POLITECNICO DI TORINO

Corso di Laurea in Ingegneria Aerospaziale

TESI DI LAUREA MAGISTRALE

Multidisciplinary Design of Rigid Airship equipped to Superyacht in Collaboration with Pininfarina

Progettazione Multidisciplinare di Dirigibile Innovativo Rigido attrezzato a Superyacht in Collaborazione con Pininfarina

Relatori

Ing. Maria Cinefra

Ing. Erasmo Carrera

Tutori Aziendali

Pininfarina Extra S.r.l.

Ing. Francesco Lovo

Dan Mattanò

Euro Airship S.a.s.

Marie Christine Bilbow

Candidato

Angelo Antonio Zagaria

Dicembre 2018

"Once you have tasted flight, you will forever walk the earth with your eyes turned skyward, for there you have been, and there you will always long to return."

— Leonardo da Vinci

Contents

I. Table of Figure .... **IV**

II. Tables .... **VI**

III. Definitions and Abbreviations .... **VII**

IV. Objective and Purpose .... **X**

V. Abstract .... **XI**

1. Introduction **1**

1.1. History 3

1.2. Typology 4

1.3. Why Airship? 7

1.3.1. Market Research 8

1.3.2. Purpose Problem and Target 10

2. Airship Design **13**

2.1. Phase 0 14

2.1.1. Stakeholder Analysis 17

2.1.2. Constraints 18

2.1.3. Needs Analysis 19

2.1.4. Requirements 23

3. Preliminary Definition of the Airship Dimensions **25**

3.1. Historical Rigid Airship Database 25

3.2. Gondola Dimensions 28

3.3. Hull Dimensions 30

4. Aerodynamic Data Estimate **33**

4.1. Historical Rigid Airship Database 33

4.2. Preliminary Assessment 35

4.2.1. Zero Lift Drag Coefficient 38

4.2.2. Airship Trim 43

5. Tail Design **45**

6. Performances **53**

6.1. Range and Endurance Estimate 57

6.1.1. #1 Cruise Strategy - Constant Cl 58

6.1.2. #2 Cruise Strategy - Constant Speed 60

6.2. Take-Off and Landing Analysis 62
6.2.1. Take-Off Analysis 62
6.2.2. Rate of Descent 67
6.2.3. Landing Analysis 68
7. Propulsion System 71
7.1. Fuel Propulsion System 72
7.2. Electric Propulsion System 73
7.2.1. Solar Power 73
7.2.2. Sizing of Solar Array and Power Storage 78
7.3. Initial Propeller Sizing 82
8. Preliminary Weights Estimate 87
8.1. #1 - Performance Method 88
8.1.1. Zero Fuel Weight 88
8.1.2. Fuel Weight 89
8.2. #2 - Weight Build-Up Method 92
8.2.1. Hull Weight 92
8.2.2. Tail Weight 96
8.2.3. Gondola Weight 97
8.2.4. Propulsion System Weight 98
8.2.5. Avionics and Electric System Weight 102
8.2.6. Landing Gear Weight 102
8.2.7. Crew and Passenger Services Weight 103
8.2.8. Unusable Fuel and Empty Weight Margin 104
9. Excel Program: RAsDEx 1.1 105
9.1. Introduction 105
9.2. Solver and Macro 109
9.3. Program Validation 114
9.4. Input, Assumption, and Output 115
10. Aesthetic Design Development 121
11. Conclusion and Future Works 125
Annex 127
A1. Pinifarina Extra 127
A2. Euro Airship 127
A3. Project Phases 129

A4. Stakeholders Classification 129
A5. Dimensions of the Gondola: Internal Space Analysis 129
A6. Tables of Conversion and Physical Quantities 133
A7. Atmospheric Data 134
A8. Data Tables 138
A9. Viscosity Estimation 143
BIBLIOGRAPHY 145

I. Table of Figure

Figure 1-1: Aircraft classification 1
Figure 1-2: Balloon (tethered) 2
Figure 1-3: Sky lantern[1] 3
Figure 1-4: LZ-129 Hindenburg burning [2] 4
Figure 1-5: Airship typology 5
Figure 1-6: Global airship market size and forecast 2015–2024 (US $ million) [3] 8
Figure 1-7:Global airship market share by region, 2024 (value %) [4] 9
Figure 1-8: Level of speed and comfort 11
Figure 2-1: V-model 13
Figure 2-2: WBS 14
Figure 2-3: Study logic 16
Figure 2-4: Timeline 17
Figure 2-5: Stakeholder mapping 18
Figure 3-1: Extrapolation of MTOW from payload 25
Figure 3-2: Extrapolation OEW from MTOW 26
Figure 3-3: Extrapolation of fuel weight from MTOW 27
Figure 3-4: Extrapolation of helium volume from MTOW 27
Figure 3-5: Prolate spheroid 30
Figure 4-1: Table of design and aerodynamic datasheet [5] 34
Figure 4-2: Experimental “K” determination 36
Figure 4-3: Comparison between CL_α expressions 37
Figure 4-4: Skin friction in cases of laminar and turbulence flow 40
Figure 4-5: Relationship between lift coefficient and incidence angle 43
Figure 5-1: Tail position schematisation 45
Figure 5-2: Construction of vertical and horizontal tail volumetric coefficient [6] 46
Figure 5-3: Performances of different tail configurations 47
Figure 5-4: Comparison of “X” and “+” configurations 48
Figure 5-5: Y-configuration schematisation 50
Figure 6-1: Forces and weights distribution on airship 53
Figure 6-2: Power breakdown in two terms 56
Figure 6-3: Take-off phases 62
Figure 6-4: Diagram of speed and ratio between thrust and static thrust 64
Figure 6-5: Diagram of PL and ratio between static thrust and power 65
Figure 6-6: Climb-out distance scheme 66
Figure 6-7: Rate of descent scheme 67
Figure 6-8: Landing phase scheme 68
Figure 7-1: Light incidence 74
Figure 7-2: Graph of solar power at varying altitudes 74
Figure 7-3: Axial tilt and solar rays incidence in summer and winter [7] 75
Figure 7-4: Solar power trend at latitude of 55.8 degrees 76
Figure 7-5: Solar power trend at latitude of 18.9 degrees 76
Figure 7-6: Scheme of electric power trend 79
Figure 7-7: Propeller diagram 82

Figure 7-8: Efficiency trend 83
Figure 7-9: Design chart for propeller [8] 84
Figure 8-1: Fuel reserve estimation 90
Figure 8-2: Tangent function 91
Figure 8-3: Gas balloon enclosed between ring and longitudinal elements 93
Figure 8-4: Number of gas balloons chart 95
Figure 9-1: Input Output Worksheet 106
Figure 9-2: Excel Solver 109
Figure 9-3: Trend line of helium volume depending on payload and altitude 110
Figure 9-4: Limit argument for solution convergence depending on altitude and payload 112
Figure 9-5: Limit argument for solution convergence depending on altitude 112
Figure 9-6: Chart of Thrust Power 118
Figure 9-7: Trend of Range at Constant Speed 118
Figure 9-8Rate of Descent 119
Figure 10-1: Technical table of the initial design process 121
Figure 10-2: First rendering of initial model [9] 122
Figure 10-3: Second rendering of initial model [10] 122
Figure 10-4: Technical Table [11] 123
Figure 11-1: Model (Airship, Corsair 1-8 T) [15] 128
Figure 11-2: Model (Airship, DGPATT 50T) [16] 128
Figure 11-3:Yacht lower deck diagram (fifty meters model) 130
Figure 11-4: Yacht main deck diagram (fifty-metres model) 131
Figure 11-5: Yacht upper deck diagram (fifty-metres model) 131
Figure 11-6: Gondola (Airship, DGPATT 50T) 132
Figure 11-7: Gondola schematisation 132
Figure 11-8: Instruction of Solver Macro 143
Figure 11-9: Air viscosity graph 144

II. Tables

Table 1: Needs Definitions and Prioritisation 20
Table 2: Needs Ranking 21
Table 3: Needs affinity and conflicts 22
Table 4: Requirements and Constraints 23
Table 5: Analysis of the Internal Area 29
Table 6: Input Needed for Aerodynamic Analysis 39
Table 7: Input Needed for Airship Trim Analysis 44
Table 8: Input Needed for Airship Range Analysis 57
Table 9: Input Needed for Propulsion System Analysis 71
Table 10: Input Needed to Size Solar Array and Power Storage 78
Table 11: Batteries and Fuel Cell Comparison 81
Table 12: Input Needed for Performance Method 88
Table 13: Specific Energy 100
Table 14: Program Validation with “DGPA 50 T” 114
Table 15: Initial Requirements Input Data 115
Table 16: Requirements and Constraints Modified 116
Table 17: Table of Conversion 133
Table 18: Useful Physical Quantities 134
Table 19: Fuel Density 134
Table 20: Temperature of Air Density and σ at the Altitude Variation 135
Table 21: Historical Rigid Airship Database 138
Table 22: Surface Plan of Tail Element (Y-Configuration): Mathematical Passages 139
Table 23:Power as a Function of Speed: Mathematical Passages 140
Table 24: Maximization of Ratio between Aero Lift and Drag: Mathematical Passages 140
Table 25: Constant Speed for Minimum Drag: Mathematical Passages 141
Table 26: Sunrise and Sunset of Main City in 2018 142
Table 27: Sutherland’s Constant and Temperature for Some Gases 144

III. Definitions and Abbreviations

θ	Angle of Fin elements Compare to Horizontal Plan
μ(T)	Dynamic Viscosity
AR	Aspect Ratio
B_{lift}	Buoyancy Lift
BR	Buoyancy Ratio
BSFC	Break Specific Fuel Consumption
c	Chord
C_{D0}	Zero Lift Drag Coefficient
C_{D0_body}	Body Zero Lift Drag Coefficient
C_{D0_cables}	Cables Zero Lift Drag Coefficient
C_{D0_engine}	Engines Zero Lift Drag Coefficient
$C_{D0\_gondola}$	Gondola Zero Lift Drag Coefficient
$C_{D0\_interf.}$	Interference Zero Lift Drag Coefficient
C_{D0_LG}	Landing Gear Zero Lift Drag Coefficient
C_{D0_tail}	Tail Zero Lift Drag Coefficient
C_f	Skin Friction Coefficient
Cl_{α}	Lift Curve Slope
CPL	Continuous Power Loading
C_S	Power Coefficient
D	Propeller Diameter
d	Airship Maximum Diameter
d_g	Gondola Diameter
d_{GB}	Gas Balloon Diameter
DL	Daylight
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
F_D	Degradation Factor
FF	Form Factor
FR	Fineness Ratio
g	Gravitational Acceleration
h_g	Gondola Height
J	Advance Ratio
K	Factor of Drag Due to Lift
l	Airship Length
L_{aero}	Aerodynamic Lift
Lat	Maximum Airship Latitude
l_g	Gondola Length
l_{GB}	Gas Balloon Length
MAC	Main Aerodynamic Chord

MTOW	Maximum Take-off Weight
NA	Need Analysis
N_{eng}	Number of engines
N_L	Number of Longitudinal Elements
N_R	Number of Ring Elements
N_y	Service Years
OEW	Operative Empty Weight
P	Thrust Power
PL	Power Loading
P_{eng}	Engine Power
P_R	Maximum power required to the shaft
q_{cruis}	Dynamic Pressure
R	Specific gas Constant
R	Range
S_A	Approach Distance
S_B	Breaking Distance
S_C	Climb Out Distance
SE	Specific Energy
S_{el}	Tail Surface Plan (one fin)
S_{ell}	External Surface
S_F	Free Roll Distance
S_G	Ground Roll Distance
SH	Stake Holder
SHA	Stake Holder Analysis
S_L	Total Landing Distance
S_{plan}	Surface plan
S_R	Rotation Distance
S_{to}	Total Take-off distance
S_{wet_body}	Wet Body Surface
t	Thickness
T(Z)	Temperature
V_{cruis}	Cruise Speed
V_{cruise}	Cruise Speed
V_{gas}	Gas Volume
Vol	External Envelope Volume
$Vol^{2/3}$	Reference Surface
Vol_{He}	Helium Volume
V_{TO}	Take-off Speed
W_{Av}	Avionics and Electronics Weight
W_{El}	Electric System Weight
W_{ES}	Outer Skin Weight
W_F	Fuel Weight
W_{FR}	Fuel Reserve Weight
W_G	Gondola Weight

W_{GB}	Gas Balloons Weight
W_{H0}	Heaviness at Take-off
W_{H1}	Heaviness at Landing
W_{IF}	Internal Framework Weight
W_{land}	Landing Weight
W_{LG}	Landing Gear Weight
W_{OE}	Operative Empty Weight
W_{PS}	Propulsion System Weight
W_{serv}	Crew and Passenger Accommodations Weight
W_{T}	Rigid Tail Weight
W_{ZF}	Zero Fuel Weight
Z	Altitude
α_{max}	Airship Incidence at Take-off
α_{TO}	Take-off Angle
η_{B}	Battery Efficiency
η_{c}	Cell Efficiency
η_{FC}	Fuel Cell Efficiency
η_{LI}	Battery Input Line Efficiency
η_{LO}	Battery Output Line Efficiency
η_{P}	efficiency coefficient
η_{p}	Parallel Line Efficiency
η_{s}	Series Line Efficiency
η_{sw}	Switch Input Output Efficiency
η_{T}	Electricity Transmission Efficiency
$\rho(Z)$	Gas Density
ρ_{SL}	Air Density at Sea Level
σ	Ration Between Altitude Air Density and Sea Level Air Density

IV. Objective and Purpose

The objective of this thesis is the realisation of an innovative rigid airship to offer VIP customers a new type of air transport for comfortable luxury travelling, with a focus on engineering and aesthetic preliminary design. Thus, weights and dimensions of the airship have been determined as well as requirements such as range, cruise, payload, and speed.

V. Abstract

Airships belong to the category of aerostat, which is an aircraft lighter than air that uses a buoyancy gas to generate its lift. It is classified into three main types - rigid airship, nonrigid airship, and hybrid airship - all of which can utilise two methods to increase or reduce (modulate) the upward force to control it. The first way involves volume changing of gas and therefore its density to balance the fuel weight decrease, manoeuvring the airship and changing its altitude. The second method is to use a hull aerodynamically to get a lift component, which can be modulated to change airship inclination, balance fuel, and reduce weight.

There are many ways to move from one part of the world to the other. So why choose to design an airship? The first motivation is that the global airship market is estimated to increase in value by 7.2 per cent from 2016 to 2024, therefore presenting a great economic opportunity. Other advantages are that it is economical and environmentally friendly.

Tools like WBS, study logic, timelines, and so on help the study manager to handle and optimise resources. The design begins with a top-down approach with an SHA and NA that allow one to get the general guidelines that define the system. The target is to define the individual elements that make up the system, where the input for preliminary design is the requirements and the output is the general dimensions and weights. At the beginning, the designer can compare the input of the project with those of rigid airships already made to get an idea of the possible output values to expect. The size of the gondola and hull are important parameters to define airship weight. The other steps provide for the calculation of a zero lift drag coefficient of main airship elements and the airship trim, preliminary tail sizing to know the fin's surface, and an estimate of range and endurance to define the take-off and landing analysis and propulsion system. These data permit one to estimate airship weight and its systems. Precise calculations of what make up the airship and fuel weight provide useful data to initiate a more detailed analysis. A fundamental output of this preliminary design phase is the gas volume needed to balance airship weight; its value has great influence on the aircraft size.

Thus, the purpose of this thesis is to show all formulas and logical steps linked to the "Aerodynamic airship model" and implemented in the Excel program RAsDEx 1.1 to get a preliminary description of airship dimensions and performances, aerodynamic data, propulsion system, weight estimation, and gas volume required.

Chapter 1

1. Introduction

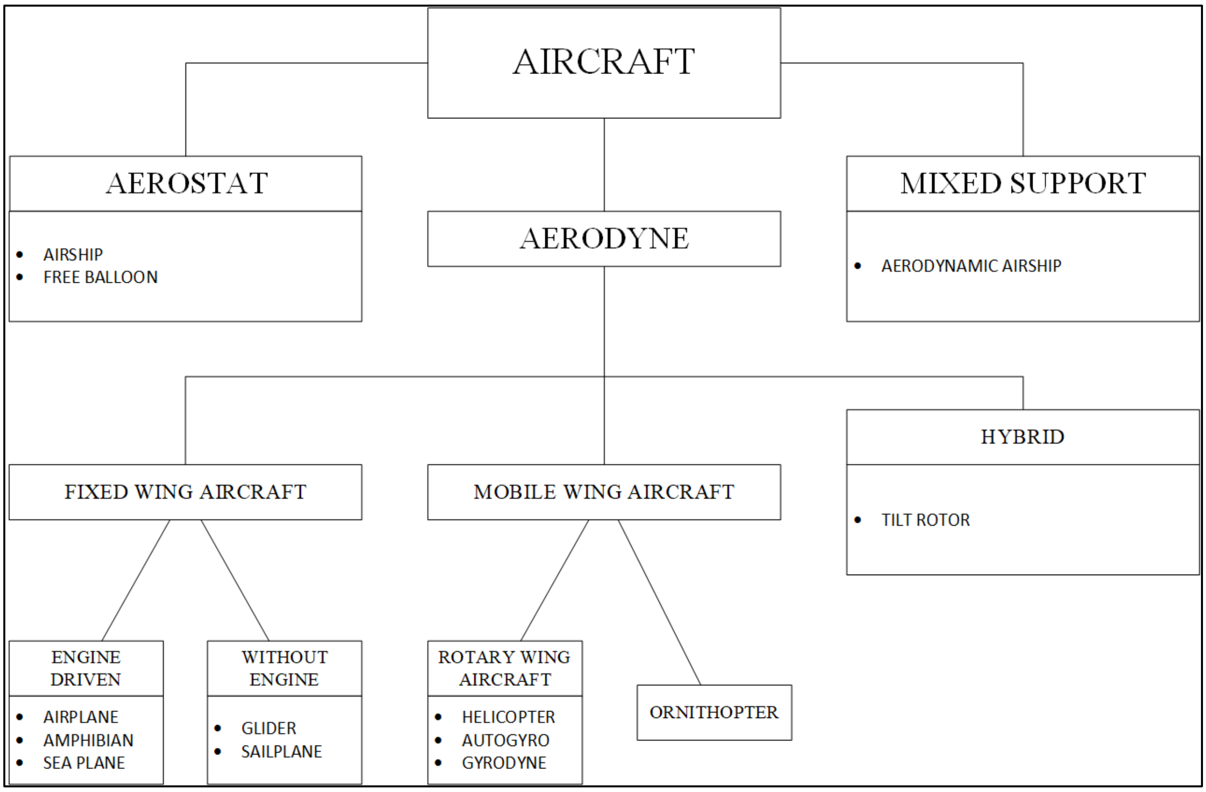


Figure 1-1: Aircraft classification

Airships (Figure 1-1: Aircraft classification) belong to the category of aerostat, which indicates every aircraft that flies primarily using aerostatic buoyancy. It is a lighter-than-air aircraft which uses a buoyancy gas to generate its lift, and it can move from one point of the atmosphere to another because it has a propulsion system (it is powered). More precisely, buoyant lift is generated by the difference between gas contained within the envelope and the outside air. Indeed, to generate an upward thrust, the buoyancy gas density must be less than the external fluid density, according to Archimedes, who stated, ‘Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object’.

Figure 1-2: Balloon (tethered)

A balloon is another class of vehicle that belongs to the category of aerostat. It is motor-free and could be anchored to the ground with a cable (Figure 1-2) or free to move uncontrollably. The change in altitude can be guaranteed in three ways:

- heat the air in the balloon to reduce its density compared to the colder outside air (hot-air balloon)
- use a buoyancy gas to generate its lift
- use both previous techniques

The first airship used hydrogen as a buoyant gas since it is abundant, economical, and has the lowest density relative to other gasses. Nevertheless, modern airships use helium; although it is rare and more expensive, it is an inert gas, while hydrogen is flammable.

In this paper, the focus is on rigid airships.

1.1. History

Since ancient time, humankind has always looked up to the sky with the desire to reach it. Even before Wright's first flight, in 200 AD the Chinese used lift gas in their signalling lanterns (Figure 1-3).

Figure 1-3: Sky lantern[1] [1]

Indeed, these were the first manmade objects able to fly, even though human transport would have to wait until 4 June 1783, when the Montgolfier brothers realised the first hot-air balloon. Later, many others perfected their idea (using different materials and combining buoyant gas and hot air), but no balloon could be controlled because they all lacked a propulsion system. Thus, in 1853, the engineer Henry Giffard put a steam engine on a balloon, making the first controllable aerostat (airship). In July 1900, von Zeppelin launched his first airship, equipped with two motors, which guaranteed a speed of 18 mph. In the next year, he became the major manufacturer of rigid airships, and he reached his peak with the realisation of the greatest airship in history, LZ-129 Hindenburg (1936). However, its accident, due to hydrogen's flammability, marked the decline of this aircraft category.

[1] File: (Richy, 2003)- SkyLanternRichy01.jpg, https://en.wikipedia.org.

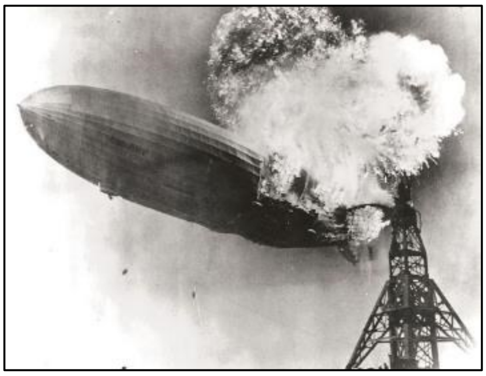


Figure 1-4: LZ-129 Hindenburg burning [2] [1]

1.2. Typology

Airships are classified into three main typologies, according to the constructive design: rigid airship, nonrigid airship, and hybrid airship, which is the most recent type (Figure 1-5).

[1] File: (Pasquerella, 1937) - Hindenburg burning.jpg, https://en.wikipedia.org.

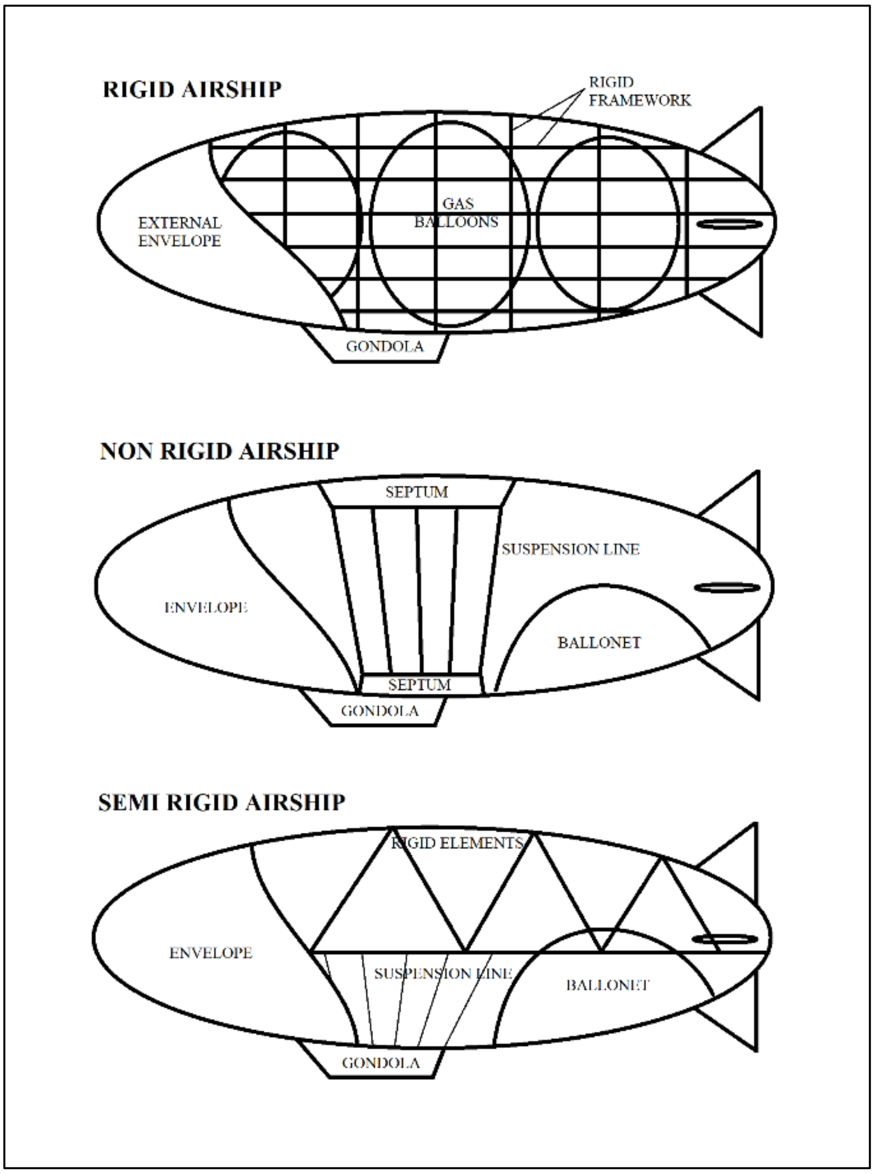


Figure 1-5: Airship typology

- Rigid airship: This is the design method used in the realisation of the first airship. The reason is due to the use of material with poor containment capacity. It was unthinkable to use a single balloon to carry a large number of goods and passengers, so the problem could be solved using more small balloons enclosed in a single rigid envelope, which guaranteed good aerodynamic performances; thus, it could reach big dimensions and carry a large payload. The rigid airship's main element is an external envelope (tensioned fabric skin) that covers the rigid framework necessary to support moments and concentrated loads; within it, there are gas balloons that contain the buoyant gas, are anchored to the bottom of the envelope, and can expand or contract to generate more or less lift.

- Nonrigid airship: This type has an envelope that contains the buoyant gas. Within the envelope, there are cables connected to the septum that transmit the concentrated loads, such as a gondola. Finally, there are ballonets, usually two, one placed in front and one behind, that ensure the maintenance of the same shape in any condition. Indeed, this airship must maintain the same differential pressure between internal and external pressure. If the external pressure changes, one can change the volume of the ballonets, introducing or expelling air, so that the envelope volume and internal pressure change.
- Hybrid airship[1]: This is a modern construction that combines the advantages of the two previous types, including lightness and ability to carry a huge payload. There is a sparse rigid frame where cables are linked for the transfer of concentrated loads, and there are ballonets to maintain the same differential pressure and improve airship handling.

All types of airships can utilise two methods to increase or reduce (modulate) the upward force necessary to control the vehicle and allow it to land, take off, and vary altitude. The first way, previously described, involves changing the volume of gas balloons for the rigid airship and ballonets for the hybrid and nonrigid airship (STANDARD AIRSHIP). This mechanism allows changing gas density to generate more or less buoyant lift. The main problems with this method are the complexity to manage the control system of the gas density, and the gas balloons must be thick enough to withstand high pressures when the volume is reduced. These things bring a considerable increase in weight.

$$pV = nRT \rightarrow \frac{p}{\rho} = nRT \rightarrow \rho = K\frac{p}{T}$$

The second way is to use a hull that is started aerodynamically (AERODYNAMIC AIRSHIP). Thus, it will have the air foil shape to get a lift component, which can be modulated, varying the airship trim. The airship inclination and consequently the gondola represent the limitation of this method. It cannot exceed an angle of sixteen degrees; otherwise, the floor would be too inclined for passengers.

However, aerodynamic airship is in equilibrium when the sum of buoyancy lift and aerodynamics lift balances the airship weight. One parameter defines to which percentage of airship weight is supported by the buoyancy lift and consequently the other percentage part is assigned at aerodynamic lift. This parameter is buoyancy ratio BR:

[1] This term also indicates an airship that provides its upward force with two components: the buoyant lift and aero lift, which can be modulated.

$$BR = \frac{B_{lift}}{W_{airship}} = \frac{B_{lift}}{B_{lift} + L_{aero}} \qquad \text{(Equation 1-1)}$$

A hybrid case sees two methods, described above, used simultaneously. Thus, volume variation balances change in altitude, while aerodynamic lift balances fuel consumption. In this case, BR at landing and take-off are two important values to consider. Designers use the BR at landing as a useful value for preliminary sizing; it is imposed as input, and the value is between 0.95 and 0.98. BR at take-off is a marker because a low value indicates that the percentage of aerodynamic lift to generate is excessive. Typical values for rigid airships are greater than 0.85, while for hybrid airships the limit is 0.75 because this category of airship can produce a multilobe configuration that makes it similar to an air foil and can develop a greater aerodynamic lift than the rigid category.

