Final Report

for the DSE assignment spring 2024

Cargo Airship for wind turbine installations

Group 03

This page is intentionally left blank.

Final Report

for the DSE assignment spring 2024

by

Group 03

Student Name	Student Number
M.V. Altuntepe	4875893
P. Arellano Benito	5486629
B.A.S. Bezemer	5228476
R. T. Bouwmeester	5485126
I.V.I. Fransen	5459354
J.W.S. Jacobs	5573890
D. Klaver	5265118
M. Mendez Garcia	5316979
G.A. Skorupska-Ruiz	5528968
J.H.C van der Meer	4997476

Change log		
Version	**Date**	**Changes**
1.0	19th June, 2024	First draft
1.1	25th June, 2024	Final version

Principal Tutor: Theodoros Michelis
Date: Tuesday 25th June, 2024
Faculty: Faculty of Aerospace Engineering, Delft

TU Delft

Executive Summary

The ever increasing demand for green energy has made wind turbines quickly grow in size. In fact, wind turbines have enlarged so much that they have hit the limits on what is possible for ground transport. Trucks are typically used for transporting these massive structures, however their size and speed pose significant challenges for transport, especially when delivering to remote locations. The solution might be found in a forgotten giant from the past; the airship.

Wind farms are located both on and offshore. Transporting wind turbine blades offshore is mostly done via the use of ships, which have a large carrying capacity and fewer limitations than other current transportation methods. For this reason, the market goal is to operate in onshore transportation of wind turbine blades within Europe.

The onshore market is mainly dominated by trucks, turning them into our main competitors. Airships present several advantages over trucks. Airships can transport large and heavy cargo over any terrain, at a reasonable speed and low cost. They do not require road closures or hiring of special regulators to help with the transportation process. Through their increased operational flexibility, airships would not only benefit the wind energy industry but also the local communities who are inevitably impacted by these disruptions.

As the airship will operate within Europe, several operating base locations have been identified in this territory. These are located in Spain, Germany, France, and Denmark. The airship will take off from its base in one of these locations and fly to the blade manufacturer to exchange the ballast for the payload. Once the payload is loaded, it will fly to the wind farm where it will exchange the payload for a new ballast. If the delivery of another blade is necessary, the airship will repeat the mentioned trip, otherwise, it will fly back to base. The typical mission is presented in Figure 1.

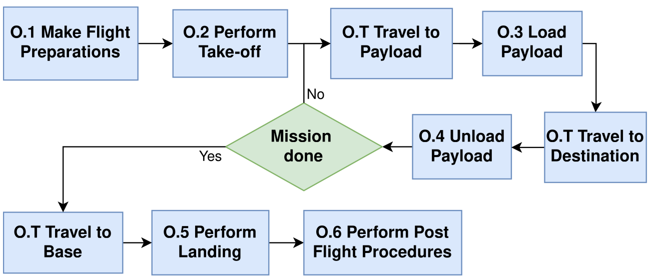


Figure 1: *Simplified version of the operational phase of the airship*

In order to design the best performing and most efficient airship that can perform the missions, a trade-off of the main system characteristics was performed. Four configurations with different characteristics such as the system's structure, cargo location, and propulsion system were compared. A visual of the chosen configuration alongside its characteristics is presented in Figure 2.

Table 1: *High-level system description of the chosen concept to enter detailed design.*

System	Choice
Type	Non-hybrid
Structure	Rigid
Cargo Hold	Internal
Remain Stationary	Moor
Landing	Vertical
Take Off	Vertical powered
Propulsion System	Fuel Cell

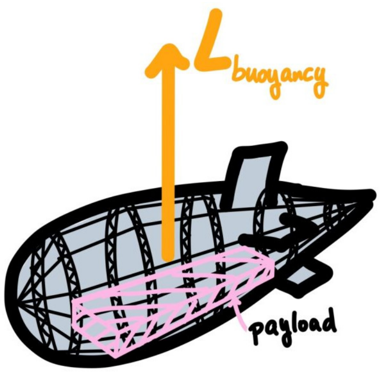


Figure 2: *Visual of the chosen concept to enter detailed design.*

With the conceptual design determined, a more detailed design process based on this concept was performed. Requirements of the main stakeholders were established to guide this process. The design process follows a classic V-model approach; first breaking up the system into smaller pieces, designing these, and building them back up while checking if they meet the requirements and needs. In this report the main subsystems of the airship are designed and analysed. The subsystems were not designed sequentially, as concurrent engineering speeds up the design and better allows for iteration. At the start, statistical estimations were used for the mass and aerodynamic coefficients.

The first subsystem was the aerostatics. The aerostatics system is the heart of the airship, as it defines the hull volume which directly and indirectly influences all other systems. The volume and mass of the lifting gas, hydrogen, were determined and a containment method was devised. The required volume was found to be 223 000 m^3 which results in a total hydrogen mass of 15.6 tonnes. To accomodate this gas, 16 gas cells are needed. To enhance the safety of the airship, both active and passive measures were taken. These include the mixing the hydrogen gas with incombustible gasses to reduce the flammability and the monitoring of the pressure inside the envelope.

The aerodynamic performance of the airship is another key element, as it establishes the hull shape as well as the aerodynamic coefficients to be used by every other sub-system. Lift, drag, and aerodynamic moments are all results of this analysis.The length of the airship was calculated to be 221 m, with a diameter of 48 m.

The stability and controllability of the system are achieved by locating the center of gravity and sizing the tail surfaces. A trade-off was performed to come to the classic *plus*-tail configuration. With this, a sizing of the tail was performed to guarantee stability in flight. A cg-excursion was also performed to make the ship controllable in all phases of operation. Lastly, it was looked into if pilot-less operation was feasible. At the start of operations, the airship will be piloted manually. If multiple airships are built, limited auto-pilot might be implemented in a later time or even developed to full autopilot in a farther future.

To propel itself forward, the airship uses a total of six vectored electric motors strategically positioned to provide controllability during low speed flight. The hydrogen fuel cells provide enough power for these engines and other systems that require electricity, such as the cockpit and tail.

For the system to be capable of supporting the mass of the payload and that of the other subsystems, the structure and materials of the airship were examined. The internal structure of the airship must have the correct stiffness to support the loads applied to it. The airship uses a truss structure to accomplish this. For the outside shape, the airship uses a combination of longerons and rings. Special attention is given to the payload bay, ensuring the load path of the rings are not disturbed. The material of the truss should be stiff, non-corrosive, weldable and recyclable, for which Aluminium 6061-T6 was chosen. The gas cells need to be flexible, gas impermeable, non-flammable and highly resistant to tear. For this, Nylon was chosen as the gas retention layer and Zylon as the load bearing layer, with an adhesive layer between them. For the envelope a layer of polyurethane is chosen, as it is UV-protective and load carrying.

Once all the other subsystems were designed, it was possible to examine the performance of the airship. The performance analysis focused on determining the ideal cruise speed, flight altitude, and buoyancy ratio. These came out to be 80km/h, 2000m, and 0.9967 respectively. Additionally, the range and endurance of the system was identified for different two different climb and descent strategies.

Finally, the method for loading and unloading the blade was examined. To do this, the airship will moor at the wind farm and ballasts will be used as counterweight to remain stable. The cables that are needed for mooring are designed followed by the design of the several types of ballast. There are two types of ballast; permanent (water tanks) and temporary (dirt). The ground infrastructure needed by the airship was also determined.

All of the previous analyses were performed parametrically in order to allow for fast iterations. With this setup, the design was iterated until the MTOW converged, hence converging the design as well. This resulted in a design with the following structure and main parameters:

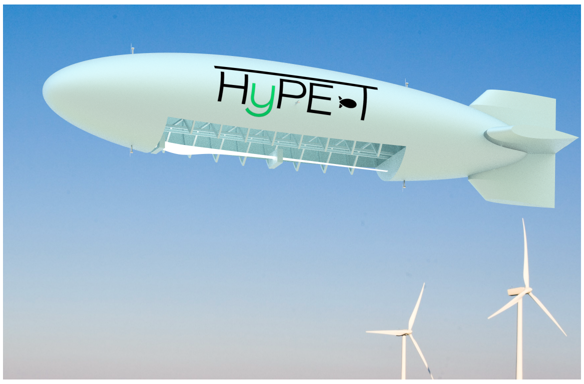


Figure 3: *Render of the airship*

Figure 4: *Main parameters of the system*

Parameter	Value
Payload Capacity	60 000 kg
MTOW	225 000 kg
Max. Payload Dimensions (l x w x h)	105 m x 12 m x 10 m
Length	221 m
Radius	48 m
Fineness ratio (FR)	4.6
Cruise Speed	80 km/h
Max. Speed	93 km/h
Endurance	16 h
Max. Range	1120 km for 1 trip, 1040 km for 2 trips
Max. altitude	2000 m under ISA condition
Buoyancy Ratio	99.7%
Lifting Gas	Hydrogen
Fuel	Hydrogen
Power Source	Fuel Cells
Engines	6 Vectored
Internal Structure Material	Al 6061-T6
Envelope Material	Polyurethane
Ballast Material	Soil and water

With the final design defined, a detailed risk analysis of the further design and operation of the airship is performed. The risk analysis identifies these risks from them, identifies mitigation strategies and finally contingencies are created if necessary. A RAMS analysis was also performed analyzing Reliability, Availability, Maintainability, and Safety.

With the eventual goal of the project, installing wind turbines in mind, sustainability is a pillar of the design. Not only does the project have a sustainability strategy, but every part of the design goes through a life-cycle analysis. Additionally, the recyclability is assessed, and critical raw materials are avoided. This showed that the requirement of 80% recyclability was reached. 12% will be downcycled and 8% will be disposed in a safe manner. Lastly, the indirect impact of the project was investigated. It is shown that a single airship over its lifespan of 50 year is capable of expanding the power grid enough to provide the Netherlands with green energy for a year (530 TWh).

Another important measure of the system is its cost to develop, manufacture and operate it. It is estimated that the total development cost of the airship will be €500M, with the production cost totaling €39M $\pm$ €8M for a rate of 1 airship per year, and the operational cost totaling €3.7M per year when operating 200 days. Using the same prices as trucks, the yearly income from transport and promotional income will be €26M, for a lifetime total of €1.3B. This results in a return on investment (ROI) of 107% for one airship in the expected scenario. The ROI rapidly increases when more airships are built and operated.

Lastly, part of the veil is lifted on the future of the project. Between now (2024) and 2040, further detailed design will be performed, followed by prototyping and testing. Afterward, the start of operation will commence, and while the ship is in operation, new opportunities will be sought, and support will continue for the existing model. A preliminary manufacturing plan has already created to set the bases for the prototype manufacturing process. Alongside this, the groundwork for a testing and certification campaign was laid out.

With the preliminary design finalized, it is important to perform a technical comparison with the main competitor: truck transport. The airship presents multiple advantages to trucks. A case study revealed that a typical mission can be performed 7.5 times cheaper and at least 33% faster in normal conditions. In terms of sustainability, trucks have lower overall energy consumption and material consumption, but the airship brings the opportunity to transport much larger blades. This allows for more wind energy to be produced, as mentioned before. with the potential of producing a year's worth of Dutch energy over its lifespan. Therefore, airships provide an interesting proposition to the market of blade transport, with Hype-T contributing to the wind turbine market that powers the future of green energy.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AoA	Angle of Attack
AC	Aerodynamic center
AERO	Aeromechanics
AP	Acidification Potential
AR	Aspect Ratio
CB	Center of Buoyancy
CFD	Computational Fluid Dynamics
CFRP	Carbon Reinforced Resin Polymer
CG	Center of gravity
COTS	Commercial-off-the-shelf
CRM	Critical Raw Material
EoL	End of Life
FBD	Free Body Diagram
FEM	Finite Element Method
FF	Form Factor
FR	Fineness Ratio
FY	Fiscal Year
MTOW	Maximum Take-Off Weight
NPL	National Physical Laboratory
OEW	Operating Empty Weight
OPS	Operations & Logistics
Pax	(Number of) Passengers
PDDL	Project Design & Development Logic
P.n.p.p	(Rate) per night per passenger
PDU	Power Distribution Unit
PP&P	Power, Propulsion & Performance
ROI	Return on Investment
SE	Systems Engineer
STP	Standard Temperature and Pressure
S&C	Stability & Control
S&M	Structures & Materials
TRL	Technology Readiness Level
V&V	Verification and Validation

Symbols

Symbol	Definition	Unit
C_D	Drag Coefficient	[-]
C_{D_0}	Zero Lift Drag Coefficient	[-]
C_F	Friction Coefficient	[-]
C_{L_α}	Lift Slope Coefficient	[rad^{-1}]
C_{M_α}	Moment Slope Coefficient	[rad^{-1}]
d	Airship Diameter	[m]
K	Drag Due to Lift Constant	[-]
l	Airship Body Length	[m]
Re_D	Reynolds Number wrt. Diameter	[-]
Re_c	Reynolds Number wrt. Chord	[-]
Re_l	Reynolds Number wrt. Length	[-]
S	Area	[m^2]
v	Velocity	[m/s]
v_T	Tail Velocity	[m/s]
V	Volume	[m^3]
R	Specific Gas Constant	[J/kgK]
p	Pressure	[Pa]
m	Mass	[kg]
T	Temperature	[K]
a	Lapse Rate	[K/m]
k	Unit Lift	[N/m^3]
V	Volume	[m^3]
A	Area	[m^2]
s	distance	[m]
α	Angle of Attack	[°]
β	Sideslip angle	[°]
λ	Taper ratio	[-]
λ	Finesse ratio	[-]
Λ	Sweep angle	[°]
θ	Pitch angle	[°]
ρ	Density	[kg/m^3]
σ_y	Yield Stress	[MPa]
ψ	Yaw angle	[°]

1 Introduction

As humanity faces a climate emergency, the need for renewable, environmentally friendly energy is higher than ever before. To satisfy this rising demand for green energy, many countries worldwide are investing heavily in wind energy, with onshore and offshore wind farms being built worldwide at an astonishing pace [1, 2]. Wind energy is an efficient and cost-effective way of generating energy. Wind turbine sizes are growing fast to increase energy production, and rotor diameters are expected to reach 350 m by 2030 for offshore turbines [3].

Larger wind turbines generate more energy, but create logistical challenges. The two current main turbine transportation options are ship and truck transport. While ship transport can accommodate large payloads, it is unfeasible for onshore farms. While being able to access inland areas, truck transport is quickly approaching its limits, as the sizes of turbines trucks can accommodate is limited. Thus, truck transport might impose limitations on the turbine dimensions that can be used, and might halt the progress of the wind energy transition [4].

As the demand for wind energy grows, the time- and cost-efficient transport of turbine components becomes crucial. Transporting turbine parts via road requires extensive planning, as appropriate permissions have to be acquired to conduct the operations, and coordination with traffic control is required[1]. Additionally, the transportation time itself is limited by the speed the transport truck can reach, which can be in the range of 5-10 km/h [2]. The large planning and operation times make truck transportation inefficient, costly, and might make it impossible to accommodate the increased demand for wind energy.

The wind energy sector requires new transportation methods to meet growing demands. These options should be competitive in this market and mitigate the transportation problems faced. There is a need for a **new, sustainable method for transporting wind turbine blades, which will be cost-effective and time-effective**. A solution that could address this need is the cargo airship. The airship avoids or reduces the challenges currently faced by truck transportation. This approach could streamline operations, handle larger blade sizes, and potentially reduce costs.

The objective of this project is to **design and determine the feasibility of using cargo airships to transport wind turbine blades and components for onshore and offshore applications**. Starting with the market and stakeholder needs, an airship concept will be developed, with an increasing level of detail at every stage.

After establishing requirements and performing a trade-off, a more detailed design of the (sub)systems could be done. In this report, the main subsystems were developed in more detail. This was done parametrically, that way the design could be iterated upon until a convergent design was reached. This design was then scrutinized, and analyzed. This all gave a better idea of the project, its shortcomings, and opportunities.

The structure of this report is as follows: firstly, the business plan, including costs and incomes is presented in Chapter 2. Secondly, a system overview is given in Chapter 3, which includes a summary of the final design and its parameters in Section 3.5. Following this are all chapters explaining the different analyses and subsystems. In order, these are aerostatics in Chapter 4, aerodynamics in Chapter 5, stability and control in Chapter 6, power and propulsion in Chapter 7, structures and materials in Chapter 8, a performance analysis in Chapter 9 and finally the design of a mooring and ballast subsystem in Chapter 10. After these chapters, there is a description of the operations of the system, in Chapter 11. A sensitivity analysis is given in Chapter 12 and the sustainability is analyzed in Chapter 13. A risk analysis is presented in Chapter 14. To close things of, the future of the project is described in Chapter 15. Finally, Chapter 16 contains the conclusion.

[1] `https://titanww.com/how-to-correctly-transport-wind-turbine-blades/` (Accessed on 20/06/2024)
[2] `https://www.iberdrola.com/innovation/blade-lifter-wind-turbine-blades-transportation` (Accessed on 20/06/2024)

2

Business Plan

2.1. Market Analysis

The goal of a market analysis is to find the purpose of the product. The first part looks at the most important stakeholders that are involved in the project. Secondly, the current airship markets are discussed. Thirdly, the market is defined. This part first discusses the current transport of wind turbine blades, secondly, the market size and trends present in the wind energy market are researched. The final part of the section gives a description of the market gap that could be filled by airship operations.

2.1.1. Stakeholders

To obtain a clear overview of the market in which the airship will be operating, it is necessary to know which parties are involved in the market. It is necessary to identify the stakeholders that are related directly or indirectly to the transportation of wind turbine blades and determine their influence on our mission. The stakeholders identified for the mission of the airship are collected in Table 2.1 and put in a stakeholder map in Figure 2.1 to determine the role and importance of each stakeholder.

Table 2.1: *Stakeholders*

Stakeholders	Interests of stakeholder
Wind Turbine Manufacturers	Wind turbine manufacturers aim to increase and accelerate sales of their products. Therefore, they are highly interested in new delivery technologies.
Lifting Gas Manufacturers	Lifting Gas Manufacturers are interested in expanding their available markets, hence they are interested in airships. They are responsible for manufacturing safe and cost-effective gases to support the demand.
Wind Turbine Installers	Wind turbine installers are responsible for assembling wind turbines and their components using crane-equipped ships or cranes on the ground. They are interested in whether airships could aid in their work.
Investors	Investors are the backers of the project. Therefore, they need to stay informed about its progress, as they play a crucial role in making this project possible.
Wind Farm Operators	Wind farm operators are responsible for maintaining the wind turbines, as an airship could potentially aid in their work.
Design Team (Group 03)	As the design team, it is important that the idea comes to realization as this could revolutionize the future of cargo transport.
Airship Developers (Competition)	Group 03 is not the only team designing cargo-carrying airships. Competitors are interested in Group 03's findings, as they could potentially incorporate them into their own designs and/or improve their version of the technology.
Academic Institutes	Academic institutions are interested in the potential of new technology that could make achieving climate goals more feasible and also act as research centers on new technology.
ATC	Air traffic control will need to incorporate significant new procedures and safety measures if airships are to join in significant numbers.
Logistical Companies	Logistical companies that facilitate cargo transport are interested in the findings of this design, as it could open up new possibilities for delivering cargo to remote locations. They could become investors in the future.

Local Public	The local public can be categorized into four groups: those living near potential airship bases, people who are interested in the project's impact on nature, people living in remote areas, people who are interested in airships delivering larger and more efficient wind turbines close to their living areas.
Airship Association	The Airship Association is a group of enthusiasts who are deeply interested in airships. They would be thrilled to see airships make a comeback and would be the spotters for them.
Pilots	Pilots are the ones who will operate the airships. The design team must ensure that the airship is designed in a way that enables pilots to perform their jobs effectively.
Cargo Charter Companies	These companies transport wind turbine blades from the production plant to their designated onshore and offshore locations. They are interested in whether this new technology could be used as a sky crane that could replace their ship-deployed cranes or at least support them.
Government Institutes	The government is keen to understand whether this new technology could reduce the cost of building wind farms. Additionally, its role is to ensure compliance with laws and regulations. If regulations drive the design, they will become a high influence.
General Public	The general public is interested in whether this new technology could improve their quality of life, by reducing environmental impacts, lowering costs, and providing passenger transport services, hence this could free up more financial resources for the government to potentially invest in the general public
The Media	The media will be closely monitoring this technology as revolutionary technologies generate significant attention and clicks.
Nature Activists	Nature Activists would express dissatisfaction, as accommodation of airships could potentially impact natural landscapes.
Climate Activists	Climate Activists would be interested in whether this technology would allow the installation of more and bigger wind turbines, to increase green energy production.

For the stakeholder diagram, each stakeholder is grouped into four possible segments. *Low influence* and *low interest* are stakeholders that do not drive major design or operational decisions on our airship. Examples are the general public, media, or government institutes. Those stakeholders shall be monitored in case their interest or influence changes. *High influence* and *low Interest* are stakeholders that impact the mission in a critical way, i.e. pilots need to be trained if pilots are required for the airship, and charter companies are major competitors that try to provide a better product or service, those stakeholders should be kept satisfied.

Low influence and *high interest* are stakeholders that have a high interest in the mission, i.e. academic institutes that look for innovation, logistical companies that could benefit from the service the mission provides, or even local people. Although those stakeholders have no major influence in the project itself, they should be kept informed as those stakeholders can become important stakeholders later on. Logistical companies can become investors for example, meaning their influence in the project grows. *High influence* and *high interest* are stakeholders that have both a high interest in the project as well as a large influence. Those stakeholders can drive the design or operation of the airship in a critical way, i.e. investors want to know their return on investment while wind turbine manufacturers drive the volume, size, and weight of the blades. Those stakeholders should be managed closely. All these segments and their respective stakeholders can be found in Figure 2.1.

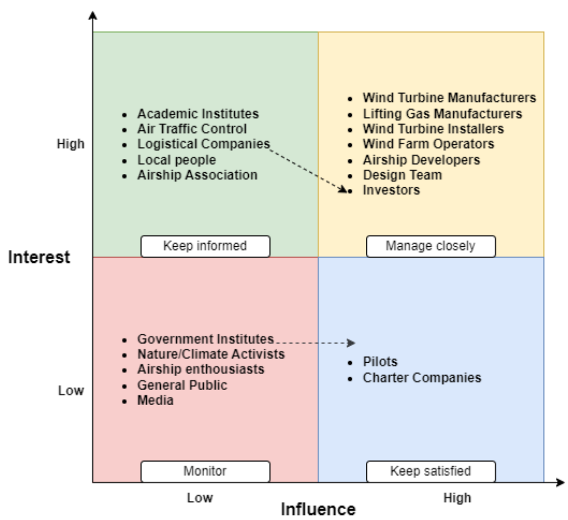


Figure 2.1: *Stakeholder map showing the influence and interest of different stakeholders on the project*

2.1.2. Current Airship markets

Nowadays, airships are present in a few markets. The application of airships is mostly limited to purposes related to tourism, such as the services provided by Zeppelin NT and Atlas Electric airships[1], which are sightseeing flights[2]. Airships are also used for marketing[3], like the Goodyear blimps for example[4]. They provide live coverage of sports events and provide aerial photos. Another niche market is surveillance, Aerovehicles is an example of this application[5]. However, these applications are user-dependent and not applied on a large scale. Other companies that are developing airships are targeting the heavy cargo transport market as a potential market to re-introduce airships. "One of the main drivers for the interest in airships is that airships are able to bypass road blockades and access remote locations that are hard to reach via other modes of transport. Airships can provide a link between isolated parts of the world and the rest of the world" [5]. In this way airships can provide opportunities to remote areas, that would normally be dependent on conventional transport options such as trucks, boats, and airplanes, by transportation of both people and cargo.

Companies like Hybrid Air Vehicles[6], Lockheed Martin together with AT-2[7] and Ohio-Airships[8] are developing hybrid-airships targeted for a range of markets but focused primarily on heavy-lifting transport. But since those airships are in an early stage of development, they are not ready to enter the market yet. Because airships serve limited purposes nowadays, and because the primary objective of the project is to come up with a sustainable and efficient airship design for the transportation of wind turbine blades, it is important to obtain insight into current options that occupy the transport market. Specifically, insight is needed in the market of oversized cargo with a focus on the transportation of wind turbine blades.

2.1.3. Market Definition

In this section, a market definition is presented, with segmentation based on technology. The market size is estimated together with a geographical indication of the market. Finally, the identified gap in the market is explained.

Blade transportation services

To start defining the market, the products or services that already exist to transport wind turbine blades have to be explored. These will form the main competitors of this project. To ensure a competitive market position, the product to be developed will have to meet the same functions for no more cost than existing solutions or provide extra functions for little extra costs.

Currently, overall transport costs for turbine blades go from €30 000[9] for short distances (240-400 km) up to €143 000[10] for long distances (400+ km) between manufacturer and wind park (conversion rate from fx-top.com[11]). The majority of the cost results from the necessary planning to properly transport the wind turbine blades. These numbers were verified by an engineer at Siemens Gamesa. It is important to note that these costs are representative of outsourcing transportation of the blade. When it done by the blade manufacturers, they can be more than double the listed cost. The different transportation options have been explained below and summarized in Table 2.3.

Truck Transport

Blade transport is often done by trucks. Currently, trucks can transport blades with a length of 88.4 m for long distances[12,13]. The record for the longest blade transported with trucks is currently 94 m, but only for a distance of 1 km[14]. These transports are often classified as superloads. Furthermore, transport takes up months of planning[10]. Transporting a super load requires approval of complete plans, which includes aspects like police escorts, route surveys, and bridge analyses[15]. Planning adds monetary costs, but also adds complexity

[1] https://atlas-lta.com/atlas-electric-airships/ (Accessed on 20/06/2024)
[2] https://zeppelinflug.de/en/(Accessed on 20/06/2024)
[3] https://www.aerovehicles.net/skyship-600/ (Accessed on 20/06/2024)
[4] https://www.goodyearblimp.com/behind-the-scenes/current-blimps.html (Accessed on 20/06/2024)
[5] https://www.aerovehicles.net/skyship-600/ (Accessed on 20/06/2024)
[6] https://www.hybridairvehicles.com/rethinking-the-skies-zero-emissions-air-services/ (Accessed on 20/06/2024)
[7] https://www.at2aero.space/team (Accessed on 20/06/2024)
[8] http://www.ohioairships.com/dynalifter--cruiser-.html (Accessed on 20/06/2024)
[9] https://www.utilitydive.com/spons/wind-turbine-blade-sizes-and-transport-a-guide/623444/ (Accessed on 20/06/2024)
[10] https://titanww.com/how-to-correctly-transport-wind-turbine-blades/ (Accessed on 20/06/2024)
[11] https://fxtop.com/ (Accessed on 20/06/2024)
[12] https://www.mammoet.com/news/record-breaking-transport-of-wind-turbine-blade/ (Accessed on 20/06/2024)
[13] https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/transport-of-longest-blade-in-the-world (Accessed on 20/06/2024)
[14] https://www.mammoet.com/news/safe-and-efficient-transport-of-94m-long-wind-blades-using-specialist-solution/ (Accessed on 20/06/2024)
[15] https://www.heavyhaul.net/super-load-hauling/ (Accessed on 20/06/2024)

and waiting time. This makes building wind farms less attractive, or in case of some geographical locations, impossible. On top of that, trucks move relatively slow, at a maximum of 60 km/h [6].

Blade Lifter
To transport blades through narrow, winding mountain roads *Blade Lifter* technology was developed. This system is attached to trucks and carries the blades. The systems, such as the BladeMAX1000 can raise the blades up to an inclination of 60° and rotate the blade by 360° and with some models also enabling a 20° lateral swivel[16]. This allows the truck to make narrow turns and drive through urban centers, where otherwise blades cannot pass. However, these operations still require extensive planning and specialized operators, while the maximum blade length is not increased compared to other trucks. Moreover, blade lifters are very sensitive to wind gusts of more than 10 m/s, and the trailer speed is limited to 5 km/h when the blade is raised[17] (Accessed on 20/06/2024).

Rail Transport
In some cases, blades are transported by rail. However, rail transport is limited by train infrastructure. Factors of influence are the location of train tracks, which might not be near the production plant and destination, and tunnels and underpasses encountered en-route. Routes that were previously used for shorter blades can sometimes not accommodate larger models, due to the physical size and capacity of certain areas on the network[18]. In March 2024, Vestas transported blades of 80.5 m by rail, which does not compete with the size of blades carried by current truck transport[19].

Ship Transport
For offshore applications, wind turbine blades are transported by cargo ships. They can have a speed between 24 and 44 km/h and can carry up to 200 blades at once over long distances[20]. The size of the blades is not limited by the weather, but the state of the sea has to be taken into account for stability. The blade is secured by lashing and welding to prevent movement under different sea conditions [21,22]. Fewer permits are needed than for truck transport, but the transport is not less complex and transport from the factory to the port might still be required unless the factory is on the quayside.

Airplane Transport
The BladeRunner is a concept aircraft being developed by Radia. Its purpose is to transport wind turbine blades, in hopes of solving problems truck transport has. It has a maximum payload length of 105 m, a range of 2000 km and only needs a semi-prepared, 1800 m long runway[23]. Commercial operations could start as soon as 2027, but no confirmed timeline is available[24].

Airship Transport
Companies are working on airship designs aimed at cargo transportation, with some specifically targeting the turbine blade transportation market. A few possible competitors are presented in Table 2.2. The airship concepts also promise loading and unloading without landing and vertical take-off and landing (VTOL). Most airships use crane concepts to lift the blades, which does not put a hard constraint on payload length. H2 Clipper promises a total cost of $0.32 per tonne-mile, or $0.20 per tonne-km [25].

[16] https://www.faymonville.com/technology/bladelifter-the-blademax/ (Accessed on 20/06/2024)
[17] https://www.iberdrola.com/innovation/blade-lifter-wind-turbine-blades-transportation
[18] https://www.freightwaves.com/news/shipping-wind-turbines-is-not-a-breeze (Accessed on 20/06/2024)
[19] https://www.projectcargojournal.com/modalities/2024/03/12/vestas-break-us-record-with-longest-blade-transport-by-rail (Accessed on 20/06/2024)
[20] https://www.vestas.com/en/media/blog/technology/vestas-ships-largest-single-vessel-blade-shipment (Accessed on 20/06/2024)
[21] https://britanniapandi.com/2023/03/carriage-of-windmill-turbine-blades/ (Accessed on 20/06/2024)
[22] https://www.skuld.com/topics/cargo/project-cargo/transportation-of-wind-turbines-as-cargo/ (Accessed on 20/06/2024)
[23] https://radia.com/windrunnerV
[24] https://edition.cnn.com/travel/windrunner-biggest-plane-in-the-world/index.html (Accessed on 20/06/2024)
[25] https://www.h2clipper.com/solutions/clipper (Accessed on 20/06/2024)

Table 2.2: *Future competitors in airship cargo transportation.*

Competitor	Payload weight [tonne]	Max. payload length [m]	Range [km]	Speed [km/h]	(Promised) maturity
Aeroscraft ML866/ML868[26]	66/250	50/-	5,000/ 10,000	190/190	Prototype built
H2 Clipper[27]	150	-	9,656	241	2029 first commercial flight
Airlander 10/50[28]	10/50	-	3,700- 7,400/2,200	148/195	1st flight 2012/2033
Flying Whales LCA60T[29]	60	96	N/A	100	Uncertain
ATLANT 30/100/300[30]	10/30/65	-[31]	2,000	140/145/ 150	Uncertain

Table 2.3: *Comparison of Transportation Methods*

Transport Method	Blade Length	Speed	Range	Costs
Truck Transport	88.4 m long distances, 94 m for short distances	Varied, limited by road conditions	Varied, primarily local and regional	Complex and costly planning required
Blade Lifter	Uses trucks' capacity	Limited to 5 km/h when raised	Limited by road network	Sensitive to wind gusts, additional costs for blade lifter
Rail Transport	Up to 80.5 m	Limited by rail conditions	Limited by infrastructure	Possibly less than trucking, depends on rail accessibility
Ship Transport	No limit on blade size	24-44 km/h	Primarily for offshore wind farms	Fewer permits, complex stability planning
Airplane Transport	Up to 105 m	Mach 0.6 (>700 km/h)	Not specified	High due to aircraft operation and infrastructure requirements
Airship Transport	No hard limit on blade length	100-150km/h	2000 km	< $0.32 per tonne-mile, competitive with other modes

Market Size

This section covers the investigation of the market size of wind turbine blade transport. Discussing the wind energy market overall to gain insight into the amount of wind turbines transported. It also covers the trends of wind energy in general, and the trends in wind turbine size.

Wind energy trends

The global market for wind energy is rapidly increasing in size. It is forecast that the total capacity of wind energy globally will reach 800 GW in the main case and almost 1000 GW in the accelerated case within the coming four/five years. Showing an increase in almost 400 GW of added capacity to the global wind energy market by 2028, see Figure 2.2a. Between 2011 and 2022 global investments in wind energy have increased from 75

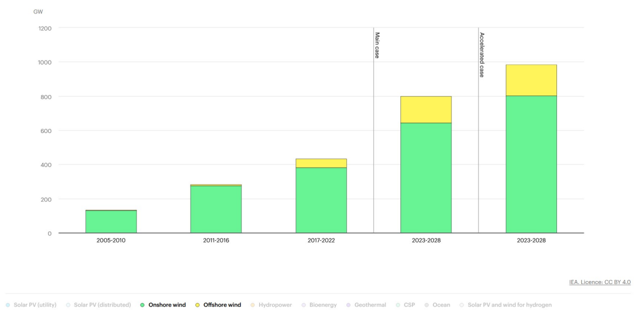
[26] https://aeroscraft.com/
[27] https://www.h2clipper.com/solutions/clipper (Accessed on 20/06/2024)
[28] https://pdf.aeroexpo.online/pdf/hybrid-air-vehicles/airlander-50/175127-205.html (Accessed on 20/06/2024)
[29] https://www.flying-whales.com/en/the-lca60t/ (Accessed on 20/06/2024)
[30] https://atlas-lta.com/atlant_cargo_airship/ (Accessed on 20/06/2024)
[31] External bay for oversized cargo such as wind turbine blades. The internal cargo bay has a larger weight capacity, but the payload is limited to a length of 25.8/36.5/51.5 m.

billion to 175 billion dollars, showing an increase of 100 billion dollars over 11 years [32] [33]. The market is largely defined by three main regions that together occupy the largest share of wind energy capacity. In Figure 2.3a it can be seen that China together with the European Union and the United States are the largest contributors to the increase in wind energy capacity. Therefore, these markets could be potential markets where the project will operate.

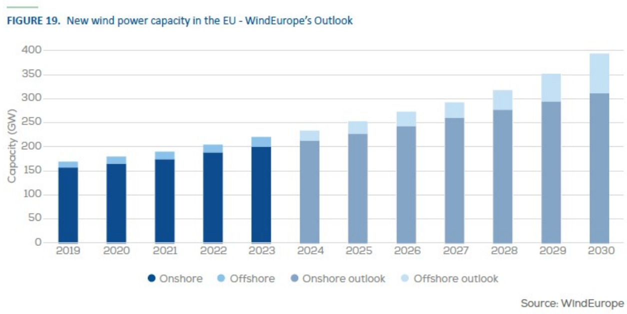
The largest contributor, China, increased their capacity by 30 GW in 2022. They did this by building a total of 11 098 new wind turbines[34], making for around 33 000 blades. In 2023, they added 59 GW of wind power capacity.

The second-largest contributor is the European Union, which added around 15 GW of extra capacity in 2022 and around 18 GW in 2023. With a single wind turbine adding 2.5 to 3 MW of power[35] and the aforementioned 18 GW increase in wind power in 2023, this means that approximately 6000 wind turbines have been installed. Which in turn means that about 18 000 blades have been transported. The EU has plans to expand the wind energy capacity by building quite a few extra turbines and wind farms, due to developments in both off-shore and on-shore building of wind turbines[36]. Looking at Figure 2.2b, it is expected that the total wind capacity in Europe will reach around 393 GW of which 310 GW will come from onshore turbines and 83 GW will be obtained from offshore turbines. In 2023, Germany, the Netherlands, and Sweden accounted for the most installations for wind energy generation in Europe measured in MW, see Figure 2.3b. This means a big portion of the European market can be found in those countries specifically.

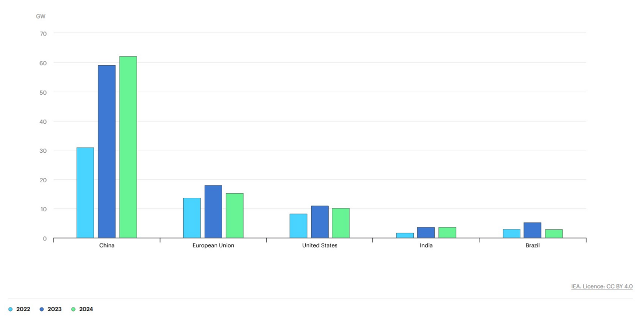
Finally, the third-largest contributor is the United States adding 8 GW of extra capacity in 2022 and around 11 GW in 2023. According to the US government, the total amount of wind turbines built each year in the US is 3000 on average since 2005[37]. This means a total of 9000 blades are transported each year.



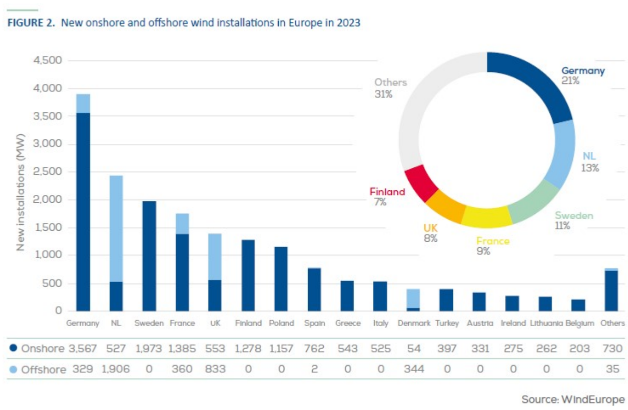
(a) *Global wind capacity growth*[38]



(b) *Europe's outlook on total wind capacity in 2030. [1]*



(a) *The annual additions to wind capacity per country/region for 2022, 2023, and 2024* [39]



(b) *New on and offshore wind installations in 2023 - Europe [1]*

[32] https://www.statista.com/statistics/186821/global-investment-in-wind-technology-since-2004/ (Accessed on 20/06/2024)
[33] https://windeurope.org/intelligence-platform/product/financing-and-investment-trends-2022/ (Accessed on 20/06/2024)
[34] https://mp.weixin.qq.com/s/OWjtwPVOTkz18HXDJFXGLg (Accessed on 20/06/2024)
[35] https://www.ewea.org/wind-energy-basics/faq/#:~:text=How%20big%20is%20a%20wind,than%203%2C312%20average%20EU%20households. (Accessed on 20/06/2024)
[36] https://windeurope.org/intelligence-platform/product/wind-energy-in-europe-2023-statistics-and-the-outlook-for-2024-2030/ (Accessed on 20/06/2024)
[37] https://www.usgs.gov/faqs/how-many-wind-turbines-are-installed-us-each-year (Accessed on 20/06/2024)

[38] https://www.iea.org/energy-system/renewables/wind (Accessed on 20/06/2024)

Wind Turbine Trends
Wind turbine size has been increasing over the past 40 years [4]. This means that for the transportation of wind turbine parts, and wind turbine blades in particular, the size and potential growth need to be kept in mind. TNO expects the size of offshore turbine blades to increase to a length of 145 meters by 2040 [7]. Whether this is the case is to be seen, as the size of current wind turbines is approaching 250 m in diameter[40] and currently planned wind turbines have sizes over 300 m in diameter [41]. For example, the biggest planned horizontal axis wind turbine is the MySE 22MW, which is supposed to deliver 22 MW and have a rotor diameter of 310 meters[42], it is scheduled for 2025. This shows that the size of blades in the offshore market is increasing fast. This is corroborated by Figure 2.4, which shows how the turbine sizes have changed over time. It also predicts offshore turbines of 25 [MW] with a rotor diameter of 350 meters for 2030.

As the same economics that drive the size increase in wind turbines offshore also influence onshore wind turbines, the size of onshore wind turbines has also been increasing [4]. But, compared to the offshore turbines, this is only to a limited degree. This is corroborated by Figure 2.4 [3], which shows how the blade sizes have changed over time. It also predicts onshore turbines of 15 [MW] with a rotor diameter of 270 meters for 2030, this is way smaller than its prediction for offshore turbines. On top of that, the figure shows that the size of onshore wind turbines has been smaller than the size of offshore turbines for a longer time. The size of all wind turbines is ultimately limited by the transportation and installation methods [7], but for onshore turbines in particular, the transportation methods required are a limiting factor [4].

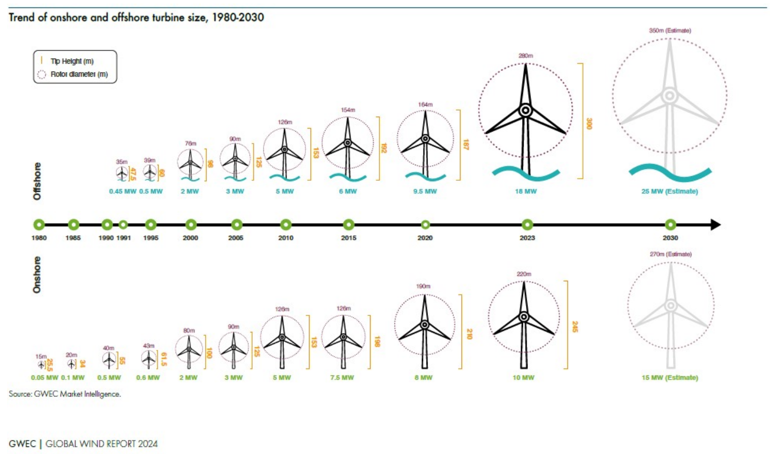


Figure 2.4: *Wind turbine trend of increased size and power output [3]*

Therefore, the project should try to accommodate as big a turbine blade as possible, to not exclude offshore operations, and to potentially create a new market for larger onshore turbines.

Important Customers
Depending on which market is targeted, different customers can be of importance. The most important customers are Wind Turbine manufacturers, Wind farm operators, and Wind Turbine installers. The most important customers will be shown in Table 2.4.

Table 2.4: *Wind turbine manufacturers production capacity (2022)*[43]

China	**Capacity [GW] (% of global)**
Goldwind Science & Technology Co.	18 (11%)
Envision Energy Co.	13 (8%)
Mingyang	8 (5%)
European Union	**Capacity [GW] (% of global)**
Vestas wind systems A/S	21 (13%)
Nordex SE	8 (5%)
Siemens Gamesa Renewable Energy S.A	15 (9%)
United States	**Capacity [GW] (% of global)**
General Electric	17 (10%)

It is important for these factories that the turbine blades are picked up from their factories and delivered to their area of duty. If this is done quickly and properly, the factory could make more sales. In Figure 2.5 it can be seen that most blade manufacturers are concentrated in the United Kingdom, Germany, and Denmark, with a few manufacturers in Portugal and Spain.

39 https://www.iea.org/energy-system/renewables/wind
40 https://www.statista.com/statistics/570678/biggest-wind-turbines-in-the-world/ (Accessed on 20/06/2024)
41 https://www.change.inc/energie/opnieuw-grootste-windturbine-ter-wereld-aangekondigd-waarom-moet-het-steeds-groter-40501 (Accessed on 20/06/2024)
42 https://www.rivieramm.com/news-content-hub/news-content-hub/chinas-mingyang-smart-energy-unveils-massive-offshore-wind-turbine-78227 (Accessed on 20/06/2024)

Meaning that in the European market, the operation will be centered around North-West Europe or Southern Europe. The current distance to offshore wind farms as of (2020) is around 20 km from the shore with a global average of 18.8 km. It varies strongly from region to region with the distance in Europe being around 23.3 km in Asia around 6.9 km and in America around 4.5 km. Figure 7 in [8] shows a concentration of wind farms in the range of 0 to 40 km distance to the shore. Table 7 in [8] states that the distance will increase to around 30 km globally and to 50 km in Europe. For off-shore wind farms, the blade manufacturers have facilities close to shore, while some facilities are more in-land. The average distance from the manufacturer would be between 100 km and 300 km.

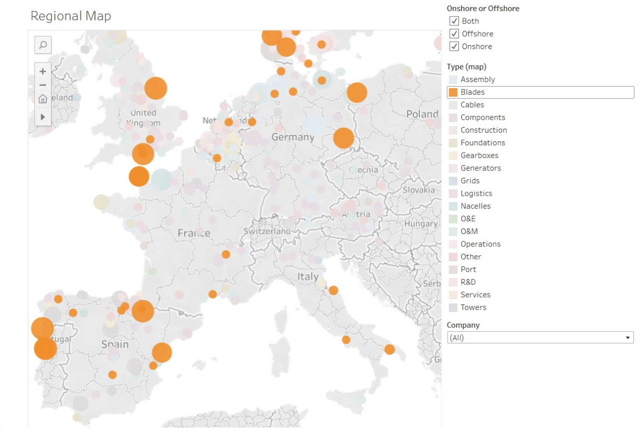


Figure 2.5: *Map showing the location of major blade manufacturers within Europe.* [44]

Finally, the market sizes are summarized in Table 2.5. The table shows a summary of the 3 biggest markets for wind turbines and the associated transport costs in euros.

Table 2.5: *Market sizes in GW, amount of blades, and M€*

Region	**Recent capacity increase [GW]**	**Recent turbines (3 MW per turbine[45])**	**Recent Blades (3 blades per turbine)**	**Expected size [M€] (€66 700 per blade, see Subsection 2.1.3)**
China	59	19 667	59 000	3 935.3
European Union	18	6 000	18 000	1 200.6
United States	11	3 667	11 000	733.7

Blade Replacement & Decommissioning

Finally, with all the aforementioned grow, there is also an increasing amount of old turbines in need of replacement parts or decommissioning, both onshore [9] and offshore [10]. Therefore, there is a potential new market for the airship.

The waste created during decommissioning will need to be transported to a recycling plant. This can be done by truck with less effort than transporting brand-new turbine blades, as the blades do not need to be delivered in one piece. Because the load is no longer oversized, the planning and other related costs decrease. As the demolition equipment is already able to reach this place, the trucks should be able to reach it as well. In all likelihood, economically competing with trucks in this case is no longer feasible.

Replacement of blades could be an interesting market. The average turbine shows 0.001 major blade replacements per year [11]. With the increasing amount of (old) wind turbines, there will be a lot of replacement blades needed. Because blades cost a lot to replace (in the order of €200 000 [11]), wind farms will of course seek to reduce the amount of replacements with better maintenance practices. However, this does not mean that there will be no blade replacements in the future. This means that there will be a market for relatively small amounts of blades to be transported to wind farms for replacement purposes. This is exactly what the airship is capable of doing.

Description of Market Gap

This subsection first describes the functions the system should provide to compete in the market or fill the market gap, then briefly explains the target cost and development time.

Functions

To compete in the market for wind turbine blade transportation, the product needs to be cheaper than current options or needs to exceed them in functions or performance, while not being much more expensive.

In the onshore market, the product needs to compete with the established trucking industry. Because current trucks and railways are not able to transport them, there is a gap in the market for blades with a length exceeding 90 m. The functions the product needs to compete against trucks are listed in Table 2.6. Since there is currently no company operating airships in this market, there is no relevant infrastructure or operation

[45] `https://www.ewea.org/wind-energy-basics/faq/#:~:text=How%20big%20is%20a%20wind,than%203%2C312%20average%20EU%20households`. (Accessed on 20/06/2024)

plan. Therefore, considerations regarding infrastructure and operations also need to be included in the system and will be determined later in the design process. The operation plan can be made in collaboration with the customers and stakeholders as presented in Subsection 2.1.1.

Table 2.6: *The functions the product must fulfill to enter the market.*

Function ID	Function description
FUN-TR-01	The system shall be able to transport wind turbine blades of at least 90 m.
FUN-TR-02	The system shall be able to transport wind turbine blades to difficult-to-reach areas.
FUN-TR-03	The system shall be able to operate in wind gusts exceeding 10 m/s.
FUN-TR-04	The system shall have an operating speed of at least 5 km/h.
FUN-TR-05	Once the system is developed and built, planning an operation shall take less than a year.
FUN-TR-06	Transporting one wind turbine blade over a long distance shall not cost more than €143 000.
FUN-TR-07	The system shall include building, maintaining, and operating relevant infrastructure for operations.

In the future, other competitors will join the market, with airplane transport and airship transport. Once these enter the market and form direct competition, the system shall in addition to Table 2.6 have to perform one or more of the functions listed in Table 2.7.

Table 2.7: *Functions needed to compete with future competitors. 'AS' functions come from competing airship transport, 'AP' from competing airplane transport.*

Function ID	Function description
FUN-AS-01	The system shall have a payload weight capacity of at least 60 tonnes. [46]
FUN-AS-02	The first commercial flight shall not be later than 2033.
FUN-AS-03	The operating cost shall be less than $0.20 fiscal year 2022 per tonne/km.
FUN-AS-04	The system shall have an operating speed of at least 150 km/h.
FUN-AS-05	The system shall have a maximum payload range of at least 2000 km.
FUN-AP-01	The system shall be able to transport wind turbine blades of at least 105 m.
FUN-AP-02	The required unloading area shall be less than 1800 m in length.
FUN-AP-03	Preparing the unloading area shall not require expensive infrastructure.

In the offshore market, the product will compete with ships. Since ships can transport many blades in a single trip and have virtually no limit on blade size, it will be difficult, maybe even impossible to compete in this market. It might be more economical and sustainable to make a trip with an airship, rather than with a large cargo ship to replace a single or a small amount of damaged blades. An analysis on whether a role in the maintenance and replacement market for offshore operations is viable should be done in a future market analysis.

Target cost
To compete in the market, the cost of transport of a blade should be equal to or less than the cost of competitors, which are described in Subsection 2.1.3. If the same functions as truck transport are performed, the target cost for the transport of one blade should be less than €30 000 for short distances and less than €143 000 for long distances. It is expected that customers will accept a larger cost if the product exceeds the trucks in functions and performance. However, customers are more likely to switch to our product if the price is not higher or even lower than current methods. The costs for planning the routes, which is one of the main drivers of total transport costs, are expected to go down regardless. Together with the large, growing market, this implies airship transport operation is a viable service to provide. A return on investment (ROI) is calculated in Section 2.3.

Development time
As mentioned in FUN-AS-2, the aimed development time is the first commercial flight in or before 2033. If this timeline is achieved, the product will enter the market at the same time as or earlier than some major future competitors and will not lose out on a possible market share. After 2033, wind farm capacity and therefore wind turbine blade transport is expected to continue growing, so the risk of a satisfied market remains low. Operation earlier than 2033 would of course be beneficial. However, even the date of 2033 will likely not be realistic when compared to other current development programs.

2.1.4. Mission Profile
For the project to be economically feasible, the ship needs to be able to provide service to the major markets. Analyzing this will give mission characteristics that will flow down to requirements later.

(Un)loading Time

The ship is only viable over trucks if loading and unloading do not cause major problems. (Un)loading from the ship should not take considerably longer than unloading from a truck.

Typically loading and unloading a blade on a truck takes around 30 min [12]. For airships, (un)loading has never been done in the real world. As such, it is very hard to get a good estimate on the time for (un)loading. The closest there is to this would be hot-loading a helicopter. This is the process in which the engines keep running while cargo or people are loaded. As landing is not allowed by the user requirements, this would be the way to go. Loading here can be as simple as securing a payload to a cable or can involve an actual touchdown. For helicopters the required time for hot loading is 3.071 min [13]. For additional (un)loading operations the total time spent around the (un)loading site can be set to 30 min.

Delivery Interval

To keep up with the construction of the turbines, the delivery interval should match the time it takes to install a blade. In today's market, the installation of a turbine (containing three blades) takes around 2 days [14]. Do note however that this is when blades are plentifully and not restricted by delivery. This means that to keep up with the construction and not have the blades pile up on the site, 2 blades should be delivered per day.

Range

To beat trucks where they perform the least it is important that the airship can deliver blades to the places that are furthest from the factories.

Taking another look at Figure 2.5 it can be seen that the furthest place from any factory is around 400 km in Western Europe. When it comes to flying from the base of operation to the factory and construction site, the same general distance can be assumed, with only 3 bases Western Europe can be covered in its entirety by 400 km circles. Do note however that these are worst-case scenarios, the ship can also perform missions closer by. Combining this with Subsection 2.1.4 the range is composed of one flight from the base to the factory, three flights between the factory and the construction site, and one flight from the construction site to the base. The first and last can roughly be assumed to be the same. This gives a range of 2000 km for each mission lasting one day when carrying full payload mass.

Operational Time and Cruise Velocity

To deliver 2 blades per day, and fly 2000 km as laid out in Subsection 2.1.4, operating hours need to be found.

Taking off and landing is not allowed at any time of day; many airports restrict these due to noise pollution. In 2013 there were already 126 airports with such restriction [15]. These restrictions can be a complete or only a partial ban of flights during 6-8 hours every night[47]. This still allows for 16 hours of operation each day in the worst case. This would require two separate pilots, as a pilot can only work for 8 consecutive hours [16].

Combining the findings from Subsection 2.1.4, 2.1.4, and 2.1.4 now should give the velocity for the ship to be viable. When taking away the pick-up/drop-off times there are 14 hours remaining to fly the 2000 km. This gives a required speed of 142.86 km/h assuming no headwind. This value should be rounded up to account for parts of the flight with decreased speed, resulting in a required 150 km/h. All of these are of course the worst-case scenarios; when all facilities are far apart and there are night flight restrictions. This speed would absolutely be faster than trucks as their average speed is below 60 km/h [6].

Cruising altitude

For the designing process of the airship, it is useful to know the cruising altitude. The cruising altitude of an airship is mostly determined by the fact that from 3000 m, the atmosphere is no longer sufficiently breathable without pressurization. Therefore a lot of airships set their service ceilings at 3000 m [48].

There are a few examples of airships designed to go higher than 3000 m. The Airlander 10, which has flown test flights, is designed to reach an altitude of 6100 m [49]. H2Clipper, which is still in the concept phase, is supposed to cruise at 4572 m [50]. However, these are only a few examples of airships. Therefore, it was decided to choose a cruising altitude dependent on other mission criteria.

The most restrictive regime for the airship is when it needs to cross over mountains, which are tall, meaning that the cruising height should be above the height of the mountains that the airship is supposed to cross. After examining a flood map[51], it was determined that the preferred altitude to still be able to cross the Alps was

[47] https://www.schiphol.nl/nl/schiphol-als-buur/pagina/vliegroutes-en-baangebruik/ (Accessed on 20/06/2024)
[48] https://oceanskycruises.com/flying-with-the-wind/#:~:text=Airships%20and%20the%20wind,corresponding%20to%20approximately%203%2C000%20m. (Accessed on 20/06/2024)
[49] https://edition.cnn.com/travel/article/airlander-10-worlds-biggest-aircraft/index.html
[50] https://lynceans.org/wp-content/uploads/2022/02/H2-Clipper-converted-1.pdf (Accessed on 20/06/2024)

[51] https://www.floodmap.net/ (Accessed on 20/06/2024)

about 2000 m.

2.1.5. Advantages over established means

There are several advantages to using airships over the current ways of transporting wind turbine blades. Most of these have been discussed in this chapter before. A short summary will be given in Table 2.8.

Table 2.8: *The advantages of airship transport of wind turbine blades.*

Advantage	Explanation
Cruise speed	Trucks can go 60 km/h (ships go even slower), the airship will go 80 km/h.
Handling of difficult terrain	Trucks have to deal with difficult terrain, the airship can fly over difficult terrain
Planning required	The required planning time for the airship transportation will be lower than that of trucks.
Cost	Partly due to less required planning, the cost of transport by airship will be lower than that of trucks.
Length of blades	Trucks have a hard time shipping longer blades, the airship can easily transport any blade that fits their cargo-bay.
Market gap	Trucks are unable to transport blades longer than a certain size, airships could open up a new market for onshore wind turbines by transporting these bigger blades.

2.1.6. Alternative Operations

Apart from the main objective of transporting wind turbine blades, other functionalities might be fulfilled by the airship. These alternative operations are not the aim of the design but might be achievable as an afterthought using little to no modification of the design. These alternative operations can be performed when no blade transport is planned for a period of time, or when the alternatives prove to be an economically more interesting option.

Alternative Cargo Transport

The main objective of the airship is transporting wind turbine blades. It might be possible to reconfigure the payload handling sub-system to allow the transport of other goods. An obvious choice is the transport of intermodal shipping containers. These containers are highly standardized and allow the airship to fit in the logistics chain next to trucks, trains, and ships. However, this also means there is no specific gap in the market and requires the costs to be extremely competitive. To stay in a market gap, alternative payloads should be other bulky, large-volume goods that currently cannot be transported by other modes, or only at very high costs. If the final design needs no infrastructure for loading and unloading, the airship could be useful in areas where no rail or ship infrastructure is present, see also Subsection 2.1.6. This can be developing areas in poorer countries or remote regions in Alaska or Canada. The Alaskan state government has had multiple meetings on the future use of airships already[52]. Finally, the airship can be used to transport large aquatic animals. These animals need to stay submerged during transport, which results in either enormous water weights or conditions that are not optimal for the animals [53]. This hinders transport by road, rail, and Heavier-Than-Air (HTA) aircraft, but is less of a problem for the airship. This would allow for the animals to be transported in large water containers than usually the case, resulting in a higher well-being of the animal.

Disaster Relief

In case of a natural disaster, such as an earthquake, flooding, or hurricane, thousands to millions of people require rapid emergency aid. If the final design needs no or almost no infrastructure for unloading, the airship could quickly arrive on the scene and deliver essential goods, including medical supplies, food, temporary housing units, and rescue equipment. The airship can do this where highways are damaged or blocked by landslides, where runways are clogged or flooded and where ports have become inaccessible. In this role, extra funding could be acquired by charitable investors, government subsidy, or United Nations funding [17].

Luxury Cruising, Leisure and Sightseeing

In the first half of the 20th century, human transport by airships was the vision of the future. However, due to the relatively low speed and the emergence of reliable airplanes, this is not a viable role in the modern day [17]. However, carrying humans might be economically interesting in the luxury cruising or sightseeing market. A 2-hour trip with the Zeppelin NT has a ticket price of €1060 per person[54]. The Zeppelin NT has a useful load

[52] `https://w3.akleg.gov/index.php`, *03/03/2014 08:00 AM House Energy*, *03/04/2014 01:00 PM House Transportation*,*04/04/2017 01:00 PM House Transportation* (Accessed on 20/06/2024)
[53] `https://www.mentalfloss.com/article/24141/how-do-you-transport-whale` (Accessed on 20/06/2024)
[54] `https://zeppelinflug.de/en/zeppelin-flights/flight-bodensee` (Accessed on 20/06/2024)

of 1575 kg and can carry 12 passengers [17]. Extrapolating this to a useful load of 60 tonnes corresponds to possibly more than 450 passengers per trip. Assuming similar prices, this results in a trip profit of around €480 000 with a possibility of around 3 trips per day, depending on turnaround times. However, it might be hard to find enough demand to fill up all the available seats, decreasing profitability. This might be solved by decreasing the number of passengers and increasing the luxury. The airship can then take these passengers on long, luxurious cruises, such as the interwar, large German airships did [17]. The airship will compete with cruise ships but with the added advantage of providing unparalleled views by flying close to landmarks and scenic landscapes. The disadvantage of this operation is the stricter regulations and potentially limited demand.

Refitting the airship for this purpose will require a redesign of the payload handling to be converted to passenger housing and entertainment. A typical cruise ship cabin has a footprint of 15-20 m^2 for an inside, oceanview or standard balcony cabin[55,56]. The payload bay has a size of 110x14 meters, see Section 8.3. While still allowing some room for a common room, kitchen, and related space, the payload can be converted to a hallway with two rows of 10 to 22 two-person cabins, depending on the level of luxury.

When traveling at a velocity of 40 km/h, the range of the airship increases to 2100 km and the endurance to 53 hr (2.2 days), allowing cruises of two nights across Europe. Note that the destination of the cruise should not be more than 200 km away, to allow operations with a constant headwind of 10 m/s, or 1100 km away for headwinds of 5 m/s.

The Hindenburg charged $450 in 1937, equivalent to €9100 in 2024, for a 2.5-day one-way trip from Europe to America. This can be compared to the price of €11 000 per night for one of the most luxurious cruise suites, which can accommodate up to six guests[57,58]. A two-night cruise in an ocean view cabin can be booked with a starting price of €270[59]. The potential cruising income is presented in Table 2.9.

For the redesign, it should be considered that the center of gravity will not shift significantly and the replacing cabin, leisure and dining area have a mass equal to the replaced bay and payload, see Section 6.4, 8.3.3 and FUN-AS-01, respectively.

Table 2.9: *Luxury cruise income per operational night.*

Scenario	P.n.p.p. [€]	Pax	Income per night [€]
Low end	270	22	5940
Expected	1833	18	33 000
High end	9100	10	91 000

Promotional

Several companies use Lighter-Than-Air (LTA) products for promotional purposes. These products range from blimps with a size of a few meters to the 75-meter-long Zeppelin NT [60,61]. Comparing advertisement rates of these companies can give an estimate of promotional income. The expected income per day is presented in Table 2.10 for a low profit, expected profit, and a high-profit estimation. For the low-end estimation, the airship is compared to aerial advertising rates[62]. The expected profit and high-profit scenarios are calculated comparing to airship advertisements[63,64].

Due to the huge size of the airship and corresponding operational costs, it will not be economically viable to do a purely promotional mission. However, the large envelope provides a big advertisement area of thousands of square meters. Advertisers could rent (part of) the surface to display their message or the logos of the main investors of the project can be displayed. Text with a letter size of 18 m, less than half the airship diameter, can be read by an audience up to 3.7 km away[65].

[55] `https://emmacruises.com/how-big-are-cruise-ship-cabins/` (Accessed on 18/06/2024)
[56] `https://www.cruise.co.uk/bulletin/how-to-choose-your-perfect-cruise-ship-cabin/` (Accessed on 18/06/2024)

[57] `https://www.forbes.com/sites/debbikickham/2019/05/27/have-10000-per-night-to-spend-on-a-cruise-ship/` (Accessed on 18/06/2024)
[58] `https://www.rssc.com/experience/suites/regent-suite` (Accessed on 18/06/2024)
[59] `https://www.royalcaribbean.com/cruises` (Accessed on 18/06/2024)
[60] `https://www.promobikes.co.uk/promoblimps/` (Accessed on 20/06/2024)
[61] `https://www.goodyearblimp.com/behind-the-scenes/current-blimps.html` (Accessed on 20/06/2024)
[62] `https://usairads.com/rates.php` (Accessed on 20/06/2024)
[63] `https://seeblindspot.com/the-only-digital-blimp-in-the-world/` (Accessed on 20/06/2024)
[64] `https://airads.com/aerial-advertising-media-options/blimps/full-size-aerial-advertising-blimps.html`, Model LTA-1000 Zeppelin (Accessed on 20/06/2024)
[65] `https://airads.com/aerial-advertising-media-options/blimps/full-size-aerial-advertising-blimps.html` (Accessed on 20/06/2024)

Table 2.10: *Promotional income per operational day.*

Scenario	Rate per day
Low end	€7800
Expected	€12 400
High end	€21 700

Surveys and Surveillance

The payload handling sub-system can be refitted to allow the attachment of scientific equipment to perform geophysical, hydrographic, cartographic, wildlife, and archaeological surveys. Similarly, the airship may fulfill surveillance roles for policing agencies or monitor (natural) disasters. The airship benefits from its long endurance and low minimum speed [17]. These functions can also be performed by smaller airships, so the large size of this design does not necessarily provide advantages. It might be possible to install scientific equipment that performs secondary missions while allowing uninterrupted performance of the primary mission.

Military Applications

Historically, the military has had some interest in airships. This interest faded with the emergence of HTA aircraft and vulnerability to artillery fire. LTA aircraft form a large, slow-moving, fragile target, so they have not been used in wartime outside the cover of total air superiority [17]. In peacetime or under this cover, the airship might be used as a transport mode, similar to transport described in Subsection 2.1.6. Possible payload includes general ammunition, personnel or a single Leopard 2A6, which is in use by the Royal Netherlands Army and has a weight of 60 tonnes[66]. Performing military applications brings the potential to new investors, but also brings ethical questions which might result in other investors abandoning the project. Furthermore, military applications might not suit the image that should fit with the re-emergence of LTA vehicles. For these two reasons, designing the airship for military applications should be decided in close collaboration with the stakeholders.

