vented[6].

If another ignitable substance is introduced to the high pressure system, an ignition can occur due to sudden change of surrounding pressure of that substance. An example is if lubricating oil mist is injected into high pressure hydrogen system[6].

Presence of oxidising gases (air with high oxygen concentration or pure oxygen) and explosive gases (hydrogen) can ignite in case of sudden pressure losses[6].

Measures:

[3] NEN. *NEN-EN 1127-1:2019 en*. Aug. 2019. URL: `https://www.nen.nl/en/nen-en-1127-1-2019-en-262504` (visited on 06/17/2023).

- Ensure that venting is done in a safe, controlled manner to prevent adiabatic compression of the vented gas.
- Make sure there are no activities in the area that cause shock waves.

7.2. Risk Analysis

Now that the previously unmitigated risks and their common factors have been sufficiently re-evaluated, the risk analysis can be performed once again. The analysis is done with largely similar risks as in the conceptual phase excluding some omissions due to the different mission design. The risk is determined by multiplying the likelihood by the impact. Following the risk analysis, mitigation methods are presented for every risk in order to lower either likelihood, impact or both. An overview of the risk analysis is shown in Table 7.2.

Table 7.2: The risk assessment shown in the table was divided in different categories, where the consequences, impact and probability of each is determined.

ID	Category	Risk Events	Consequences	Impact	Prob
R-PSU.01	Power Supply	Gas Leak	Possible risk of ignition and fuel leak results in dangerous conditions and loss of operating range	5	2
R-PSU.02	Power Supply	Ignition of stored Hydrogen	Ignition of hydrogen leads to large fires and very high temperatures resulting in catastrophic failure	5	2
R-PSU.03	Power Supply	Excessive Heating of Fuel tank	Results in weakening of the fuel tank and potential ignition of fuel	5	1
R-PSU.04	Power Supply	Short circuit	Results in failure of all electrical systems on board and loss of control, potential for electric fires.	5	2
R-PSU.05	Power Supply	Electrolyte leakage	Leakage of highly reactive substances and malfunctioning of the fuel cell	4	2
R-PPU.01	Propulsion Unit	Short circuit	Results in loss of control and potential electric fires	5	2
R-PPU.02	Propulsion Unit	Pitch Control Failure	Results in reduced propeller efficiency due to failure of control system	3	3
R-PPU.03	Propulsion Unit	Propeller Detachment	Detached propeller may fly off and damage the airship, also results in loss of power from one engine	5	1
R-PPU.04	Propulsion Unit	Propeller breakage	Broken propeller causes major vibrations and structural fatigue as well as loss of power, broken off piece of propeller could cause damage to airship.	5	1
R-PPU.05	Propulsion Unit	Single Inoperative Engine	Loss of power due to losing one of the operating engines	2	4
R-PPU.06	Propulsion Unit	Multiple Inoperative Engines	Potential loss of control due to multiple inoperative engines, guaranteed loss of power	2	2
R-PPU.07	Propulsion Unit	Overheating of wires	Results in loss of an engine and potential fire hazard	4	1
R-STR.01	Structures	Metal bending fatigue	Could cause failure of integral substructures affecting structural integrity of the airship	4	2

ID	Category	Risk Events	Consequences	Impact	Prob
R-STR.02	Structures	Failure of Linkages	Could cause failure of integral substructures affecting structural integrity of the airship	4	2
R-STR.03	Structures	Failure of Truss	Could cause failure of integral substructures affecting structural integrity of the airship	4	2
R-STR.04	Structures	Excessive Deformation	Could cause failure of integral substructures affecting structural integrity of the airship	4	2
R-STR.05	Structures	Failure of beam	Could cause failure of integral substructures affecting structural integrity of the airship	4	2
R-MAT.01	Materials	UV-radiation degradation	Weakens the envelope resulting in potential loss of lift and leakage of flammable lift gas due to increased risk of ruptures	4	1
R-MAT.02	Materials	Mechanical fatigue	Can be caused by design flaws, poor quality of raw materials. Can result in catastrophic failure in the long run	4	1
R-MAT.03	Materials	Excessive thermal exposure	Weakens the envelope resulting in potential loss of lift and leakage of flammable lift gas due to increased risk of ruptures. Also results in expansion of gases and metals leading to further complications.	4	1
R-MAT.04	Materials	Corrosion induced fatigue	Corrosion of structures or envelope could increase the risk of ruptures and weaken structural elements	2	3
R-MAT.05	Materials	Corrosion induced failure	Corrosion of structures or envelope could increase the risk of ruptures and weaken structural elements	4	1
R-MAT.06	Materials	Collision with foreign objects	Could cause ruptures or deform underlying structures resulting in loss of flammable lift gas	4	1
R-MAT.07	Materials	Impermeability failure	Loss of lift gas over time resulting in decreased lift production and therefore being unable to meet the mission requirements	2	2
R-MAT.08	Materials	Water resistance failure	Could cause rusting and create unsafe conditions for electronic equipment, may also increase mass of the airship resulting in reduced payload carrying capacity.	2	2
R-MAT.09	Materials	Difference in potential static electricity potential between the airship and the environment	Only dangerous if there is a rupture or gas leak	1	5
R-MAT.10	Materials	Rupture	Leads to loss of lift gas resulting in potential fires and guaranteed loss of lift	3	2

ID	Category	Risk Events	Consequences	Impact	Prob
R-MAT.11	Materials	Creep fatigue	In the long run this can cause permanent deformation due to cyclic and/or thermal stress	2	3
R-MAT.12	Materials	Creep failure	Potential catastrophic failure due to long term creep fatigue	4	2
R-MAT.13	Materials	Thermo-mechanical fatigue	A combination of thermal and mechanical fatigue resulting in failure of substructures and components causing complications that affect performance.	3	2
R-MAT.14	Materials	Wear failure	Damage due to movements between surfaces.	2	4
R-CTS.01	Control & Stability	Failure of TVC	Loss of thrust vector control resulting in reduced ability to control the airship and potentially unfavourable thrust direction.	3	2
R-CTS.02	Control & Stability	Failure of Aerodynamic Control Surfaces	Reduced ability to control the airship	3	1
R-CTS.03	Control & Stability	Failure of Flight computer	Loss of stability and potential loss of control	4	1
R-CTS.04	Control & Stability	Loss of Remote communication	Loss of remote controllability of airship.	5	1
R-CTS.05	Control & Stability	Loss of control due to heavy weather conditions	Loss of control over airship resulting in dangerous conditions for the payload and inability to complete the mission	4	2
R-OPL.01	Operations & Logistics	Ground handling damage	Damage to airship potentially affecting performance and raising maintenance costs	1	2
R-OPL.02	Operations & Logistics	Hangar damage	Potential damage to airship, affecting performance and raising maintenance costs	1	1
R-OPL.03	Operations & Logistics	(Un)loading damage	Damage to airship potentially affecting performance and raising maintenance costs	1	2
R-OPL.04	Operations & Logistics	Lightning Strike	Potential ignition of lift gas and failure of electronics resulting in catastrophic failure	5	1
R-OPL.05	Operations & Logistics	Hailstones	Adversely affecting the structural and propulsion units resulting in reduced efficiency and potential structural deformations.	1	4
R-OPL.06	Operations & Logistics	Exceeded airtime due to mechanical complications or avoiding weather	Possibility of not completing mission due to mission range exceeding operational range	3	1
R-OPL.08	Operations & Logistics	Ignition during refuelling	Ignition of hydrogen causing gravely unsafe conditions resulting in catastrophic failure.	5	2
R-OPL.09	Operations & Logistics	Global decrease in hydrogen use	Failure of product due to infeasible business model	3	1

ID	Category	Risk Events	Consequences	Impact	Prob
R-OPL.10	Operations & Logistics	Global hydrogen shortage	Results in failure of product due to excessive costs involved for fuel	4	1
R-OPL.11	Operations & Logistics	Excessive amount of hydrogen accidents	Public discontent resulting in rejection of hydrogen as a fuel source resulting in an unfeasible business case	3	1
R-OPL.12	Operations & Logistics	Physical Obstruction on Flight path	Causes changes in mission characteristics potentially leading to a longer mission range than operating range.	3	2
R-OPL.13	Operations & Logistics	Poor maintenance	Causes a plethora of issues ranging from envelope failure to power system failure.	4	1
R-OPL.14	Operations & Logistics	Emergency landing	Failure to complete mission and deliver payload.	3	3

7.3. Risk Map

The aforementioned risks are plotted in a risk map in order to display visually the risks that require urgent mitigation and those that pose a limited threat to the airship. The risk map indicates different colours for the tolerances of the risks, orange risks are the most that may be tolerated at this point in the design process. Anything beyond an orange risk warrants mitigation measures or, if mitigation has failed, a new design The Risk map has the probability of the event occurring on the x-axis and the Impact of the event on the y-axis, as shown in Figure 7.1

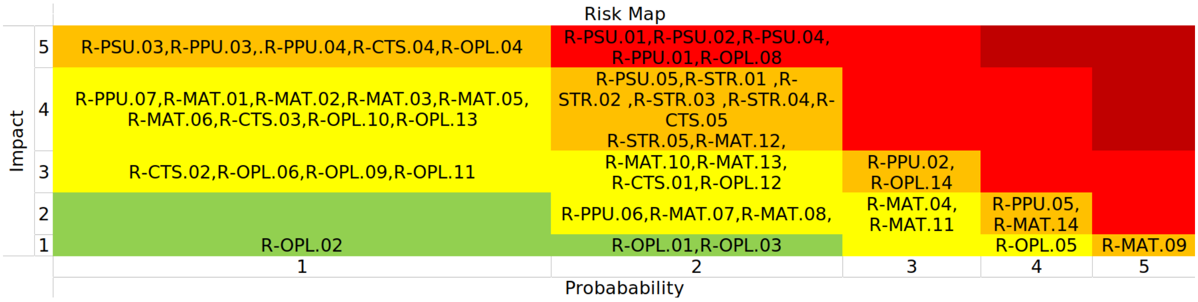


Figure 7.1: This figure shows the risk map prior to deployment of mitigation measures

7.4. Risk Mitigation

The mitigation measures are intended to reduce either the impact of the risk or the likelihood of the risk event occurring. Mitigation strategies are presented for each of the risks and their effect on the impact and likelihood score is given.

- R-PSU.01- Use of flame retardant systems onboard and applying flame retardant coating on the airship. Preventing hydrogen concentrations from exceeding 4%(by ensuring fanning off the air over the envelope when a leak is detected) and activation of emergency protocol the moment that sensors detect a gas leak.
- R-PSU.02- Use of flame retardant measures and isolation of fuel from other systems. Ensuring that hydrogen concentrations are high enough within the envelope to prevent ignition.
- R-PSU.03- Using cooling systems with redundancy and employing flame retardant measures.Jettisoning mechanism to detach fuel tank from the airship and isolating the fuel tank thermally from the gondola and envelope.
- R-PSU.04- Short circuit protection systems within the circuit and ensuring sufficient insulation of all conductive contacts.

- R-PSU.05- Routine maintenance and checks of fuel cell and application of non-reactive material in fuel cell storage area.
- R-PPU.01- Short circuit protection within the circuit and sufficiently shielding all wires and contacts.
- R-PPU.02- Routine maintenance and inspection of subsystem, mitigation of impact not worth implementing due to minimal impact.
- R-PPU.03- Use of intermediate structures to prevent damage to airship and routine maintenance and inspection of propeller. Use of flame retardant measures and activation of emergency landing protocols the moment the airship is struck. Placing the engines and the gondola as far away as possible to prevent combustion near human beings.
- R-PPU.04- Use of intermediate structures to prevent damage to airship and routine maintenance and inspection of propeller.
- R-PPU.05- Routine maintenance of the subsystem and having sufficient controllability to compensate for any resultant torques produced by in-operation of one engine.
- R-PPU.06- Routine maintenance of subsystem, mitigation of impact not possible.
- R-PPU.07- Implementing strong cooling systems and using sufficiently thick wires to prevent overheating.
- R-STR.01- Routine inspections and maintenance to check for cracks and other structural deformities. Using redundant structures to mitigate impact.
- R-STR.02- Routine inspections and maintenance to check for cracks and other structural deformities. Using redundant structures to mitigate impact.
- R-STR.03- Routine inspections and maintenance to check for cracks and other structural deformities. Using redundant structures to mitigate impact.
- R-STR.04- Routine inspections and maintenance to check for cracks and other structural deformities. Using redundant structures to mitigate impact.
- R-STR.05- Routine inspections and maintenance to check for cracks and other structural deformities. Using redundant structures to mitigate impact.
- R-MAT.01- Routine inspection of envelope, storing airship away from sunlight and use of sufficient safety factors to prevent failure of envelope.
- R-MAT.02- Routine inspections and maintenance to check for cracks and other structural deformities. Using redundant structures to mitigate impact.
- R-MAT.03- Routine inspection of envelope, storing airship away from sunlight in good weather conditions. Use of sufficient safety factors to prevent failure of envelope.
- R-MAT.04- Routine maintenance and inspection. Use of redundant structures and corrosion resistant material.
- R-MAT.05- Routine maintenance and inspection. Use of redundant structures and corrosion resistant material.
- R-MAT.06- Implementing sufficient safety factors to prevent any major problems arising from impact. Mitigation of likelihood not possible.
- R-MAT.07- Routine maintenance and inspection of the envelope and detection systems for gas leaks.
- R-MAT.08- Routine maintenance and inspection of the airship and using water detection systems at sensitive points.
- R-MAT.09- Use of a faraday cage ensures that the potential remains within the faraday cage and prevents ESD from occuring. Using flame retardant measures lowers impact.
- R-MAT.10- Use of flame retardant measures and activation of emergency landing protocols the moment a gas leak is detected. Mitigation of likelihood not possible.
- R-MAT.11- Routine maintenance and inspection of airship. Mitigation of impact not possible.
- R-MAT.12- Routine maintenance and inspection of airship. Mitigation of impact not possible.
- R-MAT.13- Routine maintenance and inspection of airship. Ensuring the airhsip is sufficiently shielded from adverse weather and extreme temperatures.
- R-MAT.14- High quality material. Regular maintenance checks.

- R-CTS.01- Implementing redundancy through alternate control options. Routine inspection and pre-flight procedures involving checking TVC system.
- R-CTS.02- Implementing redundancy through alternate control options. Routine inspection and pre-flight procedures involving checking control surfaces.
- R-CTS.03- Making the airship sufficiently stable to ensure that it can maintain a stable hover regardless of presence of flight computer. Having redundant flight control systems onboard.
- R-CTS.04- Mitigation of likelihood not possible. Implementing a return to home function to ensure the airship is not left stranded.
- R-CTS.05- Avoiding adverse weather. Mitigation of impact not possible.
- R-OPL.01- Clear ground handling procedure and regular maintenance checks.
- R-OPL.02- Clear parking procedure and regular maintenance checks.
- R-OPL.03- Have a clear loading procedure and regular maintenance checks.
- R-OPL.04- Clear overview of (future) weather conditions. Devices that indicate the electrical static potential and lightning conductor system to let the electrical energy flow into the earth when landed.
- R-OPL.05- Clear overview of (future) weather conditions. Have regular maintenance checks.
- R-OPL.06- Clear overview of (future) weather conditions. Have some extra fuel in case the maximum range is exceeded or only perform missions a little shorter than the maximum range to have some safety margin.
- R-OPL.08- Have a clear safety procedure. Use of flame retardant systems and have emergency services always ready to operate.
- R-OPL.09- Be able to transport also other products besides hydrogen. Mitigation of likelihood not possible.
- R-OPL.10- Be able to transport also other products besides hydrogen. Mitigation of likelihood not possible.
- R-OPL.11- Be able to transport also other products besides hydrogen. Mitigation of likelihood not possible.
- R-OPL.12- Determine a detailed and optimised flight plan ready each flight and have clear communication with ground stations. Have some extra fuel in case the maximum range is exceeded or only perform missions a little shorter than the maximum range to have some safety margin.
- R-OPL.13- Frequent maintenance, have the maintenance double checked and written down in a logbook. Mitigation of impact not possible.
- R-OPL.14- Clear communication with ground stations. Have emergency services ready to operate.

The risk prior to and after mitigation is given in Table 7.3.

Table 7.3: The table shows the mitigated risks.

Risk ID	Initial Risk	Mitigated Impact	Mitigated Probability	Mitigated Risk
R.PSU.01	10	4	1	4
R.PSU.02	10	4	1	4
R.PSU.03	5	4	1	4
R.PSU.04	10	4	1	4
R.PSU.05	8	3	1	3
R.PPU.01	10	3	1	3
R.PPU.02	9	3	1	3
R.PPU.03	5	4	1	4
R.PPU.04	5	3	1	3
R.PPU.05	8	2	3	6
R.PPU.06	4	1	2	2
R.PPU.07	4	3	1	3

Risk ID	Initial Risk	Mitigated Impact	Mitigated Probability	Mitigated Risk
R.STR.01	8	3	1	3
R.STR.02	8	3	1	3
R.STR.03	8	3	1	3
R.STR.04	8	3	1	3
R.STR.05	8	3	1	3
R.MAT.01	4	3	1	3
R.MAT.02	4	3	1	3
R.MAT.03	4	3	1	3
R.MAT.04	6	2	2	4
R.MAT.05	4	3	1	3
R.MAT.06	4	3	1	3
R.MAT.07	4	1	1	1
R.MAT.08	4	1	1	1
R.MAT.09	5	1	1	1
R.MAT.10	6	2	1	1
R.MAT.11	6	3	1	3
R.MAT.12	8	4	1	4
R.MAT.13	6	3	1	3
R.MAT.14	8	1	3	3
R.CTS.01	6	2	1	2
R.CTS.02	3	2	1	2
R.CTS.03	4	3	1	3
R.CTS.04	5	3	1	3
R.CTS.05	8	4	1	4
R-OPL.01	2	1	1	1
R-OPL.02	1	1	1	1
R-OPL.03	2	1	1	1
R-OPL.04	5	4	1	4
R-OPL.05	4	1	2	2
R-OPL.06	3	2	1	2
R-OPL.08	10	4	1	4
R-OPL.09	5	1	1	1
R-OPL.10	5	1	1	1
R-OPL.11	5	2	1	2
R-OPL.12	6	1	1	1
R-OPL.13	4	1	1	1
R-OPL.14	9	2	1	2

7.5. Post-Mitigation Risk Map

After implementation of the aforementioned mitigation measures, a new risk map can be obtained. This risk map shows the new risks posed by the individual events. This is also shown in Figure 7.2.

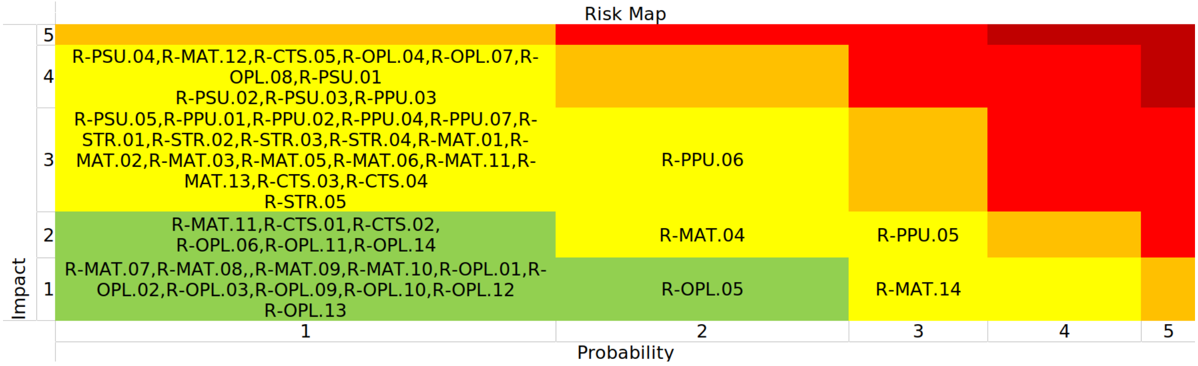


Figure 7.2: This figure shows the risk map following deployment of all mitigation measures

From the risk map it is apparent that all risks have been sufficiently mitigated, therefore no redesign is required. There are no risks of concern remaining since those have been mitigated as well and hence the design is now considered safe.

8 Sensitivity analysis

The actual design calculations of the airship were performed using a collection of Python scripts which were implemented in a manually written optimiser. The interconnection between the different parameters and subsystems made the script susceptible to errors causing the algorithm to be divergent at times. To avoid such situations, the team identified the most significant values which impact the final model. A sensitivity analysis was carried out by varying these crucial parameters and investigating the impact they had on the final result. Other values had little influence on the end result and hence were disregarded in the sensitivity analysis. This chapter will map these variables and explain their influence on the results.

8.1. Drag

The method used to calculate the drag in section 6.4 is presumed to be a reliable conservative estimate. These calculations resulted in a C_d value of 0.3. However, in the unlikely chance that this coefficient is non-conservative, it is necessary to see the design implications this would have.

Increasing the C_d by one order of magnitude results in an airship with the parameters described in Table 8.1. From the propellant mass alone, it can be concluded that if the drag coefficient was non-conservative, the airship becomes unfeasible. An airship with these parameters is not efficient, consuming 4900 kg of hydrogen to deliver 800 kg.

Table 8.1: Table shows a general overview of the airship parameters for an increased C_d.

Name	Value
Cruise altitude	1000 m
MTOW	$109\,884.0$ kg
Length	157.1 m
Width	66.0 m
Height	33.4 m
Envelope volume	$108\,349$ m^3
Cover mass	$37\,872$ kg
Number of fuel cells	19
Number of engines	27
propellant mass	4900 kg

8.2. Velocity

The airship is designed for a cruise speed of 100 km/h, if however the cruise speed is to be increased, the infamous snowball effect will have its effect on the design. The expected behaviour is similar to the sensitivity analysis explained in section 8.1 since the drag increases as a square of the velocity. The mass of the airship will grow exponentially with an increasing velocity.

This result goes both ways, if the cruise speed is lowered, the efficiency of the airship is expected to improve. The minimum number of engines attached to the airship was fixed at 5 because of control related reasons.