The equations of these parameters are:

$$BR_{land} = \frac{B_{lift}}{W_{land}} \qquad \text{(Equation 1-2)}$$

$$BR_{takeoff} = \frac{B_{lift}}{MTOW} \qquad \text{(Equation 1-3)}$$

Where the weight at landing is:

$$W_{land} = OEW + Payload + W_{res} \qquad \text{(Equation 1-4)}$$

1.3. Why Airship?

There are many ways to move from one part of the world to another. According to their needs, people can use a plane, car, ship, train, or bus. So why choose to design an airship?

In addition to the market research (1.3.1), which shows the constant growth of this sector, here is a list of the main reasons one should choose an airship instead of any other vehicle.

- They have a vertical take-off and landing.
- They don’t need infrastructures like ports or airports.
- They are economical and environmentally friendly.

1.3.1. Market Research

The global airships market has estimated that it will increase its value to reach $304 million by 2024, growing at a CAGR of 7.2 per cent from 2016 to 2024. However, three different markets can be analysed: semi-rigid airships, rigid airships, and nonrigid airships. The prediction is that the nonrigid airships, due to their low price, are anticipated to lead the global market.

Several marketing agencies and companies are opting for nonrigid airships as they are exceptionally light in weight. These airships are highly used for research, commercial tours, advertisements, covering sports events, cargo transport, and surveillance. Indeed, the rising demand is due to urgent needs for surveillance of large areas.

Thus, the low maintenance cost of airships, cost-effectiveness, and their returns on investment in the field of advertising are acting as key growth drivers for the global airships market.

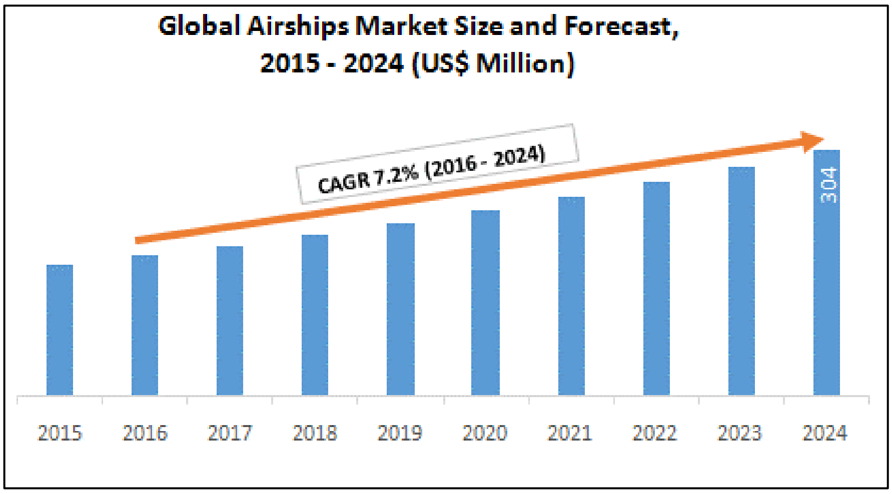


Figure 1-6: Global airship market size and forecast 2015–2024 (US $ million) [3][1]

However, several challenges must be overcome. The use of hydrogen relative to helium reduces the costs and increases performance but exposes these airships to the risk of inflammability, which can lead to fatal accidents. In view of these risks, researchers are working on developing

[1] (variantmarketresearch.com, 2017) - Variant Market Research, https://www.variantmarketresearch.com/report-categories/defense-aerospace/airships-market.

hybrid airships that will partly operate on solar energy to mitigate the possibility of hazardous accidents.

Furthermore, luxury airships represent, in the next year, another growth opportunity for commercial tours and hybrid airships.

Application and geography are two other divisions of the global airships market. Applications are segmented into commercial tours, surveillance, research, cargo transport, and other uses. Geography is segmented into North America, Europe, Asia Pacific, the Middle East and Africa, and Latin America. North America is leading the ranking of the global market, where the request for new airships is maximum. The presence of many companies in these countries and the constant technological development, such as the use of hydrogen for safety, have made this result possible. The increase in interest in this vehicle from the tourism industry has also made Europe an emerging airships market.

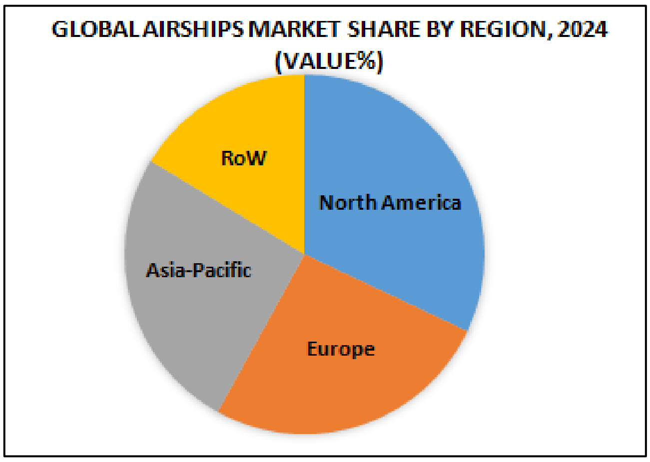


Figure 1-7:Global airship market share by region, 2024 (value %) [4][1]

[1] (variantmarketresearch.com, 2017) - Variant Market Research, https://www.variantmarketresearch.com/report-categories/defense-aerospace/airships-market.

1.3.2. Purpose Problem and Target

The project purpose is to relaunch a technology from the past that deserves more innovation. However, the problem is linked to its bad reputation and image.

- Bed reputation: Various tragic incidents that involved an airship have led to their bad reputation in mass memory. Despite increased security measures (hydrogen has been replaced with helium), people still have a negative image of this vehicle.
- Image: Airship shapes were considered cool in the twentieth century, but today, with the sci-fi culture well rooted in society, people expect more than a flying bullet.

Targets can be difficult to extrapolate; thus, the designer must write a mission statement[1] answering some questions:

- What is the root problem?
  - To find a solution which allows people to travel in comfort and luxury to a touristy place or not and where conventional aircraft can hardly take off or land;
  - To have a moving speed higher than the nautical vehicles category;
  - To create an engaging and innovative design.

- How can the problem be solved?
  - The vehicle must be independent from conventional aircraft infrastructures;
  - To guaranty vertical take-off and landing;
  - Possibility to operate above the water, deserts, or mountains, analysing every mission phase.

- Who are the end users?
  - Rich social classes
  - Celebrities
  - Heads of state

Mission Statement

To offer VIP customers a new type of air-transport proposal able to deliver a luxurious and comfortable travelling and leisure experience similar to super yachting but without boundaries and limitations that traditionally affect the naval industry.

[1] A mission statement is a proposition that explains the project target.

With regard to obtaining this target, the airship is a vehicle with a low effectiveness cost relative to others, but it is not accessible to all. Thus, the focus is on the customers, represented by super yacht owners, who are looking for private transport that is the perfect combination of innovation, adventure, luxury, comfort, privacy, and personalisation. Greater speed and freedom of movement are the advantages of using an airship instead of a yacht .

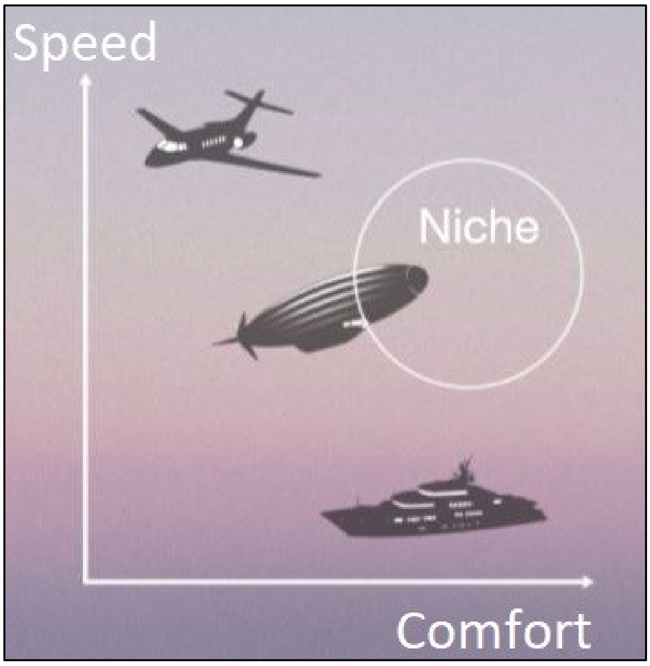


Figure 1-8: Level of speed and comfort

Chapter 2

2. Airship Design

Much knowledge is necessary in a multidisciplinary project like this, including a technical part related to engineering and an aesthetic part. Naturally, the two parties must reach a compromise to get the final system. Even before realising the systems and subsystems that characterise the airship (and, in general, for each new project), it is important to undertake a series of phases concerning the project's preliminary definition and resource management.

This project was divided into phases by choosing the ESA standard (explained in detail in Annex A3). These various phases can be graphically shown through the V-model tool (Figure 2-1). This paper considers in detail the 0, A, and B phases.

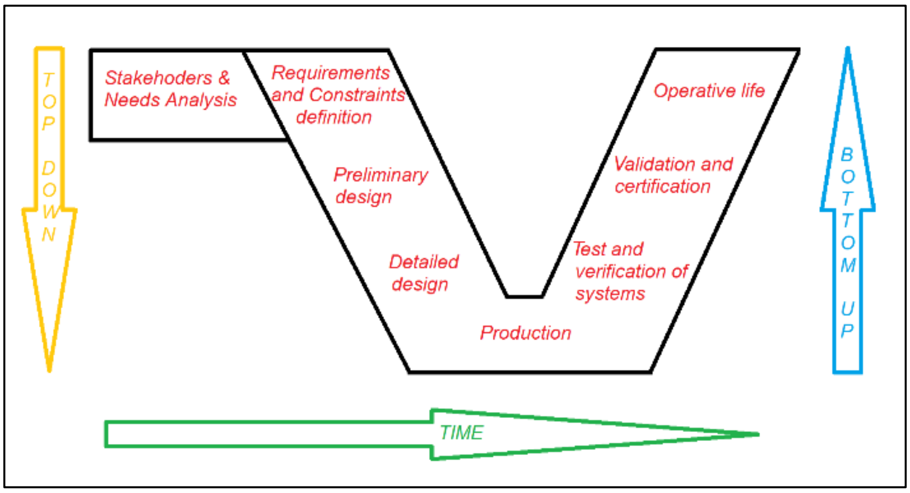


Figure 2-1: V-model

The design begins with a top-down approach, with an SHA and NA that allow one to get the general guidelines that define the system. The target is to define the individual elements that make up the system, where the input of preliminary design is the requirements and the output is the general dimensions and weights; detailed design is the next step. The design continues with the production of the total system, and a bottom-up approach concludes the process. This part of the V-model starts from the verification and the tests, in detail, of all the systems. Then the normative body certifies this, and finally the airship (in this case) is ready to operate.

2.1. Phase 0

Phase 0 encompasses both management and design aspects. The first ones are important to organise the project and use tools such as WBS (work break structure), study logic, and timeline.

First of all, WBS permits one to reduce degrees of complexity of the project by dividing it into subactivities. The figure below (Figure 2-2) shows this instrument in graphic form.

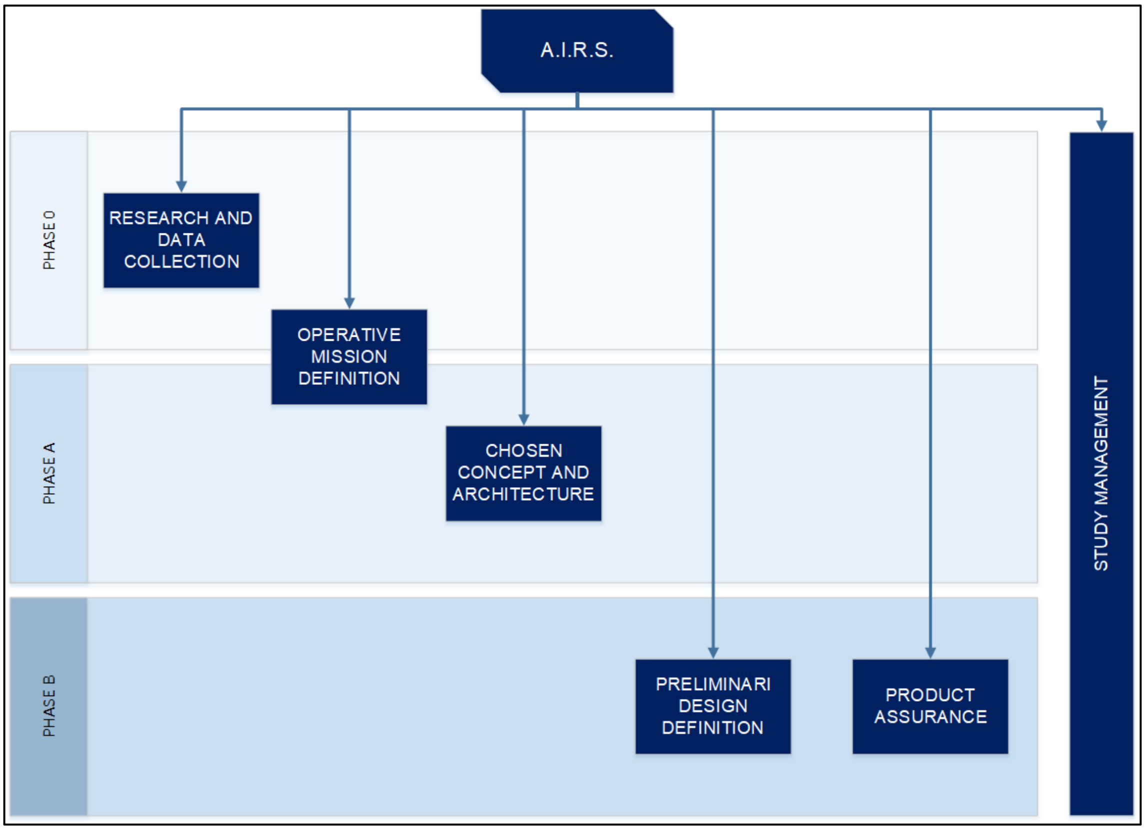


Figure 2-2: WBS

Seven activities are identified for this project:

- Study management—This activity will affect all phases of the project, and its task provides for the management and organisation of resources.
- Research and data collection—This is necessary to develop knowledge about the rigid airship. Moreover, with this information, an Excel program implemented a preliminary sizing of a rigid airship.
- Operative mission definition—The high-level requirements are the target; they become the guideline to accomplishing some concepts.

- Chosen concept and architecture—The target of this activity is the trade-off amongst the various preliminary concepts derived from the previous activity.
- Preliminary design definition—It provides a higher level of detail of systems and subsystems that make up the chosen concept and architecture.[1]
- Product assurance—Risk and cost are two of the most important aspects of each project, especially when people are the payload. However, product assurance is not covered in this paper.

Moreover, each subactivity has a section describing its content, objective, various steps, start and end dates, responsibility, and any output. The name of this document is WPD (work package description).

The study logic allows one to identify the logical and temporal flow of the various operation, as shown in Figure 2-3

[1] Concept indicates how the mission is carried out from the functional point of view, whilst architecture indicates the physical elements that allow the mission execution.

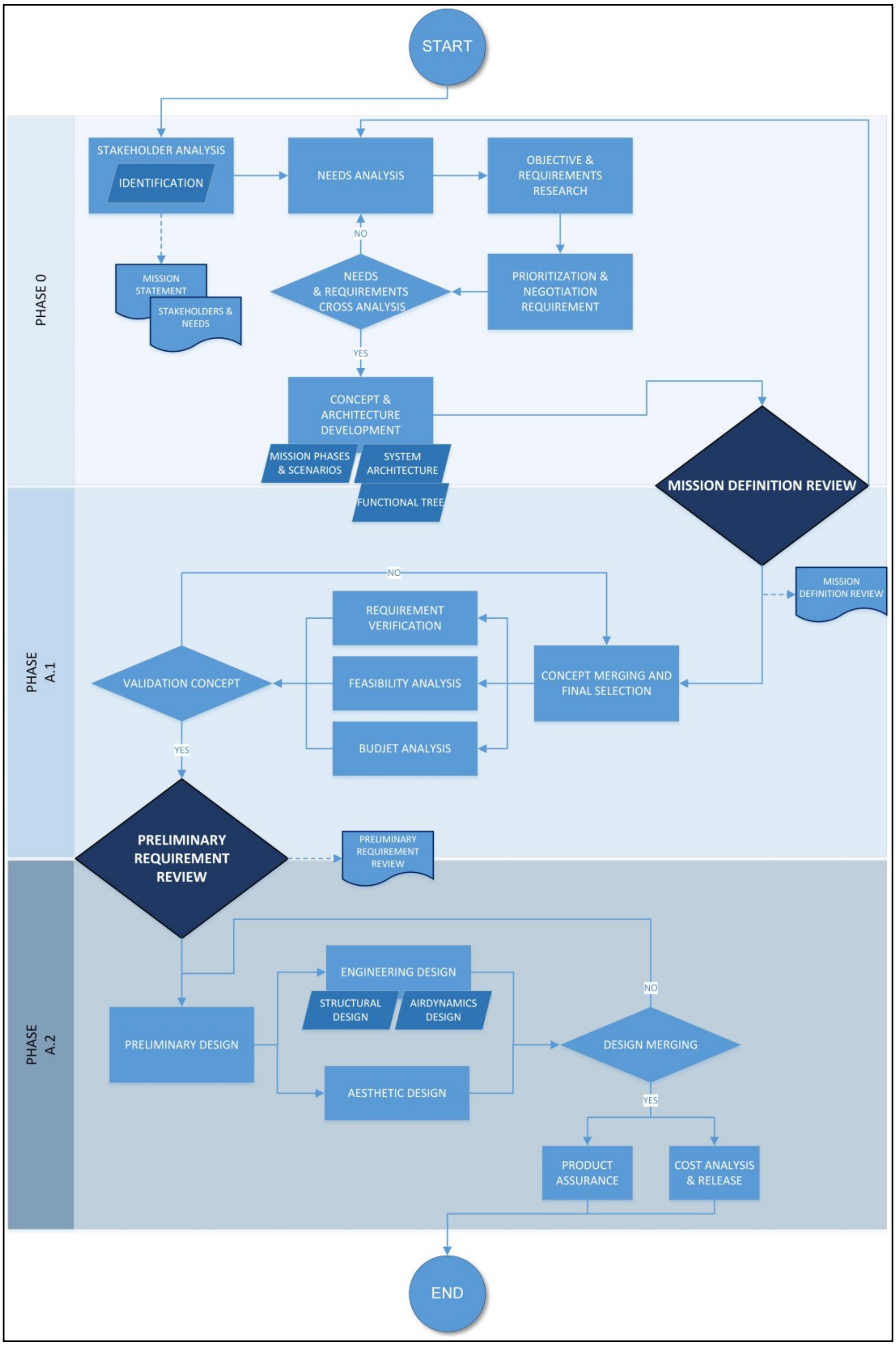


Figure 2-3: Study logic

Despite study logic being an important management tool, it cannot give any information about the project’s temporal scale. Instead, the timeline (Figure 2-4) is the instrument used for this task.

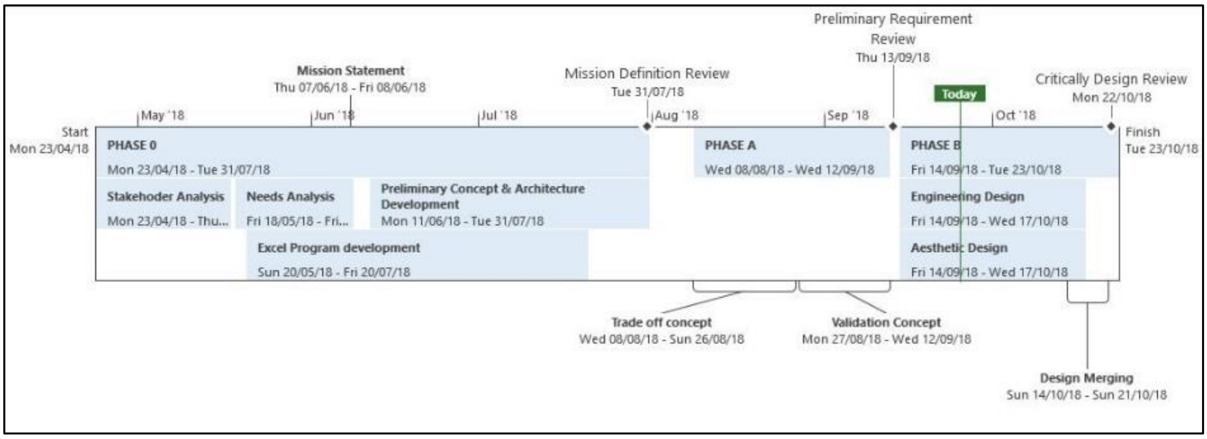


Figure 2-4: Timeline

2.1.1. Stakeholder Analysis

SHA is the first step of the wider need analysis. It allows one to identify the SHs and map them according to their roles in the mission (more details on the SH classification are in Annex A4).

- SH identification—The subject identification, linked to the project, takes place through some research into the social and economic fields. The super yacht class is the reference for this case study. The main SHs are:
  - Euro Airship (customer)
  - Rich social classes
  - Luxury hotel chains
  - Celebrities
  - Policymakers
  - Public
- SH mapping—The mapping consists of dividing the SHs into four categories, as shown below (Figure 2-5):

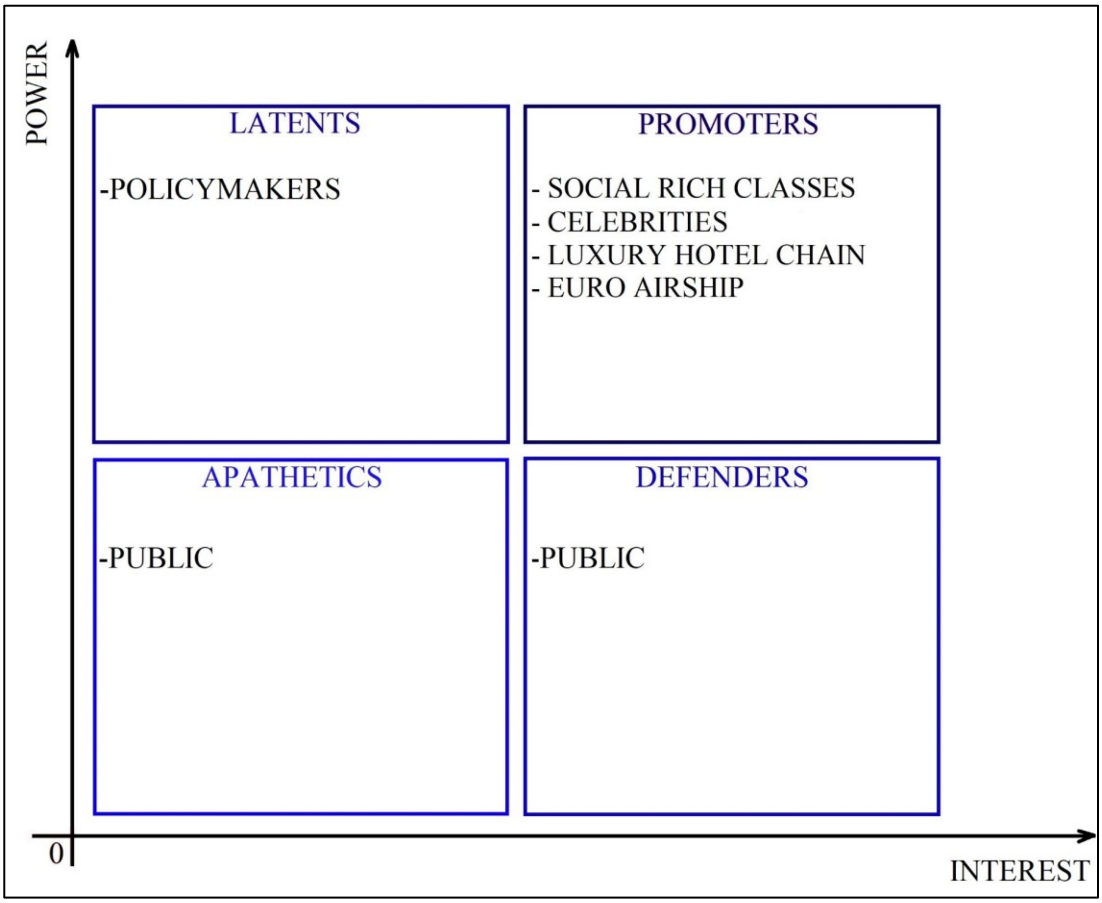


Figure 2-5: Stakeholder mapping

2.1.2. Constraints

The project starts when the promoters and the company that has to realize it, sign a contract. If promoter have some needs the designer can accept or not, or renegotiate them, while constraints must be satisfied otherwise, termination of the contract and payment of a penalty.

The Euro-Airship company imposed some constraints that Pininfarina Company accepted. They are:

- Rigid airship category;
- One body of revolution;
- Fuel propulsion system;
- Luxury yacht.

2.1.3. Needs Analysis

SHs, analysed in section 2.1.1, have needs that the designer tries to satisfy. The first step required by NA is the prioritisation (Table 2), which allows identifying primary needs and secondary needs. Every aspect of it receives a score that is the summation of the terms equal to the number of SHs. Each term is equal to the product of two scores: one is relative to the degree of importance[1]of the SH, and the other is equal to the interest that SH has in that need.[2]

SHs can express discordant needs; thus, negotiation and reconciliation are fundamental. In case of an unresolved conflict between primary and secondary needs, the first have priority. The analysis of conflicts is the name of this step.

[1] It is rated with a score from one (minimum degree of importance) to four (maximum degree of importance).

[2] Interest is rated with a score from one (minimum interest) to five (maximum interest).

Table 1: Needs Definitions and Prioritisation

NEEDS DEFINITION & PRIORITISATION

	Stakeholder Importance	To get the highest luxury comfort level	To be able to make an intercontinental travel	To permit the owner to reach every place that it wants	Moving speed higher than nautical vehicles category	Possibility to operate above the water, desert or mountain	Large windows to enjoy the view & take pictures	Economical and environmentally friendly	Stay in the air (aloft) for days or weeks	No additional infrastructure required	Proven the highest safety and reliability	Vertical take-off and landing
Social rich class	4	5	4	4	5	4	4	3	4	1	3	3
Celebrity	4	5	5	4	3	5	5	2	5	2	3	2
Luxury hotel chain	4	5	5	3	2	3	5	3	5	3	3	2
Euro airship	4	5	4	5	5	5	3	5	4	4	5	4
Policy Bodies	3	2	3	3	1	2	1	3	1	2	5	1
General Public	2	4	2	4	1	5	4	3	2	1	1	1
Absolute Importance		94	85	81	65	84	79	67	79	48	73	49
RANKING		1	2	4	9	3	6	8	5	11	7	10

Each correlation need-stakeholder has been assigned a number, to classify its priority	
5	extremely high
4	high
3	medium
2	low
1	extremely low

Each stakeholder has been assigned a number, to classify its relevance for the mission development	
4	extremely high
3	high
2	Low
1	extremely low

Table 2: Needs Ranking

	RANKING	NEEDS
PRIMARY	1	To get the highest luxury comfort level
	2	**To be able to make an intercontinental travel**
	3	To permit the owner to reach every place that it wants
	4	**Moving speed higher than nautical vehicles category**
	5	Possibility to operate above the water, desert or mountain
	6	**Large windows to enjoy the 360° view**
SECONDARY	7	Economical and environmentally friendly
	8	**Stay in the air (aloft) for days or weeks**
	9	No additional infrastructure required
	10	**Proven the highest safety and reliability**
	11	Vertical take-off and landing

Table 3: Needs affinity and conflicts

	To get the highest luxury comfort level	To be able to make an intercontinental travel	To permit the owner to reach every place that it wants	Moving speed higher than nautical vehicles category	Possibility to operate above the water, desert or mountain	Large windows to enjoy the view & take pictures	Economical and environmentally friendly	Stay in the air (aloft) for days or weeks	No additional infrastructure required	Proven the highest safety and reliability	Vertical take-off and landing
To get the highest luxury comfort level		-				+		-			
To be able to make an intercontinental travel			+	-				+			
To permit the owner to reach every place that it wants					+						+
Moving speed higher than nautical vehicles category							-	-			
Possibility to operate above the water, desert or mountain										-	
Large windows to enjoy the view & take pictures											
Economical and environmentally friendly								+			
Stay in the air (aloft) for days or weeks											
No additional infrastructure required											
Proven the highest safety and reliability											
Vertical take-off and landing											

-	Conflitti
+	Affinità

2.1.4. Requirements

The high-level requirements are the technical language translation of the needs. They are the starting point for the designer. The requirements analysis is as important as it is long and complex, because writing and keeping track of it appropriately requires many steps (not covered in this paper). The table below lists all mission requirements; they are subcategories that indicate how the mission takes place.