Search and Rescue

The long endurance and ability to hover make airships suitable for search and rescue (SAR) missions for the Coast Guard or military[17]. The airship will probably be too large and expensive to remain on call as a dedicated SAR vehicle but could be notified and deployed when necessary and available. The birds-eye view simplifies the search aspect. For the rescue aspect, however, it must be assumed that rescue missions are often performed in adverse weather. This will restrict the deployment of the airship, see Section 11.2. Furthermore, without the presence of mooring cables, see Chapter 10, the required hovering accuracy cannot be guaranteed.

2.2. System Cost Analysis

This section will cover the cost analysis of the airship system. Three different types of costs are considered: development, manufacturing, and operational costs. These are shown in the subsequent sections.

2.2.1. Development Costs

The development cost of the airship is crucial for the success of the project. If not enough funding is obtained, the airship cannot reach operations and its development will need to be halted. Hence, this figure must be carefully estimated and revised as the project moves forward. At the current stage, the estimation will be based on similar projects, but this should be reviewed by a professional financial team to obtain a more detailed figure.

The development of the airship is estimated to be €500M. This is based on the cost of the similar project H2 Clipper being €250M[67]. For Aerosmena, another similar airship, the costs of development are $120M and $150M for their 60 tonnes and 200 tonnes models respectively[68]. However, these numbers are to be taken with caution, as the company went bankrupt in 2010 because of monetary problems, which might have been caused by poor financial management. Therefore, the airship requires higher funding, even more so when considering that the goal is to start operations by 2040 (in 16 years), while the H2 Clipper aims to start operations after 18 years of design. For that reason the budget has been doubled, to account for a tighter deadline as well as any drawbacks that might come with developing the airship.

2.2.2. Manufacturing Costs

Manufacturing an airship is a costly and complex process. At this stage of the design, there is not enough detail to decide on specific manufacturing methods. Instead, a high-level estimation with some margins has

[66] `https://www.defensie.nl/onderwerpen/materieel/voertuigen/leopard-2a6-gevechtstank` (Accessed on 20/06/2024)

[67] `https://www.flightglobal.com/aerospace/h2-clipper-sails-into-series-a-funding-round-as-prototype-production-hoves-into-view/150418.article`, Accessed on 25-06-2024

[68] `https://www.pressreader.com/south-africa/african-pilot/20191201/281543702765723`

been performed to have a safe approximation.

The estimation of manufacturing cost is focused on workforce and material cost, as those account for a sizeable part of manufacturing. Other costs such as machinery, custom rigs, or learning curve have been disregarded and are assumed to be taken up by the added margin. To estimate workforce costs, the manufacturing of an A380 has been taken as a reference, as this is a big aircraft with a complex manufacturing process.

A single A380 takes around one year to be manufactured [69] [70], and the same will be assumed for the airship. From 2007 to 2019 a total of 234 aircraft were delivered [71], meaning that the average manufacturing rate is 19.5 aircraft a year. For this rate, a workforce of approximately 3 800 people was necessary [72]. From the business analysis conducted in Section 2.3, it has been determined that a rate of 1 airship per year would suffice, at least at the initial stages. Thus, the workforce needs to be scaled down to account for this difference. A workforce of 300 has been assumed for the airship, 10 times smaller than that of the A380, rather than 19.5 (ratio between production rates). The reason for this conservative estimation is that airship manufacturing is a very unexplored field and might require additional workers to perform accurately. On top of that, this underestimation also serves as a margin for the over-looked costs mentioned before. Utilizing the average yearly cost of technicians of €350 000 (reasoning shown in Subsection 2.2.3), this amounts to €13M of total workforce cost. This cost has been evenly distributed across all sub-systems, as shown in Section 3.7.

The material cost was calculated using Granta EduPack 2023 R2 [18]. The mass of each material used was estimated and then used to find the final cost. Similarly, the transportation costs were also obtained using this tool, but they have a very little impact on the total cost.

Finally, some margins were added to account for avionics costs and other unknown elements of the airship. The breakdown of the costs per sub-system is shown in Section 3.7, together with the specific margins used. The result from this breakdown is that the manufacturing cost of the airship is €39.1M $\pm$ €7.8M.

2.2.3. Operational Costs

To identify the operational costs incurred by the airship, several factors need to be examined. These factors are the cost of hydrogen, the workforce salaries, the infrastructure costs, and finally, the overall maintenance. Depending on the operational region of the airship within Europe, costs will vary. Some of the factors mentioned will be presented as ranges to account for these price variations.

As hydrogen is used as both the lifting gas and fuel of the system, it will be a permanent cost. In 2022, the cost of hydrogen in Europe was 3.89-16.44 €/kg with an industry average of 9.85 €/kg. Multiplying this value with the density at atmospheric pressure of 0.084 kg/m^3 results in an average cost of 0.8274 €/m^3. In the ideal case, it takes 37 days to lose 1% of the lifting gas. As gas is constantly in the airship and thus there is a constant loss, 0.027% of the total volume should be refilled daily. Thus the daily volume of hydrogen to be refilled is 60.21 m^3. This brings the average cost to 49.8 euros per day. Now, the cost of the fuel will be considered. The fuel tank has a capacity of 60.96 m^3 which would bring the price of refueling after every operation to 50.4 euros. To estimate the yearly cost, different operational days will be considered for the fuel cost. These days are 160, 200, and 240 per year. For the low end of the range, it is considered the airship will only fly 160 days a year at the lowest cost of hydrogen while for the high end, it is considered to travel 240 days with the maximum hydrogen cost.

Table 2.11: *Operational Cost of Hydrogen*

	Cost Range [€/m^3]	Average Cost [€/m^3]	Cost Range per Operation [€]	Average Cost per Operation [€]	Cost Range [€/year]	Average Cost [€/year]
Lifting Gas	0.327 - 1.381	0.827	19 - 83	50	6 935 - 30 295	18 250
Fuel	0.327 - 1.381	0.827	20 - 84	50.5	3 200 - 20 160	10 100
Result			39 - 167	100.5	10 135 - 50 455	28 350

For the airship to complete its mission safely and efficiently, personnel is necessary. This includes the flight

[69] https://www.quora.com/How-long-does-it-take-to-build-an-Airbus-A380-assuming-that-all-parts-are-immediately-available, Accessed on 19-06-2024

[70] https://www.businessinsider.com/how-airbus-builds-the-a380-2013-6?international=true&r=US&IR=T, Accessed on 19-06-2024

[71] https://web.archive.org/web/20190210065631/https://www.airbus.com/aircraft/market/orders-deliveries.html, Accessed on 19-06-2024

[72] https://www.flightglobal.com/airbus-adds-1200-staff-to-a380-assembly-line/68907.article, Accessed on 19-06-2024

and ground crew. Ranges for the salaries will be used, with the lower end of the range representing the incurred costs if operating in the cheapest European country, Bulgaria, while the higher end represents the most expensive, Switzerland. The flight crew includes two pilots, two payload handlers, and one logistics manager. The average commercial airline pilot salary in Bulgaria is €13.55 per hour while in Switzerland it is €80.51 per hour. By assuming a 40-hour work week, the cost per pilot would amount to €28 185 - €168 310 per year. The payload handlers will be high-lift crane operators due to the use of a crane for loading and unloading the wind turbine blade. The average crane operator's salary would amount to €13 874 - €89 523 per year per employee. The final flight crew member is the logistics manager and their average salary is €14 316 - €133 852 euros per year. It is important to note that the airship will operate for 16-hour periods and thus two sets of the mentioned flight crew will be necessary. This brings the total flight crew cost per year to €196 868 - €1 299 036. The ground crew salaries will now be investigated. The ground crew includes four aviation technicians and one logistics manager. The average aviation technician salary in Bulgaria is €11 954 per year while in Switzerland it is €62 314. The final ground crew member is once again a logistics manager. Similarly to the flight crew, there will be two sets of ground crew due to the 16-hour work periods. The total ground crew cost per year amounts to €124 264 - €766 216. For the average values, Germany has been considered. The resulting expenses are presented in Table 2.12[73].

Table 2.12: *Flight and Ground Crew Salaries*

	Cost Range [€/year]	Average Cost [€/year]
Pilots	112 740 - 673 240	304 000
Crane Operators	55 496 - 358 092	208,812
Logistics Managers	57 264 - 535 408	220 000
Aviation Technicians	95 632 - 498 512	347 580
	321 132 - 2 065 252	1 080 392

As the airship is susceptible to weather conditions, it is necessary to store it safely. To do this, a hangar is required. It is possible to either construct a hangar or rent one but due to the large airship dimensions, it is preferable to construct one that meets the sizing requirements with additional clearance. Under normal conditions, the construction cost is a one-time expense, however, upkeep is necessary. The upkeep includes utilities, insurance, hangar and pavement maintenance, and repairs. To estimate the price of this upkeep, a smaller hangar of 445.9 m^2 will be used [74] . The hangar to be constructed will have the dimensions of the airship with an additional 10% clearance on each side, bringing the dimensions to 265.4 - 57.5 meters. Thus the airship hangar is 34 times larger than the reference hangar and by assuming a linear relation, the costs will be 34 times larger. The total average infrastructure operational cost amounts to €400 000 per year. Due to the lack of further resources to provide a better estimate, a 20% margin will be included in this value.

Table 2.13: *Hangar Upkeep Expenses*

	Cost Range [€/year]	Average Cost [€/year]
Hangar Upkeep	320 334 - 480 502	400 418

Throughout its lifetime, the airship will need to be subjected to maintenance. Maintenance may be routine, scheduled, or unscheduled in which case unexpected costs may be incurred. The costs involved are direct maintenance costs, labor expenses, additional parts or materials, and that of consumables. The frequency of the maintenance depends on the age of the airship and the frequency of use. To estimate these expenses, the costs incurred by major airlines will be used. In 2022, Boeing spent €8.7 billion on line maintenance, the maintenance every 8-10 weeks. As they have over 10 000 airplanes in operation, it results in €872 000 per aircraft. Alternatively, Airbus has 12 000 planes and spent €5.4 billion which results in €452 000 per aircraft [75]. Besides line maintenance, there is heavy maintenance which occurs every six months to six years depending on the aircraft's age. To make a cost estimate, it was decided that when the airship is to operate for 40 years there will be 8 heavy maintenance events, and if it operates for 50 years, it will need 13. This can cost the company €6.5 million when it is necessary . Dividing the cost of all heavy maintenance performed over the

[73] `https://www.salaryexpert.com/salary/job/airline-pilot/bulgaria` (Accessed on 20/06/2024)

[74] `https://truckeetahoeairport.com/board_meetings/153/view_file?file=160323%2Ftab+10a+-+trk+executive+hangar+study.draft.29feb2016.pdf` (Accessed on 20/06/2024)

[75] `https://www.skylinkintl.com/blog/line-maintenance` (Accessed on 20/06/2024)

airship's life span results in a yearly cost of €1.3 million - €1.7 million. Using these estimations leads to base maintenance costs of €1.8 million - €2.6 million per year.

Table 2.14: *Maintenance Expenses*

	Cost Range [k€/year]	Average Cost [k€/year]
Line Maintenance	452 - 872	662
Heavy Maintenance	1 306 - 1 697	1 501
	1 758 - 2 569	2 163

Presented in Table 2.15 are the total operational costs incurred per year. This represents the cost of operating the airship 200 days a year with a full-time crew that works for 40h a week.

Table 2.15: *Total Operational Costs*

	Cost Range [k€/year]	Average Cost [k€/year]
Hydrogen	10 - 50	28
Crew	321 - 2 065	1 080
Infrastructure	320 - 481	400
Maintenance	1 7585 - 2 569	2 163
Total	2 409 - 5 165	3 673

2.3. Return on Investment (ROI)

To overcome the large development costs, large financial investments should be secured. It is evident that the investors must expect to get good financial returns before investing large sums in an unproven, expensive startup. To acquire investors, the Return on Investment (ROI) is calculated. ROI can be calculated as seen in Equation 2.1, where net income and is defined as in Equation 2.2. A ROI equal to 0% implies a break-even of the investments.

$$\text{ROI} = \frac{\text{Net income} - \text{Total investments}}{\text{Total investments}} \tag{2.1}$$

$$\text{Net income} = \text{Gross income} - \text{Operational costs} \tag{2.2}$$

Since the future income is very uncertain, three scenarios are presented in Table 2.16. A low profit, an expected profit, and a high profit scenario. For each of the scenario's a different lifetime and usage rate will be presented and profits and costs analyzed for the ROI. The three scenarios and their incomes and costs differ either with a 20% margin from the expected scenario or with the lower and upper bounds of different estimation methods. The airship will operate 16 hours per day, allowing two short missions, or one long mission.

Table 2.16: *Three different scenarios for lifetime return on investment analysis.*

Scenario	Lifetime [yrs]	Usage rate [days/yr]	Short missions [%]	Long missions [%]
Low profit	40	160	40	60
Expected profit	50	200	30	70
High profit	60	240	20	80

2.3.1. Gross Income for Wind Turbine Blade Transport

The yearly income that can be realized by the main mission of transporting wind turbine blades for the three different scenarios is presented in Table 2.17. The charged rates are similar to the current costs for short and long missions via truck transport, with a 20% margin for the low and high end scenarios.

Table 2.17: *Yearly income for short and long transport missions.*

Scenario	Low end	Expected	High end
Rate short mission [€]	22 400	28 000	33 600
Short missions per year	128	120	96
Yearly short mission income [€]	2 867 200	3 360 000	3 225 600
Rate long mission [€]	115 200	144 000	172 800

Long missions per year	96	140	192
Yearly long mission income [€]	11 059 200	20 160 000	33 177 600
Yearly transport income [€]	13 926,400	23 520 000	36 403 200

2.3.2. Gross and Net Incomes and Viability

For the different scenarios and operations, Table 2.18 shows the gross incomes and net incomes per year and for an entire lifetime. Yearly net income is calculated as yearly gross income minus the yearly operating costs. The low-end income scenario is compared to the low-end cost estimation, expected to expected and high end to high end. This does not give the most extreme values (high-end profit with low-end costs does) but is considered more realistic for analysis. In absolute values, the difference between the cost estimates is much lower than the difference in income estimations. The table also shows the ROI for that particular scenario and operation as well as indicates whether this could be a viable business plan that investors could be likely to invest in. The total investment to calculate ROI includes a development cost of €500 million, taken from analysis of similar airships, and a manufacturing cost of €39 million per airship, see Section 3.7.

Note that all values are in EUR fiscal year 2024 and that the actual values will increase due to inflation. It is assumed that costs and incomes increase with the same inflation value.

Table 2.18: *Gross and net income per year, and for the total lifetime of the airship for the different types of operations. Return on Investment and viability of each option.*

Operations		**Transport**			**Promotional**			**Cruise**	
Scenario	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Gross income [M€/year]	17.4	23.5	30.3	1.7	2.5	5.2	1.0	6.6	21.8
Total gross income [M€]	696.3	1 176	1 820.2	66.6	124	311.9	38.0	330	1 310.4
Net income [M€/year]	15.0	19.8	25.2	-0.745	-1.2	0.033	-1.5	3.0	16.7
Total net income [M€]	599.9	992.4	1 510.2	-29.8	-59.6	2.028	-58.4	146.4	1 000.5
RoI [%]	11.2	84.1	180.1	-105.5	-111.1	-99.6	-110.8	-72.9	85.6
Viable	No	Yes	Yes	No	No	No	No	No	Yes

The transport operation has a positive ROI in all scenarios. However, in the low end scenario, the ROI is 11.3% over a lifetime of 40 years, which is not attractive to investors. The ROI for the promotional operations is negative in all scenarios. However, this operation can be implemented as a secondary, passive mission that is automatically carried out during the transport of the wind turbine blades. Then, the gross income of both promotional and transport can be earned, while only having the operational costs once. This then results in a ROI for a single airship of 24%, 107% and 238% for the low, expected and high-end profit scenarios, respectively.

The ROI for luxury cruising is positive only for the high-end estimation. This means the development of the airship for purely this function is not worth the investment given this financial risk. Once the airship is already operational, this may be revisited with new market research and analysis.

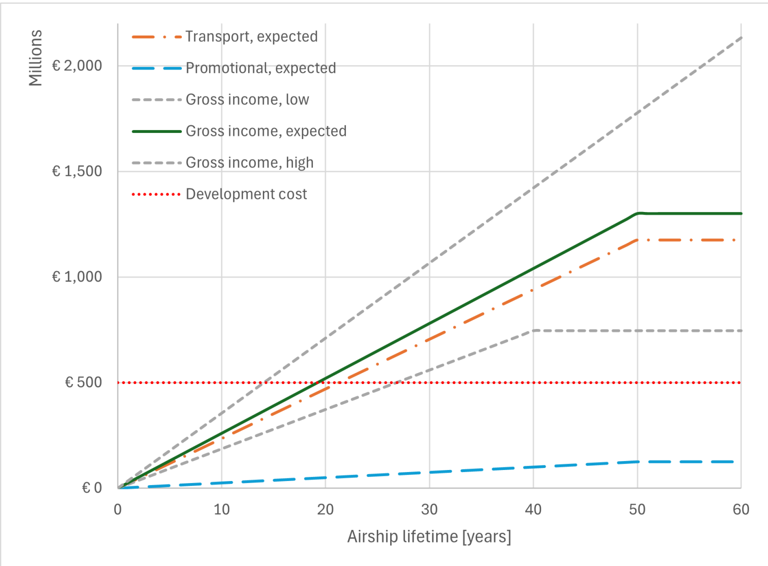


Figure 2.6: *Gross income from operations, also showing the initial development cost.*

2.3.3. Return on Investment for an Airship Fleet

The return on investment in Subsection 2.3.2 has been calculated with the assumption of operating a single airship. When building and operating airships, the manufacturing costs, operating costs, and gross incomes are assumed to scale with the number of airships.

The development cost is constant and can be carried by more airships if a fleet is operated. This means the net profit increases relatively more than the total investments. The result is that when more airships are built and operated, the ROI will increase. In the limit, the ROI will increase to 2756%, but that will require an unrealistic fleet size. This relation can be seen in Figure 2.7. This graph also includes how many wind turbines the fleet can transport the rotors for in their total lifetime, assuming three rotors per turbine.

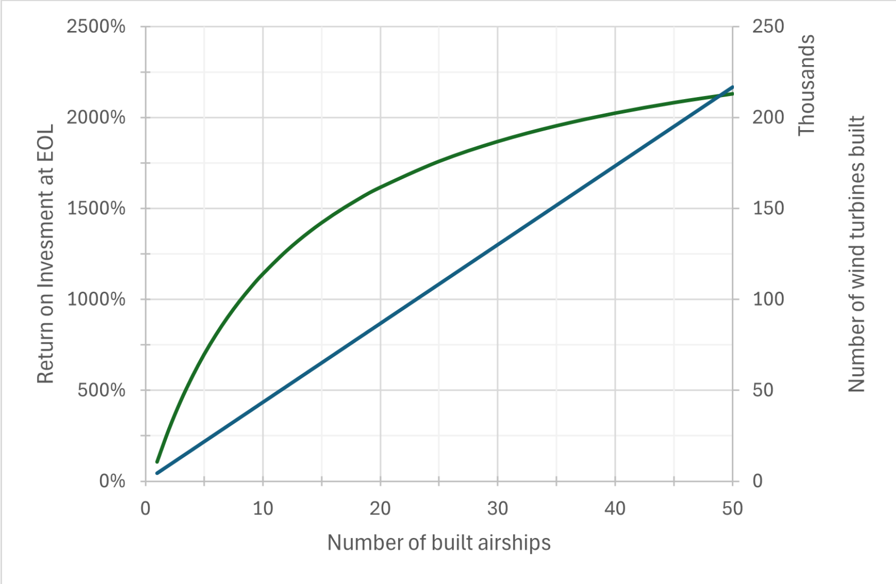


Figure 2.7: *Return on Investment (ROI) and total number of wind turbines built at the end-of-life of the airships for differing fleet sizes.*

2.4. Comparison with Truck Transport

The airship will be compared to the trucks, as the trucks are its main competitors. Several requirements are made to ensure that the airship performs better than trucks. First, the airship shall be cheaper than trucks (REQ-US-13). Secondly, the airship shall be 20% faster than trucks (REQ-US-14). Lastly, there are requirements for sustainability, although there is not a comparison requirement with trucks (REQ-US-09, REQ-US-10, REQ-US-11, REQ-US-12). In this section, the requirements for cost, time, and sustainability will be validated. For the cost and time, a case study will be performed. The specific route to be analyzed is Siemens Gamesa factory in Cuxhaven, Germany to Granswang windfarm in Hohenfels, Germany, shown in Figure 2.8.

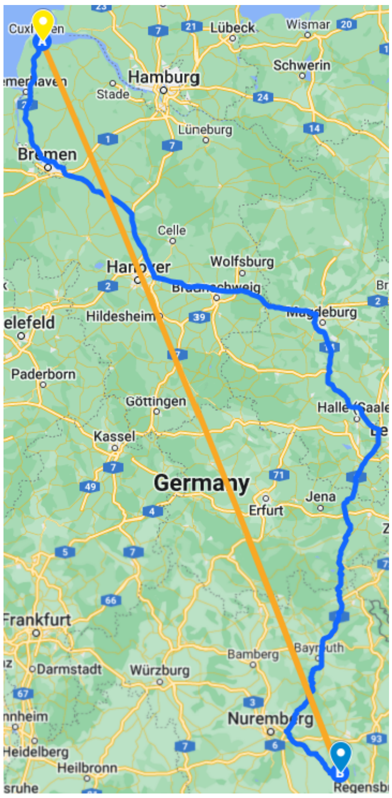


Figure 2.8: *Route for case study*

The route is representative of a long-distance route across Europe. The airship would travel a distance of 560 km in a straight line, while the most efficient route (as calculated by Google Maps) would take 750 km. This is probably an underestimation, as the trucks cannot drive everywhere and some rerouting would be needed.

2.4.1. Cost Case Study

From the requirements, an operational cost of €225 per km for trucks was defined. This was done by using the lower end cost of long-haul transport (€100 000 for 400 km). This is based on typical missions, and while not very precise it serves as a general metric. As stated before, this figure was confirmed by an engineer of Siemens Gamesa, a leading company in the wind energy industry, which provides more robustness to this assumption.

Then, using the cost of €225 per km for trucks this mission would cost approximately €165 000. Assuming the worst case for the airship of 160 flight days per year, a cost of €22 950 is obtained. This comes from the average total operational cost shown in Table 2.15, which not only includes the flight crew and fuel but also maintenance and infrastructure costs. This means that, at least under these conditions and at the current design stage, the airship is 7.5 times cheaper than trucks. This figure appears to be quite extreme, and it might be an overestimation. However, even if the cost of the airship increases drastically, the price would be below that of trucks.

2.4.2. Time case study

To compare the required time for the transportation of the blade, the same case study is used. According to requirement REQ-US-14, the delivery time shall be at least 20% less than with trucks. First, the travel time of the airship will be determined, and afterward of the trucks.

The airship's cruising speed goes up to 80 km/h or 22 m/s. The ground speed is affected by the wind speed as well, the worst case is expected to be a headwind speed of 14 m/s (equivalent to Beaufort scale 6-7).

The trucks are moving much slower, a minimum of 5 km/h and a maximum of 60 km/h are reported [6] [76]. It is assumed that the loading of the truck is twice as fast as the airship loading, 30 minutes.

For the route in Figure 2.8, the delivery time was determined for 9 cases. The airship is traveling with a tailwind, no wind, and headwind at a speed of 34, 22 and 6 m/s, respectively. The truck is traveling at slow, moderate, and fast speeds of 1.4, 8.3, and 17 m/s, respectively. This is given the matrix in Table 2.19, where the time of the airship w.r.t. the truck is calculated.

Table 2.19: *Time Matrix airship/truck. The percentages shown represent the time taken by the airship w.r.t to the truck time*

			Airship		
		Speed	Tailwind 34 m/s	No wind 22 m/s	Headwind 6 m/s
Truck	Slow	1.4 m/s	2517%	1678%	581%
	Moderate	8.3 m/s	416%	278%	96%
	Fast	17 m/s	225%	150%	52%

As can be seen from the table, the airship is 7 out of 9 times faster than the trucks. Only with a severe headwind is the airship slower than the truck. However, this is unlikely to happen, as the frequency of this wind speed is lower than 10% [19] and the direction has to be right to have this be in a full headwind. This is thus a rare occurrence, and very dependent on the route.

2.4.3. Sustainability

Another noteworthy comparison aspect is the sustainability of each transportation mode. Both a direct and indirect comparison is made. A detailed sustainability of the airship is made in Chapter 13.

For the direct sustainability, trucks are more sustainable than the airships. This is due to the large size of the airship. This induced a high drag and high material usage. For example, a route of 200 km requires 2.94 GJ for trucks to transport a blade [20], whereas for airships, at a cruising speed of 80 km/h requires 5.62 GJ. The operating empty weight of the airship is 165 tonnes, whereas a heavy-duty truck only weighs 16 tonnes [77]. This tenfold weight relates to a much higher material usage and makes airships less sustainable. An advantage of the airship is the hydrogen fuel cell system, it does not directly emit emissions, however, during the production of hydrogen, carbon or other emissions can be produced as well.

In terms of indirect sustainability, airships are much more sustainable than trucks. This is mainly due to the ability to carry longer blades of 105 meters, while trucks can only carry a blade up to 90 meters. As calculated in Section 13.3, this has the potential of producing 530 TWh of additional energy. This is equivalent to the energy production of the Netherlands in 2023. This is 2400 as much energy as use by the airship in its lifetime.

2.4.4. Conclusion

Airships perform better than trucks in all three categories. The costs are up to 7.5 times lower than for trucks. The airship is almost always faster than trucks in the delivery. Also, due to the indirect sustainability benefits, airships are more sustainable than trucks.

[76] https://www.iberdrola.com/innovation/blade-lifter-wind-turbine-blades-transportation (Accessed on 17/06/2024)
[77] https://www.onsitetruckaz.com/post/how-much-does-a-semi-truck-weigh-ultimate-guide-2022 (Accessed on 17/06/2024)

3 System Overview

An overview of the system is made to identify the connections within the system. This is crucial for performing iteration throughout the design. The requirements of the system are identified to define the design goals. Additionally, a concept trade-off is performed. The final design is presented, together with the technical budgets and sub-system overview. Lastly, a cost breakdown is made to get an estimation of the costs.

3.1. System Functions

An analysis of the system functions was conducted at the beginning of the design process. The entire life cycle of the system was considered and divided into four stages: design, production, operation, and end-of-life. Each stage is then further subdivided into more concrete tasks the system must perform. The outcome of this analysis is the Functional Flow Diagram (FFD), and Functional Breakdown Structure (FBS) which are shown below this section.

The most important phase for the design is the operational phase. A simplified version of it is shown in Figure 3.1. This diagram clearly shows the functions the airship must perform in order to deliver the payload successfully. The main element of this phase is the loop where the payload is delivered from the pick-up location, e.g. a wind turbine blade manufacturer, to the delivery location, e.g. a wind farm. This loop is broken when the mission is done, i.e. when there is not enough fuel on the airship to remain flying. Note that the travel function is the same regardless of where the airship is headed (load, unload, or base). The operational phase is further detailed in the ConOps diagram shown in Section 11.1.

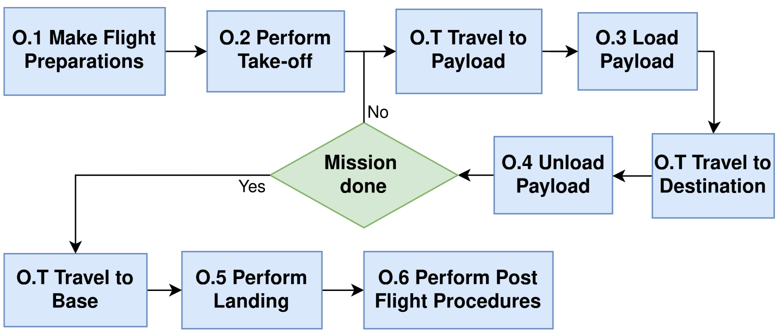
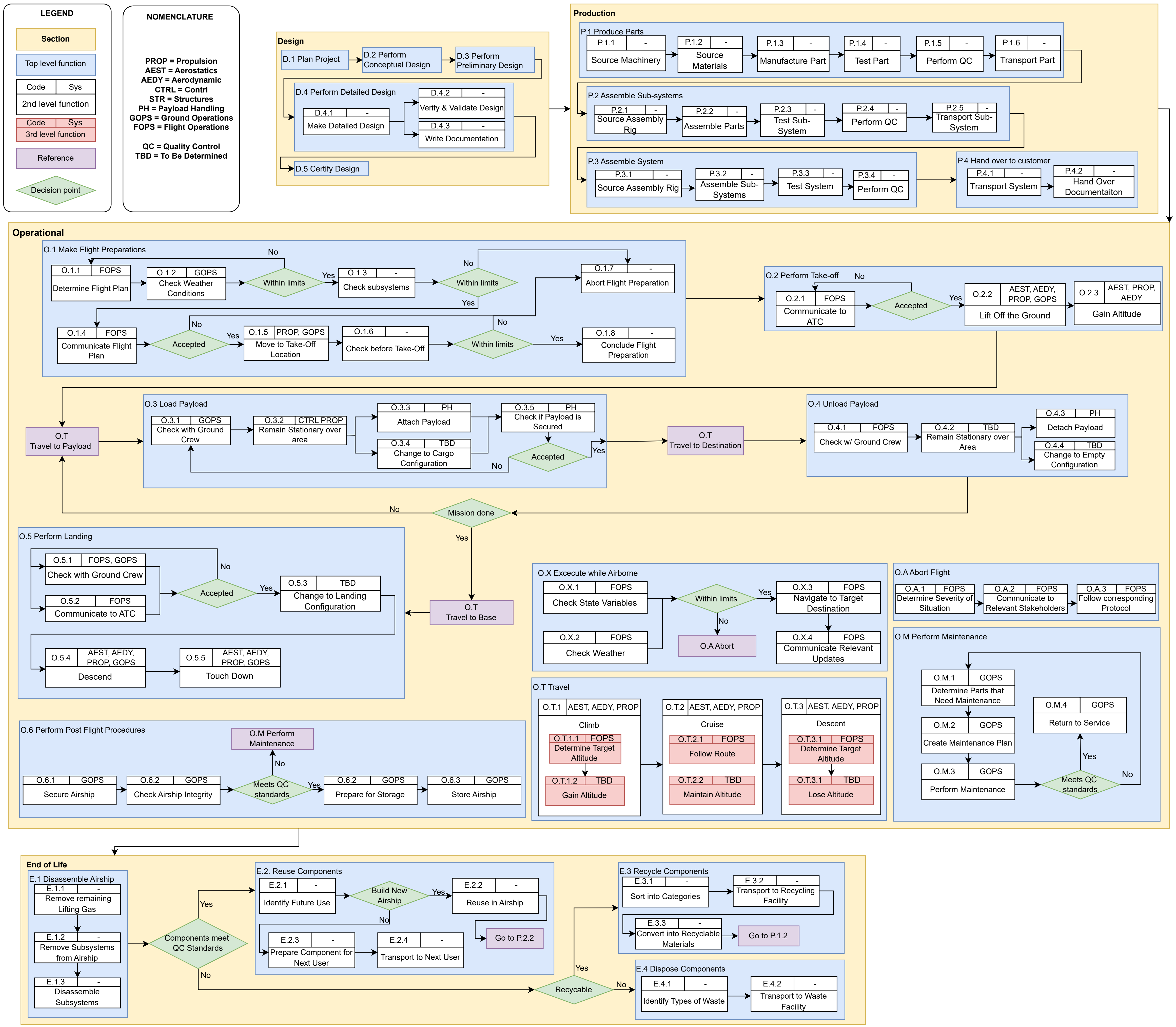
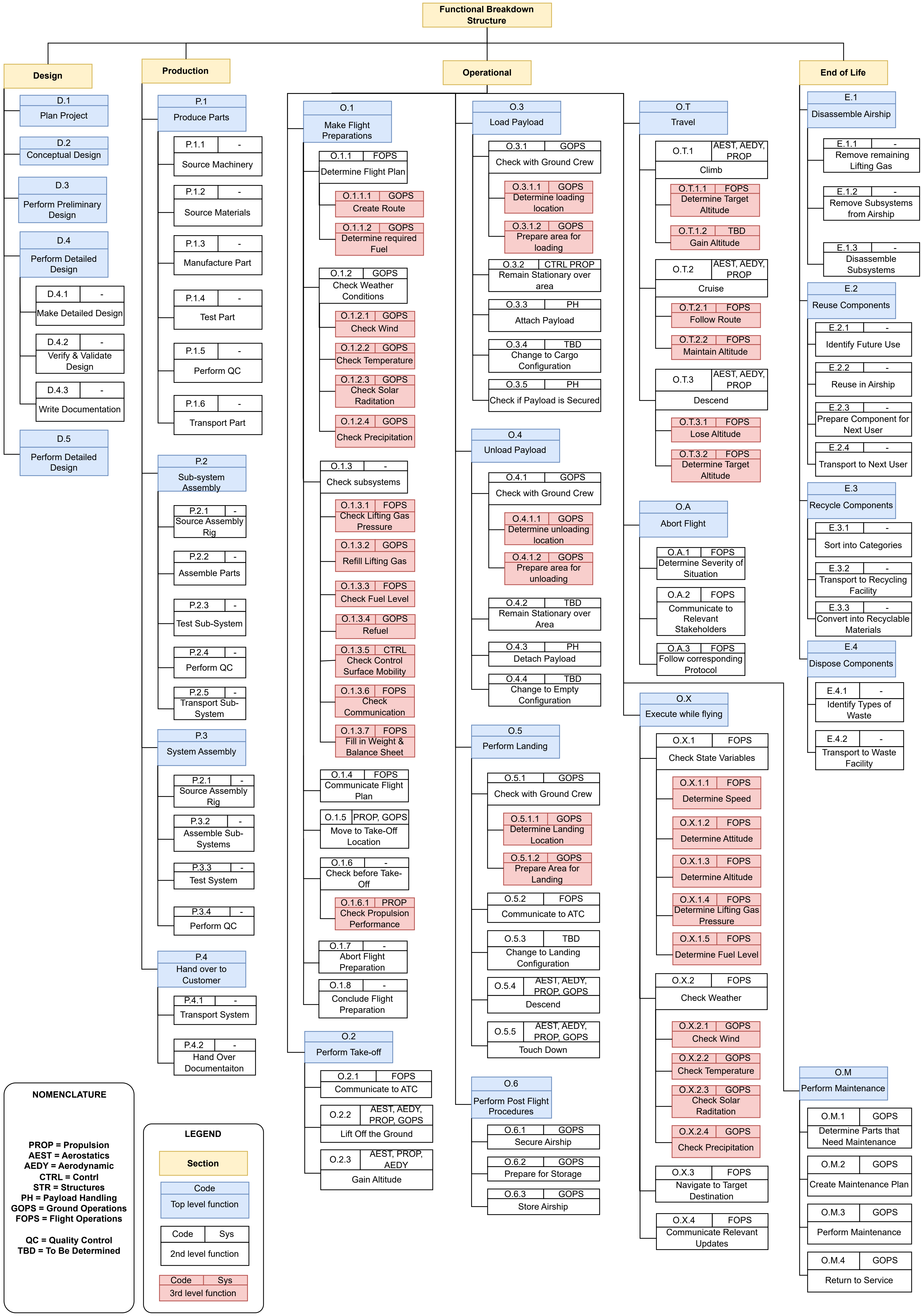


Figure 3.1: *Simplified version of the operational phase of the airship*

It is important to note that the Operational phase of the FFD has three additional phases not shown in the overview. These are *Abort Flight*, *Execute while Airborne*, and *Maintenance*. *Execute while Airborne* is to be performed continuously. *Abort Flight* and *Maintenance* are functions to be performed under certain conditions, e.g. if the weather does not allow for the flight to continue or if the airship needs to be repaired after a flight.


LEGEND
Section
Top level function
Code
Sys
2nd level function
Code
Sys
3rd level function
Reference
Decision point
NOMENCLATURE
PROP = Propulsion
AEST = Aerostatics
AEDY = Aerodynamic
CTRL = Contrl
STR = Structures
PH = Payload Handling
GOPS = Ground Operations
FOPS = Flight Operations
QC = Quality Control
TBD = To Be Determined
Design
D.1 Plan Project
D.2 Perform Conceptual Design
D.3 Perform Preliminary Design
D.4 Perform Detailed Design
D.4.1 - Make Detailed Design
D.4.2 - Verify & Validate Design
D.4.3 - Write Documentation
D.5 Certify Design
Production
P.1 Produce Parts
P.1.1 - Source Machinery
P.1.2 - Source Materials
P.1.3 - Manufacture Part
P.1.4 - Test Part
P.1.5 - Perform QC
P.1.6 - Transport Part
P.2 Assemble Sub-systems
P.2.1 - Source Assembly Rig
P.2.2 - Assemble Parts
P.2.3 - Test Sub-System
P.2.4 - Perform QC
P.2.5 - Transport Sub-System
P.3 Assemble System
P.3.1 - Source Assembly Rig
P.3.2 - Assemble Sub-Systems
P.3.3 - Test System
P.3.4 - Perform QC
P.4 Hand over to customer
P.4.1 - Transport System
P.4.2 - Hand Over Documentaiton
Operational
O.1 Make Flight Preparations
O.1.1 FOPS Determine Flight Plan
O.1.2 GOPS Check Weather Conditions
Within limits
O.1.3 - Check subsystems
Within limits
O.1.7 - Abort Flight Preparation
O.1.4 FOPS Communicate Flight Plan
Accepted
O.1.5 PROP, GOPS Move to Take-Off Location
O.1.6 - Check before Take-Off
Within limits
O.1.8 - Conclude Flight Preparation
Yes
No
O.2 Perform Take-off
O.2.1 FOPS Communicate to ATC
Accepted
O.2.2 AEST, AEDY, PROP, GOPS Lift Off the Ground
O.2.3 AEST, PROP, AEDY Gain Altitude
O.T Travel to Payload
O.3 Load Payload
O.3.1 GOPS Check with Ground Crew
O.3.2 CTRL PROP Remain Stationary over area
O.3.3 PH Attach Payload
O.3.4 TBD Change to Cargo Configuration
O.3.5 PH Check if Payload is Secured
Accepted
O.T Travel to Destination
O.4 Unload Payload
O.4.1 FOPS Check w/ Ground Crew
O.4.2 TBD Remain Stationary over Area
O.4.3 PH Detach Payload
O.4.4 TBD Change to Empty Configuration
Mission done
O.T Travel to Base
O.5 Perform Landing
O.5.1 FOPS, GOPS Check with Ground Crew
O.5.2 FOPS Communicate to ATC
Accepted
O.5.3 TBD Change to Landing Configuration
O.5.4 AEST, AEDY, PROP, GOPS Descend
O.5.5 AEST, AEDY, PROP, GOPS Touch Down
O.X Excecute while Airborne
O.X.1 FOPS Check State Variables
O.X.2 FOPS Check Weather
Within limits
O.A Abort
O.X.3 FOPS Navigate to Target Destination
O.X.4 FOPS Communicate Relevant Updates
O.A Abort Flight
O.A.1 FOPS Determine Severity of Situation
O.A.2 FOPS Communicate to Relevant Stakeholders
O.A.3 FOPS Follow corresponding Protocol
O.T Travel
O.T.1 AEST, AEDY, PROP Climb
O.T.1.1 FOPS Determine Target Altitude
O.T.1.2 TBD Gain Altitude
O.T.2 AEST, AEDY, PROP Cruise
O.T.2.1 FOPS Follow Route
O.T.2.2 TBD Maintain Altitude
O.T.3 AEST, AEDY, PROP Descent
O.T.3.1 FOPS Determine Target Altitude
O.T.3.1 TBD Lose Altitude
O.M Perform Maintenance
O.M.1 GOPS Determine Parts that Need Maintenance
O.M.2 GOPS Create Maintenance Plan
O.M.3 GOPS Perform Maintenance
Meets QC standards
O.M.4 GOPS Return to Service
O.6 Perform Post Flight Procedures
O.6.1 GOPS Secure Airship
O.6.2 GOPS Check Airship Integrity
Meets QC standards
O.M Perform Maintenance
O.6.2 GOPS Prepare for Storage
O.6.3 GOPS Store Airship
End of Life
E.1 Disassemble Airship
E.1.1 - Remove remaining Lifting Gas
E.1.2 - Remove Subsystems from Airship
E.1.3 - Disassemble Subsystems
Components meet QC Standards
E.2. Reuse Components
E.2.1 - Identify Future Use
Build New Airship
E.2.2 - Reuse in Airship
Go to P.2.2
E.2.3 - Prepare Component for Next User
E.2.4 - Transport to Next User
Recyclable
E.3 Recycle Components
E.3.1 - Sort into Categories
E.3.2 - Transport to Recycling Facility
E.3.3 - Convert into Recyclable Materials
Go to P.1.2
E.4 Dispose Components
E.4.1 - Identify Types of Waste
E.4.2 - Transport to Waste Facility



Functional Breakdown Structure
Design
D.1 Plan Project
D.2 Conceptual Design
D.3 Perform Preliminary Design
D.4 Perform Detailed Design
D.4.1 - Make Detailed Design
D.4.2 - Verify & Validate Design
D.4.3 - Write Documentation
D.5 Perform Detailed Design
Production
P.1 Produce Parts
P.1.1 - Source Machinery
P.1.2 - Source Materials
P.1.3 - Manufacture Part
P.1.4 - Test Part
P.1.5 - Perform QC
P.1.6 - Transport Part
P.2 Sub-system Assembly
P.2.1 - Source Assembly Rig
P.2.2 - Assemble Parts
P.2.3 - Test Sub-System
P.2.4 - Perform QC
P.2.5 - Transport Sub-System
P.3 System Assembly
P.2.1 - Source Assembly Rig
P.3.2 - Assemble Sub-Systems
P.3.3 - Test System
P.3.4 - Perform QC
P.4 Hand over to Customer
P.4.1 - Transport System
P.4.2 - Hand Over Documentaiton
Operational
O.1 Make Flight Preparations
O.1.1 FOPS Determine Flight Plan
O.1.1.1 GOPS Create Route
O.1.1.2 GOPS Determine required Fuel
O.1.2 GOPS Check Weather Conditions
O.1.2.1 GOPS Check Wind
O.1.2.2 GOPS Check Temperature
O.1.2.3 GOPS Check Solar Raditation
O.1.2.4 GOPS Check Precipitation
O.1.3 - Check subsystems
O.1.3.1 FOPS Check Lifting Gas Pressure
O.1.3.2 GOPS Refill Lifting Gas
O.1.3.3 FOPS Check Fuel Level
O.1.3.4 GOPS Refuel
O.1.3.5 CTRL Check Control Surface Mobility
O.1.3.6 FOPS Check Communication
O.1.3.7 FOPS Fill in Weight & Balance Sheet
O.1.4 FOPS Communicate Flight Plan
O.1.5 PROP, GOPS Move to Take-Off Location
O.1.6 - Check before Take-Off
O.1.6.1 PROP Check Propulsion Performance
O.1.7 - Abort Flight Preparation
O.1.8 - Conclude Flight Preparation
O.2 Perform Take-off
O.2.1 FOPS Communicate to ATC
O.2.2 AEST, AEDY, PROP, GOPS Lift Off the Ground
O.2.3 AEST, PROP, AEDY Gain Altitude
O.3 Load Payload
O.3.1 GOPS Check with Ground Crew
O.3.1.1 GOPS Determine loading location
O.3.1.2 GOPS Prepare area for loading
O.3.2 CTRL PROP Remain Stationary over area
O.3.3 PH Attach Payload
O.3.4 TBD Change to Cargo Configuration
O.3.5 PH Check if Payload is Secured
O.4 Unload Payload
O.4.1 GOPS Check with Ground Crew
O.4.1.1 GOPS Determine unloading location
O.4.1.2 GOPS Prepare area for unloading
O.4.2 TBD Remain Stationary over Area
O.4.3 PH Detach Payload
O.4.4 TBD Change to Empty Configuration
O.5 Perform Landing
O.5.1 GOPS Check with Ground Crew
O.5.1.1 GOPS Determine Landing Location
O.5.1.2 GOPS Prepare Area for Landing
O.5.2 FOPS Communicate to ATC
O.5.3 TBD Change to Landing Configuration
O.5.4 AEST, AEDY, PROP, GOPS Descend
O.5.5 AEST, AEDY, PROP, GOPS Touch Down
O.6 Perform Post Flight Procedures
O.6.1 GOPS Secure Airship
O.6.2 GOPS Prepare for Storage
O.6.3 GOPS Store Airship
O.T Travel
O.T.1 AEST, AEDY, PROP Climb
O.T.1.1 FOPS Determine Target Altitude
O.T.1.2 TBD Gain Altitude
O.T.2 AEST, AEDY, PROP Cruise
O.T.2.1 FOPS Follow Route
O.T.2.2 FOPS Maintain Altitude
O.T.3 AEST, AEDY, PROP Descend
O.T.3.1 FOPS Lose Altitude
O.T.3.2 FOPS Determine Target Altitude
O.A Abort Flight
O.A.1 FOPS Determine Severity of Situation
O.A.2 FOPS Communicate to Relevant Stakeholders
O.A.3 FOPS Follow corresponding Protocol
O.X Execute while flying
O.X.1 FOPS Check State Variables
O.X.1.1 FOPS Determine Speed
O.X.1.2 FOPS Determine Attitude
O.X.1.3 FOPS Determine Altitude
O.X.1.4 FOPS Determine Lifting Gas Pressure
O.X.1.5 FOPS Determine Fuel Level
O.X.2 FOPS Check Weather
O.X.2.1 GOPS Check Wind
O.X.2.2 GOPS Check Temperature
O.X.2.3 GOPS Check Solar Raditation
O.X.2.4 GOPS Check Precipitation
O.X.3 FOPS Navigate to Target Destination
O.X.4 FOPS Communicate Relevant Updates
End of Life
E.1 Disassemble Airship
E.1.1 - Remove remaining Lifting Gas
E.1.2 - Remove Subsystems from Airship
E.1.3 - Disassemble Subsystems
E.2 Reuse Components
E.2.1 - Identify Future Use
E.2.2 - Reuse in Airship
E.2.3 - Prepare Component for Next User
E.2.4 - Transport to Next User
E.3 Recycle Components
E.3.1 - Sort into Categories
E.3.2 - Transport to Recycling Facility
E.3.3 - Convert into Recyclable Materials
E.4 Dispose Components
E.4.1 - Identify Types of Waste
E.4.2 - Transport to Waste Facility
O.M Perform Maintenance
O.M.1 GOPS Determine Parts that Need Maintenance
O.M.2 GOPS Create Maintenance Plan
O.M.3 GOPS Perform Maintenance
O.M.4 GOPS Return to Service
NOMENCLATURE
PROP = Propulsion
AEST = Aerostatics
AEDY = Aerodynamic
CTRL = Contrl
STR = Structures
PH = Payload Handling
GOPS = Ground Operations
FOPS = Flight Operations
QC = Quality Control
TBD = To Be Determined
LEGEND
Section
Code
Top level function
Code Sys
2nd level function
Code Sys
3rd level function

3.2. System Requirements

To satisfy user, stakeholder, and regulatory needs, a set of well-defined requirements must be created at the beginning of the design process. These need to be thoroughly analyzed and converted into system requirements formulated in a SMART and VALID manner. Tables 3.1, 3.2, and 3.3 show the compliance with user, main stakeholder and main system requirements. A selection of the stakeholder and system requirements that have the most impact on the design has been made for the sake of conciseness.

The current stage of the design complies with all user requirements except for three. One has not been met, the control of the lifting gas temperature, as this was deemed too complex and heavy for the benefits. Two are only partially met because there is no concrete design that covers these requirements yet. However, they have been considered during the design and some preliminary decisions have been made to be able to comply to the requirement.

With regard to the driving stakeholder requirements, they have all been satisfied with the current design. However, the driving system requirements defined at the initial stages are not completely satisfied with the current design, as the range and altitude were lowered after some additional analysis and the goal for critical materials was too strict and was deemed unattainable. This was done to prevent a lower performance in other areas. The impact and reasoning of these design choices are explained in the corresponding section(s) indicated in the table.

Table 3.1: *Compliance with user requirements.*

Requirement ID	Description	Complied?	Details
REQ-US-01	The vehicle shall lift at least a medium-sized turbine blade.	Yes, the maximum blade size is 60 tonnes and 105 m long, which is considered a very large sized turbine blade and will cover the needs of blade growth	Table 2.1.3
REQ-US-02	The vehicle shall maintain hovering capability under mild side winds (5 m/s)	Yes, the airship is capable of hovering without weathervaning under side winds of up to 5 m/s	Section 7.2
REQ-US-03	The vehicle shall be self-propelled	Yes, 6 engines are mounted on the airship to provide propulsion	Section 7.4
REQ-US-04	The range shall be a minimum of 200 km	Yes, the range of the airship is over 1100 km	Subsection 9.3.1
REQ-US-05	The vehicle shall be capable of (un)loading without landing (anchoring possible).	Yes, (un)loading happens while moored with cables	Section 10.2
REQ-US-06	The lifting gas shall be handled safely	Partially, it has been considered but no concrete system has been designed yet	Section 14.4
REQ-US-07	The vehicle shall remain controllable while releasing the load.	Yes, mooring cables hold the airship in place and engines provide additional control if needed	Chapter 10
REQ-US-08	The lifting gas temperature shall be controllable.	Temperature control has been considered, but deemed too heavy and complex for the benefits	Section 4.4
REQ-US-09	Propulsion shall be achieved using renewable/green sources	Yes, renewable hydrogen is used as fuel	Section 3.5
REQ-US-10	Appropriate measures shall be taken to reuse/contain the lifting gas	Yes, gas bag materials with low permeability are used	Subsection 8.5.3

Table 3.1 (continued from previous page)

Requirement ID	Description	Complied?	Details
REQ-US-11	The vehicle shall use as many recyclable/recycled/upscaled materials as possible.	Yes, recyclability has been a key factor during material selection. 80% of the used materials is recyclable	Section 8.5 & Subsection 13.2.3
REQ-US-12	An analysis of emissions compared to trucks shall be performed	Yes, sustainability of the airship are analyzed and compared to trucks	Subsection 2.4.3
REQ-US-13	Operation shall be less costly than the equivalent transport truck.	Yes, the operational cost is under €225 per km	Subsection 2.4.1
REQ-US-14	Delivery time shall be at least 20% less than with trucks.	Yes, the airship is faster than trucks, except for severe headwind	Section 2.4
REQ-US-15	Lifting gas cost and availability shall be taken into account.	Yes, hydrogen was chosen over helium for its cost and availability	Section 3.4
REQ-US-16	Storage infrastructure (e.g., hangar) shall be considered, limiting the vehicle's size	Yes, the size of the airship has been minimized to allow for smaller storage facilities	Section 10.4
REQ-US-17	The possibility of pilot-less operation shall be considered	Yes, a trade-off has been conducted and manual control has been chosen	Section 6.6
REQ-US-18	The airship infrastructure shall provide refueling capabilities	Partially, it has been considered but no concrete system has been designed yet	Section 10.4

Table 3.2: *Compliance with driving stakeholder requirements.*

Requirement ID	Description	Complied?	Details
REQ-ST-MAN-04	The payload shall have maximum dimensions of 105x12x10 m.	Yes, the payload bay is designed to carry a payload of 105x12x10 m.	Section 8.3
REQ-ST-MAN-05	The system shall have a payload capacity of at least 20 tonnes.	Yes, the maximum payload mass is 60 tonnes.	Section 8.3
REQ-ST-LOC-01	No flights shall be conducted between 22:00 and 08:00.	Yes, the airship will not fly outside of those hours and its endurance is adjusted for it.	Section 9.3
REQ-ST-PIL-01	The airship shall remain controllable throughout the flight.	Yes, the airship is controllable in all speed regimes and hovering.	Chapter 6
REQ-ST-WF-03	The airship shall maintain a safe height while unloading	Yes, the airship will remain at a height of 75m to avoid accidents due to pitching	Section 10.2

Table 3.3: *Compliance with driving system requirements.*

Requirement ID	Description	Complied?	Details
REQ-SYS-MIS-01	The airship shall have a range of at least 2000 km.	No, this range was deemed unfeasible and was reduced to 1100 km	Subsection 9.3.1

Table 3.3 (continued from previous page)

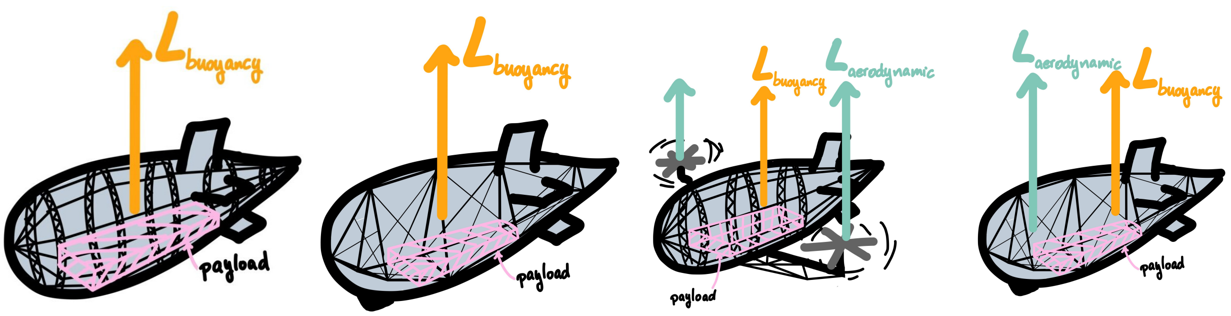
Requirement ID	Description	Complied?	Details
REQ-SYS-MIS-03	The airship shall have a minimum achievable climb rate of 2 m/s at sea level.	Yes, the climb rate at sea level is 2 m/s with all engines working	Subsection 7.2.3
REQ-SYS-MIS-06	The airship shall cruise at an altitude of 4000 m.	No, the maximum altitude was reconsidered and lowered to 2000 m	Subsection 4.2.4
REQ-SYS-MIS-16	The vehicle shall have a cruising speed of at least 60 km/h.	Yes, the cruising speed is 80 km/h	Subsection 7.2.1
REQ-SYS-SUS-03	At least 80% of the system components shall be made out of recyclable materials.	Yes, the total percentage is 80%	Subsection 13.2.3
REQ-SYS-SUS-04	The system shall use no more than 50 kg of critical minerals.	No, there are over 2000 kg of critical raw materials	Section 13.2

3.3. Driving Risks for the Design

Designing and operating an aircraft comes with many risks that must be contemplated at all times. Risks can have different levels of likelihood and severity. Some of the most likely and severe risks have been selected as driving risks for the design, i.e. those with a large impact on the system during the design process. These risks must be kept in mind while designing to ensure the airship can perform its mission successfully. There were many other risks considered, and a more detailed risk analysis is shown in Chapter 14.

3.4. System Trade-off

Once all system functions, requirements, and risks have been collected and analyzed, the concept generation and trade-off can begin. A design option tree was created, covering all possible options that could fulfill the system needs across different aspects, such as propulsion method or lifting gas. Many of these options were deemed unfeasible, leading to a smaller set of choices for the final design. Nonetheless, there were still an immense amount of potential combinations. The interaction between options across different aspects was analyzed using a compatibility matrix, narrowing down the options even further. Finally, the four highest-scoring systems from the compatibility matrix were selected. These are shown in Figure 3.2.



(a) *Option 1: Rigid-Aerostat* **(b)** *Option 2: Semi-Aerostat* **(c)** *Option 3: Rotastat* **(d)** *Option 4: Lifting-Body*

Figure 3.2: *Drawings for generated design options.*

The first two options rely purely on buoyancy force to obtain lift (non-hybrid airships), while the last two use aerodynamic lift to sustain 40% of its weight (hybrid airships). Option 3, the Rotastat, achieves it by using helicopter-like rotors. Option 4, the Lifting-Body, has an aerodynamic shape that produces lift when immersed in an airflow. Options 1 and 3 use a rigid structure to sustain all loads, while the other two options rely on a semi-rigid structure. A rigid airship has an internal truss structure that carries all loads, while semi-rigids have simpler structures that carry some load and the envelope bears the rest. There are several more aspects that differentiate the different options, and they are all listed in Table 3.4

Table 3.4: *Generated design concepts.*

	Option 1: Rigid-Aerostat	Option 2: Semi-Aerostat	Option 3: Rotastat	Option 4: Lifting-Body
Type	Non-hybrid	Non-hybrid	Rotorcraft	Lifting Body
Structure	Rigid	Semi-rigid	Rigid	Semi-rigid
Cargo Hold	Internal	Internal	Internal	Internal
Remain Stationary	Moor	Hover	Hover	Moor
Landing	Horizontal	Vertical	Vertical	Horizontal
Take Off	Horizontal Self Propelled	Vertical Buoyancy	Vertical Powered	Horizontal Towed
Propulsion System	Fuel Cell	Combustion	Fuel Cell	Combustion

These four options were then analyzed and graded on three criteria: sustainability, cost, and feasibility. Their weights were 35%, 45%, and 20% respectively, reflecting the level of importance they have on the final outcome. Cost was the most important criterion because one of the primary requirements (REQ-US-13) is to be more affordable than trucks, making the mission cost a critical factor in the design. Sustainability is close behind, as the Mission Need Statement does not only include cost and time effectiveness, but also sustainability. Time is not included as a criterion because all airships can fly faster than trucks without much additional consideration. Finally, feasibility is included to make sure a reasonably detailed design can be developed within the strict time constraints of the Design Synthesis Exercise (10 weeks) and the project as a whole (prototype built in 12 years). Note that the four presented options are already somewhat feasible, as the concept generation process already discarded unviable options. This criterion is more concerned with the likelihood of the concept being successful during design and operation.

Each of the criteria was subdivided further into more categories that could be individually analyzed, such as production cost or Technology Readiness Level (TRL). These lower-level criteria are not shown for the sake of brevity, as they do not impact the outcome and were only used to aid the analysis.

The analysis of each option showed that the Semi-Aerostat was not feasible due to, among other reasons, the hovering during (un)loading. This has never been done before and is likely to be very complex and expensive to implement, which is not desired for an airship that is planned to be operating in 16 years. The Rotastat had a high fuel consumption as well as high engine cost, making it score poorly on sustainability and cost. While the Lifting-Body scored better on those due to its lower fuel consumption, it was found that mooring would be unpractical because the buoyancy force cannot hold the airship in place and would thus need high-powered engines to stay afloat during (un)loading. This leads to the Rigid-Aerostat, which scored well in all categories and had no major drawbacks to it.

The results of the trade-off analysis are summarized in Table 3.5, where a four-level color scale was used to score the designs: red (R) for unacceptable, yellow (Y) for sufficiently well-performing, blue (B) for well-performing, and green (G) for the best option.

Table 3.5: *Trade-off table of the four design options.*

	Sustainability [35%]	Cost [45%]	Feasibility [20%]
Rigid-Aerostat	Good overall sustainability performance (B)	Low prod., low op. cost (G)	High TRL, limited safety concerns, some infrastructure (B)
Semi-Aerostat	Good overall sustainability performance (B)	Low prod. cost, mid. op. cost (B)	Unacceptable TRL, large safety concerns (R)
Rotastat	Deficient overall sustainability performance (Y)	High prod. cost, high op. cost (Y)	Low TRL, limited safety concerns, no infrastructure (B)
Lifting-Body	Good overall sustainability performance (B)	Low prod. cost, mid. op. cost (B)	Good TRL, considerable safety concerns, impractical mooring (Y)

From this table it is clear that the Rigid-Aerostat is the best option, as it has the only green score and two blue scores. However, this winner might be influenced by the choice of criteria, sub-criteria, and weights. For that reason a sensitivity analysis on the trade-off was conducted, for which all criteria and sub-criteria were removed one by one and the impact on the final choice was analyzed. Part of this process is shown on Figure 3.3, where the main criteria have been removed. In every case is the Rigid-Aerostat still the highest-scoring option, suggesting that it is indeed the best choice of the four.

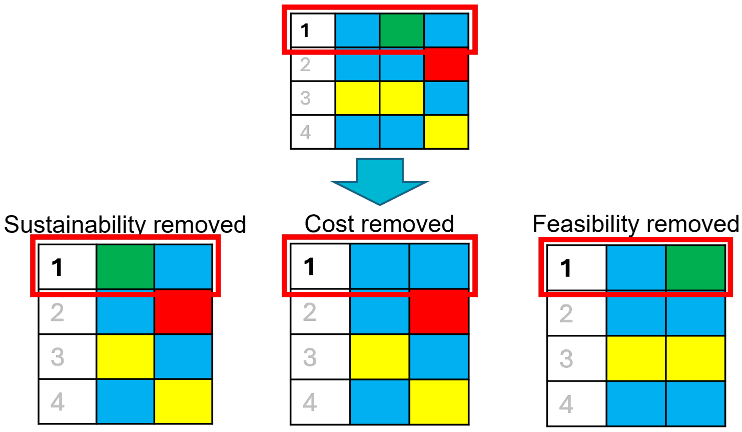


Figure 3.3: *Visualization of sensitivity analysis performed by removing the main criteria (winner circled in red).*

After this sensitivity analysis, it was investigated whether any change in the Rigid-Aerostat would affect the final decision. Some sub-systems were changed and it was found that when using vertical take-off and landing instead of horizontal its scores became slightly higher due to a reduced cost of the required infrastructure. Thus, the system was slightly modified and the final outcome of the trade-off is summarized below. This was used as the base for the sub-system design later on, which elaborated more into each one of the sub-systems as well as introducing additional ones.

Table 3.6: *High-level system description of the chosen concept to enter detailed design.*

System	Choice
Type	Non-hybrid
Structure	Rigid
Cargo Hold	Internal
Remain Stationary	Moor
Landing	Vertical
Take Off	Vertical powered
Propulsion System	Fuel Cell

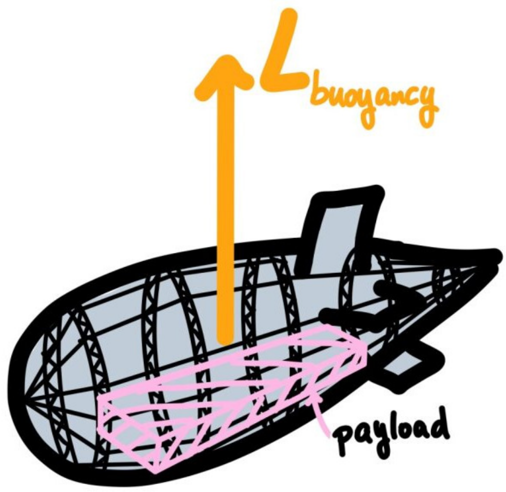


Figure 3.4: *Visual of the chosen concept to enter detailed design.*

3.5. Final Design and Parameters

This section will show the latest iteration of the design with the purpose of giving an overview of the main decisions and technical data about the system and refer the reader to the specific section where more information can be found. This section covers the key characteristics on a system level, covering the main parameters of the airship as a whole, a visualization of the configuration of the airship, the integration process performed, and the technical budget allocation. A more concrete look into the sub-systems and their interfaces is shown in Section 3.6.

3.5.1. Visualization and Main Parameters

A 3D render of the airship is shown in Figure 3.5 and the key parameters of the design are shown in Table 3.7. The airship can carry up to 60 tonnes of payload with maximum dimensions of 105 m x 12 m x 10 m, accommodated in the payload bay. These measurements refer to the length, width, and height of the payload respectively. The payload bay has total measurements of 110 m x 14 m x 12 m and its design can be found in Section 8.3. The payload mass accounts for 27% of the 225 tonnes of MTOW. The MTOW was initially estimated using statistics and was then iterated once the sub-systems had a more refined mass estimation. This process is shown in Subsection 3.5.2.

The airship itself has a length of 221 m and a maximum radius at its thickest point of 48 m, which leads to a fineness ratio (i.e. length to radius ratio) of 4.6. More details on the shape and the reasoning behind these values can be found in Chapter 5.

The airship will cruise at an airspeed of 80 km/h and can reach up to 93 km/h. This cruising speed has been chosen to be competitive with trucks even in their ideal conditions, see Section 9.3 for more detail. Note that it was originally set to 100 km/h to be more competitive with other airships, but this was deemed unreasonable due to the fuel tanks becoming too large (see Section 7.5).