8.3. Envelope

The airship's total mass consists largely of the cover material and structure. The multi-layered material is reasonably thin (around 1.48 mm), but covers the entire surface of the airship's envelope. Although the lobes are attached to each other, they have no overlap in between them. In other words, the 3 lobes acts as three individual lobes. This inefficient way of attaching lobes will in reality be solved by sewing the lobes to each other, thus covering more volume with less cover material. The cover mass is hence overestimated and the current design allows for changes in the cover material properties.

The most sensitive aspect of the envelope is largely determined by the way the thickness was calculated in Equation 6.5. The formula is primarily influenced by σ_{yield}. If it turns out the yield strength of the material was overestimated, the mass of the airship also increases. This will additionally increase the radius of the lobes, which further results in an increased thickness. These calculations remain convergent for a wide range of values. They do result in a change in the length of the airship.

Other mass contributions to the airship are however ignored since they do not have an impact severe enough to warrant a sensitivity analysis.

8.4. Altitude

As described in chapter 9, the airship will fly at an altitude of 1000 m. For an airship to fly higher it needs to have a larger envelope in order to contain the expansion of the lift gas. The increase in volume results in an increase in frontal surface area which in-turn increases the drag but also greater cover mass. At the same time, atmospheric drag decreases resulting in a reduction in overall drag.

The influence of the altitude on the drag of the airship is mapped in Figure 8.1 until FL100 (the altitude at which extra oxygen or pressurisation is required). The zigzagging of the graph is attributed to small rounding errors, however the general trend is amply clear. The drag consistently decreases with increasing altitude, however, given the relatively small approximately 100 N difference in drag over the altitude range it is reasonable to neglect this effect.

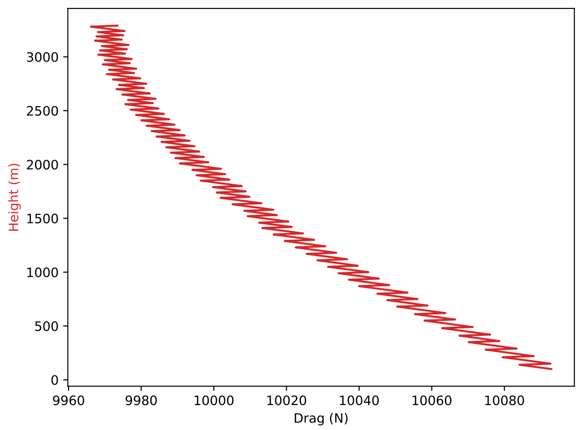


Figure 8.1: Plot shows the drag estimate from ground level to 3000 m.

9 Operations

The operations of the end-product are detailed in the following section. This is done in order to provide an overview of the more practical aspects of the functioning of the airship, the expected mission profiles and other practical considerations that arise upon exploration of these concepts in detail. The following sections detail the operations aspect of the airship.

9.1. Loading and Starting Procedures

As can can be seen in Appendix A, some mission steps are more detailed than others. The mission starts by loading the fuel, which is an amount to travel 4000 km, or there and back again. This tank is placed inside the envelope hull and has a tube on the outer part to make sure the fuel can be loaded more easily. The fuel tank has a hull that loads the hydrogen.

The payload is then loaded on board. As stated in chapter 2, before transporting hydrogen, other fuels and chemicals such as SAF can be transported. The payload itself is placed under the envelope and placed behind the gondola. It is a container assembly that can be connected and disconnected to several structural connection elements. In this container, hydrogen or chemical tanks can be placed, next to a possibility of carrying SAF. The total weight of the assembly container, plus payload is calculated to be $12\,100$ kg. However since the tanks to pressurise the hydrogen has a mass of around $10\,000$ kg, and the container of around 1300 kg, 800 kg of hydrogen can be used. This is actually quite substantial as explained in section 9.6. If transporting SAF, no heavy pressure tank is needed, and the amount is either only limited by the gondola size (which can be altered according to payload, as they can be bought of the shelf), or the mass it can carry (which is the around 10000 +/- 1000 kg

The starting procedure is similar to aircraft, except for checks necessary for subsystems such as ballonets, and buoyancy control.

9.2. Take-Off, Cruise, and Landing

The more detailed each aspect and step of the mission, the more detailed designing and analysis can be performed. To clarify and design the mission steps, one of the best ways is to visualise them. A dense and schematic drawing has been made of each aspect of the mission operations, which can be seen in 9.1.

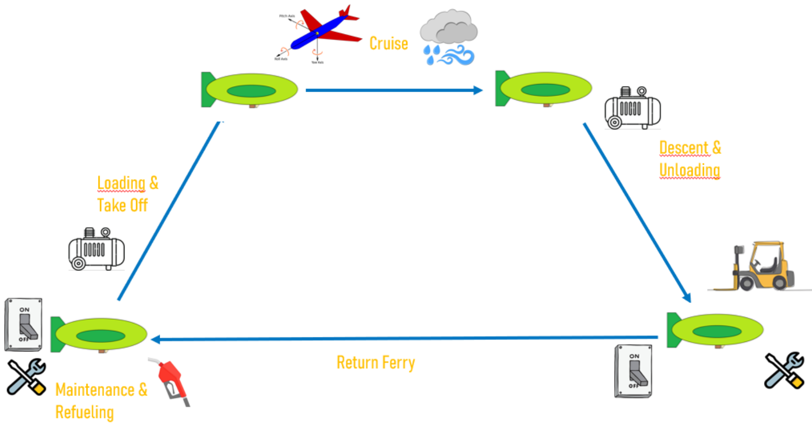


Figure 9.1: A schematic drawing that shows which operations are necessary during each phase of the design.

Next to that, several usages have been made of the functional flow diagram placed in Appendix A. After the starting procedure the actual transport is done, as can be seen in the functional flow diagram A. The transport part of the mission is shown in Figure 9.1.

The take-off is done first. Depending on the space at the place of take-off, Vertical Take-Off and Landing (VTOL) or an aircraft type of take-off is performed. Take-off will be mostly performed by compressors which let hydrogen into the envelope, enlarging it whilst reducing the size of the ballonets. This creates more buoyancy thereby lifting the airship up through the air , as can be seen in Equation 6.1.

The flight route of the airship will be determined in such way that congested ground areas are avoided as much as possible. This limits the mobility of the airship, but increases the safety of the airship. The airship has a cruise altitude of 1000 m. Airships in general prefer flying in the lower areas of the atmosphere considering that that wind velocities are lower, next to the fact that buoyancy performance is increased at lower altitudes. The proximity to the ground allows as well to keep the volume of the airship within reasonable dimensions, as at higher altitudes the gas expands more [17]. From an operational point of view, an airship flying at this altitude could still deliver hydrogen and other goods in vast areas, although it is quite limited to operate in elevated regions. Following cruise, loiter can take place if the landing ground is quite busy. This is where an airship can really outperform an aircraft. An aircraft relies on aerodynamics hence movement to fly, whilst an airship relies on aerostatics, thereby it can just hover. Following cruise, or loiter if necessary, descent can take place. This is done again by the compressor Figure 9.1. During climb and descent, the controllability is quite important, as the airship must be able to perform a go around manoeuvre at any time chapter 4. This could require one of the following actions:

1. The use of pitch manoeuvring the engines
2. The deflection of control surfaces
3. The altering of throttle of each individual engine to yaw the airship
4. Venting some of the lifting gas to drop altitude

Landing needs to be performed for periodic maintenance and inspections since it is the most practical way to do so. The other option that was considered is floating. However a small gust would move the airship, next to the aspect that unloading payload, possible maintenance would become quite complicated if not impossible. During landing the stability in both longitudinal and directional rotations will be assured by the thrusters, as they can both alter in magnitude and direction. As the airship has no speed yet, the control surfaces are out of play, which then requires the other three options mentioned above.

9.3. Unloading and Return

After the transport, the payload is unloaded from the airship container. During the (un)loading process of the airship, the buoyancy of the airship is variable. It is therefore decided that the airship is anchored on the ground and possibly to a mooring mast. This mooring mast mast allows for easy transport of the airship on the ground as well.

First the container is opened through a hydraulic system, whereafter a fork lift truck unloads each hydrogen or chemical tank individually. Then the empty tanks are put back in the container whereafter it is closed again and disconnected from the airship. Finally another container on site at the destination is connected to the airship, making for a maximum of two containers on site at the destination, where on average only one is present. The schematics of these operations are shown in Figure 9.1

After the unloading the shutdown procedure takes place. It starts with taxiing if necessary, however when vertical take off and landing can be performed, this might not be required. Then each subsystem is shut down where the engine is the last to be shut off. The storing in the hangar is only done if maintenance is required and if the facilities are present. The inspection and maintenance of each system is explained in section 9.8.

Finally, the return ferry flight is performed. For that take off is initiated again by releasing gas out of the compressor into the envelope enlarging it and thereby reducing the size of the ballonets. However now that the payload is unloaded, the airship is lighter, requiring for less decompressing when climbing but more compressing during descent at the starting location, which in the most cases is the harbour where it got the hydrogen from in the first place.

On another short note, the initial idea was to fly the airship autonomous to decrease the risk for human casualties, as hydrogen is highly inflammable when mixed with oxygen. However, we understand that socially the world is not ready yet for full autonomous flights and it would be very likely that due to regulations the airship would not be permitted to fly, even tough regarding the technical aspects it is possible. For that reason we added a gondola on the airship with a cockpit, where two to three pilots can control the air vehicle depending on the duration of the flight. When the world is ready to fly autonomous the gondola can be removed and replaced with an autonomous flight system.

9.4. Hydrogen Handling

As discussed in section 7.1, hydrogen is a hazardous substance that needs special procedures during operations. Therefore some measurements need to be taken to assure safety during the airship operation.

During ground operations airship, the method of nitrogen purging will be used before filling the airship with hydrogen. Nitrogen purging is a method where the lobes are saturated with nitrogen. This ensures no residual oxygen is left in the lobes before they are filled with hydrogen, thereby avoiding a potential reaction between the hydrogen and the oxygen. Static discharges are connected to the airship as well to avoid any sparks that could cause the hydrogen to ignite. Examples of that would be hydrogen molecules hitting a part of the structure, thereby creating enough kinetic energy to ignite the hydrogen.

While airborne, the airship will be equipped with a hydrogen release valve systems for both the payload hydrogen and envelope hydrogen. This is avoid further trouble in case of emergency. The separate hydrogen tanks will have a function as well to be realised from the airship and to realise the pressurised hydrogen.

When the hydrogen does ignite, the airship will be flying high enough to make sure that the initial explosion will not cause any direct casualties. This the first and foremost reason as to why it is preferred that the airship is controlled at a distance. Since hydrogen is lighter than air, the burning hydrogen will travel up in the atmosphere causing no real damage to the people on the ground. The structure of the airship including all its subsystems will crash. However it will crash in remote areas, as its transport route will not include densely populated areas such as cities. If on the other hand hydrogen would be transported by its competitor, a truck, it will explode on the road, near humans. This would be very dangerous, as both the explosion and burning of the hydrogen would possibly be near people. Looking at the big picture and taking these considerations into account, the airship is concluded to be relatively much safer.

9.5. Weather Conditions

Weather has always been considered as a design challenge, the airship is susceptible to changing weather. The airship will only be allowed to fly in VFR conditions for the time being. This limits however the operational availability of the airship. However the same principle applies for the airship as the hydrogen, safety must come first.

Mitigation of lightning induced failures is necessary in order to qualify for certification as an aircraft. Similar requirements apply for airships, the impact of lightning must be minimised such that it does not affect the functionality of the airship. Various measures may be deployed in order to overcome this issue ranging from lightning rods to a faraday cage. The fundamentals however remain the same, providing a path for dissipation of the charge of the lightning without affecting any intermediate systems or igniting the lift gas in the envelope. Braids of thin wire are laid across the external surface of the envelope providing a safe path around the envelope without affecting any of the essential subsystems the airship has. This is projected to add an extra 1000 kgs-1500 kgs to the airship which the airship can easily cope with at this point in time. This system requires physical validation in order to ensure the functioning of the system in real conditions however it can be safely concluded that the proposed system will significantly improve the reliability of the airship. This system also protects against random Electro-static Discharge (ESD) that may occur, effectively reducing potential sources of ignition.

9.6. Operational Design Performance

As stated in the mission need statement and explained in the market analysis the airships have to compete with trucks. The airship will not be able to compete with container ships, as those container ships could be able to carry a ridiculous amount of hydrogen. Even though, these ships are highly unsustainable through creating noise underwater and releasing a lot of carbon based green house gasses. However, unless no laws, regulations, and subsidies are implemented, the airship will not be able to compete with container ships.

The airship will act as an efficient large shuttle bus carrying payload from A to B. It will be operating between harbours, airports, and factories. With that it will be competing directly with trucks, as these trucks could take the hydrogen from hydrogen factories or major harbours to airports and other factories. The airship will be able to compete if and only if it is more efficient, as trucks are way cheaper. For this reason the following parameters were calculated:

$$Ratio_{pay} = \frac{W_{pay}}{W_{oe}} \tag{9.1}$$

$$Ratio_{dist} = \frac{W_{pay}}{R} \tag{9.2}$$

$$Ratio_{time} = \frac{W_{pay} \cdot v_{air}}{R} \tag{9.3}$$

$$Ratio_{fuel} = \frac{W_{pay}}{W_{fuel}} \tag{9.4}$$

$$SFC = \frac{\rho_{energy} \cdot \rho_{fuel} \cdot F_{cons}}{W_{pay}} \tag{9.5}$$

$$W_{H2asDiesel} = \frac{\rho_{energy}}{\rho_{energy_diesel}} \cdot W_{pay} \tag{9.6}$$

$$Ratio_{Emissions} = \frac{\rho_{emission} \cdot W_{fuel}}{W_{pay}} \tag{9.7}$$

The range, R, of course, differs for a truck and an airship, as a truck is dependent on road infrastructure which might not allow a short route, and an airship in the ideal case could travel as the crow flies. However safety regulations, will require to fly over rural areas. This ensures that if it explodes, the explosion does not cause damage to infrastructure or people on the ground. Due to these differences it is important to find the relation between the distance point to point and the travel distance of an airship and the travel distance of a truck. To calculate this relation the distance of some major harbours to the largest industrial zones within a range of 2000 km are found from point to point, by road and by air only going over rural areas. The following continents and countries are used: China, India, the USA, and Europe. The following graph, Figure 9.2, shows the relation between point to point distance and the truck and airship distance.

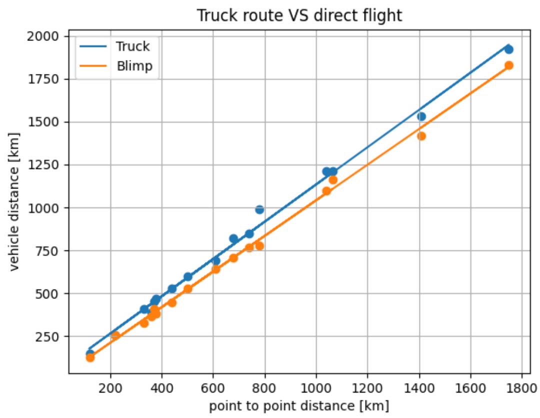


Figure 9.2: The relation between the point to point distance and the route a vehicle has to travel from big ports to industrial zones.

From Figure 9.2 there clearly is a linearly relation between the point to point distance and the distance trucks or the airship needs to travail. Also, it is visible that the airship has to travel less distance compared to the truck.
There are several reasons to use and calculate these specific values to see how well the airship compares with trucks. The first value, Equation 9.1, is used as it is a classic abundantly used value to compare payload carrying efficiency over the operational empty weight.
The second and third ratios, Equation 9.2 and Equation 9.3 respectively are used to compare the payload carried per kilometre and hour, to show payload distance efficiency, and payload speed efficiency.
The fourth ratio, Equation 9.4, the payload to fuel needed ratio is a very important one, as it shows how much kilograms of fuel is needed to transport a certain amount of kilograms of payload. It basically shows the efficiency of the ferry compared to payload carried. Furthermore it shows its performance as fuel usage is related to either friction, as trucks, or air resistance, as airships, drag. This is where the airship can really shine, as trucks still run mostly on diesel whereas the airship runs on hydrogen which is lighter relative to its energy storage. The specific fuel consumption, Equation 9.5, which has the unit of $J/kg/km$, is used to calculate the efficiency of energy usage.
For the payload carried, the actual energy should be calculated that is transported, as hydrogen is very light but carries a lot of energy. The specific energy density is then used to calculate the amount of diesel an airship would transport if the amount of energy from the 800 kg of hydrogen is still the same as can be seen in Equation 9.6.
Finally the amount of carbon based green house gasses of the transport should be calculated as well for sustainability performance considerations. The last equation 9.7 shows the total amount of emissions of the transport relative to the payload carried, thereby revealing the ”emissions of the payload”.
The following table, Table 9.1, shows the actual numbers calculated with Equations 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, 9.7.

Table 9.1: Table shows the performance parameters of a hydrogen truck and our airship.

Parameter	Truck	Airship
$Ratio_{pay}[-]$	0.0149	0.0145
$Ratio_{dist}[kg/km]$	0.329	0.3849
$Ratio_{time}[kg/h]$	26	38
$Ratio_{fuel}[-]$	0.9678	2.7586
SFC $[J/km/kg]$	20493	21750
$W_{H2asDiesel}[kg]$	730	2182
$Ratio_{Emissions}[-]$	3.258	0.0

From Table 9.1 it can be seen that the airship outperforms the truck on almost every aspect or it is a very close tie. For example the payload per kilometre and payload over empty weight are quite close, but the airship performs significantly better than the truck regarding the payload over fuel and emissions over payload. The latter is rather obvious as the truck uses diesel and the airship hydrogen. The results show that the airship seems to be more efficient than its main competitor: trucks.

Looking at the $W_{H2asDiesel}$ of the airship in Table 9.1, it can be seen that the amount of energy of the hydrogen, given its equivalent energy in kerosene, would be able to fuel 5.32 Boeing 737-800 flights, as a 737-800 on average carries 500 L of kerosene. This shows the substantial amount of payload the airship carries[1].

9.7. Noise

There are different types of noise produced by the airship, including the noise of the engine and landing gear noise [28]. There are two main aspects to noise that need to be considered for the airship : the noise it will produce to the environment and the noise the pilots will hear.
The amount of noise produced by the engine can be calculated by using Equation 9.8 [28]:

$$SPL_{max} = 83.4 + 15.3 \cdot log(P_{br}) - 20log(d) + 38.5 \cdot M_t - 3(B-2) + 10 \cdot log(N_p) \tag{9.8}$$

where P_{br} is the engine power and N_p the number of propellers given in Table 6.7, d the propeller diameter in m, being 2 m as explained in section 6.5, and B the number of blades of 4 [8].
M_t is the dimensionless rotational tip Mach number (for static conditions) for which Equation 9.9 is used [28].

$$M_t = \frac{\pi \cdot d}{c} \frac{\eta_p}{60} \tag{9.9}$$

Here η_p is the propeller rotational speed in RPM, shown in Table 6.7 and c, the speed of sound of 343 m/s.
Calculating the noise power at a certain distance from the noise source requires the use of Equation 9.10:

$$SPL = SPL_{max} - 20log(r) \tag{9.10}$$

where r is the distance between the noise source and the relevant point in m. The change in noise intensity to this distance, is shown in Figure 9.3.

[1] Epic Flight Academy. *Boeing 737-800*. 2023. URL: `https://epicflightacademy.com/boeing-737-800/` (visited on 06/16/2023).

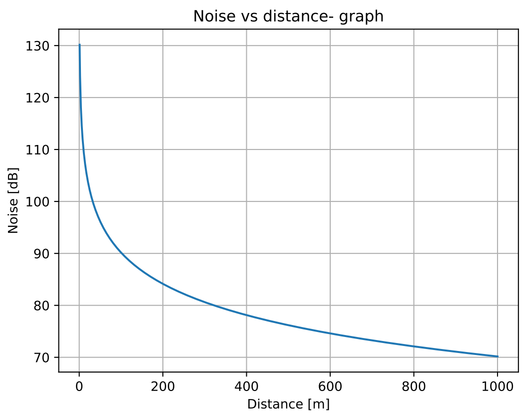


Figure 9.3: Graph shows the amount of decibels of noise as the distance between the source of noise and the point of measurement.

When the airship is in cruise, the noise received on the ground equals 70 dB. This can be compared to the noise of a dishwasher or shower and is not damaging to the human ear[2]. However, its peak value of 130 dB is extremely loud and comparable to a jet taking off[3]. Do note that populated areas are mostly avoided, thus the 70 dB does not pose a problem. Since pilots are in the gondola and thus close to the engine, an isolating material must be added to the gondola structure to ensure damping of the noise. In addition to the gondola being isolated with sound proof material, pilots may be equipped with ear-protection (which typically reduces perceived sound by an additional 18 dB-20 dB) [29]. This also follows for any personnel who may come close to the engines. An added consideration is to not use the airship engines at full power upon initiation of the descent phase and minimising use of the engines when the airship is close to the ground. Alternatively, more propeller blades may be used, but this impacts propeller efficiency adversely. The use of ducts for propellers can also be explored. This allows for a greater number of sound mitigation strategies to be deployed and also has the potential to increase the efficiency of the airship. Another way to decrease the noise would be to use smaller propeller blades or adjust the Rounds Per Minute (RPM). From Equation 9.8 it would follow that a diameter of 1 m and a RPM as small as possible would be required to have the smallest possible SPL_{max}. This is also shown in Figure 9.4.

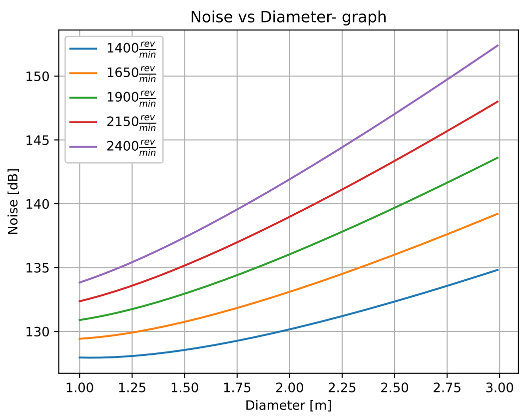


Figure 9.4: Graph shows the change in noise as a result of a change in diameter at different RPM.

[2] *How Loud Is 70 dB?*. 2023. URL: `https://decibelpro.app/blog/how-loud-is-70-db/` (visited on 06/15/2023).