Table 4: Requirements and Constraints

<table>
<tr><th colspan="3">REQUIREMENTS AND CONSTRAINTS</th></tr>
<tr><td>Payload Weight</td><td>7.5</td><td>ton</td></tr>
<tr><td>Range</td><td>6500</td><td>Km</td></tr>
<tr><td>Maximum Altitude</td><td>2000</td><td>m</td></tr>
<tr><td>Maximum Endurance</td><td>5</td><td>days</td></tr>
<tr><td>Cruise Speed</td><td>15.05</td><td>m/s</td></tr>
<tr><td>Minimum Endurance</td><td>3</td><td>days</td></tr>
<tr><td>Maximum Speed</td><td>25.08</td><td>m/s</td></tr>
<tr><td>Crew</td><td>8</td><td rowspan="2">People</td></tr>
<tr><td>Guess</td><td>10</td></tr>
<tr><td>Mission Flight Strategy</td><td>Constant Speed</td><td>/</td></tr>
<tr><td>BR (Landing)</td><td>0.98</td><td>/</td></tr>
<tr><td>FR</td><td>4</td><td>/</td></tr>
<tr><td>Propeller Efficiency</td><td>0.7</td><td>/</td></tr>
<tr><td rowspan="4">Airship Configuration</td><td>Rigid Structure</td><td>/</td></tr>
<tr><td>Body of Revolution</td><td>/</td></tr>
<tr><td>Fuel Propulsion</td><td>/</td></tr>
<tr><td>Luxury Yacht Arrange-
ment</td><td>/</td></tr>
</table>

Modifying the requirements is possible during all design phases: 0, A, B, and C. Moreover, verification of written requirements is mandatory.

Chapter 3

3. Preliminary Definition of the Airship Dimensions

3.1. Historical Rigid Airship Database

Dimensions of an airship are the outputs of the preliminary design. But the designer can compare the inputs of the project with those of rigid airships already made (data list in annex A8, Table 21) to get an idea of the possible output values to expect.

Payload can be used as an input to compare, and the first step consists of MTOW (maximum take-off weight) determination, with the help of the graph below that shows the relationship between payload and MTOW:

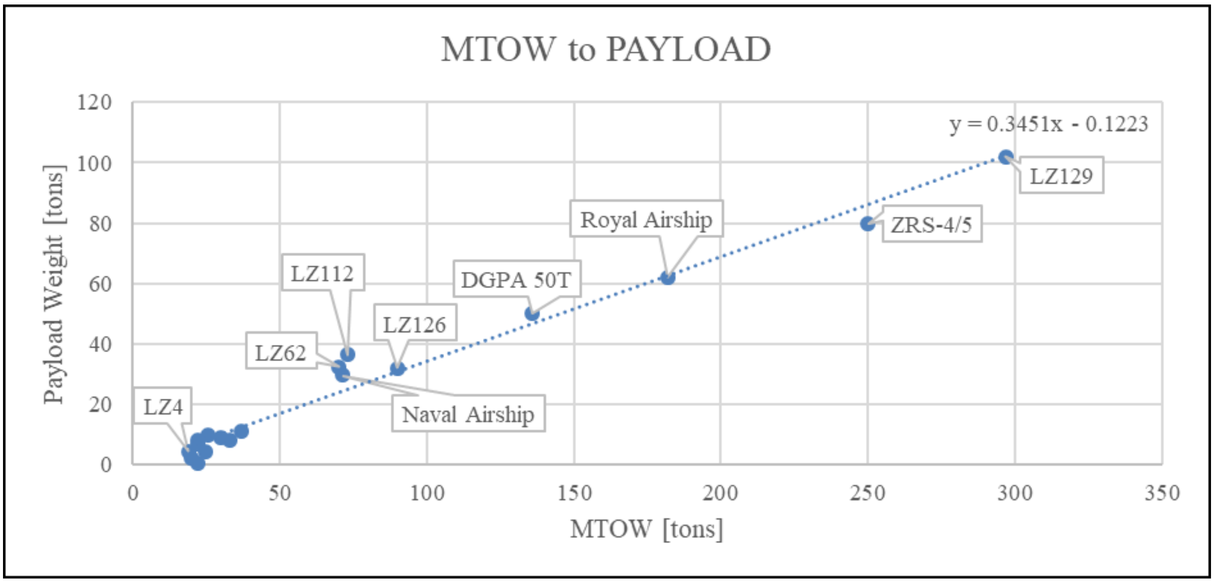


Figure 3-1: Extrapolation of MTOW from payload

The linear trend line is the function that approximates in the best way this data distribution; thus, its equation gives the value of MTOW using the payload value of 7.5 tons:

$$MTOW = (Payload + 0.122)/0.345 \qquad \text{(Equation 3-1)}$$

$$MTOW = 22.09\ tons$$

MTOW value is the input used to obtain all subsequent output, such as OEW, fuel weight, and helium volume. The next step provides the creation of the graphs of each input and output pair. Thus, the designer can generate the trend lines.

The relationship between MTOW and OEW is shown in Figure 3-2:

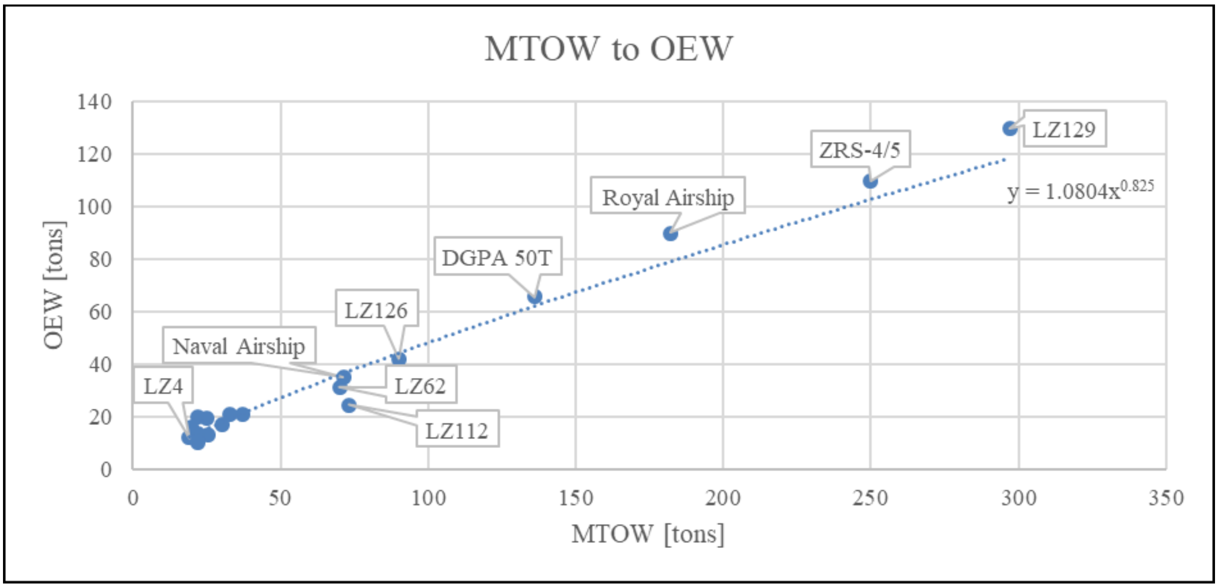


Figure 3-2: Extrapolation OEW from MTOW

Trend lines that approximate this data distribution in the best way is ‘power function’. Just enter the MTOW value in the equation to get the OEW.

$$OEW = 1.0804\ MTOW^{0.825} \qquad \text{(Equation 3-2)}$$

$$OEW = 13.88\ tons$$

The graph below (Figure 3-3) indicates the relationship between MTOW and fuel weight and power trend lines is the best function:

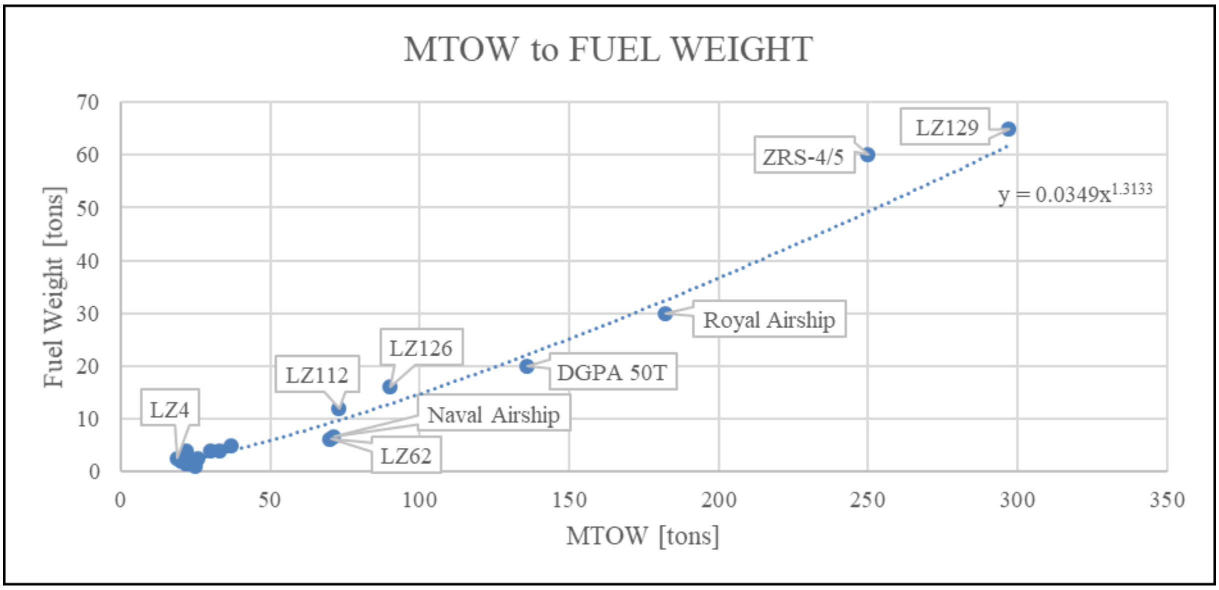


Figure 3-3: Extrapolation of fuel weight from MTOW

$$W_{fuel} = 0.0349\ MTOW^{1.313} \qquad \text{(Equation 3-3)}$$

$$W_{fuel} = 2.03\ tons$$

Finally, the linear trend line is the best fit for data distribution that permits one to obtain helium volume from MTOW, as shown in

Figure 3-4:

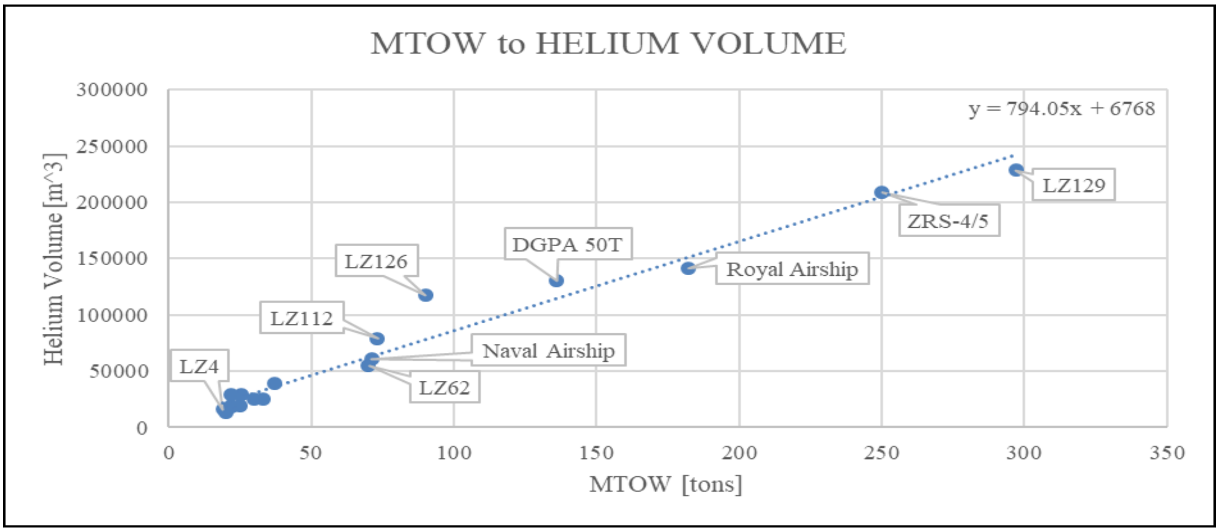


Figure 3-4: Extrapolation of helium volume from MTOW

$$V_{He} = 795.05\, MTOW + 6768 \quad \text{(Equation 3-4)}$$

$$V_{He} = 24307\, m^3$$

However, as mentioned at the beginning of the paragraph, these outputs act as guidelines for the designer, but they, of course, may not match with the outputs of the project obtained during the B phase.

3.2. Gondola Dimensions

The size of the gondola is an important parameter to define its weight through a preliminary estimate. Size depends on multiple factors such as:

- Payload weight
- Crew members
- Guest members
- Airship range and endurance
- Comfort level

Since guests on board are looking for a high level of comfort, and the target vehicle is a yacht, an analysis of the rooms and typical internal space of a yacht is important. Then this estimate must be compared with the reference gondola[1] of EUROAIRSHIP. This step serves to verify that the interior space area of a yacht (fifty metres in length) is compatible with the available surfaces of an average-size airship. Because gondola size is a constraint, the sum of the rooms area and the interior spaces typical of a yacht must be less than the gondola area.

Its value is equal to:

$$Gondola\ Area = 416\, m^2$$

In the table below, the first column shows the available surface of the yacht with detailed value of the room surface, whilst the next column presents the values of reduced surface for constraint.

[1] The gondola belongs to the model DGPA 50 Tons, produced by Euro Airship company.

Table 5: Analysis of the Internal Area

TYPICAL ROOMS		50 m SUPERYACHT		AIRSHIP GONDOLA	
PUBLIC SPACE	bar, wine cellar & dining area	29 m^2	136.5 m^2	26 m^2	133.5 m^2
	gym & toy room	35 m^2		35 m^2	
	salon cinema	22.5 m^2		22.5 m^2	
	main lobby & main saloon	50 m^2		50 m^2	
CREW & SERVICE SPACE	crew cabin & crew mess	50 m^2	190 m^2	31 m^2	107 m^2
	pilot cabin	9 m^2		20 m^2	
	suitcase, pantry & food storage	31 m^2		21.5 m^2	
	laundry, galley	20.5 m^2		20.5 m^2	
	electric panel, entrance & tech space, control & engine room	79.5 m^2		14 m^2	
GUEST SPACE	Owner's cabin	40 m^2	128 m^2	40 m^2	115 m^2
	2 x vip cabin	40 m^2		40 m^2	
	3 x guest cabin	48 m^2		35 m^2	
GARAGE FOR TENDERS, TOY & RESCUE VEHICLE		50 m^2	40 m^2		
EXTERNAL AREA		216 m^2	20 m^2		
TOT.		720.5 m^2	415.5 m^2		

Annex A5 details the determination of the yacht areas and gondola surface.

3.3. Hull Dimensions

The hull is the portion of the airship formed by the outer envelope, the rigid grid or framework, and finally the gas balloons. Its size depends on the volume of helium stored. Moreover, from historical data, the external envelope for rigid airships has a volume 10 per cent greater than the helium volume.

The first assumption is related to the solid material used to approximate the outer envelope. Constraint on the airship configuration indicates the realisation of a single body of revolution. Thus, the best solid to use is a prolate spheroid (Figure 3-5). It has the major axis ‘a’ longer than two equals axes ‘b’ and ‘c’.

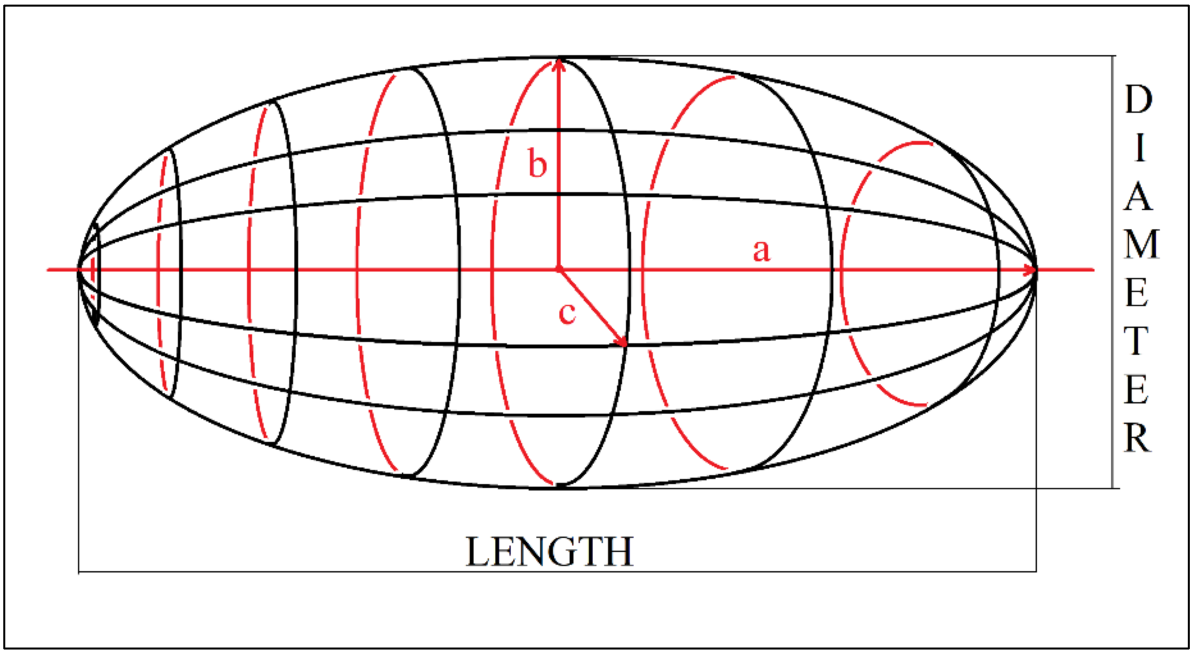


Figure 3-5: Prolate spheroid

To determine the length and diameter of the solid is necessary for the external envelope volume, and the FR (Fineness Ratio) is the starting point.

$$Vol = 1.1\,Vol_{gas} \qquad \text{(Equation 3-5)}$$

Below is the expression of prolate spheroid volume and FR:

$$\begin{cases} Vol = \dfrac{\pi l d^2}{6} \\ FR = \dfrac{l}{d} \end{cases}$$

$$\begin{cases} Vol = \dfrac{\pi\ FR\ d^3}{6} \\ l = FR\ d \end{cases}$$

The final equations are:

$$\begin{cases} d = \sqrt[3]{\dfrac{6\ Vol}{\pi\ FR}} \\ l = FR\sqrt[3]{\dfrac{6\ Vol}{\pi\ FR}} = \sqrt[3]{\dfrac{6\ Vol\ FR^2}{\pi}} \end{cases} \qquad \text{(Equation 3-6)}$$

Where:

$$\begin{cases} l = 2\ a \\ d = 2\ c = 2\ b \end{cases}$$

Two important pieces of data to calculate are the external surface and the surface plan of the airship. First it is necessary to determine the coating weight covering the framework. The second could be used as a reference surface to make a comparison of aerodynamics and, in general, performance data with other aircraft.

$$S_{ell} = 2\ \pi \left(c^2 + a\ c \frac{\arcsin(e)}{e} \right) \qquad \text{(Equation 3-7)}$$

Where:

$$e = 1 - \frac{c^2}{a^2}$$

While the surface plan:

$$S_{plan} = \frac{\pi l d}{4} \qquad \text{(Equation 3-8)}$$

Even though the reference surface for an airship is the following:

$$S_{ref} = Vol^{2/3} \qquad \text{(Equation 3-9)}$$

The number of lobes configuration of an airship permits one to link the surface plan with the reference surface through the following relationship:

$$S_{plan} = N_l S_{ref} \qquad \text{(Equation 3-10)}$$

Where N_l is determined empirically according to the number of lobes. In the case of a single body of revolution:

$$N_l = 2$$

Prolate spheroid might not be the airship's final form because to increase performance or use the second way to generate lift (paragraph 1.2), this shape must be changed.

Chapter 4

4. Aerodynamic Data Estimate

Aerodynamic data are important for any project that provides for relative movement of an object within a fluid, where performance optimisation is a primary requirement. The aerospace industry and others such as automobile and naval industries use advanced aerodynamic simulation software to get accurate information about aerodynamic drag that a body generates whilst moving in the fluid, the distribution of surface on its surface, lift or down-lift generation if the body is started aerodynamically, and many other types of information. Of course, this precision has a cost in terms of time and high use of resources.

A thorough analysis during this phase of preliminary design is not necessary because in this phase, all computing tools have many approximations and assumptions that lead to an output, however truthful.

4.1. Historical Rigid Airship Database

The first instrument is an analysis of aerodynamics in the historical rigid airship database, which allows one to obtain a preliminary estimate of the values to be used as references (Figure 4-1).

Columns in the table below show the following parameters:

- Reference—It indicates reference surface used to calculate the aerodynamic parameters. In accordance with section 3.3, reference surface for airships is $Vol^{2/3}$, whilst for other aircraft it is wing surface plan.
- AR—For an airplane, this is ratio of wingspan and medium geometric wing chord or in another form valid for rectangular wings is the ratio of wingspan squared and wing surface plan. For an airship, the aspect ratio is the ratio of diameter squared and surface plan;
- CL_α—This is the lift curve slope.
- K—It is a factor that contains effects of the drag due to lift.
- C_{D0}—This is the zero lift drag coefficient.

No.	Vehicle	Ref	AR	C_{L_α}	K	C_{D_0}	Ref
1	BoR, FR = 7.2	$Vol^{2/3}$	0.18	0.005	3.7	0.028*	6
2	BoR, FR = 6.0	$Vol^{2/3}$	0.21	0.006	2.9	0.030*	6
3	BoR, FR = 4.8	$Vol^{2/3}$	0.27	0.0088	1.7	0.0285*	6
4	BoR, FR = 3.6	$Vol^{2/3}$	0.35	0.007	1.3	0.031*	6
5a	USS Akron w/o tails, FR = 5.9	$Vol^{2/3}$	0.22	0.0063	2.8	0.019*	7
5b	USS Akron + tails, FR = 5.9	$Vol^{2/3}$	0.23	0.0125	1.24	0.025*	7
6a	ZP5K w/o tails, FR = 4.4	$Vol^{2/3}$	0.29	0.0066	2.0	0.0152*	12
6b	ZP5K + tails, FR = 4.4	$Vol^{2/3}$	0.3	0.0115	0.9	0.026*	12
7a	HALE w/o tails, FR = 3.2	$Vol^{2/3}$	0.4	0.008	1.15	0.016*	14
7b	HALE + tails, FR = 3.2	$Vol^{2/3}$	0.41	0.0122	0.55	0.024*	14
8	P-791	$Vol^{2/3}$	0.54	0.046	0.32	0.096	14
9	HA-1	$Vol^{2/3}$	0.60	0.045	0.28	0.033*	14
10	Aerocraft	$Vol^{2/3}$	0.46	0.027	0.46	0.032*	14
11	M2-F1	S_{plan}	0.65	0.0225	0.69	0.062	9
12	M2-F2	S_{plan}	0.712	0.0216	0.95	0.065	9
13	HL-10	S_{plan}	1.16	0.023	0.57	0.05	9
14	X-24A	S_{plan}	0.62	0.024	0.623	0.04	9
15	X-24B	S_{plan}	1.11	0.0217	0.5	0.025	9
16	Space Shuttle	S_{plan}	2.27	0.0437	0.33	0.061	9
17	SR-71	S_{plan}	1.72	0.04	0.3	0.006	13
18	F-117A	S_{plan}	2.06	0.05	0.33	0.0108	13
19	F-22A	S_{plan}	2.36	0.046	0.16	0.016	13
20	F-16C	S_{plan}	3.2	0.054	0.11	0.018	13
21	F-104C	S_{plan}	2.45	0.058	0.17	0.017	13
22	F-15E	S_{plan}	3.02	0.057	0.18	0.028	13
23	F-5E	S_{plan}	3.83	0.066	0.12	0.018	13

All $Re \geq 10^7$ and $M < 0.2$.
$AR = 4/\pi FR$ for bodies of revolution.
*Wind tunnel C_{D_0} value and models did not have full operational features such as lines, cooling drag, and landing gear.

Figure 4-1: Table of design and aerodynamic datasheet [5][1]

[1] (Carichner & Nicolai, 2013) - chapter 3, "Aerodynamics," table 3.1, *Airship Design and Case Studies* (2013).

4.2. Preliminary Assessment

The next step is to calculate all parameters seen in the previous paragraph. Comparison of these parameters with those in the table allows an understanding of whether results are plausible.

The first aerodynamic parameter to calculate is AR:

$$AR = \frac{d^2}{S_{plan}}$$

Expression of surface plan is referring to the elliptical surface.

$$AR = \frac{d^2}{\pi \frac{d}{2} \frac{l}{2}} = \frac{d^2}{\frac{\pi}{4}\, d^2\, FR}$$

$$AR = \frac{4}{\pi FR} \qquad \text{(Equation 4-1)}$$

The second is K. It consists of two terms; one is generated by the encounter of low-pressure and high-pressure flow at the end of the object. This phenomenon causes a trailing vortex with consequential downwash of the aerodynamic centre and drag generation. The other includes effects of pressure drag on the hull, gondola, and other airship components.

Theoretically, two formulas allow one to calculate these factors, but the diagram below was obtained with experimental aerodynamic data of the airship in Figure 4-1regarding the function of the AR parameter.