The endurance of 16 h has been set according to the REQ-ST-LOC-01 requirement shown in Table 3.2, which limits the operation hours to 8 AM - 10 PM. This leads to a maximum operational time of 16 h. In the case that this requirement is revised and the operational window is modified by the authorities, the endurance should be updated to a new optimal value. From the endurance, the range has been calculated to be 1120 km for a single trip and 1040 km for two trips. The difference is caused by the time taken to load and unload the payload, estimated to be 30 min in each case. This means that the airship can cruise for one hour less in case two blades are being delivered, as there is one additional loading procedure and another unloading procedure. Hence, the range is reduced by 80 km. Note that this range has been calculated for the airship cruising at a constant 80 km/h, and in the case of heavy winds this figure will be reduced as the airship will fly slower or burn more fuel, limiting its operating time.

The maximum altitude has been updated to 2000 m, which is half of what was set in the initial design stage. A more detailed analysis of the required height for operations was conducted and is shown in Section 9.3. It was concluded that with a maximum height of 2000 m the airship can reach most desired places (Section 9.3) with ease while significantly reducing the weight of the gas bags (Section 4.2). Note that 2000 m is the maximum height when the perfect ISA conditions are assumed. Higher temperatures or lower pressures lower the ceiling height of the airship, as shown in Section 4.2.

The airship relies mostly on buoyancy force to carry its weight. However, heaviness (weight - buoyancy) is desired throughout most of the operation, as it increases the controllability. Hence, the airship has a buoyancy ratio (i.e. the buoyant lift-to-weight ratio) of 99.7%. In other words, the airship is 0.3% or 750 kg heavy. This ”extra” weight is carried by aerodynamic lift, obtained by flying the airship at a small angle of attack during cruise. More details about this decision can be found in Section 5.2.

Hydrogen has been chosen as both the lifting gas and energy source. Despite its safety concerns, which will be addressed in Section 14.4, hydrogen performs excellently in many areas, including cost, lifting power, and energy density. The power is generated using fuel cells, as discussed in Chapter 7. This power is then transferred to six vectored engines, which together provide enough thrust for cruising. Two of these engines are located on the sides of the airship and can be used for vertical propulsion. The remaining four are placed on the top and bottom (see Figure 3.5) and can be turned to provide side force for low-speed control of the airship. Engine placement together with propeller design is further discussed in Section 7.4.

The airship is constructed out of various materials, which serve diverse functions and thus have different needs. Section 8.5 is dedicated to the material selection of some critical sub-systems. Aluminum 6061-T6 is for the internal structure, as it has great performance, is widely used in the aerospace industry, is reasonably sustainable, and can be welded. The envelope (outside shell of the airship) is usually made of fabric is made out of polyurethane, as it is light and cheap while complying with the performance requirements, which are not very demanding as the envelope in rigid airships is not load-bearing.

Soil and water are used as ballast. Ballast is a ”dead” weight used to replace the payload and keep the weight of the airship constant. Ballast is needed because the buoyant force does not vary whether the airship carries a payload or not, hence the weight cannot change when the payload is unloaded. If the weight were to be suddenly reduced by 60 tonnes, the net buoyant force would be huge, meaning that the airship would float away. Soil from the wind farm will be used as ballast, more reasoning on that can be found in Section 10.3. There is another type of ballast, the so-called permanent ballast. It is used during mooring to become light (weight < buoyancy). Permanent ballast uses water for ease of operation, as it can be easily loaded and unloaded in the airship, also during cruise. More details on this type of ballast can be found on Section 10.3.

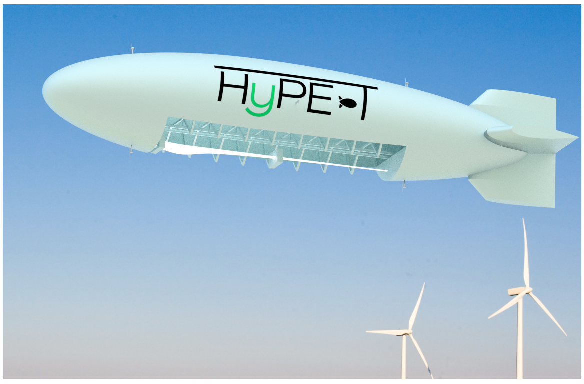


Figure 3.5: *Render of the airship*

Table 3.7: *Main parameters of the system*

Parameter	Value
Payload Capacity	60 000 kg
MTOW	225 000 kg
Max. Payload Dimensions (l x w x h)	105 m x 12 m x 10 m
Length	221 m
Radius	48 m
Fineness ratio (FR)	4.6
Cruise Speed	80 km/h
Max. Speed	93 km/h
Endurance	16 h
Max. Range	1120 km for 1 trip, 1040 km for 2 trips
Max. altitude	2000 m under ISA condition
Buoyancy Ratio	99.7%
Lifting Gas	Hydrogen
Fuel	Hydrogen
Power Source	Fuel Cells
Engines	6 Vectored
Internal Structure Material	Al 6061-T6
Envelope Material	Polyurethane
Ballast Material	Soil and water

Figure 3.6 shows the internal layout of the airship. This cross-section is made at the vertical symmetry plane of the airship. The most important elements are shown: gas bags, payload bay, fuel tank, fuel cells, tail, internal structure, and cockpit. There is some space left as a margin for additional elements that will be added later, such as gas compressors or winches for mooring, once more detail is added to the design. A 3-view drawing of the outside/internal structure of the airship is shown in Appendix A.

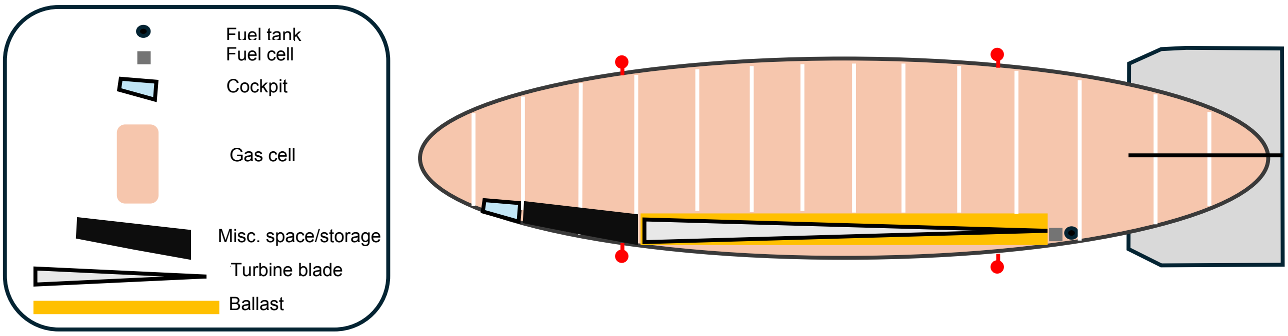


Figure 3.6: *Internal layout of the airship*

3.5.2. Integration Process

At the beginning of the design process, the MTOW and length of the airship were estimated using statistics, a so-called Class I Estimation. For this purpose, a database with 13 similar airships was created. A multivariate statistical analysis was performed to determine the mass and length of the different airships based on some of their characteristics: payload mass, rigid/semi-rigid/non-rigid, and hybrid/non-hybrid. The initial MTOW and length had values of 191 000 kg and 160 m, respectively. Naturally, these parameters are very critical and impact the system as a whole, as they are used across all sub-system analyses.

Once all sub-systems had a more accurate mass estima-

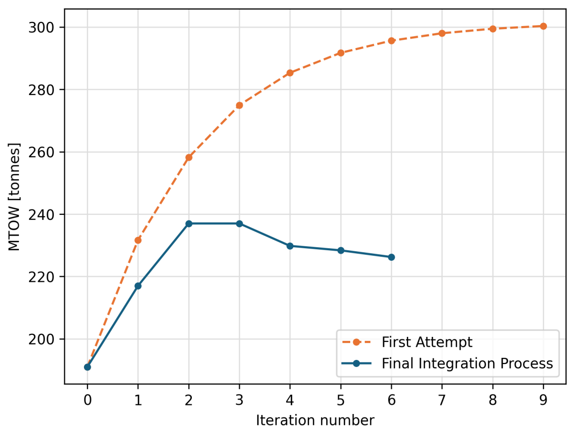


Figure 3.7: *Evolution of MTOW with every iteration. The orange curve represents the initial attempt, with a very high final MTOW, and the blue curve represents the final process, which converges to a lower value*

tion based on the analysis of its main components, the MTOW could be estimated using the values specific to our airship, a so-called Class II estimation. This creates an iterative process, as the sum of all sub-systems' mass was higher than the original MTOW from statistics. This iterative process is shown in Figure 3.7. Note that the plotted MTOW values are those used in the calculations for every iteration. At every iteration, this value is updated with the sum of all sub-systems, the "new" MTOW. This "new" value is then used in the next iteration to perform all sub-system calculations and a new MTOW is computed.

At first, the MTOW was growing rather quickly as shown with the orange line. That would potentially lead to a mass of over 300 tonnes. Note that this curve represents the impact of an incomplete set of parameters on the MTOW, as several values had to be manually inputted and were not automatically updated. This suggests that the actual MTOW would grow to a much higher value than the already large number shown in the graph.

It was thus decided to change the approach slightly, with its result shown in the blue curve of Figure 3.7. First, the formula to calculate the hull volume was revised, which led to a smaller overall hull volume, decreased aerodynamic forces, decreased structure mass and tail mass, etc. This "snowball effect" had a significant impact on the MTOW, as can be seen by the difference between the orange and blue curves on the first iteration. Then, two more iterations were performed. It was noted that the MTOW was still growing rather quickly, and the final value might get close to 300 tonnes once again. To avoid this, the cruise speed was lowered from 100 km/h to 80 km/h on the third iteration. This had a great impact on the propulsive and aerodynamic forces, significantly reducing the masses of structures and propulsion. This led to the sum of sub-systems being below the MTOW used for calculations, meaning now the MTOW showed a decreasing and converging trend.

3.5.3. Technical Budget Allocation

The mass breakdown of the main sub-systems is shown in Table 3.8. It has been divided into five categories: structure, propulsion, aerostatics, payload handling, and miscellaneous. Each one comprises 38%, 6.3%, 15%, 31%, 10.2% of the MTOW respectively. As expected, the structures and payload take up the most mass. The reasoning and calculations of the mass of each sub-system can be found in their respective chapters. The power budget for both cruise and maximum speed is shown in Table 3.9. The analysis performed to obtain these estimates can be found in Section 7.3.

Table 3.8: *Mass breakdown of the airship, subdivided into five categories.*

Element	Value [tonnes]	% of MTOW
Structure (38%)		
Envelope	3	1
Internal Structure	61	27
Control surfaces (Tail)	22	10
Propulsion (6.3%)		
Engine + Gearbox	4	2
Power Generator (Fuel Cell)	1	1
Fuel tanks	6	3
Fuel	1	0.3
Aerostatics (15%)		
Gas Cells	18	8
Lifting gas	16	7
Payload Handling (31%)		
Payload cables	4	2
Payload	60	27
Permanent ballast	5	2
Miscellaneous (10.2%)		
Flight crew	0.5	0.2
Contingency	23	10
Total MTOW	**226**	**100**

Table 3.9: *Power budget of the airship.*

Element	Power at v_{cruise}[kW]	Power at v_{max}[kW]
Propulsion	640	853
Other sub-systems	200	200
Total power	**840**	**1053**

3.6. Sub-system Overview and Interfaces

The airship comprises multiple sub-systems that together form the full system. At the current design stage, there are 15 sub-systems designed by five departments. These departments are Aeromechanics (Aero); Stability & Control (S&C); Power, Propulsion & Performance (PP&P); Structures & Materials (S&M); and Operations &

Logistics (OPS). On top of that, the Systems Engineer (SE) keeps an overview of all departments, makes sure that all analyses use the same values and serves as coordinator during the design. The SE is also responsible for the internal and external layout of the system.

Each department has a separate chapter, with Aero, PP&P, and OPS being split in two for clarity. Every chapter includes a baseline of the design, covering the design goals of the department, sub-system requirements, inputs and outputs, and main parameters for analysis of the sub-system. Some main parameters overlap with the outputs of the department, but there are other relevant variables that are only used within that department. For that reason, the main parameters section is important to keep an overview of the department as a whole. After the design baseline, the design process and reasoning is shown, followed by a cost analysis of the sub-systems and finalized with an overview of the sub-system design, some limitations of the design, and recommendations for future phases.

This section will present the sub-systems of the airship and the main interfaces between them in the form of an N^2 chart. Another N^2 chart shows the design process, including inputs and outputs for every analysis performed. Finally, the hardware diagram is shown, which shows a high-level overview of the interaction between different elements of the airship and its environment.

3.6.1. System N^2 chart

Figure 3.8 shows the N^2 chart of the system, with all its sub-systems in the diagonal and their interfaces spread across the matrix. The full system is composed of three elements: the airship, ground operations, and ground communications. At the current stage of the design, most effort has been put into designing the airship. The highlighted interfaces are those that require close attention. These are:

- Anything related to hydrogen handling, because additional safety measures must be taken. This is covered in Section 14.4
- Attachment of engines to the structure, as the loads will be highly concentrated there. This has not been designed yet and is set as a recommendation in Section 8.9
- Power transmission to the propulsion because of high current, up to 850 kW. This has not been designed in detail yet and is set as a recommendation in Section 7.9
- Shift of CoM (or c.g.) when (un)loading the payload, as this may have catastrophic consequences. Some discussion on this can be found in Section 6.4

Airship								Ground operations					Ground Communications	
Structures	Gas bag support	Rigid attachment	Rigid attachment	Attachment	Attachment	Attachment	Rigid attachment	Landing + mooring gear	Hangar attachment		Mooring gear	Mooring gear		
Buoyant forces	Gas bags				Gas bag pressure	Current gas level				Hydrogen gas	Hover	Hover		
Control forces		Control Devices			Attitude									
Thrust			Propulsion	Electric power required	Engine status						Hover control	Hover control		
		Electric power	Electric power	Electric Power Unit	Electric power	Electric power	Electric power							
		Deflection angles, trim mode	Throttle, Thrust direction	Circuit Breakers	Avionics	Telemetry, Radio comms								
				Electric power required	Radio communications	Communications Unit		Request permission		Hydrogen level	Payload data	Payload data	Telemetry, Radio communications	
					CoM shift	Payload data	Payload handling					Payload		
Protection			Rotor clearance			Weather and ground information		Take-off/landing area	Airship					
								Airship	Hangar	Protection, electricity				
	Hydrogen gas			Hydrogen refuel						Hydrogen station				
						Weather and ground information	Payload				Cargo Loading Unit			Transport request
						Weather and ground information						Cargo Unloading Unit		
						Flight plan, updates					Flight plan, updates	Flight plan, updates	Telemetry Unit	Airship updates
												Blade request	Flight plan, updates	Command Unit

Figure 3.8: *System N2 chart, containing all main subsystems. The system is divided in three elements, each one with several sub-systems*

3.6.2. Design N² chart

Figure 3.9 shows the design N^2 chart, with the analyses performed throughout the design process in the diagonal, the inputs for each analysis in the vertical, and the outputs on the horizontal. These inputs and outputs are also listed at the beginning of each design chapter, this chart serves as an overview of all processes and their interactions during design. It served as a very convenient design tool during the process of designing. Note that the Systems Engineer has their own box, as they keep an overview and handle parameters that concern the system as a whole, such as the MTOW, maximum altitude, or payload mass.

SE (coordinator)		Max. altitude MTOW		Max. altitude	Internal layout Sub-system masses Payload ass		MTOW	Sub-system c.g.'s Sub-system masses	
	Aerodynamics	Static heaviness Fineness ratio	Static heaviness C_d	C_{d0}, Cl, AoA	Airship length and shape Long. and lat. drag force	External surface characteristics	C_l, C_{lalpha}, C_d, C_{dalpha}, C_m, C_{malpha} Hull symmetry Tail C_N and C_{Nalpha}		Long. and lat. drag force
	Hull volume	**Aerostatics**		Buoyancy force Hull volume	Buoyancy force	Gas bag characteristics		Location of center of buoyancy	Buoyancy force
			Power & Propulsion	Propulsive efficiency Fuel consumption	Engine loads Engine placement				
	Cruise altitude Cruise speed		Cruise speed	**Performance**			Cruise altitude Cruise speed		
Maximum allowable loads Structure mass Structure c.g. Internal layout					**Internal structure**	Truss structure characteristics	Moment of inertia	Structure c.g. Payload bay location	Payload bay dimensions
		Gas bag material			Truss material	**Materials**			
	Tail size				Tail loads		**Tail sizing**		
C.g. ranges					C.G. ranges	Operation cases (for envelope material)	CG location	**C.G. excursion**	
	Lateral wind speeds				Ballast attachment Cable attachments				**Mooring**

Figure 3.9: *Design N2 chart, containing all analyses as well as the Systems Engineer as coordinator*

3.6.3. Hardware Diagram

A hardware diagram is a chart that shows the main physical interfaces between components. It gives an overview of what physical components talk to each other. This diagram can be seen in Figure 3.10 for the airship.

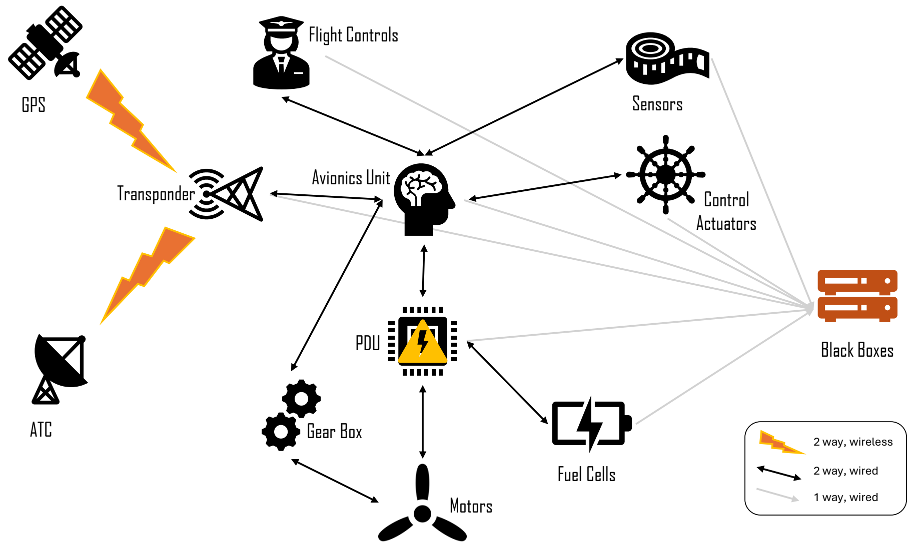


Figure 3.10: *Hardware Diagram of the Airship*

As can be seen in Figure 3.10, the black boxes are connected to everything in only one way. They are always listening but never talking. Centrally there is the avionics unit, which handles most of the communication in the system. For the power, there is a power distribution unit (PDU) that regulates power between the systems.

Not all connections are shown as some are only of secondary importance, e.g. the PDU gives power to all components but only the main ones are shown.

3.7. Cost Breakdown

Table 3.10 shows a breakdown of the cost of producing a single airship. It is split into material, manufacturing, and transport costs. The reasoning for these values can be found in Subsection 2.2.2.

Table 3.10: *Cost breakdown of the costs of producing a single airship*

Component	**Material cost [M€]**	**Manufacturing cost [M€]**	**Transport cost [M€]**	**Total per sub-system [M€]**
Mooring+payload cables	0.05	1.09	5E-03	1.14
Gas bags	2.82	1.09	5E-03	3.91
Envelope	0.01	1.09	5E-04	1.10
Truss structure	0.43	1.09	0.01	1.53
Tail structure	0.16	1.09	4E-03	1.25
Engine cables	0.01	1.09	9E-06	1.09
Fuel tank	0.12	1.09	8E-04	1.21
Cables	0.02	1.09	3E-05	1.10
Engine	4E-03	1.09	9E-04	1.09
Hydrogen	0.15	1.09	-	1.24
Avionics (30% of total)	1.62	3.26	0.01	4.40
Margin (50% of total)	5.40	14.12	0.03	19.06
Total	**10.79**	**28.24**	**0.06**	**39.09 $\pm$ 7.82**

There is some important remarks to make on the margins used. There have been 3 big margins to account for the uncertainty of the estimation. First, the avionics have been assumed to account for 30% of the ”total” cost. Note that this ”total” is taken as the sum of the components’ cost, not the actual total shown on the bottom row. This has been done because aircraft have a similar percentage [21], and it is assumed that the airship will have a comparable percentage. The second margin is meant to be a contingency of the budget and has been set to be 50% of the final cost. This should cover all the overlooked costs, hence its high value. Finally, a final margin of 20% has been added to the final cost as an uncertainty measure. Many variables affect this cost, thus a range of possible costs that the airship can have is necessary. This uncertainty margin is independent of the contingency. The contingency is meant to account for costs that will be known once the final design is obtained. The uncertainty margin is meant to serve as a range of possible prices the airship might take, which is affected by choices that might be changed in the future.

There are other costs relevant to the operation of the airship. The yearly cost to operate the airship is €3.6M per year on average, which accounts for flight crew, infrastructure, fuel, and other relevant elements. The full analysis can be found in Subsection 2.2.3. Another important figure for the cost of the airship is its development cost, which is currently €500M, as explained in Subsection 2.2.1

4 Aerostatics

The aerostatics system is the heart of the airship. It defines the size of the airship, which directly and indirectly influences all other systems to some capacity. Based on the operational parameters, the take-off weight, the requirements, and calculations using the ISA and ideal gas law, the aerostatics system is sized. Afterwards, other details of the system are designed for according to the requirements for the system.

4.1. Design Baseline

The aerostatics subsystem of an airship provides lift. In the case of a non-hybrid airship, it is the majority of the lift. The airship in this report ends up generating more than 99% of its lift using aerostatics. Because of this, the sizing of the entire design starts at the aerostatics subsystem.

The generation of lift by the aerostatics system works by using Archimedes' principle: every object submerged in a fluid generates an upward force equal in magnitude to the weight of the displaced fluid. This is why airships use gasses that are lighter than air, as this results in an upwards net force on the gas. Non-rigid or semi-rigid airships contain their lifting gas inside the envelope while rigid airships contain it inside gas cells within the envelope. These structures need to carry all of the loads caused by the containment of the lifting gas.

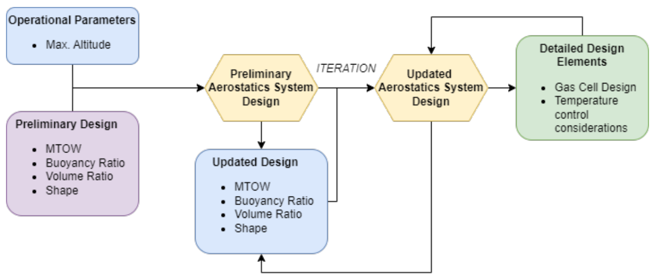


Figure 4.1: *Aerostatics Design Approach*

The design approach for the aerostatics subsystem can be found in Figure 4.1.

4.1.1. Design Goals

To keep track of the direction of the design for the aerostatics system, a set of goals are defined prior to the start of the technical analysis. These goals are defined as follows.

1. Find out how to apply the ideal gas law and ISA equations
2. Design gas cells
3. Design envelope
4. Design temperature control
5. Design for safety

4.1.2. Requirements

The design of the aerostatics system of the airship is guided by requirements set by regulations, and by the mission objectives. The system requirements for the aerostatics system can be found in Table 4.1.

Table 4.1: *System Requirements relevant to the Aerostatics System*

Requirement ID	Description
REQ-SYS-LFT-01	Safety guidelines for handling the lifting gas shall be implemented.
REQ-SYS-LFT-02	The lifting gas temperature shall be controllable.
REQ-SYS-LFT-03	Lifting gas shall be reused between missions.
REQ-SYS-LFT-04	The lifting gas shall be available at all times to refill the envelope after every mission.
REQ-SYS-LFT-05	The lifting gas shall be obtained from a renewable source.

Some of the requirements from Table 4.1 have already been satisfied to some degree by the choice of hydrogen gas as the lifting gas. Particularly, REQ-SYS-LFT-04 and REQ-SYS-LFT-05 have been achieved as the hydrogen gas can be sourced from renewable sources and as it is cheaper and more available than helium gas. Because of this choice the safety guidelines have also been narrowed down to those for hydrogen gas.

More specific requirements for the subsystem can be found in Table 4.2. These requirements drive the design of the system to a more exact extent. They also provide more clarity regarding the operational parameters of the system.

Table 4.2: *Subsystem Requirements for the Aerostatics System*

Requirement ID	Description
REQ-STA-01	The subsystem shall withstand all loading expected in operation including emergency conditions.
REQ-STA-02	The subsystem shall monitor and control lifting performance and degradation.
REQ-STA-03	The subsystem shall ensure the safety of the occupants and people on the ground in all conditions.
REQ-STA-04	The subsystem shall remain within pressure limits during maximum and minimum rates of ascent and descent.
REQ-STA-05	The subsystem shall provide the crew with gas cell pressures.
REQ-STA-06	The subsystem shall not be damaged or inflict damage to other structures when controls are used improperly.
REQ-STA-07	The subsystem shall not be damaged by being up to an additional 100 meters above its pressure height.
REQ-STA-08	The subsystem shall provide the airship with enough lift for the whole system to achieve a static heaviness of 750 kg.
REQ-STA-09	The subsystem shall have its pressure height at the maximum cruising altitude under normal ISA conditions.

4.1.3. In- and Outputs

For the sizing and calculations surrounding the aerostatics subsystem, several inputs are needed, these can be found in Table 4.3. Table 4.4 shows the outputs of the aerostatics subsystem.

Table 4.3: *Inputs for the aerostatics subsystem and their origin.*

Input	Origin
MTOW	Systems Engineer
Static Heaviness	Aerodynamics
Payload Bay Dimensions	Operations
Maximum Cruise Altitude	Systems Engineer
Fineness Ratio	Aerodynamics

Table 4.4: *Outputs for the aerostatics subsystem and their destination.*

Output	Destination
Envelope Volume (Airship Size)	Aerodynamics, Structures
Maximum Gas Volume	Systems Engineer
Gas Cells Outer Area	Materials
Pressure Height	*All*
Lifting Gas Mass	Systems Engineer
Operational Weather Conditions	Operations
Maximum Allowed Overpressure	Operations
Leak Rate	Operations, Performance

As seen, the aerostatics system determines the airship's overall size because the lifting gas takes up most of the space. Other departments then use this airship size to size design systems.

4.1.4. Main Parameters

The main parameters influencing the aerostatics system are the following.

The atmosphere; using the standard atmosphere, the general behaviour of the gas inside of the gas cells can be determined. Because of the limitations imposed by the requirements, the standard atmosphere has a huge influence on the size of the system. The lifting gas has a natural tendency to expand whenever the airship is increasing its altitude. This has to be accommodated for by the size of the system. This in turn influences the size of the ship.

The weather; this is by far the most dictating parameter for the usage cases of the airship. The standard atmosphere does not provide enough security in deciding on the operational conditions of the system. Therefore the standard atmosphere is adjusted to different temperatures and pressures which are to be expected due to the weather on the ground. Additionally, there is also the concept of superheating in airships. This is when airship's lifting gas achieves a higher than ambient temperature due to the airship's exposure to sunlight.

Other parameters for the design of the aerostatics subsystem will be discussed when they are required.

4.2. Gas Cell Design

The gas cells are the structure inside of a rigid airship that provide the aerostatic lift. Unlike non-rigid and semi-rigid airships, these gas cells do not provide the structural rigidity for the shape of the airship. This is instead done by the envelope and the internal structure of the airship.

Due to the fact that the loads on the envelope are not being carried by the gas cells, the structure for the gas cells can be designed solely for the purpose of handling the expected overpressure. The separation of the purposes of envelope and gas cell is one of the reasons the rigid airship works especially well at scale.

According to the requirements the gas cells need to be a safe system, even in the case of several failures. This is helped by the requirements indicating the need for close monitoring capabilities of the pressure and performance of the cells.

Due to time constraints the interface between the aerostatics system and the structures system has not been worked out in detail. This is instead indicated as an avenue for future research and design.

For the design, some assumptions are made. Hydrogen and air are assumed to behave like an ideal gas, and the ISA equations are assumed to be valid for this application. Another assumption is that the pressure height of the airship should be equal to the maximum cruising altitude.

4.2.1. Gas Mass Required

At this point the calculations for the gas cell design can start. First comes an estimation of the amount of gas needed to produce the required lift. By subtracting the static heaviness from the maximum take-off mass, the total lift the gas will provide is found. To find the quantity of gas required, the ratio of specific gas constants is required.

$$p = \rho R T \tag{4.1}$$

According to the ideal gas law (Equation 4.1), the density of a gas is dependent on the pressure, temperature and specific gas constant. For the majority of the flight envelope the gas will have enough room to expand. This means that the gas can be assumed to be at the same temperature and pressure as the surrounding air. Therefore the only thing that defines the ratio of densities for hydrogen and air, is the ratio of specific gas constants.

The ratio of densities can be used to find the required mass of hydrogen for the airship. According to Archimedes' principle, the buoyant lift is the mass of the displaced volume. To get the required volume, one can divide the required lift in kg by the density of air. To get the mass of hydrogen required, one needs to multiply this with the density of hydrogen. This results in Equation 4.2.

$$m_{gas} = m_{ship} \frac{\rho_{gas}}{\rho_{air}} \tag{4.2}$$

Using the previously acquired ratio of densities, the mass of hydrogen required for the airship, with a mass of 225 tonnes from Subsection 3.5.1 and 750 kg static heaviness from Subsection 5.2.2, is 15.6 tonnes.

Using this mass for the gas, the required gas volume can be found.

4.2.2. Gas Volume Required

This is the point where the ISA equations start to play a role. The temperature equation is found in Equation 4.3. The pressure equation is found in Equation 4.4.

$$T_{alt} = T_0 + ah \tag{4.3}$$

$$p_{alt} = p_0(\frac{T_{alt}}{T_0})^{-\frac{g}{aR}} \tag{4.4}$$

the application of these two equations is relatively simple in this case, as the cruising altitude is way below the threshold for the tropopause. Therefore, the only level of application to this case is the troposphere, with a = -0.0065 K/m. And for the purposes of these calculation, only the specific gas constant of air is required, as the atmosphere does not consist of hydrogen.

Using the cruising altitude given in Subsection 3.5.1 and the aforementioned equations, the air pressure at that altitude is calculated. Then, using the previously established assumption about equal pressure and temperature inside and outside the gas cells, the pressure and temperature for the hydrogen gas are found. This in turn, yields the density of hydrogen at this altitude.

Finally, we can find the required total gas cell volume to make the maximum cruising altitude the pressure height of the airship. This can be done by dividing the mass found in Subsection 4.2.1 by the density found in this section. This yields a volume of 223 000 m^3.

4.2.3. Number of Gas Cells

The number of gas cells was decided on by researching other rigid airships. The results of this research, as well as the same figures for the actual design, can be found in Table 4.5.

Table 4.5: *Gas Cell Number*

Ship Name	Nr. of Cells	Total Gas Volume [m^3]	Average Volume per Cell [m^3]
Graf Zeppelin	17[1]	75 000[1]	4 412
Hindenburg	16[2]	200 000[3]	12 500
R101	17[4]	156 018[4]	9 178
R38	14[5]	77 149[5]	5 511
USS Los Angeles	14[6]	73 599[6]	5 257
USS Akron	12[7]	193 747[7]	16 146
LCA60t	14[8]	180 000[9]	12 857
Pathfinder 1	13[10]	22 850[11]	1 758
HYPE-T	16	222 978	13 936

from Table 4.5, it is clear, that there is little to no correlation between the amount of gas cells and the total gas volume of the airship. For the older designs from the first half of the previous century, the average volume ranges from 5000 to 17000 m^3. The biggest ships having the biggest average volume per cell, and the smaller ones lingering around the 5500 m^3 mark. The third and second to last entry are designs from this century, with the Pathfinder 1 already being built. But these two ships have wildly differing average volumes, which means that the average gas cell volume has little to do with the total gas volume.

In the end, the decision was made to follow the Hindenburg in its design, as that airship shows a total gas volume closest to the one needed for the HYPE-T. Therefore, the choice was made to go for 16 gas cells.

4.2.4. Overpressure in Cells

There are multiple contributing factors to the total overpressure in the gas cells of a rigid airship. For this system sizing, the hydrostatic pressure and the overpressure due to exceeding the pressure height are considered.

1 https://www.airships.net/lz127-graf-zeppelin/graf-zeppelin-design-technology/ (Accessed on: 17/06/2024)
2 https://www.airships.net/hindenburg/hindenburg-design-technology/ (Accessed on: 17/06/2024)
3 https://www.airships.net/hindenburg/size-speed/ (Accessed on: 17/06/2024)
4 https://www.airshipsonline.com/airships/r101/index.html (Accessed on: 17/06/2024)
5 https://www.airshipsonline.com/airships/r38/index.html (Accessed on: 17/06/2024)
6 https://www.navsource.org/archives/02/99/029903.htm (Accessed on: 17/06/2024)
7 https://www.navsource.org/archives/02/99/029904.htm (Accessed on: 17/06/2024)
8 https://lynceans.org/wp-content/uploads/2021/09/Flying-Whales_R2-converted-compressed-1.pdf (Accessed on: 17/06/2024)
9 https://www.flying-whales.com/en/the-lca60t/ (Accessed on: 17/06/2024)
10 https://www.ltaresearch.com/technology (Accessed on: 17/06/2024)
11 https://lynceans.org/wp-content/uploads/2022/03/LTA-Research-and-Exploration-converted-compressed-1.pdf (Accessed on: 17/06/2024)

Hydrostatic Pressure

The hydrostatic pressure contributes to the overpressure in the gas cells. The formula for the hydrostatic pressure can be found in Equation 4.5. The same mechanics causing pressure at the bottom of your glass of water and at sea level, cause an upward pressure gradient to occur in the gas cells.

$$dp = kdh \tag{4.5}$$

The k in Equation 4.5 is the unit lift per volume in N/m^3, and dh is the maximum expected distance between the walls of the gas cell along the earth's normal. For the gas cells, we need to find the maximum dh during operation to comply with REQ-STA-01, REQ-STA-03, REQ-STA-04, and REQ-STA-06. To be on the conservative side, the maximum dh was to be the diagonal crossing a gas cell. Using the Pythagorean theorem on the diameter of the ship's envelope and the average length of a gas cell (from Subsection 5.2.1), dh is found.

By taking the difference of the densities of air and hydrogen, and multiplying this with the gravitational acceleration, we find the unit lift. Now the hydrostatic overpressure is found to be around 500 Pa, this goes for each of the circumstances to be discussed in Equation 4.2.4.

Overpressure due to Pressure Height

This part of the overpressure is harder to calculate. As this is where a multitude of changes and adjustments are introduced to the ISA calculations. This is in the form of changes to the starting pressure, and changes to the starting temperature, as well as changes to the superheat experienced by the airship. These adjustments are necessary due to the introduction of REQ-STA-07, as the pressure height and the resultant overpressure change with atmospheric conditions.

For the starting temperatures, temperatures ranging from the standard 15 °C to the very hot (but not out of the question) 45 °C. The starting pressure ranges from the normal ISA starting pressure, to a high end of 106000 Pa, and down to 94000 Pa on the low end[12]. On top of that, a 15 °C maximum superheat is taken into account for half of the cases. This should cover most of the regions and weather types the ship is supposed to operate in.

The maximum superheat is taken from a paper about a superheat thermometer for the USS Los Angeles [22]. The superheat could also have been calculated, but that would get complicated very quickly. Therefore the maximum superheat value of a similarly sized rigid airship was chosen.

With these values the pressure height of the airship can be calculated for a given available gas volume. This is done by first calculating the density of hydrogen necessary to fill the volume, and then using the ideal gas law, and the ISA equations in reverse to find the altitude at which pressure height is achieved. This was done for each of the 12 possible combinations of aforementioned parameters. Doing this for a range of gas volumes in the neighborhood of the gas volume found in Subsection 4.2.2 resulted in the graph in Figure 4.2.

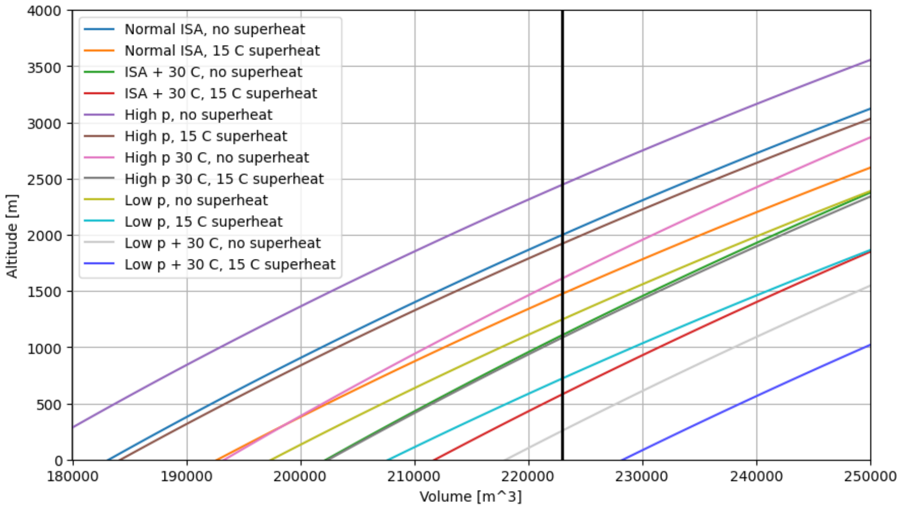


Figure 4.2: *Pressure height vs available gas volume for 12 scenarios, thick black line shows current available gas volume*

12 `https://www.knmi.nl/kennis-en-datacentrum/uitleg/luchtdruk` (Accessed on: 18/06/2024)

Looking at Figure 4.2 one can see that the pressure height under normal ISA conditions for the volume calculated in Subsection 4.2.2 is indeed 2000 m. Confirming that this plot is accurate. From Figure 4.2 it can be seen that the pressure height differs by great amounts depending on the atmospheric conditions. Particularly, the cases with 30 °C and 15 °C superheat are very restraining on the pressure height. For the gas volume from Subsection 4.2.2, the airship will not be able to operate at the combination of low pressure, high temperature and maximum superheat. However, this only is a stable weather condition over dry land with a hot surface[13], and flying the airship is not recommended for unstable weather conditions. Therefore, operation in broad daylight above deserts, without temperature control, should be avoided.

Now the calculation of the overpressure caused by exceeding the pressure height by 100 m can be calculated. Using the previously found pressure heights, 100 m is added to each of them, and then the air pressures at those altitudes are calculated. Then the density of the gas is calculated as if it does have the room to expand. This density is then used to find the volume of the gas if it had room to expand. This volume is then plugged into Equation 4.6. Assuming that all the reduced volume goes into the pressure and that the temperature remains equal to the ambient, the pressure inside of the gas is found.

$$pV = nRT \tag{4.6}$$

Subtracting the ambient pressure from the pressure inside of the gas cells, the overpressure due to exceeding the pressure height is found.

The total overpressure can now be found by adding the two overpressures. The most restrictive of the cases mentioned above, once again turns out to be the low pressure, high temperature and superheat combination. This overpressure turns out to be about 1370 Pa. But for safety reasons and any other inconsistencies or oversights an overpressure of 1500 Pa is given as an input for the materials department.

4.2.5. Leak Rate

The leak rate of the gas cells depends on the pressure inside of the gas cells and on the material containing the gas. As the previous analysis was quite extensive and time consuming this part only covers some top level estimations.

Permeation (the leak rate through the material) can be modeled using Equation 4.7[23].

$$\dot{m}_p = \frac{PAt\Delta p}{s} \tag{4.7}$$

$\dot{m}_p$ is the quantity of gas escaping in kg/s, and P is the permeation coefficient for this combination of permeant and barrier. Finding P for specific cases is done experimentally mostly, which is not possible within the allotted time and budget.

Therefore another figure from the same report is used, it most likely will not reflect the gas cells of this system, but it is more likely to be an over-estimate than an under-estimate. This figure says that for hydrogen contained at STP inside of a nylon polyurethane composite container with a 1 m^2 surface, the gas loss is 3.5 * 10^{-4} m^3 per day. This for an overpressure higher than 3% [23], which is a lot more than the overpressure this airship deals with. On top of that, this leak rate is defined for STP, which are not the atmospheric conditions experienced by the airship. Hence, the value is only a vague approximation.

Now the outer surface of the gas cells is needed. This is done by assuming the airship is a cylinder with the maximum diameter of the envelope as its diameter. This cylinder consists of cylindrical gas cells spanning the full length of the ship. The outer surface area is then equal to the outer surface of all these cylinders combined. This way the area calculation is relatively easy, but at the same time a generously conservative overestimation. This area is also used in Subsection 8.5.3.

Scaling the aforementioned 3.5 * 10^{-4} m^3 for 1 m^2 to the surface area of the gas cells the leak rate turns out to be 46 m^3 per day. This means it would take the airship 37 days to drain 1% of its lift. This helps satisfying REG-SYS-LFT. This number is given to the operations department, the performance department and used for the sustainability analysis.

Of course this is not very realistic due to the fact that HYPE-T uses a different material for the gas cells. On top of that, this calculation assumes no other imperfections exist. Which is most likely not the case, the gas cells need to have a openings for fueling, venting, and cooling. Therefore, the actual rate will most likely be higher.

[13] `https://www.theweatherprediction.com/habyhints2/613/` (Accessed on: 18/06/2024)

4.3. Envelope Design

The goal of this section is to find the volume of the envelope. For the sake of reducing aerodynamic drag (and ease of modeling) most of the equipment of the airship will be stored inside of the airship envelope. Historically, rigid airships have stored a lot of their equipment inside of the envelope. Therefore, as a first estimate for the volume fraction (gas volume/envelope volume), other rigid airships were analyzed.

4.3.1. Volume Fraction Analysis

For a lot of airships, the gas volume is trivial to find. The envelope volume of those airships is not, however. Therefore, the curve of the airship is traced and converted to a csv using graphreaderV2. This csv is read out to integrate the curve as a body of revolution. The results of the analysis can be found in Table 4.6.

Table 4.6: *Volume Fractions*

Ship Name	Air Displacement [m^3]	Total Gas Volume [m^3]	Volume Fraction
Hindenburg	211 283[2]	200 000[3]	0.9465
R101	174 584[14]	156 018[4]	0.8937
R100	167 430[15]	146 000[16]	0.8720
R38	80 453[17]	77 149[5]	0.9589
USS Macon	209 580[18]	193 747[18]	0.9245
ZR-2	83 818[19]	77 135[19]	0.9203
USS Shenandoah	64 842[20]	59 895[20]	0.9237
USS Los Angeles	78 281[21]	73 599[21]	0.9402
USS Akron	209 580[22]	193 747[22]	0.9245
average	-	-	0.9227

In Table 4.6 several airship volumetric displacements and gas volumes are shown. The method for finding the displacement volumes can be verified by comparing R38 to ZR-2 (2 names given to the same airship). The value for ZR-2 was given, and the value of R-38 was calculated. The values differ only by 3000 m^2, which is not a lot for a method that requires manually tracing lines.

From Table 4.6, it becomes clear that there is no set volume fraction for rigid airships, but the spread around the average is only 0.07. Therefore the more or less average (and relatively frequent) value of 0.92 was chosen for the design.

4.3.2. More Reasonable Volume Fraction

The volume fraction found in Subsection 4.3.1 was not deemed reasonable enough for the design of a cargo airship for wind turbine blades. The space taken up by the blades would very likely already exceed the 8% volume of the airship allotted to not being lifting gas. Therefore, at first, a new (temporary) ratio was chosen at 0.7.

However, late in the design process, a new value was proposed, keeping in mind the fact that the size of the payload bay changes very little if the size of the airship increases. Therefore, it was decided to use the volume fraction from Subsection 4.3.1 to find the envelope volume without the payload bay. The payload bay volume (defined as 1.3 times the volume specified in Section 8.3) was added directly after. This results in a volume ratio of 0.8393.

4.3.3. Volume and Envelope Dimensions

Using the volume ratio from Subsection 4.3.2, the envelope volume is found to be 265683 m^3. Using the shape from Subsection 5.2.1, a length and diameter for the full airship are found. These can be used in

[14] `https://www.airshipsonline.com/airships/r101/images/R101%20Plan%20General%20Arrangment%201930%20with%20additional%20bay.jpg` (Accessed on: 18/06/2024)
[15] `https://www.airshipsonline.com/airships/r100/images/r100plnl.jpg` (Accessed on: 18/06/2024)
[16] `https://www.airshipsonline.com/airships/r100/` (Accessed on: 18/06/2024)
[17] `https://www.airshipsonline.com/airships/r38/images/r38%20General%20Arrangement%20Plan.jpg` (Accessed on: 18/06/2024)
[18] `https://www.navsource.org/archives/02/99/029905.htm` (Accessed on: 18/06/2024)
[19] `https://www.navsource.org/archives/02/99/029902.htm` (Accessed on: 18/06/2024)
[20] `https://www.navsource.org/archives/02/99/029901.htm` (Accessed on: 18/06/2024)
[21] `https://www.navsource.org/archives/02/99/029903.htm` (Accessed on: 17/06/2024)
[22] `https://www.navsource.org/archives/02/99/029904.htm` (Accessed on: 17/06/2024)

Subsection 4.2.5

4.4. Gas Temperature Control

As shown in Equation 4.2.4, superheating the gas inside the envelope has a disastrous effect on the pressure height. Preferably, this problem should be solved in accordance with REQ-SYS-LFT-02. To be able to control the temperature, the superheat behavior should be modeled, which will be discussed first. Afterward, the possible methods for temperature control are considered

4.4.1. Modeling Superheat

To model superheat, several parts of the gas cell will need to be modeled. This includes the atmosphere, the temperatures, and the fluid [24].

In the end, the solar radiation, albedo radiation, conduction, and convection will need to be modeled to do an accurate prediction of what happens to the temperature in the gas cells from the moment the airship gets exposed to sunlight. This is a very complicated job for such a short amount of time. Therefore, it was decided not to proceed with modeling, and instead a statistical value was used for all calculations mentioned in previous sections.

The mentioned figure of 15 °C of superheat for the USS Los Angeles [22], results in 10 tonnes of extra lift. This cannot be compensated for by the aerodynamics subsystem. Therefore a temperature control system is required.

However, this figure cannot be used to design a temperature control system, as for those purposes, the change in temperature over time is more important. Therefore this section will not go into a lot of detail but will discuss some ways to control airship temperature.

4.4.2. Possible Methods for Counteracting Superheat

There are several possibilities for controlling the temperature in the gas cell system. They fall into the categories of passive and active control.

Passive temperature control is already applied to airships at this point, by using radiative coating materials to reduce the heat absorbed by the envelope [25]. This can and will be implemented at a later stage in the design. Passive control is however not likely to be enough to counter all superheat[26].

An example of active temperature control is air cooling. Air-cooled systems generally require a strong flow of air over a lot of surface area. There is a lot of surface area for the gas cells, but this is very likely not enough to have efficient cooling. The same goes for increasing the surface area of the cells, this will probably not increase the effectiveness of air cooling to a satisfying degree. Adding heat sinks to the gas cells to increase the effectiveness of cooling might help, but the gas cells and gas are not very conductive, so the heat sinks might not pull that much heat away from the gas. However, simulations have shown that air cooling with fans could be useful in an airship context [26].

A more plausible solution would be a fluid-cooled system. The fluid would be cycled through the walls of the gas cell, absorbing heat, and would then be cycled through a radiator. This radiator could be cooled by airflow from the outside the envelope, cooling the fluid before it is cycled through the gas cells again. This system does require a pump, however. Also, it may not be that effective for the same reasons as the air cooling system, which is that the gas is not that conductive.

Now there also exist heating systems. But these do not solve the problem of superheating and only serve to increase it.

4.4.3. Control Using Superheat

Superheat could also be used as intentional lift control, for changing the temperature of the lifting gas, changes its density. There are examples of technologies for controlling lift using gas temperature control[23].

The patent referenced here does not have an estimation for mass, power, or performance. The only thing it shows is an idea for a functional temperature control layout. The purpose is to control the static heaviness of the airship, as well as the pitch, with differential heating of the cells.

As the system, or any like it for that matter have not flown yet, the usefulness and applicability of the patent are not yet proven. The main concern (as with any aerospace application) is the amount of mass it adds. This could have a lot of consequences for the design.

[23] `https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2013131155` (Accessed on: 18/06/2024))

4.5. Safety Design

Some measures have already been taken to comply with REQ-STA-01, REQ-STA-03, REQ-STA-04, and REQ-STA-06. However, more measures could be applied.

4.5.1. Passive Measures

An example measure that could be taken is to mix the hydrogen gas with incombustible gasses. This would reduce the flammability of the hydrogen gas [27]. This does however reduce the net lift produced by the gas.

Another measure would be to surround the gas cells with separate smaller gas cells. When the outer gas cells get damaged, only the hydrogen in there can escape. In case of fire, not all of the hydrogen can combust immediately[24]. These separate gas cells would take up a lot of mass, however.

In case the pressure limit of the airship is breached, there could be pressure valves that open automatically to stop the gas cells from exceeding yield strength. This technology has been used on airships like the hindenburg[2]. This type of measure only adds a small amount of mass.

In general, using hydrogen in a safer way may require a heavier aerostatics system. This negates one of the benefits of hydrogen being lighter than helium.

4.5.2. Active Measures

The crew should be able to control and monitor the pressure inside the envelope. This means that pressure gauges need to be installed on each of the cells, this will satisfy REQ-STA-05. They also should have valves that they can manually operate to release gas.

According to REQ-STA-02, the system should monitor its lifting performance. This can be done by monitoring the amount of gas inside of the gas cells. The lifting performance can be controlled by decreasing the amount of gas stored by venting it through valves, or by dropping ballast.

4.6. Cost Analysis

The cost analysis is mostly outside of the scope of this chapter, as the cost of refilling the lifting gas is discussed in operational costs (Subsection 2.2.3), and the cost of the material is discussed in the materials section (Subsection 8.5.3).

The only figure found nowhere else in the report is the total value of the lifting gas. The cost of the gas per kg is given in Subsection 2.2.3. Multiplying this with the gas mass from Subsection 4.2.1, the cost of the lifting gas on the first filling comes down to €153 660.

4.7. Sensitivity Analysis

Out of all parameters covered in this section, the pressure height margin (the maximum altitude above pressure height), the number of gas cells, and the volume fraction are the only numbers that are chosen, and not determined. Therefore, a sensitivity analysis is conducted on these parameters. A more in depth analysis of the most influential parameters on the subsystem can be found in Chapter 12.

Table 4.7: *Volume fraction sensitivity analysis*

increase	-50%	-25%	-10%	10%	25%	50%
MTOW	14.7%	5.1%	1.8%	-1.5%	-3.3%	-5.5%
Envelope Volume	100.0%	33.3%	11.1%	-9.1%	-20.0%	-33.3%
gas cell mass	85.9%	29.2%	9.8%	-8.1%	-17.9%	-30.0%

Table 4.8: *Number of gas cell sensitivity analysis*

increase	-50%	-25%	-10%	10%	25%	50%
MTOW	-3.3%	-1.7%	-0.7%	0.7%	1.7%	3.3%
Envelope Volume	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
gas cell mass	-40.7%	-20.3%	-8.1%	8.2%	20.5%	40.9%

[24] https://liftinggas.com/our-innovation/ (Accessed on:: 21/06/2024))

Table 4.9: *Pressure height sensitivity analysis*

increase	-50%	-25%	-10%	10%	25%	50%
MTOW	-1.6%	-0.8%	-0.3%	0.3%	0.8%	1.6%
Envelope Volume	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
gas cell mass	-18.7%	-9.3%	-3.6%	3.6%	9.3%	18.7%

As can be seen in Table 4.6, changing the volume fraction affects the system to a significant degree. The volume and mass parameters react ass expected, increasing when the volume fraction decreases, and the other way around. Because of the relatively high sensitivity, this value should be carefully chosen, and preferably not changed during the design.

For the number of gas cells, increasing and decreasing has the expected effect of changing the gas cell mass, as can be seen in Table 4.8. More cells, is more cell walls, is more mass. It does however only have a small effect on the MTOW, so the value of this parameter can still be adjusted later on without influencing other systems to a major degree.

Finally, for the pressure height margin in Table 4.9, this again has the expected effects on the gas cell mass. A lower margin means less overpressure, and therefore, less mass. This parameter does not have that much of an effect on the MTOW, so the value of this parameter can still be adjusted later on without influencing other systems to a major degree.

4.8. Overview

In Table 4.10 an overview of the main outputs for the aerostatic subsystem are presented.

Table 4.10: *Outputs of the aerostatics subsystem*

Output	**Value**
Envelope Volume (Airship Size) [m^3]	265 684
Maximum Gas Volume [m^3]	222978
Gas Cells Outer Area [m^2]	141361
Pressure height [m]	2000 m (ISA)
Lifting Gas Mass [tonnes]	15.6
Operational Weather Conditions [-]	see Figure 4.2
Maximum Allowed Overpressure [Pa]	1520
Leak Rate [m^3/day]	49.5

4.9. Limitations and Recommendations

The current design has some room for improvement. The following limitations are acknowledged and addressed.

- The superheat is not modeled in a detailed way.
- Gas temperature control has not been designed yet.
- Safety measures have not yet been designed.
- The individual gas cells have not been designed.

Based on these limitations, the first of the recommendations is to simulate the superheat of the gas cells. This should be done in a program suitable for simulating all the processes mentioned in Subsection 4.4.1. Ansys is an example of a program capable of simulating all the processes [25].

Another recommendation is to work out the safety measures and temperature control systems in a more proper way. This way their masses and required power can be properly incorporated in the design.

A final recommendation is regarding the design of the individual gas cells. At this point the individual gas cells have not been sized due the backlog experienced by the structures department. This should be done in the future to get a better estimate for the outer area of the gas cells.

5 Aerodynamics

Aerodynamics' main goal is to provide an accurate estimation of the coefficients of the airship. The first step in to look into what is expected of the design in Section 5.1, after that aerodynamic coefficients can be found using the methods in Section 5.2. In Section 5.3, the cost of the aerodynamics will be discussed. Finally, some recommendations and limitations of the methods used and decisions made will be presented in Section 5.6.

5.1. Design Baseline

The first step is to establish a baseline for the design and analysis. Aerodynamics is different from other subsystems as it does not directly size or design the parts. Rather, it concerns the analysis of what other subsystems do and look like.

The flow of the design and analysis of the aerodynamics is shown in Figure 5.1

From the initial trade-off sizing a MTOW was available that was used to determine the volume in Subsection 4.2.2, this gave preliminary estimates of the size and shape. This in combination with the cruise velocity from initial sizing was enough to get started. To get the design started, coefficients of the similarly sized USS Akron were used as determined by NACA [28]. Once other subsystems were sized using these, their characteristics were put into a parametric Class II estimation and iterations happened to come to a converged, final design.

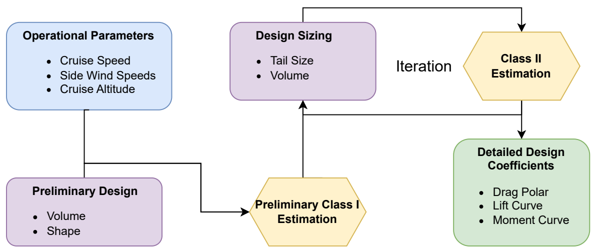


Figure 5.1: *Flow of the aerodynamic analysis and design.*

5.1.1. Design Goals

The main design goal of aerodynamics is minimizing the drag on the system. All decisions should be taken with this in mind as it directly translates to improvements in performance, mass, and sustainability. However, sometimes a balance of minimal drag and the needs of other systems need to be made. This is not a requirement, as minimizing drag cannot be quantified. Other parameters are also important as other subsystems depend on them. The main goal of aerodynamics is analyzing the design to provide aerodynamic coefficients for the design of other subsystems.

5.1.2. Requirements

As mentioned prior; minimizing the drag of the system is not a VALID requirement for the system. There is however a subsystem requirement that dictates that the ship should provide lift:

Table 5.1: *Sub-system Requirements*

Requirement ID	Description
REQ-DYN-01	The airship shall provide sufficient aerodynamic lift to counteract its heaviness in all nominal phases of flight.
REQ-DYN-02	The airship envelope shall be able to encompass a 105m by 12m by 10m box.

5.1.3. In- and Outputs

In order to design and analyze the aerodynamics, inputs from other departments are needed. Similarly, other departments need data from aerodynamics for their design.

The main inputs for the aerodynamics from other subsystem are the following:

Table 5.2: *Inputs for the aerodynamics subsystem and their origin.*

Input	Origin
Cruise Airspeed	Performance
Cruise Altitude	Performance
Envelope Volume	Aerostatics
Lateral Wind Speeds	Operations
Tail Sizing	Stability & Control

Table 5.3: *Outputs for the aerodynamics subsystem and their destination.*

Output	Destination
Fineness Ratio	Structures & Materials
Lateral Drag Forces	Operations, Propulsion
Lateral Drag Moments	Operations
Dorsal Drag Force	Propulsion
Lift Curve Slope	Stability & Control
Lift Induced Drag Constant	Propulsion, Performance
Moment Curve Slope	Stability & Control
Shape and Dimensions	*All*
Zero Lift Angle of Attack	Operations
Zero Lift Drag Coefficient	Propulsion, Performance
Heaviness	*All*

5.1.4. Main Parameters

In addition to the in- and outputs of the system, there are additional parameters that are contained within the subsystem. The main parameters that influence the aerodynamic design and analysis are the following.

The Reynolds number; this shows the importance of viscous effects over inertial effects. It determines important characteristics such as transition and separation. The value of this in cruise is about $2.87 \cdot 10^8$. As transition typically occurs in the range 300 000 - 500 000 this means that the flow will be almost entirely turbulent [29]. Another such number is the Mach number. This is however less relevant as the cruise Mach was determined to be 0.07, well within the incompressible domain [30].

Other parameters such as reference length and area are dependent on the volume and will be discussed in detail in Section 5.2.

5.2. Aerodynamic Coefficients Estimation

Most outputs of aerodynamics relate to the aerodynamic coefficients such as drag, lift, and moment.

For airships, it is common practice to not normalize these with respect to the planform area or chord but with $V^{2/3}$ for reference area and $V^{1/3}$ for reference length [31]. This is done as volume is a more meaningful parameter in airship design than the wetted area or planform area is. For this reason, the coefficients will always be normalized using these reference parameters unless specified otherwise.

All calculations in this section assume standard ISA conditions.

The first step in getting these coefficients is deciding what shape the envelope should get, this is done in Subsection 5.2.1. Once this is decided, the coefficients for the hull can be determined in Subsection 5.2.2, 5.2.3, and 5.2.4. Lastly, the lateral drag in hover or moored conditions should be determined in Subsection 5.2.5. All methods created and used have been verified and validated in accordance with methods laid out in Subsection 15.3.2.

5.2.1. Hull Shape Design

There are two main things to decide on for the shape of the hull; the fineness ratio (FR) and what function is used to create outside shape

At this stage it is assumed that the envelope is a body of rotation as that simplifies design thanks to its symmetry and historical precedent. The fineness ratio is defined as:

$$FR = \frac{l}{d_{max}} \tag{5.1}$$

It was determined that for airship the theoretically optimal fineness ratio with respect to drag is 4.62 [32]. This will be used as a starting point for the design, in later iterations it can be tuned according to the needs of the airship.

For the shape configuration; the National Physical Laboratory (NPL) put forward a shape that reduces drag [31]. This shape is created by joining two ellipsoids of different major axis where their diameter is maximal [33][34]. This shape is shown in Figure 5.2.

Adding this to Equation 5.1 defines the shape as the following:

$$\begin{cases} \frac{x}{a_n}^2 + \frac{y}{b_n}^2 = 1 & \text{For x} \leq 0 \\ \frac{x}{2a_n}^2 + \frac{y}{b_n} = 1 & \text{For x} > 0 \\ 4.62 = \frac{a_n(1+\sqrt{2})}{2b_n} \end{cases} \tag{5.2}$$

To get a parameterized formula for the length, the volume was calculated at unit length. This yielded $2.4531 \cdot 10^{-2}$ m^3. Using that the volume scales with the cube of the length; the following relation could be found:

$$\frac{l_{\text{ref}}}{V_{\text{ref}}^{1/3}} = \frac{l}{V^{1/3}} \tag{5.3}$$

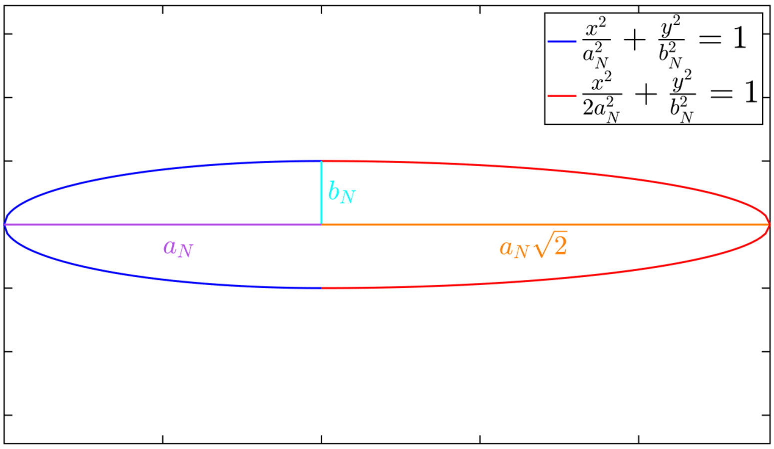


Figure 5.2: *NPL's optimal airship shape [33, p.7].*

Fixing the values with subscript *ref* in Equation 5.3 to the unit length values allows the calculation of the length for any volume.

For the volume given in Table 4.10, this yields a length of 221.25 m and a diameter of 47.89 m.

5.2.2. Lift Estimation

The lift estimation mainly consists of obtaining a plot of angle of attack (AoA) and lift coefficient. Starting with just the hull results in the following. As the shape is symmetric, the lift coefficient will be zero at zero AoA. The lift slope C_{L_α} can be estimated for bodies of rotation for Reynolds number above 10^7 by [35]:

$$C_{L_\alpha} = \frac{\pi AR}{2} \tag{5.4}$$

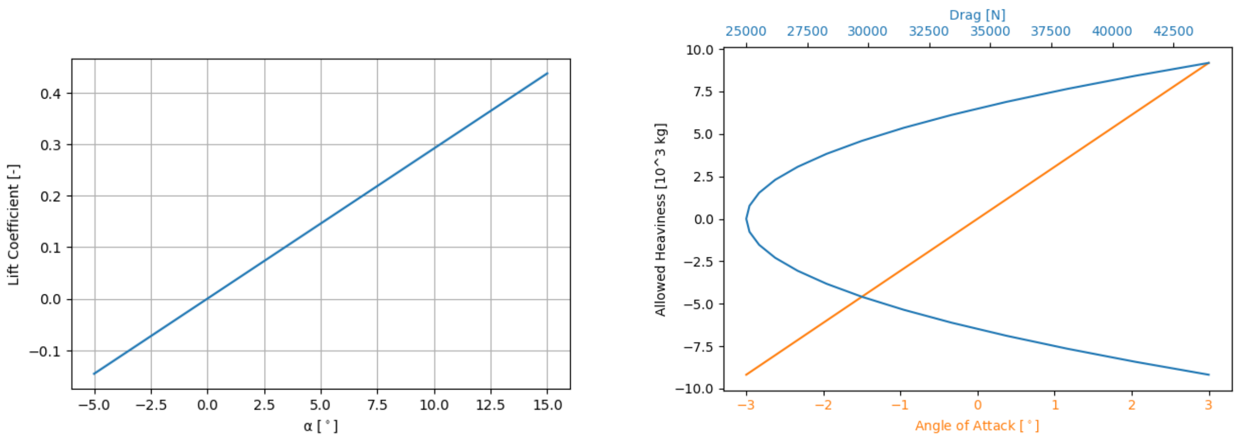
In Equation 5.4 the aspect ratio (AR) for bodies of rotation is given by [35].

$$AR = \frac{4}{\pi FR} \tag{5.5}$$

Combining the fineness ratio found in Subsection 5.2.1 with Equation 5.4 and 5.5 yields a lift slope of 0.433 $\frac{1}{rad}$ for just the hull.

Considering just the lift generated by the tail next gives the following. Firstly it is assumed that the contribution of the elevators to the overall lift is negligible. Secondly, interference between hull and tail is assumed to have no influence on the lift slope; this means that the AoA of the tail is the same as the overall AoA. In Chapter 6 the tail is decided on to have a NACA 0018 airfoil. This one is also symmetric and has a lift slope of 1.241 $\frac{1}{rad}$ as determined in Chapter 6 and converted to the volumetric reference area.