[3] *How Loud Is 130 dB?*. 2023. URL: `https://decibelpro.app/blog/how-loud-is-130-decibels/` (visited on 06/15/2023).

Sustainability Analysis

The sustainability analysis of the performance of our airship is highly intertwined with the performance of the truck, meaning that the airship should at least have equal or better performance than trucks. In Table 9.1 it was shown that the airship seems to be the more efficient design, where it especially excelled with regards to the sustainable parameters, the emissions and fuel consumption.

Another important aspect is the noise. In chapter 3 and Table C.1 it was stated that the noise produced should not exceed the 70 dB received on the ground to not disturb the rural areas we fly over. In section 9.7 this requirement was met, having similar noise pollution as trucks the airship is equally environmental friendly regarding noise.

From these results it can be concluded that the airship is improves the sustainability of intra-continental (hydrogen) transport and also SDG 7 and 12 are met.

9.8. Maintenance

To ensure reliable long-term functioning of the airship, routine maintenance work is crucial. The frequency and type of maintenance performed varies per component. This includes detecting damage and repairing the damage before it results in adverse consequences. Unexpected events including major failures could take place regardless of inspections. In that case, the component deemed responsible for the failure needs to be identified and repaired.

The rigid structure inside the envelope as well as the gondola must to be inspected after every flight. With larger failures, visual inspection shall be sufficient for the gondola. However, since the rigid structure is located inside the polyester envelope, it needs to be tested by means of acoustic emission testing. This Non Destructive Testing method (NDT) is able to detect composite failures such as fibre breakage, breaking of bonds between resin and fibre and flaws or voids [14]. It does, however, require expensive automated systems and an experienced field worker. In case of a major repair, the envelope will have to be emptied to enable entry into the airship. Emptying the entire envelope is a time-consuming practice. For this reason, chemical resistant overalls used to enter the airship, could be considered.

For the envelope, visual inspection may be performed in order to detect larger, more apparent failures. As for detection of smaller holes, ultrasonic testing or penetrant techniques can be deployed. A detailed test needs to be done at least every two months, when the available facilities allow it, since the envelope is absolutely crucial for proper functioning of the airship. For major repairs the entire envelope can be replaced, whereas smaller holes can be fixed by adding polyester and stitching it or using an adhesive agent. The ballonets are made of polyester too. Since they are located inside the balloon, however, visual inspection will not be an option and radiography or ultrasonic testing must be performed as often as possible, with a minimum of every two months [14].

Since the control surfaces also play an important role in the airship's performance, they shall be visually inspected after every flight. Less visible, small cracks can be detected using thermography, ultrasonic testing or acoustic emission testing.

Electric motors require regular maintenance. In general, their parts should be tested and maintained at least every 6 months to ensure optimal performance and efficiency of the engine. Regular maintenance is also necessary with visual inspection after every flight and checking if the engine still performs accordingly[4].

Most landing gears are revised every ten years, according to FAA regulations. Since most landing gears are made of steel and aluminium, they are susceptible to corrosion and cracks. Some parts require repair with a shorter frequency than ten years, notably dynamic linking mechanisms, such as the steering collar[5].

[4]Maintech Engineering and Supplies Pte Ltd. *Periodic Motor Maintenance: How Often Should It Be Checked?* 2022. URL: https://www.mes.com.sg/2022/07/20/periodic-motor-maintenance-how-often-should-it-be-checked/ (visited on 05/20/2023).

[5]Mario Pierobon. *Aircraft landing gear: "Landing gear overhaul requires a specific trade expertise"*. 2023. URL: https://www.aviationbusinessnews.com/mro/aircraft-landing-gear-maintenance/ (visited on 05/20/2023).

10 Financial Analysis

The budgeting and financial aspects of the airship are analysed in the following chapter. Through the use of a budget breakdown, contingencies for various subsystems are calculated to predict the changes the airship may experience in the next design phases. Afterwards, the financial aspect of the current airship design is determined, which includes the cost breakdown and the estimated return on investment such a project may provide.

10.1. Budget Breakdown

A budget breakdown is made in order to study the differences that arise between the preliminary, the budget before the airship design, and detailed phase, the budget now that the airship design has been determined. The budget breakdown compares the different budgets between the preliminary and the detailed design. The budgets are made for the mass, range and power and their descriptions can be seen below. Table 10.1 presents the budget breakdown and Table 10.2 presents the corresponding contingencies. The budget breakdown shows parameters related to their specific subsystem and how they changed from the preliminary to the detailed design phase. The contingencies table shows an approximation of how much these values will still change after the detailed design phase.

Mass Budget

The mass budget is one of the most important budgets, since increasing the mass of the airship effects all the subsystems directly. Furthermore a snowball effect is created because a larger mass means needing more buoyancy force which increases the length of the airship which in return increases the structural mass. The mass budget can be broken down into all the airships subsystems. The subsystems that contributes the most to the mass budget are the structures and the airship cover mass. Therefore, these subsystems have a larger contingency value due to their influence on the whole design.

Range Budget

The range is determined by the longest distance the airship should possibly travel which is for example from the New York harbour to the middle of the United States. This estimate gives a range of 2000 km in straight flight. This range determines the amount of fuel that will be needed on the airship. This range can be seen as an overestimate since it's the maximum possible range. Furthermore, in reality trucks would need to travel a much greater distance since they would be using roads which are not point to point.

Power Budget

The required power of the airship is calculated by multiplying the drag by the cruise speed. This number is than used in the engine trade-off to determine the type of engine that fits the requirements the best, which are mostly based on the number of engines and their accumulated weight. The power system will use fuel cells to power the engines, compressor and other systems.

Table 10.1: Table presents the resource budget for various subsystems at the preliminary - and detailed design phase.

Subsystems	Mass [tonne]		Range [km]		Power [W]	
	Preliminary	Detailed	Preliminary	Detailed	Preliminary	Detailed
Airship total	49	51	2500	2000	-	-
Structure	10	20	-	-	-	-
Propulsion	0.294	0.245	-	-	843096	489600
Payload	0.8H2+10	0.8H2	-	-	-	-

With the budget breakdown, contingencies for various subsystems are determined based on the changes from preliminary to detailed design. This is done to predict the changes the airship may experience in the next design phases during further R&D.

Table 10.2: Table presents the contingencies for subsystems as a percentage of the detailed values mentioned in Table 10.1.

Subsystems	Mass Contingency[%]	Range Contingency[%]	Power Contingency[%]
Airship total	10	0.5	-
Structure	7.5	-	-
Propulsion	5	-	5
Payload	1	-	-

10.2. Cost Breakdown

When diving into the financial aspects of the airship, the cost breakdown can be analysed for two different situations: the airship manufacturer (THETA) and the airship operator (THETA's target group).

Airship Manufacturer

The overall costs for the THETA project can be further broken down into three main categories: R&D, Manufacturing, and Certification Costs. The breakdown of these costs are outlined in the Cost Breakdown Structure in Figure 10.1.

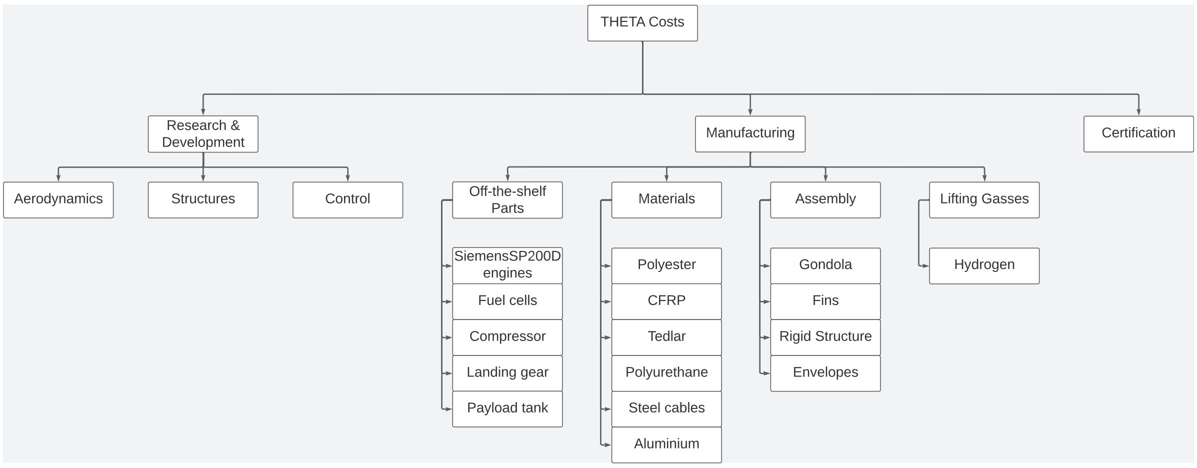


Figure 10.1: The figure presents the cost breakdown structure for airship manufacturer THETA.

The total costs of each major category are estimated and can be seen in Table 10.3.

Table 10.3: Table indicating overall costs for THETA, the airship manufacturer.

Category	Cost [M€]
R&D	500
Manufacturing (per airship)	45
Certification	200
Total	745

The R&D needed after the initial design phase is significant and would require many iterations compared to aircraft. For the Airlander 10 the R&D cost was estimated to be around 150 M€ to 500 M€[1]. Keeping this in mind, the estimated R&D cost for THETA is estimated to be 500 M€. This is coherent with the advice received from the Goodyear airship expert, whereby the estimated R&D costs of THETA would be upwards of 100 M€.

The manufacturing cost for an airship is estimated to be around 42 M$ [18]. Using an estimation method where the components of the airship are calculated based on the amount and material used, the total cost of production components comes out to be 13 M€. The individual costs of these components are outline in Table 10.4. An additional 32 M€ was added to include the costs of major manufacturing and assembly costs to construct the airship. It also includes an additional amount to mitigate the risk of underestimating the cost, therefore yielding the total manufacturing costs to 45 M€.

Table 10.4: Table with costs of individual components of the airship to provide overview of THETA's most costly components.

Name	Mass/Number/Volume	Unit Price	Total price
Lifting gas	5162 kg	2.79 €/kg	1.440e+04 €
Structures	1	1.726e+06 €	1.726e+06 €
Cover	3.967e+00 m^3	9.793e-01 €/kg	5.439e+03 €
Coating	1.344e+01 m^3	3.488e+01 €/kg	6.560e+05 €
Engines	5	1.860e+06 €	9.300e+06 €
Battery	1	1.302e+04 €	1.302e+04 €
Fuel Cell	4	3.000e+05 €	1.200e+06 €
Compressor	1	2.325e+04 €	2.325e+04 €
Propellant tank	1	1.532e+05 €	1.532e+05 €
Payload tank	60	3.000e+03 €	1.800e+05 €
Gondola	1	1.428e+03 €	1.428e+03 €
Total			1.309e+07 €

The certification cost for the airship would be on the higher end of the spectrum due to it's size and the use of hydrogen as lifting gas. The estimated certification cost for a large commercial aircraft lies in the hundreds of millions of dollars [26]. Having an estimate with high confidence for this category is difficult due to the lack of information on airship certification cost. Therefore a higher estimate is taken of 200 M€ for the certification of THETA.

In order to determine a reasonable selling price for the THETA airship, other airships on the market were used to develop a relation between the volume and cost of airships as illustrated in Figure 10.2. With this graph, the approximate cost of the THETA airship was estimated to be 70 M€ using its volume of $58\,425$ m^3.

[1]Mr. John Cummings. *Airplane pollution*. 2010. URL: `https://www.army.mil/article/41024/long-endurance-multi-intelligence-vehicle-lemv-agreement-signed/` (visited on 06/26/2023).

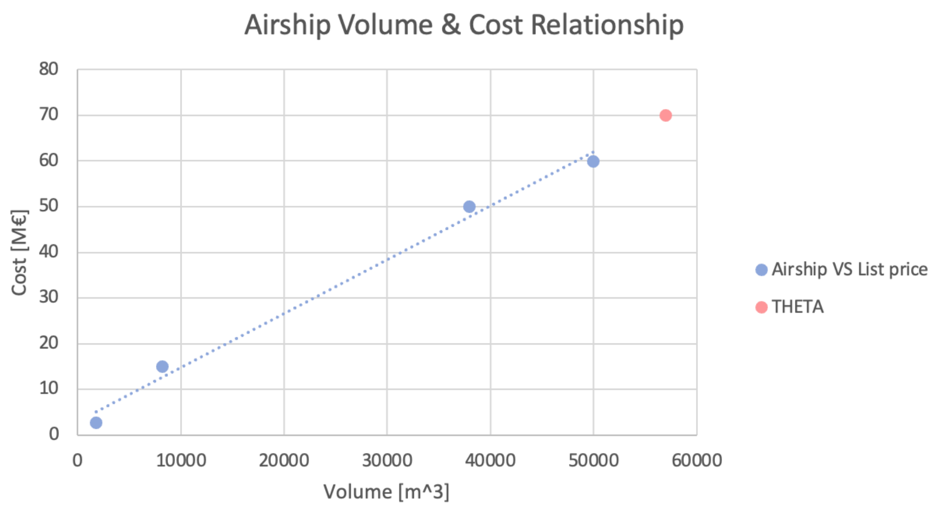


Figure 10.2: Plot shows the relationship between volume and cost of other on-the-market airships.

Hydrogen Operator

As for THETA's main customers, airship operators that aim to transport hydrogen and other high-risk payload, the yearly costs to carry out its mission are outlined in Table 10.5. Note that this does not include the initial 70 M€ purchasing cost of the airship mention in the previous subsection.

Table 10.5: Table indicating yearly costs for THETA's clients: airship operators

Category	Cost [M€/year]
Operational	
Ground Handling	0.08
Crew Wages & Benefits	0.1
~~Insurance~~	~~5~~
Fuel	0.4 or 0.7
Maintenance	0.16
Total	0.74 or 0.77

The operational costs comprises of multiple components. Ground handling, crew wages and benefits, and insurance are based on sources from other cargo airships[2], which are scaled to THETA's design. The fuel cost is estimated by taking into account the distance THETA travels, the number of trips per week and the cost of hydrogen. As can be seen in Table 10.5 there are two options for fuel cost. The higher cost belongs to a so-called best case scenario and the lower cost belongs to the so-called probable and worst case scenarios. The parameters for these scenarios are explained in Table 10.6 and will be explained in more detailed in section 10.3. The insurance is crossed out because it is assumed to be funded by the government, which is highly likely due to their interests in the sustainable fuel market as elaborated previously in section 2.5.

10.3. Return on Investment

The return on investment is made for two different situations. The first is for the airship manufacturer. The second is for the client who would buy the airship and use it to transport hydrogen. Several scenarios are analysed for the hydrogen operator break-even analysis depending on how often and how far the airship will operate.

[2] Isopolar. *Airship Costs for Intercontinental Shipping ISOPolar Airships*. URL: `https://isopolar.com/airship-costs-for-intercontinental-shipping/` (visited on 06/12/2023).

Airship Manufacturer

The total costs for THETA have been presented in Table 10.3. The only revenue THETA makes is by selling the airship which will be listed at 70 M€. Plotting the total cost against the total revenues as a function of the number of airships produced and sold (see Figure 10.3), the break-even point for THETA was found to be at 28 airships.

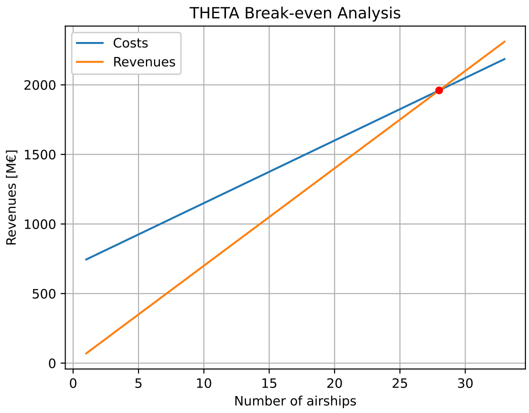


Figure 10.3: Plots depict the costs and revenues to determine the break-even point for THETA.

Hydrogen Operator

Three scenarios can be derived for the hydrogen operator as outlined in Table 10.6. The best case scenario comprises of a smaller range of 1000 km. This range is chosen because it is more realistic when looking at major harbours and the industrial areas of the respective country, for example, when looking at Shanghai and its major industrial areas close by [16]. The longest range considered would be from Shanghai to Changsha, which comes in at approximately 1000 km. Another example comes from the United-States and Canadian industrial areas which are also within a 1000 km range of the New York harbour[3]. Due to this range, a total number of seven round trips per week is chosen. The reason for this being that this would lead to a total of 28 non-flight hours per week, which is a reasonable estimate for loading, de-loading and maintenance.

The probable case also uses the range of a 1000 km but only does four round trips per week. The number of round trips is dependant on the demand of hydrogen in the industry which is still an uncertainty for what it will be by the year 2040. For that reason the number of round trips is significantly lower than for the best case scenario.

The worst case scenario does not only assume the lower demand for hydrogen, but also takes the maximum possible range that the airship could possibly travel, 2000 km. Additionally, weather limitations could restrict the airship operations hence assuming two round trips per week.

Table 10.6: Three possible scenarios for hydrogen operator which indicates the assumed range and number of round trips.

Scenario	Best	Probable	Worst
Range (one-way)	1000 km	1000 km	2000 km
Round trips per week	7	4	2

The revenue streams for each scenario, in million € per year, can be seen in Table 10.7.

[3]Smriti Chand. *8 Major Industrial Regions of USA and Southern Canada*. URL: `https://www.yourarticlelibrary.com/industries/8-major-industrial-regions-of-usa-and-southern-canada/25390` (visited on 06/26/2023).

Table 10.7: Table depicts yearly revenue for THETA's clients: airship operators

Revenue [M€/year]	Best	Probable	Worst
Transporting hydrogen	2.93	1.67	0.84
Advertisement	5.25	3	3
Total	8.18	4.67	3.84

The revenues from the hydrogen transport are calculated by taking the the price of H2, the amount of H2 and the frequency of transportation. Taking the margin of profit for transporting to be around 8.2%[4] for 2020, an estimated profit margin of 17% was found for 2040[5].

The interest from advertising follows from the total flight hours per year and the regions were will be flown[6]. The sources that were found on airship advertisement largely varied when it came to the possible revenues, therefore, to alleviate the risk, an underestimate was taken.

Summarising the above data, the profits per year are calculated. With this, the break-even point can be determined per scenario (Table 10.8), with plot comparisons shown in Figure 10.4.

Table 10.8: Break-even cases for three possible scenarios, indicating profits and number of years for hydrogen opertor to break-even.

Scenario	Best	Probable	Worst
Profits	8.1 M€/year	4.42 M€/year	3.24 M€/year
Years to break-even	9 years	16 years	22 years

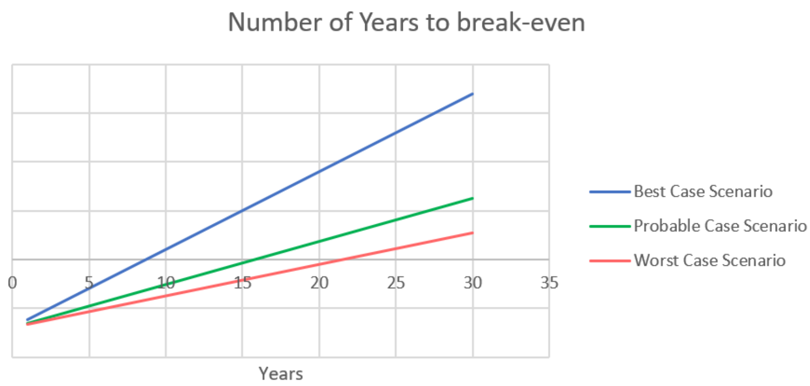


Figure 10.4: Plot depicts after how many years hydrogen operator begins to make profits for all three scenarios.

The Return On Investment (ROI) is calculated to be 12.22%, 7.01% and 5.63% for best, probable and worst case scenario respectively. This is done using Equation 10.1, whereby the revenue obtained per year is divided by the cost of purchasing the airship[7].

$$\text{ROI} = \frac{\text{Net Return}}{\text{Cost of Investment}} \tag{10.1}$$

[4]Macrotrends. *Air Transport Services Profit Margin 2010-2023*. URL: `https://www.macrotrends.net/stocks/charts/ATSG/air-transport-services/profit-margins` (visited on 06/12/2023).
[5]Ms. Newell. *Manufacturing regions*. 2005. URL: `https://newellta.weebly.com/industrial-regions.html` (visited on 05/21/2023).
[6]USAirads. *High Exposure Mobile - Rates*. URL: `https://usairads.com/mobile/rates.php` (visited on 06/12/2023).
[7]WallStreetPrep. *Return on Investment (ROI)*. 2023. URL: `https://www.wallstreetprep.com/knowledge/roi-return-on-investment/` (visited on 06/19/2023).

From Table 10.8, the three break-even points, together with the profits per year for all three scenarios can be read off. Keeping in mind the airship lifetime of approximately 25 years[8], the worst case is definitely a scenario that needs to be avoided. The best and probable scenarios are both cases that are financially feasible. Which scenario the client will be facing all depends on how the hydrogen market will develop by 2040 and how the hydrogen operator decides to operate, but it will most likely be around the probable scenario.

[8] Randall Marsh. *Goodyear replacing its current blimp fleet with zeppelins*. 2013. URL: `https://newatlas.com/goodyear-blimp-replacement-zeppelins/28335` (visited on 06/17/2023).

11 Verification and Validation

Any model that has been created and any systems that have been designed must be verified and validated in order to ensure the functionality of the model. The verification and validation methods used are detailed in the following sections.

11.1. Verification Code

Various verification methods are used in order to ensure the functionality of the code and, by extension, the resulting model. The use of different verification methods is essential since some functions need to be verified through multiple modes in order to truly ascertain whether or not their behaviour is as expected.

The various functions in the code are visually inspected, the values they produce can then be verified by hand-written calculations and if the two match up then the result for the visual inspection would be considered a ”Pass”.