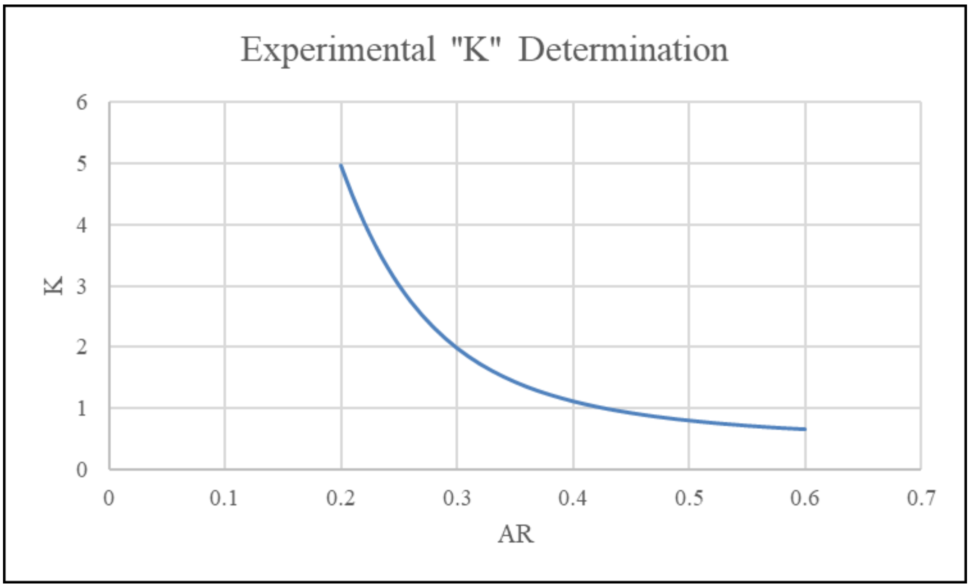


Figure 4-2: Experimental “K” determination

The equation for the graph function above is:

$$K = -0.0144\left(\frac{1}{AR}\right)^4 + 0.183\left(\frac{1}{AR}\right)^3 - 0.514\left(\frac{1}{AR}\right)^2 + 0.838\left(\frac{1}{AR}\right) - 0.05 \quad \text{(Equation 4-2)}$$

It is important to know that K value calculated through (Equation 4-2 is in reference to the surface plan. To get K in the function of reference surface for an airship, divide it by N_l (Equation 3-10):

$$(K)_{Vol^{2/3}} = \frac{K}{N_l}$$

The next parameter is CL_α, whose full expression is:

$$CL_\alpha = \frac{2\pi\, AR}{2 + \sqrt{4 + AR^2\left(1 + \frac{\tan^2\delta}{\beta^2}\right)}} \quad \text{(Equation 4-3)}$$

Where δ is sweep of the wing and β is the parameter that entails the information on Mach number:

$$\beta^2 = 1 - M^2$$

Regarding the airship design, the expression can be simplified because it is a vehicle that generally flies in the incompressible subsonic field. This means that speeds are low, and consequently so are Mach number and $\beta \cong 1$. Also, $\tan^2 \delta$ can be approximated to 1 for a small sweep angle. Thus, (Equation 4-3) becomes:

$$Cl_\alpha = \frac{2\pi\, AR}{2 + \sqrt{4 + AR^2}} \quad \text{(Equation 4-4)}$$

In case of a small AR, typical of airships, the equation can be further simplified:

$$Cl_\alpha = \frac{\pi\, AR}{2} \quad \text{(Equation 4-5)}$$

The diagram below shows the two expression graphs match up for low values of AR.

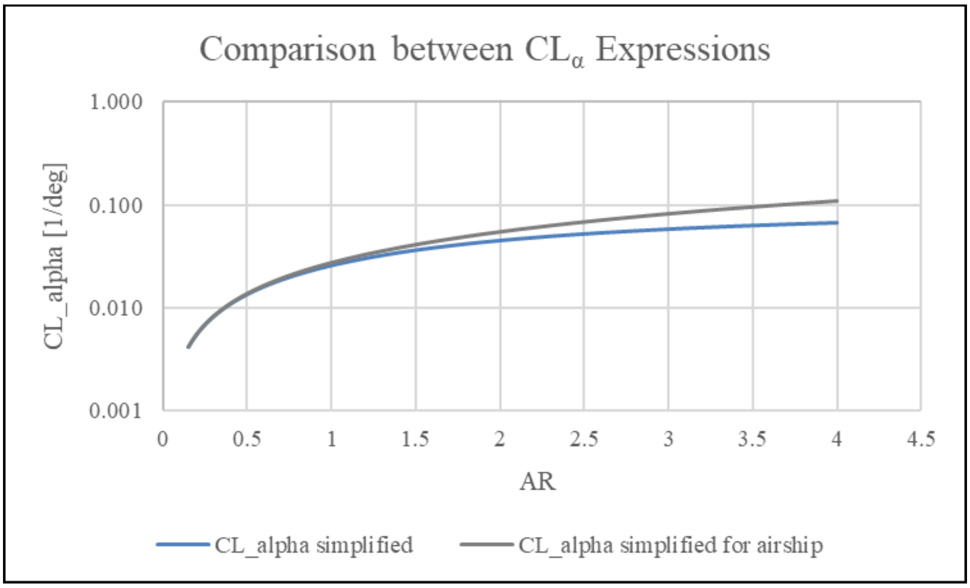


Figure 4-3: Comparison between CL_α expressions

4.2.1. Zero Lift Drag Coefficient

Overall, drag of an aircraft consists of two components. The first one is a parasitic drag that is not linked with lift generation, whilst the other is induced resistance.

$$D = D_0 + D_I \quad \text{(Equation 4-6)}$$

Total parasitic drag is equal to the sum of parasitic drag of each aircraft element invested by airflow, and it is divided into three further drag forms.

$$D_0 = \sum_{k}^{n} D_{friction_k} + D_{shape_k} + D_{wave_k} \quad \text{(Equation 4-7)}$$

The first two drag forms are always present, whilst the last takes over when the aircraft is in supersonic field. Wave drag is not present for an airship.

Total parasitic drag of all components taken individually is actually less than total drag of components assembled on aircraft because in their connecting points, swirling flows are generated that increase parasitic drag. This new component is called drag interference.

Zero lift coefficient expresses parasitic drag, and there are two ways to estimate it:

- Experimental: It is a long and expensive solution that involves building a scale model to perform tests inside a wind tunnel.
- Approximate method: It is a method used in the preliminary design phase that consists of two distinct factors, skin friction and form effects on drag, on the main airship elements such as body and tail. For the gondola, landing gear, and other components, an empirical formula can provide a good result.

This paper analyses the second method, with parasitic drag determination of all main components that make up an airship. For this study, (Equation 4-7) can be rewritten in the following way to explain the above-mentioned factors:

$$C_{D0} = \sum_{k}^{n} C_{f_k} FF_k \frac{S_{wet_k}}{Vol^{2/3}} \quad \text{(Equation 4-8)}$$

Inputs needed to analyse components in detail are shown in the Table 6:

Table 6: Input Needed for Aerodynamic Analysis

INPUT	
Z	Altitude
T(Z)	Temperature
μ(T)	Dynamic Viscosity
ρ(Z)	Air Density
V_{cruis}	Cruise Speed
q_{cruise}	Dynamic Pressure
$Vol^{2/3}$	Reference Surface
S_{wet}	Wet Surface
FR	Fineness Ratio

Some of the inputs are not available directly since some calculations are required. Annex A9 treats the calculation of dynamic viscosity in detail, whilst Annex A7 provides detailed guidance on how to calculate temperature and air density to change altitude. (Equation 3-7), and (Equation 3-9) calculates wet body surface and reference surface.

Dynamic pressure at input cruise altitude has the following expression:

$$q_{cruise} = \frac{1}{2}\rho V_{cruise}^2 \qquad \text{(Equation 4-9)}$$

This is where the collection and determination phase of input ends. One can now begin the parasitic drag determination of all components, which are:

- Body—The first step involves calculating Reynolds's number[1] :

$$Re = \frac{\rho V_{cruise} l}{\mu} \qquad \text{(Equation 4-10)}$$

[1] Reynolds's number is a dimensionless number that shows the ratio between inertial and viscous forces.

"Re" is important to determine the skin friction coefficient. With the assumption of no-laminar flow,[1] the equation is:

$$C_f = \frac{0.455}{(\log_{10} Re)^{2.58}} \qquad \text{(Equation 4-11)}$$

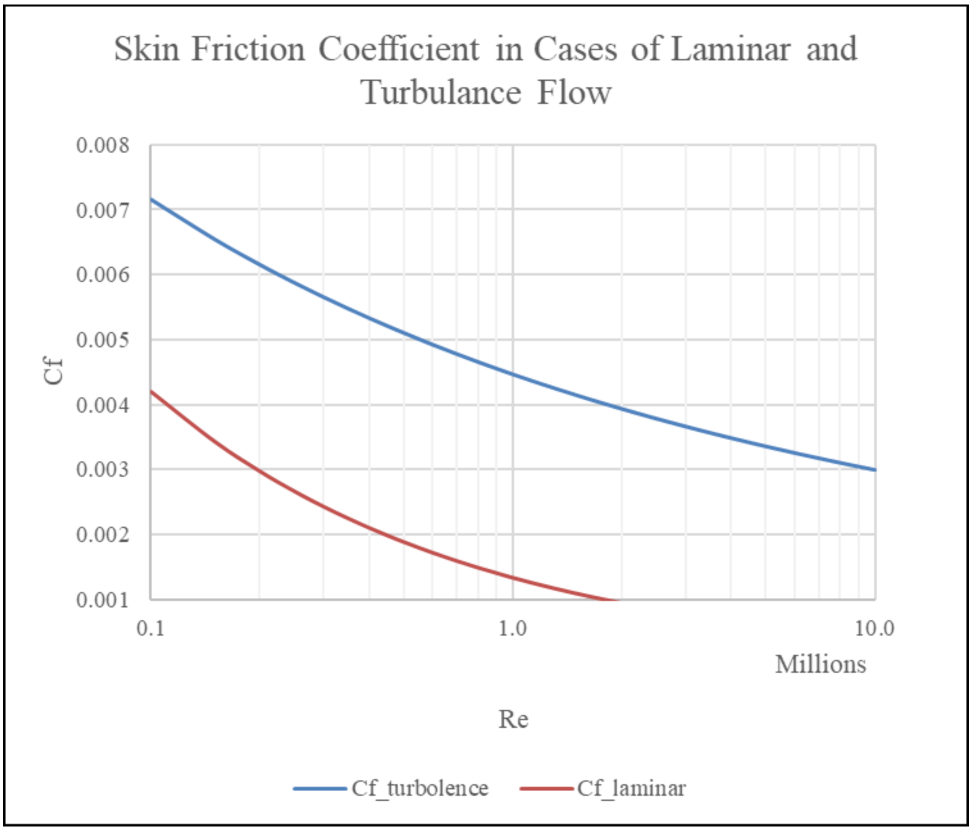


Figure 4-4: Skin friction in cases of laminar and turbulence flow

The second step provides a calculation for the form factor. The equation, which is the same for the envelope and gondola, is:

[1] It is a conservative assumption because the airship could have a flow with transition from laminar to turbulence that corresponds to a lower skin friction coefficient (Figure 4-4). However, transition point determination is complex.

$$FF_{body} = 1 + \frac{1.5}{FR^{1.5}} + \frac{7}{FR^3} \qquad \text{(Equation 4-12)}$$

Thus, one can utilise (Equation 4-11) and 4-12 enter the wet surface of the envelope into (Equation 4-8) to obtain the zero lift coefficient of the body.

- Tail - The steps are the same as those for the envelope and assumptions concerning the tail aspect ratio and the value of ratio between air foil thickness and its chord.

$$AR_{tail} = 1$$

$$\left(\frac{t}{c}\right)_{Max} = 0.15$$

The main differences are in the calculation of Reynolds's number because it changes the reference length, which for the tail is the average chord whose expression is calculated in paragraph 5, and the form factor that has another expression, which considers the ratio between air foil thickness and its chord, as shown in the equation below:

$$FF_{tail} = 1 + 1.2\frac{t}{c} + 100\left(\frac{t}{c}\right)^4 \qquad \text{(Equation 4-13)}$$

Of course, for the drag estimate, wet surface along with other parameters, to insert in (Equation 4-8)also applies to the tail.

- Cabin and gondola - Considering that the envelope and gondola form factors are equal, the zero lift coefficient of the gondola can be obtained from the parasitic drag coefficient of the body/envelope through the following relationship:

$$C_{D0_{gondola}} = \frac{0.108\ C_{D0_{body}} Vol^{2/3} + 7.7}{Vol^{2/3}} \qquad \text{(Equation 4-14)}$$

- Engine group - It consists of three elements that generate parasitic drag: the nacelles, cooling system, and structural elements that link engines with the gondola or envelope.

$$C_{D0_{nacelles}} = \frac{N°_{engine} 4.25}{Vol^{2/3}} \qquad \text{(Equation 4-15)}$$

$$C_{D0_{cooling}} = \frac{2 * 10^{-6} Vol + 4.1}{Vol^{2/3}} \quad \text{(Equation 4-16)}$$

$$C_{D0_{mounting}} = \frac{0.044 C_{D0_{body}} Vol^{2/3} + 0.92}{Vol^{2/3}} \quad \text{(Equation 4-17)}$$

Thus, total parasitic drag of the engine group is:

$$C_{D0_{engine}} = C_{D0_{nacelles}} + C_{D0_{cooling}} + C_{D0_{mounting}} \quad \text{(Equation 4-18)}$$

- Landing gear - An airship can have two types of landing gear: the standard variant with wheels and one with air cushions. The equation for parasitic drag calculation is related to the model with wheels. The expression is:

$$C_{D0_{LG}} = \frac{1.76 * 10^{-6} Vol + 0.92}{Vol^{2/3}} \quad \text{(Equation 4-19)}$$

- Cables - In this preliminary phase, design is not detailed to the point of knowing how control and structural support of the tail or other elements are managed. If structural and control cables are external to the gondola and envelope, airflow is invested, and they generate a higher parasitic drag component.

$$C_{D0_{cables}} = \frac{9.7 * 10^{-6} Vol + 10.22}{Vol^{2/3}} \quad \text{(Equation 4-20)}$$

The last contribution to the zero lift coefficient is due to interference drag. Indeed, various coefficients do not consider the junction between two elements that provides drag increase.

$$C_{D0_{interf.}} = \frac{4.78 * 10^{-6} Vol}{Vol^{2/3}} \quad \text{(Equation 4-21)}$$

The sum of zero lift coefficients of all components (described above) is equal to the total zero lift coefficient of the airship.

4.2.2. Airship Trim

Airship trim becomes important if the method of upward force modulation occurs through generation of a lift component. Indeed, lift coefficient is related to the incidence angle (Figure 4-5).

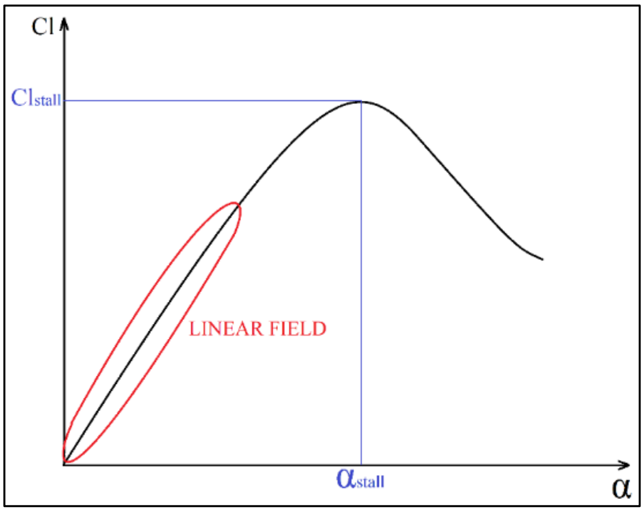


Figure 4-5: Relationship between lift coefficient and incidence angle

Analysing the first linear section of the function for higher values of incidence angle, the lift coefficient also increases, generating greater upward force with reduction of the buoyant gas, external envelope volume, and weight. However, as stated in section1.2, airship trim variation coincides with gondola inclination, which constitutes a limit for the incidence angle. For an ergonomic issue, this value must not exceed ten degrees. One way to mitigate the inclination problem is to equip the gondola with a small negative angle in reference to the envelope axis, to be subtracted from airship incidence angle. Thus, the floor plan is less inclined.

Of course, take-off is the phase with the highest rate of incidence because fuel on board is maximum, and its weight must be balanced by lift force. Thus, analysing this phase can determine if the incidence angle is less than the limit angle.

(Equation 4-3) represents the curved slope of the function linear section and is the ratio between lift coefficient and incidence angle.

$$Cl_{\alpha} = \frac{dCl}{d\alpha} \qquad \text{(Equation 4-22)}$$

Thus, the limit lift coefficient, given the values of curve slope and limit angle, is:

$$Cl_{limit} = Cl_{\alpha}\, \alpha_{limit} \qquad \text{(Equation 4-23)}$$

From this, it is possible to evaluate minimum dynamic pressure, which an airship must overcome to fit within trim limits:

$$q_{limit} = \frac{W_{H0}\, g}{Cl_{limit}\, Vol^{2/3}} \qquad \text{(Equation 4-24)}$$

Where "W_{H0}" is the airship heaviness at take-off and, more precisely, is the weight portion that is not balanced by buoyant lift. A detailed discussion of heaviness is found in section 8.

Then, the minimum speed at which an airship can fly is:

$$V_{limit} = \sqrt{\frac{2\, q_{limit}}{\rho}} \qquad \text{(Equation 4-25)}$$

If the target is to compute the maximum incidence angle of the airship, the inputs are:

Table 7: Input Needed for Airship Trim Analysis

INPUT	
q_{cruise}	Dynamic Pressure
$Vol^{2/3}$	Reference Surface
W_{H0}	Heaviness at Landing
Cl_{α}	Curve Slope

The first parameter to calculate is lift coefficient at maximum heaviness:

$$(Cl)_{W_{H0}} = \frac{W_{H0}\, g}{q_{cruise} Vol^{2/3}} \qquad \text{(Equation 4-26)}$$

From the equation below and the curve slope value, the incidence angle of airship at take-off is:

$$\alpha_{max} = \frac{(Cl)_{W_{H0}}}{Cl_{\alpha}} \leq \alpha_{limit} \qquad \text{(Equation 4-27)}$$

Chapter 5

5. Tail Design

This element provides the airship with control and stability. A horizontal tail manages longitudinal dynamic and pitch manoeuvre, whilst a vertical tail involves later-directional dynamic, roll, and yaw manoeuvre. Tail design is important during this project phase because this element significantly affects the operative empty weight. The designer defines tail configuration and through determination of distance between the front quarter of the tail MAC and gravity centre (Figure 5-1) can obtain the tail surface and consequently the weight.

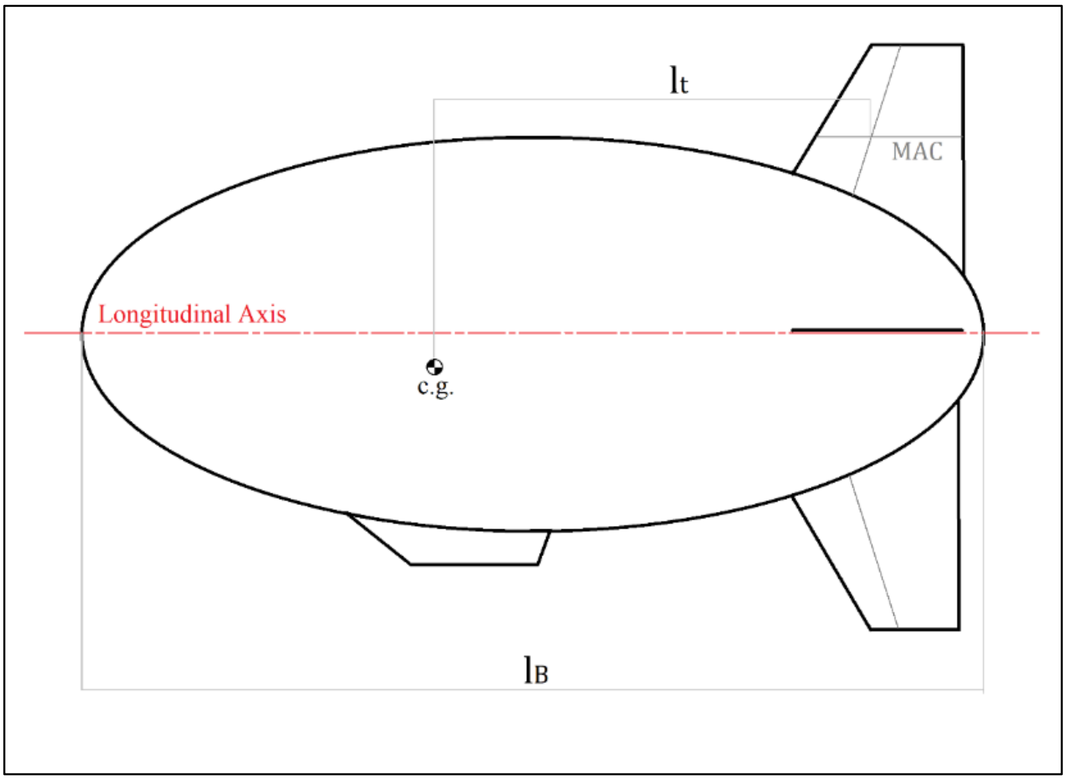


Figure 5-1: Tail position schematisation

The main problem is knowledge about the gravity centre because this is derived from the exact weight and relative position of all components and systems which constitute the airship. Thus, the preliminary approach, with different assumptions, is to use the tail volumetric coefficient, whose construction derives from historical airship data such as their reference surface, moment arm between tail and gravity centre, external volume, and airship length. With the presence of a vertical and horizontal tail, there are also two more coefficients.

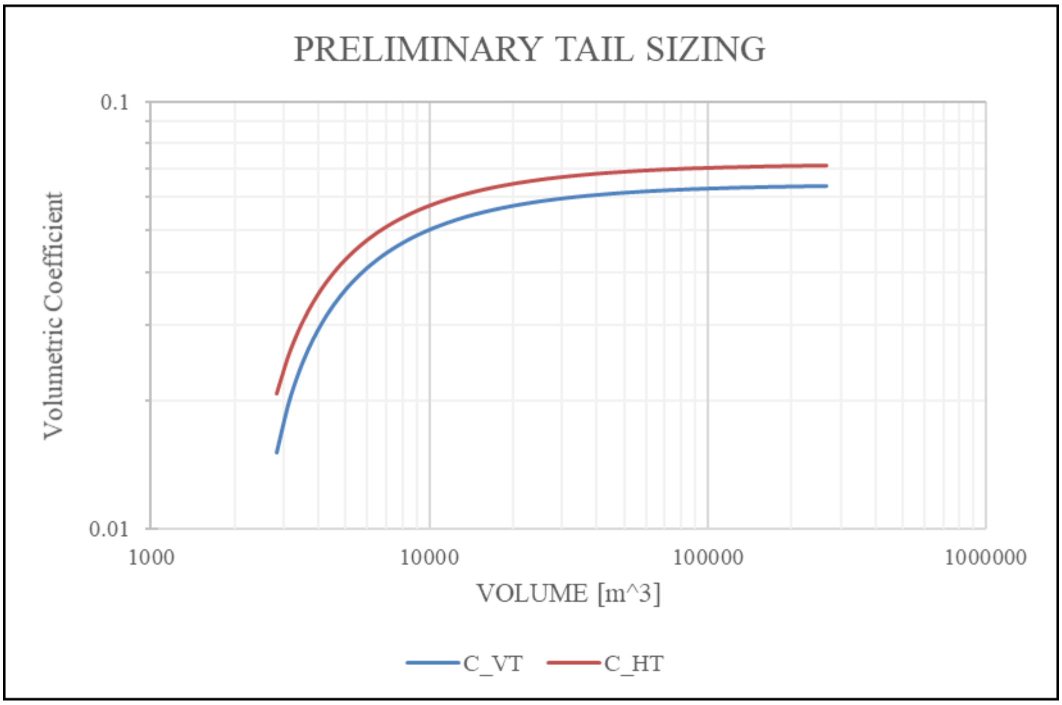


Figure 5-2: Construction of vertical and horizontal tail volumetric coefficient [6][1]

The expression of the horizontal tail volumetric coefficient is:

$$C_{HT} = \frac{S_{HT} l_{HT}}{l_b Vol^{2/3}} \qquad \text{(Equation 5-1)}$$

The equation for the vertical tail volumetric coefficient is:

[1] This graph is based on airship data found in (Carichner & Nicolai, 2013) vol. II, chapter 7, 2013.

$$C_{VT} = \frac{S_{VT} l_{VT}}{l_b Vol^{2/3}} \qquad \text{(Equation 5-2)}$$

Where the distance between the anterior quarter of vertical and horizontal tail MAC and gravity centre is the same:

$$l_{VT} = l_{HT} = l_T = 45\% \; l_b$$

The value of the moment arm set at 40 per cent of the airship length is derived from observation of the typical moment arm of the models built.

Tail configuration is the first step which a designer must take. Aerodynamic, stylistic, and constructive design influence this choice.

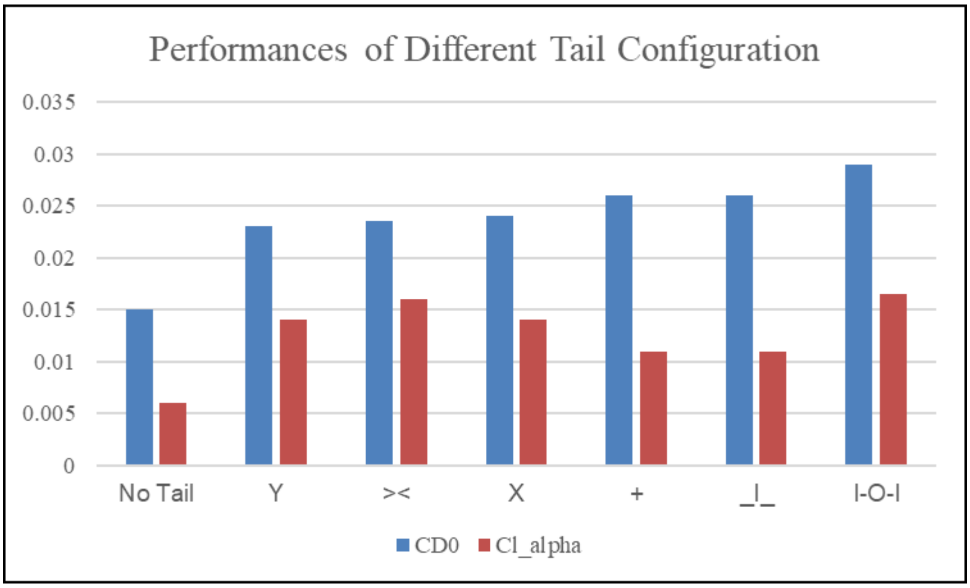


Figure 5-3: Performances of different tail configurations

Y and X configurations, shown in the graph above, are best from an aerodynamic point of view because they have lower zero lift coefficients than other configurations and a high curve slope lift.

The second step is determination of the horizontal and vertical tail surface plan. Through the diagram in Figure 5-2, the coefficients are determined by inserting the external volume value as input, and then the tail surfaces plan can be explained from equations (Equation 5-1) and (Equation 5-2):

$$S_{HT} = \frac{C_{HT} l_b Vol^{2/3}}{l_t} \qquad \text{(Equation 5-3)}$$

$$S_{VT} = \frac{C_{VT} l_b Vol^{\frac{2}{3}}}{l_t} \qquad \text{(Equation 5-4)}$$

In case an airship is equipped with propulsion for trim control, tail surface may be smaller than in a conventional airship. Thus, subtraction of 0.025 from the coefficients improves the result accuracy.

Tail elements generally have the same surface except for “_**I**_” and “**+**” configurations, where vertical tail surface plan must be assigned only vertical elements, whilst horizontal tail surface plan is applied to the horizontal element (Figure 5-4). Indeed, for tail elements which do not have their surface plan coincident with the horizontal and vertical plan, these can have the same surface plan through variation of two parameters, surface plan of the tail element and inclination relative to the horizontal or vertical plan. Therefore, for a pair of these values, surface plan of tail element projected onto the vertical and horizontal plane provides values of horizontal and vertical tail surface plan from equations (Equation 5-3) and (Equation 5-4).