As it was assumed that both lift slopes are completely independent, i.e. have the same AoA, they can just be added for the complete slope. This yields a C_{L_α} of 1.674 $\frac{1}{rad}$. This can be plotted in Figure 5.3a:



(a) *Plot of the angle of attack vs the lift coefficient.* **(b)** *Relation between allowed heaviness, angle of attack, and drag.*

Figure 5.3: *Lift characteristics of the airship.*

With this data, it is possible to decide on the heaviness of the ship during flight. In Figure 5.3b the drag and angle of attack are plotted for the overall heaviness of the ship. The drag curve is determined later in Subsection 5.2.4. The plot shows that as the heaviness increases, the drag increases as well. While heaviness advantageous for ground operation and control, it is unfavorable during flight. It was decided to set the heaviness at 750 kg, as that keeps the drag within reasonable limits. This sets the cruise AoA at about 0.245°, which is negligible, and the drag at ≈25 kN.

Keeping it this low also allows for additional lift to be generated in emergencies or when the heaviness suddenly increases. In case of rain or other issues that increase the net weight, the ship could simply fly at and AoA of e.g. 5°, reduce its speed, and lift an additional ≈15 000 kg.

5.2.3. Moment Estimation

An important factor for stability is the moment curve of the hull. Sadly, no parametric method could be found to estimate these coefficients for airships, and historical data has to be used. The closest airship in scale for which accurate data is available is the USS Akron, for which wind tunnel tests of a 1/40 scale model were performed. These tests were done at a Reynolds number of $1.734 \cdot 10^7$ and yielded the following results [28]:

The data in Figure 5.4 can be extrapolated to the negative side to better show the symmetry the hull has. Furthermore, the data has been converted, so the moment coefficient is no longer about the center of buoyancy at 46.4% the ship length but about the quarter length.

This data puts C_{M_α} at 1.3 $\frac{1}{rad}$ for small angles of attack. This value does not provide the preferred accuracy and should absolutely be verified in the future.

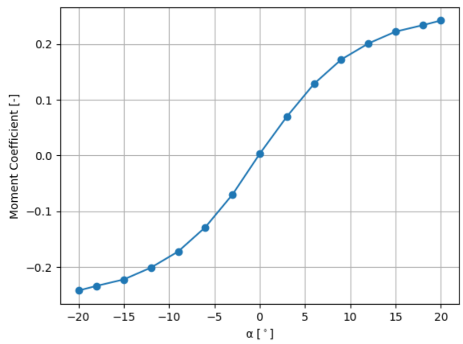


Figure 5.4: *Plot of the AoA vs the moment coefficient about 1/4 the ship length.*

5.2.4. Drag Estimation

In airship design, lift is very good and mostly constant, moment is useful and drag is bad. [35, p.86]

An important metric for the performance of the ship is the drag coefficient. For this a parametric Class-II method will be used. For each component the viscous zero lift drag area can be estimated in with the following method [35]:

Table 5.4: *Viscous zero lift drag area breakdown of the hull.*

Component	Formula for Drag Area	Value [m^2]
Envelope	$C_DS_{env} = 0.3048^2 \cdot (C_F)_{env}\ (FF)_{env}\ (S_{wet})_{env}$	33.00
Envelope Accessories	$C_DS_{ea} = 0.3048^2 \cdot 0.04 C_DS_{env}$	1.32
Tail	$C_DS_{ts} = 0.3048^2 \cdot 0.01\ (S_{plan})_{tails}$	38.13
Tail Accessories	$C_DS_{tsa} = 0.3048^{-1} \cdot 7.0 \cdot 10^{-7} V_{env} + 0.3048^2 \cdot 0.625$	0.67
Outriggers	$C_DS_{out} = 0.044 C_DS_{env} + 0.3048^2 \cdot 0.92$	1.54

Engine Nacelle	$C_D S_{nac} = 0.3048^2 \cdot 4.25(\#engines)$	2.37
Engine Cooling	$C_D S_{cool} = (\#engines)(0.3048^{-1} \cdot 2 \cdot 10^{-6} V_{env} + 0.3048^2 \cdot 4.1)$	12.75
Interference	$C_D S_i, = 0.3048^{-1} \cdot 4.78 \cdot 10^{-6} V_{env}$	4.17
Landing Gear	$C_D S_{lg} = 0.3048^{-1} \cdot 1.76 \cdot 10^{-6} V_{env} + 0.3048^2 \cdot 0.92$	1.62
Total		95.56

Table 5.4 outputs the drag area of each component. This is done so that they can just be added together in the end and normalized with the correct reference area. The hull friction coefficient $(C_F)_{env}$ can be determined using the turbulent Schoenherr-von Karman formula [35]:

$$(C_F)_{env} = \frac{0.455}{(\log_{10}(Re_l))^{2.58}} \tag{5.6}$$

Where Re_l is the length based Reynolds number of the envelope. $(FF)_{env}$ is the form factor of the envelope, given by [35]:

$$(FF)_{env} = 1 + 1.5 \cdot (FR)^{-3/2} + 7 \cdot (FR)^{-3} \tag{5.7}$$

$(S_{wet})_{env}$ is the wetted area of the envelope, which can be found using the equations in Equation 5.2. $(S_{plan})_{tails}$ is the planform area of both horizontal and vertical tail, as determined in Table 6.10. This yields a value of 0.0243 for the zero lift drag coefficient.

To get the complete drag coefficient, the pressure drag also has to be accounted for. For fineness ratios above 4 the percentage of pressure drag will tend to 5% [35][36]. With this the full C_{D_0} can be determined. For the lift induced drag, a quadratic polar can be used for uncambered airships [35]:

$$C_D = C_{D_0} + K \cdot C_L^2 \tag{5.8}$$

For this the drag due to lift constant has to be determined. This can be estimated using the following method [35]:

$$K = -0.0145AR^{-4} + 0.182AR^{-3} - 0.514AR^{-2} + 0.838AR^{-1} - 0.053 \tag{5.9}$$

For Equation 5.9 the aspect ratio can be computed using Equation 5.5. This leads to a value of 2.402, and the drag polar found in Figure 5.5.

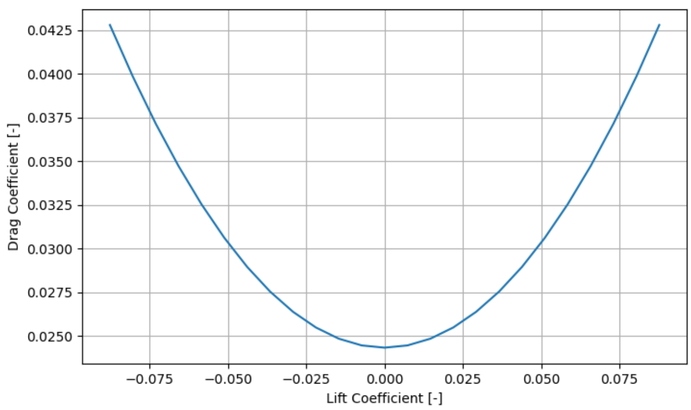


Figure 5.5: *Relation between lift and drag coefficient of the airship.*

5.2.5. Lateral Drag Estimation

Another important case is when the air is not coming from the front but from the side or the top/bottom. This often occurs at low flight speed or during hovering and mooring. As the flow over bodies of revolution is dictated by viscous effects, it is hard to model it accurately using analytical methods.

The airship can be split into two main parts when it concerns lateral drag; the hull and the vertical stabilizers. As data is scarce on non-circular shapes' drag coefficients, the airship will be discretized into circular ones

[37]. Similarly, for the tail, most data is available for plates of constant length perpendicular to the flow. The discretization is shown in Figure 5.6.

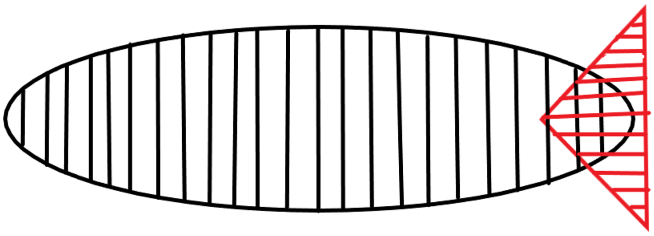


Figure 5.6: *Example of discretization of an airship.*

Starting with the cylinder-slices; the drag of infinite cylinders has been extensively researched, and the results can be seen in Figure 5.7.

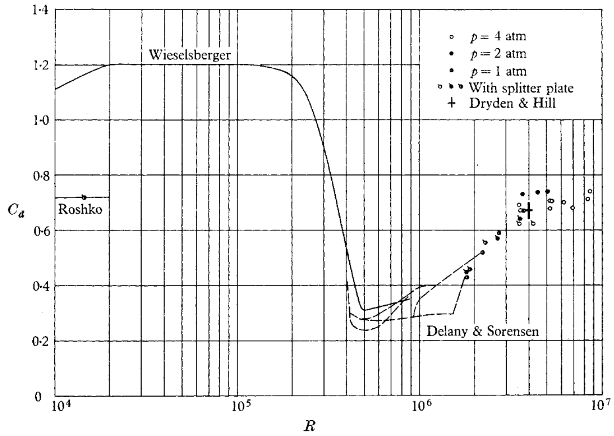


Figure 5.7: *Plot of sectional drag coefficient vs Reynolds number for the flow over a cylinder [38, p.348].*

The Reynolds numbers concerning cylinders is taken with respect to the diameter and not the length over the surface [39]. Similarly, the sectional C_d was normalized using the diameter [39]. The velocities for this are specified to be in the range of 5 to 10 m/s in Subsection 11.2.3. This puts the range of Reynolds numbers in the range of 10^6 and up for sea-level viscosities. In that range the C_d can be observed to move from about 0.3 at $Re_D = 10^6$ to about 0.7 at $Re_D = 3.5 \cdot 10^6$ quite linearly (on a log-plot that is), after which it levels off at 0.7 [38]. The drag coefficient in that range can thus be modelled using the following equations:

$$\begin{cases} C_d = \frac{0.7-0.3}{\log_{10}(3.5)}\left(\log_{10}(Re_D) - 6\right) + 0.3 & \text{For } 10^6 \leq \mathrm{Re_D} \leq 3.5 \cdot 10^6 \\ C_d = 0.7 & \text{For } 3.5 \cdot 10^6 \leq \mathrm{Re_D} \end{cases} \tag{5.10}$$

As towards the edges of the airship the Reynolds number tends to zero, it goes outside the range of Equation 5.10's approximation. Therefore, points should not be placed too close together near the edges. With these coefficients, the dimensional drag can then be computed, as well as the moment the section creates about the nose.

The way this is done is by taking using the shape from Equation 5.2 and getting the radius at discrete points. With these the diameter based Reynolds number can then be determined at the points. This leads to a drag coefficient via Equation 5.10. By multiplying this sectional drag coefficient with the diameter and then integrating it over/multiplying it with the width of the discrete section yields the total drag generated by that slice. The moment can then be computed by multiplying the drag with the distance between the nose and the centroid of the slice.

Now turning to the tail surfaces; these can be modelled as flat plates perpendicular to the flow. For this type of plates the drag coefficient is not as dependent on the Reynolds number [40]. This is due to the flow separating behind it, no matter the viscosity or airspeed. The value of this C_d was determined to be around 1.6 [36]. Using a method similar to the one for the cylinders, the tail shape from Subsection 6.2.1 can be cut into horizontal slices as seen in Figure 5.6. Calculating the drag of these slices results in the overall drag and the moment the tail creates around the nose.

This method can also be used for determining the *Dorsal* drag coefficient; i.e. when drag when the ship is ascending or descending vertically. Lastly, it is important to note that this method neglects the contribution of the tail surfaces that are in plane with the airflow. These would mainly contribute to the drag via viscous drag over a flat plate. They have however been neglected for this estimation. An argument can be made that they are compensated for by the parts of the tail surface that end up inside the airship hull. The same applies for interference effects.

The results of these analyses are found in Table 5.5.

Table 5.5: *Lateral and Dorsal drag values.*

Case	Drag [kN]	Moment about nose [MNm]
5 m/s side	130.335	13.752
10 m/s side	521.539	55.020
2 m/s up	20.266	N/A

It is worth mentioning that the lateral and dorsal drag are orders of magnitude larger than the frontal drag values. It is not possible to summarize these with one C_D value as they are very dependent on the Reynolds number.

5.3. Cost Analysis

While the aerodynamics of the airship have no direct cost to them, even though fuel usage contributes indirectly, but there can be a large cost in the analysis of the ship. In initial stages of the design all that is needed is an engineer and a computer, but as the analysis becomes more detailed, specialized facilities will be needed.

The main issue in the design and analysis is the high Reynolds number, order of 10^8, while the Mach number stays low. Finding suitable testing facilities might be an issue as most tests are done while both Mach number and Reynolds number are either low or high. Most vehicles of this size do not move this slow. One vehicle that is comparable in Mach and Reynolds number is a train [41].

For more detailed analysis wind tunnels could be used. However, due to the before mentioned niche of conditions, very few wind tunnels would be able to produce these. Tunnels that allow for this are for example German-Dutch Wind Tunnels' Large Low-Speed Facility [1], and NASA's National Full-Scale Aerodynamics Complex at Ames Research Center[2]. This however come at a high cost, estimates are around 1% of the total program cost or 20 000$ per hour[3]. It will likely be even higher, as large testing facilities are rare and will cost more.

The option of using computational fluid dynamics (CFD) would be more attractive in earlier stages of the design. However, the large difference in scale between the boundary layer and the overall ship can become problematic as simulations become more complex. This can drive up the computational cost and time to an extent where wind tunnel experiments might be more advantageous.

5.4. Overview

In Table 5.6 an overview of the main outputs for the aerodynamic subsystem are presented.

[1] https://www.dnw.aero/wind-tunnels/llf/, (Accessed on: 15/05/2024)
[2] https://www.arnold.af.mil/About-Us/Fact-Sheets/Display/Article/409302/national-full-scale-aerodynamics-complex/ (Accessed on: 15/05//2024)
[3] https://lsleds.com/how-much-is-a-wind-tunnel/, (Accessed on: 15/06/2024)

Table 5.6: *Outputs of the aerodynamic subsystem*

Output	Value
Fineness Ratio [-]	4.62
Lateral Drag Force @ 5m/s [kN]	130.334
Lateral Drag Force @ 10m/s [kN]	521.539
Lateral Drag Moment @ 5m/s [MNm]	13.752
Lateral Drag Moment @ 10m/s [MNm]	55.020
Dorsal Drag Force @ 2m/s [kN]	20.827
Lift Curve Slope [rad^{-1}]	1.674
Lift Induced Drag Constant [-]	2.402
Moment Curve Slope [rad^{-1}]	1.3
Length [m]	221.25
Diameter [m]	47.89
Zero Lift AoA [°]	0
Zero Lift Drag Coefficient [-]	0.0243
Heaviness [kg]	750
Wetted Area [m^2]	26133.79

5.5. Sensitivity Analysis on Heaviness

As in Subsection 5.2.2 the heaviness was chosen rather than determined, it would be good to perform a sensitivity analysis on it to test the robustness. Chapter 12 goes deeper into the reasons and methods for a sensitivity analysis. The effect of heaviness on relevant parameters is presented in Section 5.5.

Table 5.7: *Sensitivity Analysis on the Heaviness*

Increase	-50%	-25%	-10%	10%	25%	50%
Drag Coefficient	-0.4 %	-0.2 %	-0.1%	0.1 %	0.3%	0.7%
MTOW	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Horizontal Stabilizer area	0.1%	0.0%	0.0%	0.0%	0.0%	-0.1%
Fuel Weight	-0.3%	-0.2%	-0.1%	0.1%	0.2%	0.5%

As can be seen in Section 5.5, changing the heaviness has only a small impact on the overall design. For the purpose of fuel and drag it can be seen that lowering it has a beneficial effect, for control it has the opposite however. This means that if future design requires the heaviness to be changed it can be done without affecting the overall design all to much. The main reason to keep the heaviness low for now is that it allows for a lot of addition lift to be added in case of emergency, with the low drag as a bonus.

5.6. Limitations and Recommendations

For further design and analysis of the subsystem it is important to know where its strengths and weaknesses lie. The methods used to come to this design have their limitations. It is important to take note of these and to come up with methods on how to improve on them in the future.

- The fineness ratio selected is the theoretical optimum, the real optimum can vary under real world conditions
- Although the selected shape was created to reduce drag; it seems to have blunt rear, which might cause a lot of separation drag.
- No semi-empirical method could be found to estimate the moment coefficient of the airship.
- It was assumed that the lift coefficient for hull and tail were full independent, in reality there might be down-wash effects.
- The reference are for the tail extends through the hull, this is inaccurate as this part will generate no lift.
- Lift and drag were estimated using parametric equations, they might be too general and give low quality estimates.
- The lift contribution of the elevators is neglected, they have a positive impact on the lift slope.
- The lift slope might not be perfectly linear, it can be cubic for airships [28].

- The percentage of pressure drag is only an estimate, it can vary a lot depending on Reynolds number and shape
- The lateral drag estimation neglects the contribution of the control surfaces that point into the flow.
- The lateral drag estimation neglects interference effects between tail and hull.
- Part of the tail in the lateral drag estimation is inside the fuselage and thus has no contribution in reality.
- The lateral drag estimation uses approximate values to model the C_d-Re_D relation.
- The lateral drag might induce vibrations due to unsteady vortices.
- It was concluded that the ship can generate additional lift, however no procedures have been developed for the case this would be necessary.

The problems relating to the shape of the ship can best be solved by performing an extensive sensitivity analysis. For the fineness ratio, it suffices to look into the difference in drag as the number varies. For the shape it would be wise to try and reduce the blunt-ness of the stern by shaping the rear part of the ship more like a cone. Additionally, boundary layer suction could be considered to reduce drag. This postpones transition or separation and reduce drag. For all concerns relating to the longitudinal aerodynamic coefficients CFD can be used in the further design stages until they reach their limit. For the lateral analysis it would be good to first refine the existing method to get the exact geometry. In later design stages it is recommended to do unsteady CFD simulations or wind tunnel experiments. The need for real world experiments will arise earlier for the lateral case due to the very unsteady nature of the flow. For the additional lift it should be looked into how this limits operation of the ship is e.g. rain. Procedures for what to do in that case should be investigated.

6 Stability and Control

The airship requires adequate controllability and stability to fly safely and to deliver the payload undamaged. Previous airships have suffered from instability, with considerable damage as a result. As the airship is both flying and hovering, it needs to be designed for both cases.

6.1. Design Baseline

The airship should be controllable and stable at both the high speed during cruise and low speed during hovering. For high speed, a tail is utilized, for low speed, the propulsion is used.

The tail is designed such that the airship is controllable and statically stable for a large range of pitch and sideslip angles. The tail is designed using similar tools to aircraft design. The difference is that the airship has additional buoyancy force and a smaller aerodynamic lift. For the low-speed control, the propulsion is placed such that the airship can maneuver quickly enough to provide a stable unloading procedure of the payload.

6.1.1. Design Goals

Next to the high and low-speed control, the CG location and a trade-off of the auto-pilot is made. The CG location is crucial for the stability of both the high and low-speed control. A trade-off of the auto-pilot is performed to choose the optimal piloting method, which influences the design and operations.

1. Design high-speed control: Tail
2. Design low-speed control: Propulsion
3. Determine and set CG Excursion
4. Tradeoff Auto-pilot

6.1.2. Requirements

To know what needs to be designed for, requirements have been set up. The requirements are listed in Table 6.1.

Table 6.1: *Sub-system Requirements*

Requirement ID	Description
REQ-CTR-03	The airship shall make a 360° turn in 3 minutes with cruise speed
REQ-CTR-05	The sub-system shall provide full controllability during hovering for a side wind of 10 m/s
REQ-CTR-06	The airship shall make a 180° turn in 2 minutes during hovering
REQ-CTR-07	The airship shall be laterally statically stable during cruise for a side-slip angle between -20°and 20°
REQ-CTR-08	The airship shall be longitudinally statically stable during cruise for a pitch angle between -20°and 20°
REQ-CTR-09	The airship shall be laterally controllable during cruise for a side-slip angle between -20°and 20°
REQ-CTR-10	The airship shall be longitudinally controllable during cruise for a pitch angle between -20°and 20°

6.1.3. Inputs and Outputs

For the sizing and calculations surrounding the stability and control sub-system, several inputs are needed, these can be found in Table 6.2. The stability and control calculations also give several outputs which are required by other systems. These outputs can be found in Table 6.3.

Table 6.2: *Inputs*

Inputs
Inputs for tail sizing:
• MTOW
• Cruise speed
• Cruising density
• CG location
• Airship length
• Buoyancy force
Inputs for CG excursion:
• Payload bay location
• Sub-system CG location
• Sub-system masses

Table 6.3: *Outputs*

Outputs
Tail sizing:
• Tail planform
• Tail airfoil
• Tail mass
• Tail configuration
CG Excursion:
• CG locations at different airship masses

6.1.4. Main Parameters

The main parameters of the stability and control subsystem is the tail and the pilot option. The parameters are: horizontal tail area, vertical tail area, tail platform, and piloting option.

6.2. Tail Sizing

Tails can make up around 15% of an airship's total drag contribution and 10-14% of the empty weight[35, 42], therefore it is beneficial if a shape with low aerodynamic drag is chosen and the tail surface area is minimized. However, the tail should still provide sufficient stability and controllability. First, the tail configuration is determined, and afterward, the area of the tail in combination with the aspect ratio, taper ratio, and sweep angle will be chosen.

6.2.1. Tail Configuration

The first step in sizing the tail is choosing a tail configuration. To this end, a trade-off is performed. Multiple tail configurations were considered. A sketch of the different tail types is included in Figure 6.1b. The different configurations of airship tails are as follows:

Tailless An airship without aerodynamic surfaces for stability and control.

Plus A plus-tail consists of a horizontal surface with elevators and a vertical surface with rudders. The surfaces meet perpendicularly in the center line of the airship.

Cross Also known as X-tails. Similar to a plus tail, but the surfaces are angled with respect to the envelope. The surfaces can be perpendicular to each other but do not need to be.

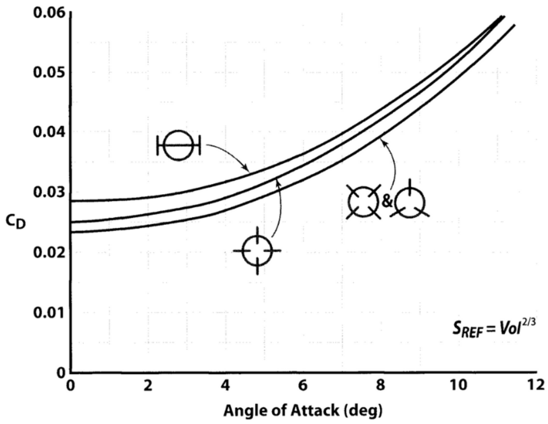
Inverted Y This tail has three surfaces, one vertical pointing upward and two surfaces pointing slightly downwards with an angle of 120° to the vertical surface.

H-tail A tail with a horizontal surface and two vertical surfaces attached to the end of the horizontal surface.

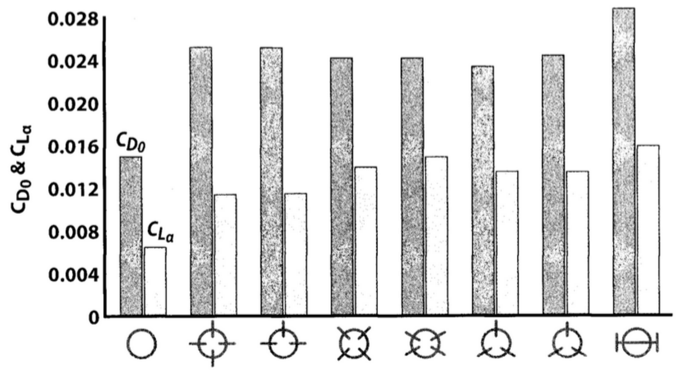
The criteria that will be considered for the trade-off are airship drag, tail mass, controllability and ease thereof of the airship, and ground and hanger clearance. The drag strongly influences performance and the power & propulsion subsystem. Because drag differences between different configurations are limited, this criterion gets a small weight of 15%. The tail is one of the heaviest subsystems, and increasing mass has a snowball effect. Therefore, mass gets the highest weight of 35%. High-speed control is the design goal of the tail and design time is rather limited. Thus, controllability gets a large weight of 30%, but not the largest, as all options except tailless can provide sufficient controllability. Lastly, hangar and ground clearance represent how much the tail needs to stick out on the sides, top, and bottom. If the tail sticks out far, the hangar and landing system might need to take this into account. This possibly increases development cost or hangar size and cost. Since this should be avoided, but does not majorly impact the design or performance, this criterion gets a medium weight of 20%.

Figure 6.1 presents the drag data of the ZP5K airship for several tail configurations. Since the different configurations are used on the same airship, this data can be used for comparing the drag performance of the different options. Figure 6.1a presents the airship drag versus angle of attack for four different tail types. Figure 6.1b presents the zero-lift drag coefficient, C_{D_0}, and the lift slope coefficient, C_{L_α}

The different configurations can get one of four scores for each criterion. 'Unacceptable (R)', meaning that this option is not suitable for the design due to this criteria; 'Correctable (Y)', meaning the option has some deficiencies, but these drawbacks can be solved or accepted; 'Good (B)', meaning the option is suitable and has the performance meets expectations; finally, 'Excellent (G)', meaning this option beat the other options significantly and is a perfect match in this criteria. The trade-off for the tail type is presented in Table 6.4. The cross and inverted Y tail have a very small drag decrease compared to the plus tail, all three get the same 'Good' score. The difference in drag is small compared to the drag increase of the H-tail or the drag decrease of the tailless configuration.



(a) *Drag coefficient of the ZP5K airship with different tail configurations.*



(b) *Zero lift drag coefficient and lift slope coefficient of the ZP5K airship with tail types from left to right: tailless, plus tail, inverted T-tail, cross tail, cross tail with shallower angle, two inverted Y-tails, H-tail.*

Figure 6.1: *Drag and lift slope characteristics for the ZP5K airship with different tail configurations[43]. Note that drag coefficients are for the complete airship.*

Table 6.4: *Trade-off table for tail configuration.*

Tail Type	Drag [15%]	Mass [35%]	Controllability [30%]	Ground and Hanger Clearance [20%]
Tailless	No tail drag (G)	No tail mass (G)	No control surfaces, unstable and full propulsion control required at all times (R)	Full clearance (G)
Plus	Nominal drag (B)	Nominal surface and mass (B)	Uncoupled control (G)	Limited clearance on all sides
Cross	Small difference, $\sim 5\%$ drag decrease (B)	Nominal surface and mass (B)	Fully coupled control (Y)	Decent clearance due to angle (B)
Inverted Y	Less interference, $\sim 5-10\%$ drag decrease (B)	Slightly decreased mass, one less surface (B)	Partly coupled control (Y)	Good ground clearance, limited hangar clearance (B)
H-tail	More interference, $\sim 17\%$ drag increase (Y)	Large structural mass increase (Y)	Uncoupled control, split rudder (B)	Ground and roof clearance, limited side clearance (B)

6.2.2. Initial sizing of the tails

To get a baseline to know what numbers are reasonable, historical tail sizes are acquired. The airship size needs to be comparable with the current airship size, therefore the Hindenburg and the Graf Zeppelin, both with a comparable length of 245 and 237 meters respectively were selected. The parameters were determined from technical drawings, see Table 6.5[1]. Another initial sizing method based on historical data gave surface

[1] `http://highriskadventures.com/airships/lz130/` (Accessed on: 12/06/2024)

sizes about half or less of this [35].

Table 6.5: *Hindenburg and Graf Zeppelin Tail Data.*

	Vertical tail total area [m^2]	Vertical tail exposed area [m^2]	Tail span vertical [m]	Aspect Ratio vertical	Horizontal tail total area [m^2]	Horizontal tail exposed area [m^2]	Tail span horizontal [m]	Aspect Ratio horizontal
Hindenburg	2131	1026	51	1.22	1512	728	43.42	1.25
Graf Zeppelin	1500	669	42	1.18	1279	634	42	1.38

Remarkable differences are the differences in the tail area, even though the Hindenburg and Graf Zeppelin are very similar airships. The vertical tail is also larger than the horizontal tail, due to the natural dynamic lateral instability of airships.

The formula for aspect ratio is given in Equation 6.1, the formula for 6.2 and the formula for the tip and root chord is given in Equation 6.3.

$$b = \sqrt{S \cdot AR} \quad (6.1) \qquad c = \frac{b}{AR} \quad (6.2) \qquad c_t = \lambda c_r \quad (6.3)$$

Where b is the tail span, S is the total tail area, AR is the aspect ratio, c is the mean aerodynamic chord, c_t is the tip chord, λ is the taper ratio and c_r is the root chord. Lastly, the sweep angle for any angle is given by Equation 6.4.

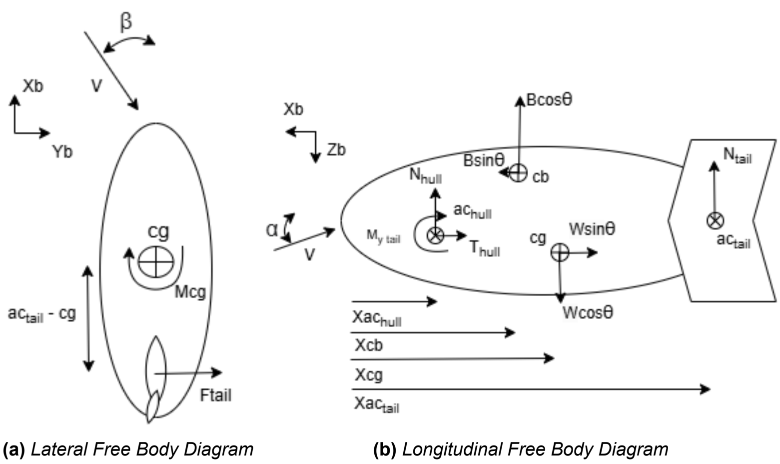
$$\tan \varphi_n = \tan \varphi_m - \frac{4}{AR}\left[\frac{n-m}{100} \cdot \frac{1-\lambda}{1+\lambda}\right] \quad (6.4)$$

Where m and n are the sweep angles, AR is the aspect ratio and λ is the taper ratio.

6.2.3. Detailed sizing of the tails

The tail will now be sized based on flight dynamics instead of statistics. Various aerodynamic coefficients are required to be able to design the tail. Due to time constraints, these coefficients were not obtained. To be able to design the tail anyway, aerodynamic data of a similar airship, the USS Akron, was used [44]. The Reynolds number of the USS Akron is significantly higher than the Reynolds number of this airship, with 4.3 million to 77 million, respectively. Due to the lack of other more comparable data, this difference is accepted currently.

To derive the required equation, first free body diagrams need to be constructed, shown in Figure 6.2. The main difference is the large buoyancy force and a smaller main lifting force. The free-body diagrams have already been simplified. Gliding flight is assumed, removing the propulsion forces, and the down- and sidewash angle is assumed to be zero, as the aerodynamic lift is low.



(a) *Lateral Free Body Diagram* **(b)** *Longitudinal Free Body Diagram*

Figure 6.2: *Free body diagrams*

For the lateral free body diagram, Figure 6.2a, it is assumed that the CG is directly underneath the CB, eliminating a moment due to the buoyancy force. NASA gives the moment coefficient around the center of buoyancy, meaning that the lift and drag do not have to be considered in the lateral free-body diagram. Furthermore, the tail drag and tail moment are assumed to be negligible. The airfoil has been chosen to be NACA0018, as a symmetrical airfoil is required and the NACA0018 is frequently used in airships [45]. The equation for controllability is given in Equation 6.5 and the equation for stability is given in Equation 6.6.

$$\sum Mz : C_{M_{CG}} + C_{Y_{tail}} \frac{V_T}{V} \frac{S_V}{S} \frac{x_{ac_t ail} - x_{CG}}{l} = Izz\ddot{\psi} \tag{6.5}$$

$$\sum Mz : -C_{M_{CG_\beta}} + C_{Y_{tail_\beta}} \frac{V_T}{V} \frac{S_V}{S} \frac{x_{ac_t ail} - x_{CG}}{l} = Izz\ddot{\psi} \tag{6.6}$$

Where $C_{M_{CG}}$ is the moment coefficient of the hull $C_{Y_{tail}}$ is the force coefficient of the vertical tail $\frac{V_T}{V}$ is the ratio of the tail airspeed and the airship airspeed $\frac{S_V}{V^{\frac{2}{3}}}$ is the ratio of the tail surface and the reference surface area, $\frac{x_{ac_t ail} - x_{CG}}{l}$ is the relative distance between the CG and the ac of the tail, I_{zz} is the moment of inertia around the z-axis and $\ddot{\psi}$ is the angular acceleration of the yaw angle. The subscript α indicates the derivative with respect to the angle of attack.

For the longitudinal free body diagram, Figure 6.2b, it is assumed that the tail has a negligible tail drag and moment. The equation for controllability is given in Equation 6.7 and the equation for stability is given in Equation 6.8.

$$\sum My : C_{N_{tail}} \frac{1}{2} \rho v_{tail}^2 S_H \frac{x_{CG} - x_{ac_{tail}}}{l} = -Bcos\theta \cdot \frac{x_{CG} - x_{cb}}{l} - Bsin\theta \cdot \frac{z_{CG} - z_{cb}}{l} - C_N q V^{\frac{2}{3}} \frac{x_{CG} - x_{ac}}{l} \tag{6.7}$$
$$+ C_T q V^{\frac{2}{3}} \frac{z_{CG} - z_{ac}}{l} - C_M q V + \frac{Iyy\ddot{\theta}}{l}$$

$$\sum My : C_{N_{tail_\alpha}} \frac{1}{2} \rho v_{tail}^2 S_H \frac{x_{CG} - x_{ac_{tail}}}{l} = -Bcos\theta \cdot \frac{x_{CG} - x_{cb}}{l} - Bsin\theta \cdot \frac{z_{CG} - z_{cb}}{l} - C_{N_\alpha} q V^{\frac{2}{3}} \frac{x_{CG} - x_{ac}}{l} \tag{6.8}$$
$$+ C_{T_{alpha}} q V^{\frac{2}{3}} \frac{z_{CG} - z_{ac}}{l} - C_{M_\alpha} q V + \frac{Iyy\ddot{\theta}}{l}$$

Where $C_{N_{tail}}$ is the force coefficient of the horizontal tail, ρ is the air density, v_{tail}^2 is the tail airspeed, S_H is the horizontal tail area, $\frac{x_{CG} - x_{ac_{tail}}}{l}$ is the relative distance between the CG and the AC of the aerodynamic tail, B is the buoyancy force, θ is the pitch angle, $\frac{x_{CG} - x_{cb}}{l}$ is the horizontal distance between the CB and CG, $\frac{z_{CG} - z_{cb}}{l}$ is the vertical distance between the CG and the CB, C_N is the normal force coefficient of the hull, q is the dynamic pressure $V^{\frac{2}{3}}$ is the reference volume based on the envelope volume.

Setting the angular acceleration to zero in all four equations, the minimal tail area can be acquired. For controllability, a rudder deflection of up to 30°is taken. For the various aerodynamic hull coefficients, an interpolation is performed with a linear or cubic polynomial using the USS Akron data. For the aerodynamic tail coefficients, airfoil tools are used [2]. The horizontal tail area is determined by the limiting stability to be 1974 m^2. The vertical tail area is determined by the limiting stability to be 1839 m^2. This is in the same order of magnitude as the Hindenburg and Graf Zeppelin, see Table 6.5. The horizontal tail is larger than the vertical tail, which is not in line with historical airships.

The tail shape parameters have been based on various aspects, the stick-out length, stall characteristics, hull geometry, and tail area. To limit the stick-out length and increase the stall angle, a low AR of 1.41 is selected. A taper ratio of 0.8 is picked to lower the tail weight. The tail sweep starts at the hull-tail intersection, and the swept ratio $\frac{a}{b}$ is set accordingly. The parameters can also be found in Table 6.10.

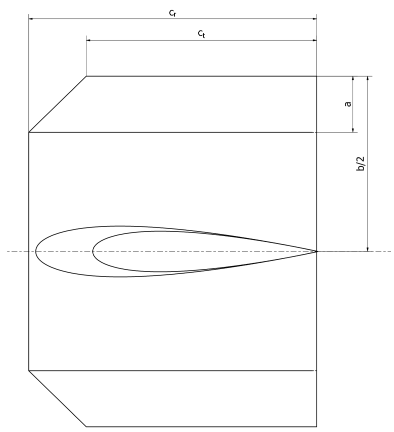


Figure 6.3: *Technical side view drawing of the tail, including the dimensional parameters.*

Figure 6.3 shows a technical side view drawing of the tail, explaining the shape and the dimensional parameters of the tail.

[2] http://airfoiltools.com/airfoil/details?airfoil=naca0018-il (Accessed on: 13/06/2024)

The airship also has a requirement on the turn rate during cruise, (REQ-CTR-03: The airship shall make a 360° turn in 3 minutes with cruise speed). To verify if the requirement is met, an analysis is made [45]. With a rudder deflection of 20°, a radius of turn radius over airship length of three can be reached. With a turn speed of 19 m/s, the time to turn 360°is 220 s, slower than the requirement demands. However, the airship does not need a high turn rate during cruise, as long distances are traveled. If required, the propellers can also help to turn the airship.

The tail weight is calculated using the Lockheed Martin book [45]. This is based on statistics, once a structural design is made for the tail, a more accurate weight estimation can be made. The estimation is split up into three parts: main tail, control surfaces, and actuators, resulting in a weight of 18.8 tonnes, 3.7 tonnes, and 0.7 tonnes.

6.3. Low speed control

The airship has to be controllable during hovering to prepare for mooring. As no lift generation by the tail is possible due to the low speed, the propulsion system needs to be used. The requirements for low speed are given by REQ-CTR-05 (The sub-system shall provide full controllability during hovering for a side wind of 10 m/s) and REQ-CTR-06 (The airship shall make a 180° turn in 2 minutes during hovering).

REQ-CTR-05 has not been designed for, as more complex control theory is required and that was deemed too time intensive for the given time. The other requirement has been designed for by the placement of the propellers, such that the moment arm is large enough to be able to turn quickly. The first placement iteration was to place the propellers, which can rotate the airship around the z-axis, at the edge of the payload bay, giving each propeller a moment arm of $\frac{105}{2}$, this gives enough moment to be able to turn in 2 minutes. More justification of the propeller placement can be found in Chapter 7.

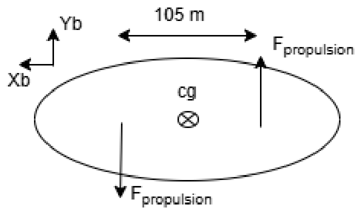


Figure 6.4: *Propulsion forces during hovered turn*

6.3.1. Virtual Mass

When a body accelerates or rotates in a fluid, it displaces this fluid. This causes aerodynamic forces that can be described in an aerodynamic model. The forces result in the body behaving as if the mass and inertia is increased. That is why this is called these aerodynamic force are called added, apparent, or virtual mass [35].

The inertia coefficient to describe this mass can be calculated. The fineness ratio of 4.62, gives a thickness ratio of $\frac{1}{4.62} = 0.216$. The airship can be estimated as an ellipsoid of revolution with a thickness ratio of 0.2, giving the inertial coefficients in Table 6.6 [17]. The values for a thickness ratio of 0.25 are also included, to bound the value of the coefficients, since the thickness ratio of the airship has a value between these.

Table 6.6: *Inertia, or virtual mass, coefficients of an ellipsoid of revolution [17].*

Thickness ratio	Axial coefficient	Transverse coefficient	Rotation coefficient
0.2	0.07	0.86	0.70
0.25	0.09	0.86	0.61

6.4. Center of Gravity Excursion

For stability and control, it is important to know the location of the center of gravity (CG) of the airship. For airplanes, this is normally used to size the tail. However, the tail sizing is not the only critical case for CG location. During hover and low-speed flight, it is ideal to have no pitching moment due to an arm between the weight and buoyancy forces. Thus, the longitudinal location of the CG and the center of buoyancy (CB) should coincide as much as possible. The CB was assumed to be located at the center of the volume, which was calculated to be located at $x_{CB} = 0.4786l$

In the lateral direction, the body y-axis, the CG, and CB should also coincide. The airship is assumed to be symmetrical about the longitudinal x-z plane, thus they both lie on the center line. Furthermore, the CG is located underneath the CB in the z-axis, since the low-mass hydrogen gas bags are located in the top of the airship and the heavy subsystems and payload in the bottom of the airship. This provides passive roll stability.

The CG is found using the CG location and mass of the subsystems in the airship, after which the CG range is presented as a function of loaded mass, in Subsection 6.4.1 and Subsection 6.4.2, respectively.

6.4.1. Center of Gravity Location of sub-systems

The overall system CG is composed of the mass-weighted CG's of the sub-system, as can be seen in Equation 6.9, where x_{CG} is the longitudinal coordinate of the CG, measured in the body axis and x_i and M_i is the CG location and mass of each sub-system.

$$x_{CG} = \frac{\sum x_i M_i}{\sum M_i} \tag{6.9}$$

Therefore, the CG location of the sub-systems needs to be known to get the airship CG location. This CG location should then be checked to be close to the desired value. The locations of sub-systems can then be changed to move the CG. This is an iterative process, shown in Figure 6.5. This results in the CG locations of each component as shown in Table 6.7.

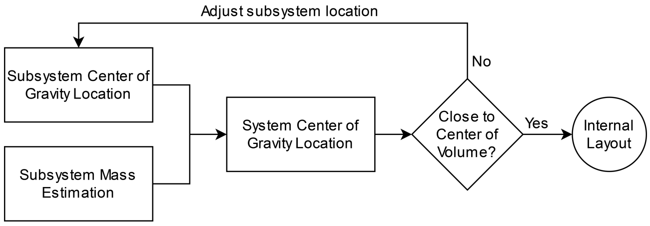


Figure 6.5: *Iterative process of CG location and internal layout.*

Table 6.7: *Minimum, expected, and maximum longitudinal CG location of each component, including the range between the minimum and maximum, expressed in a percentage of total length. *Included in Operating Empty Weight.*

Component	$x_{CG,min}[\frac{x}{l}]$	$x_{CG,expected}[\frac{x}{l}]$	$x_{CG,max}[\frac{x}{l}]$	range [l%]
Payload cables*	0.342	0.347	0.351	1
Envelope*	0.429	0.479	0.529	10
Structure*	0.429	0.479	0.529	10
Engine + Gearbox*	0.439	0.479	0.518	8
Power Generator (Fuel Cell)*	0.730	0.737	0.750	2
Fuel tanks*	0.730	0.772	0.800	7
Gas Bags*	0.429	0.479	0.529	10
Miscellaneous*	0.383	0.479	0.574	19
Control surfaces (Tail)*	0.880	0.953	1.030	15
Lifting gas	0.429	0.479	0.529	10
Fuel	0.730	0.772	0.800	7
Flight crew	0.100	0.265	0.500	40
Payload	0.336	0.336	0.604	27
Permanent ballast	0.379	0.479	0.579	20
Rain, snow & ice†	0.329	0.479	0.629	30

6.4.2. Potato Diagram

Due to the uncertainty of the subsystem location during design, a minimum and maximum CG location diagram has been calculated as well. However, the tail has been sized for the expected CG locations. As can be seen in Figure 6.6, the CG shifts mostly when filling the gas bags, starting with the gas bags either in the front or the back. When this happens, the airship is stored in the hangar. This shift in CG can be overcome by making sure the carts holding the airship, see Subsection 11.1.2, have a wide enough base. The base must extend from at most $x_{base,front} = 0.42l$ to at least $x_{base,back} = 0.65l$, including a $0.02l$ margin. Then the CG has a big shift when loading the cargo or ballast.

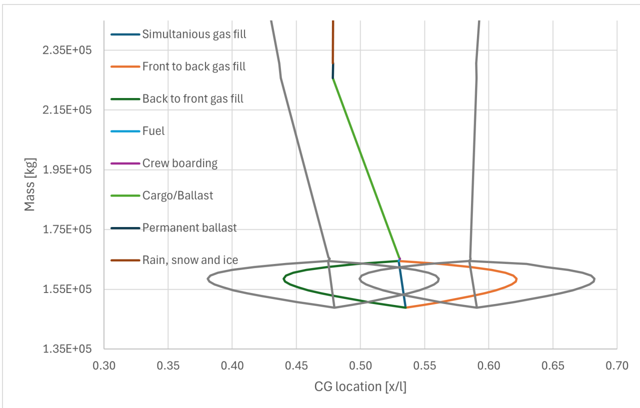


Figure 6.6: *Potato diagram showing the minimum CG, expected, and maximum CG locations.*

However, the payload and ballast will be exchanged at the moment one of them is unloaded, limiting the

CG shift happening to the airship. Furthermore, the CG shift will not cause the airship to rotate, as it will be constrained by mooring cables, see Section 10.2. Afterward, when lowering or raising the permanent ballast, see Section 10.3, the CG does not shift, as they are located at the CG. Rain, snow, and ice accumulating on the airship will add mass. This can be carried by increasing the angle of attack to increase dynamic lift. It will not affect the overall CG location. The CG location for MTOW configuration is longitudinally 3.3 cm in front of the CB.

6.5. Avionics

The pilots will have avionics similar to large transport aircraft. This includes communication channels such as a VHF radio for voice communication, Aircraft Communications Addressing and Reporting System (ACARS) to receive text updates in flight, and ramp mics to stay in contact with ground operation crew, see also Figure 11.5 in Section 11.3. Additionally, there will be an interphone, so that the pilots in the cockpit can communicate with crew monitoring the rest of the airship, located in or near the payload bay. Furthermore, the cockpit will include normal avionics systems, such as a weather radio, flight recorders ('black boxes'), a Fuel Quantity Indication System, satellite navigation (GPS), altimeters, and airspeed indicators. The main difference with aircraft is that the airship will also feature multiple cameras to include pilot visibility. These cameras will be included at least pointing down at the payload bay, and pointing forward and backward for a full field of view during operations.

6.6. Trade-off Piloting

Different levels of automation to control the airship are scored, to pick the best method. As there are not many airships anymore, autopilot systems for airship have developed slower than for aircraft. Even though this airship is not carrying passengers, a strict certification is required as the size and lifting gas of the airship pose serious safety concerns when an autopilot system fails. The number of produced airship will influence the trade-off, for now a small manufacturing number is assumed.

Options

Four options are evaluated and compare to each other. The first option is manual control, a pilot is mainly controlling the airship, with the limited help of autopilot which have been used on airships or aircraft. Secondly, a remote control is considered. Even though remote control does not have many benefits, it can be used as a step towards a full autopilot. Thirdly, a limited autopilot is weighted, which performs major parts of the flight, but a pilot always has to be available to take over. Lastly, a full autopilot is investigated. A full autopilot is fully autonomous and eliminates the need for a pilot.

Criteria

The main consideration to choose a manual or autonomous control is the related costs. An autonomous control eliminates the need of training and using pilots. As airship aren't common vehicle, there are not many pilots. This causes an expensive training and hiring of an airship pilot. To cover the costs in the trade-off, both the development and operational costs are considered. The risk is evaluated as well. The airship should be in operation in 2040, this is an ambitious planning, so the development risk and duration should be minimized.The development risks and duration are represented by risk.

An equal weight of 33% is given to the development and operational costs, and the risk is given a weight of 33%. For the investors, all the criteria were deemed as equal value for the investors.

Analysis

Development costs

For the development costs, the technology readiness level (TRL) is consulted to make an estimation. A low TRL indicates a low development cost, and a high TRL gives a high development cost. As the development costs for autopilot systems are generally not shared by companies, a qualitative scoring is performed.

The manual control has a low development, as all large rigid airship have used manual control. The cost comes from the development to make a gondola together with the avionics. For a remote controlled airship, a robust communication system, ground control system and sensors on the airship have to be developed.

For both autopilots, more development needs to be performed. The limited autopilot requires less development costs compared to the full autopilot, however, still needs a gondola as a pilot should be monitoring the airship at all times. Another factor which increases the complexity is the low speed control, below the reversing speed the control are switched and for hovering the thrusters are heavily used. This makes the limited autopilot more expensive than the manual control and remote control, and cheaper than the full autopilot.

Operational costs

The operational cost is the part which can be saved on by autopilots. For manual control, remote control and the limited autopilot pilots are required during operation. From Subsection 2.2.3, it is known that the average yearly salary of commercial pilots is €76 000. As four pilots are required to be able to fly continuously throughout the year, the total salary cost sums to €304 000. The remote control will have higher costs due to the required robustness of the communication. Only the full autopilot will not require pilots and is therefore the cheapest option.

Risk

For the risk, the TRL is used. When technology is not developed and tested fully yet, the risk of a longer development time and higher costs than expected get significantly higher. The risk are increasing when the autonomously raises.

Table 6.8: *Trade-off table for piloting method.*

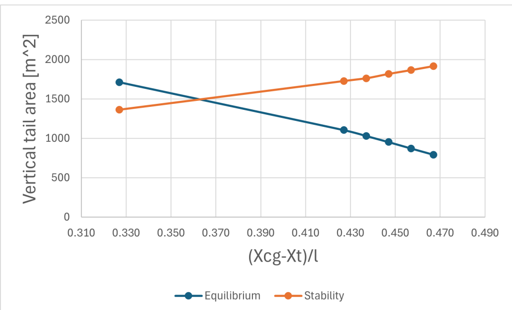
	Development cost [33%]	Operational costs [33%]	Risk [33%]	Final score
Manual control	No new technology used (G)	Performance decreases, only pilot costs (B)	Proven technology on airships (G)	Low cost and feasible (G)
Remote control	Technology used, not for airships (Y)	Performance remains, connection required (B)	Technology proven on aircraft (B)	High development cost, but feasible (B)
Limited autopilot	Technology development limited (R)	Performance decreases, only pilot costs (B)	Technology still in development (R)	High development costs, not proven yet (R)
Full autopilot	Technology non existing (R)	Performance increases, no pilot costs (G)	Technology still in development (R)	Very high development costs, not proven yet (R)

Conclusion

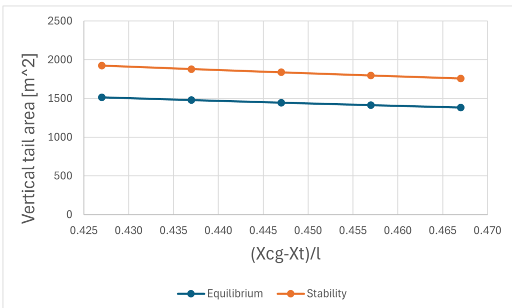
From Table 6.8, manual control appears to be the best option, as it does not score bad in any category. When the number of produced airships increases, the full autopilot can become more attractive. The remote control and limited autopilot do not have one big advantage, but can be used as in between step to full autopilot.

6.7. Sensitivity Analysis

For the sensitivity analysis of the stability and control system, the tail will be examined, as the tail has the biggest impact on the airship. The distance between the CG and AC of the tail will be changed to see the impact on the tail surface area. The results are presented in Figure 6.7.



(a) *Horizontal tail*



(b) *Vertical tail*

Figure 6.7: *Sensitivity analysis CG-tail location*

From Figure 6.7, it can be concluded that the CG-tail location has a higher impact on the horizontal tail. The plot represents a scissor plot, used similarly for aircraft design. For the horizontal tail, it is beneficial to decrease the CG-tail distance for stability, as the horizontal tail area can be minimized for a $\frac{X_{CG}-X_{tail}}{l}$ of 0.36. This does increase the vertical tail area, so a trade-off would have to be performed to choose the most optimal tail location in the future design.

6.8. Limitations and Recommendations

During the design of the control and stability subsystems, a lot of limitations and recommendations were found, which need to be taken into account with the future design.

Table 6.9: *Limitations and recommendation of the stability and control subsystem*

Limitations	Recommendations
The aerodynamic coefficients from the USS Akron are used	It is recommended that the aerodynamic coefficients of the designed airship are determined
The tail is sized for α and β below 20°	The aerodynamic coefficients should be determined to higher α and β
The stall angle of the tail has not been determined	More aerodynamic analysis should be performed on the tail
The tail is sized using simplified equations	Reevaluate the assumptions, and include the non-neglectable assumptions
Roll stability has not been considered	Consider the roll stability in further design
Dynamic stability has not been considered	Make a linear model of the airship to investigate the dynamic stability
The hull-tail interference has not been considered	Perform wind tunnel test or CFD to quantify the interference effects
The virtual mass has not been investigated completely	Investigate the virtual with more detail
The location of the tail is not optimized	Find relations of the tail locations with the structural weight, CG location, controllability, and stability.
The weight estimation is based on statistics	Design the structures of the tail to achieve an accurate weight estimation
The low-speed control has not been designed fully	Design control loop to be able to hover automatically
The reversing speed has not been calculated	Investigate the reversing speed and identify the reversing speed
The avionics and cockpit have not been designed	Start the design of the avionics and cockpit
Potato plots for roll stability have not been made	Create the potato plots for the roll stability
The control and stability during mooring has not been investigated	Determine the provided stability of the mooring methods

6.9. Cost Analysis

The costs of the stability and control subsystem is given by the cost of the tail, the cost of the avionics hardware and the avionics development costs. The tail cost is broken down into three parts: material, manufacturing, and transportation costs, which cost €160 000, €1 220 000 and €3 500, respectively. According to Introduction to Avionics Systems, the cost of the avionics is about 20% to 30% of the production of aircraft. The development costs of the avionic system are substantial, however no sources were found.

6.10. Design Overview

The final overview of the stability and control subsystems is given in Table 6.10. A 3D drawing of the tail group is shown in Figure 6.8.

Table 6.10: *Final overview parameters*

Parameter	**Symbol**	**Value**	**Equation/source**
Piloting option		Manual control	Table 6.8
Tail configuration		Plus tail	Subsection 6.2.1
CG location			
Horizontal surface required for equilibrium [m^2]	$S_{h,eq}$	892.6	Equation 6.7
Horizontal surface required for stability [m^2]	S_h	1974	Equation 6.8
Horizontal aspect ratio	AR_h	1.41	Chosen
Total horizontal span [m]	b_h	52.8	6.1
Mean horizontal chord	c_h	37.4	6.2
Horizontal taper ratio	λ_h	0.8	Chosen
Horizontal quarter chord sweep [rad]	Λ_h	0.23	Equation 6.4
Horizontal swept ratio	$\frac{a}{b}$	0.16	Chosen

Horizontal root chord	$c_{r,h}$	38.66	Equation 6.3
Horizontal tip chord	$c_{t,h}$	30.93	6.3
Horizontal tail airfoil		NACA0018	[31]
Vertical surface required for equilibrium [m^2]	$S_{v,eq}$	1447	Equation 6.5
Vertical surface required for stability [m^2]	S_v	1839	Equation 6.6
Vertical aspect ratio	AR_v	1.41	Chosen
Total Vertical span [m]	b_v	48.05	6.1
Mean Vertical chord	c_v	38.27	6.2
Vertical taper ratio	λ_v	0.8	Chosen
Vertical quarter chord sweep [rad]	Λ_v	0.26	Equation 6.4
Vertical swept ratio	$\frac{a}{b}$	0.16	Chosen
Vertical root chord	$c_{r,v}$	39.53	6.3
Vertical tip chord	$c_{t,v}$	31.63	6.3
Vertical tail airfoil		NACA0018	[31]

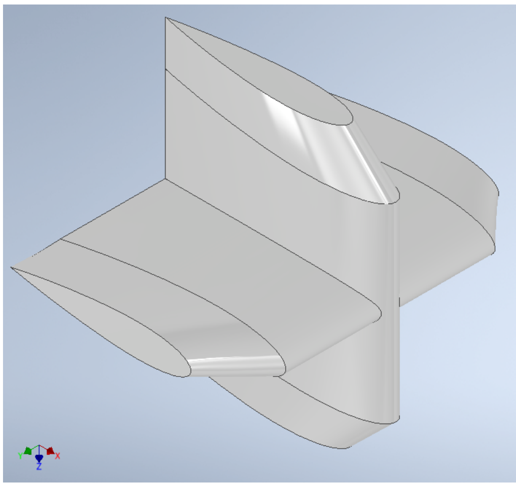


Figure 6.8: *CAD render of the tail.*

7
Power & Propulsion

The design process of the power and propulsion subsystem is described in this chapter. First, the goals and requirements for the design are defined in Section 7.1, and after that the thrust forces are determined in Section 7.2. A power estimation is provided in Section 7.3Subsequently, the propeller placement and characteristics are described in Section 7.4, this is followed by both a mass estimation as well as a cost breakdown in Section 7.5 and Section 7.6 respectively. Section 7.7 provides an overview of the final design of the subsystem and Section 7.8. Finally, the limitations and recommendations are discussed in Section 7.9.

7.1. Design Baseline

The airship's power and propulsion system provides power to all the subsystems and propels the airship during flight. The baseline for the design of this subsystem is defined in the paragraphs below.

7.1.1. Design Goals

It is vital to clearly define the goals of the design as best as possible before the design starts. The main design goals for the power and propulsion subsystem are shown below:

- Determine thrust forces
- Estimate power consumption
- Size the power generation system
- Determine the size and position of the propulsion system
- Estimate mass of the subsystem

7.1.2. Requirements

The requirements for the power and propulsion subsystem are presented in Subsection 7.1.2. They are separated into power and propulsion requirements.

Table 7.1: *Sub-system Requirements*

Requirement ID	Description
REQ-POW-01	The system shall provide power from renewable sources
REQ-POW-02	The system shall provide power to all subsystems that require it during all phases of a mission
REQ-POW-03	The system shall provide enough energy storage such that the airship can operate for a full day (16 hours)
REQ-PRO-01	The system shall provide enough thrust to be able to cruise at 80 km/h when 75% of the total propulsion power is used
REQ-PRO-02	The system shall provide enough thrust to move upward with a speed of 2 m/s
REQ-PRO-03	The system shall provide enough lateral thrust to be able move at 5 m/s laterally

7.1.3. In- and Outputs

Since the power and propulsion subsystem needs to be integrated into a larger system, it is important to determine what the connections to other parts of the design are. The inputs and outputs of the design of the power and propulsion system are shown in Table 7.2 and Table 7.3 respectively.

Table 7.2: *Inputs for the power and propulsion subsystem and their origin.*

Input	Origin
Cruise Airspeed	Performance
Cruise Altitude	Performance
Drag Coefficient	Aerodynamics
Static Heaviness	Aerodynamics

Table 7.3: *Outputs for the power and propulsion subsystem and their destination.*

Output	Destination
Thrust Forces	Structures
Mass Estimates	*All*
Fuel Consumption	Operations
Propeller Positioning	Structures

7.1.4. Main Parameters

Aside from the inputs and outputs, there are other parameters that have a large impact on the design of the power and propulsion subsystem. These are primarily the efficiencies of the different components, specifically the fuel cells, electric motor, and propeller.

7.2. Thrust Force

In this section, the required thrust forces in each direction are calculated. For this analysis, the thrust force is considered to equal the drag force and it can be calculated using Equation 7.1:

$$T = D = \frac{1}{2} C_D \rho v^2 V^{\frac{2}{3}} \tag{7.1}$$

7.2.1. Longitudinal Thrust

In order to determine the thrust the drag force at the cruise and max speeds of the airship needs to be determined. These values can easily be calculated if the C_D is known. The method for determining the drag coefficient is described in Subsection 5.2.4. From this, the thrust forces at cruise and maximum velocity are respectively 25.1 kN and 34 kN.

7.2.2. Lateral Thrust

The amount of thrust needed in a lateral direction is a vital consideration for an airship due to the large force applied by wind (gusts) in this direction. REQ-PRO-03 states that the airship should be able to achieve a lateral airspeed of at least 5 m/s. The thrust required for this purpose could be determined from the drag force in this direction. The method of determining this drag force is explained in Subsection 5.2.5. The lateral drag value is provided in Table 5.5. The maximum lateral thrust is therefore 132.2 kN.

7.2.3. Upward Thrust

REQ-PRO-02 states that the airship should be able to move at 2 m/s vertically. In Table 5.5 the drag force is determined in a similar method as the lateral drag. After this, the static heaviness of the airship is added. The resulting force then equals the thrust, which is 30.6 kN. An overview of the different thrust forces is provided in Table 7.4.

7.3. Power Estimation

To size the fuel cell system an accurate estimation of the maximum power available is needed. The power required is calculated using Equation 7.2

$$P_r = Tv \tag{7.2}$$

The power required for the different directions is presented in together with the thrust forces. Table 7.4.

Table 7.4: *Thrust Forces and Power Required in Each Direction*

Direction	Thrust [kN]	Power Required [kW]
Longitudinal (Cruise)	25.1	558.3
Longitudinal (Max Power)	34	880.4
Lateral	132.2	660.8
Upward	30.6	61.2

From the results in Table 7.4 it is clear that the cruise case is the limiting case and is the one that should be considered for the maximum power required. Converting this power required to power available can be done using Equation 7.3

$$P_a = \frac{P_r}{\eta_{prop} \cdot \eta_{motor}} \tag{7.3}$$

This conversion gives the maximum power available for just the propulsion system as 880 kW.

This leaves the power for the other subsystems to be estimated. During the design process, it was found that for some subsystems there would be no specific power estimate during this phase of the design. However, a number is still needed to continue sizing the power subsystem. Therefore it was decided that this number is assumed to be similar to that which an APU provides for a conventional aircraft. As this is a very preliminary estimate a large margin was taken to make sure that the design would not be impacted negatively if the estimate turned out to be wrong. The APU of the Airbus A380 provides 100 kW to 120 kW of power[46]. The value to use for the other subsystems on board the airship was determined to be 200 kW. Power estimates for different components are provided in Table 7.5

Table 7.5: *Power estimates for propulsion system*

Component	Power [kW]
Propulsion (Max)	880
Other Subsystems	200
Total	**1080**

7.3.1. Electrical Diagram

In Figure 7.1 a simple electrical diagram of the airship is shown. It shows how the different parts of the airship's electrical system are connected. The motors and control surface actuators are connected to the AC bus, and other airship parts such as the avionics are connected to the DC bus. Connecting as many components as possible to the DC bus is advantageous because it avoids energy losses from the inverter.

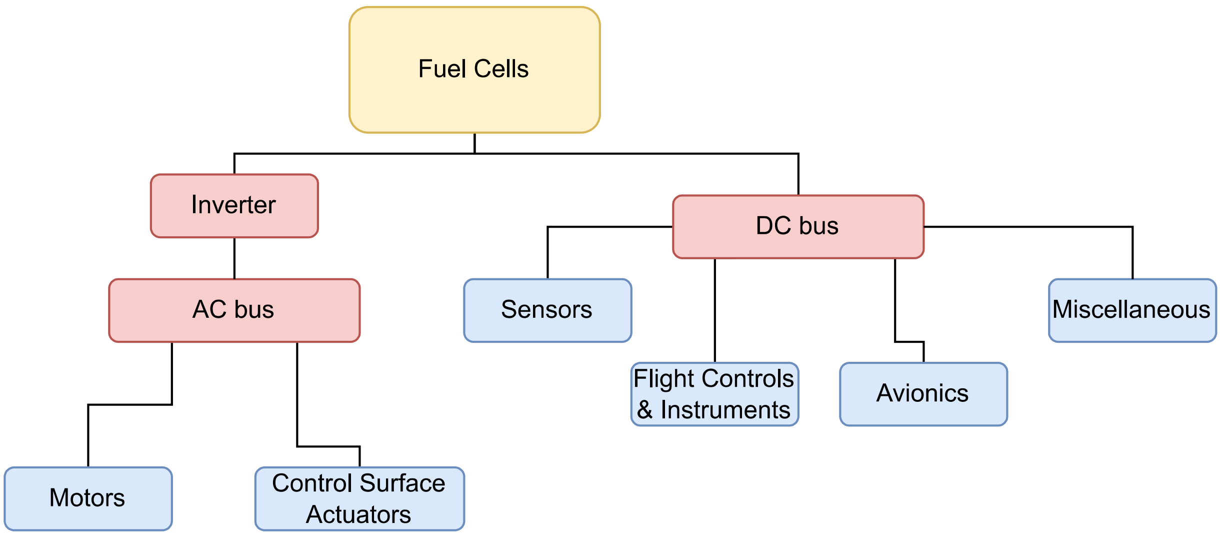
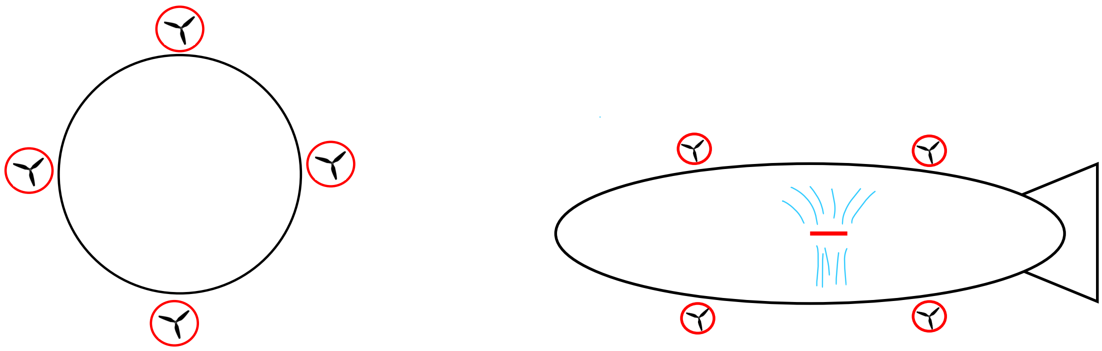


Figure 7.1: *Electrical Diagram of the Airship*

7.4. Propeller Placement & Design

For the ease of the control and stability analysis performed in Chapter 6, it was decided that the placement of the propellers should be symmetric about both the horizontal and vertical planes. Since the airship will need to provide a significant amount of thrust in several directions, solutions, where the propellers & motors could be rotated to be used in multiple directions, were preferred since this can save a large amount of mass. From these considerations, it was decided that some motors would be placed on the side of the airship and these would have the capability to provide both forward and upward thrust. Then some additional motors will be placed above and below the airship to have the capability to provide both longitudinal and lateral thrust.