Table 11.1: This table provides an overview of all the performed unit tests and code inspections done on the functions used in the code

Test ID	Function/Method	Test	Result	Confidence
1.1	Performance.py: ReynoldsNumber	Visually inspect the function and verified working of function with external calculation	Pass	High
1.2	Performance.py: Drag_coefficients	Visually inspect the function and verified working of function with external calculation	Pass	High
1.3	Performance.py: Drag	Visually inspect the function and verified working of function with external calculation	Pass	High
1.4	Performance.py: Power_required	Visually inspect the function and verified working of function with external calculation	Pass	High
1.5	Performance.py: Energy_required_H2	Visually inspect the function and verified working of function with external calculation	Pass	High
2.1	Concept_2_multilobed.py: __init__	Visually inspect the function and verified working of function with external calculation	Pass	High
2.2	Concept_2_multilobeds.py: coverparameters	Visually inspect the function and verified working of function with external calculation	Pass	High
2.3	Concept_2_multilobed.py: gasvolumeparameters	Visually inspect the function and verified working of function with external calculation	Pass	High
2.4	Concept_2_multilobed.py: volumemainlobe	Visually inspect the function and verified working of function with external calculation	Pass	High
2.5	Concept_2_multilobed.py: volumesidelobe	Visually inspect the function and verified working of function with external calculation	Pass	High
2.6	Concept_2_multilobed.py: thickness	Visually inspect the function and verified working of function with external calculation	Pass	High
3.1	Optimization.py: Optimize	Visually inspect the function and verified working of function with external calculation	Pass	High
3.2	Optimization.py: printline	Visually inspect the function and verified working of function with external calculation	Pass	High

3.3	Optimization.py: tablegeneratorgeneraltable	Visually inspect the function and verified working of function with external calculation	Pass	High
3.4	Optimization.py: tablegeneratorpowertable	Visually inspect the function and verified working of function with external calculation	Pass	High
3.5	Optimization.py: tablegeneratorbuoyancytable	Visually inspect the function and verified working of function with external calculation	Pass	High
3.6	Optimization.py: tablegeneratortanktable	Visually inspect the function and verified working of function with external calculation	Pass	High
3.7	Optimization.py: tablegeneratorcosttable	Visually inspect the function and verified working of function with external calculation	Pass	High
4.1	Classes.py: Gas	Visually inspect the function and verified working of function with external calculation	Pass	High
4.2	Classes.py: Material	Visually inspect the function and verified working of function with external calculation	Pass	High
4.3	Classes.py: Pressuretank	Visually inspect the function and verified working of function with external calculation	Pass	High
4.4	Classes.py: Engine	Visually inspect the function and verified working of function with external calculation	Pass	High
4.5	Classes.py: Fuelcell	Visually inspect the function and verified working of function with external calculation	Pass	High
4.6	Classes.py: Compressor	Visually inspect the function and verified working of function with external calculation	Pass	High
4.7	Classes.py: Gondola	Visually inspect the function and verified working of function with external calculation	Pass	High
5.1	Truck_Calculations.py: spc_fuel_consumption	Visually inspect the function and verified working of function with external calculation	Pass	High
5.2	Truck_Calculations.py: weight_efficiency	Visually inspect the function and verified working of function with external calculation	Pass	High
5.3	Truck_Calculations.py: travel_time	Visually inspect the function and verified working of function with external calculation	Pass	High
6.1	TotalAirship.py: __init__	Visually inspect the function and verified working of function with external calculation	Pass	High
6.2	TotalAirship.py: x	Visually inspect the function and verified working of function with external calculation	Pass	High
6.3	TotalAirship.py: y	Visually inspect the function and verified working of function with external calculation	Pass	High
6.4	TotalAirship.py: z	Visually inspect the function and verified working of function with external calculation	Pass	High
6.5	TotalAirship.py: weighted_average	Visually inspect the function and verified working of function with external calculation	Pass	High
6.6	TotalAirship.py: Eniginеposition	Visually inspect the function and verified working of function with external calculation	Pass	High
6.7	TotalAirship.py: WeightedAverageMultipleSubsytems	Visually inspect the function and verified working of function with external calculation	Pass	High
6.8	TotalAirship.py: total_price	Visually inspect the function and verified working of function with external calculation	Pass	High
6.9	TotalAirship.py: verticalfin	Visually inspect the function and verified working of function with external calculation	Pass	High

11.2. Verification Structural Analysis

In order to verify the structural analysis performed in section 6.3, a few simplified calculations were done by hand to compare with the values the FEM software computes. The FEM software itself is of course verified already given it is a commercially licensed. However, whether you use it correctly, thus whether you model is correct still has to be verified. This is what is done here.

First of all, the structure is modelled as a truss structure shown in Figure 11.1 The assumptions as made in the FEA models external loads, explained in section 6.3, were applied. For instance assuming the buoyancy force to be uniformly distributed. The buoyancy force is hence assumed to be applied individually at each node resulting in a load of $\frac{B_{total}}{13}$. The simplified structure is used in 2D, while the actual model used in FEM is three-dimensional. This is why the buoyancy force at the bottom beam is assumed to be twice as high as the buoyancy force on the upper one. In other words, $B_2 = 2 \cdot B_1$. Furthermore, the bottom beam is assumed to be straight for simplicity. This is a fairly reasonable assumption since the inclination of the bottom beam is very small in reality with a maximal element inclination angle of $0.45\,°$ to the horizon, as shown in section 6.3.

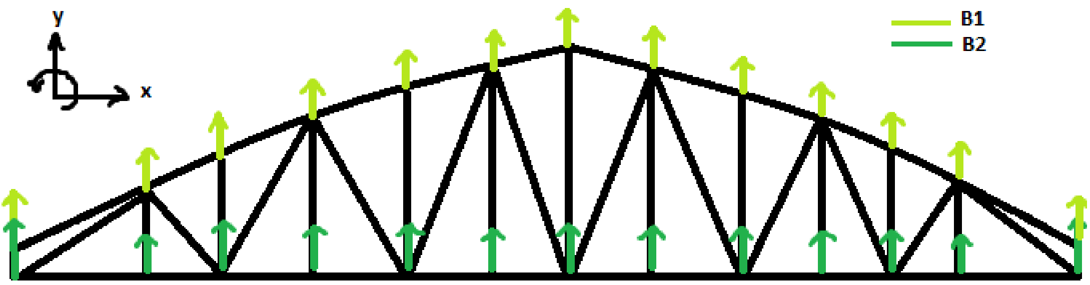
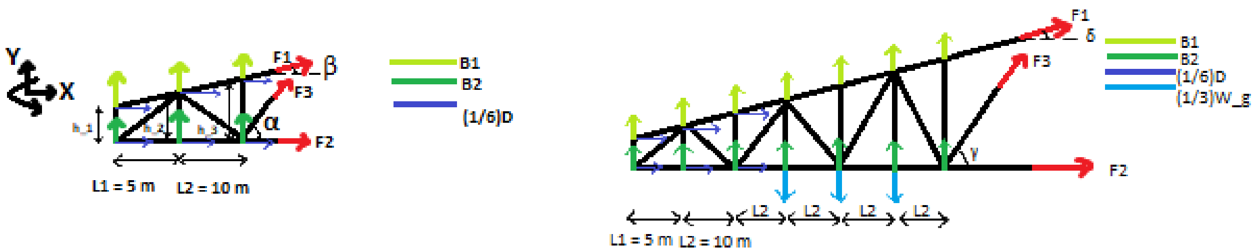


Figure 11.1: Sketch of the simplified structure used for verification of structural analysis. In reality it is not symmetrical. The buoyancy force, assumed to be uniform, is drawn.

By making a cut at three different locations in the structure, the internal force in a member can be calculated. All three cuts, between node 3 & 4, 7 & 8 and 10 & 11, as well as the relevant forces, are presented in Figure 11.2 and Figure 11.3.



(a) Sketch of the cut made between node 3 and 4 of the simplified truss structure shown in Figure 11.1. This was used to calculate the reaction forces.

(b) Sketch of the cut made between node 7 and 8 of the truss structure. Here the gondola weight, W_g, is also relevant.

Figure 11.2: The cuts made in the system were used for calculating the internal force.

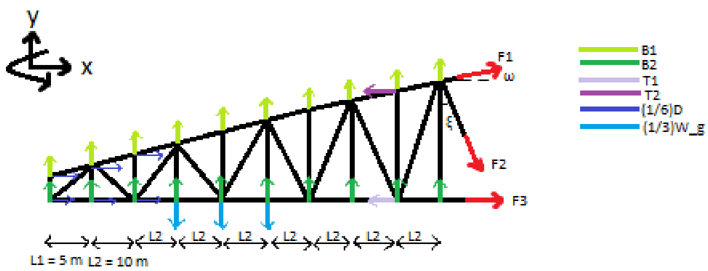


Figure 11.3: Sketch of the cut made between node 10 and 11 of the truss structure. Here the gondola weight, W_g and thrust, denoted by T_1 and T_2, are also relevant.

In order to calculate the diagonal reaction force, F_3, Equation 11.1, Equation 11.2 and Equation 11.4 must be used.

$$\overset{+}{\rightarrow}\Sigma F_x = 0 = F_{1_x} + F_2 + F_{3_x} + D \tag{11.1}$$

where F_{1_x} = $F_1 \cdot cos(\beta)$ and F_{3_x} = $F_3 \cdot cos(\alpha)$ as shown in Figure 11.2 and D is the drag, all in N.

$$+\uparrow\Sigma F_y = 0 = F_{1_y} + F_{3_y} + B_1 \cdot 3 + B_2 \cdot 3 \tag{11.2}$$

Since B_2 = $2B_1$, this becomes:

$$\Sigma F_y = F_{1_y} + F_{3_y} + 9 \cdot B_1 \tag{11.3}$$

where F_{1_y} = $F_1 \cdot sin(\beta)$, F_{3_y} = $F_3 \cdot sin(\alpha)$ and B_1 is the uniform buoyancy force shown in Figure 11.2 in N.

$$\circlearrowleft + \Sigma M_3 = 0 = -(L_1+L_2)\cdot B1-(L_1+L_2)\cdot B2-L_2\cdot B1-L_2\cdot B2+F_{1_x}\cdot h_3-\frac{1}{6}\cdot D\cdot(h_1+h_2+h_3) \tag{11.4}$$

Here h and L are the heights and lengths of the respective parts for the values from section 6.3. The angles α and β are determined from the geometry.

Doing this for three different members gives the results summarised in Table 11.2. The three members that were analysed are all diagonal and positioned such that a new force is added to the structure with every node that is examined. The first member is located between node 3 and 4, right before the gondola, where the drag, which was assumed to have the same value at every node, is already relevant. The second one is right after the gondola, adding gondola weight to the analysis. Finally, the member between 10 and 11 is analysed, where thrust is also relevant. This could have been analysed from the right, but purposefully has been examined from the left to include the thrust force. Taking these three points is crucial to have verified the overall structure as in this way all relevant forces are used at some point of the verification process.

Node	Force FEM [kN]	Force Manual [kN]	Difference (%)
3-4	8.4	8.2	2.4
7-8	27.7	90.2	69
10-11	-13.5	-3.5	75

Table 11.2: Values obtained in the analysis of a simplified truss structure, compared to the ones determined by FEM. This was used for the verification of the structural analysis.

In conclusion, the first value, which is an analysis done before the fixed support, matches almost perfectly. Node 7-8 is closest to the supports in the FEA model. Given the reaction forces and moments the support introduces, it makes sense that the manual calculations do not match up well with model. After the support, node 10-11, the differences between the values is also due to the support that changes the internal forces drastically aft of the supports. All in all this verification is still considered to be adequate for its purpose, and the somewhat early stages of the design phase. On top of that, the FEA model is an overestimation of what is necessary.

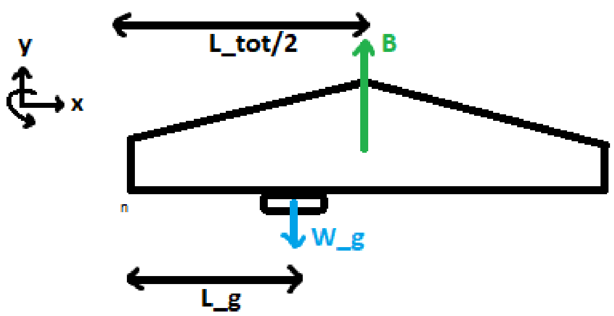


Figure 11.4: Sketch of the outline of the simplified truss structure shown in Figure 11.1. This was used to gondola position.

Another method to verify the structure is applied to make sure the position of the loads is correct. By taking the sum of moments around the leading edge with all relevant forces and distances as shown in Equation 11.5 is obtained.

$$\circlearrowleft + \Sigma M_n = \frac{L_{tot}}{2} B - L_g \cdot W_g \tag{11.5}$$

where L_{tot} is the total length of the structure in m, B is the buoyancy force in N, L_g the position of the gondola with respect to the nose and W_g the weight of the gondola in N. All relevant values were given in section 6.3.

The sum of moments around the nose, ΣM_n, was exerted from ANSYS[1]. This reaction moment at the leading edge has a value of $2.235 \cdot 10^6\ Nm$.

Substituting all these values in Equation 11.5 and rearranging the equation gives the position of the gondola, which is calculated to be 34.0 m. This matches up perfectly with the FEA model gondola position in section 6.3. Thus, the structural analysis is verified.

11.3. Verification Stability Analysis

The stability to trim the aircraft should be validated as its longitudinal stability is vital for the the mission because it will determine whether cruise would be possible before having to analyse climb, descent, disturbance and dynamic stability. When taking the data of the airship the following forces are calculated with the values from Table 11.3.

Table 11.3: This table shows the airship parameters for which the stability forces were calculated.

Parameter	Value
Airship mass	$69\,023$ kg
Main envelope volume	$66\,724$ m^3
Side envelope volume	6930 m^3
Horizontal tail surface	218 m^2
Elevator surface	54 m^2
Airship length	134 m

On top of this the following parameters influencing the stability are positions as follows:

- A Centre of Gravity location of x:58 m, y:0 m, z:3.2 m
- A Centre of Buoyancy location of x:59 m m, y:0 m, z:0 m
- A horizontal tail location of x:105 m m, y:14 m, z:0 m
- A horizontal elevator tail location of x:120 m, y:14 m, z:0 m
- A engine position placed at x:26 m, where the top engine is at the top of the main lobe, where each engine is then placed 72 ° apart looked at from a front view.
- The drag acting through the noses of the lobes.
- A pitch angle of 5 °, as that is what is usually necessary to fly horizontally during cruise.

Using a cruise speed of 100 km/h, several forces were calculated. As can be seen in figure 11.5:

[1] ANSYS. *Ansys Mechanical Finite Element Analysis (FEA) Software for Structural Engineering*. 2022. URL: `https://www.ansys.com/products/structures/ansys-mechanical` (visited on 06/20/2023).

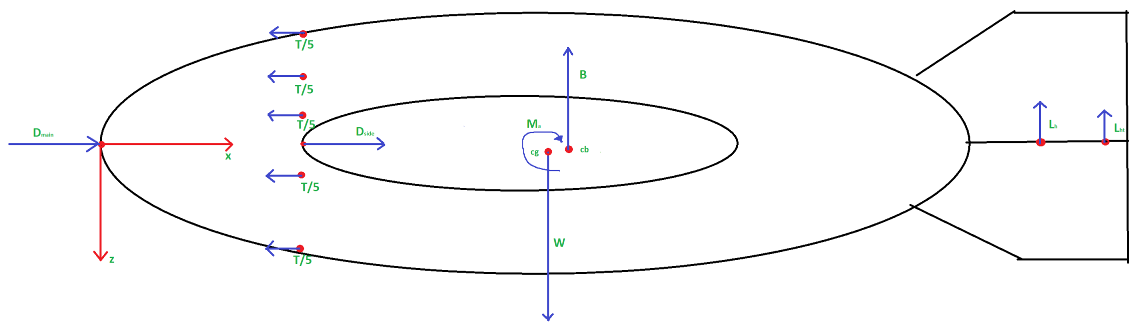


Figure 11.5: Figure shows the Free Body Diagram of an airship.

Then, by using the figure with its positions and calculated forces, a analysis done by hand with pen and paper was done to calculate the moments around the cg which resulted in the following moments defined earlier in 6.8:

- M_a = $2\,484\,501$ Nm
- M_p = $75\,520$ Nm
- M_c = 140 Nm
- M_g = 0 Nm
- M_b = $2\,999\,251$ Nm

Which when added using the following equation should applied oppositely with the same magnitude by the elevator surface, which leads to a deflection angle of $24\,°$. Comparing that to the value calculated by the stability code, it is only a 20 % difference, which in this stage of the design can be considered insignificant.

11.4. Validation

Validation of the main parameters driving the design of the airship is performed by both analytical and experimental means in order to ensure that the model of the airship is functional. The validation process is a necessary step which determines the feasibility of the model, if the model fails validation it would need to be re-evaluated.

Assumptions

- ASS-STRUC-01- Point loads acting on the structures nodes. In reality some of the loads are distributed and act along the length of elements. This will result in increased bending within the elements compared to point loads acting only on the nodes because the latter causes displacements of nodes rather than bending elements.
- ASS-STRUC-02- During FEA analysis, due to modelling difficulties of a truss structure for the elements, they were not modelled. Instead, a hollow circular tube cross-section was created such that its moment of inertia and cross-sectional area matched that of the truss structure. This

assumption does not have great impact on the global structure because the geometry has the same properties, but the analysis locally with FEA could not be done for the trusses.

- ASS-STRUC-03- It was assumed that the airship is fixed at 25 m from the nose, This assumption had to be made because FEA requires a boundary condition to perform computations. In reality, the airship floats freely under the loads defined. To mitigate the discrepancy, force equilibrium around the boundary condition was created.
- ASS-STRUC-04- It was assumed that the discretely attached elements are transferring loads ideally. Since a (UD) epoxy carbon fibre has continuous fibres, this continuity is actually disturbed due to manufacturing limitations which require elements to be produced in different parts. Therefore, the fibres do not follow through between elements and therefore the loads are not transferred optimally as estimated in the FEA.
- ASS-STRUC-05- Deformations in the FEA are small. In ANSYS, the large deformations option was not selected since it was not required for the analysis. This becomes more important when non-compression elements (cables) are used in the analysis but this was not the case.
- ASS-AERO-01- Aerodynamic effects due to flow separation at side lobes and the reduction in wetted area due to connection of side lobes are neglected. This results in a slightly higher drag value which is acceptable since it ensures the estimate is conservative.
- ASS-AERO-02- Skin friction drag is not analysed but estimated empirically. This assumption holds valid since the estimation includes a safety factor to account for the additional skin friction drag.
- ASS-CONTROL-01- Steady symmetric horizontal straight flight assumed for stability calculations. This assumption does not have any major implications for the accuracy of the stability calculations and is hence considered valid.
- ASS-CONTROL-02- Assumed the airship to be a rectangle when performing weather calculations. This assumption produces an effective overestimate for the moment that the airship will face when confronted with a strong sideward gust since the rectangular profile is greater than the airship's own ellipsoidal profile. Hence this assumption is valid since it results in a conservative estimate.

Validation of Parameters

The primary design driving parameters are validated in order to ensure their accuracy. Validation at a further subsystem level is deemed unnecessary since they are purely influenced by the parameters mentioned below and hence if any of these parameters are valid it is reasonable to assume that other subsystems are valid too.

Due to the lack of information on airships, the criteria to determine the validity of an option was lowered initially from a quantitative confidence interval of +/- 10% to merely the value being a conservative estimate. This was done to greatly simplify the validation process and ensure that the model represents a conservative estimate for THETA. Once it is established that all estimates are conservative the model is considered valid.

Drag Values

The drag values were validated against existing airships. This was done by means of identifying airship dimensions (which affect the drag value), identifying the power capabilities of the airship and cruise speed. This can be used to determine a ”real” drag value for the airship given by:

$$D = \frac{P_{max}}{V_{max}} \tag{11.6}$$

where P_{max} and V_{max} are the maximum power and the maximum velocities respectively.

The drag is also estimated using the empirical methods detailed in section 6.4. The mean drag value from the 3 estimations is then compared with the drag value obtained from Equation 11.6.

Performing this for multiple airships yields that the estimated drag value is indeed an overestimate with a general overestimation factor of approximately 25%. This is not only within reason it is also a conservative estimate, meaning that designing for this drag value would definitely result in a functional airship, hence the drag values are considered valid.

Structural Deflections

In order to validate the structure, the entire airship was idealised as a cantilever beam with an equivalent uniform load and the deflections obtained from this were compared to the deflections obtained from the ANSYS model. The cantilevered beam idelisation is shown in Figure 11.6. The beam is fixed from a wall at 25 m from the nose.

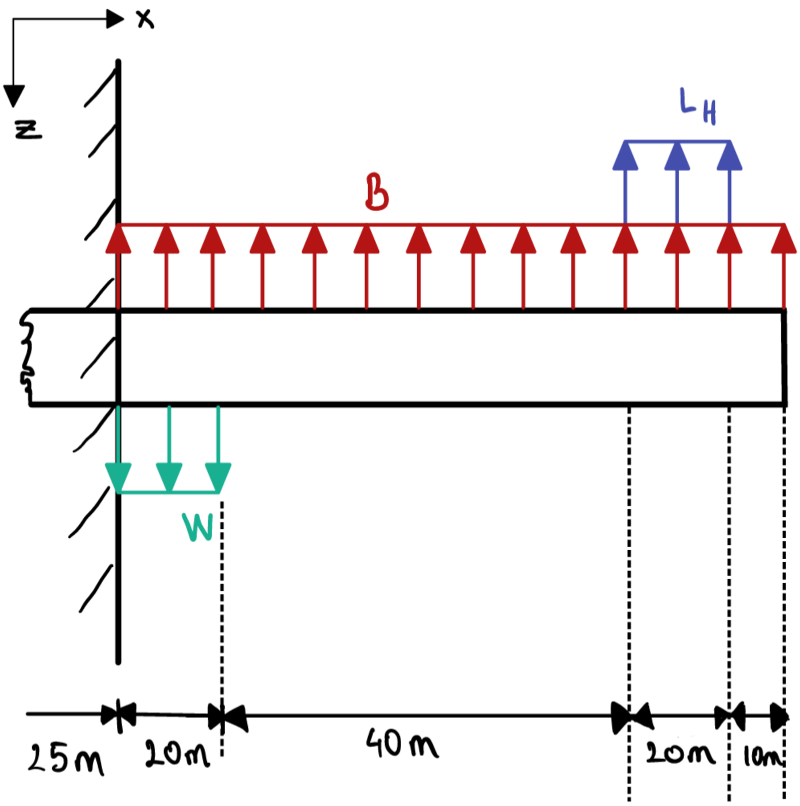


Figure 11.6: Diagram shows the beam idealisation with the used loads for validation.