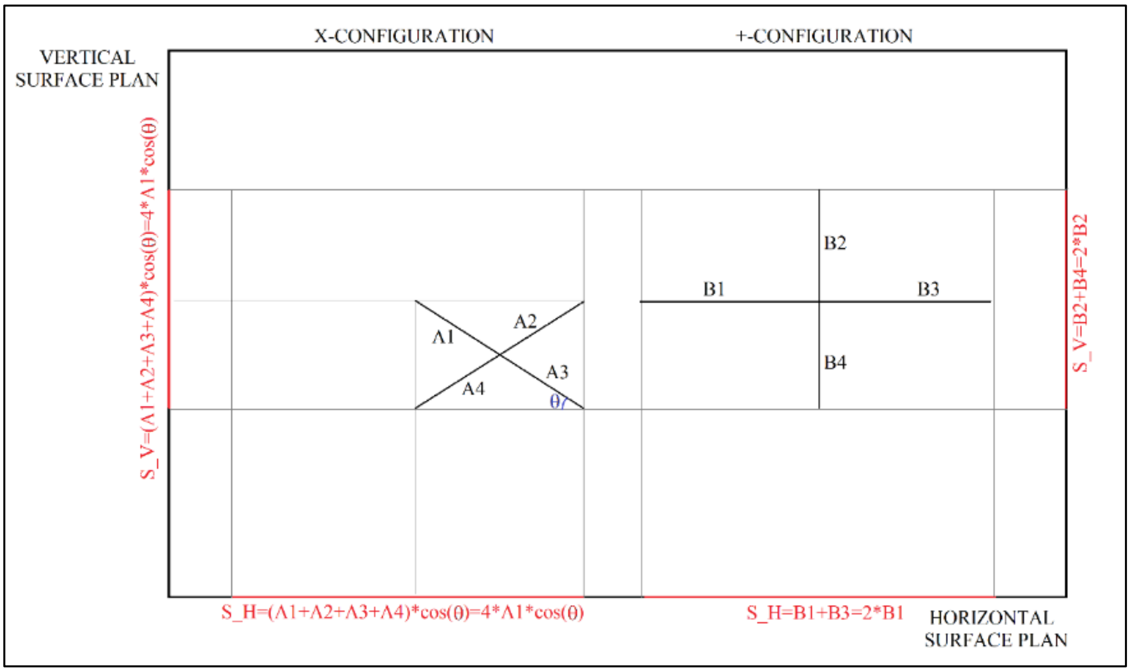


Figure 5-4: Comparison of “X” and “+” configurations

- X-Configuration - Values to determine this configuration are surface plan of the tail element, which is the same for all elements, and its relative angle within the horizontal plan. First, the horizontal and vertical surfaces plan must be divided into four because there are four tail elements that are symmetrical. Then the element surface plan is obtained through the Pythagorean theorem:

$$S_{el} = \sqrt{\left(\frac{S_{HT}}{4}\right)^2 + \left(\frac{S_{VT}}{4}\right)^2} \qquad \text{(Equation 5-5)}$$

Whilst the inclination angle of the tail element is:

$$\theta = \arctan\left(\frac{S_{VT}}{S_{HT}}\right) \qquad \text{(Equation 5-6)}$$

- +-Configuration - In this case, it is sufficient to divide the surface plan of the vertical tail by two to distribute it in an equal way between the two vertical tail elements. The same is true for the surface plan of a horizontal tail. Thus, equations to determine the vertical and horizontal elements are:

$$S_{el_H} = \frac{S_{HT}}{2} \qquad \text{(Equation 5-7)}$$

$$S_{el_V} = \frac{S_{VT}}{2} \qquad \text{(Equation 5-8)}$$

Using this configuration is less convenient than the previous one because the elements' surface is greater than X-configuration elements, as shown in Figure 5-4.

- Y-Configuration - This procedure is similar to the X-configuration, but the lack of symmetry and presence of an element surface plan coincident with a vertical plan complicates the equation to calculate the surface plan of the element and its inclination angle.

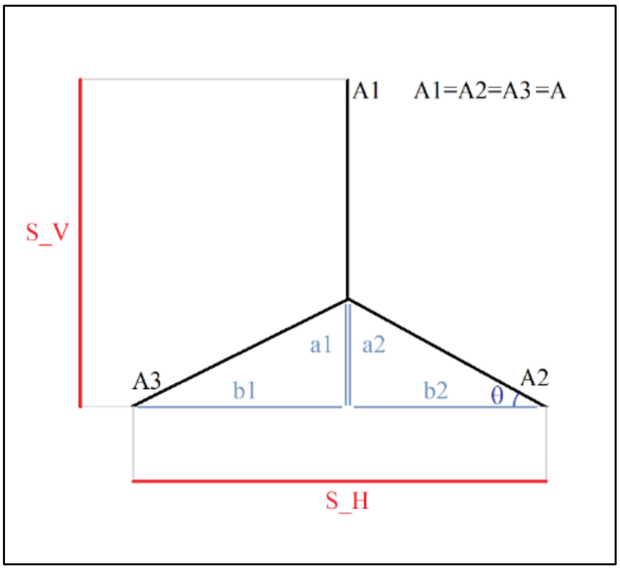


Figure 5-5: Y-configuration schematisation

Where the equations system is:

$$\begin{cases} S_{VT} = A + a_1 + a_2 \\ S_{HT} = b_1 + b_2 \\ A = \sqrt{b_1^2 + a_1^2} \end{cases} \quad \text{(Equation 5-9)}$$

This is with three equations and five unknowns (element surface plan and four horizontal and vertical projections of the two elements). Two more equations are needed; otherwise, this system is not solvable. From Figure 5-5, it is possible to see that:

$$\begin{cases} a_1 = a_2 = a \\ b_1 = b_2 = b \end{cases}$$

Now the system is solvable, and the final equation for the element surface is:

$$S_{el} = A = \frac{-\frac{2}{3}S_{VT} + \sqrt{\left(\frac{2}{3}S_{VT}\right)^2 + \frac{4}{3}\left(S_{VT}^2 + S_{HT}^2\right)}}{2} \quad \text{(Equation 5-10)}$$

Whilst through the trigonometric expression below, the inclination angle is:

$$S_{HT} = 2S_{el}\cos(\theta)$$

$$\theta = arcos\left(\frac{S_{HT}}{2\ S_{el}}\right) \qquad \text{(Equation 5-11)}$$

Chapter 6

6. Performances

Performances such as distance and power, required from an airship for precise flight conditions, are important for determining the fuel amount to be loaded on board to travel the route established and the propulsion system weight. Eventually the airship uses a hybrid method to vary its altitude, and performances allow one to gather information about take-off and landing distances.

The first thing to do is calculate the power required during the flight with straight and uniform motion, as shown in Figure 6-1.

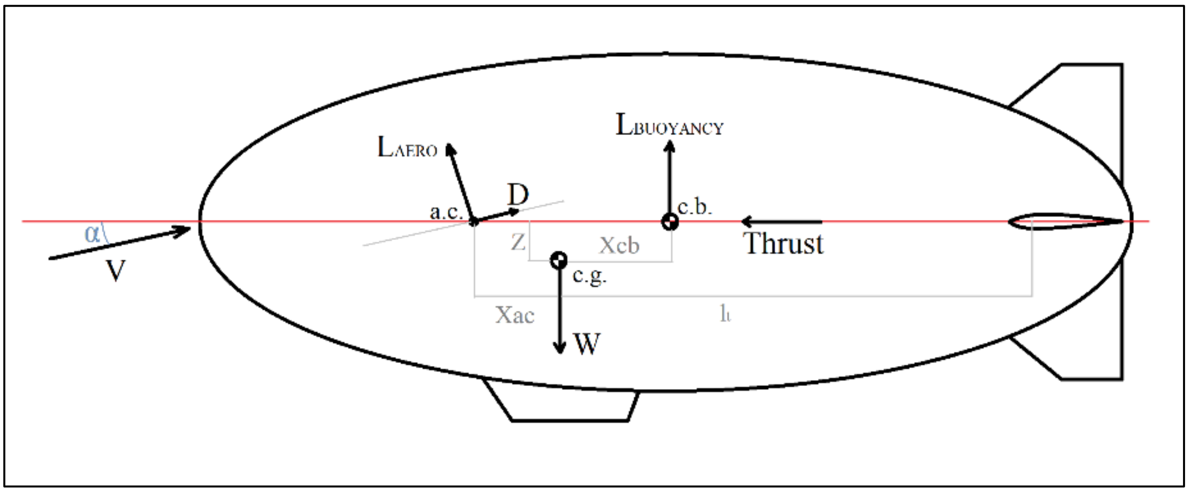


Figure 6-1: Forces and weights distribution on airship

During this type of flight, the airship is in equilibrium, and therefore the result of vertical and horizontal forces is null:

$$\begin{cases} W = L_{buoy} + L_{aero}\cos(\alpha) + D\sin(\alpha) \\ T = D\cos(\alpha) - L_{aero}\sin(\alpha) \end{cases} \quad \text{(Equation 6-1)}$$

Moreover, the angle between speed and airship is small, and the equation above can be simplified as:

$$\begin{cases} W = L_{buoy} + L_{aero} \\ T = D \end{cases} \qquad \text{(Equation 6-2)}$$

Because:

$$\alpha \cong 0 \rightarrow \begin{cases} \cos(\alpha) \cong 1 \\ \sin(\alpha) \cong 0 \end{cases}$$

(Equation 6-2) shows two terms that balance the weight. As mentioned in paragraph 1.2, buoyancy lift is constant at a certain altitude, whilst aero lift varies to balance the fuel burn; thus, it varies between two heaviness values: heaviness at take-off when fuel on board is maximum and heaviness at landing when fuel tanks are empty.

Whilst drag in the second equation can be expressed with a drag coefficient, this in turn has a parasitic drag coefficient and drag due to the lift coefficient. Thus, the equation above can be rewritten as:

$$\begin{cases} W = L_{buoy} + q\ Cl\ Vol^{2/3} \\ T = q(C_{D0} + K\ Cl)Vol^{2/3} \end{cases} \qquad \text{(Equation 6-3)}$$

Where aero lift is also equal to heaviness at a precise time of flight:

$$L_{aero} = q\ Cl\ Vol^{2/3} = g\ W_H \qquad \text{(Equation 6-4)[1]}$$

To get the thrust power, multiply the force needed to advance - in this case, drag force - with airship flight speed, as shown in (Equation 6-5).

$$P = V\ D = q(C_{D0} + KCl)Vol^{2/3}V \qquad \text{(Equation 6-5)}$$

[1] Pay attention to units of measure. Indeed, Newton is the unit of measure for aero lift, whilst Kg is used for heaviness.

Power is described through two terms as a function of the speed. Replace the lift coefficient of the equation above with those of (Equation 6-4:

$$P = \frac{1}{2} C_{D0} \rho Vol^{2/3} V^3 + \frac{2K(gW)^2}{\rho Vol^{2/3}} \frac{1}{V} \qquad \text{(Equation 6-6)}$$

Table 23 shows all mathematical considerations to get the equation above. The first term is derived from parasitic drag and increases with cubic speed. The second term is power linked to the induced drag and decreases with hyperbolic trend as the speed increases. Figure 6-2 shows the curve's trend:

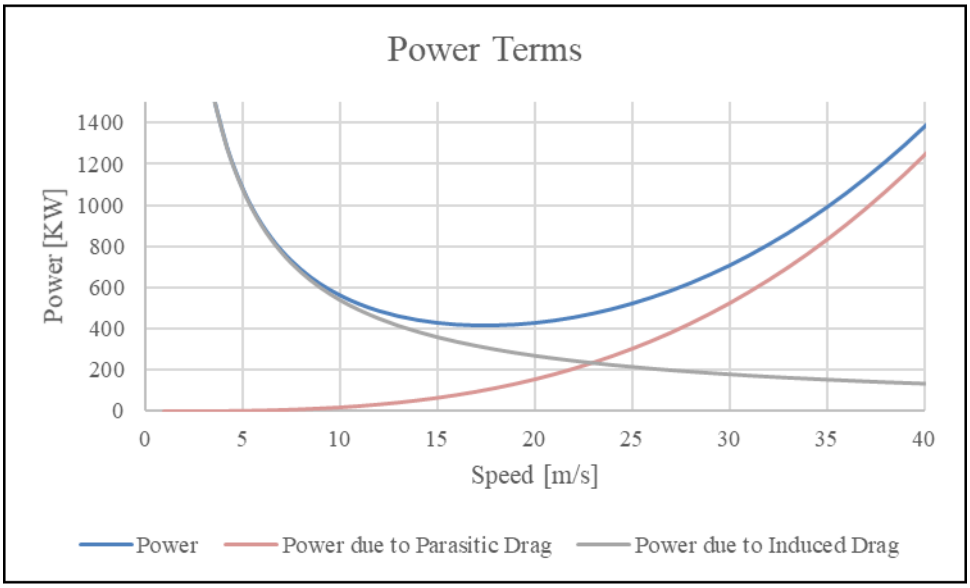


Figure 6-2: Power breakdown in two terms

Indeed, the speed of minimum power does not correspond to the minimum speed because induced drag is a function directly proportional to the square of the lift coefficient, which increases considerably with decreased speed. Thus, power increase due to the induced drag is the negative aspect for the aerodynamic airship.

However, power expressed through (Equation 6-6) is not that required by the engine because propellers generate thrust, which balances the drag, and these elements, although well-constructed, have an efficiency of less than one. Thus, engines must provide a greater power than necessary power because propellers do not convert all power into thrust.

$$P_R = \frac{P}{\eta_P} \qquad \text{(Equation 6-7)}$$

Sea level power is an important value to define airship performances and preliminary sizing. It can be entered into (Equation 6-5) with the following parameters:

$$q_{SL_{max}} = \frac{1}{2}\rho_{SL}V_{max}^2 \qquad \text{(Equation 6-8)}$$

$$Cl_{\max\_power} = \frac{W_{H0}[N]}{q_{SL_{max}} Vol^{2/3}} \quad \text{(Equation 6-9)}$$

$$P_{R_{SL\_max}} = \frac{q_{SL_{max}} \left(C_{D0} + KCl^2_{\max\_power}\right) Vol^{2/3} V_{max}}{\eta_p} \quad \text{(Equation 6-10)}$$

6.1. Range and Endurance Estimate

Although the title of this section implies calculation of the airship flight distance, generally the range is a value provided as input. Thus, initially, the unknown is the range, an assumption used to obtain formulas necessary to explain (in a second step) the real unknown, which is the heaviness at take-off.

However, as well as for airplanes, two possible flight strategies exist for airships. First is constant lift coefficient strategy, and second is constant speed strategy. Actually, a third strategy exists that combines the advantages of the previous two. The input needed to make this analysis is:

Table 8: Input Needed for Airship Range Analysis

INPUT	
R	Range [Km]
$\mathbf{W_{H1}}$	Heaviness at Landing [Kg]
$\mathbf{C_{D0}}$	Drag Coefficient
K	Factor of Total Drag Due to Lift
BSFC	Brake Specific Fuel Consumption [lb/hp/h]
q	Dynamic Pressure [Pa]
$\mathbf{Vol^{2/3}}$	Reference Surface [m^2]
$\boldsymbol{\eta_p}$	Propeller Efficiency
$\boldsymbol{\sigma}$	Ration between Altitude Air Density and Sea Level Air Density

6.1.1. #1 Cruise Strategy - Constant Cl

To keep the lift coefficient constant during flight, the speed must decrease because of fuel reduction and, consequently, lift. This strategy guarantees maximum range, but during the final phases, the speed is too low; thus, the duration of the flight increases considerably.

The equation that allows calculating the range is the Breguet range equation shown below:

$$R = \int_{i}^{W_f} \frac{V}{dW/dt} dW \qquad \text{(Equation 6-11)}$$

Where weight variation against time is:

$$\frac{dW}{dt} = BSFC\ P_R[hp] \qquad \text{(Equation 6-12)}$$

The power expression ((Equation 6-5)) and weight variation (Equation 6-12) are entered into (Equation 6-11). Since lift and heaviness are in equilibrium and therefore are equal, multiplying and dividing these terms into the equation does not make any changes but makes the expression easier to integrate.

$$R = \int_{W_i}^{W_f} \frac{\eta_p}{BSFC} \frac{L_{aero}}{D} \frac{dW}{W_H} \qquad \text{(Equation 6-13)}$$

An exact solution of the integral is possible by making some assumption before solving it. For example, lift coefficient, BSFC, and propeller efficiency are constant during all airship flights. Thus, final expression of the range for flight strategy at lift coefficient constant is:

$$R[nm] = \frac{326\ \eta_p}{BSFC} \left(\frac{L_{aero}}{D}\right)_{max} \ln\left(\frac{W_{H0}}{W_{H1}}\right) \qquad \text{(Equation 6-14)}$$

The number 326 serves to express the units of measurement of the BSFC coherently, with the result expressed in nautical miles because this is the only dimensional value. Heaviness is also a dimensional value, but the expression presents a ratio. Thus, both forms of heaviness must have the same unit of measure.

However, as shown in (Equation 6-14), lift coefficient used in this strategy is not a random value but is the value that maximises the ratio between lift and drag or makes less drag. Thus, the expression of the ratio between lift and drag maximised is:

$$\left(\frac{L_{aero}}{D}\right)_{max} = \left(\frac{C_{Laero}}{C_D}\right)_{max} = \frac{1}{2\sqrt{C_{D0}K}} \qquad \text{(Equation 6-15)}$$

The calculation of the airship endurance or time in flight occurs through the following expression:

$$E(hh) = \int_{t_i}^{t_f} dt = \int_{W_i}^{W_f} \frac{1}{dW/dt} dW \qquad \text{(Equation 6-16)}$$

(Equation 6-12) into (Equation 6-16) making the same step to determine range.

$$E = \int_{W_i}^{W_f} \frac{550\,\eta_p}{BSFC\ V\ D} dW = \int_{W_i}^{W_f} \frac{550\,\eta_p L_{aero}}{BSFC\ V\ D} \frac{dW}{W_H} \qquad \text{(Equation 6-17)}$$

Where 550 is the number that converts the power from [hp] to [ft lb/s].

The equation above shows that an airship has maximum endurance when it flies at minimum power if propeller efficiency and BSFC are constant, as assumed. In the integral speed and drag, assume the following expressions:

$$\begin{cases} V = \sqrt{\dfrac{L_{aero}}{\frac{1}{2}\rho Vol^{2/3} Cl}} \\ D = \frac{1}{2}\rho V^2 Vol^{2/3} C_D = \dfrac{L_{aero}}{Cl} C_D \end{cases}$$

Replacing (Equation 6-17), after integration, the endurance final equation is:

$$E = \frac{26.8\eta_p}{BSFC} \frac{Cl^{3/2}}{C_D} \sqrt{\frac{2\sigma Vol^{2/3}}{W_{H0}}} \left[\left(\frac{W_{H0}}{W_{H1}}\right)^{1/2} - 1\right] \qquad \text{(Equation 6-18)}$$

6.1.2. #2 Cruise Strategy - Constant Speed

In this case, stakeholders and designers define a cruising speed that will remain constant for the flight duration. At constant speed, whilst fuel decreases, aero lift follows the same trend; therefore, the aero lift coefficient must also decrease.

Up to (Equation 6-13), to calculate range, the steps are the same. The difference is in the variable of speed for this flight strategy. Thus, entering this into (Equation 6-4) for aero lift and (Equation 6-3) for drag, the equation becomes:

$$R = \int_{W_i}^{W_f} \frac{\eta_p}{BSFC} \frac{1}{qVol^{\frac{2}{3}}\left[C_{D0} + K\left(\frac{W_H}{qVol^{2/3}}\right)^2\right]} dW \qquad \text{(Equation 6-19)}$$

With dynamic pressure, BSFC, and propeller efficiency constant, as are the assumptions, the integral calculation provides an exact solution:

$$R[nm] = M\left[\tan^{-1}\left(\frac{W_{H0}}{N}\right) - \tan^{-1}\left(\frac{W_{H1}}{N}\right)\right] \qquad \text{(Equation 6-20)}$$

Where:

$$\begin{cases} M[nm] = \dfrac{326\,\eta_p}{BSFC\,\sqrt{K\,C_{D0}}} \\ N[lb] = q\left[\dfrac{lb}{ft^2}\right] Vol^{2/3}[ft^2]\sqrt{\dfrac{C_{D0}}{K}} \end{cases} \qquad \text{(Equation 6-21)}$$

In this case, a speed that maximises the ratio between the aero lift coefficient and drag, or minimises drag or power required, exists. An equation for the speed for minimum drag is:

$$V_{D_{min}}^4 = \frac{4KW_H^2}{(\rho Vol^{2/3})^2 C_{D0}} \qquad \text{(Equation 6-22)}$$

Instead, a velocity equation that allows maximising range is one where the ratio between aero lift and drag is maximised:

$$V_{R_{max}}^4 = \frac{4KW_{H0}W_{H1}}{(\rho Vol^{2/3})^2 C_{D0}} \qquad \text{(Equation 6-23)}$$

Finally, a speed equation that reduces the power required is:

$$V_{P_{R_{min}}}^4 = \frac{4KW_H^2}{3(\rho Vol^{2/3})^2 C_{D0}}$$ (Equation 6-24)

Regarding the calculation of the flight time or airship endurance, assuming speed, BSFC, and propeller efficiency constants and explaining the speed in terms of aero lift coefficient, it is possible to integrate it into (Equation 6-17) to obtain the following equation:

$$E[hh] = \frac{550\,\eta_p}{V\ BSFC\ \sqrt{C_{D0}K}}\left[\tan^{-1}\left(\frac{W_{H0}}{N}\right) - \tan^{-1}\left(\frac{W_{H1}}{N}\right)\right]$$ (Equation 6-25)

In a real design problem where the constant speed is the flight strategy, range and cruise speed are generally inputs provided by the stakeholders. Thus, the equation above must be solved because the unknown is fuel consumption. There are two steps to determine it. The first is to calculate heaviness at take-off (Equation 6-20):

$$W_{H0}[lb] = N\tan\left(\frac{R[nm]}{M} + \tan^{-1}\left(\frac{W_{H1}[lb]}{N}\right)\right)$$ (Equation 6-26)

Of course, the units of measure can change, but they must be coherent; thus, a dimensional analysis is fundamental to avoid an erroneous result. The second step is fuel weight determination. The value of heaviness at landing and fuel weight is treated in detail in section 8.

6.2. Take-Off and Landing Analysis

The airship can make vertical landings and take-offs, but if part of its weight is not balanced by the buoyant lift of the gas like aerodynamic airship case, these flight phases become equal to the airplane landings and take-offs phases. To generate the lift component, the airship must have a relative speed with air and incidence non-zeros.

6.2.1. Take-Off Analysis

The take-off phase begins when an airship is stationary on the runway and then accelerates; it ends, for regulation, when it exceeds an obstacle placed at fifty feet from the ground. Three steps make up this phase:

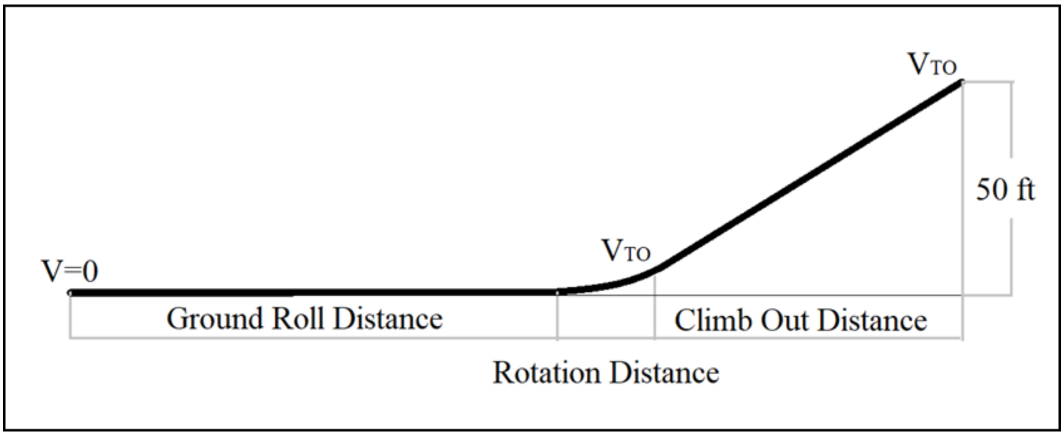


Figure 6-3: Take-off phases

- Ground Roll Distance - This is the necessary distance for the airship to reach the speed which allows it to rotate to an angle useful to generate the lift needed to take off. A higher value to equal enough lift to generate involves a lower speed; thus, ground roll distance decreases. It cannot be too high because the tail might crash into the ground. Historical data provides the incidence angle value of:

$$\alpha_{rot} \cong 12°$$

The first value to calculate is the lift-off speed which generates the aero lift that is 1.2 times greater than heaviness at take-off:

$$V_{TO} = 1.1\sqrt{\frac{W_{H0}}{\frac{1}{2}\rho Vol^{2/3} Cl_{TO}}} \quad \text{(Equation 6-27)}$$

Where lift coefficient at take-off is:

$$Cl_{TO} = \alpha_{rot} Cl_{\alpha}$$

An equation to calculate distance is:

$$S_G = \int_0^{V_{TO}} \frac{V}{a} dV = \frac{V_{TO}^2}{2a_{(@0.707\,V_{TO})}} \qquad \text{(Equation 6-28)}$$

Acceleration depends on the speed, and therefore it should be integrated, but a constant acceleration (Equation 6-28), evaluated for a speed equal to 0.707 times the take-off speed, approximates the result well. However, Newton's law says that acceleration is equal to the ratio between the force and mass on which it acts. Force is the result of three components—thrust, drag, and landing gear friction—whilst mass constitutes take-off mass and gas mass.

$$a_{(@0.707\,V_{TO})} = \frac{(T_{TOT} - D - F_F)_{(@0.707\,V_{TO})}}{m_{TOT}} \qquad \text{(Equation 6-29)}$$

$$m_{TOT} = \frac{W_{TO}}{g} + m_{gas} = \frac{W_{TO}}{g} + \rho_{gas}\, Vol_{gas} \qquad \text{(Equation 6-30)}$$

To calculate drag, the expression is:

$$D = \frac{1}{2}\rho_{SL}(0.707\,V_{TO})^2(C_{D0} + K\,Cl_{TO}^2)Vol^{2/3} \qquad \text{(Equation 6-31)}$$

Whilst the expression of the landing gear friction is:

$$F_F = \mu(W_{H0} - L_{aero})_{(@0.707\,V_{TO})} \qquad \text{(Equation 6-32)}$$

$$L_{aero} = \frac{1}{2}\rho_{SL}(0.707 V_{TO})^2 Cl_{TO} Vol^{2/3}$$

Where take-off lift coefficient inserted into aero lift is an approximation. Indeed, the incidence angle at 0.707 times take-off speed is lower than the limit incidence angle. The last force to analyse is thrust, and the equation to determine it for one engine is:

$$T_{TOT} = T\,N_{eng} \qquad \text{(Equation 6-33)}$$

$$T = \frac{T}{T_0}\frac{T_0}{P}P$$

The first term (in red) is the ratio between the thrust of the engine mounted on the airship and static thrust, produced at a speed of zero. The diagram below allows one to calculate this ratio.

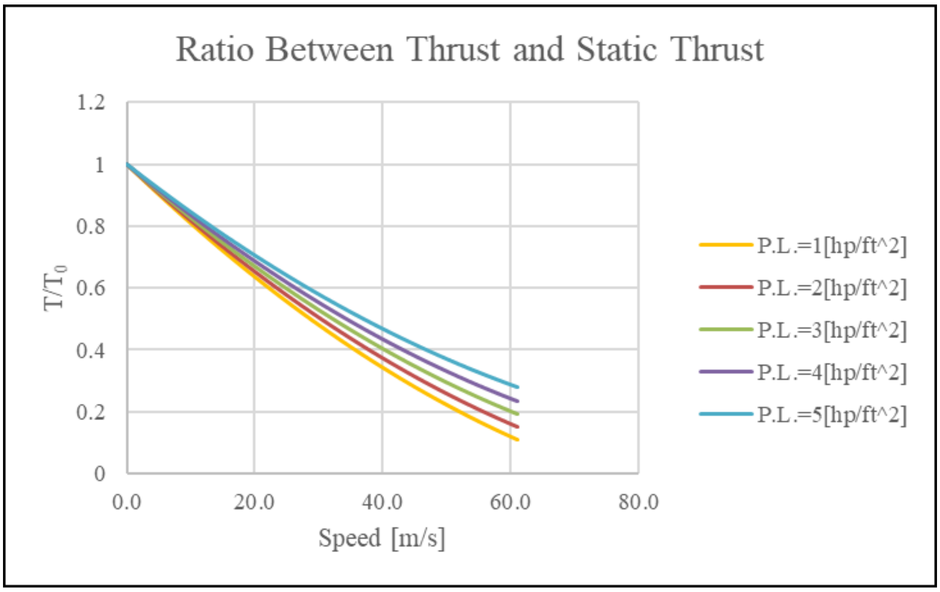


Figure 6-4: Diagram of speed and ratio between thrust and static thrust

Input parameters are the PL (power loading) and speed. The first indicates the ratio between engine power and surface of the disc propeller,[1] whilst the second is the airship speed to which thrust must be calculated. The diagram in Figure 6-5 is useful to calculate the second term in blue. PL is the input parameter.

[1] Propeller parameters are treated in detail in section 7.3.