The propeller needs enough clearance from the boundary layer over the side of the airship. For this reason, the hub of the propeller is placed (1 m + the radius of the propeller) away from the airship. The results from these considerations lead to the propeller placement seen in Figure 7.2.



(a) *Frontview of the propeller placement* **(b)** *Sideview of the propeller placement*

Figure 7.2: *Propeller Placement*

To find the size of the propellers two things were considered: the usual propeller loading and the maximum practical size for the propellers.

7.4.1. Propeller Loading

The process was started by obtaining the feasible propeller loading from literature, which stated that between 2 kN/m^2 and 6 kN/m^2 is a general range for propellers on airships [31]. From momentum theory, it can also be shown that the propeller loading should be minimized. For this reason, the starting point in this design process was chosen as 2 kN/m^2.

7.4.2. Propeller Size

The size of the propeller has a significant impact on the practicality of storing and landing the airship. Because some propellers will be positioned underneath the airship, their protrusion is limited. Therefore, it was decided that the propeller radius should not exceed 2 meters.

7.4.3. Propeller Efficiency

The propeller efficiency during cruise was estimated by calculating the advance ratio using Equation 7.4.

The advance ratio is a crucial parameter in propeller design as it reflects the relationship between the aircraft's airspeed and the rotational speed of the propeller blade, significantly impacting its efficiency.

$$J = \frac{v}{nD} \tag{7.4}$$

From this, a value of 0.89 was obtained from literature which also lies in the usual range of efficiencies of 0.7 to 0.9 [47, 48]. Since this value is on the high end of the range it should be investigated in more detail at a later phase of the design.

Another consideration is the speed of the propeller and the motor. Since many motors have a quite large minimum rpm of around 1000 - 1500 rpm[1], it was decided to add a gearbox to each motor. However, this has not yet been included in the efficiency calculations and should be included in further design stages.

7.5. Mass Estimation

The power and propulsion subsystems greatly contribute to the mass of the entire airship. For this reason, this mass is estimated to be used in the design of other subsystems and the iterations. The mass estimates for the most important parts of the system are described below. Other components such as pipes, cables, etc. are not estimated here and are part of the miscellaneous part of the mass budget.

To estimate the mass of the fuel cell a power density of 860 W/kg was used which is the current state-of-the-art value according to the US Department of Energy [49].

[1] `https://www.safran-group.com/products-services/engineustm` (Accessed on 13/06/2024)

The electric motor mass was estimated using the power density (peak) 4 kg/kW[1]. The mass of the gearbox is estimated as being similar to an automotive gearbox with approximately the same power[2].

To estimate the size and mass of the fuel tank the first step is to estimate the fuel required for a maximum duration flight. The fuel flow is calculated using Equation 7.5.

$$\dot{m}_f = \frac{P}{\text{LHV} \cdot \eta_{total}} \tag{7.5}$$

During cruise, the mass flow is 0.015 kg/s. The efficiency of the fuel cell was taken to be 0.6, obtained from literature [49]. Combining this with 14 hours of maximum flight time gives a total fuel mass of 756.3 kg.

The fuel tank mass was estimated by designing a simplified tank. The tank is assumed to be spherical and a safety factor of 2.35 is used which is required by EU regulations [50]. The hydrogen is not stored at cryogenic temperatures since the volume is not a limiting factor in this case. This also reduces the mass, as no insulation and other equipment related to cryogenic storage is needed. The materials in this analysis are not necessarily meant to be a final decision but are used to get a reasonable indication of the mass of the fuel tank.

The material chosen for this analysis is Carbon Fiber composite due to this being a common choice in pressure vessel design. Using a density of 1600 kg/m3 [51] and a maximum allowable strength of 800 MPa [51], final material weight of 6446.3 kg was obtained.

Table 7.6: *Mass estimates for propulsion system*

Component	Mass [kg]
Fuel Cell	1256.3
Electric Motors	3521.7
Gearbox	600
Fuel Tank	6446.3
Fuel	756.3
Total	**12 580.6**

This leads to the mass of the power and propulsion subsystem accounting for 5.8% of the MTOW of the airship. However, this is greatly influenced by several parameters such as the determined cruise speed. The precise effect of the cruise speed is seen in the sensitivity analysis performed in Chapter 12.

7.6. Cost Analysis

The propulsion system can be a significant portion of the total cost of an airship. Therefore it is important to estimate the costs of its components.

The fuel cell cost of 37.3€ per kW (converted from dollars) was obtained from literature by taking an average of the current fuel cell system price and the long-term price goal [49]. The price of electric motors was determined at 95€ per kW [52]. The price of the gearboxes was estimated at 3000€ per gearbox by looking at equivalent automotive gearboxes[3]. Lastly, the cost of the fuel tank was found using the Granta EduPack 2023 R2 [18]. An overview of the costs is presented in Table 7.7.

Table 7.7: *Cost estimates for propulsion system*

Component	Cost [k€]
Fuel Cell	40.3
Electric Motors	83.6
Gearbox	18
Fuel Tank	120
Total	**261.9**

It should be stated that this analysis is rather limited and does not take into account things such as production and transportation costs for most parts.

[2] `https://measuringly.com/weight-of-transmission/` (Accessed on 13/06/2024)
[3] `https://bowlertransmissions.com/collections/tremec-transmissions-1` (Accessed on 13/06/2024)

7.7. Overview

The system that provides power to the airship consists of hydrogen fuel cells. The propulsion system consists of 6 propellers placed in the positions outlined in Figure 7.2.

The propellers located on the side of the airship are also able to provide upward thrust and the propellers located on the top and underneath the airship can provide sideways thrust for low-speed operations. To provide a clear overview of the final state of the power and propulsion subsystem an overview of key parameters is provided in Table 7.8.

Component	Value
Maximum Power Consumption [kW]	1080
Propeller Efficiency [-]	0.89
Number of Propellers [-]	6

Table 7.8: *Main parameters of Power & Propulsion system*

7.8. Sensitivity Analysis on Efficiency

In this section, a sensitivity analysis concerning the total efficiency is performed. The efficiency was chosen as the most relevant parameter since the exact values are still relatively unsure and it is expected to have a large impact on the design of the subsystem.

Table 7.9: *Sensitivity analysis for Power Train Efficiency*

Change in efficiency	-50%	-25%	-10%	0%	10%	25%	50%
Fuel Consumption [kg/s]	100%	33%	11%	0%	-9%	-20%	-33%
Total System Mass [kg]	57%	19%	6%	0%	-5%	-11%	-19%

From the results of the sensitivity analysis presented in Table 7.9, it can be seen that the total efficiency has a large impact on both the mass of the system and the fuel consumption. Decreasing the total efficiency can considerably increase fuel consumption and the total system mass, and therefore, it is vital for this value to be as high as possible and optimized. The sensitivity analysis with respect to the main parameters of the system is performed in Chapter 12.

7.9. Limitations and Recommendations

For this analysis, it is important to keep in mind what the limitations of the applied method are and how it could be improved in the future. The most important limitations and recommendations are listed below.

- Improving the accuracy of the power estimation
- Choosing specific components to increase the accuracy of both mass and power estimation
- Including more parts of the subsystem into the design for better accuracy
- Add additional upward thrusting propellers for better pitch control at low speed
- Account for the efficiencies not being constant for different power levels.

8
Structures & Materials

To satisfy the mission goals and support the load safely and efficiently, the internal structure of the airship must be designed. Within a rigid airship, this internal structure constitutes a significant portion of the system and forms a basis for the placement of the subsystems along the ship's length. The structural design has to be performed in parallel with the material and manufacturing process selections, and therefore, all these aspects will be considered in this chapter.

8.1. Design Baseline

The design of the structure of the airship is guided by a set of goals, originating from high-level, mission, system, and subsystem requirements. To ensure that the objectives of the overall systems are met, the guiding principles and requirements should be defined comprehensively before the start of the design. Additionally, the inputs and outputs of the design process should be determined to keep track of the project scope.

8.1.1. Design Goals

To ensure that the objectives for the structural system design are clear and realistic, a set of design goals was determined prior to the start of technical analysis. These goals will guide the subsystem design and are defined as follows:

1. Analyze the loads on the airship during mooring and flight
2. Design frame
    - Design and size the longerons
    - Design and size the support rings
    - Select the envelope material
3. Design payload fairing
    - Determine payload bay configuration
    - Size the payload bay
4. Design attachment points for all relevant sub-systems (propulsion, tails, etc) (Propulsion. Tail)
    - Design attachment points for the propulsion subsystem
    - Design attachment points for the tails
    - Design attachment points for the permanent ballast
5. Select the materials for the structural components
    - Select the material for the airship frame
    - Select the material for the airship envelope
    - Select the material for the gas cells
6. Analyze the manufacturing techniques for the structural components
7. Create CAD model with internal layout and structure

8.1.2. Requirements

The design of the structure of the airship is guided by requirements set by the mission objectives, as well as certain regulations. A set of well-defined requirements for the structural design is vital for ensuring the satisfaction of stakeholder needs, as well as the safety of the airship. The system requirements guiding the airship design are given in Table 8.1. These are top-level requirements that will guide decisions about the general layout of the structure.

Table 8.1: *System Requirements Relevant for the Structural Design*

ID	Requirement	Implication
REQ-SYS-GE-02	The system shall be capable of loading and unloading without landing.	The payload bay must be adjusted to allow for (un)loading from the air; the rest of the structure must be adjusted accordingly.
REQ-SYS-GEN-03	The system shall contain mooring interfaces.	The airship structure must make accommodations for the attachment of mooring interfaces.
REQ-SYS-GEN-06	The surface of the airship shall be capable of visual surface changes.	The material of the envelope must allow for visual changes.
REQ-SYS-PAY-01	The system shall be able to transport a payload of 60,000 kg.	The payload bay and the structure of the airship must support a 60 tonne load.
REQ-SYS-PAY-02	The system shall transport a payload with a length of at least 105 m.	The payload bay and the structure of the airship must support a 105 m payload.
REQ-SYS-PAY-03	The system shall not cause damage to the payload.	The payload bay must support the payload safely.
REQ-SYS-REG-03	The system shall comply with EASA requirements for the given aircraft category.	The structural design must comply with EASA regulations.
REQ-SYS-SUS-03	At least 80% of the system components shall be made out of recyclable materials.	The structure must be designed using predominantly recyclable materials.
REQ-SYS-SUS-04	The system shall use no more than 50 kg of critical minerals.	The use of critical minerals within the design must be strictly monitored.
REQ-SYS-MIS-10	The system shall operate in wind speeds of at least 10 m/s.	The airframe will need to be designed to take bending loads due to wind gusts

The above-mentioned requirements influence the overall structural design to a large extent on the high level, i.e. they will set a baseline for what should be included in the design. Throughout the design, higher-level stakeholder and user requirements will also be consulted to ensure a driven design. The more specific design objectives and limitations are defined by the subsystem requirements for the payload and structural subsystem. It can be said that the payload bay is part of the wider structures subsystem and therefore, its design and requirements will be treated as part of the overall structural design. The subsystem requirements are defined in Table 8.2.

Table 8.2: *Subsystem Requirements Relevant for the Structural Design*

ID	Requirement
REQ-STR-01	The subsystem shall have load path redundancy
REQ-STR-02	The subsystem components shall have a safety factor of at least 1.5

8.1.3. In- and Outputs

With the subsystem requirements defined, the limitations and objectives of the design are set. Next, the inputs and outputs of the structural analysis have to be introduced. They are shown in Table 8.3 and Table 8.4 respectively and will be discussed more extensively in Section 8.2. For inputs originating from other subsystems, the origin was specified.

Table 8.3: *Inputs of the structures subsystem and material selection.*

Inputs
Weight (Class I and II):
• Subsystem Weights (All Subsystems)
• Structure Weight
• Payload Weight
Airship Geometry:
• Airship Length
• Airship Shape (Aerodynamics)
• Wetter Area (Aerodynamics)
• Payload Bay Dimensions
External Loads:
• Drag (Aerodynamics)
• Distributed Weight
• Buoyancy (Aerostatics)
• Engine Loads (Propulsion)
• Tail Loads (Stability and Control)
Internal Point Loads:
• Payload Attachment
• Ballast Attachment (Operations)
• Engine Attachment (Propulsion)
Gas Cell Parameters (for material choice):
• Gas Cell Area (Aerostatics)
• Maximum Allowed Overpressure

Table 8.4: *Outputs of the structures subsystem and material selection.*

Outputs
Weight (Class III):
• Updated Structure Weight
Internal Geometry:
• Longeron Sizing and Positioning
• Ring Sizing and Positioning
Global Failure Mode Calculations:
• Bending (from wind gust)
• Bending (from buoyancy-weight imbalance)
• Shear and Torsion Failure
• Local Longeron Failure
• Longeron Buckling
Local Failure Mode Calculations:
• Local Bending (from point loads)
• Local Shear Failure (from point loads)
• Local Buckling
Material Choices:
• Truss Material
• Gas Bag Material
• Envelope Material

8.1.4. Main Parameters

Within the structural design of the airship, with known dimensions and shape, the main parameters are the cross-sections of structural components. These comprise of the cross-sectional areas and the second moments of inertia of the longerons and rings, which will then give a basis for the design of the cross-section geometry. Within the cross-section, the critical dimensions to be found will be the width of the truss boxes, as well as, the inner and outer diameters of truss box chords. The critical parameters of the design are also the number of longerons and the placement of rings throughout the structure. These parameters will be determined based on the required performance for carrying the design loads.

For the choice of materials within the design, the required parameters will be the function of a given part, the objectives to be achieved during its design (ie. minimum mass), and the constraints within the design (ie. fatigue strength limit).

8.2. Internal Structure Design

With the requirements, inputs, outputs, and main parameters now defined, the design of the airship structure can commence. In this section, the designing approach will be introduced and followed by a step-wise description of the design process.

8.2.1. Structural Breakdown and Design Approach

To facilitate the design process, the airship structure can be broken down into several main components. A rigid airship consists of a frame and an envelope, where the envelope is non-load carrying. Within the frame of the airship, the main structural components are the longerons and rings, which support the loads acting on the vehicle. A view of the internal structure of an airship is shown in Figure 8.1. While some parallels can be drawn with the construction of an aircraft fuselage, the lack of a load-bearing skin changes the analysis method significantly. However, in parallel with a fuselage, it can be assumed that the longerons carry primarily the longitudinal bending moments within the ship, while the rings will support the point loads applied to the structure. These point loads will come from frames and attachments within the structure and will include the weight of the payload.

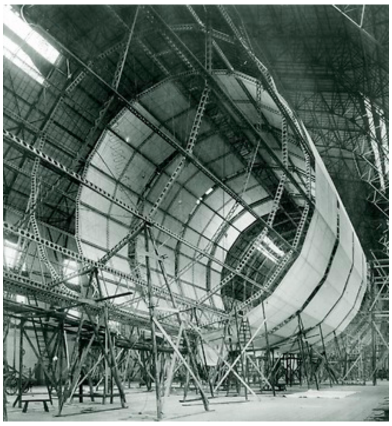


Figure 8.1: *Airship Frame Assembly* [1]

[1] https://airandspace.si.edu/multimedia-gallery/2000-1382wk-sjpg, accessed 25-06-2024

The structural design of the airship will therefore comprise primarily of the design of the longerons and rings. Here, the design of the rings will be largely affected by the design of the payload bay, since the rings must support the entire weight of the payload. Therefore, the structural design will be conducted in two steps, so that a preliminary structure is obtained first, before including the design of the payload bay in the calculations. This will also follow from a choice of the payload bay layout and the inclusion of the internal point loads. A schematic of the airship's structural design process is shown in Figure 8.2.

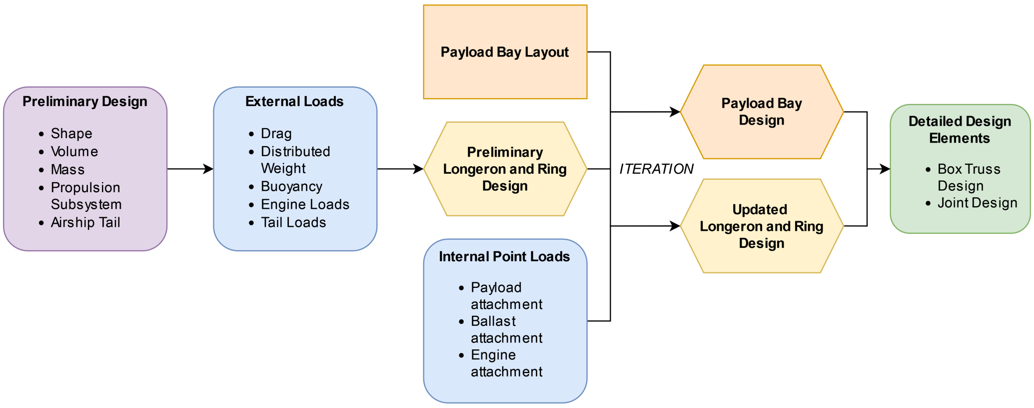


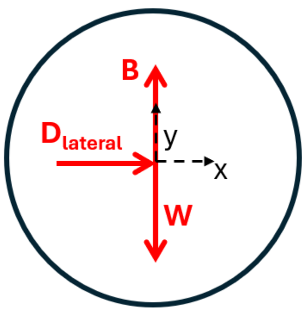
Figure 8.2: *Structural Design Approach*

As seen above, a bottom-up approach was chosen for the design of the structure. This approach aims to iterate on the design sequentially, going further into detail step-by-step and finishing with a detailed design of the structural elements. To comply with REQ-STR-02, the design will use a safety factor of 1.5 throughout.

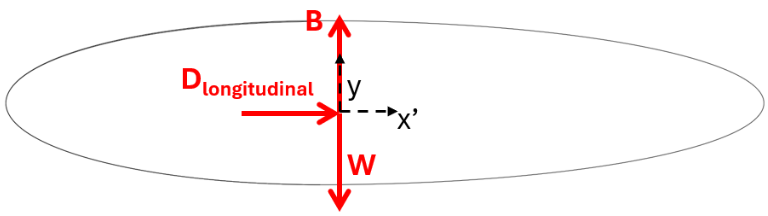
8.2.2. Design Loads

To design the airship structure for all conditions it will experience throughout its lifetime, the loads it experiences have to be thoroughly analyzed. While aircraft are commonly designed with flight load factors exceeding 2 in mind, the airship does not experience such loads; for a nearly perfectly buoyant airship, the load factors are always close to 1. In airship design, the flight loads are not the limiting factors for the structure, and the structure is primarily designed to sustain the bending loads the airship experiences due to wind-gust-induced loads, as specified by REQ-SYS-MIS-10.

In addition to the wind gusts, which can be analyzed as the lateral drag on the airship under specified wind conditions, the airship will experience longitudinal drag during flight, both of which will be obtained from the aerodynamic analysis of the airship. It'll also be subjected to its own buoyancy and weight. In addition, it will experience loads due to the engine use and the tail deflections. Free body diagrams of the airship are shown in Figure 8.3. Point loads, or loads applied on only part of the structure, such as tail loads, are not shown of the diagrams.



(a) *Free Body Diagram along the Airship Cross-section*



(b) *Free Body Diagram along the Airship Length*

Figure 8.3: *Free Body Diagrams of the Airship (B = Buoyancy Force, W = Weight, D = Drag)*

8.2.3. Initial Sizing of Longerons

Prior to starting the design of the longerons and ring, the airship frame material was chosen to be Aluminum 6061 T6 (AA6061-T6). The reasoning behind this material choice is presented in Section 8.5. For the initial design, the longerons and rings were assumed to be made out of box trusses, with four point masses across the cross-section. A box truss was chosen due to its particular feasibility for a large airship structure. A box truss can ensure enough resistance to bending of the structure and can be highly optimized.

For the design of the longerons, five principal modes of loading were considered and assigned a corresponding failure mode:

- Bending due to wind gust loads - failure (yield) due to a compressive or tensile stress from bending
- Bending due to a buoyancy-weight imbalance - failure (yield) due to a compressive or tensile stress from bending
- Local bending - failure (yield) due to a local bending moment applied on longeron segment due to a wind gust
- Shear and torsion - failure (yield) due to the shear stresses resulting from shear forces and torques
- Compression - buckling or failure due to yield

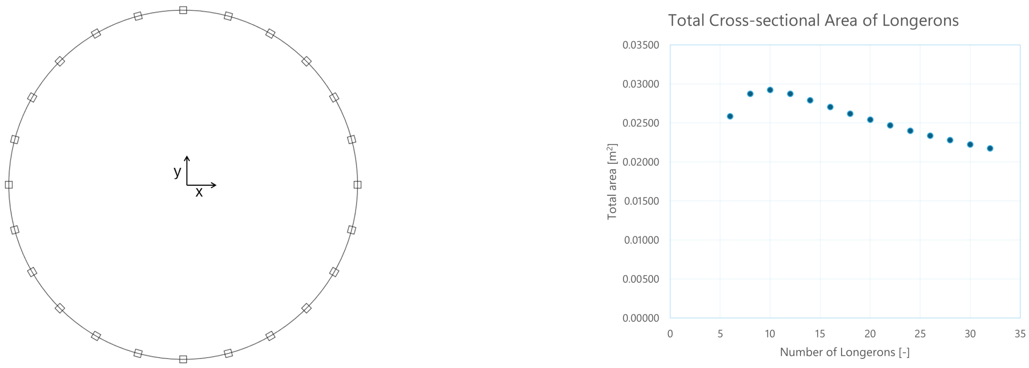
It is important to note that the loads from bending and axial (compressive) loads will be coupled and therefore should be considered jointly.

To begin the sizing of the longerons, the cross-section of the longerons within the structure was approximated as a set of point areas within a circular cross-section. This is shown in Figure 8.4a. The areas of all longerons were assumed to be the same due to the bi-axial loading of the structure.

The choice of the number of longerons is based primarily on the mass of the options. Since bending is considered the primary loading mode of the structure, there will be a required second moment of area of the cross-section based on a given bending moment at a cross-section with a defined radius. For a point-mass simplification of a structure, a relation between the total area of the cross-section A and the second moment of area I_{xx} about the x-axis can be derived:

$$I_{xx} = A \cdot \sum_{i=0}^{n} y_i^2 \tag{8.1}$$

where n is the number of longerons and y represents the distance of a point area from the x-axis. For n divisible by 4, the second moment of area about the y-axis, I_{yy} is equal to I_{xx}. Based on the relation given in Equation 8.1, and a known geometrical dependency between the y^2 and the number of longerons, the total required cross-sectional area of the longerons versus the number of longerons was plotted in Figure 8.4b.



(a) *Longerons Cross-section Approximation* **(b)** *Cross-sectional Area for a Number of Longerons*

Figure 8.4: *Longeron Cross-section Dependencies*

Figure 8.4b can be used to trade-off the number of longerons and the manufacturability of the structure. While both the lowest and the highest numbers yield low total areas, their choice would prove difficult to manufacture and pose additional problems within the airship design. Additionally, a too-high or a too-low number of longerons might make the assumption of bending being the primary mode of loading no longer valid. Therefore, based on the mass and feasibility trade-off, the preliminary number of longerons was chosen to be 20. This choice was also made after investigating previous airship designs to find an optimum. This number, however, is highly arbitrary and will be subject to change.

For failure mode calculations, longerons within the airship were separated into segments spanning about 1% of the structure each, for which the minimum required area was determine. This area is that required to withstand the critical failure mode with a safety factor of 1.5 (REQ-STR-02). For the bending, shear, and torsion calculations, the entire airship cross-section was considered, while for local bending, a box truss cross-section was taken and assumed to be subjected to a bending moment resulting from a point force (wind gust) in the middle of a section. The critical modes of failure for different sections of the airship are shown in Table 8.5.

Location [m]	Failure Mode
0 to 20	Yield due to local bending (due to wind gust) and compressive loads
20 to 32	Yield due to vertical bending moment (from weight-buoyancy imbalance)
32 to 64	Yield due to local bending (due to wind gust) and compressive loads
64 to 152	Yield due to vertical bending moment (from weight-buoyancy imbalance)
152 to 164	Yield due to local bending (due to wind gust) and compressive loads
164 to 168	Yield due to vertical bending moment (from weight-buoyancy imbalance)
168 to 220	Yield due to local bending (due to wind gust) and compressive loads

Table 8.5: *Principal Failure Modes of the Longerons*

It is evident that the primary failure mode of the structure results from the bending moments generated by wind gusts and the uneven distribution of the weight within the airship. The results shown in Table 8.5 correspond to the conditions experienced by the airship: local bending dominates at the nose due to the low local diameter there. This is followed by a vertical-bending-dominated region, due to the local high difference between the lift generated and the weight of the structure. Local bending dominates the next section, up to the payload bay, due to the higher airship diameter and therefore higher local lateral drag. The payload bay section is dominated by vertical bending due to the high mass distributed along its length. Finally, the principal failure mode goes back to being the local bending, with a section of vertical bending at the engine attachment point. It is important to note that, while the tail attachment imposes a significant load on the structure, the critical bending load at the aft end of the airship is not changed.

With the minimum required areas determined, the total volume of the longeron material was determined. This was translated into a **total longeron mass of 26.08 tonnes**. It should be noted that the mass estimate is based on a continuously changing cross-sectional area, whereas this area will be stepped in the actual design due to manufacturing constraints.

8.2.4. Initial Sizing of Rings

Once the longerons have been preliminarily sized, the rings can be sized to ensure that point loads within the structure can be carried. The rings also ensure structural integrity within the structure and provide load transfer interfaces. To start the design, the rings were preliminarily placed at critical points within the structure. The number of rings chosen was based on the number of gas cells used within the airship, as is commonly done in rigid airship design. Since the airship contains 16 gas cells, as determined for the aerostatics subsystem, 18 rings were chosen to provide redundancy at the front and the back of the airship, where the cockpit and the tails are positioned respectively. The rings were initially spaced equally but later changed to accommodate the high loads on the tail. The rings were therefore placed every 13 meters until the 180-meter mark, after which they were placed every 10 meters. This spacing will be iterated upon during the payload bay design.

For the calculation of the critical cross-sectional area, the same loads as considered for the longerons were used. After a consultation with Dr. ing. Saullo Castro, the assumption was made here that the load distributed to the rings within a section is proportional to the length of the ring section adjacent to where the load acts, i.e. $L_{element,ring}/L_{perimeter}$ of the load within the element is transferred to the ring. The sections are shown in Figure 8.5 for an envelope element. It should be noted that this assumption was not used in the design of the longerons, since the rings were not placed at that point; this will be iterated upon.

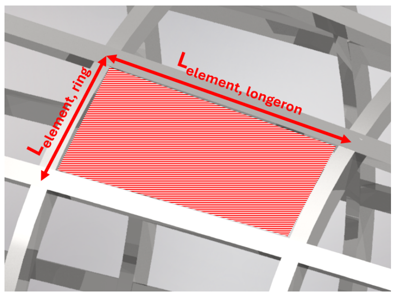
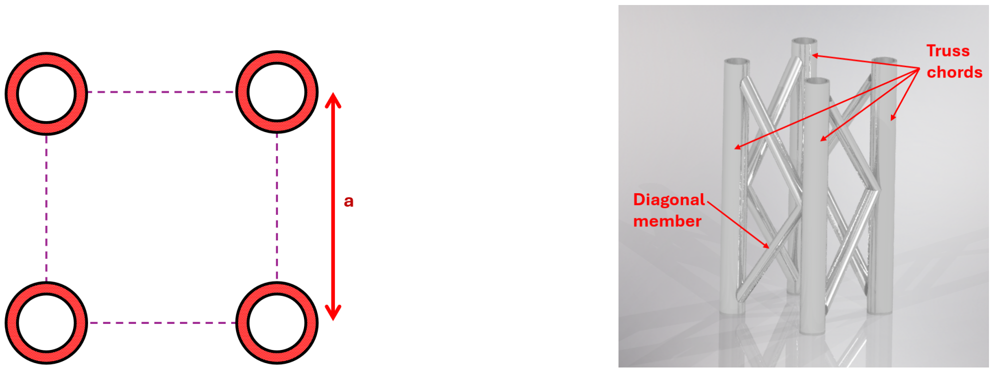


Figure 8.5: *Sections within an Element on which a Load Acts*

Due to the bending moments present within the structure, the critical area for the design of rings is the cross-sectional area of a box truss, as shaded in red in Figure 8.6a. For representative purposes, an example of a truss box is shown in Figure 8.6b. The second moment of inertia of such a section will be related to the cross-section area, such that $I_{xx} = A_{red} \cdot \left(\frac{a}{2}\right)^2$ when truss chord cross-sections are considered to be point masses. The second area to be considered is the total cross-sectional area of the ring in the local coordinate system defined in Figure 8.4a. This cross-section will be significant for carrying the shear forces within the frame and will predominantly determine the sizing of the diagonal beams within the box truss.



(a) *Cross-section of a Box Truss* **(b)** *Truss Box Components*

Figure 8.6: *Truss Box Structure*

Within the first design of the rings, the vertical (due to buoyancy-weight imbalance) and horizontal (due to wind gusts) bending was critical for determining the cross-sectional area. As expected, the rings positioned at the payload and tail sections fail due to vertical bending, while all other rings fail due to bending from the wind gusts. Local bending from point loads was not considered at this point and will be discussed in Section 8.3 when the payload bay is designed. Based on the minimum cross-sectional areas determined for each ring, the mass of the **preliminary ring design was calculated to be 28.47 tonnes**.

8.2.5. Summary of the Preliminary Longeron and Ring Design

With the preliminary design of the longerons and rings concluded, a mass estimate of the airship frame can be given. The **total mass of the longerons and rings** was therefore calculated as **54.55 tonnes**.

The completion of the preliminary frame design coincided with the global iteration of the system design as described in Subsection 3.5.2. To ensure that the mass of the airship can be adapted with the possibility of implementing further changes to the design, a 33% contingency margin was placed on the structural mass of the airship prior to the iteration. Therefore, the **total mass of the frame** was estimated to be 72.55 tonnes. After the conducted iteration, this was brought down to **62.46 tonnes** for the structures subsystem, which translates to **19.88 tonnes for the longerons**, **27.08 tonnes for the rings**, and a 15.5-tonne contingency margin.

8.3. Payload Bay Design

Within this section, the payload bay design and the frame design iteration will be described. The concepts considered for the payload bay layout will be first presented, followed by the sizing of the payload bay. Finally, the changes in the design will be described.

8.3.1. Payload Bay Concepts

To start the payload bay design, several concepts for it were proposed. The design of an internal payload bay within a cargo airship is quite a complicated problem, amplified by the required ability to (un)load the payload from the air. The main difficulty in designing such a structure is the fact that an internal bay requires the structure of the airship to be able to open and therefore disturb its integrity. To combat this, two main options were considered: an internal payload bay within the circular cross-section, with a hatch opening in the rings (Figure 8.7a), and a payload bay outside of the main frame, but within the airship envelope (Figure 8.7b).

(a) *Concept 1: Integral Payload Bay with a Hatch Opening* **(b)** *Concept 2: Semi-closed Payload Bay*

Figure 8.7: *Payload Bay Concepts*

After analyzing the available options and consulting with Dr. ing. Saullo Castro, the second option, as shown in Figure 8.7b was chosen for the payload bay. This was done due to the fact that the opening of an alternative hatch would weaken the structure of the airship to an unacceptable extent while (un)loading the payload.

Another aspect of the conceptual design of the payload bay is the way of mounting the payload within the airship. Since there is no support structure under the payload, it will have to hang within the airship, supported by clamps to constrain lateral and longitudinal movement. This could be done either by either having fixed support points on specified rings, which would support the cables from which the payload would hang or by having movable support points within the airship. Since the airship should be able to accommodate different lengths of wind turbine blades, as well as, possibly, other payloads, it was decided that a movable set of payload supports shall be used. As such, a rail system was proposed to allow for the adjustment of attachment positioning. Within this system, the payload cable spools can be moved along the length of the payload bay, as long as the resulting center of gravity does not compromise the stability and controllability of the airship.

It was decided that to constrain the turbine blade as much as possible, while not adding too much additional weight to the structure, the blade would be clamped at two points: at the root of the blade and a specific location along the blade. These clamps would then be attached through cables to the rails placed within the airship. The location of the two clamps on the turbine blade depends on its center of gravity. For sizing purposes, this c.g. was estimated for a typical wind turbine blade based on a known linear mass distribution along its length. It was determined that an approximate location of the wind turbine blade c.g. lies at approximately 23% of its length [53]. If then half of the weight is to be distributed to each of the clamps, one clamp would lie at the root of the blade, with the other at 46% of the length. With this distribution, a third clamp could be added to constrain the deflection of the blade tip in transport.

8.3.2. Payload Bay Placement and Sizing

With the initial layout of the payload bay chosen, the sizing of it can be conducted. Firstly, the stakeholder requirement specifying the payload dimensions to be 105x12x10 meters (REQ-ST-MAN-04) was considered. The desired size of the payload bay was derived from this requirement, with clearances applied on all sides. A clearance of 1 meter on each side was applied to the payload in the vertical and lateral direction, while the longitudinal clearance was chosen to be 2.5 meters. This yields the payload bay dimensions of 110x14x12 meters. The clearance distances were chosen to accommodate the displacement of the payload during loading and flight, with a higher clearance in the longitudinal direction, where less control is achieved.

With the payload bay dimensions decided, the payload bay can be positioned longitudinally and vertically. The lateral positioning of the payload is assumed to be in the middle, to ensure symmetry of the cross-section. The longitudinal and vertical positioning is constrained by the shape of the airship envelope, which is not flat at the bottom. As it is desired to minimize the volume of the structure in favor of maximizing the volume of the lifting gas, the positioning of the payload will be conducted, such that non-functional volume is minimized. An optimal positioning of the payload bay is shown in Figure 8.8.

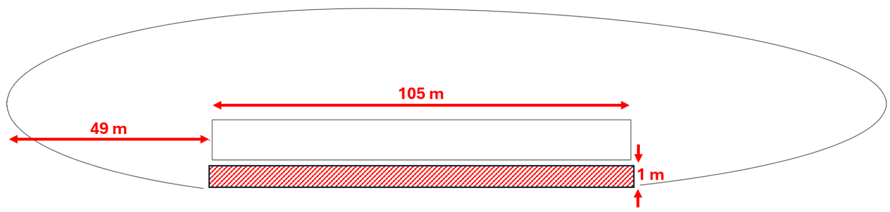


Figure 8.8: *Positioning of the Payload*

The red, striped pattern denotes the empty space below the payload bay. This space is minimized while still providing the 1-meter clearance at the most narrow diameter within the bay. The payload bay is positioned between 49 and 159 meters from the nose of the airship and its top point is displaced 7 meters from the center point of the airship's cross-section.

With the payload positioning determined, the bay dimensions can be set. As shown in Figure 8.9, the payload bay is restricted by the bay width and the angle of the diagonal beams. This angle was taken to be 45° to the horizontal, or 90° from the center of the cross-section to ensure optimal load transfer to the half circle. With the 45° layout the lateral clearance within the payload bay is large and can be used to accommodate the ballast.

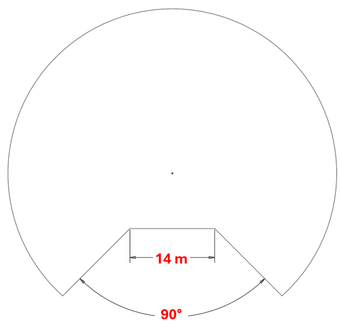


Figure 8.9: *Payload Bay Cross-section Design*

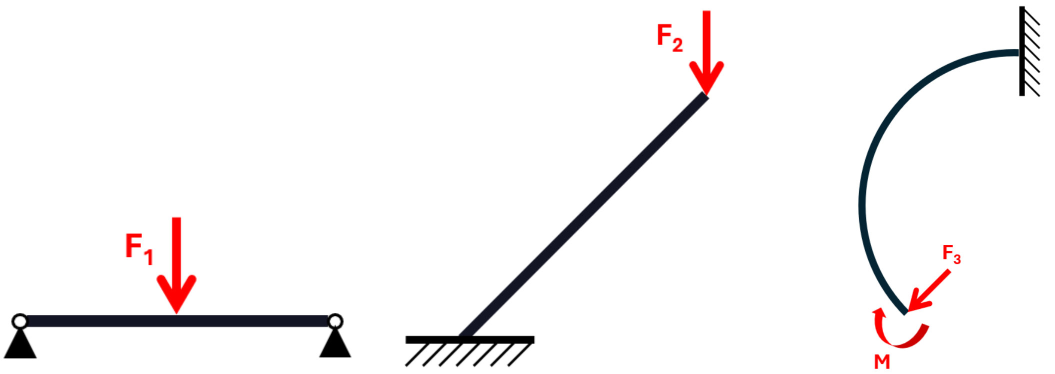
To support the load placed on the horizontal beam within the structure, the horizontal section will be connected to the ring perimeter using cables. This way, the load can be distributed evenly throughout the ring and can allow for a more optimized structure. The design of these cables constitutes a statically indeterminate problem, but at least half of the point load should be redistributed to the cables during nominal flight. The limiting case for the cable placement and design is the maximum roll angle during flight.

8.3.3. Updated Longeron and Ring Sizing

The design of the semi-open payload bay has significant implications for the design of the airship's longerons and rings. Firstly, it will require a significant length of the longerons to be removed from the cross-section, which will decrease the second moment of inertia of the longeron assembly and might cause asymmetric effects under lateral loads. While these effects were neglected in the design of the current structure, with an assumed unchanged second moment of inertia I_{yy} around the vertical axis, the I_{xx} of the structure will noticeably decrease. To account for this change, the required total area of the cross-section was recalculated based on a new value of $\sum_{i=0}^{n} y_i^2$ (see Equation 8.1). Parallel to this, the number of longerons was increased to 24 to minimize the impact of removing the most displaced point masses. The effective change in mass resulting from these modifications constituted less than 2% of the total longeron mass and was deemed insignificant due to the local bending being the dominant failure mode for the longerons. The 2% difference can be neglected, as similar accepted discrepancies might result from the assumptions taken within the design.

The iteration of the design of the rings requires a more detailed analytical approach. As a point load is applied in the middle of the structure, the ring will experience significant bending moments and stresses throughout the cross-section. For the calculations, the point load was assumed to be at the center of the horizontal beam in the payload bay. The payload weight was assumed to be distributed evenly between the ten rings along its span, yielding a magnitude of the point load of about 60 kN after including the safety factor of 1.5 and a 50% load distribution between the beam and the cables.

The applied load causes bending stresses throughout the structure. To analyze this loading and determine the optimal cross-sectional areas of the beams, the payload bay rings were split into three cross-sections, as shown in Figure 8.10.



(a) *Horizontal Beam Loading* **(b)** *Diagonal Beam Loading* **(c)** *Curved Beam Loading*

Figure 8.10: *Loading of Payload Bay Cross-section Elements*

The horizontal beam subjected to bending is assumed to be pinned at the ends (Figure 8.10a). This assumption was made to allow the beam to displace once the load is applied, due to twisting at the pinned ends. Were this not the case, excessive stresses would be induced at the joints, due to a high and complex loading. Note that the beam is supported by cables from the top of the cross-section, which will be effective once in tension.

The diagonal beams are assumed to be clamped at the lower end, with the vertical load transferred from the horizontal section (Figure 8.10b). Note that no moment is transferred, due to the pinned supports of the horizontal beam. The diagonal beams are subject to a coupled bending moment and normal compressive stresses.

For the analysis of the circular part of the cross-section, the circular beam is discretized into nine connected straight beams at a gradually varying angle to the horizontal. The nine-beam discretization corresponds to the actual design of the rings, wherein the rings comprise straight beam sections connected at the longerons. The load and resulting moments are transferred across every beam, as each beam is assumed to be clamped at one end, with the load transferred from the adjacent element applied at the other end (Figure 8.10c). The discretization of the circular cross-section allows for the iterative calculation of the load on each beam, as well as the calculation of the required cross-sectional areas for all payload bay rings.

A similar sectioned approach is taken for the loads applied within the cables at the top of the cross-section, as well as the engine attachment loads, and the loads originating from the cable attachments during mooring. The stresses from those loadings were combined and a total required area was calculated from them. This calculation yields a total mass of the payload bay rings of 30.31 tonnes (from 22.08 tonnes) and a **total mass of 35.31 tonnes of the rings** (from 27.08 tonnes). This yields a **total structural mass of 55.19 tonnes**. With this, the iteration is complete. The design of the clamped joints, payload bay rail and the truss boxes will be discussed in Section 8.4.

8.4. Detailed Structural Analysis

After the dimensions of the longerons and rings have been determined, the detailed design and analysis of critical design points can be conducted. Due to the size and weight of the structure, the degree of detail possible for an in-depth analysis is limited due to limited resources and testing possibilities. However, a discussion of the most important aspects of the design is included in this section and comprises joint design, truss box design, as well as the design of the payload bay beams.

8.4.1. Joint Design

Due to the large size of the airship, as well as manufacturing constraints, the airship will be required to contain joints along its structure. The major joints within the design will be: joints connecting the longeron sections, joints connecting the ring elements, corner joints within the payload bay, and connections between the longerons and rings. As the structural design of the airship is subject to several critical assumptions and requires additional computational analysis (such as FEM) to achieve certain results, the methodology for joint design, along with the applicable loads acting on them will be discussed, without a detailed joint sizing. This way, once a more detailed structural analysis is available, the design process can be conducted straight away.

A typical way of connecting box trusses in series is using pins and conical connectors between truss sections. The conical connectors must be designed to withstand local stresses due to bending moments applied to the structure. Such connectors will be made out of the truss material and will sit flush inside the truss box chords.

Figure 8.11: *Truss Box Connection Using Conical Connectors and Pins* [2]

An exploded view of such a connection method is shown in Figure 8.11 Sizing the connectors based on the truss chord diameter will provide a margin for a safe structural design since the total cross-sectional area of the pins will most likely be larger than the cross-sectional area of the box truss along its length. Another consideration for the design of the connections are the stresses experienced due to a circular hole through which a pin should be connected. To withstand these stresses, the end of the truss chord will have to be reinforced to withstand the normal stresses within the structure with a stress concentration factor of 3 for a circular cutout. The chords must have a safety factor of at least 1.5 for bearing failure, shear-out failure, and net shear failure. The pins locking the conical connectors to the structure must also be designed to not fail in shear.

To connect the ring sections, custom connectors will have to be created. Such connectors would typically be either angled conical connectors, or reinforced angled truss box sections (shown in Figure 8.12). For both of these options, the design of the connections can be determined using methods parallel to the previously mentioned conical connector and truss box bending calculations.

Figure 8.12: *Angled Truss Box Connector* [3]

For ring to longeron connections, custom connection mechanisms will be used to connect the parts together. The connector will consist of a plate section bolted to the respective ring and longeron elements, such that a rigid connection is formed between them. An alternative connection method would entail welding the parts together; however, this way the parts are not replaceable in case of failure, and additional thermal stresses are introduced into the structure.

Payload Bay Joint Design

[2] `https://shop.h-of.de/en/event-technology/truss-systems/hofkon-conical-connectors/` (Accessed on: 20/06/2024)

[3] `https://www.proxdirect.com/products/view/12-Degree-F34-Square-Truss-Angle-Connector-2mm-Wall-XT-SQ12D` (Accessed on: 20/06/2024)

During the payload bay design, two critical joints were identified within the structure, as shown in Figure 8.13. Joint 1 will need to transfer the high loads from the horizontal payload bay beam to the diagonal beams connected to the ring section. This load will be equal to 30 kN, and will induce high shear stresses within the pinned joint. No moments should be transferred through the joint, or should be limited to those resulting from friction around the pin. To make joint 1, custom connection plates will be made and mounted to the adjacent beams.

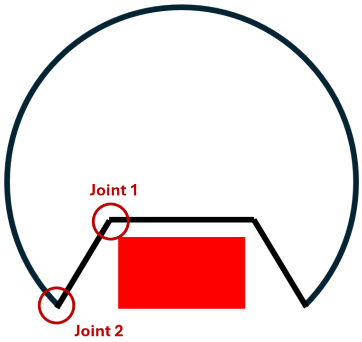


Figure 8.13: *Critical Joint Locations*

The design of joint 2 is more critical, due to the high moment applied on it, as well as high shear and normal forces. The moment joint 2 experiences reaches 421 kNm for the payload bay section with the largest diameter. The joint is assumed to be fixed and therefore will need to take both the moment and the forces acting upon it. To sustain this load, the connection point between the diagonal and circular beams will have to consist of four solid circular elements of diameter of 0.15 meters each. This means that if the joint section is 1 meter long on each side of the joint (along the diagonal and circular beams), the total joint mass would be in excess of 0.4 tonnes. Due to the multitude of assumptions taken within the design of the payload bay, no further design will be conducted at this point, as the structure is not sufficiently developed to take into account all aspects of the loading. The detailed design can be made once a computational model of the structure is available.

8.4.2. Truss Box Design

In previous sections, the sizing of the longerons and rings was discussed, with a strong emphasis on sequential and iterative design. The sizing of the longerons entailed the sizing of the cross-section of the truss boxes. With the individual point areas known, the inner and outer diameters of each truss chord can be determined. As the design of the trusses is limited by bending and therefore the tensile and compressive stresses introduced, the limiting factor in the design is the cross-sectional area of the truss, as well as the length of straight chord elements. The chord elements, being columns in compression, will be subject to buckling.

With the cross-sectional area of the trusses determined, the diagonal elements within the truss can be placed. The spacing, as shown in Figure 8.14 will be based on the critical length of each element based on the Euler buckling relation. Therefore, it can be said, that in the final design, the length between the diagonal members will be:

$$d_{truss} = \left(\frac{\pi^2 EI}{P}\right)^{0.5} \tag{8.2}$$

where the critical load P will be the maximum compressive load within the structure, E is the Young's modulus of the truss material, and I is the second moment of area of the cross-section.

In addition to determining the spacing between diagonal elements within the truss box, those elements should be sized such that they do not fail in shear from torques applied on the airship rings. The cross-sectional area required for the diagonal beams was one of the outputs of the calculations in Subsection 8.2.4.

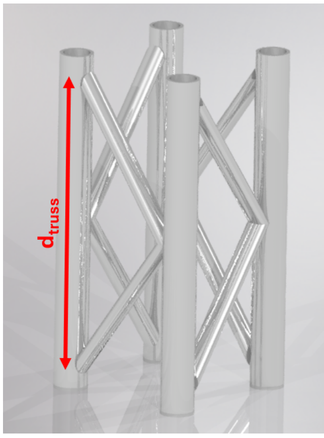


Figure 8.14: *Truss Box Design Dimensions*

8.4.3. Payload Rail Design

The design of the payload bay specified the use of a payload rail for supporting the weight of the turbine blade within the structure. The payload rail must be able to carry the full weight of the turbine blades without yielding. The payload rail is supported on the rings throughout the payload bay.

To assess the feasibility and mass of using a rail system, a preliminary design of the rail was formulated. For the sake of simplicity, a mono-rail in the form of an I-beam will be assumed as can be seen in Figure 8.15. The material for the mono-rail will be the same as the truss structure (Al6061-T6) as it is suitable for the rail as well, being strong, non-corrosive, and cheap. Alternative options, such as titanium alloys were also considered for the rail material, but were rejected due to sustainability and cost concerns.

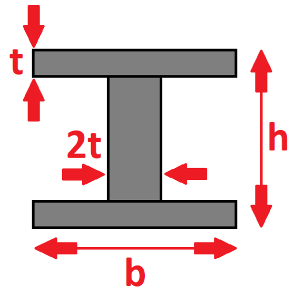


Figure 8.15: *Cross-section of the Payload Rail*

For the beam's design, a shape factor of 10 was assumed based on the beam material. Here, a relation of $I_{xx} = \phi_B^f I_0$ can be defined, with I_0 being the second moment of inertia of an solid square beam with an equivalent cross sectional area [51]. To calculate the minimum cross-sectional area of the payload beam, this relation was used, and a required cross-sectional area of 0.0421 m2 was obtained based on a calculated maximum bending moment of 2.7 MNm.

With the size of the cross-sectional area determined, values for the h/b and h/t ratios were assumed and dimensions of the I-beam profile were calculated. This resulted in a cross-section with $h = 1.14m$, $b = 0.76m$, and $t = 0.01m$.

The resulting total mass of this payload rail design is 12.55 tonnes. This mass is equal to 21% of the payload mass, which makes this weight addition highly influential on the overall structure design. To accommodate the additional weight, the structure of the airship would need to be redesigned and payload ring support would require strengthening. It should be also noted that this design is based on a maximum achievable shape factor and its dimensions, as they currently stand, are not feasible for manufacturing due to the large height and width of the beam and a comparably small thickness. With a height to thickness ratio exceeding 100, the beam will fail in crippling, or other failure modes other than pure bending.

Therefore, the design of the payload rail as it is now is unfeasible and will require a significant redesign. There a multiple ways in which this could be done. Firstly, the length of the rail could be reduced to decrease its total mass, while still being able to accommodate turbine blades. This change is highly realizable, as the blades are supported at their root and around the 46% mark along their length, and therefore the rail length could be reduced to around 50% of the payload bay length. Secondly, the rail cross-section could be varied to reduce the beam area where the highest loads are not carried. This could be done based on an estimate of the typical points of support along the rail for different turbine sizes. More options are available for the redesign of the rail system, but they will not be explored here in more detail. However, it can be expected that the rail mass can be decreased to around 50% of the preliminary mass estimate.

8.5. Material Selection

Material selection is an integral part of any design process. Mechanical design aims to coordinate the design geometry, material, and manufacturing process to form a trinity [51]. Within this section, the approach to the material selection used within the airship design is introduced.

8.5.1. Material Choice Methodology

When selecting materials, engineering strategies must be implemented to translate the design requirements into a unified final selection. This was conducted in four steps, as follows:

Step 1 - Translation

The function, objectives, constraints, and free variables for the material choice for each part are defined. For every airship (sub)system, the following table was completed clearly guide the material choice process.

Table 8.6: *Function, Objectives, Constraints and Free Variables*

Function	What does the component do?
Objective	What is to be maximized or minimized?
Constraints	What nonnegotiable conditions must be met? What negotiable but desirable conditions must be met?
Free variable	Which parameters of the problem is the designer free to change?

Step 2 - Screening

In the next step the available materials and their properties were screened. The most important properties considered within the airship design are shown in Table 8.7

Table 8.7: *Material Properties and Suitable Materials*

Property	Description
Weight	Lightweight materials are essential for improving fuel efficiency and overall performance.
Strength	High strength-to-weight ratio materials are necessary to withstand the stresses experienced during flight and must maintain structural integrity.
Fatigue Resistance	Materials must resist fatigue failure due to cyclic loading over time.
Corrosion Resistance	Aerospace materials must resist corrosion from the environment such as humidity, saltwater, and chemicals.
Thermal Stability	Materials must maintain their properties at both high and low temperatures (engines).
Cost	The cost must be within budget.
Durability	Materials should have a long service life as possible and should require as low maintenance as possible.
Impact Resistance	Materials should be able to absorb energy from impacts without catastrophic failure.
Environmental Impact	The materials should not have a heavy impact on the environment and the world's climate.
Regulatory Compliance	Materials must meet the regulatory requirements set by the EASA.
Machinability	Materials should be able to be manufactured easily to lower production cost and time.

Step 3 - Ranking

The next step is ranking the materials based on their suitability. This was done using Granta EduPack 2023 R2 [18]. Within this software, constraints, as specified in Step 1 of the process are applied to filter out unsuitable materials. Then, the materials were ranked using a material index derived to fulfill each part's objectives. The typical material index used within the current design maximizes the strength and minimizes the density of the material, and is defined as $M_1 = \sigma/\rho$ where σ denotes the yield strength of the material, and ρ denotes its density.

Step 4 - Documentation

The final step is to document the top-ranked candidates. Research on the history, uses, behavior in the relevant environments, and availability of the materials was done until a detailed picture was built up. An internal materials database with the applicable materials for the intended use was created.

8.5.2. Truss Material Choice

The material of the truss structure was chosen in parallel to the design of the truss. The truss structure must provide high load-bearing capability and stiffness for the airship. It should be non-corrosive and yield before fracture to avoid sudden failures. These requirements can be formulated as can be seen in Table 8.8.

Table 8.8: *Function, Objectives, Constraints and Free Variables for Airship Truss Structure*

Function	• Provide Airship Shape • Provide Stiffness • Hold the weight
Objective	• Minimize Weight
Constraint	• Non-corrosive • Non-brittle • Yield before fracture
Free Variables	• Material choice

Aluminum is one of the metals that are most used in the aerospace industry (75%-80% of modern aircraft). It is light, cheap, strong, recyclable, and has a high resistance against corrosion, especially when protected [4]. Additionally, research on aluminum and its alloys is ongoing, while aerospace manufacturers worldwide have broad experience with the manufacturing and processing of aluminum. For these reasons, the truss structure shall be made of aluminum as well. Aluminum is chosen as the preferred material due to its recyclability, which cannot be ensured by its composite alternatives.

A set of promising forged aluminum series to choose from was determined to be: AA2014, AA2024, AA3003, AA5052, AA6061, AA6063, AA7050, AA7068, and AA7075.

[4] https://www.metalsupermarkets.com/history-of-aluminum-in-the-aerospace-industry/ (Accessed on: 20/06/2024)

Table 8.9: *Properties of Selected aluminum Alloys*

Name	CO_2 footprint (kg/kg)	Price (EUR/kg)	Weldability
Aluminum 2024 T6	7.3-8.41	3.01-4.03	Unsuitable
Aluminum 6061 T6	2.3-2.48	2.74-3.77	Good
Aluminum 7050 T7451	7.18-8.29	5.65-7.61	Poor
Aluminum 7075 T62	7.24-8.35	5.54-7.78	Poor

The truss structure was assumed to consist of light stiff beams, for the sake of simplicity. The material index of σ_y/ρ shall be maximized to find the most suitable alloy for optimal strength and mass. Based on this material index and fatigue and environmental resistance constraints, four top materials were shortlisted: AA2024-T6, AA6061-T6, AA7050-T7451, and AA7075-T62. Since the mechanical properties of the shortlisted alloys are in the same range, the selection will be made based on the properties shown in Table 8.9.

The most suitable candidate for the truss is Aluminum 6061 T6 (Al6061-T6). It is relatively cheap (typical grade), has a low CO_2 footprint, and most important of all: it is weldable. The truss structure will consist of beams joined together, but the structure of the beams themselves is welded, hence it is of utmost importance that the material is weldable. The material has been implemented in the truss structure design, giving a structure mass of 62.46 tonnes as discussed in Subsection 8.6.1. It should be noted that a safety factor of 1.5 was implemented in the structural design of the trusses.

8.5.3. Gas Cells

The gas cells of the airship will contain the lifting gas. This is needed for the airship to be able to lift and have buoyancy. The gas cells need to be gas impermeable, as well as carry loads resulting from gas bag pressure, and external forces. These needs can be formulated as follows in Table 8.10

Table 8.10: *Function, Objectives, Constraints, and Free Variables for gas cells*

Function	• Contain the lifting gas within the airship
Objective	• Minimize weight
Constraint	• Gas impermeable • Non-corrosive • Flexible • High tear resistance • Non-flammable
Free Variables	• Material choice • Thickness

As the gas cells are in the airship, they are already protected from the UV radiation of the sun, and therefore, no UV protection layer is needed within the gas bag fabric. Hence, the layers of the gas cells will be as can be seen in Figure 8.16

The gas retention layer is designed such that it is gas impermeable, hence gas escaping shall be prevented by this layer. Escaping gas could pose hazards based on the amount of escaping gas, and its location (see Chapter 14). The load-bearing layer shall bear all the loads that are created by the pressure inside the bag. This layer shall have great resistance to tear and not be corrosive. Finally, both layers shall be held together by a polyurethane-based adhesive layer. This layer shall have great resistance to tear as well.

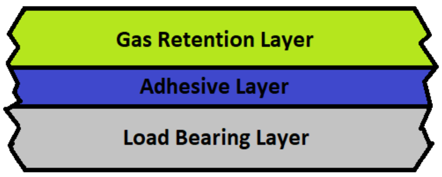


Figure 8.16: *Gas Cells Layers*

The best candidates for the gas retention layer were deemed to be Nylon or Polyester (due to their low permeability), while for the adhesive layer polyurethane-based adhesives [17, 18] will be used. Vectran and Zylon are both suitable materials to use for the load-bearing layer, due to their high tensile strength, which is needed to make sure the gas cells can take the overpressure.

To determine the mass of the gas bags or the load-bearing layer, the thickness is calculated using values for the overpressure in the gas bags. Calculations made in Chapter 4 show that the highest overpressure the gas cells need to maintain is 1520 Pa, with a safety factor of 2.35 as required by regulations. The calculations for the outer area of the gas cells can be found in Subsection 4.2.5. Based on the thickness, outer area, and material density, the mass of the load bearing layer was determined.

Assuming thicknesses of 0.03mm and 0.01mm for the gas retention layer and the adhesive layer respectively, the masses of the gas bags for different layer material configurations were determined. This is shown in Table 8.11.

Table 8.11: *Gas Cell Material Results*

Results	Mass [tonnes]	Price [k EUR]	Thickness [mm]
Nylon + Vectran	29.67	868	0.16
Nylon + Zylon	19.47	2127	0.10
Polyester + Vectran	30.92	877	0.16
Polyester + Zylon	20.73	2136	0.10

The final material choice was made based on the lowest achievable mass of the design. Hence the final choice of material for the gas retention layer was chosen to be Nylon and for the load-bearing layer, Zylon. While the price of this combination is significantly higher than for Vectran fabrics, it is superior in terms of weight.

8.5.4. Envelope

The airship envelope must maintain the airship's aerodynamic form, be light, protect the gas cells and other internal systems from UV radiation, and provide sufficient durability to withstand varying weather conditions. These can be formulated as seen in Table 8.12.

The envelope could be made in two ways. One option is having two layers (similar to the gas bag material discussed in Subsection 8.5.3): one UV-protecting layer and one load-bearing layer with an adhesive that bonds them together. The other option is achieving this in a single layer, that is both UV Protecting and load-bearing. The lightest option between them will be chosen.

Table 8.12: *Function, Objectives, Constraints, and Free Variables for Airship Envelope*

Function	• Provide UV Protection • Maintain Aerodynamic Shape
Objective	• Minimize weight
Constraint	• Non-corrosive • Non-brittle • Flexible • Resistant to environment
Free Variables	• Material choice

Based on the available literature, thicknesses of 0.1mm and 0.15mm were assumed for the one- and two-layer envelope fabrics respectively [5, 17]. Using these thicknesses and the total wetted area of the airship, the masses of the envelope options were determined, as shown in Table 8.13. All options listed have good or excellent weatherability and flexural fatigue resistance.

Table 8.13: *Airship Envelope Material Options*

Two Layer Results		
Material	**Mass [tonnes]**	**Price [k EUR]**
Polyurethane	2.93	15
Polyvinyl fluoride + Kevlar 29	5.66	143
PTFE + Kevlar 29	6.60	150
Polyvinyl fluoride + Polyurethane (thermoset)	4.82	43
PTFE + Polyurethane (thermoset)	5.76	51
PTFE + Zylon	6.88	684
Polyvinyl fluoride + Nylon HT	4.87	326

Both the mass and cost of the polyureathane as a single layer are lower than those of the competing materials, and therefore this material will be used for the airship envelope.

8.6. Design Overview

With the design steps specified in Figure 8.2 completed, the developed design can now be compiled. The characteristics of the airship structure will be presented in Subsection 8.6.1, followed by a discussion on the mass budget compliance within the structures subsystem.

8.6.1. Subsystem Characteristics

The created structural subsystem of the airship is described in Table 8.14. The table contains the first design parameters, the updated first design parameters (after system iteration), and the final parameters of the design.

Table 8.14: *Summary of the Structure Design*

Parameter	**First Design**	**First Design After Global Iteraton**	**Final Design**
Number of Longerons [-]	20	20	24
Total Mass of Longerons [tonnes]	26.08	19.88	19.88
Number of rings [-]	18	18	18
Total Mass of Rings [tonnes]	28.47	27.08	35.31
Total Structure Mass [tonnes]	54.55	46.96	55.19
Structure Mass Budget [tonnes]	72.55	62.46	62.46
Margin	33%	33%	13%

A mass margin for the structure's mass was defined to account for added structural mass from factors not accounted for in the structural design. The final design margin of 13% is discussed in Subsection 8.6.2. The materials chosen for the system components are presented in Table 8.15, along with the masses of the resulting components.

Table 8.15: *Final Material Selection for System Components*

Component	**Material**	**Mass [tonnes]**
Truss Structure	AA6061-T6	62.46
Airship Envelope	Polyurethane	2.93
Gas Bags	Nylon + Zylon Composite	19.47

8.6.2. Structural Mass Budget

While for the first design of the structure, a set mass margin was defined, the final design aimed to be realized within this preliminary budget. Therefore, the final design was made for a defined total structural mass of 62.46 tonnes. This mass is that of the entire structural subsystem comprising longerons, rings, joints and connections, as well as parts of the frame not accounted for so far, such as diagonal truss sections.

The margin of 13% at the end of the frame design translates to a 7.27 tonne mass allowance for the structural elements not included in the final design. This margin will be used for connections between the frame elements, the payload rails, and the addition of diagonal elements to the box truss. The margin should also be able to account for any changes to the mass when the cross-sectional area of the longerons and rings is evaluated for stepped cross-sections, instead of continuously changing ones. For those elements, the exact masses and mass changes are not known and therefore only a rough estimation can be made. Based on an assumed connection mass of 0.1 kg and the preliminary structure sections established during the design, the total mass of the connections and joints should not exceed 1 tonne. The estimate of the payload rail mass after a design iteration would be about 6 tonnes. Finally, based on the assumption that the diagonal elements of the trusses constitute about 5% of the total truss weight, the added mass due to those elements would be 2.8 tonnes. It is unknown what the added mass of the other additional structural fairings would be, but this mass can be attributed to the miscellaneous budget for the entire system.

The quick mass budget analysis yields a total structure mass that exceeds the structure mass budget by 4%. While this percentage should not be neglected and should be kept in mind to ensure subsystem budget compliance, it is based on a set of conservative assumptions about the structure design, and therefore its value should not be taken as a set. The structure design will be further iterated upon and looked at in more detail, and therefore the compliance with the mass budget will be reevaluated at later design stages. At this stage, the 4% margin is deemed acceptable and current mass budget estimates are kept.

8.7. Cost Analysis

The cost of the structures subsystem comprises the material cost, the manufacturing cost, and the transportation costs of the parts. The disposal cost of the parts should also be considered in this analysis. A cost breakdown for the truss structure, airship envelope, and gas cells is presented in Table 8.16. For the calculation of the costs, the previously determined material masses were used. The manufacturing costs were calculated using the manufacturing methods specified in the manufacturing plan in Section 15.2. For transportation, transport of the parts by truck was assumed over a 1000 km distance.