This idealisation assumes that the beam cross-section is 3 point areas as shown in Figure 11.7. The 3 cross-section point areas have area equal to the spars of the structure from section 6.3. Other elements including the diagonal elements have been neglected for this analysis. This implies within the idealisation that the bending moment is supported purely by the 3 main spars, which negates the existence of the cross-braces hence severely limiting the stiffness of the idealisation relative to the ANSYS model. The resulting moment of inertia is used to calculate the final deflection. Only vertical forces were used for simplicity. The FEA analysis was re-run with the only vertical loads applied along with updated boundary conditions that suit the assumed validation boundary condition.

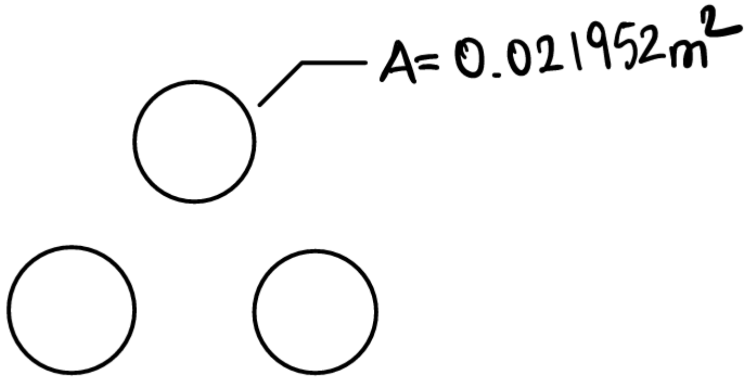


Figure 11.7: Diagram shows the cross-section of the idealised beam for structure validation.

The resultant deflection of this idealisation is a total deflection of 0.005 m, compared to the model deflection of $0.001\,211\,3$ m (lower by a magnitude of 4) This is within the expected range of the estimate since the actual structure is a truss which has significantly better equivalent stiffness characteristics than the beam idealisation. For this specific reason it was concluded that the value of the model deflection was within reasonable bounds and hence the model is valid.

Static Stability and Controllability

While the controllability of the airship itself can not be validated without using experimental means, the sizing of control surfaces can be validated. They are validated by comparing their sizes to ones that are typically present on airships. If the control surface areas on other airships are in a similar order of magnitude as those on THETA the model could be considered valid by means of comparison with existing functional examples.

The exact areas of the control surfaces of existing airships can not be found in public domain, however the lengths can be estimated with reasonable accuracy from still images of airships.

For the Zeppelin NT the surfaces were 6 m by 10 m which is a surface area of about 60 m^2. For the GZ-20 the control surfaces were 5 m by 9 m which is a surface area of 45 m^2. This is in comparison with THETA which has 2 vertical stabilisers of approximately 6 m by 11 m resulting in a total area of approximately 132 m^2. This is consistent with the size difference between the airships and is hence considered valid. For the Zeppelin NT and the GZ-20 both it is apparent that the vertical stabiliser and horizontal stabiliser are assumed to be the same area, this can be inferred by the fin placement however it cannot be calculated with a greater degree of accuracy owing to the confidentiality of the information. The horizontal stabiliser for THETA is 218 m^2 in total, the Zeppelin NT and the GZ-20 have areas which when interpolated from are very similar. The areas are 214 m^2 and 204 m^2 for the Zeppelin NT and GZ-20 respectively. Hence the empennage sizing is considered valid for THETA.

Noise

Similarly to validation of the control surfaces, the noise generated by existing airships is compared to the noise generated by THETA. It is worth noting that the noise generated by THETA is likely to be higher than the noise generated by the other airships since THETA has not been optimised for sound isolation and analytically determining the level of noise produced and the effect of mitigation measures can not be done with any reasonable degree of certainty within the current time-frame.

The noise generated by THETA at peak engine power, at 1 m from the engines is 130 dB, this is similar to a jet engine. The noise level at the gondola, purely mitigated by the distance from the engines is projected to be approximately 106 dB. The Wingfoot 2 and the GZ-20 are taken as reference points for comparison of sound values. Noise in the GZ-20 reached almost 110 dB in the gondola, slightly louder than the projected maximum noise in the gondola of THETA. Wingfoot 2 on the other hand is significantly quieter with a noise level outside the gondola of 69.4 dB. The noise within the gondola of Wingfoot 2 is 64 dB.

Since the noise levels of THETA and the GZ-20 match up the noise value is considered valid. Wingfoot 2 has a significantly lower noise level than THETA this is attributed to the relatively weaker engines, their placement further out from the gondola relative to the GZ-20 and the likely deployment of various noise mitigation strategies that they deployed to curtail excessive noise. Using Equation 9.8 on the GZ-20 and Wingfoot 2 result in values of a peak noise of 125 dB for each of the airships.

Both the GZ-20 and Wingfoot 2 are however combustion engines whereas THETA makes use of an electric engine, hence the difference in sound may seem inexplicable at first. However the noise emitted by THETA is estimated empirically, and this empirical estimation makes use of the same combustion engines as the GZ-20 and Wingfoot 2 with the engine power being the only parameter that is explicitly different (since the other parameters had to be visually estimated in some capacity) The engine noise for THETA is therefore likely to be a conservative estimate considering the difficulty of estimating the difference deployment of mitigation measures would have caused, resulting in a valid subsystem.

12 Project Design & Development

The final design concept must undergo additional stages until it can be formally introduced into the market. Therefore, the post-design synthesis activities are outlined in the following section along with the approximated timeline. The planning begins with the R&D required to finalise the airship design, and ends with its end-of-life.

12.1. Project Phases

The next phases of the project can be divided into three main sections: further R&D, manufacturing of the airship, and its operational lifetime. The overview of the activities carried out in each section is outlined in Appendix H.

12.2. Project Gantt

The Gantt Chart found in Appendix I presents the project activities along a timeline ranging from 2024 to 2065. Due to the complexity of the airship and the safety considerations for the large volume of hydrogen used, the R&D can be estimated to take a longer period of time, for instance 12 years. This is also due to the dependency of funding and other external factors such as regulations. Manufacturing is estimated to take 4 years, due to the aforementioned reasons, notably size and quality assurance process. Lastly, the estimated lifetime for such an airship is approximated to be 25 years. This is based on comparable airships such as the Zepplin NT which was found to have a lifespan of 25 years[1].

[1] Randall Marsh. *Goodyear replacing its current blimp fleet with zeppelins*. 2013. URL: `https://newatlas.com/goodyear-blimp-replacement-zeppelins/28335` (visited on 06/17/2023).

13 Recommendations

Due to practical constraints such as time and manpower some design aspects of subsystems were neglected or left unexplored. The most relevant aspects are detailed in the following sections as recommendations in case future research is carried out into a transport airship.

Single Lobed

At the end of the design phase it has became clear that the a tri-lobed airship may not have been the most efficient configuration for the mission profile. This can be shown by plotting two key parameters: the length of the airship and the fuel needed to cover a certain distance. The length is important to the structure group and the fuel consumption affects the overall efficiency of the airship.

Figure 13.1 plots both parameters in a graph, the x-axis shows the distribution of the volume in the lobes. The required total volume of the lobes remains constant in the graph. The same goes for the shape of the lobes, which can only be scaled. An x-value of zero indicates that no volume is present in the main lobe and the rest of the volume is divided over the side lobes. This is essentially a two-lobed airship. An x-value of 1 indicates that all the volume is present in the main lobe and no volume in the side lobes, which is essentially the single-lobed, conventional airship.

The conclusion of this graph is that the shortest length and highest consumption happens at a ratio of $\frac{1}{3}$. The short length is logical considering that at this ratio the airship has three equal lobes. When looking at the high fuel consumption at this point, it should be noted that this is mainly influenced by the drag the airship experiences, which in turn is determined by the vertical cross section of the airship. The cross section area is highest when the volume is distributed amongst the three equal lobes. It is important to note that the length and fuel consumption are two separate design parameters that differ in importance, depending on engineering preference. The range in which these values lay are not comparable neither, this however does not debunk the conclusion drawn.

The current designed airship is at $\frac{1}{4}$ which is both longer and consumes more fuel than than a double lobed airship. If the team wanted to design for efficiency, a convectional airship would have been the choice of design direction. The team decided to still design a tri-lobed airship because of operational reasons and expectation which were underestimated compared to the final results.

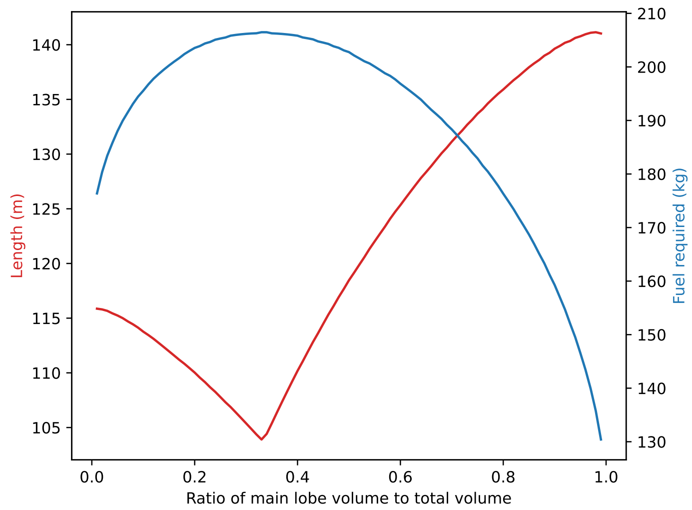


Figure 13.1: This figures shows the efficiency plot of different configurations.

Structures and Materials

Due to the complexity of the structure and time limitations, the structure design has been finalised with only one iteration. The iteration focused on buckling and deflection issues that were faced in the initial design but no weight optimisation iterations were done. Therefore, it is recommended that future work focuses on reducing the weight of the structure by analysing multiple load cases and determining maximum forces on each members to optimise the cross-section type, area and material member by member. A cost analysis can be made to determine if keeping the same cross-section for different members would be beneficial to reduce the costs of production in the short-term which compromises operational costs due to higher weight in the long term.

Additionally, the way the load transfers elements within trusses and between structural members should be investigated. Since FEA cannot simulate the transfer of loads between smaller elements, an in-depth analysis is required to determine a method to improve load transfer efficiency. It was mentioned that using aluminium rings at the ends of elements would improve load transfer, but further research has to be made to back-up this claim.

Once the weight is reduced with iterations, if the weight budget allows, it is recommended that GFRP is used. GFRP is 9 times cheaper than CFRP which will make the project more feasible financially. GFRP has lower stiffness in all directions compared to CFRP (UD) which was used in the design. This will increase the deflection slighlty because the difference is not great but still needs to be re-analysed. However, due to very low deflections in the current design, a margin for additional deflection is possible without having to further reinforce the structure. GFRP also has lower tensile and compressive yield strength compared to CFRP (UD) which requires the reconsideration of failure of elements which may result in thicker elements.

In addition, the structure of the engine mounts, vertical and horizontal tail and landing gears have not been considered. As mentioned in section 6.3, the loads were assumed to act on the internal structure from a virtual distance. In reality, a structure should extend from the inner structure for each aerodynamic surface and engine. Although the structural analysis were not made for these extensions, a rough estimate of the additional mass has already been calculated which is contained within the total mass calculated for the structure.

Finally, the thickness of the coatings was based on helium permeability. In the case of the THETA mission, hydrogen is used. Hydrogen has a lower permeability than helium [15]. This means that for an airship filled with hydrogen, potentially a thinner coating would suffice. Further research into coating thicknesses is required to know the exact thickness required to still ensure low permeability, but use less material and thus make the design lighter and cheaper.

Propulsion

Section 9.7 already provides some recommendations as to how to reduce the noise level. Summarising these, smaller propeller blades or more propeller blades can be used. Another solution would be to adjust the RPM. The engine noise of at max 70 dB as perceived on the ground is not necessarily an issue, especially as rural areas are avoided. However, with minimal effort this could be reduced slightly. The propellers need to be resized and analysed in much further detail to ensure they are not operating in the compressible regime resulting in a great efficiency loss. The blade may be analysed and variable pitch may be introduced to improve the characteristics of the propeller and ensure the functioning of the airship.

Besides, resonance is a crucial aspect. The tanks being transported in the airship must not vibrate too much as this might be catastrophic. An attempt was made to determine the natural frequency of the structure, however there was not enough information to do this. Thus, another recommendation would be to perform further research into the topic of resonance for an airship.

Lifting surfaces

In designing several calculations were done that utilised lifting surfaces. During the analysis, the following problems arose when utilising lifting surfaces:

- The surfaces would be useless without horizontal speed, hence during take off and landing
- The lobes themselves in the designing calculations were designed to carry the entire weight
- The lobes themselves could not alter in size in cruise to allow for the surfaces to take over some of the buoyancy, allowing for less drag

Although the first point states that lifting surfaces are useless at low speed, they are recommended to be included in further designing. Lifting surfaces are extremely efficient at creating lift for a minimal drag, due to its high C_L/C_D ratios. Next to that, if the size of the lobe could be reduced during cruise, some of the buoyancy could be taken over by lifting surfaces. This is done during cruise as the speed is the highest, making lifting surfaces more efficient. Additionally, if the lobes are reduced in size, the drag of the airship could be reduced massively, for the same amount of lift (due to the high C_L/C_D ratios of wings). Adding to that the fraction of total propellant used during cruise due to cruise time and distance fractions, the propellant needed to be taken on board would reduce as well, causing for a slightly smaller airship. These effects describe the well known snowball effect, however in the reverse direction.

Calculations were done on how much wing surface would be needed to replace a certain amount of envelope volume, which can be seen in Figure 13.2.

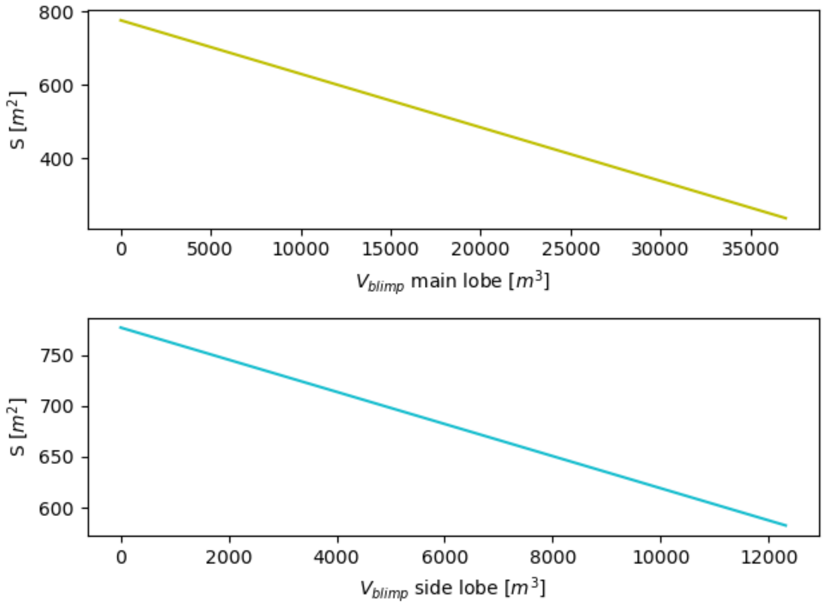


Figure 13.2: The plot on the top shows the area of lifting surface required to generate the same lift at cruise speed as a given volume of main lobe which contains helium. The plot at the bottom indicates the same but for the side lobes which contain hydrogen.

Here only cruise conditions are taken into account. On the x-axis the surface of a wing is placed. On the y-axis, the volume of either the main lobe or side lobe is placed. The purpose of these graphs is to show how much volume, and thereby indirectly the length and cross-sectional area, could be replaced during cruise by lifting surfaces such as wings. It shows that at a wing surface of $400\,\mathrm{m}^2$ could theoretically replace $10\,000\,\mathrm{m}^3$. This would massively reduce the drag during cruise, and thereby reduce fuel usage, or it allows the airship to fly faster than $100\,\mathrm{km/h}$.

With this new concept added, a new problem arises. Namely, achieving the reduction of the envelope volume and shape during cruise. For that, the already existent compressor could be used, indirectly allowing a size reduction. However, it might require adding a smaller hull shape inside the envelope, such that its size changes uniformly, causing no interference with stability, control, and propulsion.

Control surface

Besides the previously done back of the envelope calculations in section 6.7, a more in depth sizing method was performed. This method uses a scissor plot which shows the minimal required tail area based on the stability, control and C.G. range.

For the C.G. range, firstly the C.G. of the OEW is determined by using the C.G.'s of all subsystems and structures. The cargo is added first into the gondola and lastly the fuel is added. It could be concluded that the C.G. location does not change significantly and is therefore taken to be a constant value of $62.57\,\mathrm{m}$ from the nose.

The stability and control curve can be derived by making an FBD of the forces in the longitudinal direction and the increase or decrease of forces when a change of angle of attack is applied. The FBD can be seen in Figure 13.3. In the figure, B stands for body and h for the horizontal tail.

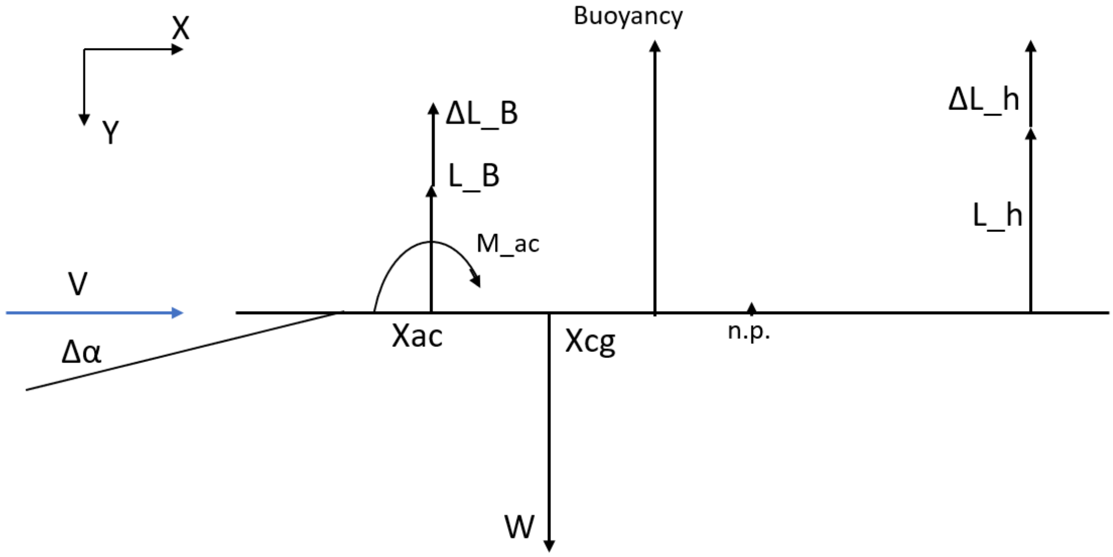


Figure 13.3: This figure shows the FBD of the airship.

Instead of the change in lift coming from the wing, for THETA, this change comes from the lift generated by the whole body. The stability curve can be derived from the FBD and the resulting formula can be seen in Equation 13.1 [22].

$$\frac{S_h}{S} = \frac{1}{\frac{Cl_{\alpha_h}}{Cl_{\alpha_B}}(1-\frac{d\epsilon}{d\alpha})\frac{l_h}{c}\frac{V_h}{V}^2} \cdot x_{cg} - \frac{x_{ac} - SM}{\frac{Cl_{\alpha_h}}{Cl_{\alpha_B}}(1-\frac{d\epsilon}{d\alpha})\frac{l_h}{c}\frac{V_h}{V}^2} \tag{13.1}$$

Here $\frac{l_h}{c}$ is the tails x-coordinate from the nose divided by the chord length, SMis a safety factor which is taken to be 5% and $\frac{d\epsilon}{d\alpha}$ is the change is angle of attack that the tail sees in comparison to what the body sees.

Since the airship is relatively large in volume and does not travel fast, the stability curve can be neglected. This is due to the disturbances created would take a relatively long time to take effect.

The controllability curve can be created in a similar manner but it is based on the static moment equilibrium about the C.G. instead of the change in moment around the neutral point. The formula that can be derived from this can be seen in Equation 13.2 [22].

$$\frac{S_h}{S} = \frac{1}{\frac{C_{l_h}}{-C_{l_B}}\frac{l_h}{c}\frac{V_h}{V}^2} \cdot -x_{cg} + \frac{\frac{C_{m_{ac}}}{-C_{l_B}} + x_{ac}}{\frac{C_{l_h}}{-C_{l_B}}\frac{l_h}{c}\frac{V_h}{V}^2} \tag{13.2}$$

Here x_{ac} is the normalised aerodynamic chord location, $C_{m_{ac}}$ is the moment around the aerodynamic chord and the parameters that were discussed before remain the same.

From the scissor plot it can be seen that the required horizontal tail surface area is zero. This is an interesting result for THETA and further research should be done to increase confidence in these findings. Since if this is true, this would result in the total weight going down due to the horizontal tail not being necessary.

Other markets

Through the use of external modular cargo, the design is multi-functional. Therefore, THETA can cater to a variety of markets.

As a secondary mission to the hydrogen-transport mission, the airship can be used for recreational purposes namely eco-tourism. This is a market which is already established, meaning that there exists a demand for such missions. The external cargo tank can be easily replaced with a gondola. Competitors in this industry include hot-air balloons and other airships which provide passenger transport such as the Zeppelin NT. Comparing THETA's capabilities with our competitors, a business case can be made for recreational use as THETA is competitive with their number of passengers, and use of green energy as fuel (see Table 13.1).

As the payload mass of the airship is fully replace by a larger gondola with passengers, the amount of potential passengers the airship can carry is significant, but difficult to estimate. But to provide an absolute minimum 16 passengers can at least be transported.

Table 13.1: Table compares competitors in the recreational eco-tourism market.