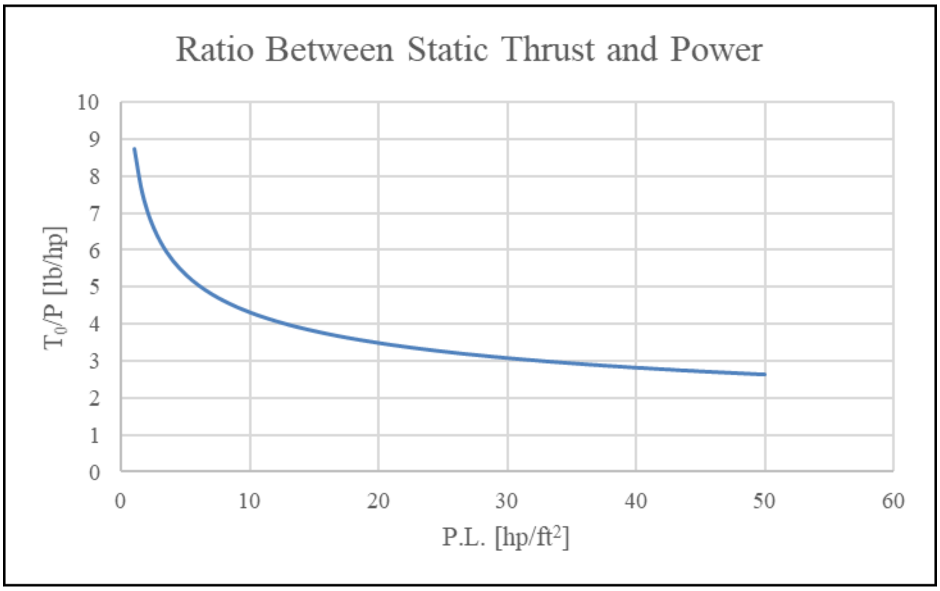


Figure 6-5: Diagram of PL and ratio between static thrust and power

The last term is maximum power required at sea level (Equation 6-10), referred to in a single engine as horse power.

- Rotation distance is the distance travelled during the airship rotation. FAA considers a three-second time to carry out this manoeuvre at take-off speed:

$$S_R = t_{rot} V_{TO} = 3\ V_{TO} \qquad \text{(Equation 6-34)}$$

- Climb-out distance is the horizontal segment necessary for the airship to overcome fifty feet of altitude, ending the take-off phase. During this phase, the airship flies at the same speed, which is take-off speed, and at the same slope angle; thus, resulting forces acting on it must be zero, as shown in Figure 6-6.

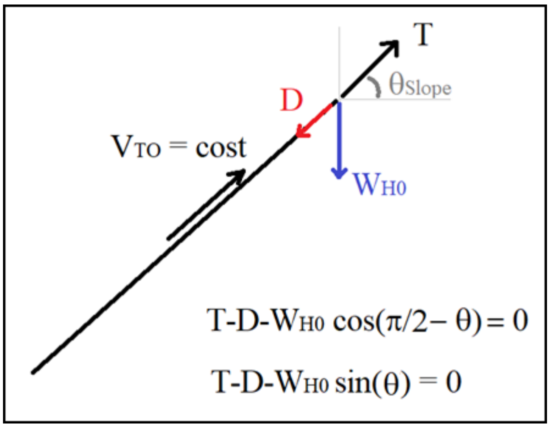


Figure 6-6: Climb-out distance scheme

$$S_C = \frac{\tan(\theta_{Slope})}{l_{obstacle}}$$ (Equation 6-35)

Where:

$$\tan\left(\theta_{Slope}\right) = \frac{(T_{TOT} - D)_{(@V_{TO})}}{W_{H0}[N]}$$ (Equation 6-36)

Of course, steps to calculate thrust and drag are the same as those seen for ground roll distance, but this time speed reference is the take-off speed.

Finally, take-off distance is given by the sum of these three contributions:

$$S_{to} = S_G + S_R + S_C$$ (Equation 6-37)

6.2.2. Rate of Descent

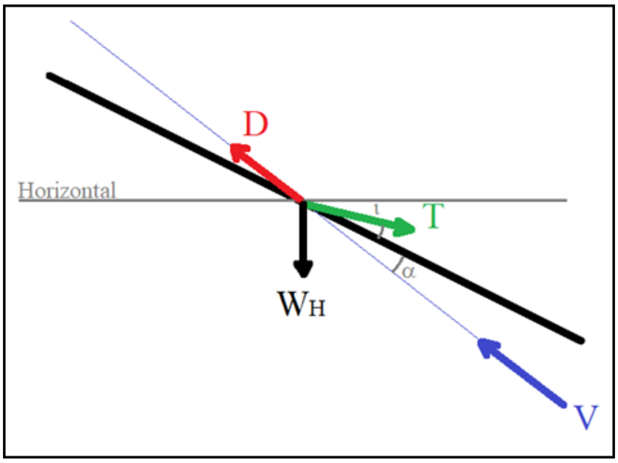


Figure 6-7: Rate of descent scheme

The prelanding stage, when the airship passes from the cruise altitude to the fifty-feet altitude, represents the obstacle to avoid during the landing phase. The equation that shows altitude variation in time is:

$$\frac{dZ}{dt} = V\sin(\gamma) = \frac{V(T\cos(\alpha+i) - D)}{W_H} \qquad \text{(Equation 6-38)}$$

Actually, (Equation 6-38) is also valid for the ascent phase. To adapt it to the descent phase, it is sufficient to consider the thrust about zero and the descent angle as small.

$$\begin{cases} \gamma \cong 0 \rightarrow \sin(\gamma) \cong \tan(\gamma) \\ T \cong 0 \\ W_H = L_{aero} \end{cases}$$

Thus, the equation becomes:

$$ROD = V\tan(\gamma) = -\frac{V\,D}{L_{aero}} \qquad \text{(Equation 6-39)}$$

However, two different approaches to descents exist. One favours the maximum range, whilst the other prefers minimum ROD (Rate of Descent). Speed is the parameter that discriminates between the two cases. Indeed, for maximum range, the airship must be flying with a maximum ratio between aero lift and drag, and the speed assumes the expression of (Equation 6-23). For minimum ROD, the speed has the expression of (Equation 6-24) which is referred to as the minimum power condition.

6.2.3. Landing Analysis

This phase is opposite to the landing phase and starts when the airship is at an altitude of fifty feet, ending when its speed on the runway is zero. Also, in this case, landing distance is obtained by the sum of three segments relative to three sequential subphases. They are shown in fFigure 6-8 and are:

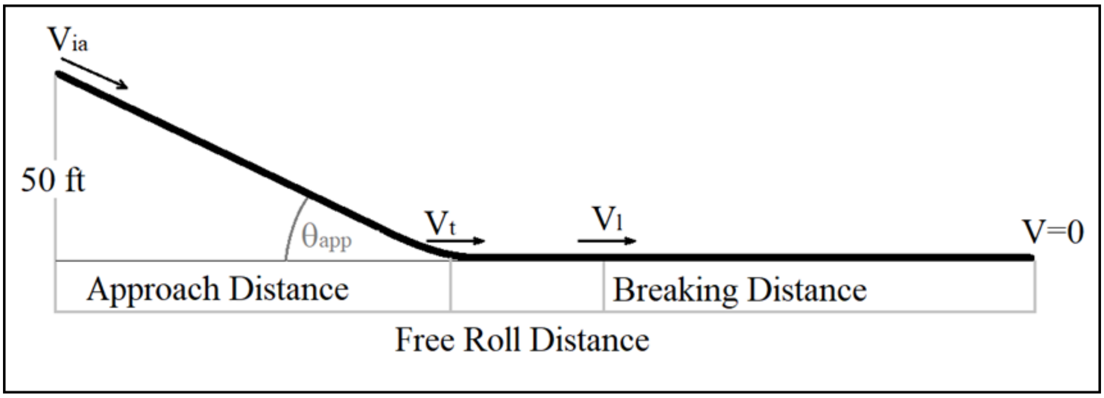


Figure 6-8: Landing phase scheme

- Approach distance - This is the descent phase in which the airship reduces its altitude almost to the ground. Two different approaches allow for calculating this segment. The first is analytical and consists of analysing the variation of kinetic and potential energy. The second considers the descent angle known, which is equal to a typical approach angle by about three degrees. During the preliminary project phase, the value obtained through the second approach is preferable to the other because it is simple to calculate and more conservative.
  The equation of the first approach is:

$$S_{A\#1} = \frac{m_{TOT}}{F_B}\left(\frac{V_{ia}^2 - V_t^2}{2} + g\Delta Z\right) \quad \text{(Equation 6-40)}$$

  Where reduction of kinetic energy is due to the speed decrease from initial approach speed to the touch down speed, whilst the reason for potential energy variation is altitude reduction, from fifty feet to the ground. Energy reduction is possible with a resultant breaking force.

$$F_B = \left(D + T_{TOT_{vectoring}}\right)_{(@V_l)}$$

Steps to calculate thrust and drag are the same as those seen for ground roll distance but are used for landing speed. Speed value in the equation below has the following expression:

$$\begin{cases} V_{ia} = 1.3\,V_l \\ V_t = 1.15\,V_l \\ V_l = \sqrt{\dfrac{L_{aero}}{\frac{1}{2}\rho_{SL} Cl\, Vol^{2/3}}} \end{cases}$$

Where the equations of aero lift and its coefficient are:

$$\begin{cases} L_{aero} = W_{H0} - \frac{1}{2} W_{fuel} \\ Cl = Cl_{TO} \end{cases}$$

The equation of the second approach is:

$$S_{A\#2}[ft] = \frac{50}{\tan(\theta_{app})} \qquad \text{(Equation 6-41)}$$

- Free roll distance—According to regulations, this phase goes on for three seconds, and changes to the airship's trim bring the aero lift value equal to zero; brakes are applied, and thrust is reversed to stop it.

$$S_F = 3\,V_t \qquad \text{(Equation 6-42)}$$

- Breaking distance—This is the last segment necessary to bring the airship speed value to zero.

$$S_B = \left(\frac{\frac{W_{TO}}{g} + m_{gas}}{\rho_{SL} C_D Vol^{2/3}}\right) \ln\left(\mu_b W_{H1} + T_{TOT} + \frac{1}{2}\rho_{SL} Vol^{2/3} C_D V_t^2\right) \qquad \text{(Equation 6-43)}$$

Where μ_b is the breaking friction coefficient and total thrust reverse is equal to:

$$T_{TOT_{reverse}} = 60\%\; T_{TOT\,(@V_{TO})}$$

Finally, landing distance is given by the sum of these three contributions, adding the FAA margin equal to 60 percent:

$$S_L = \frac{(S_{A\#2} + S_F + S_B)}{FAA_{margin}} \qquad \text{(Equation 6-44)}$$

Chapter 7

7. Propulsion System

The main elements that characterise the propulsion system are the engine and propeller. The former generates the power required to counteract airship drag indirectly, whilst the latter transforms the engine power in thrust. Mechanical coupling between these two components plays a key role in the airship's performances because, especially for combustion engines, the crankshaft rotation is higher than the propeller rotation and guarantees high efficiency. Thus, speed reduction becomes fundamental. The propulsion system mounted on an airship can be either a fuel or an electric propulsion system. Depending on the propulsion type, other important elements exist such as a fuel tank for first category, whilst a solar array can generate power and a battery or fuel cell can be used as storage for the electric category. Both need an engine control system to manage the power developed. Preliminary sizing of this system has the purpose of obtaining the following outputs:

- Choice of an engine whose power covers the airship's required power
- Sizing of solar panel, battery, and fuel cell
- Propeller sizing

Inputs necessary for analysis are:

Table 9: Input Needed for Propulsion System Analysis

INPUT	
P_R	Power Required by Engine
P	Thrust Power
N_{eng}	Number of engines
Z_{cruis}	Cruise Altitude
Lat	Maximum Airship Latitude
P_{eng}	Engine Power
ρ	Air Density at Cruise Altitude
ρ_{SL}	Air Density at Sea Level

7.1. Fuel Propulsion System

A reciprocating piston engine and turboprop engine are two typical models of engines mounted on airships, and both exploit the power generated by hydrocarbon combustion, generally gasoline or diesel as fuel. The task of the designer is to understand, at this preliminary phase, how much power every engine has, according to the engine number chosen. Then it must be checked whether these exist on the market engines with comparable power; otherwise, speed, altitude, and the engine number must change. Indeed, by increasing the engine's number, the power that each one has to develop will be smaller, whilst reducing cruise and maximum speed allows for decreasing the power required. In regard to altitude, decreasing it implies a lower reduction of engine power that generally operates at sea level.

The first analysis step is the division of the power required for the engine's number:

$$P_{R_{1eng}} = \frac{P_R}{N_{eng}} \qquad \text{(Equation 7-1)}$$

Then the designer seeks an engine with similar power, generally referred to as sea-level altitude, and for an optimum revolution per minute between 2400 rpm and 2800 rpm. In this case, the designer must correct the power, taking into account the altitude and therefore air rarefaction that decreases engine performances.

$$P_{eng}[hp] = P_{SL_{eng}}[hp]\left(\frac{\rho}{\rho_{SL}} - \frac{1-\frac{\rho}{\rho_{SL}}}{7.75}\right) \qquad \text{(Equation 7-2)}$$

The last step is a comparison between the engine power developed in altitude and power required. When the first is greater than the second, preliminary sizing of the propulsion system ends; otherwise, the designer has to change the inputs.

$$P_{1eng} \geq P_{R_{1eng}} \qquad \text{(Equation 7-3)}$$

7.2. Electric Propulsion System

In this propulsion system, energy does not come from fuel combustion but is external to the airship and comes from the sun. This implies an advantage that it is not necessary to carry fuel on board, thus eliminating the tanks. But solar energy is not directly usable; thus, solar panels are necessary on board to capture and convert it into electricity, whilst batteries store excess energy to use when it is not available from the sun.

An advantage is that due to the higher efficiency of the electric engine than a fuel engine to convert electrical power, the chemical for fuel propulsion is converted into mechanical power that puts the propeller into rotation.

$$P_{R_{el}} = \frac{P}{\eta_{SEE}}$$

where η_{SEE} is efficiency that includes the electric motor, propeller coupling, and line losses.

It is a great alternative to a fuel propulsion system when the power at stake is small. Indeed, available solar power to the square meter is generally low, although it may depend on the conditions. Therefore, more power requires the propulsion system, and surfaces of the solar panels will be higher to satisfy it. The first step is to get information about solar energy as the inputs change.

7.2.1. Solar Power

Solar power value per surface units varies depending on the object's distance from the sun. At 150 million kilometres, equivalent to the distance between the earth and sun, the value of power in the vacuum is:

$$P_{S_{v\perp}} = 1367\frac{W}{m^2} = 127\frac{W}{ft^2}$$

To obtain this value, sunlight must be perpendicular to the incident surface; otherwise, the power decreases through the relationship of:

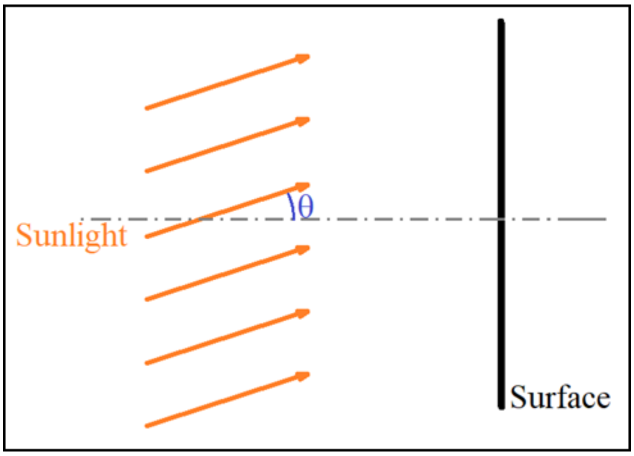


Figure 7-1: Light incidence

$$P_{S_v} = P_{S_{v\perp}} \cos(\theta) \qquad \text{(Equation 7-4)}$$

In the next steps, with the assumption of having the incidence angle of the light equal to zero, sunrays will always be perpendicular to the solar panel surface.

Of course, the airship does not travel in a vacuum, but it is within the atmosphere. Particles that make it up absorb part of the power; thus, available power decreases with altitude, as is shown in the graph below.

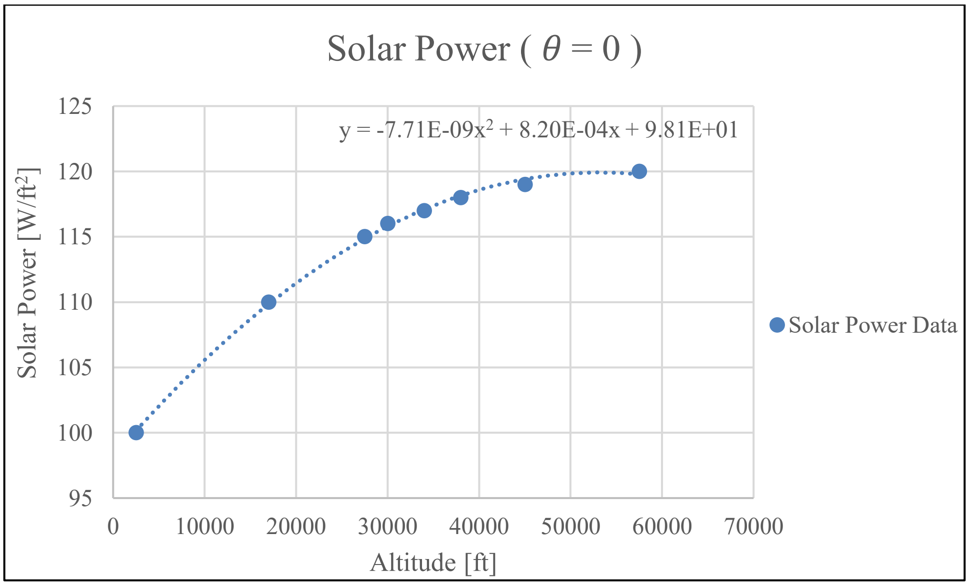


Figure 7-2: Graph of solar power at varying altitudes

The function that best interpolates solar power data is of the polynomial type, and its equation is:

$$P_{S_z}\left[\frac{W}{ft^2}\right] = -7.71 * 10^{-9} Z^2[ft] + 8.20 * 10^{-4} Z[ft] + 98.1 \quad \text{(Equation 7-5)}$$

The last two elements that affect the solar power value are the time of year and latitude at which the airship flies. Indeed, at low latitudes, the sun's rays are more perpendicular to the earth's surface than those at higher latitudes. Moreover, earth's axial tilt makes it so that the sun's rays can be more or less perpendicular to the surface piece placed at a certain latitude, depending on the time of year (Figure 7-3). In addition, the duration of the day and therefore the energy that the sun can provided depend on it.

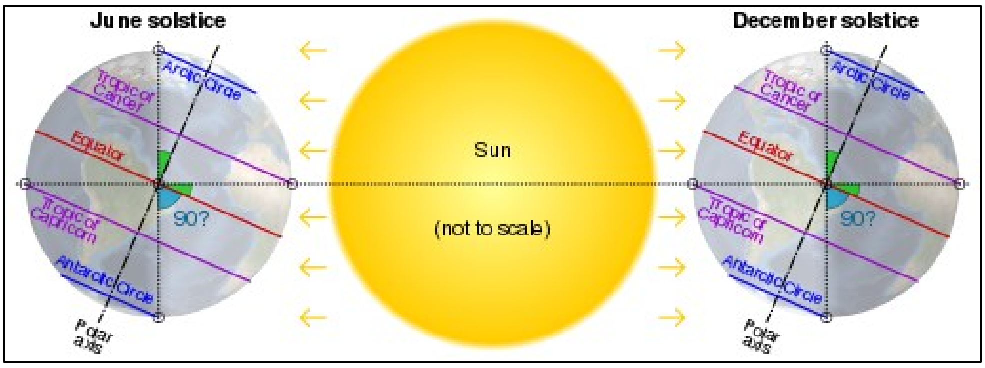


Figure 7-3: Axial tilt and solar rays incidence in summer and winter [7][1]

In fixed latitude, the boundary cases for the northern hemisphere correspond with the maximum duration of the day in summer and minimum in winter. In these cases, solar power is:

$$\begin{cases} Longest\ DL\ 04-Jul \rightarrow P_{S_{Lat}} = P_{S_z}\cos(Lat_{city} - \alpha_T) \\ Shortest\ DL\ 04-Jan \rightarrow P_{S_{Lat}} = P_{S_z}\cos(Lat_{city} + \alpha_T) \end{cases} \quad \text{(Equation 7-6)}$$

[1] File: (cmglee, 2015) - Axial tilt vs tropical and polar circles.svg, https://en.wikipedia.org.

where the result is the maximum power that the sun provides when it is in the highest point in the sky and its rays are more perpendicular with the surface. Lat_{city} is the maximum latitude that guarantees sufficient energy for the airship's daytime and night-time flight, and α_T is the earth's axial tilt angle. Exceeding that latitude value, the solar panels' surface is not sufficient to provide the onboard energy required. The graphs below show the solar power trend during the day for the longest and shortest amounts of daylight in two cities.

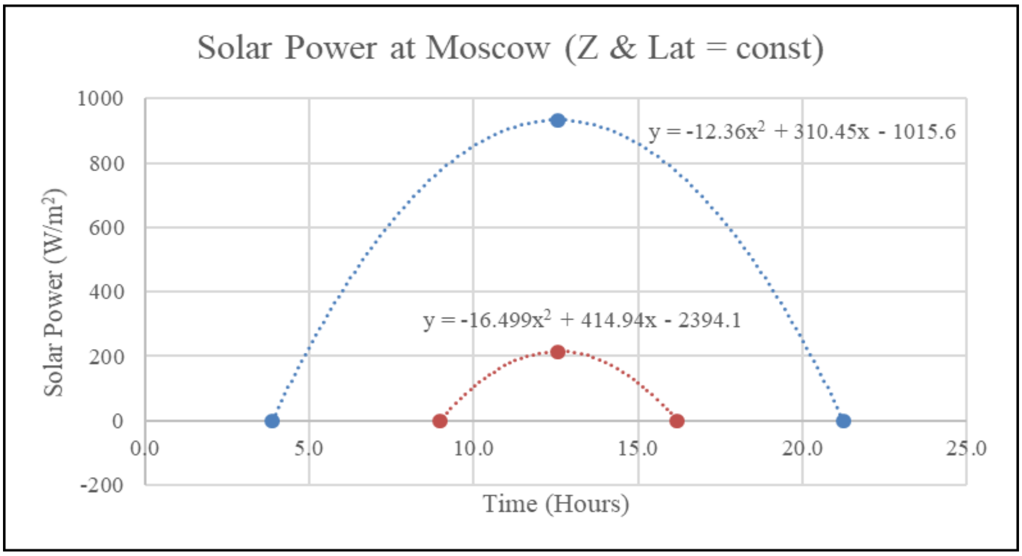


Figure 7-4: Solar power trend at latitude of 55.8 degrees

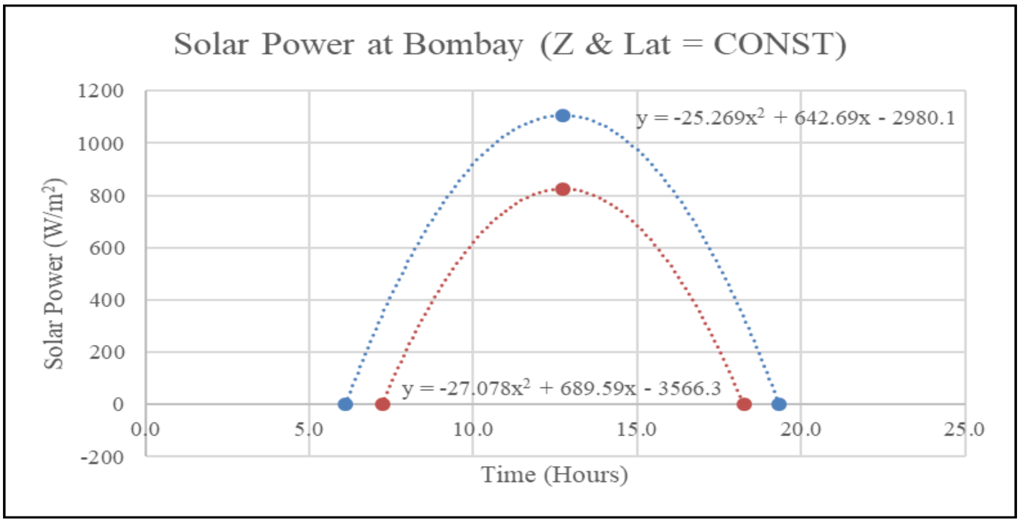


Figure 7-5: Solar power trend at latitude of 18.9 degrees

These two graphs reveal that although during the summer, the peak solar power is greater for the city at the lowest latitude, the energy, whose value is equal to the area under the curve, which the sun radiates during the day is greater for the cities at higher latitudes.

7.2.2. Sizing of Solar Array and Power Storage

Table 10: Input Needed to Size Solar Array and Power Storage

INPUTS		
η_c	Cell Efficiency	0.3
F_D	Degradation Factor	0.015
N_y	Service Years	(designer chosen)
η_s	Series Line Efficiency	0.98
η_p	Parallel Line Efficiency	0.96
η_B	Battery Efficiency	0.90
η_{LI}	Battery Input Line Efficiency	0.98
η_{LO}	Battery Output Line Efficiency	0.98
η_{sw}	Switch Input Output Efficiency	0.90
η_{FC}	Fuel Cell Efficiency	0.60
η_T	Electricity Transmission Efficiency	0.75

The case chosen for preliminary sizing of the electric propulsion system is relative to the period with the shortest daylight and therefore the lowest amount of solar power available throughout the year. Solar panels do not convert all solar power into electrical power due to the reflection of part of the sun's rays and the panels' heating. The value of the electrical power converted depends on the solar cells' efficiency. Some of last generation reach an efficiency of 30 per cent but are much more expensive, whilst commercial panels have an efficiency value of 20 per cent.

This means that considering maximum solar cell efficiency, from a thousand watts of solar power, only three hundred watts become useful for propulsive purposes without considering any other type of loss. The other seven hundred watts increase universal entropy. This explains why the electric propulsion system is valid for low speed.