Table 8.16: *Cost Breakdown of the Airship Structure*

Part	**Total Mass [tonnes]**	**Material Cost [EUR]**	**Manufacturing Cost [EUR]**	**Transport Cost [EUR]**	**Total Cost [EUR]**
Truss Structure	62.46	430 000	26 900	9 400	466 300
Airship Envelope	2.93	12 000	23	460	12 483
Gas Cells	17.90	2 821 000	24 590	2 850	2 848 440

Table 8.16 shows that the highest cost of the structural subsystem originates from the mass of the used material. This cost is the highest for the gas cells, which have to be manufactured from specialized materials. It should be noted that the cost of the truss structure is relatively low compared to its mass due to the low material costs.

8.8. Sensitivity Analysis

To ensure robustness of the design, a sensitivity analysis of the structures subsystem was conducted. This analysis aims to quantify how changes in assumptions and design choices influence the features of the final design.

The main parameter identified for the sensitivity analysis of the structure is the truss structure material. The material of the trusses influences the mass, cost and environmental footprint of the structure. A comparative analysis was conducted with respect to the chosen AA6061-T6 alloy. Two main alternative metals alloys were analysed in the comparison: the structural steel alloy A500 and the titanium alloy Ti6Al4V. Composite materials were not considered here due to manufacturing constraints. Table 8.17 presents the relative value changes with respect to AA6061. The influence of the choice of material for the gas bags and the envelope was investigated in Section 8.5, and therefore this will not be further discussed in this section.

Table 8.17: *Sensitivity Analysis on the Truss Box Material*

Material	**Mass**	**Cost**	**CO_2 Footprint**	**Embodied Energy**
Structural Steel A500	233%	82%	57%	39%
Ti6Al4V	49%	698%	245%	301%

Table 8.17 highlights the unique feasibility of aluminum within the truss box design. The use of both alternative metals leads to unfeasible designs. While structural steel is cheaper and more sustainable than AA6061, its use would increase the structural mass over two fold, which would be unacceptable. The titanium alloy would have a mass advantage over aluminum, but would increase the cost of the material seven times, while also increasing the design's environmental footprint. The choice of aluminum as the truss box material ensures the robustness of the design in this aspect.

Other parameters that influence the design of the airship structure are the number of longerons and the number of rings within the structure. The influence of the number of longerons was investigated in Subsection 8.2.3 and will not be explored further, as it been sufficiently explored. Since the ring design within the airship is preliminary and subject to changes once the detailed joint design is established, the weight of the structure increases quasi-linearly with the increasing number of rings, as the payload load is redistributed along adjacent rings. It was decided that, because a more complex relation has not been established, the discussion of the ring number influence will be limited to defining a 6.2 tonne increase in structural weight per ring added.

8.9. Limitations and Recommendations

With the design of the airship structure concluded the limitations of this design should be discussed to ensure that it can be implemented safely and iterated upon in the future. Recommendations for this subsystem's design are also explored.

8.9.1. Frame Structural Design

The main limitation of the structural design of the frame is the relatively low level of detail and complexity of the current design. While the structure of the airship is fully designed and could be built after minor design additions, not all applicable effects on the structure were considered. These effects concern mostly loads and vibrations experienced by the airship in-flight and while mooring, and can result from load coupling, atmospheric effects, as well as vibrations occurring within the structure. To ensure a safe and complete design, a more detailed load analysis should be conducted, considering both the external loads acting on the airship, as well as the internal point load distribution. As an important part of the detailed analysis, the eigenmodes of the structure should be studied.

Another limitation of the current design results from the way engine, tail, and ballast attachment points within the structure were considered. While the structure was designed to withstand critical (extreme) loads resulting from subsystem attachments, the calculations considered those to be point loads. A more detailed analysis of the loads applied to the structure by the connected subsystems should be conducted in the future, with the inclusion of vibration loads.

As the design currently stands, many conservative assumptions were made that likely resulted in an overdesigned structure. This included assumptions about the load transfer, wherein the loads were taken as point loads, instead of being distributed along the structure. Load transfer within the airship frame should be investigated in more detail to reduce the system mass.

It is highly recommended and required that Finite Element Methods (FEM) are used in the next stages of the structural design. The use of FEM will allow for a more detailed load analysis, a vibrational analysis, and an analysis of the structural deflections, all of which are needed to verify that the structure is safe to operate.

8.9.2. Payload Bay Design

The design of the payload bay as it stands now, provides a framework for a future detailed analysis, but is not a standalone entity that is able to be manufactured without further changes. The payload bay is subject to limitations originating from the assumptions taken. The design of the payload bay was highly simplified to allow for analytical calculations. However, in future designs, the analysis of the payload bay cross-section should be done using FEM to find the stresses and deflections of the structure. Joint design should be revisited in particular, as payload bay joints are a weak point of the airship cross-section.

Another recommendation for future design is, as mentioned in Subsection 8.4.3, the detailed design of the payload bay rail. This part of the design should be done alongside the design of the clamping mechanism for the payload to constrain the movement of the turbine blade within the airship. A comprehensive payload support method needs to be designed to ensure safety of the structure.

8.9.3. Material Considerations

While specific materials were chosen for different parts of the airship structure, they pose some limitations to the design. The first limitation is the availability of equipment and manufacturers able to produce desired parts out of a desired material. While the material chosen for the airship frame satisfied the required mechanical properties and the weldability requirements, it is more common for box trusses to be made out of other aluminum alloys, such as AA6050. As such, the material of the airship frame should be reevaluated, taking into account the availability of producers. The same should be done for the envelope material, as well as the gas cell material: the final decision on the material types should be done in consultation with manufacturing companies.

While the material choice process included some environmental and fatigue properties of the materials, it is highly recommended that these properties be looked at in more detail in future design. Only after considering these properties, the structure of the airship can be verified to be safe. The corrosion resistance of the airship frame can be ensured by using corrosion coatings on the exposed parts, while the fatigue resistance of the airship can by analytically analyzed and tested.

8.9.4. Safety and Durability

The safety and durability of the airship structure is of the utmost importance within the design. While safety factors, as specified by regulations, were applied to all parts of the structure, the load path redundancy (as required by REQ-STR-01) could not be ensured at this point in the design. It is vital that in future additions to the design, a fail-safe strategy is applied to ensure that this requirement is satisfied and the airship can be operated safely. Additionally, it is recommended and required that the next design iterations include the assessment of the crashworthiness of the airship.

9
Performance

Performance analysis serves to investigate how well the airship performs during operations. For this, there are certain goals and requirements presented in Section 9.1. Then, the airship itself is analysed in Section 9.2. Following this is an analysis of the mission profile, and lastly some recommendations are provided in Section 9.4.

9.1. Design Baseline

Firstly, a baseline for the performance has to be established. This section will elaborate on the goals and requirements of performance. Lastly it is also important to consider the in- and outputs from and to other subsystems.

9.1.1. Performance Goals

The things that this chapter aims to accomplish are listed below.

1. Analyze the effect of different parameters on performance curves
    - Analyze buoyancy ratio effects
    - Analyze mass reduction effects
    - Analyze altitude effects
2. Create the performance curves
    - Create and analyze the power curve
    - Create drag curve
    - Create L/D curve
3. Determine the mission profile
    - Determine the endurance of the system
    - Determine the range of the system
    - Analyze cruise
    - Analyze climb
    - Analyze descent
    - Analyze hovering

9.1.2. Requirements

When a performance analysis is executed, it is necessary to ensure its compliance with several requirements. The user-, mission-, and system requirements influencing the performance of the system are presented in Table 9.1

Table 9.1: *User, Mission, and System Requirements Relevant for Performance Analysis*

ID	Requirement
REQ-US-04	The range shall be a minimum of 200 km
REQ-US-12	An analysis of emissions compared to trucks shall be performed
REQ-SYS-GEN-04	The airship shall not emit noise louder than 140 dB
REQ-SYS-GEN-05	The noise at ground level over inhabited areas shall not exceed 80dB
REQ-MIS-02	The delivery time of the payload shall be less than 7.5 hrs for a distance of 400 km
REQ-SYS-MIS-01	The airship shall have a range of at least 2000 km
REQ-SYS-MIS-03	The airship shall have a minimum achievable climb rate of 2 m/s at sea level
REQ-SYS-MIS-04	The airship shall have a steady climb angle of at least 1:12 at sea level.
REQ-SYS-MIS-16	The vehicle shall have a cruising speed of at least 60 km/h.

9.1.3. In- and Outputs

To get a better overview of the role of performance within the entire system, it is helpful to look into the in- and outputs of the performance.

Table 9.2: *Inputs of the performance analysis.*

Inputs
Weight:
• Maximum take-off weight
• Operational empty weight
Aerodynamic Parameters:
• Airship Area
• Drag (zero-lift drag and induced drag constant)
Propulsion
• Efficiencies (engine, fuel cell, propeller)
• Specific energy
• Fuel mass

Table 9.3: *Outputs of the performance analysis.*

Outputs
Power Curves:
• Flight height
• Buoyancy ratio
• Operational weight
Plots:
• Power curve
• Lift-to-drag ratio curve
• Drag curve
Mission Profile:
• Flight profile diagram
• Range
• Endurance

9.2. Performance Analysis

To get a good overview of the performance, two graphs can be plotted; the power curve, and the lift and drag vs. velocity. For the power curve the influence of certain parameters is also investigated.

9.2.1. The Power Curve

Many flight profile analyses can be performed from a required power vs. velocity graph. Additionally, several parameters such as the buoyancy ratio, mass, and cruising altitude of an airship can be visualized. By changing the aforementioned parameters in these plots, their effects can be analyzed. To create these plots, the following assumptions are used:

1. Horizontal, unaccelerated flight conditions
2. Small angle assumption

These assumptions allowed the simplification of the equations of motion. The simplified EOMs are presented below.

$$W = L_{aero} + L_{buoy} \cdot cos(\alpha) + T \cdot sin(\alpha) \tag{9.1}$$

$$T \cdot cos(\alpha) = D + L_{buoy} \cdot sin(\alpha) \tag{9.2}$$

In Equation 9.1 L_{aero} represents the lift generated due to aerodynamics, L_{buoy} represents the lift generated due to buoyancy, T is the thrust, D is the drag, and α represents the angle of attack. By using the small angle assumption, the angle of attack can be considered small, leading to further simplifications presented below:

$$W = L = L_{buoy} + L_{aero}$$

$$T = D$$

The power required was calculated using the relation:

$$P_r = \frac{Tv}{\mu_p \mu_m} = \frac{Dv}{\mu_p \mu_m} = \frac{C_d q_\infty V^{2/3} v}{\mu_p \mu_m} = \frac{(C_{d_0} + kC_{L_{aero}}^2) q_\infty V^{2/3} v}{\mu_p \mu_m} \tag{9.3}$$

In Equation 9.3 P_r is the power required, C_d is the drag coefficient, q_∞ represents the dynamic pressure at a given altitude, $Vol^{2/3}$ is an approximation of the area of an airship, and v is the airspeed. Additionally, C_{d_0} is the zero-lift drag coefficient, k is the induced drag constant, and $C_{L_{aero}}$ is the aerodynamic lift coefficient. Finally, μ_p and μ_m represent the propeller and electric motor efficiencies respectively. This power is then plotted versus a range of velocities, from 30 to 150 km/h, while varying different parameters, such as the buoyancy ratio, the weight of the airship, and the altitude.

Varying Buoyancy Ratio

The optimal buoyancy for the airship was determined to be 99.67% in Section 3.5. To confirm if this ratio is the ideal, various buoyancies will be compared and their effects analyzed. The examined ratios are 1, 0.99, 0.95, and 0.90.

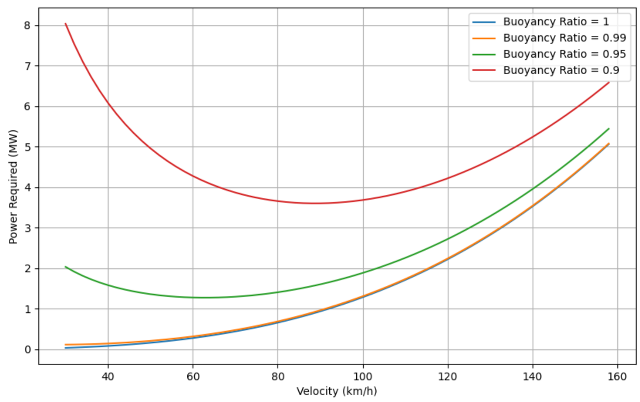
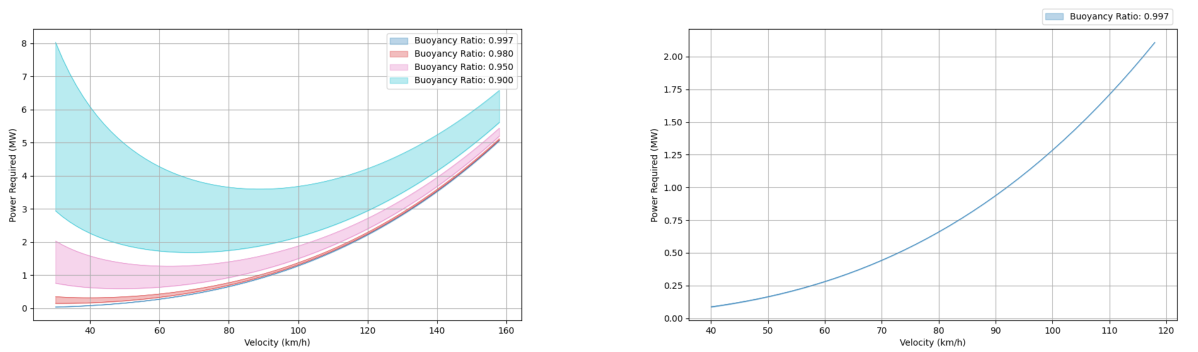


Figure 9.1: *Power Required vs. Velocity for Different Buoyancy Ratios*

In Figure 9.1, the total power required is plotted against velocity for various buoyancy ratios. In the plot, the MTOW of the airship and an altitude of 2000 m are used for all four curves. As can be seen, having a buoyancy ratio of 1 results in the least power required, while lower buoyancy ratios show an increase in the power required across all velocities. The ideal value for the buoyancy ratio is inferred to be 1, however, due to the aerodynamic shape of the airship, it is impossible to reach this value. This justifies the selection of the value of 99.67%.

Varying Weight

As the optimum buoyancy ratio has been established, it is time to determine the effect of a decreasing airship mass. Similarly to how the buoyancy ratio was plotted, the mass effects can now be analyzed by plotting the power required vs. velocity graph for changing masses.



(a) *Power Required vs. Velocity for a Range of Weights* **(b)** *Power Required vs. Velocity for a Range of Weights (Zoomed)*

Figure 9.2: *Comparison of Power Required vs. Velocity for Different Weights*

The curves with the different buoyancy ratios are once again presented in Figure 9.2a, replacing the full buoyancy with the projected value of 99.67%. Each ratio now includes two curves. The top curve represents the power required when cruising at the MTOW while the bottom curve represents the cruising power required when operating at OEW. The shaded regions between each curve represent the range of masses the airship may operate at.

It is clear from Figure 9.2a that operating at a lower weight is beneficial for the performance of the airship, especially when having lower buoyancy ratios. Furthermore, there is a minimal difference between the MTOW and OEW curves for the chosen 99.67% buoyancy. This is more evident in Figure 9.2b. The difference in the required power can be considered negligible at any velocity. As a result, the design choice involving the collection of water waste from the fuel cell and thus keeping the airship's weight constant can be justified. Keeping the weight constant does not impact the performance but it does have a positive effect on the overall system, as it allows for constant lift generation throughout the flight, which is desired for operations.

Varying Altitude

The final changing variable in the power equation is air density. The density depends on the altitude at which the airship is operating, decreasing with increasing height. The effects of variable altitudes will now be examined. To do this, the power required vs. velocity graph is plotted for a buoyancy ratio of 0.9967 while operating at the MTOW.

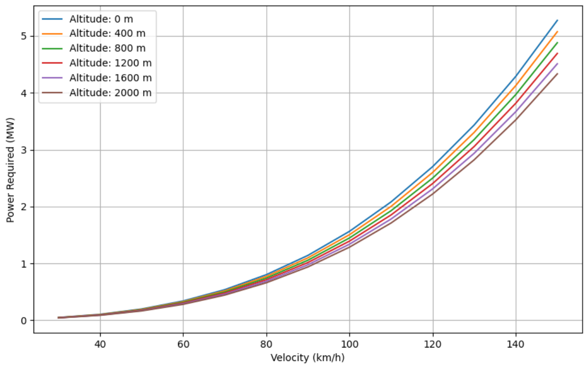


Figure 9.3: *Power Required vs. Velocity for a Range of Altitudes*

The results presented in Figure 9.3 clearly show that an increase in altitude leads to a decrease in the power required for a specific cruise speed. This effect is greater when traveling at higher speeds. As a result, the choice to fly as high as possible within the allowable limit is justified as this will decrease the power required, thus allowing the allocation of less weight for fuel.

Power vs. Velocity

Once the preferred buoyancy ratio, airship mass, and altitude have been identified, it is possible to plot the complete power vs. velocity graph. To do this, both the power required and the power available must be present. In Table 9.4, the values used to create the power vs. velocity graph are presented.

Table 9.4: *Final Parameter Selection*

	Value Used
Buoyancy Ratio	0.9967 [-]
Mass	225206.9 [kg]
Altitude	1950 [m]

The focus is first on the power required. To fly at 75% of the power available for propulsion, the total power required for propulsion is calculated by dividing the power required to fly at a certain cruise speed by 0.75. However, additional power is required to counteract the forces applied on the system due to side winds of speeds up to 5 m/s. In Chapter 5, the magnitude of the exerted drag force due to the side winds was determined and thus the power required is found by multiplying it by the velocity of the winds. Additionally, the propulsion subsystem is not the only one that requires power to operate. The power required by these other subsystems was determined in Chapter 7. Introducing these additional power requisites results in a larger power required during the operation.

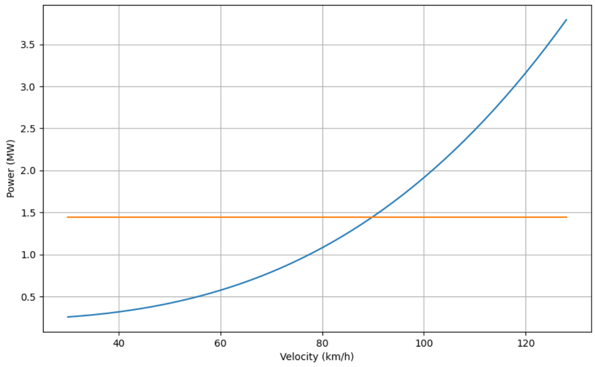
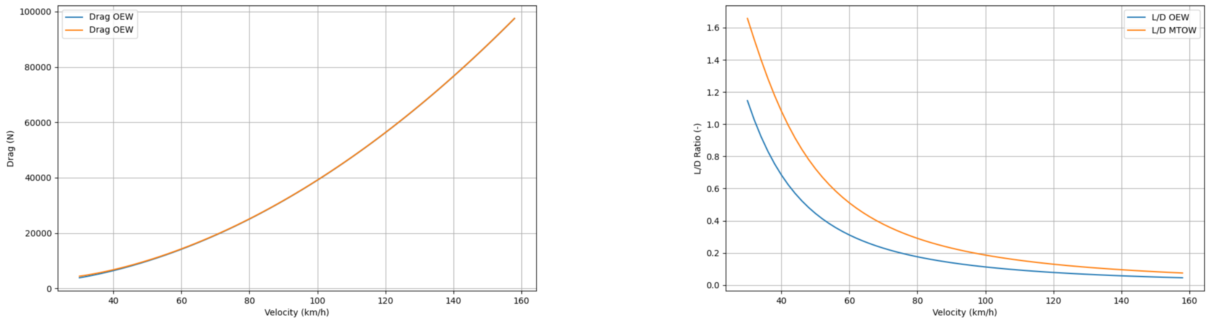


Figure 9.4: *Power Required and Power Available vs. Velocity*

In Figure 9.4, one can see the total power required plotted against the cruise speed, and the power available. This plot shows some operational limits, as the cruise speeds past the intersection of the two lines cannot be reached, since not enough power would be available to cruise forward, combat side winds and perform other functions simultaneously.

9.2.2. Drag and L/D vs. Velocity

Additionally, the drag and lift-to-drag ratio can be plotted against the cruise velocity. These plots are indicative of the performance of the airship, and aid in the selection of a cruise speed.



(a) *Drag vs. Velocity for a Range of Weights*

(b) *Lift-to-drag Ratio vs. Velocity for a Range of Weights*

Figure 9.5: *Drag and L/D Ratio Plotted Against Velocity*

In Figure 9.5a one can clearly observe that the drag increases as velocity increases. Additionally, Figure 9.5b shows that the lift to drag ratio decreases with increasing velocity, and flying at a lower mass results in a higher L/D across all velocities. This leads to the conclusion that flying slower is important for climb, when a high L/D ratio is necessary, however for cruise, higher velocities may be considered.

9.3. Mission Profile

With the analysis of the airship completed, it is now possible to analyse the missions is going to fly.

9.3.1. Endurance and Range

Since the mass of the airship remains constant, endurance can be simply calculated by dividing the amount of fuel by the fuel mass flow. The fuel mass flow can be calculated by the following formula:

$$\dot{m}_{fuel} = \frac{P_r}{E_{sp}\mu_{cell}} \tag{9.4}$$

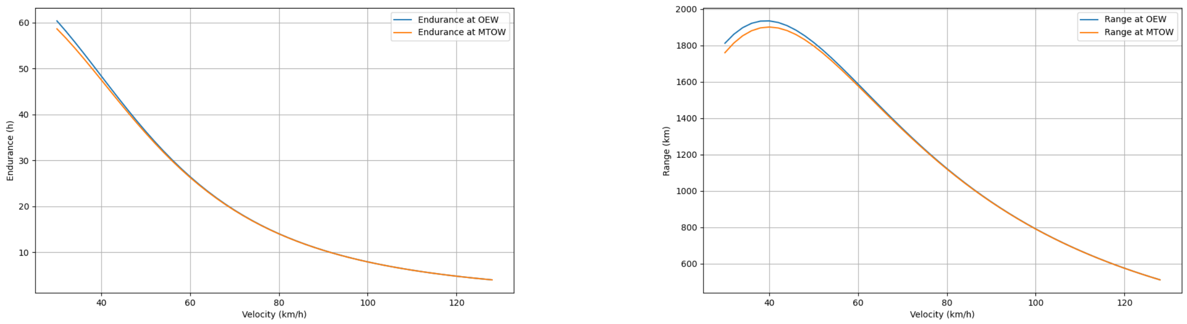
In Equation 9.4 P_r represents the power required to travel at a specific velocity (including the power to counter side winds and the power needed for other subsystems), E_{sp} represents the specific energy of the fuel, and μ_{cell} is the fuel cell efficiency.

For a given velocity, the endurance and range can be calculated using the following formulas:

$$Endurance = \frac{m_{fuel}}{\dot{m}_{fuel}} \tag{9.5}$$

$$Range = Endurance * v \tag{9.6}$$

Where m_{fuel} in Equation 9.5 is the fuel mass. The results of these calculations for changing airspeed can be seen in Figure 9.6 below. These graphs simply show how endurance and range change with a change in velocity. They will be relevant for the operation of the airship.



(a) *Endurance vs. Velocity for a Range of Weights*

(b) *Range vs. Velocity for a Range of Weights*

Figure 9.6: *Endurance and Range Plotted Against Velocity*

9.3.2. Flight Profile Diagram

The flight profile diagram illustrates the flight of a typical mission. There are two different options for the climb and descent phase, either to climb normally with a given gradient, or to first climb vertically to cruise altitude and then continue the cruise. Two sets of flight profile diagrams are made, one for each of these cases. It is important to note that due to regulations the climb speed should be at least 2 m/s, which was the case that was considered for the following calculations.

"Traditional" Climb

During regular climb and descent phase the airship moves vertically at a speed of 2 m/s while still maintaining the forward cruise speed of 80 km/h. This was done by angling the engines at 5.21° or -5.21° respectively, and producing a velocity vector of 80.3 km/h. It is important to note that during the loitering times and climb and descent times fuel is used at a different rate than the value calculated for cruise, therefore the total duration of a trip will vary from the endurance obtained for cruise in Subsection 9.3.1.

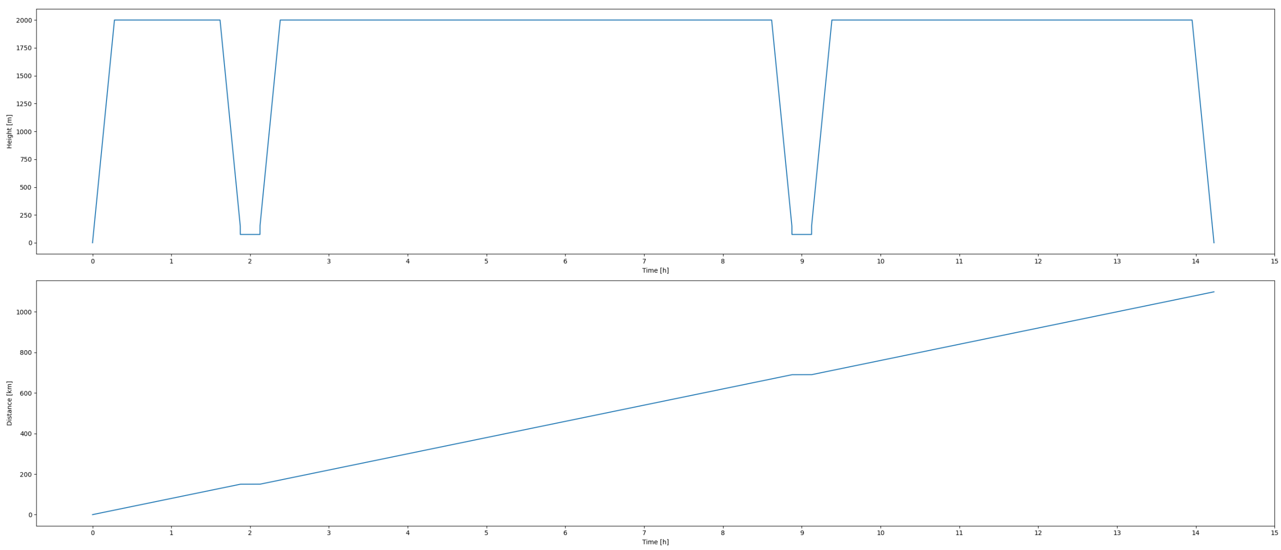


Figure 9.7: *Flight Profile Diagram for Typical Mission*

In Figure 9.7 one can observe two plots, the first depicting the height of the airship at different times, and the second depicting the distance traveled as a function of time. A steep slope characterizes the cruise and descent times, while for the rest of the flight, the airship is cruising at 2000 m or loitering at 75 m at either the pick-up or drop-off location of the blades.

Vertical Climb

During vertical climb the airship remains at a constant location during the climb and decent phases, during this time the airship moves vertically up or down at a speed of 2 m/s. This results in the following flight profile diagram.

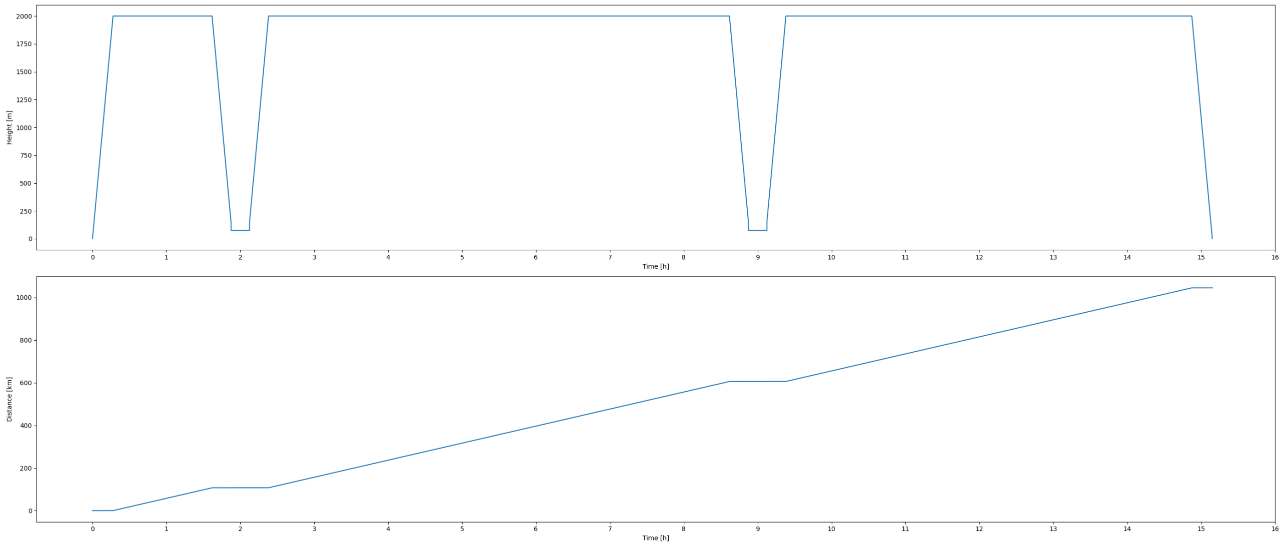


Figure 9.8: *Flight Profile Diagram for Typical Mission*

It is important to note that this flight goes on for longer than the expected 14 hours since the energy used when climbing and descending is relatively small compared to the rest of the flight. The endurance and range of the two different flight profiles can be observed in the table below.

Table 9.5: *Range and Endurance for Different Climb Options*

	Traditional Climb	Vertical Climb
Endurance [h]	14.23	15.15
Range [km]	1098.5	1045.5

9.4. Limitations and Recommendations

Once the performance analysis is complete, and the mission profile has been determined the limitations of this procedure must be examined. Additionally, recommendations for further analysis must be observed.

9.4.1. Further analysis

Typically, during a performance analysis, loading diagrams, payload-range diagrams and other diagrams are included. However, most of the methods found in the literature to determine these were assuming the vehicle to be an aircraft. It is recommended that for further analysis, more research is done into these diagrams. However, the current analysis covers all missing aspects of the mission profile, including information about the climb, cruise and descent stages of the flight.

9.4.2. Noise analysis

A recommendation for future analysis of the performance of the airship is to include analysis of the noise emitted by the propellers and other elements of the airship. Since it flies at a relatively low altitude, a noise emission analysis is necessary to ensure that the airship does not disturb the population of the areas it flies over. The majority of methods for the noise analysis use empirical formulas, however it would be beneficial to research current testing methods implemented for aircraft propellers.

10
Mooring and Ballast Design

To ensure cargo transport is done safely different operational elements need to be identified and designed. For the operation of the airship, three technical elements have been identified: the mooring infrastructure, the ballast and payload storage and the ground infrastructure. The mooring infrastructure will ensure a stable environment during the loading and unloading phases. The ballast and payload storage provides space and safe stowage of ballast and payload. The ground infrastructure is needed to handle the airship close to the ground, say storage of the airship in a hangar, mooring of the airship to ensure (un)loading capabilities, etc. In this section, all three elements will be discussed, alongside the discussion of their design goals, requirements, inputs, and outputs. Additionally, the limitations of the analysis will be introduced, along with recommendations for future design.

10.1. Design Baseline

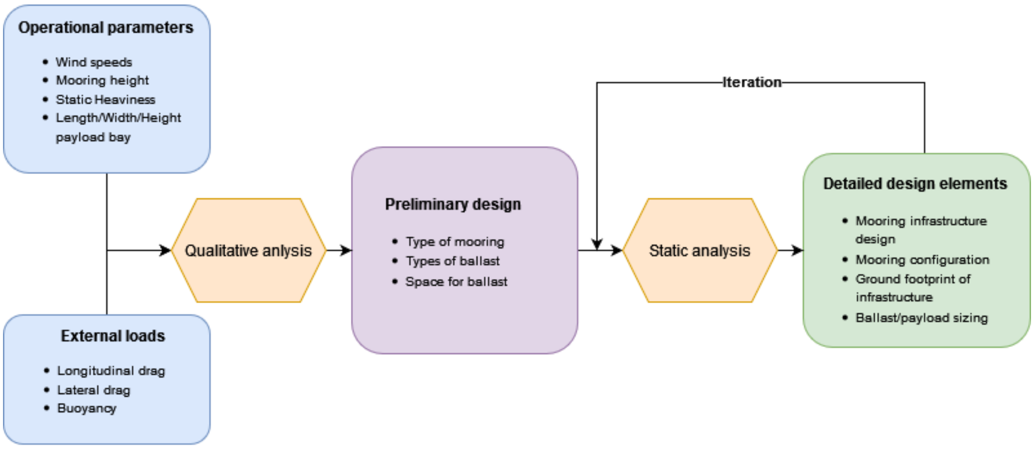


Figure 10.1: *Design Flow Operational Elements*

10.1.1. Design Goals

To obtain a well-rounded design that can perform the intended operation, a set of design goals has been determined prior to the analysis. The design goals are as follows:

1. Mooring infrastructure
    - Select the mooring infrastructure that is needed.
    - Determine the loads that occur during mooring.
    - Design and size the mooring infrastructure.
    - Define the ground footprint of the mooring infrastructure.
2. Ballast
    - Define the type of ballast needed for operations.
    - Size the ballast.
3. Ground infrastructure
    - Define needed infrastructure
    - Size of hangar
    - Define the ground footprint of the infrastructure used.

10.1.2. Requirements

The design of the three operational elements are guided by a set of requirements applicable to the airship as a whole or on the sub-systems themselves. The system requirements that will guide the operational design are given in Table 10.1.

Table 10.1: *System Requirements Relevant for the Operational Design.*

ID	Requirement	Implication
REQ-SYS-GEN-02	The system shall be capable of loading and unloading without landing.	The mooring infrastructure will have to provide the necessary stability and rigidity to ensure that the loading and unloading of the payload is done safely.
REQ-SYS-GEN-03	The system shall contain mooring interfaces.	Depended on the type of mooring technique used mooring interfaces on the airship and on the ground will have to be present.
REQ-SYS-GEN-07	The system shall be able to reach locations where ground transport is limited due to inadequate infrastructure.	The infrastructure used on ground must be able to be build or transported to those sites.
REQ-SYS-GEN-08	The system shall be able to reach locations where ground transport is limited due to size constraints.	The ground footprint needed to perform airship operations must be limited in size.
REQ-SYS-CRG-04 & -05	The airship shall maintain static longitudinal equilibrium during loading/unloading.	The mooring infrastructure must be able to provide this equilibrium and be able to resist the loads present.
REQ-SYS-CRG-06 & -07	The airship shall maintain static lateral equilibrium during loading/unloading.	The mooring infrastructure must be able to provide this equilibrium and be able to resist the loads present.
REQ-SYS-CRG-11 & -12	The airship shall maintain a height of at least 30% of its length while loading/unloading.	The mooring infrastructure will have to be sized in such a way to accommodate the required clearance.
REQ-SYS-MIS-1	The system shall operate in wind speeds of at least 10 m/s.	The mooring infrastructure must be able to carry loads that loads that occur due to 10 m/s wind.
REQ-SYS-INF-01	The hangar shall be sufficiently large to accommodate the airship's dimensions	The hangar must be sized to accommodate the airships size.

Next to the top-level system requirements, subsystem requirements have been defined that will guide the design and sizing of the subsystems in a more detailed way. The subsytem requirements are shown in Table 10.2.

Table 10.2: *System Requirements Relevant for the Operational design.*

ID	Requirement	Implication
REQ-SBST-MOR-01 & -02	The mooring infrastructure shall provide support under 10 m/s of side/head wind	The mooring infrastructure must be able to withstand loads that occur due to the wind.
REQ-SBST-MOR-04	The mooring infrastructure shall provide a clearance of at least 30% of the length of the airship	The mooring infrastructure will have to be sized in such a way to accommodate the required clearance.
REQ-SBST-MOR-06	The mooring infrastructure shall constraint the airship from moving in all Cartesian directions	The mooring infrastructure must be sized in such a way that the directions can be constrained.
REQ-SBST-MOR-07	The mooring infrastructure shall constrain the airship in yaw	The configuration of the mooring infrastructure must be such that yaw motion can be constrained.
REQ-SBST-MOR-08	The mooring infrastructure shall constrain the airship in roll	The configuration of the mooring infrastructure must be such that roll motion can be constrained.
REQ-SBST-MOR-09	The mooring infrastructure shall constrain the airship's tail in pitch up motion	The configuration of the mooring infrastructure must be such that pitch up motion of the tail can be constrained.

Table 10.2 (continued from previous page)

ID	Requirement	Implication
REQ-SBST-BAL-01	The normal ballast shall have a mass equal to the payload	The normal ballast will have a weight of 60 tons to replace the payload.
REQ-SBST-BAL-02	The normal ballast shall have a size equal to the payload	The normal ballast will have dimensions of 105 x 10 x 12 m (L x H x W).
REQ-SBST-BAL-03	The normal ballast shall be of a solid type	The normal ballast will have to be stored in containers that can carry solid ballast. eg. containers.
REQ-SBST-BAL-04	The permanent ballast shall have a mass of atleast 5 +/-2 % payload mass	The permanent ballast will have a mass of at least 3000 +/- 1200 kg.
REQ-SBST-BAL-05	The permanent ballast shall be of a liquid type	The permanent ballast will have to be stored in containers that can carry liquid ballast. eg. Tanks or bags.

10.1.3. Inputs and Outputs

To be able to reach the design goals certain inputs are needed that help in sizing and determining certain design aspects. The inputs and outputs for the operational design of the mooring infrastructure, the ballast and payload storage, and the ground infrastructure elements are given in Table 10.3 and 10.4.

Table 10.3: *Inputs for the operational design.*

Input
Wind speeds
Longitudinal drag
Lateral drag
Buoyancy
Mooring height
Static heaviness/lightness
Length/Width/Height payload bay

Table 10.4: *Outputs for the operational design.*

Output
Mooring configuration
Internal loads
Size of mooring infrastructure
Ballast sizing

10.2. Mooring Infrastructure

Before the mooring infrastructure can be designed it is important to determine what method of mooring is to be used. Mooring of the airship is needed to load or replenish the airship (payload/ballast), for storage when not in operation (maintenance, non-operating) and to ensure the airship is secure under all weather conditions. For the current design, mooring for (un)loading payload and ballast is considered, as those are the driving operational phases for a cargo airship.

Mooring can be done via a mast or by anchoring. The mooring mast is essentially a steel column/steel structure to which the airship is attached via its nose. Anchoring, however, is done by attaching wires from the airship to anchor points on the ground[1]. For the purpose of (un)loading G. A. Khoury suggest to utilise a mooring mast or anchoring based on the size of the cargo airship [17]. Table 10.5 shows the pros and cons of mooring masts and anchoring [54, 55].

Table 10.5: *Pros and Cons of Mooring Masts and Anchoring*

Mooring method	Pros	Cons
Mooring mast	Allows consistent ground clearance, little mooring infrastructure needed onboard, provides a stable platform	Expensive to build, mast is not easily transportable, requires a lot of material to build, multiple masts have to be present, constraint at one point only
Anchoring	Cheaper to build, cables can be transported easily or taken onboard, multiple constraining points	Attachment points needed onboard and on the ground, large ground footprint needed, no consistent ground clearance, airship must be in static light condition

Anchoring is the preferred mooring method because cables are more accessible and cheaper, can be transported more easily, and can provide flexible configurations. Anchoring can be done using the Osborne method

[1] `https://www.wondersofworldaviation.com/mooring_airships.html` (Accessed on: 19/06/2024)

(two cable system), a three-wire system, or a four-wire system ([55], p.20). However, those methods of anchoring have often proved to be unstable. Within all those methods all cables attach to the airship at a single point, just like the mooring masts. In a multi-wire system where the cables are attached at different points along the airship, the instability can possibly be resolved. Figure 10.2 shows the final choice for the anchoring method.

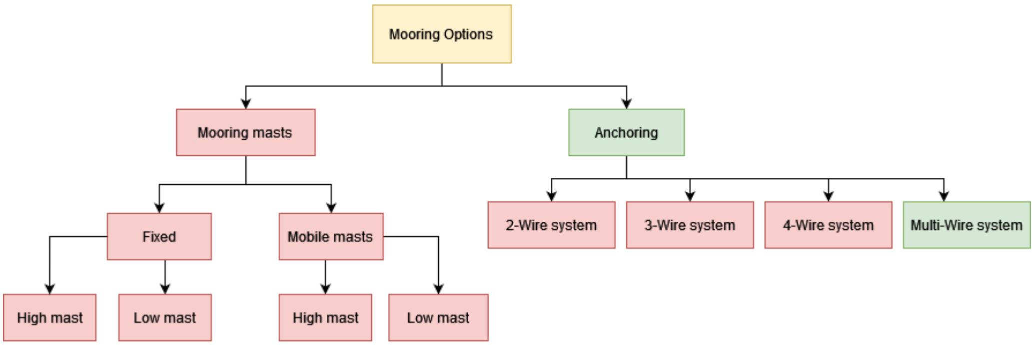


Figure 10.2: *Design Option Tree for Choosing Mooring Type*

10.2.1. Load Cases

The choice for a multi-wire system is made and a possible implementation of this system can now be made. The design starts with a general load case of the multi-wire system.

General Load case

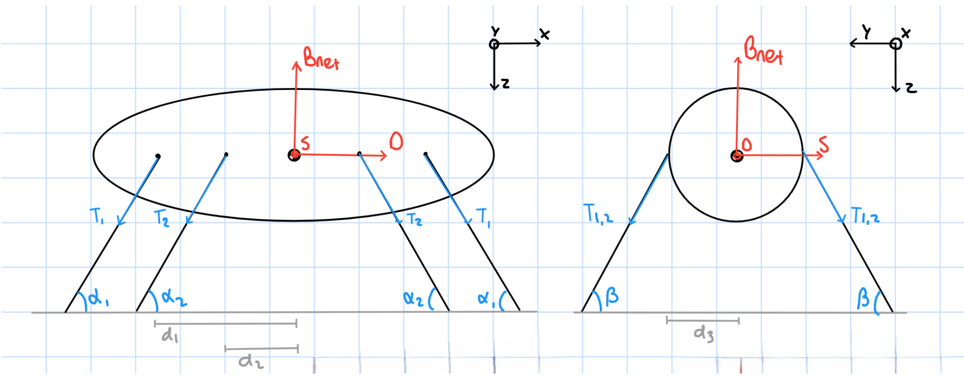


Figure 10.3: *Mooring - General load case, three applied forces*

A free body diagram for the general load case is given in Figure 10.3. The general load case includes three externally applied forces: the net buoyancy force in the negative z-direction, the longitudinal drag in the positive x-direction, and the lateral drag in the negative y-direction. There are tensile forces present in the eight cables. It is assumed that the outside cables carry the same tension force T_1 and have an angle α_1 with the x-axis in the XZ-plane. Correspondingly, the inner cables carry the same tension force T_2 and have an angle α_2 with the x-axis in the XZ-plane. All cables have an angle β with the y-axis in the YZ-plane. When the components of the tension forces in a certain direction act in the same direction as the externally applied force, then the tension is assumed zero, as the cable is assumed to be slack. Assumed is that all the externally applied forces act on the center of gravity. The equilibrium equations are as follows:

$$\sum F_x = 0 : -2 \cdot T_1 \cdot \cos(\alpha_1) \cdot \sin(\beta) - 2 \cdot T_2 \cdot \cos(\alpha_2) \cdot \sin(\beta) + D = 0 \tag{10.1}$$

$$\sum F_y = 0 : 2 \cdot T_1 \cdot \sin(\alpha_1) \cdot \cos(\beta) + 2 \cdot T_2 \cdot \sin(\alpha_2) \cdot \cos(\beta) - S = 0 \tag{10.2}$$

$$\sum F_z = 0 : 4 \cdot T_1 \cdot \sin(\alpha_1) \cdot \sin(\beta) + 4 \cdot T_2 \cdot \sin(\alpha_2) \cdot \sin(\beta) - B_{net} = 0 \tag{10.3}$$

$$\sum M_{xcg} = 0 : (2 \cdot T_1 - 2 \cdot T_1) \cdot \sin(\alpha_1) \cdot \sin(\beta) \cdot d3 + (2 \cdot T_2 - 2 \cdot T_2) \cdot \sin(\alpha_2) \cdot \sin(\beta) \cdot d3 = 0 \tag{10.4}$$

$$\sum M_{ycg} = 0 : (2 \cdot T_1 - 2 \cdot T_1) \cdot \sin(\alpha_1) \cdot \sin(\beta) \cdot d1 + (2 \cdot T_2 - 2 \cdot T_2) \cdot \sin(\alpha_2) \cdot \sin(\beta) \cdot d2 = 0 \tag{10.5}$$

$$\sum M_{zcg} = 0 : (2 \cdot T_1 - 2 \cdot T_1) \cdot \sin(\alpha_1) \cdot \cos(\beta) \cdot d1 + (2 \cdot T_2 - 2 \cdot T_2) \cdot \sin(\alpha_2) \cdot \cos(\beta) \cdot d2 \\ +(2 \cdot T_1 - 2 \cdot T_1) \cdot \cos(\alpha_1) \cdot \sin(\beta) \cdot d3 + (2 \cdot T_2 - 2 \cdot T_2) \cdot \cos(\beta) \cdot \sin(\beta) \cdot d3 = 0 \tag{10.6}$$

Taking the moment equilibrium around the center of gravity makes it apparent that the three moment equations, around the three axes, result in trivial equations that cannot be used to solve for the tension forces and angles. There are three equations (Fx, Fy, Fz) and five variables (T1, T2, α_1, α_2, β) present. Therefore, the general loading case will be split into multiple load cases. In this way, the static analysis can be solved more easily and provide the loading cases that will drive the design of the mooring cables. A simplification for the angles, α_1 = α_2 was made, meaning that each cable has the same orientation to the airship. This simplification also means that the tension in each cable can be set equal. The tension is equally distributed over the cables that need to carry the external loads. Also, the assumption for slack cables still applies. The general load case is split into three individual load cases for the three external loads. Within the three load cases five new distances will be defined, see Table 10.6, that apply to all three load cases. The lengths are only needed for the ground footprint and moment equations, not for force equations. The five new distances can be calculated from L3, airship parameters, and the preset angles. To determine the tension for each load case, the external loads will be used with a range of preset configurations for the angles.

Table 10.6: *Five Distances as Defined for the Simplified Load Cases*

Length	Equation
L1	$\frac{L3}{\tan(\alpha)}$
L2	$\frac{L3}{\tan(\beta)}$
L3	$0.3 \cdot length_{airship} + radius_{airship}$
L4	L1 + $0.4 \cdot length_{airship}$
L5	L2 + $radius_{airship}$

Load case 1

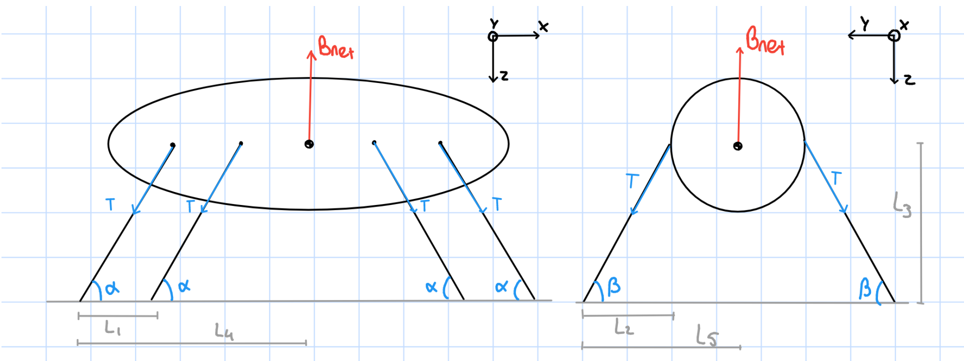


Figure 10.4: *Mooring - Load case 1, Buoyancy force*

The first load case is tension due to the net buoyancy. With the mentioned assumptions the free body diagram is shown in Figure 10.4. The net buoyancy acts in the negative z-direction. The equilibrium equation in z-direction is as follows:

$$\sum Fz = 0 : 8 \cdot T \cdot \sin(\alpha) \cdot \sin(\beta) - B_{net} = 0 \tag{10.7}$$

$$T = \frac{B_{net}}{8 \cdot \sin(\alpha) \cdot \sin(\beta)} \tag{10.8}$$

The net buoyancy of the airship can in essence be arbitrarily set. Therefore the tension will be determined for several buoyancy values. The net buoyancy occurs during operation in the load exchange event. The net buoyancy is around 2% when the permanent ballast is released and 28.9 % $\approx$ 30 % when the 60-ton ballast is exchanged with the payload or vice versa.

Load case 2

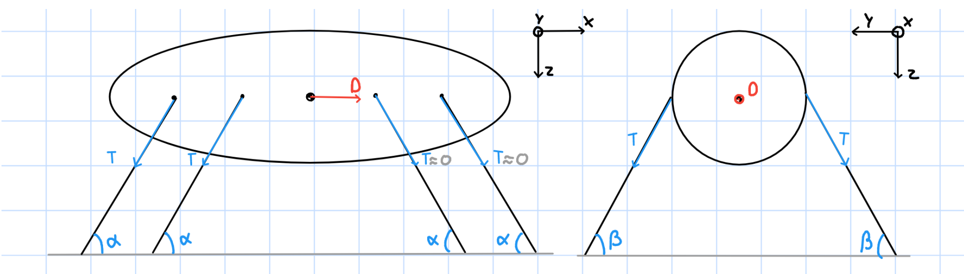


Figure 10.5: *Mooring - Load case 2, longitudinal drag*

The second load case is tension due to longitudinal drag. The free body diagram is shown in Figure 10.5. The longitudinal drag acts in the positive x-direction. The equilibrium in the x-direction is as follows:

$$\sum Fx = 0 : -4 \cdot T \cdot \cos(\alpha) \cdot \sin(\beta) + D = 0 \tag{10.9}$$

$$T = \frac{D}{4 \cdot \cos(\alpha) \cdot \sin(\beta)} \tag{10.10}$$

The longitudinal drag will be the drag due to a 10 m/s headwind during mooring. This is estimated to be around 6191.133 N, according to Equation 10.11, where ρ is density at sea-level, S_{ref} is the airship reference area.

$$D = \frac{1}{2}\rho V^2 S_{ref} C_D \tag{10.11}$$

Load case 3

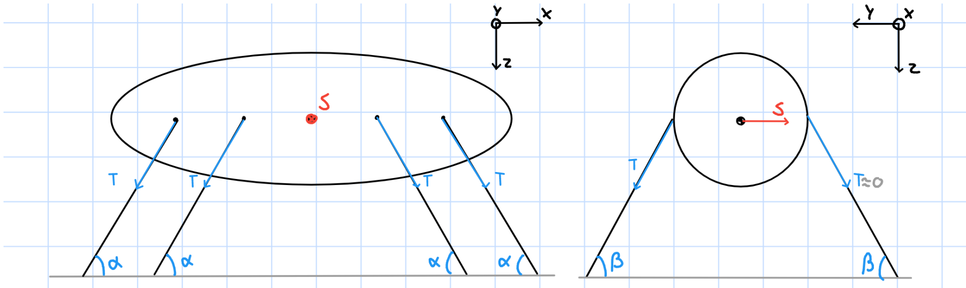


Figure 10.6: *Mooring - Load case 3, side drag*

The third load case is tension due to side drag. The free body diagram is shown in Figure 10.6. The side drag acts in the negative y-direction. The equilibrium in the y-direction is as follows:

$$\sum Fy = 0 : 4 \cdot T \cdot \sin(\alpha) \cdot \cos(\beta) - S = 0 \tag{10.12}$$

$$T = \frac{S}{4 \cdot \sin(\alpha) \cdot \cos(\beta)} \tag{10.13}$$

The side drag will be the drag due to 10 m/s side wind during mooring. This is estimated to be around 521539 N, as shown in Table 5.5.

10.2.2. Analysis and results

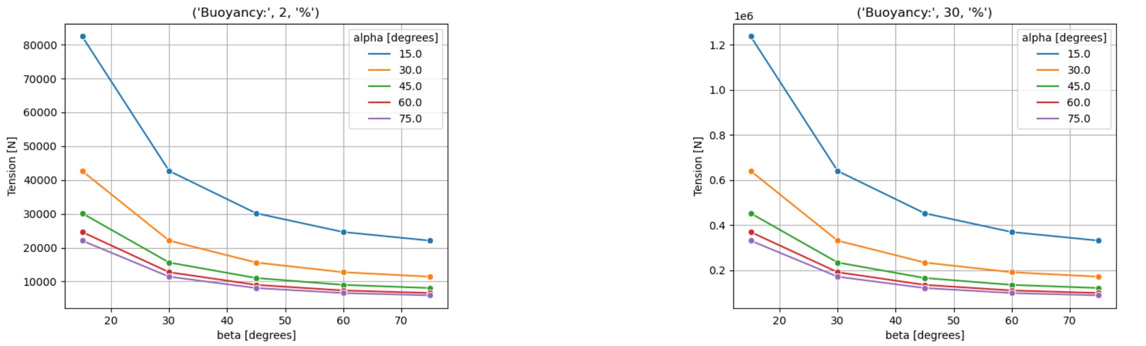
For each load case, an equilibrium equation has been defined. To determine the tension in the cables, the input for the external forces must be known as well as the configuration of the cables, angles α and β. The equations and their inputs are summarised in Table 10.7.

Table 10.7: *Equilibrium Equations for Each Load Case and the External Loads*

Load case	Equilibrium equations	Input	Source
Load case 1	$T = \frac{B_{net}}{8 \cdot \sin(\alpha) \cdot \sin(\beta)}$	2% and 30% of MTOW	REQ-SBST-BAL-04, payload to final MTOW
Load case 2	$T = \frac{D}{4 \cdot \cos(\alpha) \cdot \sin(\beta)}$	D = 6191 N	Equation 10.11
Load case 3	$T = \frac{S}{4 \cdot \sin(\alpha) \cdot \cos(\beta)}$	S = 521539 N	Table 5.5

For each load case the configurations of the cables are the same and the following ranges for α and β are analyzed: $15° \leq \alpha \leq 75°$ and $15° \leq \beta \leq 75°$, with steps every 15 degrees. The extreme angles (0 and 90 degrees) are omitted as this will lead to an invalid equation or infinite values for tension for load cases 2 and 3.

Loadcase 1



(a) *Tension Due to a Net Buoyancy of 2% of MTOW*

(b) *Tension Due to a Net Buoyancy of 30% of MTOW*

Figure 10.7: *Tension Due to a Net Buoyancy of 2 and 30% of MTOW*

In Figure 10.7 the following can be seen: for every combination of alpha and beta (beta on the x-axis, alpha represented by the colored lines), the tension in the cables is shown. It can be seen that the *larger* alpha becomes the *lower* the tension. This is because cables can carry load more efficiently the more the cable and direction of applied force are aligned (z-direction in this case). The same holds for beta in this case. A significant drop can be observed when changing alpha from 15 to 30 degrees, which also holds for beta. Going to larger angles the tension drops further but not at a significant rate. Observed from the graphs, from around 45 degrees for both alpha and beta, the decrease in tension with an increase in angle is limited. To keep tension as low as possible, the following configurations are preferred: $\alpha \geq$ 45 deg, $\beta \geq$ 45 deg, with a margin of 15 degrees the following configurations will be designed for: $\alpha \geq$ 30 deg, $\beta \geq$ 30 deg. This means that the design tension due to buoyancy occurs at $\alpha = \beta = 30°$. For a buoyancy of 2%, the tension is 22093 N and for a buoyancy of 30% the tension is 331391 N.

Loadcase 2

In Figure 10.8 the tension in the cables is shown for every combination of alpha and beta. It can be seen that the *lower* the alpha the *lower* the tension as in this case the drag is horizontal (note the difference with loadcase 1). For beta holds the *larger* the angle the *lower* the tension. A significant drop can be observed when changing alpha from 75 to 60 degrees. Going to smaller angles of alpha the tension drops further but not at a significant rate. When changing beta from 15 to 30 degrees also a significant drop can be seen. Going to larger angles for beta, the tension drops but not at a significant rate. Observed from the graphs, from around 45 degrees for both alpha and beta the decrease in tension with respectively a decrease and increase in angle is limited. To keep tensions as low as possible, the following configurations are preferred: $\alpha \leq$ 45 deg, $\beta \geq$ 45 deg, With a 15 degree margin the following configurations will be designed for $\alpha \leq$ 60 deg, and $\beta \geq$ 30 deg. The maximum tension due to longitudinal drag occurs then at $\alpha = 60$ deg and $\beta = 30$ deg. The tension in the cables is 6191 N which is exactly the drag. This is due to the angle configuration and having four load-carrying cables.

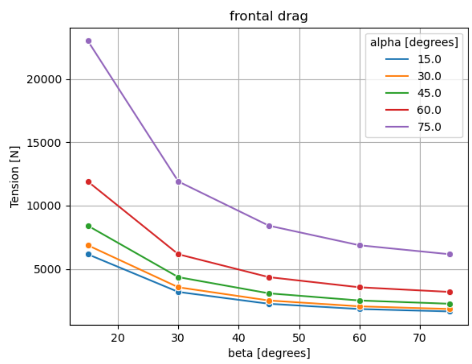


Figure 10.8: *Tension due to a longitudinal drag, imposed by a 10 m/s headwind.*

Load case 3

In Figure 10.9, the following can be seen: for every combination of alpha and beta, the tension in the cables is shown. It can be seen that the *larger* alpha, the *lower* the tension. For beta holds the *larger* the angle, the *larger* the tension. A significant drop in tension can be observed when changing alpha from 15 to 30 degrees. Going to larger angles of alpha the tension tension drops further but not at a significant rate. When changing beta from 75 to 60 degrees also a significant drop in tension can be observed. Going to smaller angles for beta the tension drops but not at a significant rate. Observed is that around 45 degrees for both angles the decrease in tension with respectively an increase in angle and decrease in angle is limited. To keep tensions as

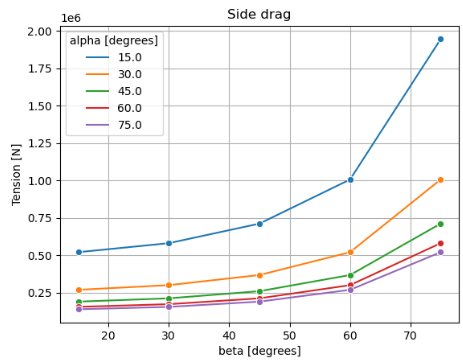


Figure 10.9: *Tension due to a side drag, imposed by a 10 m/side wind.*

low as possible, the following configurations are preferred: $\alpha \geq$ 45 deg, $\beta \leq$ 45 deg, with a 15 degree margin the following configurations will be designed for: $\alpha \geq$ 30 deg, $\beta \leq$ 60 deg. The maximum tension due to side drag occurs then at $\alpha = 30$ deg and $\beta = 60$ deg. The tension in the cables is 521539 N which is exactly the side drag. This is due to the configuration of (60,30) and having four load-carrying cables. Summarising the tensions for each load case and the design configurations in Table 10.8. It can be seen that load case three is the driving load case with the highest tension.

Table 10.8: *Equilibrium equations for each load case and the external loads*

Load case	Design configuration	Maximum tension
Load case 1	$\alpha \geq 30°$, $\beta \geq 30°$	331391 N
Load case 2	$\alpha \leq 60°$, $\beta \geq 30°$	6191 N
Load case 3	$\alpha \geq 30°$, $\beta \leq 60°$	521539 N

Now that the driving load case has been determined the cables can be sized based on the tension and the design configuration. Sizing of the cables is done using a data sheet on galvanized steel wire rope by SWR [2]. This rope can be utilized as a mooring cable and is pulley-suitable. Based on the maximum tension of 521539 N a cable with a 30 mm diameter is needed that has an approximate linear mass of 3.681 kg/m. However, the relative service life of the cable can be extended by applying a safety factor to the working load. A safety factor of 5 can already double the service life[3]. A safety factor of 2.75 will extend the service life by around 50%. Adopting a safety factor of 2.75 allows the cable to carry a tension up to around 1.43 MN. Under this working load the cables can handle most configurations except the $\alpha = 15$ deg and $\beta = 75$ deg case, as shown in Figure 10.6. This means that a cable is needed with a diameter of 48 mm and a mass of 9.420 kg/m. At the configuration of $\alpha = 30$ deg and $\beta = 60$ deg, a value for L3 of 90.3 m, and applying REQ-SBST-MOR-04 the cable length can be determined. The cables will have a length of 188 m leading to a mass per cable of 1771 kg. The finalized design configuration of the multi-wire system is as follows:

Table 10.9: *Tension design configuration for the multi-wire system*

Element	Configuration
Load case 3	$\alpha = 30°$, $\beta = 60°$
Cable length	188 m
Cable mass	1771 kg
Cable diameter	48 mm
Cable tension	521539 N
Safety factor	2.75

10.3. Ballast

Ballast can be provided in multiple forms. The following requirements provide guidance for sizing and defining the ballast used. REQ-SBST-BAL-01 constrains the normal ballast to have a mass of 60 tonnes. REQ-SBST-BAL-02 constrains the normal ballast to have a size equal to the payload, see Section 8.3, meaning 105 m x 10 m x 12 m. REQ-SBST-BAL-03 constrains the normal ballast to be of a solid type. REQ-SBST-BAL-04 constrains the permanent ballast to be at least 3000 kg. The permanent ballast is set at 5000 kg. REQ-SBST-BAL-05 constrains the permanent ballast to be of liquid type.

Note that there are two ballast types mentioned. The first type is normal ballast. This is the ballast that is taken onboard to replace the 60-tonne payload. This ballast is needed to ensure that the airship can operate around neutral buoyancy during a large part of the operation. The second type is permanent ballast. Permanent ballast is the ballast that is used to make the airship slightly heavy and to provide the net buoyancy force during mooring. The net buoyancy is then obtained by unloading the permanent ballast first. Since the permanent ballast is of a liquid type, the ballast can also be used as dump able ballast during emergency situations.

[2] https://www.steelwirerope.com/WireRopes/Galvanised/6x36-IWRC-wire-rope.html (Accessed on: 16/06/2024) [3] https://www.deruiterstaalkabel.nl/wp-content/uploads/Usha-Martin-User-Manual1.pdf (Accessed on: 16/06/2024)

TABLE 5-1

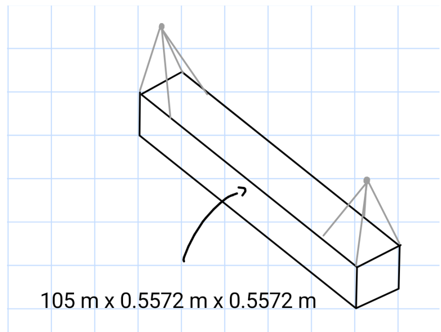
COMMON BALLAST MATERIALS

Material	Volume to equate ballast weight					
	Density		Phase I,		Phase II,	
	Kg/m3	lbs/ft3	m3	ft3	m3	ft3
Water	1000	62.4	29.5	1042	119	4200
Earth	1840	115	16.0	565	64.3	2278
Concrete	2400	150	12.3	433	49.5	1747
Steel	6250	390	4.7	167	19.0	671

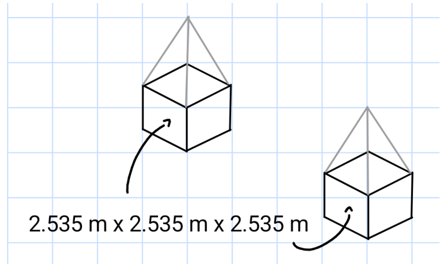
Figure 10.10: *Common ballast materials [56]*

Concrete and steel could be viable ballast materials, however, they are not sustainable compared to soil or sand. Concrete and steel would have to be produced or be obtained as a residual material from other concrete and steel processes. Soil has the advantage that it is widely available, especially in locations where new wind farms are being built. Wind turbines will have to be anchored in the ground and the earth obtained from that process could be used by the airship as normal ballast. In this way, the earth can be reused in a functional way. Utilizing soil as ballast material for the normal ballast will result in the following ballast sizing: the payload of 60 tons must be replaced with 60 tons of soil which takes up approximately 32.6 m^3. To ensure equal ballast distribution along the payload bay the length of the container will be set to 105 m. If height and width are assumed equal the container will have the following dimensions 105 m in length, and 0.5572 m in width and height, see Figure 10.11a. Another option could be to separate the ballast in 2.535 m x 2.535 m x 2.535 m containers and have them placed at each side of the payload bay (in the longitudinal direction), see Figure 10.11b. Technically the sizing of the containers is correct but designing new containers is not efficient as standardized containers for transport are widely available. A good option for solving this problem is by utilizing ISO (global) standard containers [4]. The 20-foot standard height containers have an internal volume of around 33 m^3 and can carry up to around 30500 kg or 30.5 tons. Building upon the preference for two separate containers, see Figure 10.11b, two containers of this type both with a size of 6.058 m in length, 2.438 m in width, and 2.591 m in height will suffice. This allows the airship to utilize standardized containers and handle the ballast in an easy and standardized way.