	Hot-Air balloons	Zeppelin NT	THETA
Number of passengers	4-10	15	>16
Fuel type	Propane	Avgas	Hydrogen
Fuel consumption	66 kg/h	100 kg/h	7.2kg/h

14 Conclusion

The aim of this report was to document the design process of a multi-lobed airship. The design is named THETA which stands for Tri-Lobed Hydrogen Emission-Free Transport Airship. The mission statement is as follows: *"Provide sustainable transport of hydrogen payload over intra-continental distances by 2040"*.

The presented design solution is a multi-lobed airship consisting of three lobes, all filled with hydrogen as lifting gas with the ability to carry a payload of 800 kg hydrogen and $\approx 11\,000$ kg of any other payload. The airship uses five electric Siemens SP200D engines, powered by hydrogen fuel cells. The payload will be carried in pressurised tanks and delivered to its destination which can be at a range of 2000 km. The tanks will be dropped off and empty tanks will be taken back as payload. THETA furthermore has a horizontal and vertical tail in a plus configuration. THETA's overall design and it's specifications can be seen in Table 14.1.

Table 14.1: This table contains the overview of parameters of THETA airship.

Parameter	Values
Airship mass	$69\,023$ kg
Airship volume	$66\,724$ m^3
Pressure difference	50 Pa
Cover thickness	0.3 mm
Cover mass	26.958 kg
Main lobe cover mass	$17\,119$ kg
Side lobes cover mass	4920 kg
Airship length	134 m
Airship width	56 m
Number of fuel cells	4
Power available fuel cells	$1\,200\,000$ W
Number of engines	5
Power available engines	$816\,000$ W
Propellant mass	340 kg
Total drag	$10\,975$ N

The structure that has been sized for the extreme cases with a safety factor of 2 for each member has a total mass of $23\,007$ kg. The materials used for each component are outlined in Table 14.2.

Table 14.2: This table contains the material choices for the airship components.

Component	Material
Envelope	Polyester
Coating	Polyurethane & Tedlar
Structure	CFRP (UD)
Gondola	Aluminium
Fin	GFRP

THETA needs to sell 28 airships to break-even due to its high total costs at 745 M€ and revenues obtained by solely by selling the airship listed at 70 M€. With the operation of the airship, the hydrogen operator breaks-even at 22 years. The growth of the hydrogen market shows great promise and the sustainability that the THETA airship provides outweighs its profitability. THETA consumes less energy, uses green energy namely hydrogen, and creates zero emissions. This puts THETA and its clients in a good position for government funding and support.

The design can still be greatly improved upon with iterations and more accurate estimation models for the technical aspects. Chapter 13 discusses these recommendations which may be followed after the design synthesis. The most important recommendation is to switch to a single lobed airship as that would greatly reduce the fuel usage, simplify the structure and allow for a much lighter and cheaper airship capable of accomplishing the same mission. Furthermore the possibility of reaching other markets should be explored, as that would add versatility to the design .

The hydrogen market is expected to grow rapidly in the coming decades which comes with an increase in demand and supply for hydrogen. This expedites opportunities for transport methods concerning hydrogen for which THETA is a more sustainable solution than presently available alternatives.

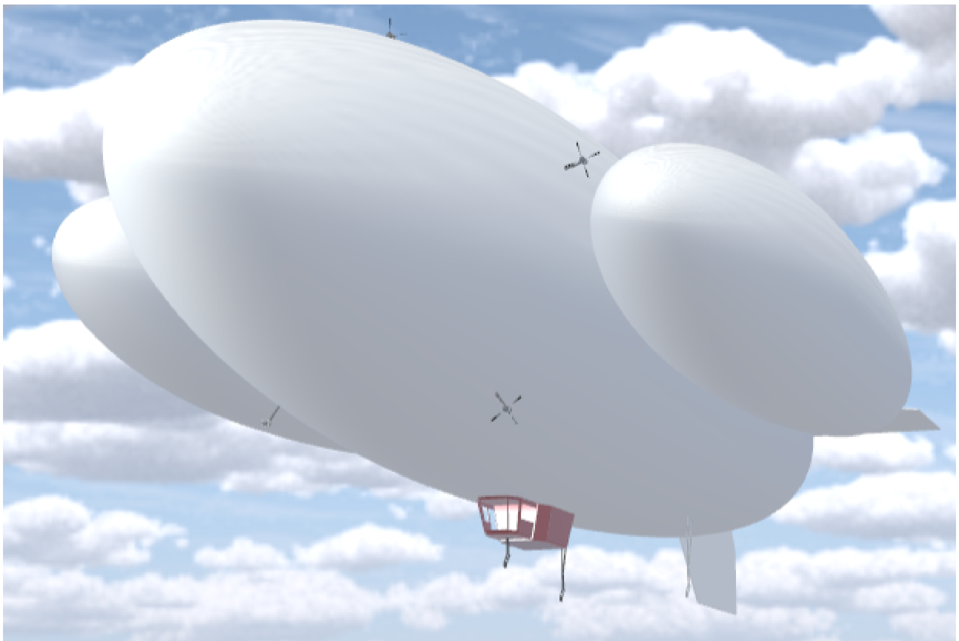


Figure 14.1: Picture shows a representation of the final render

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A

Appendix A: Functional Flow Diagram

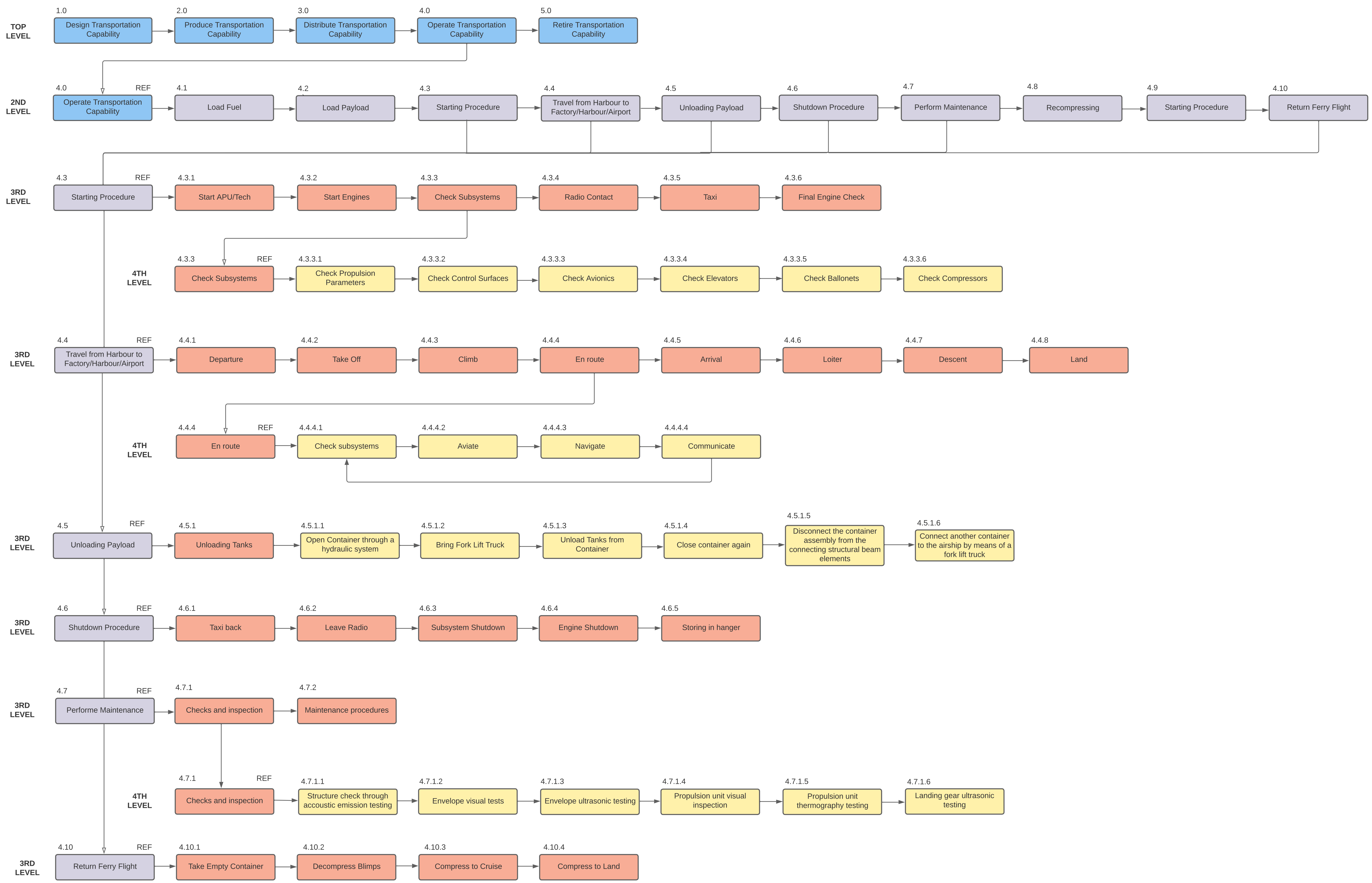


Figure A.1: Figure shows the Functional Flow Diagram of the mission.

B

Appendix B: Functional Breakdown Diagram

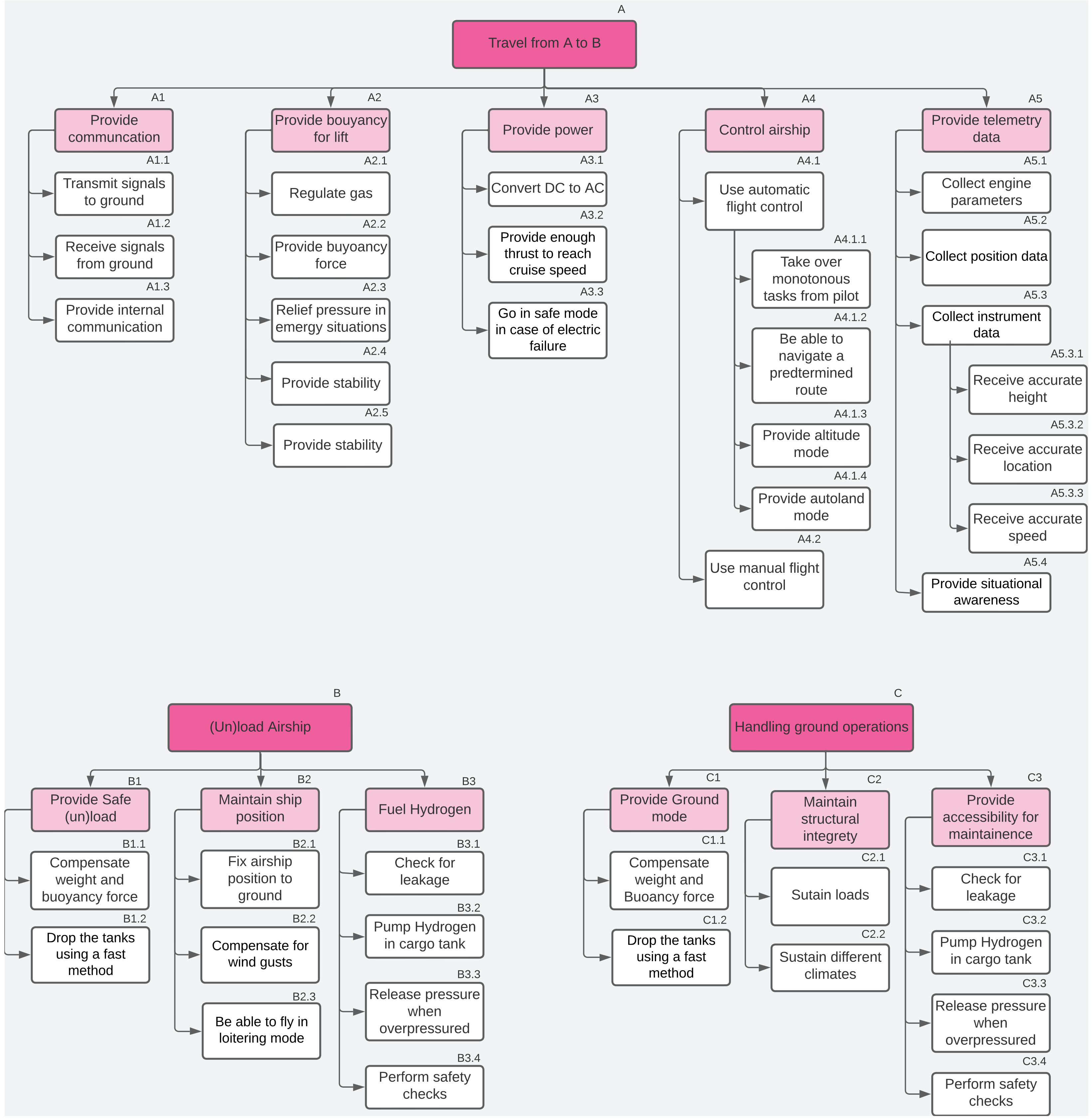


Figure B.1: Figure shows the Functional Breakdown Structure describing the mission phases, and the functions the airship carries out to satisfy its mission

C

Appendix C: Compliance Matrix

A compliance matrix is generated in order to determine whether the multi-lobe design meets the user and technical requirements. Some requirements may not be met, but the reason for this is explained in the comments. The different matrices for user requirements and technical requirements can be found in Table C.1 and Table C.2 respectively.

User Requirements

Table C.1: The table shows the compliance matrix of multi-lobe airship for user requirements.

Identifier	Requirement	Compliance	Comments
THETA–STAKE–01	The airship shall produce no emissions during operation.	Yes	Requires removal of jet and combustion engines from the design-options.
THETA–STAKE–02	The airship shall be safe to operate without requiring exceptional pilot skill.	Yes	Requires the airship to be trimmable, controllable and stable in conditions of the flight envelope.
THETA–STAKE–03	The airship shall carry at least two passengers, excluding pilot.	Yes	Given that the dimensions of the gondola is larger than a space that would be occupied by 3 people and the payload weight of a multi-lobe is very high, this is feasible.
THETA–STAKE–04	The airship shall maintain comfortable pressures, temperatures and noise level for the passengers.	Yes	The airship shall not fly at altitudes where pressurisation is necessary hence a comfortable pressure is maintained by not exceeding altitude.
THETA–STAKE–05	The airship shall be wheelchair accessible.	No	The gondola is limited only to pilots in the transport design case and hence will not feature accessibility for passengers. A transfer of markets by swapping the payload assembly to a gondola will provide wheelchair accessibility.

Identifier	Requirement	Compliance	Comments
THETA–STAKE–06	The airship shall offer low altitude tourist attractions.	Yes	Low altitude of less than 500 meters.
THETA–STAKE–07	The airship shall provide easy entry and exit of the vehicle.	Yes	The door size and location must be designed taking these factors into account.
THETA–STAKE–08	The airship shall look aesthetically pleasing.	Yes	The multi-lobed design looks futuristic and aesthetically pleasing
THETA–STAKE–09	The airship shall be pilot-able by a trained person.	Yes	
THETA–STAKE–10	The airship shall be able to operate autonomously.	Yes	Requires sensors such as radar, cameras etc. which do not interfere with the hydrogen and installation of on-board computers with a software.
THETA–STAKE–11	The airship shall have remote controllability.	Yes	Requires sensors such as radar, cameras etc. which do not interfere with the hydrogen and installation of on-board computers with a software.
THETA–STAKE–12	The airship shall comply with the certification requirements of laid out by the FAA	Yes	
THETA–STAKE–13	The airship shall transport hydrogen safely.	Yes	This is ensured by designing with respect to the regulations and having ensuring safety is a driving factor in the design stages.
THETA–STAKE–14	The airship shall land on the retrieval site.	Yes	While this is still an option, it is dependent on whether the end-consumer chooses to do so or not.
THETA–STAKE–15	The airship shall land on the delivery site.	Yes	
THETA–STAKE–16	The airship shall be 80% recyclable in terms of mass percentage.	Yes	
THETA–STAKE–17	The manufacturing shall be on-demand.	Yes	This requires the multi-lobe to be easily manufacturable and as simple as possible.
THETA–STAKE–18	The airship shall provide space for advertisements and promotions.	Yes	The large surface over the multi-lobe envelope can be used.
THETA–STAKE–19	The product shall be able to compete with substitutes or be able to fill a void in the aviation transport market.	Yes	After extensive market analysis, a gap in the market for safer hydrogen transport has been identified which can be exploited.

Technical Requirements

Table C.2: The table shows the compliance matrix of multi-lobe airship for technical requirements.

Identifier	Requirement	Compliance	Comments
THETA–SYS–VEH–01	The airship shall cover a range of at least 2000 km.	Yes	Multi-lobe can maintain flight for long periods of time. If it uses hydrogen onboard, this range will be easily met.
THETA–SYS–VEH–02	The airship shall operate below 3 km.	Yes	The multi-lobe is designed for altitudes below 3km.
THETA–SYS–VEH–03	The airship shall not exceed 60000 kg.	Yes	The airship has been designed with sufficient factors of safety and still meets this requirement
THETA–SYS–VEH–04	The airship shall have a length of at most 150m.	Yes	The airship length has been constrained and is well below 150m
THETA–SYS–VEH–05	The airship shall carry a minimum payload of 800 kg of hydrogen.	Yes	Airship is able to carry more than 800 kg due to its size.
THETA–SYS–VEH–06	The airship shall have a maximum velocity of 100 km/h.	Yes	A power system capable of powering the airship at this velocity has been implemented
THETA–SYS–VEH–07	The airship shall have a turn-over time of 1 year.	Yes	The currently designed airship is a limit case and is the most difficult one to produce, assuming that all parts can be sourced the deadlines can be met with relative ease.
THETA–SYS–VEH–08	The airship shall have the capability for complete autonomous flight.	Yes	Requires sensors such as radar, cameras etc. which do not interfere with the hydrogen and installation of on-board computers with a software.
THETA–SYS–STR–01	The structure shall not fail due to external loads in the worst-case scenario.	Yes	The structure is designed with FEM analysis and verified such that it is able to withstand all external loads at maximum possible magnitude applied at the same time with a safety factor of 2.
THETA–SYS–STR–02	The airship shall be capable of enduring lightning strikes.	Yes	Alternate current dissipation paths are provided over the airship in order to minimise impact from lightning strikes.
THETA–SYS–STR–03	The centre of buoyancy shall be above the centre of gravity of the airship.	Yes	The distance between the centre of gravity and buoyancy is approximately 1m longitudinally which can be assumed negligibly small relative to the size of the airship.

Identifier	Requirement	Compliance	Comments
THETA–SYS–STR–04	During manoeuvring, sloshing around of the lift gas bags or ballonets shall not interfere with the dynamics of the airship.	Yes	The volume of the gas bags/ballonets and the inertia of gasses are not large enough to impact the dynamics of the airship.
THETA–SYS–STR–05	Ballonets and gas bags shall not rupture during expansion.	Yes	
THETA–SYS–STR–06	Composites shall include a safety factor of 2.	Yes	This has been considered during structural design for all loading cases.
THETA–SYS–STR–07	Metallics used shall have a safety factor of 1.5.	Yes	This has been considered during structural design for all loading cases.
THETA–SYS–STR–08	The fabrics shall have a safety factor of 4.	Yes	This has been considered during structural design for all loading cases.
THETA–SYS–STR–09	External loads shall not cave in the envelope.	Yes	The structural layout has been designed such that the profile of the envelope is conserved under loads with additional reinforcement at the nose where aerodynamics loads are greatest. The truss structure extends along the envelope for continuous support.
THETA–SYS–MAT–01	The airship shall have an end-of-life duration of at least 15 years.	Yes	The materials used for the airship, specifically tedlar(tm) has excellent weather-ability and only needs to be replaced every 20 years, the fuel cells only need maintenance and replacements. Hence the airship shall satisfy this requirement.
THETA–SYS–MAT–02	The strength of the ballonet material shall be at least 35 MPa.	Yes	This is a structural consideration that can only be ascertained upon examination of the specific loads that will act on the design choice in flight conditions.
THETA–SYS–MAT–03	The permeability of the envelope material shall at most be 2 $g * mm/m^2$.	Yes	
THETA–SYS–MAT–04	The permeability of the ballonet material shall at most be 2 $g * mm/m^2$.	Yes	
THETA–SYS–MAT–05	The adhesive material shall be heat seal or RF weldable.	Yes	

Identifier	Requirement	Compliance	Comments
THETA–SYS–PERF–01	The airship shall use a lighter-than-air gas as lifting gas, as a means of generating aerostatic lift.	Yes	The mission profile uses hydrogen to generate lift and the concept of multi-lobe airships use a lifting gas.
THETA–SYS–PERF–02	The lift of the airship shall use a combination of aerostatic and aerodynamic lift.	No	This requirement can not be fulfilled since the design option chosen is one that relies solely on a lighter-than-air gas to provide aerostatic lift alone.
THETA–SYS–SUS–01	The airship shall have an emission lower than 60 g of CO2 per km.	Yes	The CO2 emissions will be non-existent since the multi-lobe option will make use of an electric motor.
THETA–SYS–SUS–02	The company shall aid in the global hydrogen demand through the utilisation of hydrogen carrying airships to every continent by 2060	Yes	This is the mission profile for which the multi-lobe is designed around.
THETA–SYS–SUS–03	The company shall aid in reaching the sustainable development goal 7 target 1: "By 2030, ensure universal access to affordable, reliable and modern energy services"	No	The airship is still a very expensive vessel for most companies and will likely only be profitable and affordable well into the future.
THETA–SYS–SUS–04	The company shall aid in reaching the sustainable development goal 7 target 2: "By 2030, increase substantially the share of renewable energy in the global energy mix"	Yes	The airship is designed to improve the transportation of pure hydrogen thus increasing the accessibility of renewables, hence aiding this SDG.
THETA–SYS–SUS–05	The company shall aid in reaching the sustainable development goal 8 target 4: "Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead"	Yes	The airship will ensure that a switch to a renewable hydrogen based economy is smoother, hence aiding this SDG.