A solar panel is not made up of a single cell, because each one generates 0.5 volts, but a set of them arranged in a series and in parallel to obtain the voltage and power required from the propulsion system, and the line that links the various cells is a source of further losses. To finish, the exposure of the solar panel with the external environment causes the panel's degradation and lowers its performance. Thus, efficiency value for sizing considers the end-of-life performances:

$$\eta_{SA} = \left(\eta_{cell} - F_D\, N_y\right)\eta_s \eta_p \qquad \text{(Equation 7-7)}$$

Multiply the solar power trend at the latitude chosen for the efficiency value of the equation above to obtain the trend of the extractable electric power with a specific solar array.

$$P_E = P_{S_{Lat}}\, \eta_{SA} \qquad \text{(Equation 7-8)}$$

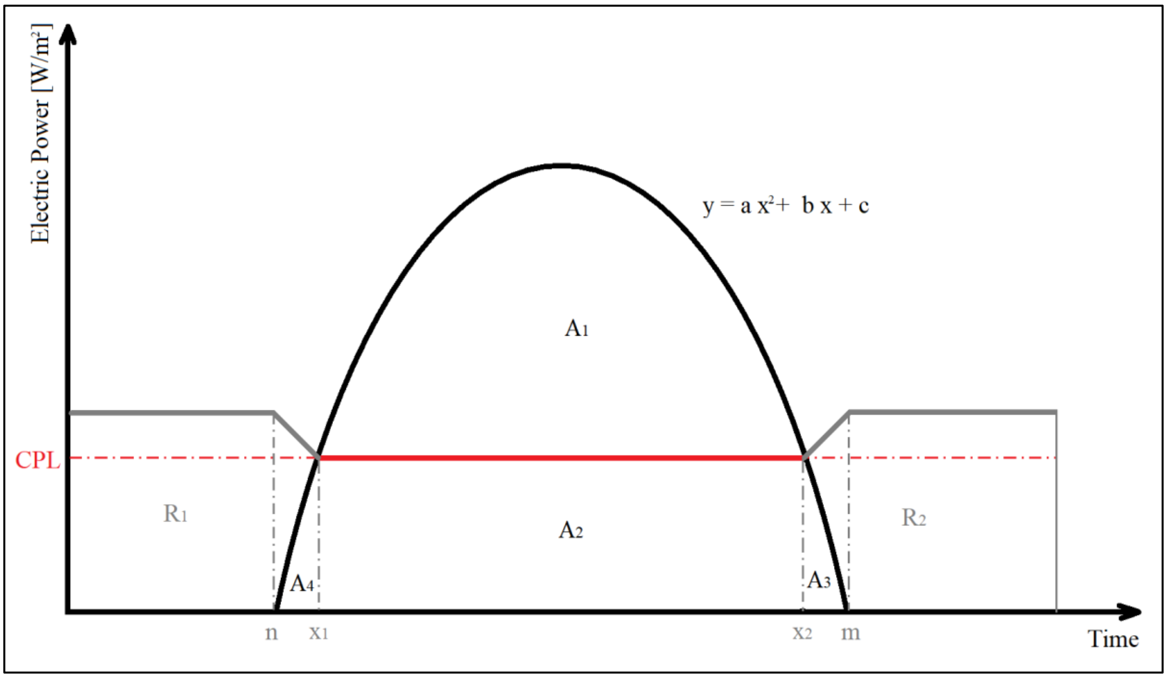


Figure 7-6: Scheme of electric power trend

Sizing of the propulsion system requires that part of the available electric power must cover the power required by the electric engines during the day, whilst the excess of energy ends up in the energy storage system to cover the required power during the night-time hours. It is an iterative process, and the first step is the choice of a power value called CPL that must ensure during the daytime that the airship has the power required; thus, the surface of the solar array is:

$$S_{SA} = \frac{P_R[W]}{CPL} \quad \text{(Equation 7-9)}$$

The next step is the calculation of excess energy per unit surface to be stored.

$$e_{Ex}\left[\frac{W\,h}{m^2}\right] = A_1 - A_2 \quad \text{(Equation 7-10)}$$

where area A_1 is obtained by solving the definite integral of the electric power function, and A_2 corresponds to the rectangular area:

$$\begin{cases} A_1 = \frac{a}{3}(x_2^3 - x_1^3) + \frac{b}{2}(x_2^2 - x_1^2) + \frac{c}{2}(x_2 - x_1) \\ A_2 = CPL(x_2 - x_1) \end{cases} \quad \text{(Equation 7-11)}$$

The x_1 and x_2 values are the intersection point on the horizontal axis between parabolic function and line:

$$x_{1/2} = \frac{-b \pm \sqrt{b^2 - 4a(c - CPL)}}{2a} \qquad \text{(Equation 7-12)}$$

Now the expression of excess energy stored is:

$$E_{Ex}[W\,h] = R_1 + R_2 = e_{Ex}\,S_{SA} \qquad \text{(Equation 7-13)}$$

Finally, the last step involves comparing this value with the value of the energy storage system, increased by a margin of 5 per cent:

$$E_{Ex} = 1.05\,E_S \qquad \text{(Equation 7-14)}$$

The amount of energy to be stored to satisfy the engine's power demand during the night depends on the efficiency of the energy storage system. Two main solutions are:

- Rechargeable batteries—convert chemical energy into electrical energy. Battery efficiency is relatively high. Thermal dissipation linked to the chemical reaction and electricity transfer from the solar panel, batteries, and engines represent the major losses. Moreover, another loss is related to the switch system that manages the input and output electricity.

  $$\eta_{BS} = \eta_B \eta_{LI} \eta_{LO} \eta_{sw} \eta_{sw} \qquad \text{(Equation 7-15)}$$

  Thus, battery power is:

  $$P_B = \frac{P_{R_{el}}}{\eta_{BS}} \qquad \text{(Equation 7-16)}$$

  whilst its energy value to compare with (Equation 7-14) is:

  $$E_S = E_B = P_B\big(24 - (x_2 - x_1)\big) \qquad \text{(Equation 7-17)}$$

- Fuel cells—generate electricity from chemical energy by reacting to hydrogen and oxygen, generally a fuel and an oxidizing. The reaction product, during the night, is water that can be stored in the tank, and during the day excess energy divides it into hydrogen and oxygen with electrolysis. However, losses of this system are higher than the battery system, and they are relative to the fuel cell component and the electricity transmission.

$$\eta_{FCS} = \eta_{FC}\eta_T \qquad \text{(Equation 7-18)}$$

Finally, power and therefore energy value, respectively, are:

$$P_{FC} = \frac{P_{R_{el}}}{\eta_{FCS}} \qquad \text{(Equation 7-19)}$$

$$E_S = E_{FC} = P_{FC}\big(24 - (x_2 - x_1)\big) \qquad \text{(Equation 7-20)}$$

If compared, both systems have strengths and weaknesses, and the choice of one rather than the other depends on the requirements and constraints imposed by the stakeholders.

Table 11: Batteries and Fuel Cell Comparison

Rechargeable Batteries	**Fuel Cell**
Easy to install	High complexity
Higher system efficiency	Lower system efficiency
Discharge cycle limit	Unlimited use
Higher weight	Lower weight

7.3. Initial Propeller Sizing

This element transforms the engine power in thrust. Geometric and performance parameters such as diameter and efficiency are the objective of the propeller preliminary sizing. Indeed, in absence of efficiency value, it is equal to 0.7 (typical propeller efficiency value of the aircraft).

Main propeller elements (

Figure 7-7) are blades that generates thrust and the hub to which they are connected. Typically, a nose cone covers the hub to reduce drag.

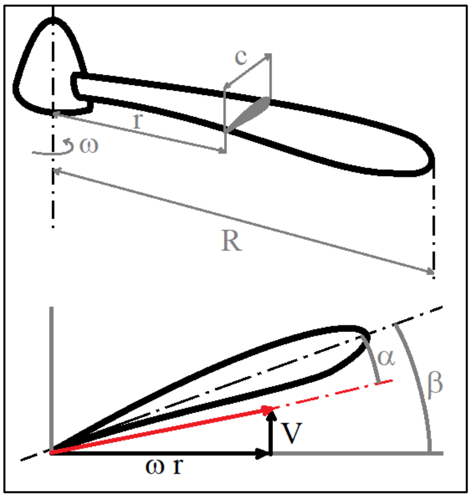


Figure 7-7: Propeller diagram

In the figure above, β is the geometric bending angle, α is local incidence, and the difference between these angles is aerodynamic bending angle φ. Then ω is angular speed. Efficiency depends on airship speed and propeller diameter, and these parameters are included in the advanced ratio:

$$J = \frac{V}{\omega D} \qquad \text{(Equation 7-21)}$$

Without deepening the argument, the figure below shows typical efficiency trends varying with advanced ratios:

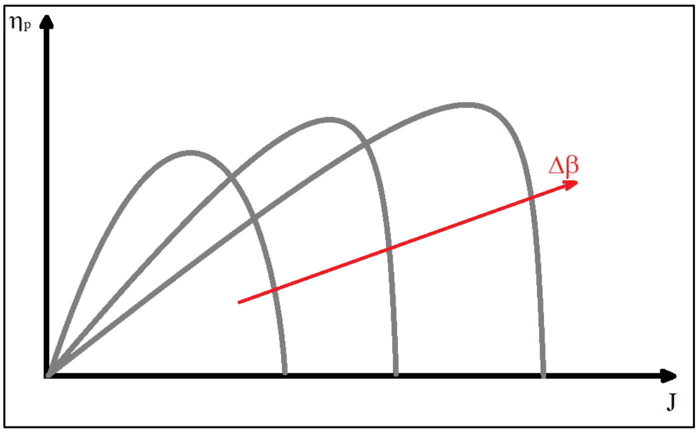


Figure 7-8: Efficiency trend

Two types of propellers are:

- Fixed-pitch propeller—Blades are welded to the hub, and the geometry cannot vary. They are very simple to build, weigh little, and require little maintenance, but efficiency is maximum for only the flight condition.
- Variable-pitch propeller—The engine works at constant rpm of about 600 from existing aircraft data, because blades can vary their geometric bending angle to maintain high efficiency in every flight condition (Figure 7-8). Disadvantages are high cost and weight, high construction complexity, and more maintenance than fixed-pitch propellers.

In this project, the choice is for the variable-pitch propeller to ensure high performance during all flight phases.

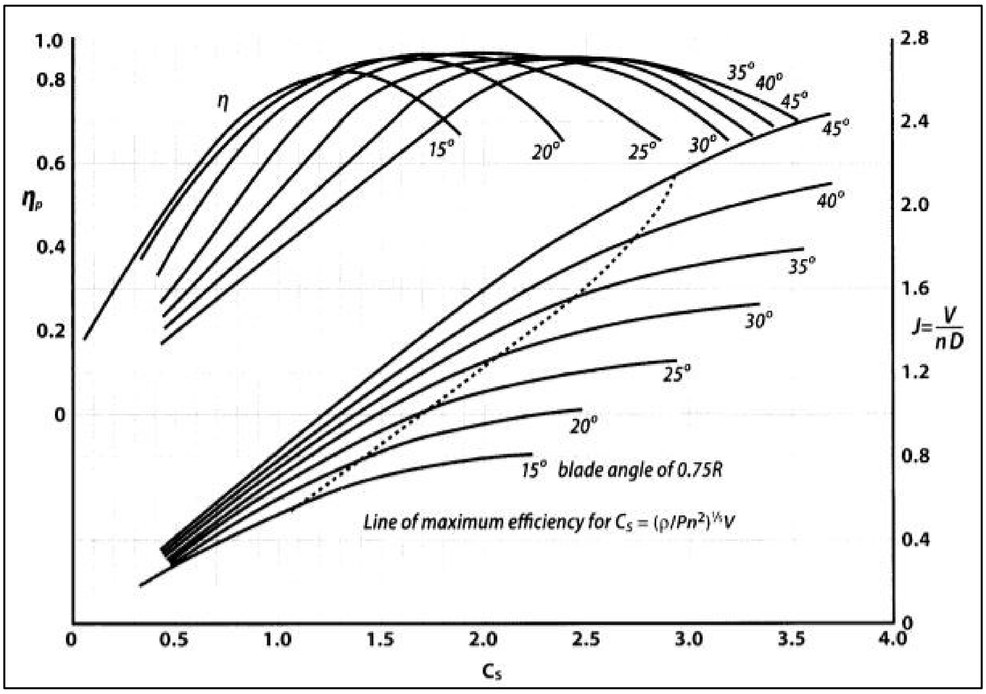


Figure 7-9: Design chart for propeller [8][1]

The first step to calculate diameter and propeller efficiency consists of estimations through Figure 7-9 power coefficients:

$$C_S = \left(\frac{\rho[slug/ft^3]}{\omega[rps]^2 \frac{P_{R_{SL\_max}}[ft\ lb/s]}{N_e}} \right)^{1/5} V_{max}[ft/s] \qquad \text{(Equation 7-22)}$$

[1] Source: (Carichner & Nicolai, 2013)*Airship Design and Case Studies Vol. 2*, chapter 5: Propeller Sizing Figure 5.9b—Design chart for a three-bladed propeller using a Clark-Y airfoil section, 2013:(l, 12).

Then advanced ratio and propeller efficiency must be estimated through an equation of line of maximum efficiency (

Figure 7-9) that links them with the power coefficient:

$$J = 0.156\ C_S^2 + 0.241\ C_S + 0.138 \qquad \text{(Equation 7-23)}$$

$$\eta_p = 0.139\ C_S^3 - 0.749\ C_S^2 + 1.37\ C_S + 0.0115 \qquad \text{(Equation 7-24)}$$

Finally, through (Equation 7-21) it is possible to calculate diameter value, useful later to estimate the weight.

$$D = \frac{V_{\max}[ft/s]}{\omega[rps]^2 J} \qquad \text{(Equation 7-25)}$$

Chapter 8

8. Preliminary Weights Estimate

Weight analysis of an aircraft represents a fundamental point in the design process. An approximate estimate of the maximum take-off weight and operative empty weight has been carried out through the previously executed statistical analysis based on existing airships. However, a more precise calculation of the weight systems that make up the airship and fuel weight provides useful data to initiate more detailed analyses such as stability and control, tail sizing, detailed envelope diagrams, and others. A fundamental output of this preliminary design phase depends heavily on the weight value obtained during this analysis. It is the gas volume needed to balance airship weight, and its value has great influence on the aircraft size.

Moreover, a good project aims to reduce the aircraft weight, decreasing the overall cost and increasing performance.

Preliminary weight estimation consist of calculating the maximum take-off weight in two ways. The first uses the performance method, whilst the second calculates the airship system's weight or operative empty weight. Both maximum take-off weight values obtained by these two methods depend on the volume gas. Thus, for a single value of gas volume, two weights calculated below are equal, and analysis ends.

8.1. #1 - Performance Method

This method estimates the maximum take-off weight using the weight's expression that composes it as a function of the performance parameters indicated in the table below.

Table 12: Input Needed for Performance Method

INPUT	
V_{gas}	Gas Volume
η_p	Propeller Efficiency
C_{D0}	Zero Lift Drag Coefficient
K	Factor of Total Drag Due to Lift
BSFC	Break Specific Fuel Consumption
Z	Altitude
σ	Ratio between Altitude Air Density and Sea Level Air Density
V_{cruise}	Cruise Speed
q_{cruise}	Dynamic Pressure at Cruise Speed and Altitude
V_{max}	Maximum Speed
R	Range
BR(landing)	Buoyancy Ratio at Landing
W_{FR}	Fuel Reserve Weight
W_P	Payload Weight

The starting equation to determine the maximum take-off weight is the following:

$$MTOW_{\#1} = W_{ZF} + W_F + W_{FR} \quad \text{(Equation 8-1)}$$

where W_{ZF} is zero fuel weight, W_F is fuel weight, and W_{FR} is fuel reserve weight.

8.1.1. Zero Fuel Weight

This corresponds to the airship weight loaded with payload but totally fuel free, or else this is the airship weight at landing, with fuel terminated and without considering the fuel reserve weight.

$$W_{ZF} = W_{land} - W_{FR} \quad \text{(Equation 8-2)}$$

where landing weight W_{land}, is balanced totally or partly from the buoyant lift generated by the gas depending on the BR at landing value. In partial cases, the aero lift generated by the aerodynamic envelope shape balances the remaining weight. The advantage of having a BR at landing of less than one emerges during the taxi phase and anchorage to the ground. Indeed, setting the aircraft incidence equal to zero, aerodynamic lift becomes null. Thus, the resultant downforce keeps the airship and allows it to carry out ground manoeuvres.

$$W_{land} = \frac{B_{lift}}{BR_{land}} \qquad \text{(Equation 8-3)}$$

A gas generates the buoyant lift when its density is less than the fluid surrounding it.

$$B_{lift} = gas_{force}Vol_{gas} = (\rho_{air} - \rho_{gas})g\ Vol_{gas} \qquad \text{(Equation 8-4)}$$

The last weight obtainable from the zero fuel weight is operative empty weight. It includes the weight of all systems and subsystems that compose it. Therefore, it corresponds to the working airship which lacks payload and fuel to start.

$$W_{OE} = W_{ZF} - W_P \qquad \text{(Equation 8-5)}$$

8.1.2. Fuel Weight

Fuel weight is a value that depends strongly on the choice made by the designer during requirements analysis and depends on many performance parameters such as engine fuel consumption, range or distance covered from airship during travel, cruise speed, airship total drag, propeller efficiency, altitude, gas volume, and payload weight. Of course, an airship does not have to finish its fuel at the end of the travel but must have a reserve fuel for any eventuality. A margin of 6 percent is more than enough for this type of aircraft.

$$W_{FR} = 6\%\ W_F \qquad \text{(Equation 8-6)}$$

The program described in chapter 9 has allowed the collection of several items of data, including fuel reserve for different configurations. Drawing the chart of fuel reserve weight depends on range and payload parameters.

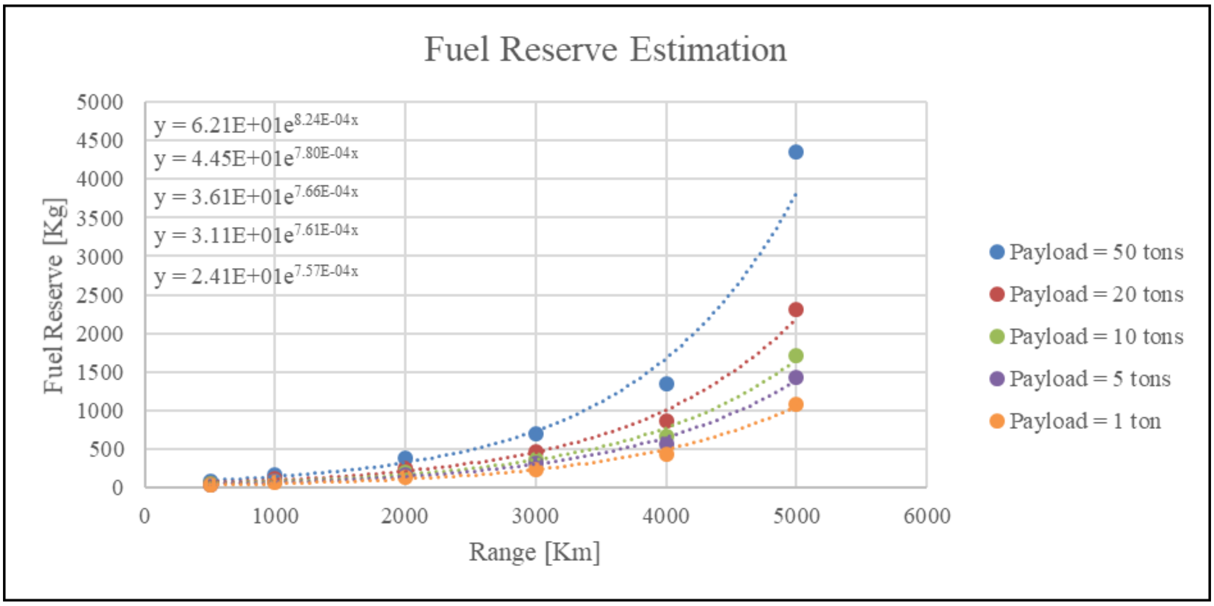


Figure 8-1: Fuel reserve estimation

The chart above shows that fuel reserve weight increases in an exponential way as the range increases. Its growth rapidity depends on the payload value.

The next step is fuel weight estimation. The way to calculate it involves the use of heaviness that indicates airship weight, which is not balanced from the buoyant lift but from aero lift. When the airship does not generate the aerodynamic lift because its incidence corresponds to the zero lift angle, a portion of weight initially balanced now becomes ballast or heaviness. The most important heaviness values are relative to the landing and take-off phases, in the two opposite flight phases. Subtract these values to obtain the fuel weight since the aerodynamic lift, which is equal to the heaviness, balances the fuel weight in the hybrid airship during all of flight time.

$$W_F = W_{H0} - W_{H1} \quad \text{(Equation 8-7)}$$

Therefore, heaviness at landing is:

$$W_{H1} = L_{aero} = W_{land} - B_{lift} \quad \text{(Equation 8-8)}$$

(Equation 6-26) describes heaviness at take-off. The equation follows the tangent trend; thus, for arguments values of a few degrees fuel grow slightly, whilst if the argument assumes values close to ninety degrees, which corresponds to the function asymptote, fuel weight increases exponentially, as shown in the figure below. Having an angle greater than ninety degrees has no physical sense because fuel weight cannot be negative.

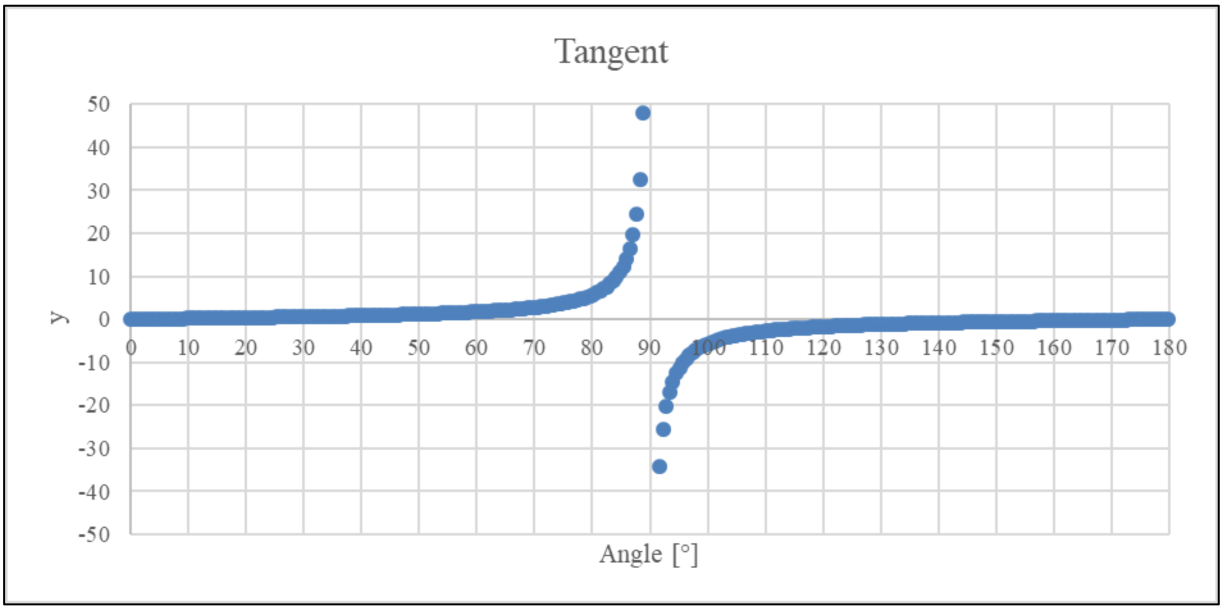


Figure 8-2: Tangent function

Moreover, payload and range are some of parameters that make up the tangent argument, and this explains the fuel reserve trend in Figure 8-1.

8.2. #2 - Weight Build-Up Method

The main equation to obtain the maximum take-off weight is:

$$MTOW_{\#2} = W_{OE} + W_P + W_F + W_{FR} \qquad \text{(Equation 8-9)}$$

where payload weight is the input of the stakeholders, whilst equations of the fuel weight and its reserve are shown in the previous paragraph. The difference is in the operative empty weight expression. This method breaks it down into terms of the main airship's macro systems by calculating weights for each of them, as shown in the equation below:

$$W_{OE}[lb] = W_H + W_T + W_{Gond} + W_{PS} + W_{Av} + W_{El} + W_{LG} + W_{Serv} + W_{uf} + W_{Margin}$$

(Equation 8-10)

8.2.1. Hull Weight

The hull is the largest element of the airship, and in the case of a rigid airship, it consists of the following elements, starting from the outside: outer skin or external envelope, internal framework, and gas balloons.

- Outer skin is the element that isolates the internal environment of the airship from the outside. It is in tension on the rigid structure to act as an aerodynamic surface. The choice of material is important since the outer skin has to withstand the aerodynamic loads that act on it. Fortunately, the material evolution, with introduction of new fibres and resins, makes this element resistant and light at the same time when compared to previous materials. The fabric chosen for this project is vectran laminated, which has triplicated mechanical characteristics and half the weight compared with early Zeppelins that used rubberised cotton.

  $$w_{vectran(laminated)} = 7.6\,\frac{oz}{yd^2} = 0.258\,\frac{Kg}{m^2} \qquad \text{(Equation 8-11)}$$

  To obtain the weight of the fabric applied to the airship, multiply the surface density of the material with the external surface of the ellipsoid computed by (Equation 3-7):

  $$W_{ES} = w_{material}\, S_{ell} F_{MA} \qquad \text{(Equation 8-12)}$$

  where F_{MA} is the manufacturing and assembly factor that accounts for the doublers and joints and is equal to 1.2.

- Internal framework consists of a grid of rings and longitudinal elements that maintain the aerodynamic shape of the hull, contain gas balloons, and withstand concentrated loads. The choice of the grid material requires two features: high mechanical performances and low weight. Generally, aeronautical aluminium alloys are the material used for the grid, but in this project, it is possible to use carbon composite since the economic requirement belongs to the secondary requirements category. Carbon composite is more expensive than aluminium alloys but at the same time has superior mechanical performances and low density:

$$\rho_{carb.comp.} = 2100\frac{Kg}{m^3}$$

In the first approximation from comparative analyses with existing airships, the number of rings is such that three elements enclose one gas balloon, thus:

$$N_R = N_{GB} + 1 \qquad \text{(Equation 8-13)}$$

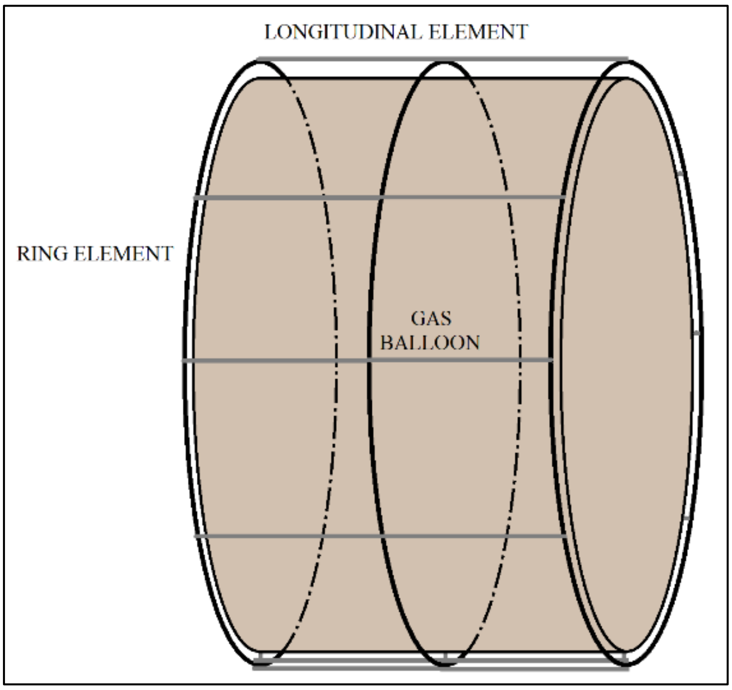


Figure 8-3: Gas balloon enclosed between ring and longitudinal elements

To simplify the calculation to determine the rings' weight, the diameter of each of them remains constant and equal to the maximum diameter of the airship. This is a conservative assumption since in reality the diameter decrease to the extremities to follow the shape and weight of the rings is lower than the one calculated. Thus, the weight of all rings is:

$$W_R = N_R l_R S_{sec} \rho_{material} \quad \text{(Equation 8-14)}$$

where l_R is the circumference length of the ring:

$$l_R = \pi d \quad \text{(Equation 8-15)}$$

Finally, S_{sec} is the cross section for grid elements. Empirical expression derives from the statistical analysis of some airships made by the Euro Airship Company, which has kindly offered its confidential data, and for this reason the paper does not show the passages but only the final equation:

$$S_{sec}[m^2] = 8.33 * 10^{-9} W_P[Kg] + 1.03 * 10^{-4} \quad \text{(Equation 8-16)}$$

Whilst the weight of longitudinal elements is:

$$W_L = N_L l_L S_{sec} \rho_{material} \quad \text{(Equation 8-17)}$$

where N_L is the number of longitudinal elements that permit a distance between two adjacent longitudinal elements on the ring, equal to the gas balloon length.

$$N_L = \frac{l_R}{l_{GB}} \quad \text{(Equation 8-18)}$$

L_L indicates length of a single longitudinal element. Its shape is approximate to the semi-perimeter of the maximum ellipse obtained from an ellipsoid.

$$l_L = \frac{P_{ellipse}}{2} \cong \frac{2\,\pi\sqrt{\left(\frac{l}{2}\right)^2 + \left(\frac{d}{2}\right)^2}}{2} \quad \text{(Equation 8-19)}$$

The total weight of the internal framework is:

$$W_{IF} = (W_R + W_L) F_{MA} F_A \quad \text{(Equation 8-20)}$$

where F_A is the attached factor that accounts for a linked structure between framework and gas balloons and is equal to 2.6.