The permanent ballast will be water. Water is easily disposed of and non-toxic. Water can be dropped in case of emergency but can only make the airship lighter. Hydrogen can also be vented but is a critical source for the airship. Hydrogen will make the airship less buoyant when vented, and should only be used in extreme circumstances. Lastly, water is more sustainable as opposed to utilizing i.e fuel as ballast. Therefore water will be chosen as permanent ballast. Water will be stored in cylindrical tanks or large water bags. Cylindrical tanks are rigid and can be standardized more easily. However, they require more mass and materials than water bags. Water bags are flexible but are harder to hoist and maneuver when at a considerable size. To ensure scalability within the ballast design, the option of water tanks is chosen. The water will have a mass of 5 tons meaning the tanks will take up 5 m^3. This is a small size and can easily be fit into the airship. It is preferred to have two tanks both on each side of the payload bay, but now in the lateral direction. This will lead to two cylindrical water tanks that each hold 2500 liters of water. The tanks will have a size of 1.5 m in height and 0.728 m in radius. Height and width are approximately the same.



(a) *Normal ballast replacing the payload - one narrow container*



(b) *Normal ballast replacing the payload - two box containers at each side of the payload bay*

Figure 10.11: *Simple sizing of ballast container size*

[4] https://www.icontainers.com/help/20-foot-container/

10.4. Ground Infrastructure

The ground infrastructure needed to ensure mooring capabilities will have a certain ground footprint. The eight cables will have to be anchored to the ground. In the current configuration the ground footprint is of rectangular size, see. From the final configuration, $\alpha = 30°, \beta = 60°$ and a cable length of 188 m, the ground footprint can be determined. Using the equations for L4 and L5 as provided in Table 10.6 and multiplying both by two will result in the length and width of the rectangular footprint. In Figure 10.12 the ground width and ground length are given for the aforementioned ranges for alpha and beta. The smaller the angles for alpha and beta the larger will the ground footprint be, see Figure 10.12.

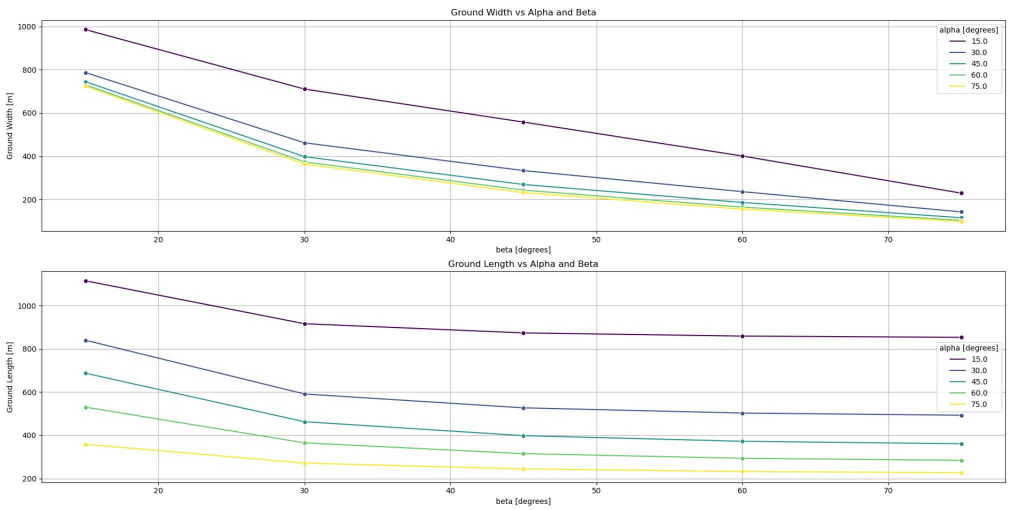


Figure 10.12: *Ground footprint properties.*

With the design configuration of $\alpha = 30°, \beta = 60°$ the ground footprint will be 236 m in width and 501 m in length. This is a considerable area. It is desired to limit this area. The area can be limited by increasing both angles as much as possible. Alpha can be increased to $75°$ and beta is already at its maximum of $60°$. With this new configuration, the ground footprint is scaled down to 155 m in width and 232 m in length. The cables will be 107 m long and have a mass of 1009 kg. Looking at the tension in the driving load case Figure 10.9, the new configuration results in a lower tension than designed for. Implementing the new configuration allows for minimizing the ground footprint while still maintaining the load-carrying capabilities of the cables.

Table 10.10: *Final design configuration for the multi-wire system.*

Element	Configuration
Load case 3	$\alpha = 75°$, $\beta = 60°$
Cable length	107 m
Cable mass	1009 kg
Cable diameter	48 mm
Cable tension	2.70E5 N
Safety factor	2.75

Regarding other ground infrastructure, no designs are given but the infrastructure needed is defined.

Needed ground infrastructure

To successfully operate an airship, several parts of infrastructure are needed. These include the field for landing and take-off at base as well as the hangar. Since the airship utilizes hydrogen as both a lifting gas and as fuel, specific attention is needed for the handling of hydrogen, requiring specialized infrastructure such as storage tanks and pumps. Especially with hydrogen, safety measures have to be taken.

For the airship to land and take off, a field is needed. The field needs to be big enough to house the airship and all other parts of its infrastructure. Even though no pavement is needed for the airship itself, pavement might be needed for the transportation of ground personnel, ballast, or other vehicles supporting the airship on ground. In principle, any sufficiently sized field is enough for the airship to land. Such a field is also needed during loading and unloading of payload and ballast. The size must be able to accommodate the aforementioned ground floor print of the mooring infrastructure.

Whenever the airship is not needed in operation for extended periods of time, needs maintenance, or is being built, it will reside in a hangar. The hangar is supposed to shield the airship from most outside influences. Therefore, the hangar must be able to withstand wind, rain, and sun. During storms, leaving the airship outside would not be advisable, as the wind could tear it from its mooring cables, or damage it beyond repair. Currently, several hangars for airships exist around the world. Most of these are either in use or completely neglected. It is possible that the current size of hangars is not sufficient for the size of our airship. Therefore, it would be best to build a new hangar for the airship. The minimum area required for the hangar is around 11000 m^3 at 50 meters high. Note that this is without clearance and is essentially just the airship's footprint and height. The area needed will be larger than 11000 m^3.

For the handling of hydrogen, storage tanks will be needed. The hydrogen will need to be transported to the airship, which will be done by connecting the airship to the tanks. Just like in normal aviation, static electricity can build up on the airship will need to be kept in mind whilst refueling the airship. Therefore, the airship and the hydrogen station will need to be grounded during refueling. An extensive hydrogen infrastructure is needed to ensure hydrogen can be kept and handled safely.

10.5. Design overview

To finalize the design of the three elements all major characteristics are summarised and presented in Table 10.11

Table 10.11: *Final design configuration for the multi-wire system*

Design Element	Properties
Mooring infrastructure	
Mooring method	Multi-wire system
Cable working load	270 kN
Cable design load	1.434 MN
Cable length	107 m
Cable mass	1009 kg
Number of cables	8
Cable orientation	$\alpha = 75°, \beta = 60°$
Safety factor	2.75
Ballast	
Normal ballast	Ground, 2x standardised ISO 20-feet containers
Permanent ballast	Water, 2x cylindrical tanks (1.5 length, 0.728 radius)
Ground footprint of mooring infrastructure	
Ground width	155 m
Ground length	232 m

10.6. Limitations and Recommendations

Mooring infrastructure

1. The buoyancy force applied during mooring was assumed based on the requirements for ballast, leading to a range of static values for buoyancy that does not really change with a change in airship design. A method should be sought that can help determine the buoyancy force as a function of other subsystem parameters. An approach can be detemined to check moment equilibrium around anchor points.
2. A static analysis has been performed under constant point loads. In reality, loads are seldom point forces but are distributed over an area, especially drag forces. In a more extensive structural analysis, distributed loads should be considered.
3. The static analysis provides only information on equilibrium conditions, it is advised to perform a dynamic analysis. This way, the behavior and movement of the airship as well as acceleration loads can be determined.
4. No lifetime is provided for the mooring cables, meaning that the method assumes cables are strong enough throughout their whole lifetime. Fatigue and load cycles should be analyzed to determine how long the mooring cables can be used. This is important for operations, as reliable and maintained cables are of high importance for safety.
5. The load cases were considered individually and no combined load case was considered. Stepping away from ideal cases can help define the tension in the cables in more realistic scenarios.

6. At the moment cables are considered in-extensible. FEM could be utilized to determine how the cables deform under the applied loading.

Ballast

1. Ballast is simply sized at the moment. The ballast does fit in the payload bay. However, how the payload bay exactly constrains the ballast is not known. The clamping mechanism used for the wind turbine blade cannot be applied directly to the ballast, due to a difference in dimensions and standardization. Concepts should be developed on how to constrain the ballast.

Ground infrastructure

1. Ground infrastructure for airships consists of many different elements: the anchoring points on ground, a hangar for storing for long periods of time, a field to take off and land from and lastly infrastructure needed to handle hydrogen. The ground footprint due to mooring has been provided, which results in a requirement for the field size. However, other parts of ground infrastructure such as the hangar and field should also be sized. It is advised to determine if and what ground infrastructure is needed per sub-phase. In this way, a proper collection of the ground infrastructure used during operation can be obtained.

10.7. Sensitivity Analysis for Mooring and Ballast

The tension in the cables is dependent on the limiting load case, which is tension due to side drag as induced by side wind. An increase in side wind can have a dramatic effect on the tension the cables have to withstand. To determine this a sensitivity analysis is performed on the wind speed to examine its influence on both the design and the working load.

Table 10.12: *Sensitivity Analysis on Windspeed*

Increase	-50%	-25%	-10%	10%	25%	50%
Cable design load	-74.99 %	-43.74 %	-18.97%	21 %	56.3%	125%
Cable working load	-74.99%	-43.74%	-18.97%	21%	56.3%	125%

It is assumed that the shape of the airship is constant and that only the wind speed is changed. Increasing the wind speed with 50% more then doubles the tension force, while decreasing the wind speed with 50% decreases the tension force by 75%. The two loads have the same percentage change as the cable working load is just the cable design load multiplied by a safety factor of 2.75. The sensitivity analysis has shown that the increase in the wind speed leads to a high increase in the cable loads. The absolute change of the loads is higher than when the wind speed is decreased, which means that it is critical to consider all possible increased values of the wind gusts. The change of the cable loads is quadratic, and therefore a sharp increase in the wind gust can yield extreme loads. It is vital to consider this when determining the operating conditions of the airship.

11 Operations

11.1. Concept of operations

Before the mission can be performed, an overview of the general mission phases is needed. This is to identify phases during the operation of the airship, that are needed to perform the mission successfully. Besides the general mission phases different sub-phases must be identified and explained in more detail to indicate how the airship will operate at different phases of the operations. Operations deals with how the mission is executed once the airship is in use.

11.1.1. General Operational Phases

From the functional flow diagram, overall operational functions can be identified. The description of the operational phases will be based on the functional flow diagram and expanded upon in more detail. The project team identified different operational functions and together with the flight phase definitions as obtained from the CAST/ICAO Common Taxonomy the operational sub-phases can be defined.

Operational phases as defined by the team:

- Making Flight Preparations (O.1)
- Perform Take-Off (O.2)
- Travelling/Cruise (O.T)
- Load Payload (O.3)
- Unload Payload (O.4)
- Perform Landing (O.5)
- Perform Post-Flight Procedures (O.6)
- Abort flight (O.A)

The different phases of flight as defined by the CAST/ICAO Common Taxonomy [57, p.5-11]:

- Standing (STD): 'Prior to pushback or taxi, or after arrival, at the gate, ramp, or parking area, while the aircraft is stationary.'
- Pushback/Towing (PBT): 'Aircraft is moving in the gate, ramp, or parking area, assisted by a tow vehicle (tug).'
- Taxi (TXI): 'The aircraft is moving on the aerodrome surface under its power prior to takeoff or after landing.'
- Take-Off (TOF): 'From the application of takeoff power, through rotation and to an altitude of 35 feet above runway elevation.'
- Initial Climb (ICL): 'From the end of the Takeoff sub-phase to the first prescribed power reduction, or until reaching 1,000 feet above runway elevation or the VFR pattern, whichever comes first.'
- En-route (ENR): 'From the completion of Initial Climb through cruise altitude and completion of controlled descent to the Initial Approach Fix'
- Maneuvering (MNV): 'Low altitude/aerobatic flight operations.'
- Approach (APR): 'From the Initial Approach Fix to the beginning of the landing flare.'
- Landing (LDG): 'From the beginning of the landing flare until aircraft exits the landing runway, comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing.'

Note that the definitions as provided by CAST/ICAO Common Taxonomy [57] focus on fixed-wing powered land and rotor-craft operations. ”The intent is to provide “target” taxonomies and definitions for adoption by organizations planning for, and implementing new safety systems” [57, p.1]. However, they can form a basis for the definition of the operational sub-phases of the airship. Three operational main phases have been identified which are: *OPS-Phase-I*, traveling from base to payload provider, *OPS-Phase-II*, traveling from payload provider to payload receiver, *OPS-Phase-III*, traveling from payload receiver back to base. Furthermore, the following eight operational sub-phases, with their abbreviations, are defined as taxi (TXI), take-off (TOF), climb (CLM), cruise (CRS), descent (DC), load exchange (LEX), landing (LDG), (un)mooring (MOR). It is important to note that they do not necessarily occur in this order. An overview of the main mission to be flown is shown in the Figure 11.1. In Figure 11.1 the different sub-phases are indicated by their abbreviations. The three main operational phases are indicated as well. The center of operations stays in contact from Phase I to Phase III meaning it is present the whole time, overseeing the operation. Air traffic control will also be present during all phases from exiting the hangar to stowage of the airship. Furthermore, when more than one trip from the payload provider to the payload receiver is required Phase II can be repeated. This is indicated by the loop from Cruise in Phase III to Cruise in Phase I.

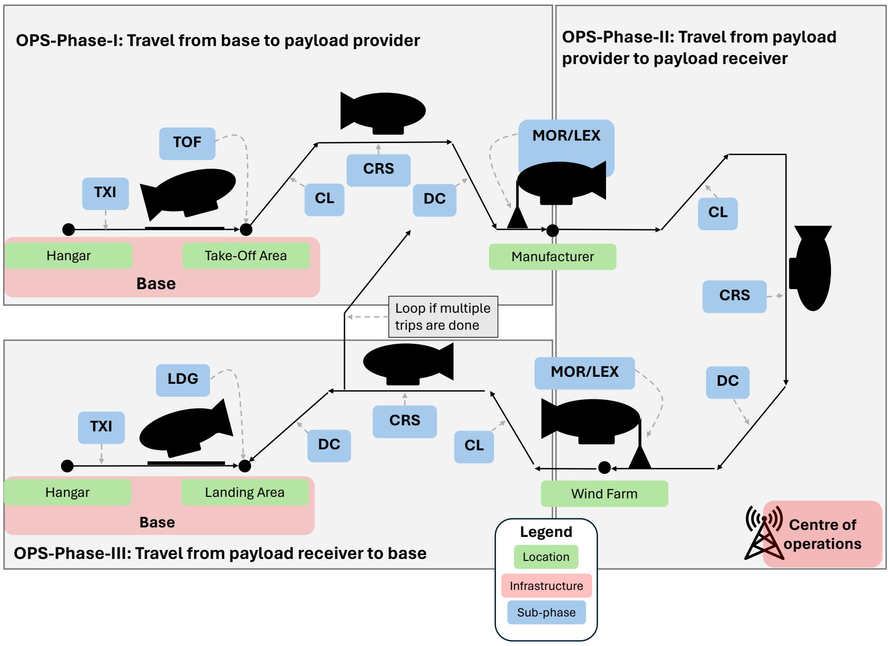


Figure 11.1: *General Mission Overview showing the destinations (Manufacturer and Wind Farm) and different (sub)phases throughout the mission.*

11.1.2. Description of operational sub-phases

As indicated in Subsection 11.1.1 there are eight operational sub-phases. To obtain a complete view of the operations, it is necessary to describe the sub-phases in more detail. A visual is provided, see Figure 11.2, to show the connections between sub-phases and if the sub-phases are performed under static heaviness or static lightness conditions.

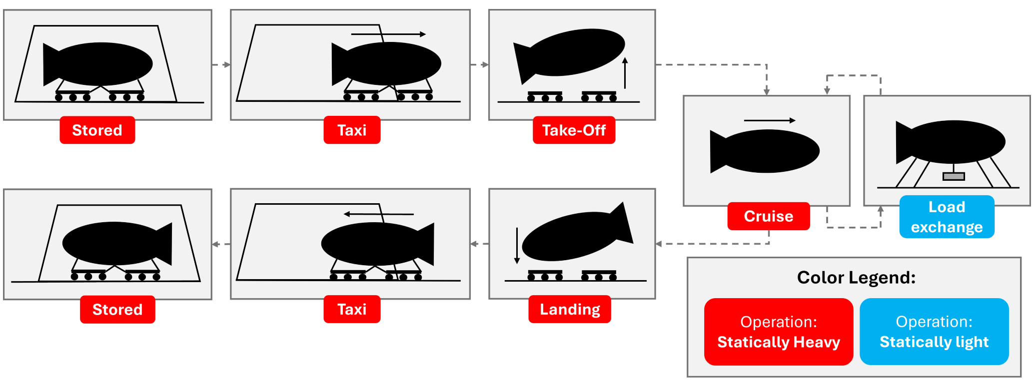


Figure 11.2: *Operational sub-phases from phase to phase*

The *first sub-phase* is *taxiing*. Taxiing is done from the hangar to the take-off/landing area. The airship is stored on two large carts on which the airship is moved in and out of the hangar. The airship is connected to these carts via cables that attach to the mooring points on the airship. Taxiing is done un-powered to prevent unnecessary loads and movements.

The *second sub-phase* is *take-off*, in which the airship starts ascending from the take-off area until a certain clearance altitude is reached. Before the take-off can take place the cables are disconnected from the cart and the engines are turned on. The take-off is done utilizing vectored thrust by rotating the propeller engines upward.

The *third sub-phase* is the *climb*, in which the airship starts ascending towards cruise altitude, the airship ascends with a minimal climb rate of 2 m/s. The climb is performed until the cruise altitude is reached. The climb is performed at MTOW conditions, having normal ballast and permanent ballast is place.

The *fourth sub-phase* is *cruise*, this is the sub-phase in which the airship will operate most of the mission. The airship is designed to cruise at 80 km/hr at 75% of power.

The *fifth sub-phase* is *decent*, the airship descends to the required altitude at which load exchanges or landings can be performed. The airship must descend to around 70 m above the ground.

The *sixth sub-phase* is *mooring*. The airship, when at the required height, will lower its cables. When all cables are connected, the airship lowers the permanent ballast to obtain static lightness to ensure the cables are in tension. The airship will perform mooring utilizing cables anchored to the ground, see Section 10.2. For unmooring the airship, the process is done in reverse. The permanent ballast is hoisted up to obtain static heaviness, the cables are slackened, and the cables can be disconnected.

After the mooring has been done, the *seventh sub phase*, namely the *load exchange*, can take place. This can refer to either loading or unloading the payload and or ballast. Whenever the payload is unloaded, the ballast should be loaded on the airship and vice versa.

The *eight sub phase* is *landing*. The airship will descend from the preset altitude for mooring, which is around 70 meters above the ground. The airship will decent and touch down on the two carts that taxi the airship in and out of the hangar. After touching down on the carts the airship is fastened with cables.

All sub-phases, except *mooring* and the *load exchange*, are performed under static heaviness conditions. This is needed to ensure control close to the ground and to prevent the airship from overshooting its pressure height limit. It also allows to decent more easily if there is an emergency. The (un)mooring and load exchange phases are performed under static lightness. This is to ensure a stable platform for loading and unloading. Tension must be on the mooring cables to restrain the airship from moving in unwanted directions.

An important part of the operations occurs at the load exchange sub-phase. During this sub-phase, payload and ballast will be interchanged to either pick up or deliver the payload. The actions performed during this phase are as follows:

1. The airship descends to an altitude of 70 meters above the ground.
2. At the desired altitude the airship will hover utilizing the propeller engines.
3. When stable the airship will lower the mooring cables.
4. When the mooring cables are down on the ground, the ground crew will connect the cables to the anchor points.
5. When connected to the anchor points, the airship will lower the permanent ballast until the ground carries the weight of that ballast.
6. When the permanent ballast is on the ground the airship will go from being statically heavy to being statically light. In this way, the cables can be loaded in tension.
7. When stably moored the payload or normal ballast can be hoisted down.
8. Once on the ground the payload is interchanged with ballast or the other way around depending on the phase of the operation. The payload or ballast is then hoisted back up.
9. Once the payload or ballast is secured inside, the permanent ballast can be hoisted up again. In this way the airship becomes statically heavy again.
10. Once statically heavy the mooring cables can be slackened and disconnected.
11. Once disconnected the cables can be hoisted up and the airship can climb away to continue operations.

11.2. Operational characteristics

To be able to carry out the transport operation is it important to know where the airship will operate from, where it will travel to, how far the airship will need to go etc. An early look at the operation of the airship is provided in Section 2.1. In this section, the operation will be analyzed in more detail. From the market analysis, it became apparent that Europe is a promising market when it comes to wind power capacity. The wind power capacity in Europe is predicted to reach 393 GW in 2030 and a large part will be provided by onshore wind energy. The operations of the airship will be centered around the onshore wind market in Europe. Within this section, a dataset collected by the team in which locations of manufacturers and wind farms is used.

11.2.1. Manufacturers

The first important stakeholders are the wind turbine blade manufacturers. Those are the stakeholders that will provide the airship with the payload it has been designed for. The biggest manufacturers of blades in Europe are *Siemens Gamesa Renewable Energy*, *Vestas wind systems A/S*, see Table 2.4, and *LM Wind power*. For those three manufacturers, some major locations are collected.

Most manufacturers are located in the north of Europe, in the United Kingdom or in the south-west of Europe. For each location, the average wind speed and wind direction are gathered. The wind direction is determined by looking at wind roses at each location. The wind rose shows from which direction the wind comes from. The manufacturers are abbreviated in Table 11.1 as follows: Siemens Gemesa (SG), Vestas wind systems A/S (VS) and LM wind power (LM). Wind data is obtained from the global wind atlas [1].

Table 11.1: *Wind characteristics at different manufacture locations*

Manufacturer + location	Average Windspeed @ 100 m	Wind direction
SG - Aalbourg	8.14 m/s	270° : West
SG - Brande	8.13 m/s	$190^\circ \leftrightarrow 305^\circ$: West/South-west
SG - Cuxhaven	8.91 m/s	$190^\circ \leftrightarrow 305^\circ$: West/South-west
SG - Alexandra Dock	8.44 m/s	$190^\circ - 265^\circ$: West
VS - Nakskov	8.86 m/s	$225^\circ - 295^\circ$: West
VS - Hansensvej	9.11 m/s	$190^\circ - 305^\circ$: North-west/West/South-West
VS - Taranto	4.77 m/s	$280^\circ - 10^\circ$: North/Northwest
VS - Daimiel	5.24 m/s	$225^\circ - 280^\circ$ and 45° : West/North East
VS - Newport	8.14 m/s	$225^\circ - 260^\circ$: South-West
LM - León	4.63 m/s	$225^\circ - 260^\circ$: South-West
LM - Castellón	5.76 m/s	195° and 310° : North-West/South-West
LM - Cherbourg	8.18 m/s	$190^\circ - 270^\circ$: South-West
LM - Goleniów	6.93 m/s	$190^\circ - 270^\circ$: South-West

The wind mostly comes from the South-West, West or North-West. With an average wind speed of 7.32 m/s. This data is based on the 10% windiest areas in a 9 by 9 km grid centered around each manufacturer. The airship will performing loading and unloading at a height of around 70 meters. Including a 2-3 m/s margin airships will have to perform in wind speeds of minimum 10 m/s. The mooring infrastructure will have to be positioned in West or South-West direction. This is to ensure side-wind is as low as possible.

11.2.2. Operational ranges

It is required to establish the location of wind farms across Europe, to know which areas have the highest demand for airships. In Figure 11.3 the locations of different wind farms across Europe are presented.

Figure 11.3: *Location of on-shore wind farms across Europe*

In Norway and the United Kingdom, most of the wind farms are located close to shore and in the North. In Germany and France the wind farms are mostly scattered across the country. To determine how far the wind farms are located from the manufacturers, distances for some arbitrary routes can be determined. Routes were chosen from manufacturer to wind farm in the same country, or from manufacturer to a neighboring country. From manufacturer to country, ranges are given instead of one value. The distances for the following routes were determined:

[1] `https://globalwindatlas.info/en/` (Accessed 16/06/2024)

Table 11.2: *Approximate distances from manufacturer to windfarms*

Route	Approximate Distance [Km]
SG Borupvej Denmark → Storheia Windfarm	917
SG Borupvej Denmark → Markbygden Sweden	1202
SGBorupvej Denmark → Clyde windfarm	772
SG lexandra Dock UK → Clyde windfarm	311
VS Newport UK → Clyde wind farm	586
SG Borupvej Denmark → Ergesund wind farm	348
SG Borupvej Denmark → Bjornbeget Windfarm	804
SG Cuxhaven Germany → Germany (South West)	433
SG Cuxhaven Germany → Germany (South East)	560
VS Newport UK → Ireland (South West)	573
VS Newport UK → North Ireland	578
LM Goleniow Poland → Sweden (South East)	496
SG Cuxhaven Germany → South Sweden	606
VS Daimiel Spain → Araba wind farm	428
VS Daimiel Spain → Gamesa, Teba wind farm	260
VS Daimiel Spain → Spain (North East)	341
LM Tourlaville France → Germinon wind farm	427
LM Tourlaville France → Vergnet wind farm	739
LM Tourlaville France → East France	504
LM Goleniow Poland → South Germany	658

From the table it can be seen that distances range from 260 km to 1202 km. Note that those distances are one way only. With a limited range of the airship, limited trips can be done. Short haul is defined in this data set as 600 km and lower. Short haul distances are around 461 Km, while long haul, 600 km and higher can go up to around 814 km. Note that these distances are in a very broad range and differ from location to location. Looking at Figure 11.3 potential locations for bases of operations can be determined.

To be as central as possible all across Europe, five potential base locations are determined at the locations as shown in Figure 11.4. Those base locations allow the operation to be performed in Northern-Europe (Denmark, Sweden, and Germany), Western-Europe (France and the United Kingdom), and Southern-Europe (Spain and Portugal).

Figure 11.4: *Potential base of operation locations in Europe*

11.2.3. Weather conditions

Weather is an airship's worst nightmare. Airships are very prone to harsh weather conditions. This is mostly due to the large size and low speeds of airships. Wind gusts, high wind speeds, and random turbulence pose a great challenge in handling airships. In essence, all weather conditions are not in the airship's favor, therefore the limits in which the airship can operate will be provided.

Wind conditions

The airship will have to deal with wind conditions in most phases of the operation. The most important phases are the cruise and the load exchange. The airship is designed for cruising at 2000 m, at 80 km/h of airspeed, see Section 7.3. With a direct head-wind of 22.22 m/s, the airship would not be able to operate. Figure 7.5 in [58] shows the mean wind speed at different altitudes during different seasons. The wind speeds at 2000 m are well below the limit of 22.22 m/s and the airship will be able to operate during all seasons. For the load exchange phase the airship will have to operate in wind speeds of around 7.32 m/s, see Section 11.2. The mooring infrastructure used during this phase can handle wind speeds of up to 10 m/s side wind, see Section 10.2. The mooring infrastructure will have to be put in one of the following wind directions, South-West, West or North-West. This is to limit the side wind as much as possible.

Temperature
The temperature is of influence on the lifting gas. The pressure height as described in Section 4.2 changes under changing atmospheric conditions. The pressure height is determined for temperatures between 15 and 45 degrees and for pressures between 94000 Pa and 106000 Pa. Operation over dry land with a hot surface should be avoided. The airship cannot operate properly in environments with a combination of low pressure, high temperature and where the airship can get superheated easily.

11.3. Communications

Although the airship is controlled by human operators inside, as resulted from the trade-off in Section 6.6, there still needs to be a near-constant communication flow within the system and from the environment to the system and back. This starts before operations when a wind farm operator needs wind turbine blades to construct, expand, or repair their farm. They contact the blade manufacturer, who then contacts the system Command Unit to arrange transport. The Command Unit creates a flight plan and distributes it to the relevant stakeholders, after which the operations loop starts. In this loop, there is close contact especially between the airship crew through the Communications Unit with the different crews of the ground operations and air traffic control. After operations are concluded, all parties should evaluate the performed mission to improve performance, decrease cost, or prevent accidents in future missions. Figure 11.5 shows the communication channels in the form of a flow diagram.

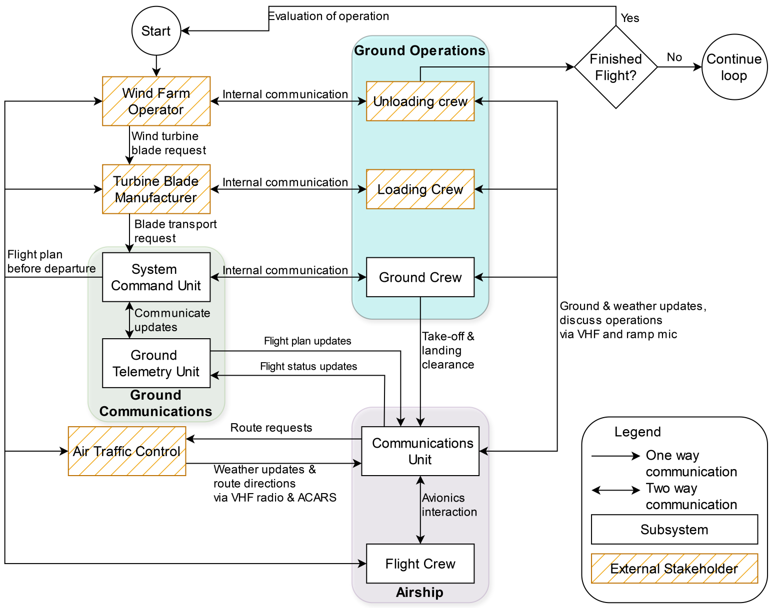


Figure 11.5: *Schematic overview of the communication channels before and during operations.*

11.3.1. Comparisons to Truck Transport

The biggest advantage that airship transport provides over truck transport is that airships do not depend on road infrastructure. 'Transporting heavy/oversized cargo via roads can inflict injuries to people and damage to materials' [6], mainly because multiple stakeholders are present. Think of normal traffic, private properties, road infrastructure, public services helping with road closures, and the transport crew itself. Sometimes rough terrain and narrow roads will increase the risk of injury and damage even more. The airship however will be present in airspace and only has to deal with itself, air traffic, and big cities. Risk of injury and damage is very low allowing for safer transport by bypassing constraining infrastructure and bystanders. As can be seen in Table 11.2 there are a lot of different routes and locations. For truck transport each of those routes has to be planned individually as the operating conditions differ a lot from route to route. For airships, however, this planning takes less time as airships can fly straight from point A to B and only have to account for weather. This eliminates a lot of the required planning time for wind turbine blade transport.

As mentioned, weather plays an important role for airships while this is less important for trucks. For airships, the weather plays a role in the performance of the airship, temperature, pressure, and wind conditions influence the pressure height and the speed at which the airship can operate. For trucks, weather impacts the blade as the blade is transported unprotected in open weather. The airship has an internal payload bay that provides protecting from environmental factors providing a safer transport of the blade over trucks.

Overall airships can reduce the planning time needed for certain routes, can bypass infrastructure constraints and bystanders, and provides a safer environment for transporting wind turbine blades. Both airships and trucks need to be stored somewhere, the infrastructure needed for airships however will be larger than is needed for trucks, e.g. large hangars and open areas. Therefore, multiple central bases as provided in Figure 11.4 would be needed and can be a limiting factor in where the airship can operate. Lastly, weather will limit in what areas the airship can operate and should be continuously monitored.

12 Sensitivity Analysis

In order to get a better insight into the design, a sensitivity analysis can be conducted. A sensitivity analysis gives insight into the uncertainty of output parameters with a variation in input parameters. Three main mission parameters will be varied, and the change in subsystem parameters will be recorded. The results of this will be discussed thereafter.

12.1. Sensitivity Analysis per Sub-system

To analyze the sensitivity of every subsystem, three important mission parameters were varied. The MTOW, cruise speed, and altitude were in- or decreased by 10, 25, and 50%. Subsequently, the effects of this change on different subsystems was documented, see Table 12.1. The largest effects will be discussed.

12.1.1. MTOW

Changing the MTOW has a large impact on the system, an increase shows an increase in all values across the board. This is largely due to the volume, which has to increase to keep up with the increases mass. This in turn causes an increase in overall dimensions, and as such all masses, power, and drag increase. The opposite is also true when the MTOW decreases. The location of the cg, zero lift drag coefficient, and the lift slope vary little. For the latter two this is because they are normalized. For the cg however this is because the increase in mass in quite uniform all over the ship.

12.1.2. Cruise Speed

Varying the cruise speed primarily impacts the propulsion system. This is due to the fact that the power required by the airship varies with the cube of the airspeed. Another notable change is that the horizontal tail surface changes by almost 50%, but the vertical tail remains unchanged. This is because all forces governing the vertical tail size change with the velocity, but the horizontal tail size is governed the buoyancy and weight which do not depend on the airspeed, leading to the change in surface area. The zero lift drag is changed due to the change in Reynolds number. Finally, the lift slope changes because the horizontal tail surface changes and this is not accounted for in the normalization which used the volume of the airship.

12.1.3. Altitude

The most remarkable change due to varying the altitude is the mass of the structure. The exact cause of this effect should be investigated further. Another factor that changes, is the overpressure. This is because the overpressure is defined at 100 m above the pressure height, and the pressure gradient is not constant at the different altitudes.

12.2. Conclusions

The sensitivity analysis was conducted to gain insight into the design parameters. One of the main take-aways is that any increase in MTOW will snowball into large increases in system mass. The cruise velocity has a smaller effect on most parameters, however it has an extremely large effect on the propulsion and power system. Changing the altitude had some mixed effects; in further design, a deeper look into its optimazation should be taken. It was however noted that changing the altitude produced strange effects, that should be looked into in the future.

Table 12.1: *Sensitivity Analysis*

Subsystem	MTOW						V_{cruise}						Altitude					
Parameter	-50%	-25%	-5%	+5%	+25%	+50%	-50%	-25%	-5%	+5%	+25%	+50%	-50%	-25%	-5%	+5%	+25%	+50%
Max Power	-17%	-13%	-5%	5%	12%	24%	-69%	-45%	-21%	26%	74%	182%	3%	1%	1%	-1%	-1%	-3%
Power & Propulsion Mass	-17%	-13%	-5%	5%	13%	25%	-70%	-46%	-21%	26%	75%	185%	3%	1%	1%	-1%	-1%	-3%
Fuel Consumption	-17%	-13%	-5%	5%	12%	24%	-69%	-45%	-21%	26%	74%	182%	3%	1%	1%	-1%	-1%	-3%
Lateral Drag Force 5m/s	-33%	-24%	-6%	6%	15%	29%	0%	0%	0%	0%	0%	0%	-6%	-3%	-1%	1%	3%	6%
Lateral Drag Moment 5m/s	-46%	-38%	-9%	9%	23%	46%	0%	0%	0%	0%	0%	0%	-9%	-4%	-2%	2%	5%	10%
Zero Lift Drag	0%	0%	0%	0%	1%	1%	13%	4%	1%	-1%	-2%	-4%	2%	-1%	-1%	-1%	0%	0%
Lift Slope	-3%	-1%	0%	0%	1%	2%	35%	9%	3%	-2%	-4%	-7%	0%	0%	0%	0%	0%	0%
Length	-18%	-8%	-3%	3%	7%	13%	0%	0%	0%	0%	0%	0%	-3%	-2%	-1%	1%	2%	3%
Horizontal Tail Surface	-36%	-17%	-7%	7%	16%	32%	47%	12%	4%	-3%	-6%	-9%	-6%	-3%	-1%	1%	3%	7%
Vertical Tail Surface	-33%	-16%	-6%	6%	15%	28%	0%	0%	0%	0%	0%	0%	-6%	-3%	-1%	1%	3%	6%
CG location	1%	0%	0%	0%	0%	1%	1%	0%	0%	0%	1%	3%	0%	0%	0%	0%	0%	0%
Tail Mass	-35%	-17%	-6%	6%	16%	30%	25%	6%	2%	-1%	-3%	-5%	-6%	-3%	-1%	1%	3%	7%
Envelope Mass	-29%	-16%	-6%	6%	15%	29%	0%	0%	0%	0%	0%	0%	-6%	-3%	-1%	1%	3%	6%
Structure Mass	-51%	-35%	-20%	6%	13%	22%	-24%	-14%	-6%	6%	18%	41%	-14%	-10%	-7%	-6%	-6%	-4%
Gas Cell Mass	-42%	-21%	-8%	8%	20%	46%	0%	0%	0%	0%	0%	0%	-8%	-1%	-1%	1%	1%	3%
Overpressure	-7%	-3%	-1%	2%	6%	11%	0%	0%	0%	0%	0%	0%	9%	4%	1%	-1%	-4%	-8%
Lifting Gas Mass	-50%	-25%	-10%	10%	25%	50%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Cable Length	-18%	-8%	-3%	3%	7%	13%	0%	0%	0%	0%	0%	0%	-3%	-2%	-1%	1%	2%	3%
Cable Mass	-18%	-8%	-3%	3%	7%	13%	0%	0%	0%	0%	0%	0%	-3%	-2%	-1%	1%	2%	3%
Cable Tension	-33%	-24%	-6%	6%	15%	29%	0%	0%	0%	0%	0%	0%	-6%	-3%	-1%	1%	3%	6%

13 Sustainability Analysis

A sustainable development strategy is needed when designing new systems to ensure that the product does not have a detrimental environmental effect. The sustainability analysis addresses the method of implementing sustainability into the design and the way the airship system contributes to sustainability.

13.1. Sustainable development strategy

The twelve principles of green engineering can provide a framework to mitigate environmental and human health impacts. When the principles are followed during the design, it ensures environmental, economic, and social factors are taken into consideration [59]. The sustainability manager will test each major design decision on these principles to ensure the design is as sustainable as realistically possible. The three most applicable and important principles are listed in Table 13.1.

Table 13.1: *Three most Applicable Principles of Sustainable Design*

Number	Description
1	It is better to prevent waste than to treat or clean up waste after it is formed.
2	Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
3	Material and energy inputs should be renewable rather than depleting.

During the design, sustainability will be scored by the energy consumption, recyclability, and critical raw materials. The energy consumption is equivalent to the CO2 emissions, but due to the use of various energy sources with different emissions per kWh, the energy consumption gives a fairer comparison than greenhouse gas emissions. Due to time constraints, other sustainability indicators such as acidification and human toxicity were not considered. Recyclability is mainly used in the material selection, where recyclability has been preferred. Lastly, the critical raw materials are taken into account as well, to prevent the exhaustion of resources.

13.2. Direct sustainability analysis

In the direct sustainability analysis, the environmental impact of the airship during its life cycle is determined. This includes the production, transportation, use, and disposal, as seen in Figure 13.1. The energy consumption, use of critical raw materials and recyclability is quantified.

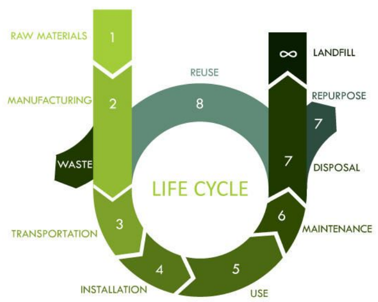


Figure 13.1: *Life cycle analysis [60]*

13.2.1. Energy consumption

To assess the sustainability of the airship, the energy consumption of the airship is determined. The life cycle phases where energy is consumed are the material production, manufacturing, transportation and use phase. To determine the energy usage, a life cycle inventory has to be made to identify all the components, in combination with their mass and material.

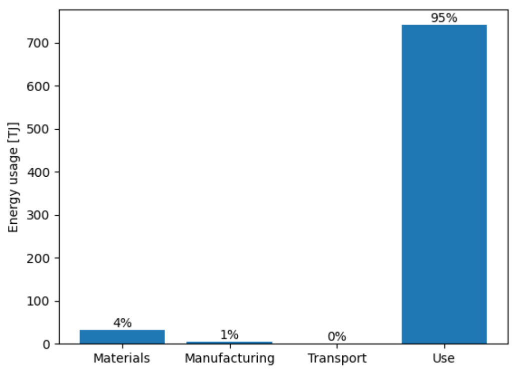
The life cycle inventory can be seen in Table 13.2 and is made with Granta EduPack [18]. The mass is the mass of one complete airship. Together with the lifetime and maintenance, a total mass is calculated, which is the mass that is expected to be used over the entire lifespan. The maintenance factor indicates how much materials are required for repairs, where a factor of 1 indicates that no additional materials are required for maintenance. Note that refilling the lifting gas is included in the use phase.

Table 13.2: *Life cycle inventory*

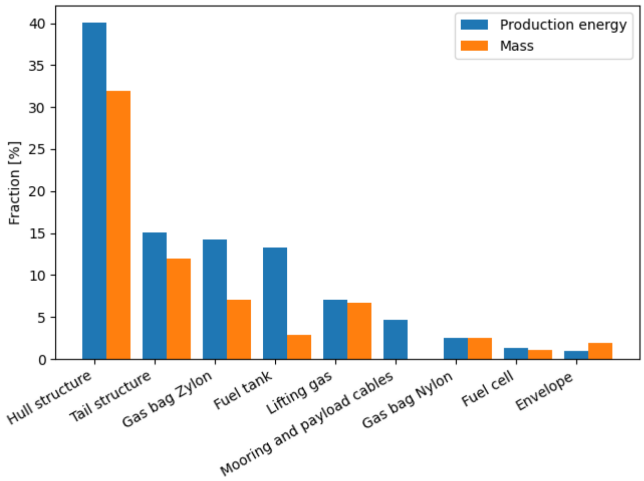
Component	Mass [kg]	Material	Lifetime [yr]	Maintenance factor	Total mass [kg]
Mooring and payload cables	32000	Galvanized steel	25	1	64000
Gas bag	13150	Zylon	50	1.2	15780
Gas bag	4830	Nylon 6	50	1.2	5796
Lifting gas	15004	Hydrogen	50	1	15004
Envelope	2930	Polyurethane	50	1.2	4395
Hull structure	60000	Aluminum 6061T6	50	1.2	72000
Tail structure	22500	Aluminum 6061T6	50	1.2	27000
Fuel tank	6446	CFRP QI lay-up	50	1	6446
Engine electrical power cables	68	Copper	50	1	68
Miscellaneous power cables	223	Copper	50	1	223
Engine electric sheets	1365	Soft magnetic Alloy 2.5 Si-Fe	25	1	2731
Engine cast iron	1365	Cast iron, gray, flak graphite, EN GJL 100	25	1	2731
Engine copper	348	Soft copper C10100	25	1	695
Engine steel	322	Carbon steel, AISI 1010, annealed	25	1	645
Aluminum extrusion	96	Aluminum 6061T6	25	1	191
Impregnation resin	25	Epoxy resin	25	1	50
Fuel Cell	1256	Various	25	1	2513

Using Ansys Granta EduPack, the energy consumption of the phases are determined. It is assumed that all components are transported 1000 km by truck. For the usage phase, a lifetime of 50 years, a usage rate of 200 days per year and a daily use of 12 hours is assumed. As fuel cells are complex to manufacture and contain many materials, the required energy is taken from literature and requires 414 GJ [61].

The results are shown in Figure 13.2. Figure 13.2a gives the energy consumption during the life cycle phases. Figure 13.2b gives more detail into the energy consumption of the material production, both the production energy and the component mass are given to be able to score the relative sustainability of the components. For the mooring and payload cables, a mass is not given, as the mooring cables are not on board of the airship.



(a) *Life phases*



(b) *Material production energy fraction*

Figure 13.2: *Energy consumption*

From Figure 13.2a, the use phase requires the most energy after the material production. The manufacturing and transportation have a negligible energy consumption. Any further design changes which increases the efficiency, but increases the material production is worthwhile to investigate as the use phase is significantly larger than the material production.

Looking at Figure 13.2b, the components with the highest mass, such as the hull and tail structure, contribute the most to the energy consumption. Some components have, compared to the mass fraction, a high energy consumption, for example the Zylon gas bag and the fuel tank. Big improvements are possible, although these components have more constraining requirements than other components.

13.2.2. Critical Raw Materials

Every three years, the European commission identifies the critical raw materials (CRM). The European commission defines CRM as: *CRMs combine raw materials of high importance to the EU economy and of high risk associated with their supply*[1]. Next to that, CRMs are important for sustainable technology such as wind turbines and solar panels as well. The use of CRM should therefore be minimized, as requirement REQ-SYS-SUS-04 dictates to have a maximum of 50 kg of CRMs.

Currently, five components are or contain CRMs, as listed in Table 13.3. The mass of CRMs are listed as well to be able to validate the requirement. The CRM mass of fuel cells are unknown as fuel cells are still being developed, also with the aim to reduce the amount of CRMs, currently fuel cells are using iridium, platinum, and titanium [62].

Table 13.3: *Used Critical Raw Materials*

Component	Material	CRM mass [kg]
Mooring and payload cables	Galvanized Steel	185
Hull structure	Aluminum 6061T6	1548
Tail structure	Aluminum 6061T6	581
Engine Aluminum extrusion	Aluminum 6061T6	4.12
Fuel cell	Various	Unknown
		2318

The total CRM mass is 2318 kg, so requirement REQ-SYS-SUS-04 is not met. To reduce the amount of CRMs, alternatives will be considered. For the mooring and payload cables, alternative materials are evaluated. Looking for similar materials without CRMs, low alloy steel 16Mo3 was found to be a good replacement. This lowers the CRM mass to 2133 kg.

The used aluminum alloy is a high-end aluminum alloy. The alloy combines good weldability, lightweight, and strength. As the structure is a big part of the airship, the material choice has large influences. Any weight increase will increase the size and increase the usage of energy consumption. A metal with comparable properties and without CRMs was not found. Another option for the structure is CFRP, as CFRP does not require any CRMs. However, CFRP are generally not recyclable, violating requirement REQ-SYS-SUS-03. Additionally, CFRP is harder to manufacture, especially on the required scale. Considering the disadvantages of alternatives, it was decided that the use of CRMs is acceptable for now, but further analysis to reduce the usage of CRMs is recommended.

13.2.3. Recyclability

The airship should be decently reusable or recyclable to reduce the impact at the end of life. A list of the non-recyclable components is given in Table 13.4. All other materials mentioned before but not shown below can be recycled. The recyclability of some material is ambiguous, sources give conflicting information about the recyclability. For example, Zylon is recyclable according to Fiber Brokers [2], whereas Ansys Granta Edupack does not label Zylon as recyclable. For now, it is assumed that these materials are downcycled, at the EoL recycling might be possible through innovation. The downcyclable materials are gathered in Table 13.4b.

[1] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en (Accessed on: 15/06/2024)
[2] https://fiberbrokers.com/technical-materials-recycling/all-about-zylon/ (Accessed on: 15/06/2024)

Table 13.4: *List of all materials that cannot be recycled*

(a) *Non-recyclable used materials*

Component	Material
Lifting gas	Hydrogen
Fuel cell	Various

(b) *Downcyclable materials*

Component	Material
Gas bag	Zylon
Envelope	Polyurethane
Fuel tank	CFRP
Electrical power cables	Copper

The percentage of recyclable materials is 80 %. This is exactly the target recyclability of 80 %, set by requirement REQ-SYS-SUS-03. In the later design, more recyclable materials should be used, or current materials should be changed to keep the recyclability high. The percentage of downcyclable materials is 12 %. Downcycling is less favorable than recycling, but better than dumping the material on landfills. The remaining 8% will need to be disposed without any recycling. This will be done in a safe and responsible manner to minimize its negative effects as much as possible.

13.3. Indirect Sustainability Assessment

The airship has an indirect sustainability impact by the transportation of wind turbines. The impact is made by two points: the ability to transport longer blades than trucks and transportation to more favorable places.

13.3.1. Transporting longer blades

Currently, trucks are able to carry wind turbine blades with a maximum length of 90 m [3] [4]. With the ability to move blades up to 105 meters, the wind turbines can produce more power. The power of wind turbines is given by Equation 13.1 [63].

$$P = \frac{1}{2}\rho U^3 C_p A = \frac{1}{2}\rho U^3 C_p \pi r^2 \tag{13.1}$$

Assuming a size increase from 90 to 105 meters, the power will increase by 36 %. If the wind turbine produces 10 MW [5], an increase of 3.6 MW is realized. Assuming that the airship transports 56 wind turbines per year and that the airship is operational for 50 years, the airship moves a total of 2800 wind turbines. Using Equation 13.2, the total increase of energy is determined.

$$E_{total} = nPF_{op}t \tag{13.2}$$

Where E_{total} is the extra energy produced by the wind turbines, n is the number of placed wind turbines, P is the power rating, F_{op} is the fraction of the operational over non-operational time and t is the lifetime of the wind turbine. Assuming a fraction of F_{op} of 0.3 and a wind turbine lifetime of 20 years, the total extra energy is $1.9 \cdot 10^6$ TJ or 530 TWh. This is equivalent to the total energy usage in the Netherlands in 2023[6].

13.3.2. Beneficial placement

In studies of optimization of wind farm locations, the accessibility of the location is often considered [64] [65]. In those studies accessibility has been given a weight that is less than 5%. This indicates accessibility is not deemed important enough for optimizing wind farm locations. This suggests that airships would have limited effect on the chosen locations of wind farms. On top of that, to install the blades, large cranes and trucks are still required when airships are being used. Meaning that road accessibility is still favorable. Due to this combination, this effect is not investigated further as little impact is expected.

[3] https://www.mammoet.com/news/record-breaking-transport-of-wind-turbine-blade/ (Accessed on: 16/06/2024)
[4] https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/transport-of-longest-blade-in-the-world (Accessed on: 19/06/2024)
[5] https://cleantechnica.com/2018/09/26/mhi-vestas-launches-worlds-first-10-megawatt-wind-turbine/ (Accessed on: 19/06/2024)
[6] https://www.cbs.nl/nl-nl/nieuws/2024/23/energieverbruik-uit-hernieuwbare-bronnen-gestegen-naar-17-procent (Accessed on: 19/06/2024)

14 Risk Analysis

This chapter presents the technical risk assessment and the risk mitigation plan for the mission. Section 14.1 identifies the potential risks, explaining their likelihood and impact. Section 14.2 mitigation plans are outlined for the risks with the highest impact. Section 14.3 provides risk maps to illustrate these risks. Lastly a reliability, availability, maintainability and safety analysis (RAMS) analysis is presented in Subsection 14.4.1.

14.1. Risk Identification

The following technical risk analysis concerns the technical, scheduling, cost, and programmatic risks of the mission, as defined in the NASA Systems Engineering Handbook [66]. The likelihood and severity were determined for each of the identified risks.

A risk is defined as a product of the likelihood and the severity of an event, with numerical values assigned to each category of both metrics. The likelihood of an event has been separated into five categories. These categories can be seen in Table 14.1

Table 14.1: *Probability of Event Occurrence*

#	Probability Level	Description
5	Very high	Probability of event exceeds 50%
4	High	Probability of event between 30 and 50%
3	Medium	Probability of event between 10 and 30%
2	Low	Probability of event between 1 and 10%
1	Very low	Probability of event below 1%

These categories were determined to ensure that different levels of likelihood are separated in the particular working environment. The severity categories can be found in Table 14.2

Table 14.2: *Severity of Event Consequences*

#	Severity Level	Description
5	Catastrophic	Results in a catastrophic failure of the system, mission, and project; further operation or development is impossible
4	Severe	Results in severe damage to the system or permanent and uncorrectable prevention of realizing some mission goals or severe delays
3	Critical	Results in major, but correctable damage to the system, a significant hindrance in realizing the mission objectives, or significant delays
2	Marginal	Results in minor, correctable damage to the system, noticeable hindrance in realizing the mission objectives, and temporary delays
1	Negligible	Results in a temporary, correctable setback in realizing the mission objectives

The defined categories of likelihood and severity result in the creation of risk maps as presented in Section 14.3. The maps are color-coded to denote the combined impact of the risk. Red (R), yellow (Y), and green (G) represent high, medium, and low risk respectively. The colors from the risk map are presented in the risk assessment and mitigation tables for further clarity. It is desired that the high and medium risks shall be mitigated, while low risks are deemed acceptable. The technical risks are presented in Table 14.3. For the revised cells an asterisk has been placed on the risk ID.

Table 14.3: *Technical risks (L = Likelihood pre-mitigation, S = Severity pre-mitigation)*

Risk ID	Risk	Consequence	L	S	
		Technical risks			
During Development					
TECH-1.1	Parts of the product assembly are not able to be manufactured	The designers will have to look for alternatives, delaying the timeline	2	2	G
TECH-1.2	Materials do not meet sustainability requirements	Stakeholder needs not satisfied, stakeholder might withdraw funding	4	3	R
TECH-1.3	All solutions found emit too much noise	Airship not able to fly over populated areas	2	3	Y
TECH-1.4	No materials that allow for visual changes to the outside can be found	Stakeholder contract not able to be satisfied, renegotiation needed	1	2	G
TECH-1.5	Quality assurance methods cannot be found for certain parts	Quality policy not able to be implemented, resulting in decreased trustworthiness	1	4	G
TECH-1.6	The design is unable to accommodate the required payload	Airship not able to satisfy stakeholder needs, no customer available	2	5	R
TECH-1.7*	The design does not comply with regulations	Airship not able to be certified, mission failure	2	5	R
TECH-1.8*	Key technologies used in the design are no longer available for use within the product	Other, less optimal options will have to be considered	2	2	G
TECH-1.9	Allocated technical budgets get exceeded	Development time increases, design becomes less environmentally friendly and material cost increases	2	4	Y
TECH-1.10*	Rapid technological advancements in the world	Newly developed technologies can make current designs obsolete (or less competitive), hence causing redesigns and delays	1	3	G
TECH-1.11*	Insufficient testing facilities	Inadequate testing can leave design flaws undiscovered. This could potentially lead to failures and increasing costs.	2	4	Y
TECH-1.12*	Insufficient communication and collaboration between development teams.	Potential misalignments in the design and/or planning of the project.	2	3	Y
During Production					
TECH-2.1	A produced part does not meet the specified quality	The product might fail certification or decreases efficiency	2	3	Y
TECH-2.2	Quality control fails to find an issue with a part or other produced item	A flaw goes undetected and can cause issues during operation	2	3	Y
TECH-2.3	Parts or the system get damaged during transport	The part needs replacement or fixing and recertification	2	3	Y
TECH-2.4	The appropriate documentation is not handed over to the customer	The customer cannot use the ship, operational delays and compensation costs	1	4	G
TECH-2.5	The tests fail to find an issue that the system has	A flaw goes undetected and can cause issues during operation	2	4	Y
TECH-2.6	A problem or issue is not covered by the tests	Unexpected failures occur during operation	2	5	R
TECH-2.7	Assembly of parts is not done to specification	Parts will fail certification	2	4	Y
TECH-2.8	The required machinery cannot be sourced or does not exist	The parts cannot be manufactured the intended way	2	3	Y
TECH-2.9	Quality control is not extensive enough	Flaws will show up during operation	2	3	Y
TECH-2.10	Preferred sources or machines/materials become unavailable	Machines/materials will be different to the preferred type or not available	2	2	G
TECH-2.11*	Poor inventory management of parts	Improper parts delivery, overstock in unused parts, shortages of necessary parts	2	3	Y
TECH-2.12*	Inadequate workforce training	Decreasing quality of parts, errors in production process	2	4	Y

TECH-2.13*	Supply delays	Timeline of production is delayed, increasing costs	2	3	Y
TECH-2.14*	Assembled system parts become heavier than expected	Design becomes heavier than expected, may become imbalanced and fail to meet performance requirements	2	5	R
During operation					
TECH-3.1	The airship gets struck by lightning	The ship can catch on fire or suffer major failures	1	4	G
TECH-3.2	Pre-flight checks are failed	The ship is not allowed to take off and do its mission	1	4	G
TECH-3.3	The airship collides with an object	(Major) structural failure resulting in possible crash	2	5	R
TECH-3.4	The airship gets blown off course by heavy winds	The ship has to use more fuel than planned and has to shorten the mission	3	3	Y
TECH-3.5	A fire breaks out onboard the airship	Parts of the airship burn, possibly causing an explosion of the lifting gas	1	5	Y
TECH-3.6	The airship goes down over a populated area	Chance of major casualties on the ground and loss of the ship	1	5	Y
TECH-3.7	The payload mass is different than specified in the documentation	The payload cannot be accommodated by the airship for a flight	3	4	R
TECH-3.8	The airship does not follow the route correctly	The pilot and company get in trouble with the aviation authority	2	4	Y
TECH-3.9	Loss of contact with the airship	The airship is not traceable during flight	2	4	Y
TECH-3.10	The airship cannot change configurations	Cargo cannot be picked up or be delivered, the mission cannot be performed	2	4	Y
TECH-3.11	The destination is not expecting the delivery	No delivery can be made as precautions are not in place	1	3	G
TECH-3.12	The airship's maintenance cannot reach the specified quality	The airship is not allowed to perform a mission	2	4	Y
TECH-3.13	Landing at designated location no longer possible	Another place for landing the airship needs to be found	2	3	Y
TECH-3.14	Static arcing occurs during mooring	The airship structure is electrically charged, which might result in sparks and fire	2	4	Y
TECH-3.15	The airship's ballast becomes nonoperational due to damage	Airship becomes too heavy to land and becomes less controllable	2	4	Y
TECH-3.16	Environmental temperature changes	Airship's maneuverability gets affected	3	2	Y
TECH-3.17	Oscillations occur due to the propulsion system	Airship's structure may get damaged and the airship becomes less maneuverable.	3	4	R
TECH-3.18	Outer shell gets damaged during operations	Ship's aerodynamic form is affected and/or the gas bags are exposed	2	5	R
TECH-3.19	Fuel cell gets damaged	Electrical power is not generated anymore	2	5	R
TECH-3.20	Propulsion systems give out	Airship's maneuverability is seriously affected and the airship must perform an emergency landing	2	4	Y
TECH-3.21	Landing systems/infrastructure damaged or not ready	Airship must abort landing, continue hovering or perform an emergency landing	2	4	Y
TECH-3.22	Fast getaway not possible	Airship exceeds allocated time budget	1	3	G
TECH-3.23*	Interference with mooring cables	Interference with the mooring cables by foreign objects or equipment may cause entanglement or wear or even failure	2	4	Y
TECH-3.24*	Mooring cable failure due to wear, tear or corrosion	More load on remaining mooring cables, further increasing wear and increasing the risk of cable failure during high-tension situations	2	4	Y

TECH-3.25*	Improper mooring procedures are implemented by the ground crew	Incorrectly secured cables may cause the mooring to be unstable or detachment of the airship, hence damaging it and/or causing safety hazards	2	4	Y
TECH-3.26*	Navigation system malfunctions	Airship may deviate from the planned route, causing delays	2	3	Y
TECH-3.27*	Fuel runs out earlier than expected	Airship must perform emergency landing	2	5	R
At end of life					
TECH-4.1	Airship cannot be safely disassembled	Airship disassembly is prevented or delayed	2	3	Y
TECH-4.2	Too large part of components is not fit for recycling/reuse	Sustainability goal not reached which could cause stakeholders to pull out of the project	3	2	Y
TECH-4.3	No future use for components can be found	Sustainability goal not reached which could cause stakeholders to pull out of the project	3	3	Y
Scheduling					
TECH-S-1.1	Unrealistic/improper scheduling	Things are consistently delivered late, leading to loss of confidence	2	3	Y
TECH-S-1.2	Natural disasters occur in development and operation area	Flight infrastructure can be unusable for extended periods, delaying operations	2	4	Y
TECH-S-1.3	Political difficulties during development or operation	Delays to the project appear, governmental support decreased, part suppliers limited	2	4	Y
TECH-S-1.4	Inadequate time is allocated for the realization of the complete project	The project will run longer than the allocated time or the quality of the developed product will be subpar, costs will increase	3	3	Y
TECH-S-1.5	Organizational changes in executive management	Productivity is reduced temporarily while the team adapts to the changes, scheduling delays occur	2	2	G
TECH-S-1.6	Project objective changes	Past work needs to be reevaluated, causing major delays	2	4	Y
TECH-S-1.7	Inadequate time is allocated for the design of the product	The design is finished later than expected, pushing back the timeline, and possibly increasing cost	2	3	Y
TECH-S-1.8	Not enough personnel available	Delays in the project development, production, or operation, decreased productivity	3	2	Y
TECH-S-1.9	Inadequate time is allocated for the production of the product	Assembly is delayed, causing a total schedule delay and cost increases, customers have to wait longer than promised	2	3	Y
TECH-S-1.10	Stock or parts of the product are unavailable to purchase	Production has to wait until there are parts in stock again or designers have to look for alternatives, delays to production occur	3	3	Y
TECH-S-1.11	Personnel strikes	No work is conducted for some time, delays to the project occur	1	2	G
TECH-S-1.12	Part delivery delayed	Production has to wait until parts arrive, assembly and project delayed	3	2	Y
TECH-S-1.13	Inadequate time is allocated for the product delivery to customer	The product arrives late to the customer, causing scheduling delays and cost implications	1	2	G
TECH-S-1.14	Payload cannot be provided in time	The airship cannot pick up the payload at the expected time, causing a delay of a mission	1	2	G
Cost risks					
TECH-C-1.1	Project not able to secure funding	Without funding no work can be done, stopping the project immediately	3	5	R
TECH-C-1.2	High emissions lead to budget for carbon credits being exceeded	The stakeholders might stop supporting the project, environmental sanctions	2	3	Y
TECH-C-1.3	Fuel prices increase	Operations become more expensive, delaying the Break Even Point	3	4	R
TECH-C-1.4	Lifting gas prices increase	Operations become more expensive, delaying the Break Even Point	3	4	R

TECH-C-1.5	Developmental cost exceeds budget	Development cannot be completed without seeking extra funding	2	3	Y
TECH-C-1.6	Production cost exceed allocated budget	Buying the ship will become more expensive for the customer or profit margins decrease	2	3	Y
TECH-C-1.7	Operational cost exceed budget	Usage of the ship will become more expensive for the customer or profit margins decrease, possibility of loss of customer	2	4	Y
TECH-C-1.8	End of life cost exceed budget	Not all parts can be reused/recycled as extracting them costs too much	2	3	Y
TECH-C-1.9*	Airship infrastructure costs exceed budget	Operating the ship becomes more expensive, profit margins decrease	2	3	Y
		Programmatic risks			
TECH-P-1.1	Certain parts fall under ITAR regulations	International sales are hindered	1	3	G
TECH-P-1.2	Stakeholders pull support for the project	Continuation of work is prevented or made more difficult	2	5	R
TECH-P-1.3	Subcontractor drops out of agreement	Machines or materials will be unavailable	2	3	Y
TECH-P-1.4	Material source runs out of materials	Material will be unavailable	1	3	G
TECH-P-1.5	Certifying agency refuses to certify system or part of it	Parts cannot be used within the airship, System is not certified and cannot be operated	2	5	R
TECH-P-1.6	Adverse weather conditions prevent operations	Mission not able to be performed	4	2	Y
TECH-P-1.7	Flight plan is not approved	The mission cannot be started	3	3	Y
TECH-P-1.8	Airspace is closed along the route	Airship needs to make a detour or cannot get to destination	2	2	G
TECH-P-1.9	Unplanned weather conditions form during operation	The mission cannot be performed because the weather prevents the airship from completing it	4	2	Y
TECH-P-1.10	Delivery crew is unavailable for delivery on arrival	The mission cannot be performed because there is no crew available for the unloading procedure	1	3	G
TECH-P-1.11	Airship fails certification after large maintenance	The airship can no longer be used	2	5	R
TECH-P-1.12	Lifting gas supply dries up	The project cannot be continued due to unavailability of lifting gas	1	5	Y
TECH-P-1.13	Equipment gets stolen	Delays of the missions occur	1	3	G
TECH-P-1.14	Foreign forces destroy project infrastructure	The project cannot be continued due to facilities being unavailable	1	5	Y
TECH-P-1.15	Ground facilities are refused the required permit	The mission cannot be performed due to facilities being unavailable	2	4	Y
TECH-P-1.16	Corrupt government officials refuse to further the development without bribe	The development is halted	2	5	R
TECH-P-1.17	Sanction get imposed on customer	There is no customer for the system	1	4	G
TECH-P-1.18	Sanctions prevent material delivery	Required materials cannot be obtained	2	4	Y
TECH-P-1.19	Airship loses certification due to regulation changes	The airship cannot fly until it is changed and recertified	2	5	R

14.2. Risk Mitigation

After identifying all relevant technical risks in Section 14.1, methods are sought to mitigate these risks as much as possible. There are multiple methods available. For example, preemptive measures could be used to lower the likelihood of the risks, or measures could be taken that will limit the severity of the risks. The mitigation strategies for medium and high risks are presented in Table 14.4, along with the corresponding risks' likelihood and severity scores after applying the mitigation method.