Identifier	Requirement	Compliance	Comments
THETA–SYS–SUS–06	The company shall aid in reaching the sustainable development goal 8 target 9: “By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products”	No	The tourism use case for the airship, while very possible is not explored within this report and hence it is impossible to comply with this aspect of the SDG.
THETA–SYS–SUS–07	The company shall aid in reaching the sustainable development goal 12 target 2: “By 2030, achieve the sustainable management and efficient use of natural resources”	Yes	The airship will ensure that a switch to a renewable hydrogen based economy is smoother, hence aiding this SDG.
THETA–SYS–SUS–08	The company shall aid in reaching the sustainable development goal 12 target 5: “By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse”	Yes	The airship shall be mostly recyclable at the end of the product lifecycle, hence aiding this SDG.
THETA–SYS–SUS–09	The company shall aid in reaching the sustainable development goal 12 target B: “Develop and implement tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products”	No	The tourism use case for the airship, while very possible is not explored within this report and hence it is impossible to comply with this aspect of the SDG.
THETA–SYS–SUS–10	The airship, when its purpose is used for tourism, shall comply with local regulations.	No	The tourism use case for the airship, while very possible is not explored within this report and hence it is impossible to comply with this aspect of the SDG.
THETA–SYS–SUS–11	The airship shall have a noise level lower than 110 decibels during manoeuvring, take-off, and landing.	No	The multi-lobe is a large vehicle which produces noise. Noise mitigation measures can not be adequately designed within the timeframe.
THETA–SYS–SUS–12	The airship shall have a noise level lower than 60 decibels during cruise operation perceived on ground.	No	The multi-lobe is a large vehicle which produces noise. Noise mitigation measures can not be adequately designed within the timeframe.
THETA–SYS–SUS–13	The airship interior noise level shall not exceed 70 decibels during operations.	No	The multi-lobe is a large vehicle which produces noise. Noise mitigation measures can not be adequately designed within the timeframe.

Identifier	Requirement	Compliance	Comments
THETA–SYS–HAND–01	The envelope material shall be able to withstand a temperature of 50° C.	Yes	
THETA–SYS–HAND–02	The airship shall provide safe landing and be strong enough to support the full structural weight	Yes	
THETA–SYS–HAND–03	The airship shall be able to withstand rain fall.	Yes	
THETA–SYS–HAND–04	The airship shall be able to withstand snow fall.	Yes	
THETA–SYS–HAND–05	The airship shall be able to withstand hail.	Yes	
THETA–SYS–REG–01	The structure shall not fail when subjected to ultimate loads for 3 seconds.	Yes	The structure is able to withstand ultimate loads for more than 3 seconds due to a safety factor of 2. This is verified by FEM analysis.
THETA–SYS–REG–02	Airship shall have deicing systems on the propulsion system.	Yes	
THETA–SYS–REG–03	Airship shall have deicing systems on aerodynamic surfaces including the envelope.	Yes	
THETA–SYS–REG–04	Airship shall have all engines operative rate of climb of at least $1.524ms^{-1}$.	Yes	
THETA–SYS–REG–05	Airship shall have an all engines operative climb angle of 1:12.	Yes	The airship has completely vertical take-off capabilities.
THETA–SYS–REG–06	The airship shall be capable of maintaining level flight following critical failure of one engine if there are multiple engines.	Yes	The multi-lobe has fail-safe features that allow it to remain at level flight after one or more engine failures.
THETA–SYS–REG–07	The distance between the engines shall be at least 5 meters.	Yes	
THETA–SYS–REG–08	Multi-engine airship shall have steady rate of climb at sea level of at least $0.508ms^{-1}$ at one-engine inoperative condition	Yes	

Identifier	Requirement	Compliance	Comments
THETA–SYS–REG–09	The airship shall demonstrate manoeuvrability with neutral elevator controls when in static trim and equilibrium.	Yes	
THETA–SYS–REG–10	Airship shall have redundant structures in which partial failure of individual elements would result in applied loads being safely distributed to other load carrying members.	Yes	The structure has been designed such that load paths are not disturbed completely in case of a failure of a member. Due to safety factor of 2, all members are able to carry loads that adjacent members should carry.
THETA–SYS–REG–11	Cables used for the envelope shall not be smaller than 3.175 mm in diameter.	Yes	The cable diameter is not limited by regulations but by stiffness required.
THETA–SYS–REG–12	Flight controls, engine mounts and other structures located in the engine compartment shall be constructed of fireproof material.	Yes	The materials used are largely carbon fiber reinforced polymers and aluminium, both of which have good fire resistance properties.
THETA–SYS–REG–13	Ballonets shall be designed and installed such that their centre of displacement coincides longitudinally with the centre of buoyancy of the envelope.	Yes	
THETA–SYS–REG–14	The lifting gas shall be sectioned into separate compartments/tanks.	Yes	Multi-lobe airships have several compartments that contain the lifting gas separately.
THETA–SYS–REG–15	Each fuel tank shall be integrated such that it does not carry structural loads.	Yes	The fuel tanks are loaded in a subassembly that is designed to carry any loads.
THETA–SYS–REG–16	Passenger compartment shall be protected by a firewall resistant to more than 2500 K from possible flame sources.	No	
THETA–SYS–REG–17	Hydraulic lines shall not deform from external loads.	Yes	No hydraulic line is designed such that they carry significant loads.

Identifier	Requirement	Compliance	Comments
THETA–SYS–CON–01	Airship shall allow for redundant buoyancy control in case of lift surface devices fail.	Yes	Since lifting surfaces are not used this requirement is fulfilled by extension.
THETA–SYS–CON–02	Airship shall provide capability to maintain its attitude.	Yes	Multi-lobe airship designs can maintain attitude with aerodynamic stabilisers if necessary.
THETA–SYS–CON–03	Airship shall be capable of receiving ground instructions (autonomous control system).	Yes	
THETA–SYS–CON–04	Gondola shall be pressurised if personal flight at high altitude above 3 km is necessary.	Yes	The mission profile has changed and does not reach this altitude with people onboard.
THETA–SYS–CON–05	Airship shall have multiple access points to allow for easy inspection for maintenance.	Yes	
THETA–SYS–CON–06	Airship shall have automatic flight control.	Yes	
THETA–SYS–CON–07	Airship shall be manoeuvrable by non-mechanical means.	Yes	The airship shall utilise differential thrust based controls.
THETA–SYS–CON–08	Airship shall be safely operable with wind loads of $\approx 8ms^-1$.	Yes	
THETA–SYS–EMER–01	The airship shall have a venting rate of 50 % of the volume in the first minute.	Yes	
THETA–SYS–EMER–02	The airship shall follow the civil certification requirements for crash landings.	Yes	Progress in the design of the multi-lobe is made based on the criteria set by civil certification requirements.
THETA–SYS–EMER–03	The envelope shall not deform upon exceeding the ballonet ceiling.	Yes	The airship envelope is designed with the ceiling in mind and shall not deform upon reaching it.
THETA–SYS–EMER–04	The airship shall have sufficient capability for evacuation.	Yes	Multi-lobe airships have easily accessible gondolas which make the evacuation efficient.
THETA–SYS–RES–01	The production cost shall be lower than $10.000.000.	No	Number is set too low for such a large and complex airship design. The manufacturing cost is approximated to be 45 M€ for THETA's design.
THETA–SYS–RES–02	The team shall deliver a final design by 27 june 2023.	Yes	The team is on track and meeting the deadlines to achieve this requirement.

D

Appendix D: Material Options

The properties of potential materials for the rigid structure can be found in Table D.1 and Table D.2. Note that for composite, σ_{yield} and $\sigma_{tensile}$ coincide as composites do not yield, but they fracture at the ultimate strength.

Table D.1: Table gives an overview of the main material options for the rigid structure inside the balloon from [17] and [11].

	Density	σ_{spec} [kN.m/kg]	E [GPa]	σ_{yield} [MPa]	$\sigma_{tensile}$ [MPa]
Wood	850-1030	50.82-51.26	20.6-25.2	43.2-52.8	133-162
Carbon steel	7800	48.21-119.10	200-220	376-929	591-1190
Alloy steel	7750-8050	16.52-198.76	200-210	469-1600	699-1800
Stainless steel	7610-7870	32.77-144.85	190-210	257-1140	515-1300
Aluminium	2650-2770	44.53-94.95	69-76	118-263	193-341
Duraluminum	2670-2840	90.26-183.10	68-76	241-520	288-571
Titanium	4430-4790	158.24-227.56	110-120	701-1090	763-1190
Nickel	8830-8950	7.93-100.56	190-220	70-900	345-1000
CFRP	1800-1840	1333.33-1309.78	370-390	2400-2410	2400-2410
GFRP	2550-2600	745.1-788.46	72-85	1900-2050	1900-2050

Table D.2: Table gives the continuation of the overview of main material options for the rigid structure inside the balloon based on [17] and [11].

	Cost [€/kg]	Sustainability*
Wood	5.71-9.21	Sustainable
Carbon steel	0.595-0.626	Sustainable
Alloy steel	0.642-0.769	Sustainable
Stainless steel	2.4-2.57	Sustainable
Aluminium	1.71-1.86	Sustainable
Duraluminum	3.03-3.2	Sustainable
Titanium	19.3-20.9	Sustainable
Nickel	6.71-9.03	Fairly Sustainable
CFRP	44.7-89.5	Sustainable
GFRP	1.39-2.78	Sustainable

The properties of potential materials for the load-bearing component of the envelope can be found in Table D.3 and Table D.4.

Table D.3: Table shows an overview of the different options for envelope material of the airship [11] [17].

	Density	σ_{spec} [kN.m/kg]	E [GPa]	σ_{yield} [MPa]	$\sigma_{tensile}$ [MPa]	Cost [€/kg]
Cotton	1520-1560	65.79-224.36	7-12	100-350	360-660	1.53-4.43
Nylon HT	1140	34.21-56.14	0.94-2.04	39-64	800	3.73-5.51
Polyester HT	1340-1500	24.63-26.67	2.07-4.41	33-40	1000	1.65-1.74
HMPP	840	28.69-33.81	0.824-1.02	24.1-28.4	630	1.09-1.14
Nomex	1380		17		650	10.7-12.5
Vectran HT	1410		75		3200	
Vectran UM	1400	2071	75	3.0		
ZylonAS	1540		180		5800	
Zylon HM	1560		270		5800	
HMPE	970		110		3500	
Graphite-AS4	1800	2083.33-2222.22	225-260	3750-4000	4400-4800	21.4-28.6
E-Glass	2600	730.77-788.46	72-85	1900-2050	1900-2050	1.39-2.78
Aluminium	2650-2770	44.53-94.95	69-76	118-263	193-341	1.71-1.86
Titanium	4500	155.77-242.22	110-120	701-1090	1300	19.3-20.9
Steel Fibre	7800-7900		200		2800	
Kevlar	1440-1450	1562.5-1896.55	125-135	2250-2750	2500-3000	59.9-169
Mylar	1290-1390	38.76-39.57	2.8-3	50-55	55-60	0.614-1.08

Table D.4: Table shows the continuation of the overview of different options for envelope material of the airship [11] [17].

	Sustainability*
Cotton	Fairly sustainable
Nylon HT	Unsustainable
Polyester HT	Unsustainable
HMPP	Fairly sustainable
Nomex	Fairly Sustainable
Vectran HT	
Vectran UM	
ZylonAS	Sustainable
Zylon HM	Sustainable
HMPE	
Graphite-AS4	Unsustainable
E-Glass	Sustainable
Aluminium	Highly Sustainable
Titanium	Sustainable
Steel Fibre	Sustainable
Kevlar	Very Sustainable
Mylar	Unsustainable

The properties of potential materials for the coating can be found in Table D.5, Table D.6 and Table D.7. Here "UV light" is the resistance to UV light. Note that from the source, the permeability of helium is given, whereas for THETA hydrogen is used. However, hydrogen has a lower permeable coefficient, meaning that if a material has a low helium permeability, this will be even lower for hydrogen[1] [15].

[1] T. Welter et al. "Hydrogen Permeation Through Glass". In: (2020). URL: `https://www.frontiersin.org/articles/10.3389/fmats.2019.00342/full` (visited on 05/25/2023).

Table D.5: Table shows the material options for the coating of the envelope of the airship [11] and [17].

	Density [kg/m^3]	$\sigma_{tensile}$ [GPa]	σ_{yield} [MPa]	Abrasion Resistance	Permeability*
Natural rubber	930	3.0	21-28	Excellent	Fair
Neoprene	1230	3.0	12-24	Excellent	Low
Butyl	920	2.0	2.4-10	Good	Very low
Silicone	1100-1600	1.0	7-11.5	Poor	Fair
Hypalon	1120-1280	3.0		Excellent	Low
Hythrel	1170-1250	3.6-5.5		Excellent	High-Fair
Polyurethane	1050-1300	4.0	36-42	Excellent	Low
PVC	1200-1350	1.5-3.5	37.6-45.5	Excellent	Fair-low
Saran film	939-960	0.207-0.448	17.9-29	Excellent	
TiO_2	4010	0.33-0.37		Moderate	
Tedlar	1400	0.06-1.2	19.7-21.7		Low

Table D.6: Table shows a continuation of the material options for the coating of the envelope of the airship [17] [11].

	Weatherability*	UV light	Adhesion to fabrics	Sustainability*
Natural rubber	Poor	Poor	Excellent	Fairly sustainable
Neoprene	Good	Poor	Excellent	Unsustainable
Butyl	Excellent	Poor	Good	Sustainable
Silicone	Excellent	Good	Good	Sustainable
Hypalon	Excellent		Good	Fairly unsustainable
Hythrel	Good (with additives)		Good	Sustainable
Polyurethane	Good	Fair	Excellent	Sustainable
PVC	Good	Fair	Excellent	Unsustainable
Saran film		Moderate	Fair	Fairly sustainable
TiO_2			Moderate	Sustainable
Tedlar	Excellent	Moderate	High	Sustainable

Table D.7: Table shows a continuation of the material options for the coating of the envelope of the airship [17] [11].

	Flammability*	Cost [€/kg]
Natural rubber	Highly flammable	1.93-2.09
Neoprene	Self extinguishing	3.11-3.65
Butyl	Highly flammable	1.53-1.63
Silicone	Self extinguishing	3.18-3.56
Hypalon		0.60-4.83
Hythrel		
Polyurethane	Slow burning	2.54-2.82
PVC	Self extinguishing	1.5-1.64
Saran film	Highly flammable	1.19-1.24
TiO_2		4.101
Tedlar	Non-flammable	34-41

In Table D.8 and Table D.9 an overview of the main options for film materials are shown.

Table D.8: Table shows an overview of film materials that could be used for the airship [17].

	$\sigma_{tensile}$ [MPa]	ϵ_{ult} [%]	Gas permeability*	Adhesion to fabrics/film
Polyurethane	31-62	400-600	Low	Excellent
Tedlar	60-1200	90-250	Low	Poor
Polyester	41.4-89.6	40-120	Low	Fair
Nylon	42-72	300-500	Very Low	Fair
Saran	20.7-44.8	30-60	Very low	Fair
PTFE	20.7-34.5	300	Fair	Poor
Low-density polyethylene	20.7-44.8	90-800	Fair	Poor
PVC	38-46	200-400	Fair-Low	Excellent

Table D.9: Table shows the continuation of the overview of film materials that could be used for the airship [17].

	Heat Sealable	Weatherability*	Flex fatigue resistance
Polyurethane	Yes	Good	Good
Tedlar	Yes (with adhesives)	Excellent	Excellent
Polyester	No	Fair	Fair
Nylon		Poor	Excellent
Saran	Yes	Poor	Fair
PTFE	Yes (some grades only)	Excellent	Good
Low-density polyethylene	Yes	Good if pigmented	Excellent
PVC	Yes	Good	Good

Table D.10: Table shows the continuation of the overview of film materials that could be used for the airship [17].

	UV light	Dimensional stability	Sustainability*
Polyurethane	Fair	Poor	Fairly sustainable
Tedlar	Moderate	Good	Fairly sustainable
Polyester	Fair	Excellent	Unsustainable
Nylon	Fair	Excellent	Fairly sustainable
Saran	Moderate	Good	Fairly sustainable
PTFE	Good	Good	Fairly sustainable
Low-density polyethylene	Fair	Poor	Fairly sustainable
PVC	Fair	Poor	Fairly sustainable

*Following the example of Khoury (2014), sustainability, permeability, flammability and weatherability are expressed in general terms , not in exact numbers, as this provides a clear overview of which materials are good options in these regards and which are not [17]. For easier visualisation of the best options, the exact numbers are deemed unnecessary.

E

Appendix E: Cockpit Layout

The cockpit lay out will contain the following elements, schematically shown in Figure E.1. It is based on the cockpit layout of other existing airship, mainly the Goodyear[1]:

- **a** Conventional circuit breakers.
- **b** On/off engines control system.
- **c** Electrical power system for avionics, light, etc.
- **d** Fuel system, used to balance the airship as well.
- **e** Heater/airco.
- **f** Fire protection system.
- **g** Cabin lights and signs system.
- **h** Emergency valve system.
- **i** Air control system valves. For controlling the ballonets to maintain a constant pressure and to balance the airship.
- **i** Helium/hydrogen control system.
- **j** Crew communication system.
- **k** Side lobe deflating/inflating and folding systems.
- **l** Old fashioned compass in case of electrical navigation fails
- **m** Navigation system.
- **n** Primary flight Display. Usually the helicopter edition is used, as helicopters also fly relatively slow and low.
- **o** Radar screen to spot other air vehicles and the weather conditions.
- **p** Emergency stand by equipment on batteries.
- **g** crew alerting system, screens to monitor every system in the airship.
- **h** Thrust vector control systems.
- **i** Joystick for steering.

[1] Goodyear. *Goodyear blimp gondola and cockpit tour*. 2020. URL: `https://www.facebook.com/GoodyearBlimp/videos/goodyear-blimp-gondola-and-cockpit-tour/245983633161283/` (visited on 06/01/2023).

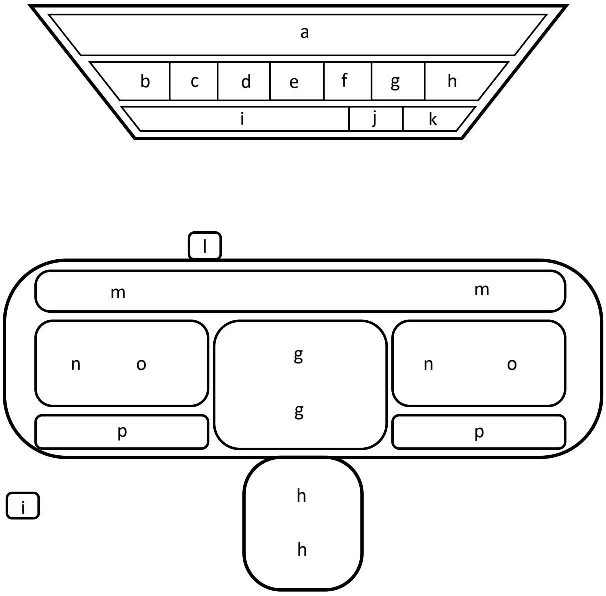


Figure E.1: The schematic overview of the cockpit layout. It was mostly based on the Goodyear airship cockpit.

Other elements in the gondola are a resting place for the pilots in case of a long flight and a toilet. For the toilet chemical or vacuum flush toilets can be used. The water created by the hydrogen fuel cells could be utilised in case of the latter option.

F

Appendix F: Engine Options

The engine options are shown in Table F.1. They are ranked from best to worst in terms of their most important criterion, being the $\frac{power}{mass}$ ratio.

Table F.1: Table shows engine options for the airship. These are all electric engines.

Engine Type	Power/Mass [kW/kg]	Number of engines	Total mass [kg]
Siemens SP200D	4.16	3	147
ENGINeUS™ XL-100	3.5	6	171.4
MagniX 650	3.22	1	200

G

Appendix G: Empirical Data

The landing gear positioning, done in subsection 6.7.3, makes use of Figure G.1 and Figure G.2 from [20].

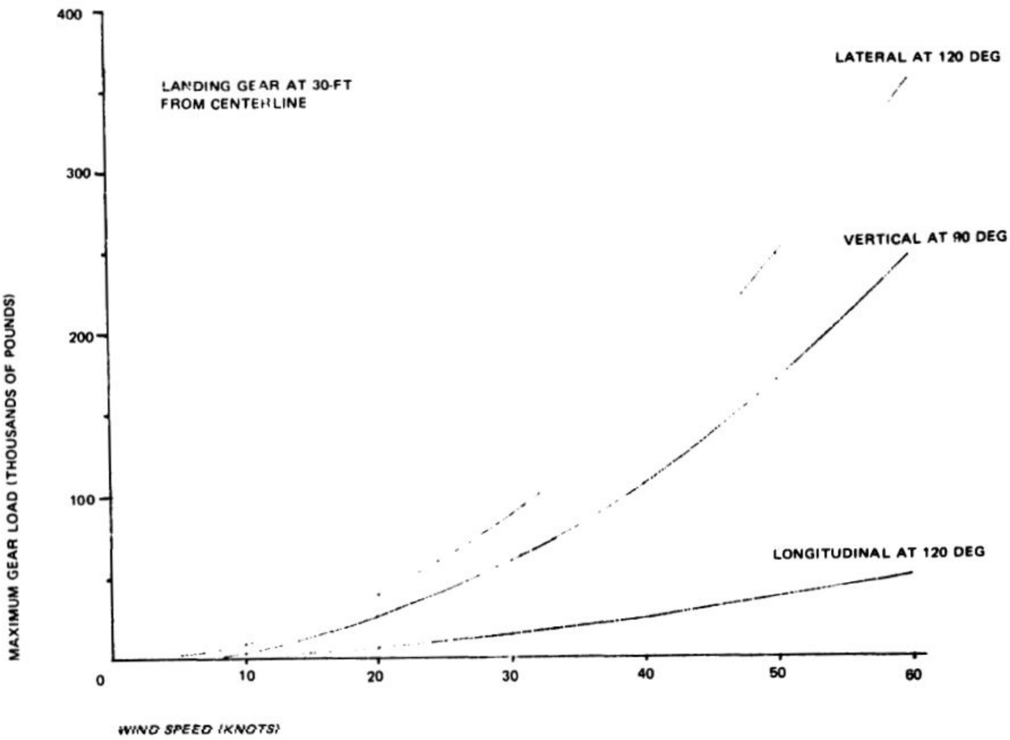


Figure G.1: Graphs shows the maximum gear load plotted against the wind speed.

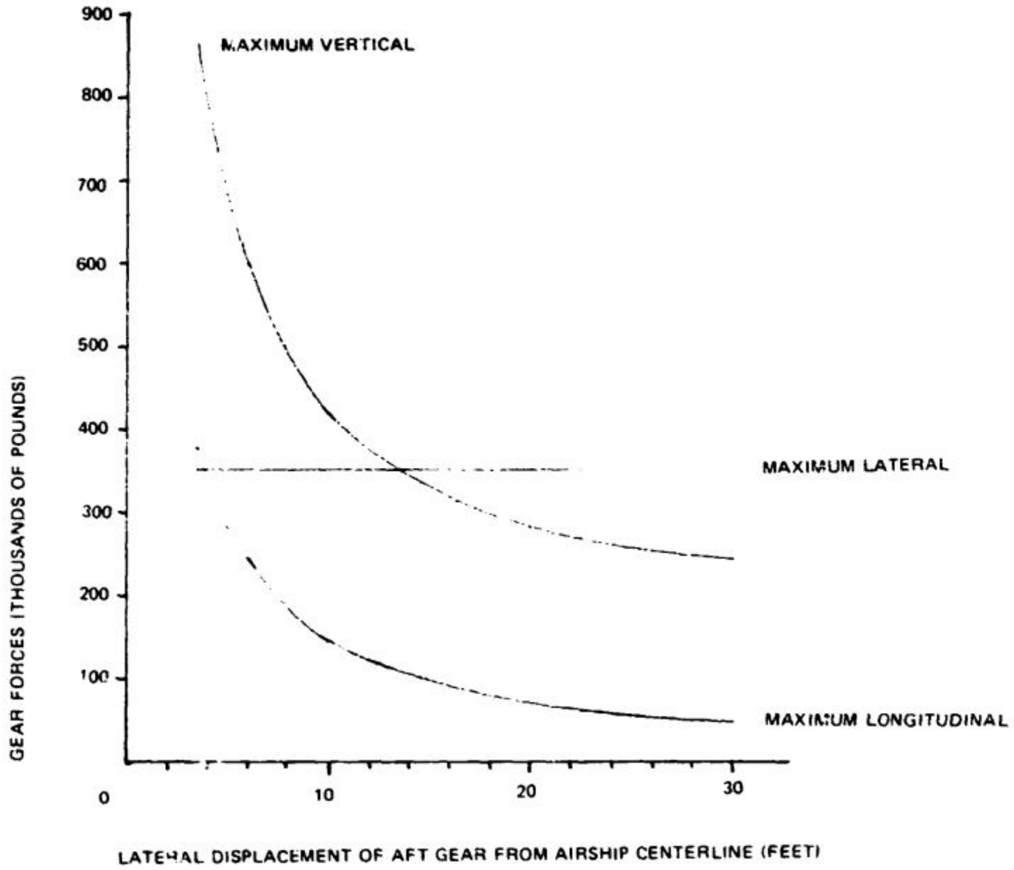


Figure G.2: Graphs shows the gear forces plotted against lateral placement of aft gear from the center of gravity.

H

Appendix H: Project phases

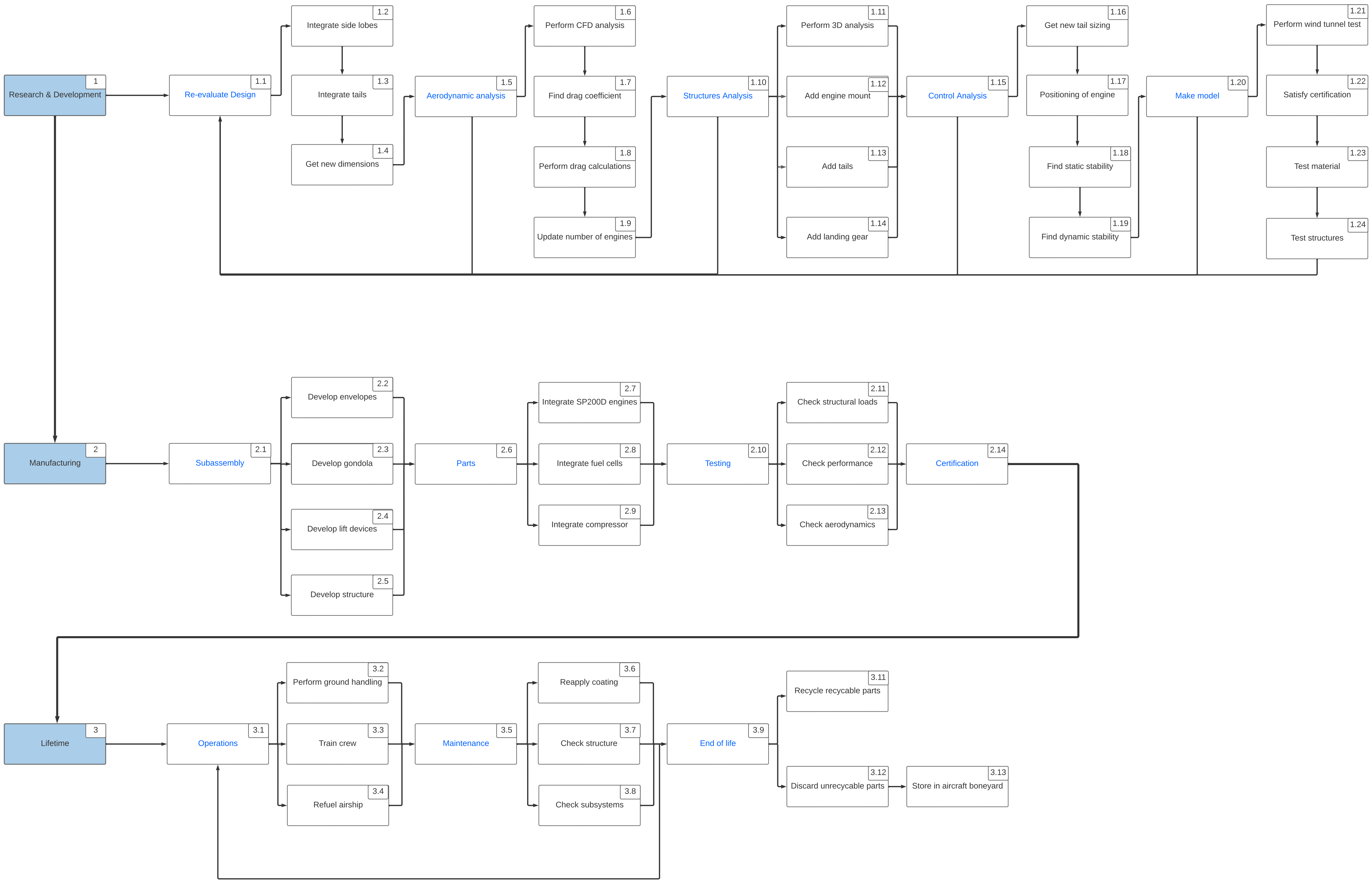


Figure H.1: Figure presents an overview of project phases and activities post-design synthesis.

I

Appendix I: Gannt Chart

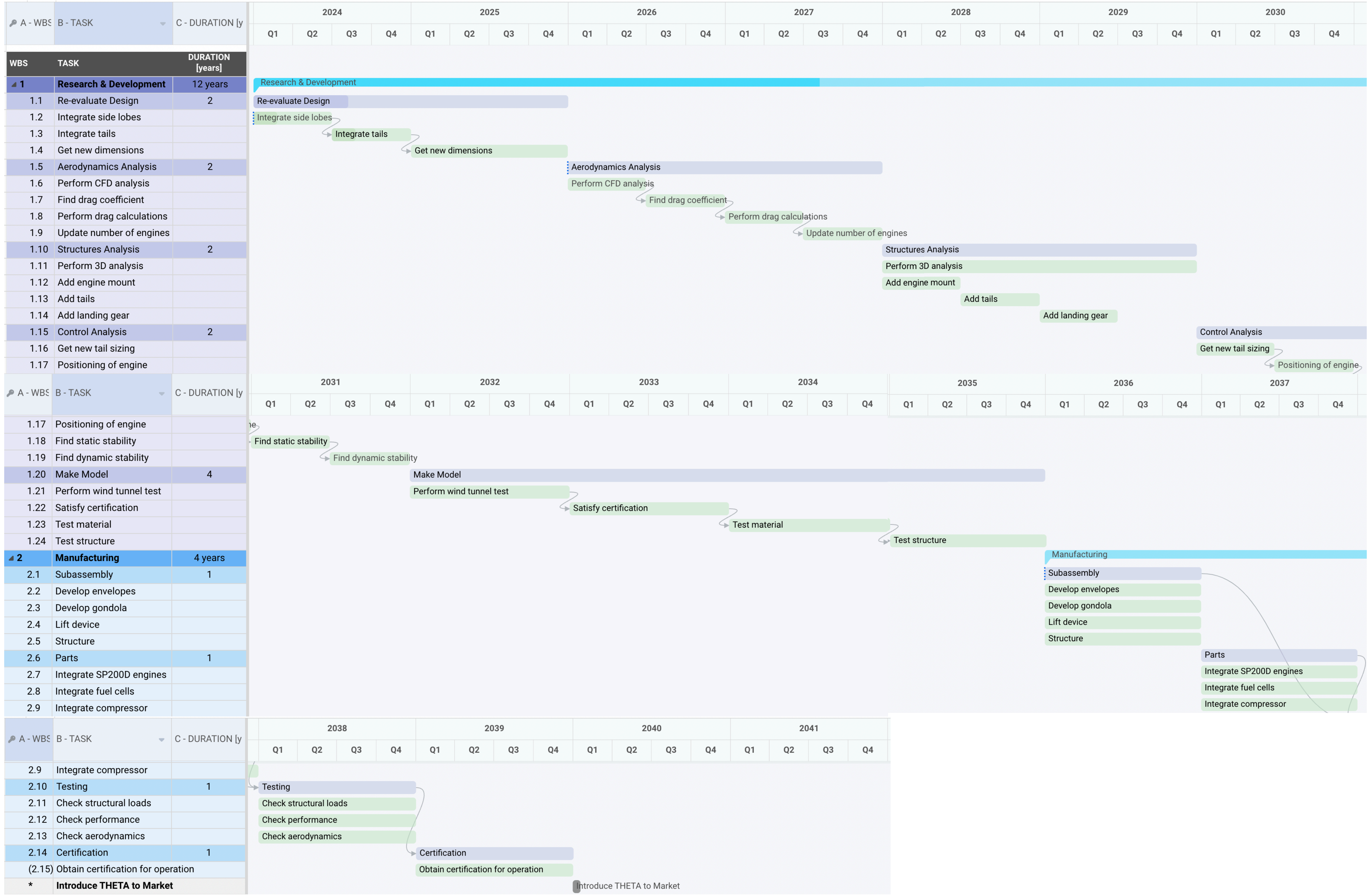
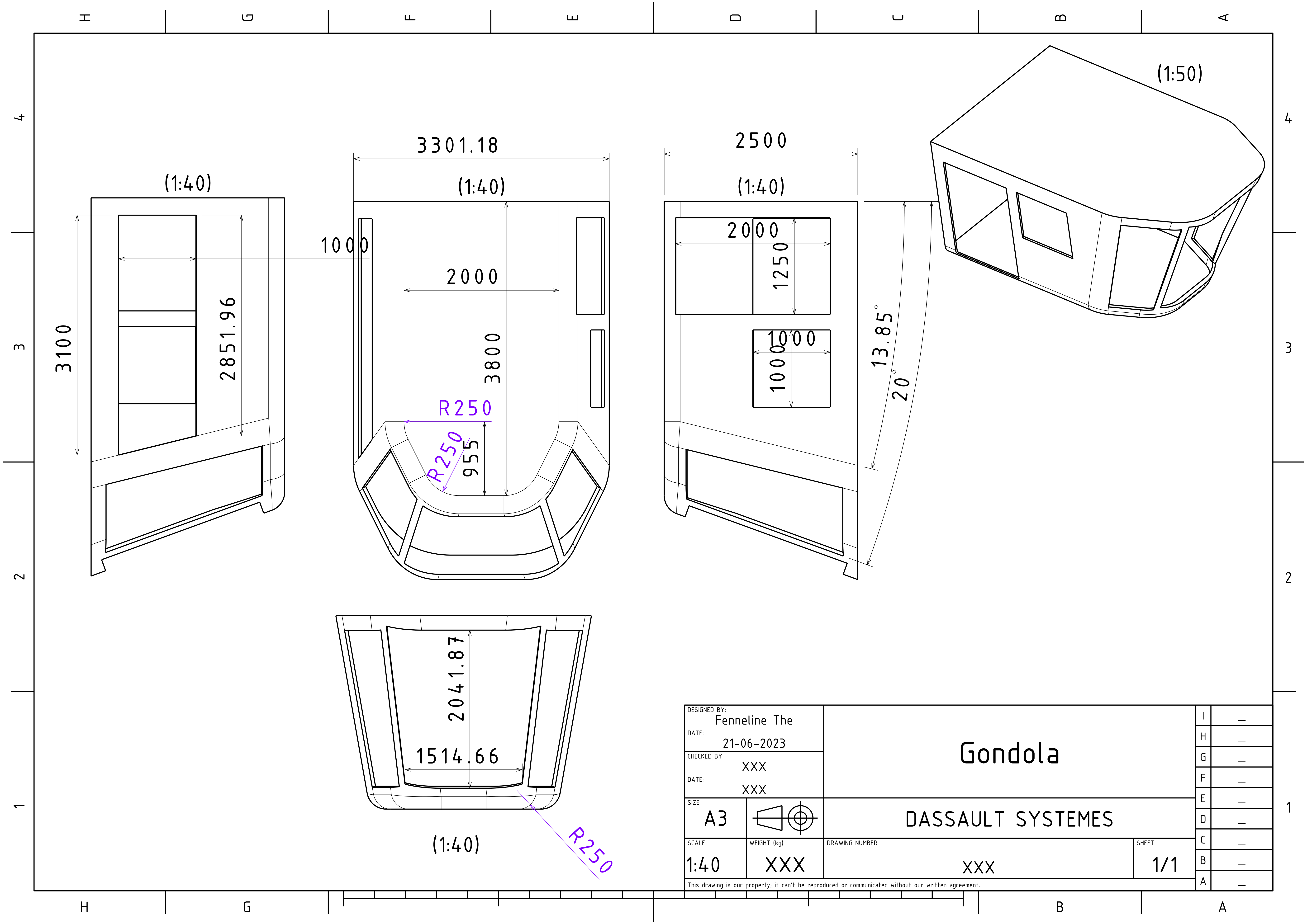


Figure I.1: Gantt chart depicting THETA's next phases to develop the airship post-design synthesis.

Figure I.2: Gantt chart depicts the operational lifetime of the airship.

J

Appendix J: Technical Drawing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DESIGNED BY:
Fenneline The
DATE:
21-06-2023
CHECKED BY:
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DATE:
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SCALE
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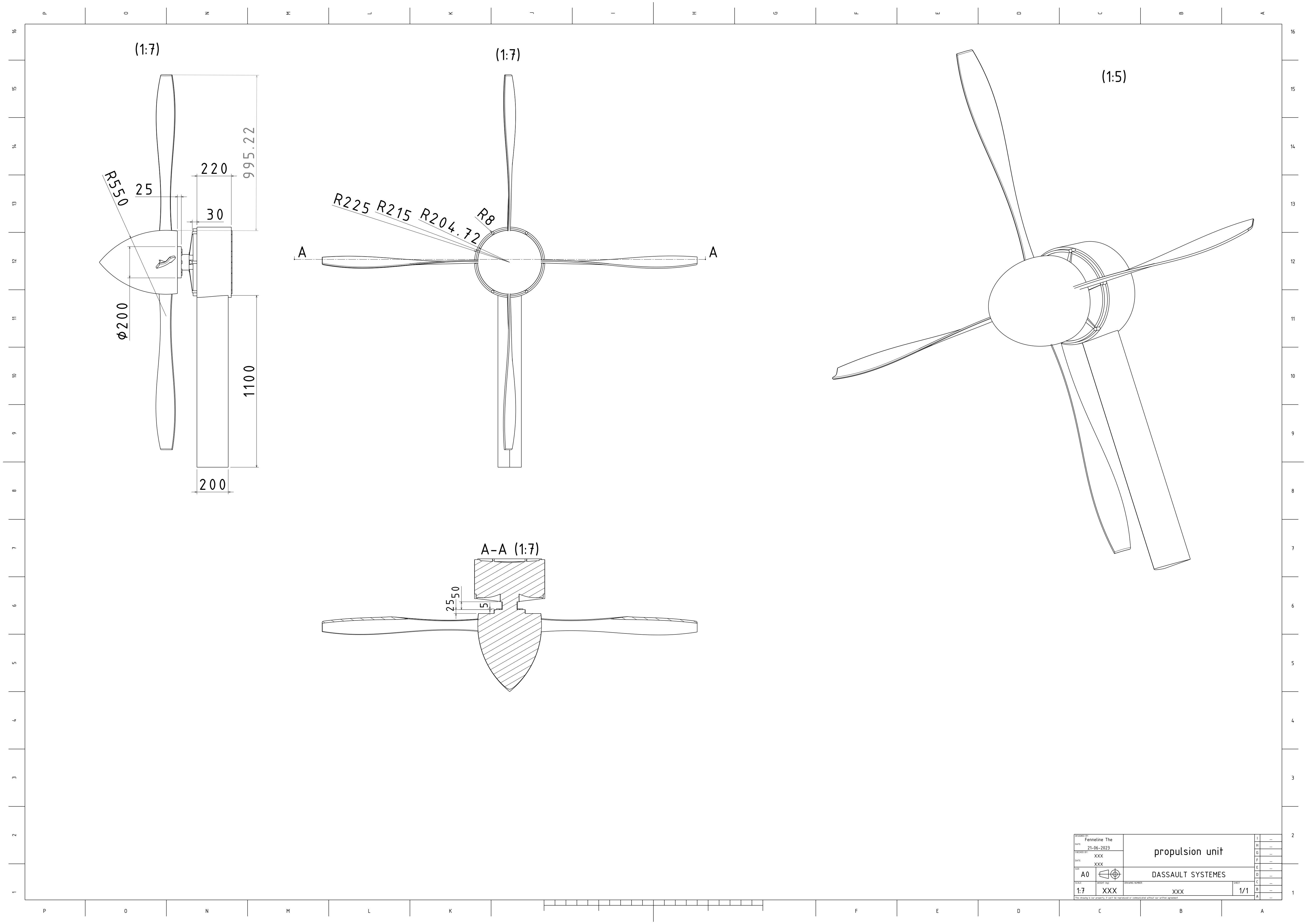
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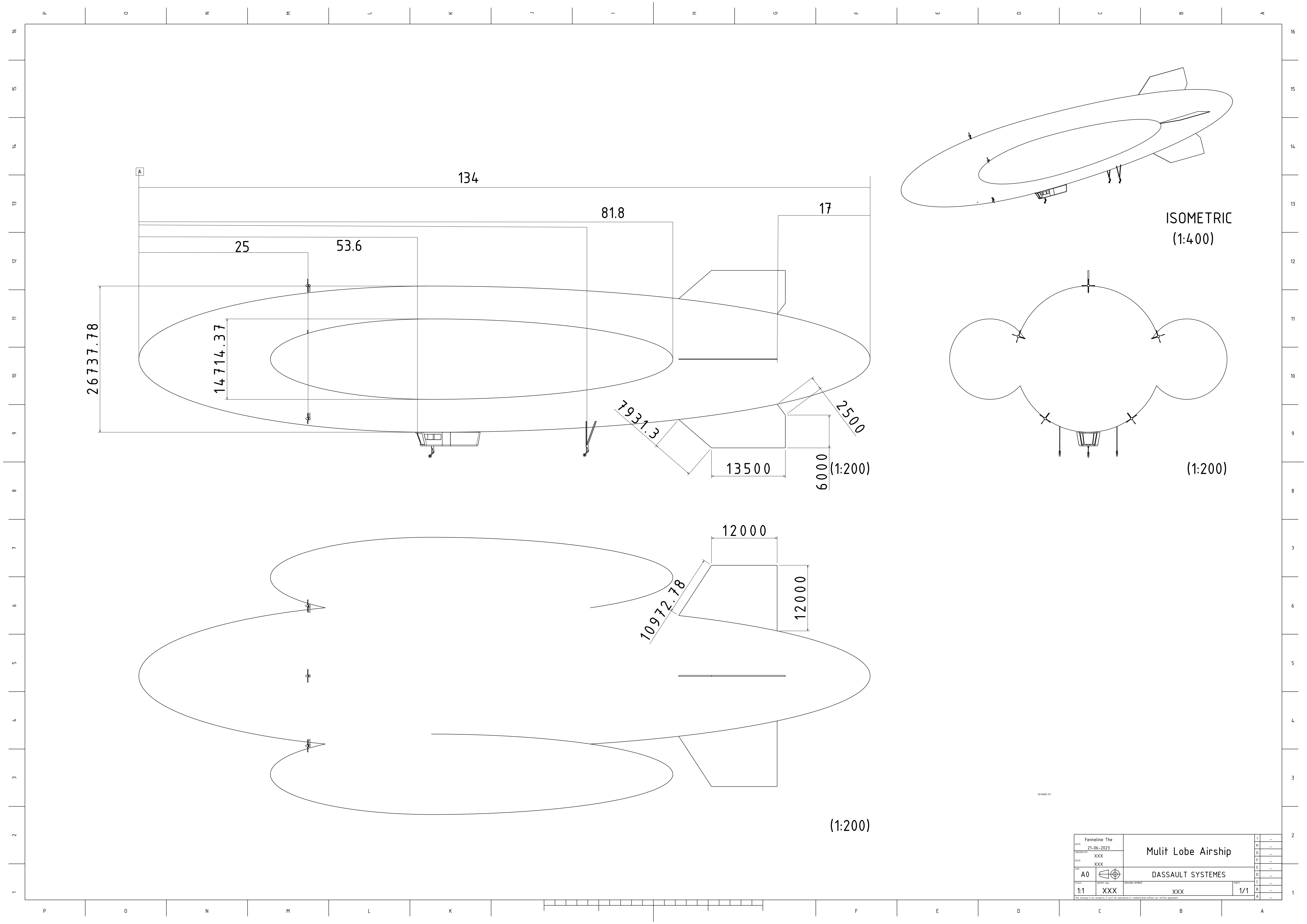

134
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14714.37
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