Table 14.4: *Risk Mitigation Results (L = Likelihood after mitigation, S = Severity after mitigation)*

Risk ID	Mitigation strategy	L	S	
	Technical risks			
During Development				
TECH-1.2	Sustainability should be a part of the material selection from the start. Even if not sustainable, the material should minimize its impact on the environment.	2	3	Y
TECH-1.3	Noise pollution should be carefully considered during the design phase if necessary sound dampening materials/design should be implemented	2	2	G
TECH-1.6	During the design phase the required payload capacity is studied by the team, and it is kept in mind during the rest of the design phase.	1	5	Y
TECH-1.7	The team will make sure they are aware of the regulations that apply to the system and follow these. If any doubts persist, the appropriate authority should be contacted.	1	5	Y
TECH-1.8	Develop a backup plan with alternative technologies and maintain close communication with technology providers.	1	2	G
TECH-1.9	Apply frequent budget monitoring and control. Identify cost-saving opportunities and review and adjust the budget as necessary.	1	2	G
TECH-1.10*	Monitor industry and technology developments regularly. Design subsystems such that space is accommodated for new technology to be implemented.	1	2	G
TECH-1.11*	Establish multiple partnerships with different testing facilities; invest in in-house testing facilities if needed.	1	3	G
TECH-1.12*	Implement project management tools and conduct regular cross-functional meetings.	1	2	G
During Production				
TECH-2.1	During production the quality is monitored carefully and if any issues arise a plan to prevent it from happening again is made.	2	2	G
TECH-2.2	Quality control should cover areas where problems might arise to ensure a detailed analysis of probable problem areas is performed when designing the QC process.	1	3	G
TECH-2.3	Parts should be protected by appropriate packaging when transported. Different transportation option should be considered for especially fragile parts	1	2	G
TECH-2.5	The testing procedure should be followed to ensure nothing that should be caught goes unnoticed	1	4	G
TECH-2.6	Testing should be as comprehensive as is practical. Mission-critical systems should always be tested if possible.	1	5	Y
TECH-2.7	During production, the quality is monitored carefully and if any issues arise a plan to prevent it from happening again is made.	1	3	G
TECH-2.8	During the design phase, the team pays attention to the intended manufacturing methods and their limitations.	1	3	G
TECH-2.9	Quality control should cover areas where problems might arise to ensure a detailed analysis of probable problem areas is performed when designing the QC process.	1	3	G
TECH-2.11*	Implement an extensive inventory management to track and optimize parts supply.	1	3	G
TECH-2.12*	Provide regular training programs for the workforce.	2	2	G
TECH-2.13*	Stock up on critical parts and develop relationships with multiple suppliers.	1	2	G
TECH-2.14*	Apply weight tracking throughout production, make small adjustments on the design if necessary.	2	3	Y
During operation				
TECH-3.3	The airship should be operated in open areas where chances of collisions are minimized. During design, some considerations are made to ensure that the airship can withstand collisions to a certain level	1	4	G
TECH-3.4	The wind should be considered when planning a mission. When blown off course, a new optimal course should be created.	2	2	G
TECH-3.5	Common causes of fires should at all costs be avoided on the airship (smoking etc.) Proper firefighting procedures should be prepared, and the relevant crew should perform training regularly.	1	4	G
TECH-3.6	Minimize the time flying over populated regions.	1	5	Y

TECH-3.7	The team should develop a standardized way to communicate the payload specification to minimize the possibility for miscommunications.	1	4	G
TECH-3.8	The pilot should be reliable and certified. The route should stay clear of dangerous areas.	1	4	G
TECH-3.9	Redundancy should be built into the design for critical systems. An independent, second communication system should be available.	1	2	G
TECH-3.10	Pre-flight checks should be done to check if everything works before taking off. The ground base should be contacted with the option of aborting the mission.	1	3	G
TECH-3.12	Maintainability should be considered during the design. Maintenance plans should be made well in advance and checked with regulations.	1	3	G
TECH-3.13	The flight plan should be carefully put together before the flight. Alternative landing places should be considered beforehand.	2	2	G
TECH-3.14	The static charge in the air around the airship is monitored and hydrogen is not released while mooring. Mooring is not performed in unsuitable conditions. Safety procedures and grounding systems are implemented in the system	2	3	Y
TECH-3.15	Conduct regular inspections and maintenance and train the operational crew on proper handling. Make the crew aware of emergency procedures.	1	2	G
TECH-3.16	Monitor the weather frequently and use materials that are able to withstand temperature variations.	2	1	G
TECH-3.17	Incorporate vibration damping and test the system thoroughly. Train the crew to recognize oscillations and let them respond accordingly.	2	3	Y
TECH-3.18	Use durable materials and conduct regular inspections. Develop repairing procedures.	2	3	Y
TECH-3.19	Use protective casings for the fuel cells and conduct regular maintenance. Have redundant fuel cells available.	1	3	G
TECH-3.20	Maintain the propulsion system regularly, use high-quality propulsion systems and have redundant propulsion systems available if possible.	2	3	Y
TECH-3.21	Back-up landing sites shall be implemented in the flight plan, they shall be maintained regularly and the crew shall be adequately trained for emergency situations.	2	2	G
TECH-3.22	Maintain airship regularly for optimal performance. Implement speed and maneuverability more into the design. Train the crew accordingly.	1	2	G
TECH-3.23*	Implement clear areas around mooring stations and regularly inspect mooring sites.	1	2	G
TECH-3.24*	Frequently inspect mooring cables and maintain them, estimate remaining lifetime.	1	2	G
TECH-3.25*	Train ground crew extensively on mooring procedures and implement checklists.	2	4	G
TECH-3.26*	Maintain and update the navigation system regularly. Have a backup navigation system ready.	1	2	G
TECH-3.27*	Conduct a detailed pre-flight fuel checklist and monitor fuel consumption closely.	2	3	Y
At end of life				
TECH-4.1	End of Life should not be overlooked in the design phase. Under no circumstance should it be harmful when disposed of.	1	2	G
TECH-4.2	Recyclability/reusability should be considered from very early on. They should under no circumstance be harmful when disposed of.	2	1	G
TECH-4.3	Recyclability/reusability should be considered from very early on. They should under no circumstance be harmful when disposed of.	1	1	G
	Scheduling			
TECH-S-1.1	Develop a more thorough scheduling process with contingency plans. Conduct regular reviews to update the schedule	1	2	G
TECH-S-1.2	Implement a comprehensive disaster recovery plan, avoid areas prone to such disasters.	1	3	G
TECH-S-1.3	Development and operation decisions are taken with consideration of political landscape	2	4	Y
TECH-S-1.4	Establish strong relationships with local authorities and monitor the political landscape	2	2	G
TECH-S-1.6	Before approving the objective change, implement an evaluation of the impact of changes on the project's scope, timeline, and budget.	1	3	G
TECH-S-1.7	Design teams should be involved in the early stages of the project planning to provide accurate time estimates and buffer time.	2	2	G

TECH-S-1.8	Plan the hiring of the workforce based on the project needs and maintain an overview of skilled personnel, who should be cross-trained so they can cover critical roles in case of shortages.	1	1	G
TECH-S-1.9	Conduct production planning with manufacturing experts to estimate timelines and include buffer times in them.	1	2	G
TECH-S-1.10	Maintain a stockpile of critical components and maintain relationships with multiple suppliers	2	2	G
TECH-S-1.11	Keep your workers happy and maintain communications with them. Also develop a contingency plan in case of strikes.	2	1	G
TECH-S-1.12	Maintain a buffer stock of critical parts and create a network of different suppliers/alternatives and discuss delivery deadlines well with suppliers.	2	1	G
	Cost risks			
TECH-C-1.1	Attract potential investors early in the project lifecycle by preparing a robust business plan and diversify funding resources.	2	4	Y
TECH-C-1.2	Plan the manufacturing of the airship using energy-efficient technologies in the early stages of design and only work with environmentally aware energy companies.	1	2	G
TECH-C-1.3	Hedge fuel costs through long-term contracts. Optimize logistics to reduce overall fuel consumption.	3	3	Y
TECH-C-1.4	Hedge long-term contracts with gas suppliers to lock in prices.	3	3	Y
TECH-C-1.5	Keep a thorough financial logbook to track all expenses and implement cost-saving measures where possible.	2	3	Y
TECH-C-1.6	Keep a thorough financial logbook and streamline production processes to improve efficiency. Review it regularly.	1	3	G
TECH-C-1.7	A good cost estimation should be done and revised as the design matures. Margins should be added early on in the estimation.	1	3	G
TECH-C-1.8	EoL should not be overlooked in the conceptual phase. No harmful materials should be used altogether.	1	2	G
TECH-C-1.9*	Perform a thorough cost estimation and planning, and apply cost controlling measures.	1	2	G
	Programmatic risks			
TECH-P-1.2	Stakeholder requirements should always be taken seriously. A wide enough base should be obtained so that work can continue after one drops out.	1	4	G
TECH-P-1.3	Only reliable contractors should be considered. Full payments should not happen until delivery.	2	2	G
TECH-P-1.5	Regulations should always be checked before certifying. Certification should not happen just before delivery to allow for feedback implementation.	1	4	G
TECH-P-1.6	Conditions should be monitored before and throughout the flight. Design should allow for conditions up to a certain threshold.	4	1	G
TECH-P-1.7	The flight plan should always be checked against regulations well before handing it in. Secondary flight plans should be considered.	1	2	G
TECH-P-1.9	Multiple sources should be checked for weather. Secondary flight routes should always be considered beforehand.	3	1	G
TECH-P-1.11	Before starting maintenance or modifications, regulations should be considered. For time-consuming maintenance extra care should be put into this.	1	4	G
TECH-P-1.12	Before committing to a specific gas the team will see if the gas under consideration has future renewable sources ensuring a future supply.	1	4	G
TECH-P-1.14	The ground infrastructure should not be built in locations with high-security risks. The safety of personnel should always be put first.	1	5	Y
TECH-P-1.15	Research should be done beforehand on local regulations. Local legislators should be included in the project.	1	4	G
TECH-P-1.16	Avoid conducting business in countries known for corruption. Local governments should always be included in the project.	1	4	G
TECH-P-1.18	Materials should not be sourced from places that have a history of sanctions, a second option for such resources should always be considered.	1	3	G
TECH-P-1.19	The team keeps up with developments in regulations to preemptively implement changes, should they occur they can also schedule maintenance more easily.	1	4	G

14.3. Risk Maps and Contingency Planning

A risk map is a useful tool for visualizing the risk level of various events. This is done by plotting the likelihood of risks against their severity. In the risk maps, green indicates low risk, yellow indicates medium risk, and red indicates high risk. These are the same colors that were used in the risk assessment and mitigation tables.

The likelihoods and severities found in Table 14.3 and 14.4 are used to plot the risks in the risk maps. These can be found below in Figure 14.1 for both pre- and post-mitigation.

		Negligible	Marginal	Critical	Severe	Catastrophic
		1	2	3	4	5
Very high	5					
High	4		P-1.6	1.2		
Moderate	3		3.16, 4.2, S-1.8, S-1.11, S-1.12, P-1.9	3.4, 4.3, S-1.4, S-1.10	3.7, 3.17, C-1.3, C-1.4	C-1.1
Low	2		1.1, 1.8, 2.2, S-1.5, P-1.8	1.3, 1.12, 2.1, 2.2, 2.3, 2.8, 2.9, 2.11, 2.13, 3.13, 3.26, 4.1, S-1.1, S-1.7, S-1.9, C-1.2, C1.5, C-1.6, C-1.8, C-1.9, P-1.3, P-1.7	1.9, 1.11, 2.5, 2.7, 2.12, 3.8, 3.9, 3.10, 3.12, 3.15, 3.20, 3.21, 3.23, 3.24, 3.25, S-1.2, S-1.3, S-1.6, C-1.7, P-1.15, P-1.18	1.6, 1.7, 2.6, 2.14, 3.3, 3.18, 3.19, 3.27, P-1.2, P-1.5, P-1.11, P-1.16, P-1.19
Very low	1		1.4, S-1.13, S-1.14	1.10, 3.11, 3.22, P-1.1, P-1.4, P-1.10, P1.13	1.5, 2.4, 3.1, 3.2, P-1.17	3.5, 3.6, P-1.12, P-1.14

(a) *Pre mitigation risk map*

		Negligible	Marginal	Critical	Severe	Catastrophic
		1	2	3	4	5
Very high	5					
High	4	P-1.6				
Moderate	3	P-1.9		C-1.3, C-1.4		
Low	2	3.16, 4.2,S-1.11, S-1.12	1.3, 1.12, 2.1, 2.12, 3.4, 3.13, 3.21, 3.25, S-1.4, S-1.7, S-1.10, P-1.3	1.2, 2.14, 3.17, 3.18, 3.20, 3.27, C-1.5	S-1.3, C-1.1	
Very low	1	4.3, S-1.8	1.8, 1.9, 1.10, 2.3, 2.13, 3.9, 3.15, 3.22, 3.23, 3.24, 3.26, 4.1, S-1.1, S-1.9, C-1.2, C-1.8, C-1.9, P-1.7	1.11, 2.2, 2.7, 2.8, 2.9, 2.11, 3.10, 3.12, 3.19, S-1.2, S-1.6, C-1.6, C-1.7, P-1.18	2.5, 3.3, 3.5, 3.7, 3.8, P-1.2, P-1.5, P-1.11, P-1.12, P-1.15, P-1.16, P-1.19	1.6, 1.7, 2.6, 3.6, P-1.14

(b) *Post-mitigation risk map*

Figure 14.1: *Technical risk maps*

As can be seen in Figure 14.1b there are still some risks in the medium risk area; for these, contingency plans have been developed as can be seen in Table 14.5. The revised contingency plans have been marked with a bold ID and an asterisk.

Table 14.5: *Contingency plan for risks*

Risk ID	Contingency
TECH-1.2	To minimize the impact without suffering large setbacks, the first ships can be built with less sustainable material. Later versions can then be improved upon while not suffering delays.
TECH-1.6	Early versions can start with reduced payload capacity which will be increased in later versions. That way losses can be minimized.
TECH-1.7	Find solutions that comply with regulations without altering the design too much. Preferably, they can be retrofitted on already-produced models such that production is not held back.
TECH-2.6	New methods of testing must be sought, keeping in mind that tests should only find flaws large enough to be critical.
TECH-2.14*	Prepare lighter backup components. Develop rapid redesign protocols.
TECH-3.6	Contact local emergency services to prevent further damage and casualties. Assist in the following investigation to determine the cause
TECH-3.14	Evacuate the airship and close all gas valves. Clear the surrounding area
TECH-3.17	Reduce speed to reduce the change for oscillations to occur. Develop a vibration damping system.
TECH-3.18	Deploy temporary repair kits, monitor the damage, and perform an emergency landing.
TECH-3.20	Switch to emergency propulsion systems, perform emergency landing.
TECH-3.27*	Carry more fuel than necessary. Consider multiple airports in the area as emergency airports, develop an emergency plan.
TECH-S-1.3	Consider engaging in different lobbying activities
TECH-C-1.1	Obtain funding from elsewhere or reduce the scope/cost of the entire project
TECH-C-1.3	Consider alternative fuels or enter the production of the fuel

TECH-C-1.4	Consider alternative gasses or enter the production of the lifting gas
TECH-C-1.5	Try to obtain more funding from other sources
TECH-P-1.14	Inform the relevant authorities to limit further damage and casualties and consider leaving the affected area entirely

14.4. RAMS Analysis

The RAMS analysis addresses the safety concerns, see Subsection 14.4.1, the reliability and availability in Subsection 14.4.2 and the maintainability of the airship in Subsection 14.4.3.

14.4.1. Safety

The safety of the airship is an important part that must be considered. It is needed to identify what major elements can impact safety during operation of the airship. This is mainly its size and the use of hydrogen

Firstly hydrogen handling. The airship utilizes hydrogen as both a lifting gas and fuel. Hydrogen is a flammable gas and must therefore be stored and used under the right conditions. Hydrogen's primary hazards are its flammability and explosion risk [67]. At the hangar, care must be taken that hydrogen stored for later use is positioned away from critical infrastructure such as the airship itself, the hangar or other ground equipment. When (re)fueling and inflating the airship, only specialized and highly trained personnel may perform the actions and care should be taken to prevent hydrogen from escaping during this process. Within the airship, systems that utilise hydrogen must be placed as far as possible from systems that can cause electric sparks or initiate combustion of hydrogen. The airship design accounts for this by placing the gas cells in the upper part of the airship. The payload bay and other systems are isolated from the cells in the bottom part of the airship. The hydrogen tank and fuel cells are placed at the back of the airship, while the crew is located in the front of the airship.

Gas performance during cruise is dependent on atmospheric conditions, meaning the atmospheric conditions must be monitored very closely. This is to ensure the pressure height does not change too quickly when ascending and descending and that overpressure is prevented as much as possible, see Section 4.2. When overpressure gets too high the gas cells can tear and fail. The airship is a lighter then air vehicle and relies almost completely on the buoyancy obtained from the lifting gas. When failure of the gas cells causes hydrogen to escape, lifting capabilities greatly diminish. The airship utilises 16 gas cells, which is redundant. This means that loss of lift due to one gas cell failing, has limited impact. When the airship is losing lift and starts descending the terminal velocity has order of magnitude of 1 m/s. However, this is a rough approximation due to the method used to calculate it. It does indicate that in emergencies the crew can react on time.

Ground handling the airship is difficult mainly due to the airships size and slow speed when handled close to ground. Due to its size it has a large inertia. Airships do not bounce and can suffer structural damage when impacting structures on the ground. Low speed control cannot be easily provided by the tail, but the engines can provide enough thrust for low speed control. In the past, there were collisions of airship with the mooring mast. In this design, however, mooring is done via cables. This eliminates the presence of a large structure close to the airship. The airship is also slightly heavy meaning the airship can be ground handled easier. The airship will stored in the hangar attached to two carts that will taxi the airship in and out of the hangar, see Subsection 11.1.1. This is to ensure proper control during the movement in and out of the hangar.

14.4.2. Reliability and availability

Having a reliable airship is a must. In the past a lot of accidents with airships happened where people died or got injured and where considerable structural damage occurred. A dataset was made including 96 airship disasters. Within that dataset Technical failure accounted for 17.5%, ground handling for 15.5% and unknown reasons accounted for 19.6% of past disasters, see Figure 14.2. Among the technical failures were causes like engine failure, over pressured gas and envelope rupture.

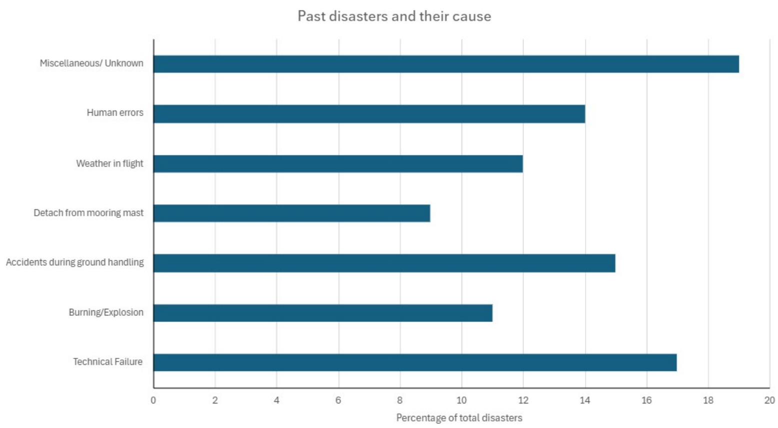


Figure 14.2: *Past disasters and their cause*

It is of upmost importance that the airship is as much available as possible to perform missions, as this directly influences financial profitability. Availability concerns if the airship can be used for operations. A nominal mission of 1100 Km will take around 14 hours to complete. This is from take-off to landing. Storing the airship and taking it out of storage will take around 1 hour. A complete mission will take around 16 hours to complete. This means in principle the airship can perform a mission everyday. However, this is not taking into account the planning and preparation for the mission.

An important factor that determines if the airship is available, is gas availability. Hydrogen gas will be stored on site at base of operation and the airship will be refueled before every flight. At the moment hydrogen gas is widely available but care must be taken to keep this in mind as the airship uses a lot of gas for both filling the gas cells and using it for fuel.

14.4.3. Maintainability

Throughout the lifetime of the airship, maintenance will be required occasionally to ensure safe and reliable airship operations. For optimal performance, the planned and unplanned maintenance tasks must be taken into account. All of the activities should be logged for record-keeping. Some maintenance tasks that have to be performed are shown in the list below.

Daily Tasks

- **Pre-flight Check:** Conduct a quick visual inspection of the airship, including flight controls and control surfaces, before every flight.
- **Envelope Inspection:** Inspect the airship envelope for tears and other damage.
- **Mooring Cable Inspection:** Perform quick checks of the mooring cables before every mooring phase to check for damage.
- **Fuel Cell Inspection:** Perform a quick inspection of the fuel cells before every flight.
- **Payload Hoist System Check:** Inspect the payload hoist system for damage before and after every flight.

Monthly Tasks

- **Envelope Cleaning:** Clean the airship envelope to maintain its integrity and appearance.
- **Gas Cell Refilling:** Refill the gas cells as the airship loses about 1% of its buoyancy each month to maintain the required heaviness [17].

Annual Tasks

- **Structural Integrity Check:** Inspect the rings and longerons for structural integrity.
- **Thorough Fuel Cell Inspection:** Conduct a detailed inspection of the fuel cells.
- **Major Payload Hoist System Maintenance:** Perform comprehensive maintenance on the payload hoist system.
- **Engine Maintenance:** Conduct major maintenance on the engines to ensure optimal performance.

Concluding, logging every activity is of utmost importance because it helps in tracking the airship's maintenance history, enhancing overal safety and reliability of the airship. Ground infrastructure maintenance is also included, but it has not been designed in detail, hence the maintenance will be defined in a later stage in the design. The cost of maintenance is considered Subsection 2.2.3.

15
Future of the Project

15.1. Long-term Timeline
In this section, the long-time timeline of the project is laid out. In Subsection 15.1.1 a timeline of the project with the duration is presented. In Subsection 15.1.3 the project design and development logic is shown, followed by a Gantt chart in Subsection 15.1.2.

15.1.1. High-level timeline
A high-level overview of the future development phases can be split into four parts: the continuation of the detailed design, followed by testing and certification of said design, setting up all facilities and infrastructure, and lastly the continued support and continuation of the project past the first deliveries.

As mentioned in Chapter 2 the first delivery of an airship should take place in 2040, which allows for the construction of a high-level timeline. For reference on the schedule, two recent wide-body aircraft were taken; the Airbus A380 and the A350. By seeing what portion of the total time each phase took it was possible to create the following timeline [68, 46].

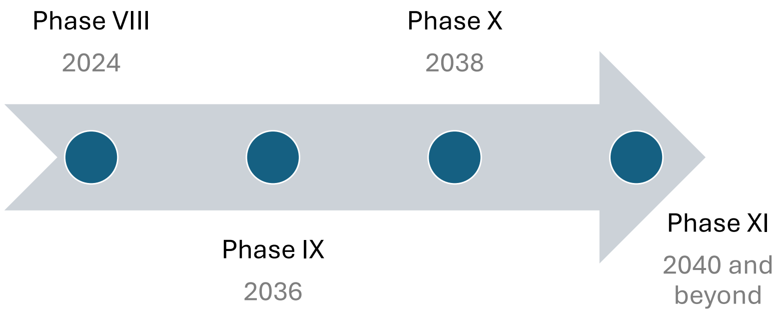


Figure 15.1: *High-level project Timeline*

15.1.2. Project Gantt Chart
In Figure 15.2 a preliminary Gantt chart is shown. It provides a quick overview of the post-DSE phases. A more detailed breakdown is presented in Figure 15.3.

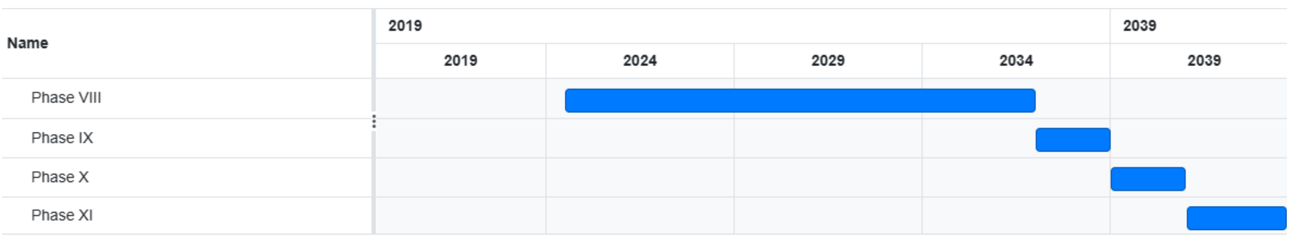


Figure 15.2: *Project Gantt Chart*

15.1.3. Project Design & Development logic
The project design & development logic (PDDL) outlines the sequence of activities to be carried out during the post-DSE phases of the project. This includes phases VIII through XI of the project. Initially, a more detailed version of the current design will be created. During phase IX, however, the design should be finished and a testing and certification campaign can start. Once this is complete, the project moves into the operational set-up phase. This entails the construction of infrastructure for operation. All throughout the timeline, new

investors will be looked for to keep the ever-growing project from grinding to a halt. Finally, when operation has commenced, post-operation support for the system can be provided. A schematic representation of this can be found in Figure 15.3.

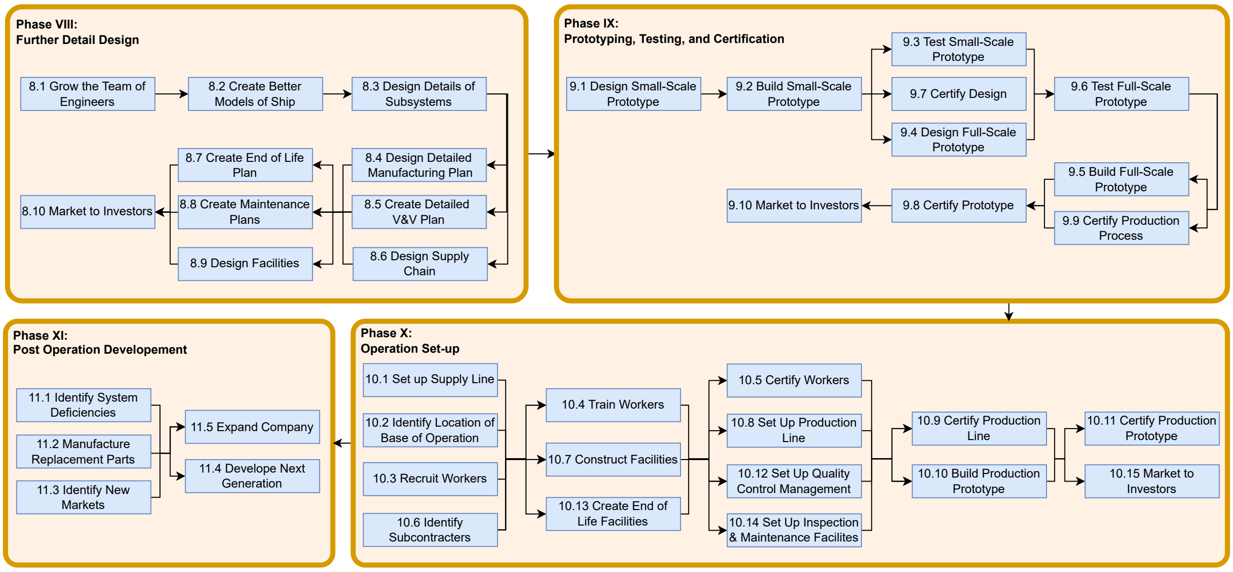


Figure 15.3: *Project Design and Development Logic Chart.*

15.2. Manufacturing Plan

In this section, a plan for the manufacturing of the airship will be outlined. This plan will be split between the main components of the airship, and followed by a discussion of the airship assembly, as well as other things to consider for the manufacturing.

15.2.1. Frame Manufacturing

With the airship frame consisting primarily of longerons and trusses, the manufacturing of the frame can be brought down to the manufacturing of box truss sections. While the longerons consist of continuously curved parts, the airship rings consist of straight truss beam segments, which create a polygon which approximates the circular cross-section shape.

The manufacturing of box trusses starts with the manufacturing of aluminum tubes that constitute the truss structure. These tubes can be easily extruded and outsourced. For each section of the truss, a separate tube will have to be produced for the box truss chords and the diagonal members. The tube size and cross-section can be easily varied by changing the extrusion die accordingly and within manufacturability limits. In case the tube needs to be bent to shape, cold forming can be used to achieve this purpose [1].

Once the aluminum tubing is produced, parts of the truss can be welded together. To do this, spot welding is used initially to hold the structure together, and is followed by the full full welding of the joints. This process can be partially automated, but will, for the most part, require manual assembly. This is due to the custom curved beams used within the structure.

After the truss box components are welded together, secondary processes, such as drilling holes for the connection pins can be conducted. Once the truss boxes are manufactured, they are checked for defects by the manufacturer; the manufacturer will be required to provide quality assurance of delivered parts.

A number of separate box truss sections will be outsourced for the airship. The longeron trusses can be connected via pins or conical connectors, which allows for easy assembly of this part of the structure. Such pins can be bought commercial-off-the-shelf (COTS) and are commonly made out of aluminum. For the assembly of the airship rings, reinforced connection parts will be sourced and custom-made. Such parts can be small, reinforced truss elements, which would follow a parallel manufacturing process to the truss box production; alternatively, custom-designed connectors can be made and machined, in which case the cost of the assembly would increase.

[1] `https://www.tecnocurve.com/tubing-bending/aluminium-tube-bending-how-to-do-it-right/` (Accessed on: 17/06/2024)

15.2.2. Tail Manufacturing

The structure of the tail of the airship can be taken as parallel to the design of an aircraft wing. Therefore, such a tail will consist of spars and a series of ribs across the span of the tail.

The manufacturing of the tail spars starts with obtaining aluminum sheet sections in the desired shape. This can be done by punching sections out of the sheet. Depending on the spar design, one or multiple sheets of aluminum can be used for the web and the flanges. Alternatively, water jet cutting or laser cutting can be used for this purpose. Next, lightning holes and rivet holes are punched and drilled within the material pieces. Once this is done, the aluminum sections are bent to form the desired shape of the spar. In case multiple sheets of aluminum are used for the flanges and web of the spar, the pieces are bolted or riveted together.

A similar manufacturing process can be used for the manufacturing of tail ribs. First, the rib shape, along with the lightening holes and internal cutouts within the rib, is punched out of an aluminum sheet. Subsequently, the cut element is formed using rubber forming, and the rib flanges are created.

To create the tail subassemblies, parts of the structure are first fastened together using rivet clamps, and then riveted together. The tail subassemblies are then bolted to the designated rings and supports within the airship structure.

15.2.3. Gas Bag and Envelope Manufacturing

The material chosen for the gas bags is a composite material consisting of Zylon fibers and a Nylon matrix. Such gas bags are typically manufactured in sections and sealed together securely.

The gas bags to be used will most likely be outsourced from a specialized company. The manufacturing of the Zylon/Nylon composite will consist of the manufacturing of the Zylon fabric, followed by the impregnation of the reinforcement by a Nylon matrix. Once the load-bearing layer is cured, the gas retention layer will be connected to it using an adhesive. The manufacturing of the fabric will be done in sections or so-called gores. The sections will then be sealed together and the gas bag shape will be produced. As the last step, protective and anti-static-electricity treatments can be applied to the gas bag material.

Since the envelope of the airship is made out of a single layer of polyurethane elastomer, its manufacturing will consist of the manufacturing of the envelope sections (gores) and their assembly onto the airship frame. The ready material will be outsourced and gores will be attached to the airship structure during final assembly. This will be done using adhesives and fasteners attached to the airship's frame.

15.2.4. Propulsion System Manufacturing

The manufacturing of the propulsion system will be largely outsourced due to the complexity of the propulsion system. The rotors and fuel cells will be ordered from an appropriate manufacturer and assembled onto the structure on-site.

The fuel tank within the airship will be custom-ordered and manufactured out of carbon fiber-reinforced polymer. The manufacturing of such a tank can be done using filament winding, wherein impregnated carbon fiber filament is spun onto a mandrel. The internal and external surfaces of the tank are then subjected to special treatments to prevent leaks.

15.2.5. Assembly

Once the components of the subsystems within the structure are manufactured, the final assembly can be conducted. To do this, an assembly jig will be created in the airship hangar, within which the airship frame will be built. The payload bay and internally placed subsystems are inserted and mounted in the structure. The exact order in which this is done will be determined based on subsystem placement. A temporary internal truss structure will be built inside the airship to allow for access to the top parts of the structure. The tail is mounted on the structure using a separate jig for its exact positioning and is fastened to the existing truss structure.

The gas bags are placed within the airship once a sufficient part of the truss structure has been built to support them. Following the insertion of all subsystem parts along with the placement of the gas bags, the truss structure is closed and the envelope material is placed along the external truss structure. Unless changes to the internal structure of the payload are needed that cannot be made when accessed through the payload bay, the envelope is fully created.

As the last step of the assembly, the outside of the envelope can be painted and coated as desired. With this, the airship assembly is complete. Note that the filling of gas bags and the filling of the fuel tanks is not part of the airship assembly and is included in pre-flight operations.

15.2.6. Other Considerations

Although outside of the scope of this project, the building and assembly of the airship hangar should be considered. Due to the large size of the airship, hangar size limitations can potentially impose significant difficulties for the manufacturing of the hangar. It can be expected that the building of the hangar will take a considerable time and workforce to complete, as well as consume a significant amount of resources.

The manufacturing plan for the building of the airship hangar will therefore need to be made long in advance of the planned airship manufacturing. While a hangar will be most likely based on a simple truss structure, the size of it increases the complexity in its design.

15.3. Verification and Validation procedures

During product development, it must be ensured that the produced design is the one that was intended to be created. This has to be done at various stages of the design and development process of a mission or system to ensure that mission needs and objectives are met. For this reason, validation and verification (V&V) strategies have to be implemented in the design. To accomplish this, the V-model presented in Figure 15.4 can be used.

The advantage of the approach in Figure 15.4 is that V&V is implemented at all levels of the design, and allows for iteration. It also shows that for a good design process the system should first be broken up into smaller parts and later built up again. During this last stage, it is important that the interfaces between the subsystems are verified along the way. The goal is to catch and correct errors as early as possible.

The main parts of V&V are the validation of the requirements, of the models, verification and validation of the product. For aircraft there is an additional part that is not present for all systems; airworthiness. It is mainly the last three parts that will be discussed in detail here.

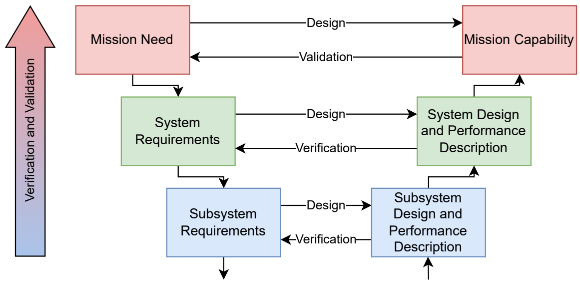


Figure 15.4: *V-Model Diagram*

15.3.1. Requirement Validation

The first step in having a verified and valid system is validating the requirements. This ensures that the stakeholder needs have been correctly translated into design-able requirements. This must be done every time a new requirement is created. This is done using the VALID method, it stands for Verifiable, Achievable, Logical, Integral, and Definitive. Once a requirement is phrased in a way such that it has these characteristics, it can be used for the design.

15.3.2. Model Validation

Model validation ensures that the models used throughout the design represent real-world conditions with sufficient accuracy. These can be statistical or mathematical models, but also graphical and physical models. Typical ways to validate these are analysis, experience, or comparison with existing models. It can often be assumed that reputable models are sufficiently accurate for this stage of the design. Whenever the design becomes more intricate or models are created, it is necessary to do this.

15.3.3. Product Verification

A more classical part of V&V is product verification. Product verification looks into whether the created product meets the set requirements. This can only be done definitively when the design has sufficiently matured. However, during the design it should be kept in mind, as these requirements guide the design.

Product verification follows a bottom-up approach; starting with small parts and working its way up. Product verification can only start once the hardware (or software if that is what is being created) design is finalized. The first step is to verify the component on its own in a simulated environment. Once this has been completed, and all feedback has been implemented, the verification can move onwards. The next step is interface verification; two or more systems are put together and verified in a simulated environment. This is repeated with different interfaces/ combinations until all the interfaces have been verified. Once this is the case, the components can be integrated, and this can all be done one level higher. This is done until all subsystems have been integrated into the system. Only then the full system can be verified. Throughout this process, it is of utmost importance that everything is well documented.

A visual representation of what the process would look like is given in Figure 15.5

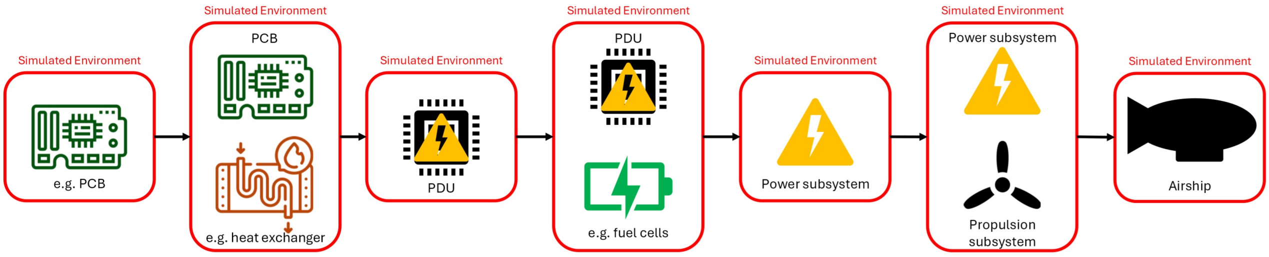


Figure 15.5: *Example of the product verification process.*

Verifying that these components meet the requirements in the simulated environments can be done in four different ways. The first one is inspection, which means the product or its documentation is looked at to check if it meets the requirements. The second one is analysis. For this calculations or other analysis methods are used to check that the requirements are met. Thirdly there is testing, where the part's compliance is checked under representative conditions. Lastly, there is demonstration, where the requirements are validated by using it in operation.

It is important to note that these checks do not have to be performed on physical parts. The entire process can be checked in a virtual environment using models. This allows for product verification in earlier stages of the design. It is however of the utmost importance that at some point they are done in the real world. Some of these are to check requirements set by users or stakeholders, but many will also come from certifying agencies. Those will be done in collaboration with said agencies to get certified as will be explained in more detail in Subsection 15.3.5.

15.3.4. Product Validation

Product validation shows if the final product can fulfill the original intended purpose or mission. The verified airship is cross-referenced to the original stakeholder needs. This can be split into several steps.

End-to-end system validation shows the compatibility within the system and with the outside world. For the airship, this would include things that are very similar to pre-flight checks. These checks can mostly be performed inside the hangar but some parts can be performed outdoors. Some examples that are validated in this step include buoyancy with differing temperatures, testing the payload exchange in controlled conditions, and trialling ground operations without the ship being present.

Mission scenario testing demonstrates that the product can perform its intended mission, in both nominal and contingency cases. This is not necessarily done in real time. The airship would display the ability to perform different mission phases such as load exchange, climb, descent, cruise, etc. It is important to gather data on the handling of the airship during this stage.

Operations readiness testing displays realistic mission scenarios in real time. The airship will perform a realistic mission and its performance will monitored. Due to this stage being performed in real time and real conditions, it accurately validates the interaction between the different mission components.

Stress testing and simulation aims to assess the robustness of the entire system and it's tolerance to different fault states. Different emergency and other off-nominal situations both in the air and on the ground are performed and the behavior of the airship is documented.

These tests are always performed in cooperation with certifying agencies.

15.3.5. Airworthiness

"For an aircraft, or aircraft part, airworthiness is the possession of the necessary requirements for flying in safe conditions, within allowable limits." [69, p.3] This certification process happens in parallel with the V&V process. It consists of the following 4 steps.[2]

1. Technical familiarisation and certification basis
2. Establishment of the certification program
3. Compliance demonstration
4. Technical closure and issue of approval

Firstly, the aircraft design is presented to EASA when it is deemed mature enough to do so. Subsequently, the set of rules that the aircraft will need to follow will be established, this is called the certification basis.

[2] `https://www.easa.europa.eu/en/domains/aircraft-products/aircraft-certification` (Accessed on: 20/06/2024)

Secondly, for all the requirements in the certification basis EASA and the design team will need to agree on the way in which the compliance with these requirements is shown.

Thirdly, it must be demonstrated that the aircraft meets regulatory requirements by analyzing the structure, engines, control systems, electrical systems, and flight performance. This involves ground and flight testing, with experts thoroughly examining the compliance demonstration. The process can take up to five years for large aircraft and may be extended if needed.

Finally, in case EASA find the testing campaign to be satisfactory, it will issue a type certificate. This certificate only applies to the design of the airship, not to the individual ones produced. For that, every produced ship has to conform to the type certificate and must be in condition for safe operation [69]. If this proves to be the case, the ship will be granted an airworthiness license and can enter operation.

16 Conclusion

Within this report, the work of DSE Group 3 was described and discussed. The aim of Group 3 was to design a cargo airship to transport wind turbine blades in a sustainable, cost-effective, and time-efficient way. This objective was guided by the current market need for turbine part transportation options caused by the rapid increase in demand for green energy, as well as the increasing turbine size.

The work conducted throughout the project proved that transportation of wind turbine blades using a cargo airship is a feasible endeavor. The feasibility has been proven across the board, especially at the market level: this application of the airship is both cost-effective for the users and highly profitable for airship developers. Airship operation for turbine blade transport is 7.5 times cheaper and at least 33% faster than truck transportation, which makes it a highly competitive and appealing solution. It is sustainable both directly, through the use of green propulsion and recyclable materials, as well as indirectly, through supporting the development of wind energy infrastructure.

The final design consists of a rigid airship using hydrogen as lifting gas, and is shown in Figure 16.1. The airship is capable of taking off vertically, reducing the need for infrastructure. A wind turbine blade up to 105 meters and 60 tonnes can be transported. This increases the energy production of wind turbines significantly. To (un)load the payload, mooring cables are being used, this eliminates the usage of a mooring mast, significantly reducing the cost. To propel the airship, a combination of fuel cells and propellers are used, as this does not emit greenhouse gasses and is optimal for the flight regime.

Throughout the research and design process, several problems within airship development were highlighted. Firstly, limited resources exist for the design of cargo airships, which makes first-order estimations of the airship design difficult. Secondly, the current lack of operational cargo airships makes the airship certification a lengthy and complex process, with few clear regulation guidelines present. Lastly, due to its novelty and developmental uncertainties, the airship has to have a clear competitive advantage on the market.

With the continuation of the design and the realization of the project, a few points are recommended. For the design, mainly the ballast system, as currently the required ballast system is too heavy. Additionally, the ground infrastructure and the safety need to be designed in more detail, to provide a better insight for the costs and feasibility. A better aerodynamic analysis has to be performed, as this is crucial for many subsystems. For non-technical aspects, the costs, and ROI need to be analyzed in more detail. To get this project running, investors are required, which can be convinced by a detailed cost and ROI analysis.

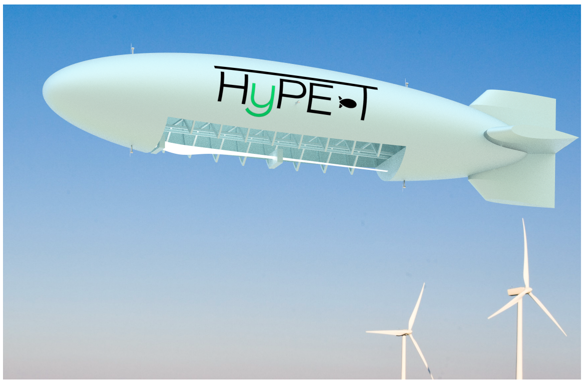


Figure 16.1: *Render of the airship*

Figure 16.2: *Main parameters of the system*

Parameter	Value
Payload Capacity	60 000 kg
MTOW	225 000 kg
Max. Payload Dimensions	105x12x10 m
Length	221 m
Cruise Speed	80 km/h
Endurance	16 h
Max. Range	1120 km
Lifting Gas & Fuel	Hydrogen
Production costs	39 ± 8 million euros
Operational cost	3.7 million per year
Development cost	500 million

References

[1] R. O'Sullivan. *Wind Energy in Europe, statistics and the outlook for 2024-2030*. Tech. rep. Brussels, Belgium, 2024.

[2] Leszek Dawid. "Perspectives on Offshore Wind Farms Development in Chosen Countries of European Union". In: *Journal of Water and Land Development* 38 (2018), pp. 27–34. DOI: 10.2478/jwld-2018-0039.

[3] Global Wind Energy Council. *GWEC Global Wind Report 2024*. Tech. rep. Brussels, Belgium, 2024.

[4] R. Thresher, M. Robinson, and P. Veers. "The Future of Wind Energy Technology in the United States". In: Oak Ridge, TN, USA: U.S. Department of Energy, July 2008.

[5] Peter Lobner. *Modern Airships Part 1*. Tech. rep. San Diego, CA, USA, 2019.

[6] Albara Mustafa and Aziz Al-Mahadin. "Risk Assessment of Hazards Due to the Installation and Maintenance of Onshore Wind Turbines". In: Feb. 2018, pp. 1–7. DOI: 10.1109/ICASET.2018.8376789.

[7] M. Hagenbeek, S.J. van den Boom, N.P.M. Werter, F. Talagani, M. van Roermund, B.H. Bulder, and H.J. van der Mijle Meijer. *The Blade of the Future: Wind Turbine Blades in 2040*. Tech. rep. Delft, Netherlands, 2022.

[8] Hugo Díaz and C Guedes Soares. "Review of the Current Status, Technology and Future Trends of Offshore Wind Farms". In: *Ocean Engineering* 209 (2020), p. 107381. DOI: 10.1016/j.oceaneng.2020.107381.

[9] R. O'Sullivan. *Decommissioning of Onshore Wind Turbines - Industry Guidance Document*. Tech. rep. Brussels, Belgium, Nov. 2020.

[10] Thomas Hajonides van der Meulen, Ton Bastein, Siddharth Krishna Swamy, Novita Saraswati, and Jelle Joustra. *Offshore Wind Farm Decommissioning*. Tech. rep. Rotterdam, Netherlands, 2020.

[11] Leon Mishnaevsky Jr. and Kenneth Thomsen. "Costs of Repair of Wind Turbine Blades: Influence of Technology Aspects". In: *Wind Energy* 23.12 (2020), pp. 2247–2255. DOI: 10.1002/we.2552.

[12] *Unloading of Blades from a Truck*. Tech. rep. 2019.

[13] Diana Deimling, Rose DeJamette, Michael Rouse, Holleran Reneé, Carol Downing, and Steve Carleton. "Helicopter Loading Time Study: Hot Versus Cold". In: *Air Medical Journal* 18.4 (1999), pp. 145–148.

[14] Roberto Lacal-Arántegui, José M Yusta, and José Antonio Domínguez-Navarro. "Offshore Wind Installation: Analysing the Evidence Behind Improvements in Installation Time". In: *Renewable and Sustainable Energy Reviews* 92 (2018), pp. 133–145.

[15] International Civil Aviation Organization. "Worldwide Air Transport Conferencec (ATCONF) Sixth Meeting". In: Montréal, Canada, Mar. 2013.

[16] Federal Aviation Administration. *14 CFR § 135.267 Flight Time Limitations and Rest Requirements: Unscheduled One- and Two-Pilot Crews*. Washington, D.C., USA, Jan. 2023.

[17] G.A. Khoury. *Airship Technology*. Airship Technology. Cambridge University Press, 2012. ISBN: 9781107019706.

[18] Ansys. *Granta EduPack 2023 R2 Properties*. Application. (Date accessed: 18 June 2024). July 2023.

[19] J. Wieringa. "Shapes of Annual Frequency Distributions of Wind Speed Observed on High Meteorological Masts". In: *Boundary-Layer Meteorology* 45 (Aug. 1988), pp. 85–110. DOI: 10.1007/BF00122324.

[20] P. Liu and C.Y. Barlow. "The Environmental Impact of Wind Turbine Blades". In: *IOP Conf. Series: Materials Science and Engineering* 139 (2016), pp. 3–5.

[21] R.P.G. Collionson. *Introduction to Avionics Systems*. Springer Science & Business Media, Dec. 2002. ISBN: 9781441974662.

[22] D. H. Strother and H. N. Aeton. *A Superheat Meter or Differential Thermometer for Airship*. Technical Report. Washington, D.C., USA, Oct. 1927.

[23] Maurizio Bonnici, Alessandro Tacchini, and Dean Vucinic. "Long Permanence High Altitude Airships: The Opportunity of Hydrogen". In: *European Transport Research Review* 6.3 (Sept. 2014), pp. 253–266. ISSN: 1866-8887. DOI: 10.1007/s12544-013-0123-z.

[24] Kun Zhao, Xixiang Yang, Zhongxi Hou, Lixue Zhang, and Zhang Weihua. “Superheat Simulation of the High Attitude Scientific Balloon During Floating Flight”. In: June 2013. DOI: 10.13140/RG.2.1.3762.7363.

[25] Chenrui Fu, Ming Zhu, Dongxu Liu, Da Zhao, and Xiaojun Zhang. “Multilayer Nanoparticle-Polymer Metamaterial for Radiative Cooling of the Stratospheric Airship”. In: *Advances in Space Research* 72.2 (2023), pp. 541–551. ISSN: 0273-1177. DOI: 10.1016/j.asr.2023.03.004.

[26] Mei Ke, Sun Xueyin, Pu Yuanzhu, Li Cheng, Li Xinying, Di Jingjing, and Hou Zhegui. “Thermal Design and Optimization of the Stratospheric Airship Equipment Module”. In: *Journal of Physics: Conference Series* 1678.1 (Nov. 2020), p. 012050. DOI: 10.1088/1742-6596/1678/1/012050.

[27] Азатян Вилен Вагаршевич (RU), Тимербулатов Тимур Рафкатович (RU), and Школдыченко Виктор Захарович (RU). *Газовый Состав для Предотвращения Воспламенения и Взрыва Водородовоздушных Смесей*. Feb. 2010.

[28] H.B. Freeman. *Force Measurements on a 1/40-scale Model of the U. S. Airship ”Akron”.* Technical Report NACA-TR-432. Langley Research Center, Hampton VA 23681-2199, USA: NACA, Jan. 1933.

[29] W.M. Kays and M.E. Crawford. *Convective Heat and Mass Transfer*. McGraw-Hill Series in Management. McGraw-Hill, 1980. ISBN: 9780070334571.

[30] J.D. Anderson. *Fundamentals of Aerodynamics*. McGraw-Hill series in aeronautical and aerospace engineering. McGraw-Hill Education, 2017. ISBN: 9781259251344.

[31] G.A. Khoury and J.D. Gillett. *Airship Technology*. Airship Technology. Cambridge University Press, 1999. ISBN: 9780521607537.

[32] A.F. Zahm, R.H. Smith, and F.A. Louden. *Drag of C-Class Airship Hulls of Various Fineness Ratios*. Technical Report NACA-TR-291. Naval Facilities Engineering Systems Command 1322 Patterson Ave. SE Suite 1000 Washington Navy Yard: NACA, Jan. 1929.

[33] Mohamed Atyya, Gamal M ElBayoumi, and Mohamed Lotfy. “Optimal shape design of an airship based on geometrical aerodynamic parameters”. In: *Beni-Suef University Journal of Basic and Applied Sciences* 12.1 (2023), p. 25. DOI: 10.1186/s43088-023-00352-1.

[34] Sagar Kale, Pankaj Joshi, and Rajkumar Pant. “A generic methodology for determination of drag coefficient of an aerostat envelope using CFD”. In: *AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences*. 2005, p. 7442. DOI: 10.2514/6.2005-7442.

[35] L.M. Nicolai and G. Carichner. *Fundamentals of Aircraft and Airship Design*. 2nd ed. AIAA education series. American Institute of Aeronautics and Astronautics, 2010. ISBN: 9781600868986.

[36] S.F. Hoerner. *Fluid-dynamic Drag: Practical Information on Aerodynamic Drag and Hydrodynamic Resistance*. Liselotte A. Hoerner, 1965. ISBN: 9789991194448.

[37] Noel K. Delany and Norman E. Sorensen. *Low-Speed Drag of Cylinders of Various Shapes*. Technical Note NACA-TN-3038. Ames Aeronautical Laboratory Moffett Field, CA, USA: NACA, Nov. 1953.

[38] Anatol Roshko. “Experiments on the flow past a circular cylinder at very high Reynolds number”. In: *Journal of fluid mechanics* 10.3 (1961), pp. 345–356. DOI: 10.1017/S0022112061000950.

[39] CF Heddleson, DL Brown, and RT Cliffe. *Summary of drag coefficients of various shaped cylinders*. General Electric, 1957.

[40] B.R. Munson, D.F. Young, and T.H. Okiishi. *Fundamentals of Fluid Mechanics*. v. 1. Wiley, 1998. ISBN: 9780471355021.

[41] E Willemsen. “High Reynolds number wind tunnel experiments on trains”. In: *Journal of wind engineering and industrial aerodynamics* 69 (1997), pp. 437–447. DOI: 10.1016/S0167-6105(97)00175-X.

[42] *Technical Manual of Airship Aerodynamics*. Tech. rep. TM 1-320. Feb. 11, 1941.

[43] S.A. Ross and H.R. Liebert. *LTA Aerodynamics Handbook*. Goodyear Aircraft Corp., 1965.

[44] Freeman B. “Force Measurements on a 1/40-scale Model of the U. S. Airship ”Akron.”” In: (Jan. 1933).

[45] L.M. Nicolai and G.E. Carichner. *Fundamentals of Aircraft and Airship Design: Aircraft design and case studies*. AIAA education series. American Institute of Aeronautics and Astronautics, 2013. ISBN: 9781600868986.

[46] G. Norris and M. Wagner. *Airbus A380: Superjumbo of the 21st Century*. Zenith Press, 2005. ISBN: 9780760322185.

[47] J. D. Maynard and L. B. Salters Jr. *Aerodynamic Characteristics at High Speed of Related Full-Scale Propellers Having Different Blade-Section Cambers*. Technical Report NACA-TR-1309. Langley Aeronautical Laboratory Langley Field, Va.: NACA, Jan. 1957.

[48] S. Gudmundsson. *General Aviation Aircraft Design: Applied Methods and Procedures*. Elsevier Science, 2013. ISBN: 9780123973290.

[49] G. Padgett E. Kleen. *Automotive Fuel Cell Targets and Status*. Tech. rep. 20005. Department of Energy, Aug. 2020.

[50] M. Gardiner. *Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs*. Tech. rep. 9013. Department of Energy, Oct. 2009.

[51] Michael F. Ashby. *Materials Selection in Mechanical Design*. 4th ed. United States: Elsevier, 2011.

[52] A De Almeida, FJTE Ferreira, Paula Fonseca, Bruno Chretien, Hugh Falkner, Juergen CC Reichert, Mogens West, Sandie B Nielsen, and Dick Both. "VSDs for electric motor systems". In: *Final Report, SAVE Programme, European Commission, Brussels* (2001).

[53] Denja Lekou. *Scaling Limits and Costs regarding WT blades*. Sept. 2010.

[54] N.J C. E. Rosendahl Lakehurst. "The Mooring and Ground Handling of a Rigid Airship". In: *Journal of fluids engineering* 55 (1933). DOI: `https://doi.org/10.1115/1.4022232`.

[55] Goodyear Aerospace Corporation. *STUDY OF GROUND HANDLING CHARACTERISTICS OF A MARITIME PATROL AIRSHIP*. Study NASA CR- I6625. Goodyear: 1210 Massillon Road Akron, Ohio 44315, NASA: Ames Research Center Moffett Field, Calif.: NASA Ames Research Center, Mar. 1981.

[56] C.j. Huang and Charles Dalton. *Cargo transportation by airships: a systems study*. Study NASA CR- 2636. University of Houston Houston, TX 77004: University of Houston, May 1976.

[57] ICAO. *Phase of Flight, Definitions and usage notes*. Apr. 2013.

[58] Philip V. Hunt. *Advanced Airship Technologies and Design Approaches*. American Institute of Aeronautics and Astronautics, 2015.

[59] "Peer Reviewed: Design Through the 12 Principles of Green Engineering". In: *Environmental Science & Technology* 37.5 (2003). PMID: 12666905, 94A–101A. DOI: `10.1021/es032373g`.

[60] Lina Agudelo. "Aide à la décision en conception préliminaire par l'estimation du poids de la performance environnementale - DECISION MAKING SUPPORT THROUGH THE CONSIDERATION OF ENVIRONMENTAL CRITERIA IN PRELIMINARY DESIGN". PhD thesis. Oct. 2016. DOI: `10.13140/RG.2.2.36786.61126`.

[61] "Life-cycle assessment of fuel cell stacks". In: *International Journal of Hydrogen Energy* 26.1 (2001), pp. 91–101. ISSN: 0360-3199. DOI: `https://doi.org/10.1016/S0360-3199(00)00053-7`.

[62] "Critical and strategic raw materials for electrolysers, fuel cells, metal hydrides and hydrogen separation technologies". In: *International Journal of Hydrogen Energy* 71 (2024), pp. 433–464. ISSN: 0360-3199. DOI: `https://doi.org/10.1016/j.ijhydene.2024.05.096`.

[63] "Chapter 2 - Wind Power Fundamentals". In: *Wind Energy Engineering*. Ed. by Trevor M. Letcher. Academic Press, 2017, pp. 17–24. ISBN: 978-0-12-809451-8. DOI: `https://doi.org/10.1016/B978-0-12-809451-8.00002-3`.

[64] "Wind farm land suitability indexing using multi-criteria analysis". In: *Renewable Energy* 44 (2012), pp. 80–87. ISSN: 0960-1481. DOI: `https://doi.org/10.1016/j.renene.2012.01.004`.

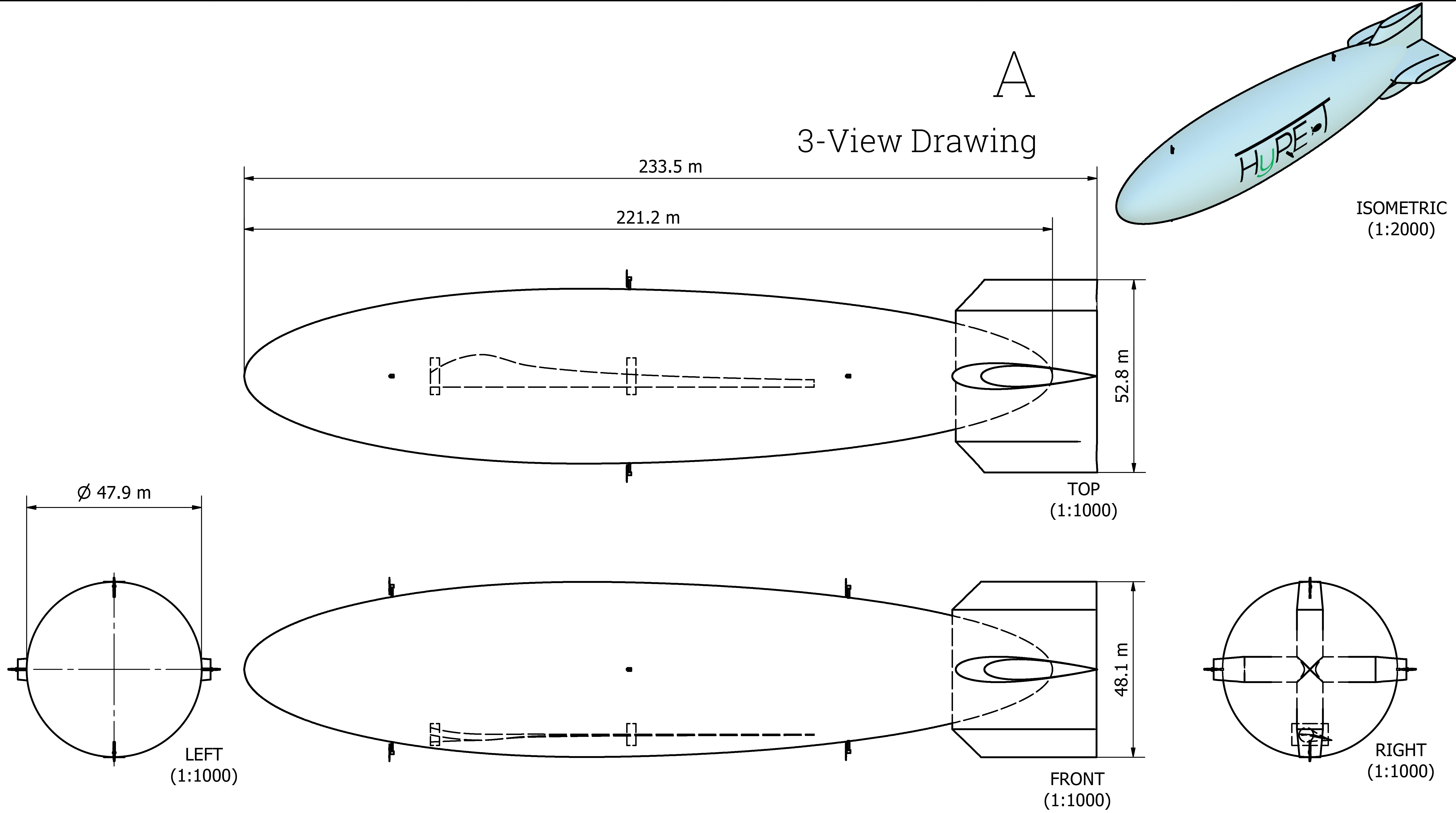
[65] Rahim Moltames, Mohammad Sajad Naghavi, Mahyar Silakhori, Younes Noorollahi, Hossein Yousefi, Mostafa Hajiaghaei-Keshteli, and Behzad Azizimehr. "Multi-Criteria Decision Methods for Selecting a Wind Farm Site Using a Geographic Information System (GIS)". In: *Sustainability* 14 (Nov. 2022), pp. 1–19. DOI: `10.3390/su142214742`.

[66] Steven Hirshorn. *NASA Systems Engineering Handbook*. 2nd ed. Washington, D.C., USA: NASA, 2017.

[67] Air Products. *Safetygram Gaseous Hydrogen*. Tech. rep. 2014.

[68] Abel Jiménez-Crisóstomo, Luis Rubio-Andrada, María Soledad Celemín-Pedroche, and María Escat-Cortés. "The constrained air transport energy paradigm in 2021". In: *Sustainability* 13.5 (2021), p. 2830. DOI: `10.3390/su13052830`.

[69] F. De Florio. *Airworthiness: An Introduction to Aircraft Certification*. Butterworth-Heinemann Limited, 2011. ISBN: 9780080974736.



DRAWN J.W.S. Jacobs	25-6-2024	TU Delft		
CHECKED G.A. Skorupska-Ruiz	25-6-2024			
		TITLE Cargo Airship HyPE-T		
SIZE A3		DWG NO airship_ASSEMBLY v1-1		REV 1
SCALE 1:1000	MASS 225e5 kg	SHEET 1 OF 1		