- Gas balloons are the elements that contain the buoyant gas, generally helium. Since it is expensive, these balloons must be resistant, and fluid must not leak out. Good material for this task is the same as the external skin (vectran). The best form to guarantee the maximum gas tightness is the sphere, but it is not the form used because of the space required. Thus, the choice falls to the cylindrical solution because of the absence of empty space between two gas balloons, and consequently less space is required. Thus, the weight of gas balloons is:

$$W_{GB} = N_{GB} S_{GB} w_{material} F_{MA} F_A \qquad \text{(Equation 8-21)}$$

The number of gas balloon from historical data (Figure 8-4) depends on fineness ratio. This value may not be too small; otherwise, each gas balloon would have a high volume of buoyant gas with an increase of leaking:

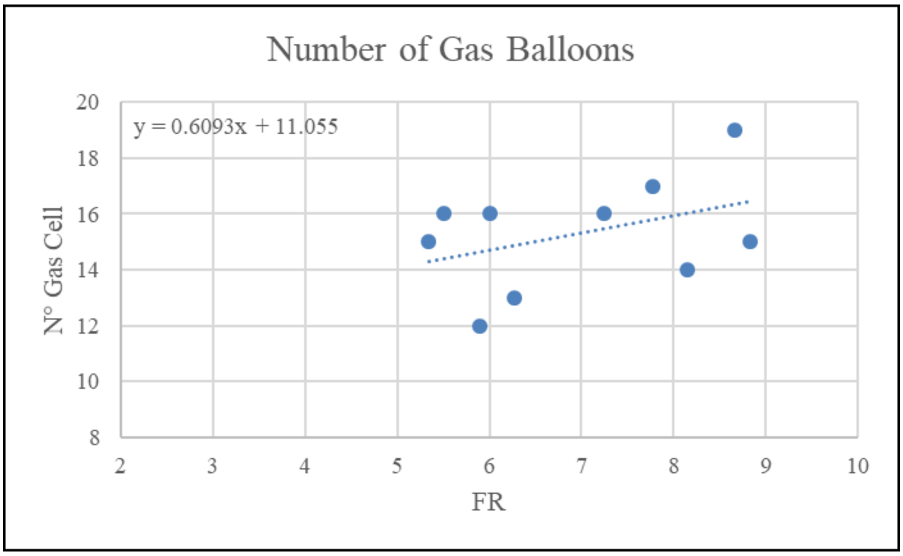


Figure 8-4: Number of gas balloons chart

$$N_{GB} = int(0.61\ FR + 11.05) - 4 \qquad \text{(Equation 8-22)}$$

The number is rounded to the next integer and then is subtracted by four to consider the material's evolution compared to those used to contain the gas related to the old airship present in the statistics.
The equation of cylindrical surface, S_{GB}, corresponds to the sum of two bases, cylinder and lateral surface:

$$S_{GB} = 2\pi \left(\frac{d_{GB}}{2}\right)^2 + \pi d_{GB} l_{GB} \qquad \text{(Equation 8-23)}$$

d_{GB} is the diameter of a gas balloon; that is smaller than the maximum envelope diameter of 15 per cent. Thus, all balloons find the housing even at the ends of the ellipsoid, where the section is smaller.

$$d_{GB} = d(1 - 0.15) \quad \text{(Equation 8-24)}$$

Now the calculation of the gas balloon length derives from knowing the maximum volume of each one:

$$Vol_{GB} = \frac{Vol_{gas}}{N_{GB}} = 2\pi\left(\frac{d_{GB}}{2}\right)^2 l_{GB} \quad \text{(Equation 8-25)}$$

Thus:

$$l_{GB} = \frac{Vol_{gas}/N_{GB}}{2\pi\left(\frac{d_{GB}}{2}\right)^2} \quad \text{(Equation 8-26)}$$

Finally, the total hull weight is the sum of (Equation 8-12), (Equation 8-20) and (Equation 8-21):

$$W_H = W_{ES} + W_{IS} + W_{GB} \quad \text{(Equation 8-27)}$$

8.2.2. Tail Weight

Tail empennage has a horizontal and a vertical element. Both consist of a fixed part and mobile part managed by an actuator. The constructive method is typical of aeronautical structure; that is the use of semi shell structures in light aeronautical materials.

$$W_T = W_F + W_M + W_A \quad \text{(Equation 8-28)}$$

Where the fixed parts have the following expression:

$$W_F[lb] = (S_{Tail} - S_M)[ft^2]\, F_{AF} F_{WST} \left[\frac{lb}{ft^2}\right] \quad \text{(Equation 8-29)}$$

Where S_{Tail} is the total tail surface plan:

$$S_{Tail} = S_{HT} + S_{VT} \quad \text{(Equation 8-30)}$$

Whilst in first approximation, the mobile control surface is about 20 per cent of the total tail surface plan:

$$S_M = 0.2\, S_{Tail} \qquad \text{(Equation 8-31)}$$

where F_{AF} is the factor that considers the possible presence of external structural cables linking the fixed part of the empennages to the envelope and is equal to 1.26. F_{PSQ} indicates the aeronautical material weight of the tail's external surface depending on dynamic pressure value:

$$\begin{cases} q_{max} < 1\dfrac{lb}{ft^2} \rightarrow F_{WST} = F_{Act} = 0.08\dfrac{lb}{ft^2} \\ 1\dfrac{lb}{ft^2} < q_{max} < 10\dfrac{lb}{ft^2} \rightarrow F_{WST} = F_{Act} = 0.08(2 - q_{max}) \\ q_{max} > 10\dfrac{lb}{ft^2} \rightarrow F_{WST} = F_{Act} = 0.80\dfrac{lb}{ft^2} \end{cases} \qquad \text{(Equation 8-32)}$$

The weight of the mobile tail part is:

$$W_M = S_M F_{WST} \qquad \text{(Equation 8-33)}$$

Finally, the actuator weight has the following expression:

$$W_A = S_M F_{Act} F_{Inst} \qquad \text{(Equation 8-34)}$$

Where F_{Act} is the actuator factor that accounts for the dimension of this system depending on dynamic pressure, as shown in (Equation 8-32). The installation factor, equal to 1.15, considers connections and housing.

8.2.3. Gondola Weight

This is the element in which payload, crew, and systems are accommodated. Depending on the payload weight, three categories of gondola exist to have a preliminary estimate weight of this element.

- Light gondola—It is small, generally unmanned, and can carry a maximum payload of one thousand pounds. The empirical equation to estimate gondola weight is:

$$W_{Gond} = 0.15\, W_P \qquad \text{(Equation 8-35)}$$

- Medium gondola - It can transport a payload value between one thousand and four thousand pounds and has three compartments: the control cabin for crew, payload, and systems cabin. The equation to determine gondola weight provides a minimum knowledge of its geometry.

$$W_{Gond}[lb] = 353\left(\left(\frac{l_g[ft]}{10}\right)^{0.857}\left(\frac{d_g + h_g}{10}\right)[ft]\left(\frac{V_{max}[knt]}{10}\right)0.338\right) \quad \text{(Equation 8-36)}$$

l_g, d_g, and h_g parameters indicate, respectively, length, width, and height.

- Heavy gondola -This is the useful category for this project because it considers payload with weight greater than four thousand pounds. The empirical equation is:

$$W_{Gond} = 1.875\, S_{Gond} + W_{Crew} + W_{Syst} \quad \text{(Equation 8-37)}$$

where S_{Gond} indicates the gondola surface, including the walkable surface and four sides, imagining it as a rectangular parallelepiped (Figure 11-7. Thus, the total surface is:

$$S_{Gond}[ft^2] = l_g d_g + 2 l_g h_g + 2 d_g h_g \quad \text{(Equation 8-38)}$$

To calculate weight of crew and systems compartments, (Equation 8-37). From statistical data, their surface is about 30 per cent of the walkable gondola surface. This expression is also valid for the length because the assumption of the rectangular parallelepiped as the shape of the gondola means that dimensions of width and height are constants; thus, dimensions to calculate the weight of crew and systems are:

$$\begin{cases} l_{C+S} = 30\%\, l_g \\ d_{C+S} = d_g \\ h_{C+S} = h_g \end{cases} \quad \text{(Equation 8-39)}$$

8.2.4. Propulsion System Weight

A propulsion system represents a substantial fraction of the airship's operative empty weight, independent of whether the system to generate power is electric or uses fuel combustion.

- Fuel propulsion systems consist of the blade and engine unit, the support structure that links the engine with the gondola or envelope, fuel tanks, engine control unit, and the electric starter system. The equation below shows all weight components:

$$W_{PS} = W_{eng} + W_{str} + W_{FT} + W_{EC} + W_{prop} + W_{ESS} \quad \text{(Equation 8-40)}$$

Through the collection of the power and weight values of various types of existing engines, a trend line is possible to generate from which the weight can be calculated by entering in the chart the power required from one engine. The trend line equation is:

$$W_{1eng}[lb] = 4.848\ P_{R1eng}[hp]^{0.7956} \qquad \text{(Equation 8-41)}$$

Thus, the total weight of the engines is:

$$W_{eng} = N_{eng} W_{1eng} \qquad \text{(Equation 8-42)}$$

The alternative is to find and engine on the market with the required power from the project and extract the weight from the technical datasheet.
Weight of the support structure and its installation has the following equation:

$$W_{str} = F_{str} W_{eng} \qquad \text{(Equation 8-43)}$$

where the installation factor F_{str} varies depending on the type of engine and the connection point:

$$\begin{cases} F_{str} = 0.57 \rightarrow Combustion\ engine\ mounted\ on\ the\ gondola \\ F_{str} = 0.64 \rightarrow Combustion\ engine\ mounted\ on\ the\ hull \\ F_{str} = 1.2 \rightarrow Electric\ engine\ mounted\ on\ the\ hull \end{cases} \qquad \text{(Equation 8-44)}$$

The fuel tank system has three main weight contributes: tanks, fuel pumps, and fuel line. Having the tanks close to the engines reduces the length and consequently the weight of the fuel lines and of the fuel pumps. Generally, tanks are inside the gondola; thus, the best solution is to have engines mounted on the gondola. However, the empirical equation to estimate the weight of the fuel tanks is:

$$W_{FT}[lb] = 2.49(Vol_F[gallons])^{0.6} N_{FT}^{0.2} N_{eng}^{0.13} \qquad \text{(Equation 8-45)[1]}$$

N_{FT} is the number of fuel tanks.
The equation to estimate the weight of the engine control unit is:

[1] Fuel volume is obtained from fuel weight and density of typical aeronautical fuel in tTable 19.

$$W_{EC}[lb] = 60.27 \left(\frac{l_{EC}[ft] N_{eng}}{100}\right)^{0.724} \quad \text{(Equation 8-46)}$$

where l_{EC} is the distance between the control room and the most distant engine, to be conservative.
Propeller weight has the following equation:

$$W_{prop}[lb] = 31.92\ N_{prop} N_{blade}^{0.391} \left(\frac{D P_{1eng}[hp]}{1000}\right)^{0.782} \quad \text{(Equation 8-47)}$$

The number of propellers is equal to the number of engines, whilst the number of blades is assumed to equal three. D is the propeller diameter.
The last one is the electric starter system, whose equation to estimate the weight is:

$$W_{ESS}[lb] = 50.38 \left(\frac{N_{eng} W_{1eng}[lb]}{1000}\right)^{0.459} \quad \text{(Equation 8-48)}$$

- Electric propulsion system - The total weight of the electric propulsion system is made up of the weight of the propeller and electric engine group, the support structure, and engine control unit. Tanks and electric starter systems, typical of the fuel propulsion system, are missed here, but the solar panel and energy storage system appear as new weights.

$$W_{PS} = W_{eng} + W_{str} + W_{EC} + W_{SA} + W_{ES} \quad \text{(Equation 8-49)}$$

The table below, of the specific energy, allows one to determine the weight of engines, solar array, and storage system. Values indicate the ratio between the power or energy of the components and their weights. The element is performing if this value is high.

Table 13: Specific Energy

Specific Energy		
Electric Motor	0.2	KW/lb
Fuel Cell	0.89	KW h/lb
Battery	0.336	KW h/lb

Thus, engine weight is:

$$W_{eng} = \frac{P_{R_{el}}[KW]}{60\%\ SE_{eng}} \qquad \text{(Equation 8-50)}^{1}$$

Whilst the weight of the solar array and energy storage system, battery, or fuel cell is:

$$W_{SA}[lb] = w_{SA}\left[\frac{lb}{ft^2}\right]S_{SA} \qquad \text{(Equation 8-51)}$$

$$\begin{cases} W_{ES_{battery}} = \dfrac{E_{Ex}}{SE_{batt}} \\ W_{ES_{fuelcell}} = \dfrac{E_{Ex}}{SE_{fuelcell}} \end{cases} \qquad \text{(Equation 8-52)}$$

where w_{SA} is the installed surface weight of the solar array and is equal to 0.1, considering new solar array technologies. S_{SA} is solar array surface (Equation 7-9), and E_{Ex} is the excess energy (Equation 7-13).
The weight of the support structure is:

$$W_{str} = F_{str}W_{eng} \qquad \text{(Equation 8-53)}$$

where F_{str} is the factor of the third case in (Equation 8-44).
The engine control unit has the same expression (Equation 8-46) seen in the case of the fuel propulsion system.

[1] Sixty per cent value indicates that an engine at 60 per cent of its maximum power can guarantee the airship the power required. Therefore, an engine will never be under stress and will have a longer operational life.

8.2.5. Avionics and Electric System Weight

Two ways exist to calculate the weight of the avionic and electronic equipment. The first plan requires searching on the market for the useful equipment for the airship and collecting the weight from each manually. The alternative, in case of a preliminary design, involves the use of a statistical equation based on existing rigid airships.

$$W_{Av} = 3\%\ W_{OE} \qquad \text{(Equation 8-54)}$$

An electric system requires the management and distribution of electric currents for utilities and instruments onboard.

$$W_{El} = K_{El}(W_{Av})^{0.51} \qquad \text{(Equation 8-55)}$$

where K_{El} is the factor account of range and payload value:

$$\begin{cases} K_{El} = 12.57 \rightarrow Low\ range\ and\ payload \\ K_{El} = 33.75 \rightarrow High\ range\ and\ payload \end{cases}$$

8.2.6. Landing Gear Weight

Classic landing gear and air cushion landing gear are two possible solutions. Generally, airships mount a single landing gear, and a structure keeps it locked for ground operation, but a tricycle landing gear configuration allows the hybrid airship to land as if it is a plane. The equations below permit obtaining the landing gear weight for single or tricycle configurations:

$$W_{LG} = K_{LG}\left(\frac{2\ W_{H0}[lb]}{1000}\right)^{0.84} \qquad \text{(Equation 8-56)}$$

where:

$$\begin{cases} K_{LG} = 24.2 \rightarrow single\ landing\ gear \\ K_{LG} = 31.2 \rightarrow tricylce\ landing\ gear \end{cases} \qquad \text{(Equation 8-57)}$$

8.2.7. Crew and Passenger Services Weight

This term includes all services necessary to accommodate passengers onboard the airship. Since the main requirement provides the realisation of a luxury aircraft, weight of this category will be high. Main services are:

- Seats
- Lavatories
- Food
- Water
- Beds

Thus, the total weight for crew and passenger accommodation is:

$$W_{Serv} = W_{seats} + W_{lav} + W_{food} + W_{water} + W_{beds} \quad \text{(Equation 8-58)}$$

Statistical equations to estimate the seats' weight is:

$$W_{seats}[lb] = F_{Lux}K_{seat}N_{guest} + K_{seat}N_{crew} \quad \text{(Equation 8-59)}$$

where N_{guest} indicates the number of guests and N_{crew} the number of crew people. F_{Lux} is the luxury factor specific to the class of luxury airship, and its value is two, whilst K_{seat} is the ergonomic factor:

$$F_{Lux} = 2$$

$$\begin{cases} K_{seat} = 55 \rightarrow flight\ deck\ seats \\ K_{seat} = 32 \rightarrow reclining\ passenger\ seats \\ K_{seat} = 17\ for\ troop\ seats \end{cases}$$

Of course, for guests, the ergonomics factor must be maximum, whilst it may be lower for the crew seats.
The equation to determine the lavatories' weight is:

$$W_{lav}[lb] = F_{Lux}K_{lav}\left(N_{guest} + N_{crew}\right)^{1.33} \quad \text{(Equation 8-60)}$$

where:

$$\begin{cases} K_{lav} = 5.6 \rightarrow long\ range \\ K_{lav} = 2.3 \rightarrow short\ range \end{cases}$$

For food and water, the statistical equation is the same:

$$W_{food}[lb] = W_{water} = 5.06\left(F_{Lux}N_{guest} + N_{crew}\right)N_{days} \quad \text{(Equation 8-61)}$$

Finally, the equation to calculate the weight of the beds is:

$$W_{beds}[lb] = 28\ (F_{Lux} N_{guest} + N_{crew}) \quad \text{(Equation 8-62)}$$

8.2.8. Unusable Fuel and Empty Weight Margin

This category includes weights related to fluids that remain on the airship (for example, the fuel in the transmission lines from tanks to engines, oils, and refrigerant fluids). Moreover, a conservative margin is applied on the operative empty weight due to the uncertainties and approximations of the results.

Thus, the equations are:

$$W_{uf} = 0.01\ W_F \quad \text{(Equation 8-63)}$$

$$W_{margin} = 6\%\ W_{OE} \quad \text{(Equation 8-64)}$$

Chapter 9

9. Excel Program: RAsDEx 1.1

9.1. Introduction

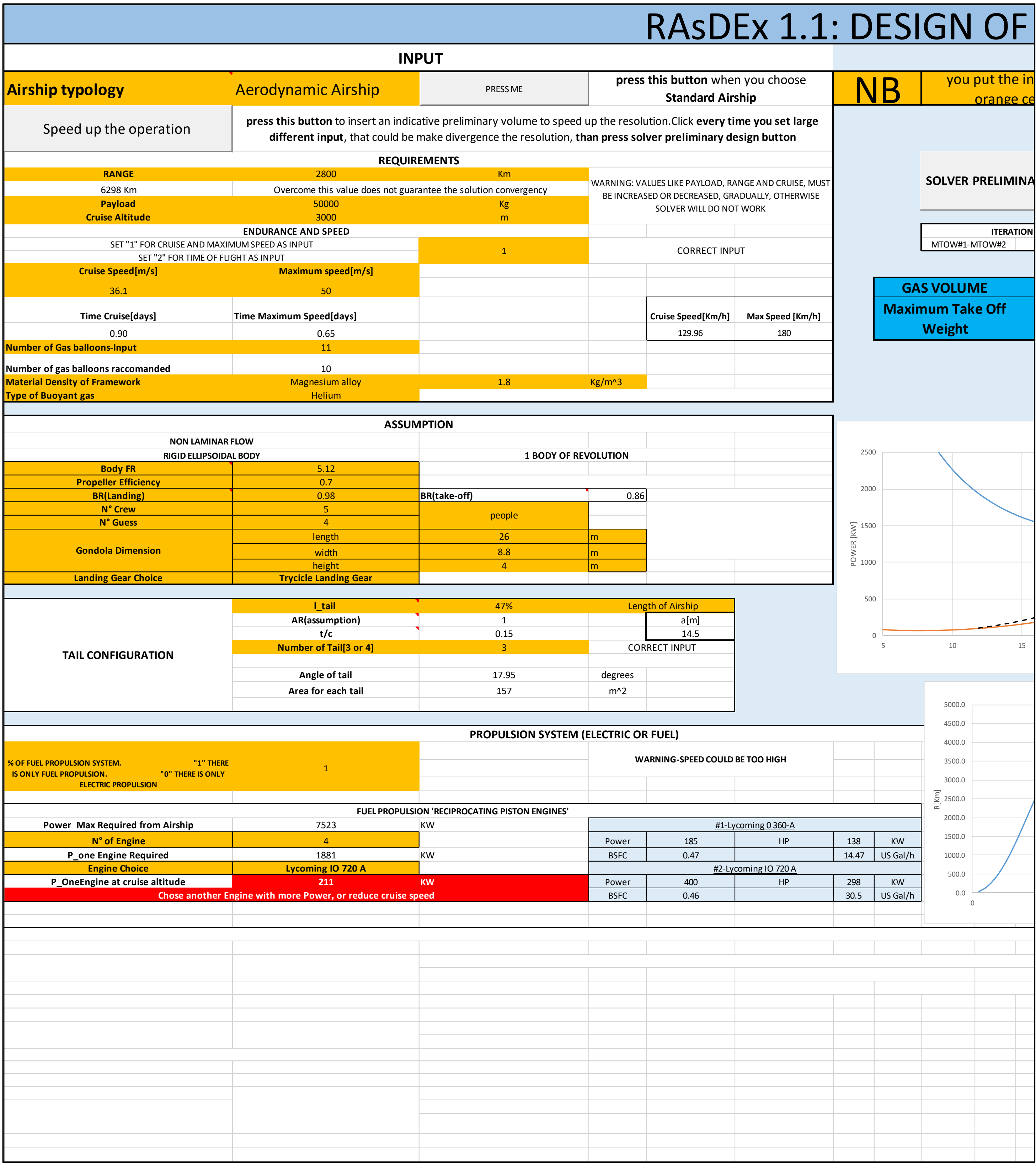
A multidisciplinary project like this needs a large amount of data and information. During the preliminary design phase, the input data change frequently, and a manual updating of all parameters connected to them would require a huge use of resources such as time and energy. Thus, the best option is to make a program in which a user can insert inputs to start analysis, and it automatically reveals the presence of errors in the input by reporting them and otherwise provides the output.

The software chosen as the basis for the implementation of the program is Excel because of its wide use in computers and companies to increase the ability to consult, modify, and share data. The name chosen for the program is the acronym RAsDEx, or Rigid Airship Preliminary Design based on Excel Program. The current program version can provide outputs with a respectable accuracy for the following airship configurations:

- Rigid airship
  - Fuel propulsion system
    - Hybrid lift category (BR < 1)
  - Electric propulsion system;
    - Only buoyant lift category (BR = 1)
    - Fuel cell
    - Batteries

The program structure follows the Excel logic; thus, it is divided into eight worksheets each of which carries out its function. First is the INPUT-OUTPUT sheet, which provide the graphic interface to insert inputs and to see outputs, as shown in

Figure 9-1. This sheet is the only one that interest the user. In the last paragraph of this chapter, the input and output are discussed.



RAsDEx 1.1: DESIGN OF

INPUT				
Airship typology	Aerodynamic Airship	PRESS ME	press this button when you choose Standard Airship	NB — you put the in orange ce
Speed up the operation	press this button to insert an indicative preliminary volume to speed up the resolution.Click every time you set large different input, that could be make divergence the resolution, than press solver preliminary design button			

REQUIREMENTS

RANGE	2800	Km	WARNING: VALUES LIKE PAYLOAD, RANGE AND CRUISE, MUST BE INCREASED OR DECREASED, GRADUALLY, OTHERWISE SOLVER WILL DO NOT WORK
6298 Km	Overcome this value does not guarantee the solution convergency		
Payload	50000	Kg	
Cruise Altitude	3000	m	

SOLVER PRELIMINA

ITERATION

MTOW#1-MTOW#2

ENDURANCE AND SPEED

SET "1" FOR CRUISE AND MAXIMUM SPEED AS INPUT SET "2" FOR TIME OF FLIGHT AS INPUT		1	CORRECT INPUT
Cruise Speed[m/s]	Maximum speed[m/s]		
36.1	50		
Time Cruise[days]	Time Maximum Speed[days]	Cruise Speed[Km/h]	Max Speed [Km/h]
0.90	0.65	129.96	180
Number of Gas balloons-Input	11		
Number of gas balloons raccomanded	10		
Material Density of Framework	Magnesium alloy	1.8	Kg/m^3
Type of Buoyant gas	Helium		

GAS VOLUME

Maximum Take Off Weight

ASSUMPTION

NON LAMINAR FLOW			
RIGID ELLIPSOIDAL BODY		1 BODY OF REVOLUTION	
Body FR	5.12		
Propeller Efficiency	0.7		
BR(Landing)	0.98	BR(take-off)	0.86
N° Crew	5	people	
N° Guess	4		
Gondola Dimension	length	26	m
	width	8.8	m
	height	4	m
Landing Gear Choice	Trycicle Landing Gear		

TAIL CONFIGURATION	l_tail	47%	Length of Airship	
	AR(assumption)	1		a[m]
	t/c	0.15		14.5
	Number of Tail[3 or 4]	3	CORRECT INPUT	
	Angle of tail	17.95	degrees	
	Area for each tail	157	m^2	

PROPULSION SYSTEM (ELECTRIC OR FUEL)

% OF FUEL PROPULSION SYSTEM. "1" THERE IS ONLY FUEL PROPULSION. "0" THERE IS ONLY ELECTRIC PROPULSION	1	WARNING-SPEED COULD BE TOO HIGH

FUEL PROPULSION 'RECIPROCATING PISTON ENGINES'

Power Max Required from Airship	7523	KW
N° of Engine	4	
P_one Engine Required	1881	KW
Engine Choice	Lycoming IO 720 A	
P_OneEngine at cruise altitude	211	KW
Chose another Engine with more Power, or reduce cruise speed		

#1-Lycoming 0 360-A				
Power	185	HP	138	KW
BSFC	0.47		14.47	US Gal/h
#2-Lycoming IO 720 A				
Power	400	HP	298	KW
BSFC	0.46		30.5	US Gal/h

Figure 9-1: Input Output Worksheet

SUPER LUXURY AIRSHIP

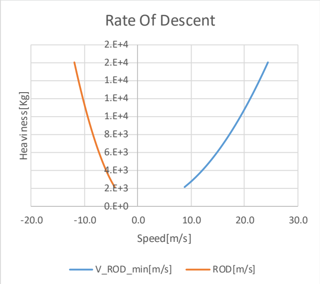
nputs in
ells

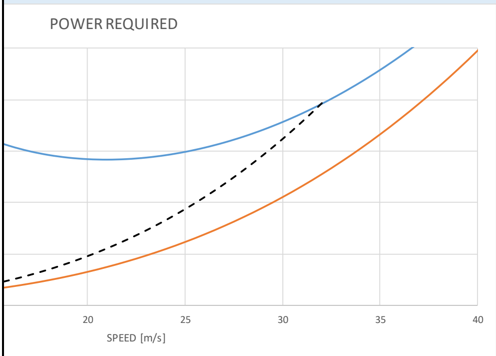
ARY DESIGN

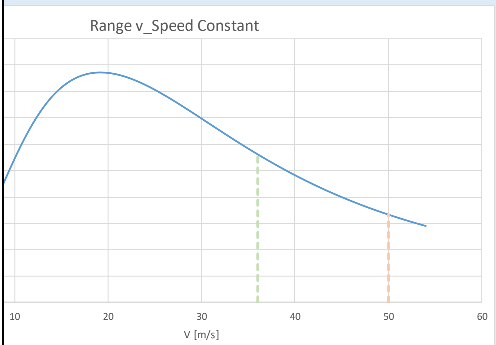
PRESS BUTTON WHEN YOU CHANGE THE INPUT PARAMETERS

0 Kg

132938	m^3
118118	Kg







OUTPUT

ASSET			
alpha_limit	10	Degrees	
alpha_maximum Heaviness(At TakeOff)	7.08	Degrees	ThisValue is OK

TAKE OFF AND LANDING DISTANCE					
Alpha_Take-Off	10 degrees				
Take-off Speed	28.78 m/s				
TAKE-OFF DISTANCE					
GROUND ROLL DISTANCE(at Take off)[m]	+	ROTATION DISTANCE[m]	+	CLIMB OUT DISTANCE[m]	
224		86		29	
TOT_TAKE OFF DISTANCE		339			m
LANDING DISTANCE					
APPROACH DISTANCE[m]	+	FREE ROLL DISTANCE[m]	+	BREAKING DISTANCE[m]	
291		68		76	
TOT_LANDING		725			m

External Enveloope		
External Vol	146232	m^3
Vol^2/3	2776	m^2
Surface	18468	m^2
Surface_plan	5784	m^2
Length	194	m
Diametre	38	m

Aerodynamics Data	
C_D0_body	0.01342
C_D0_tail	0.00134
C_D0_cabin+gondola	0.00171
C_D0_Engine	0.00312
C_D0_cables	0.00202
C_D0_landing gear	0.00034
C_D0_interference	0.00083
C_D0(total)	0.02277

WEIGHT (considering speed and altitude at cruise flight)		
W_Fuel	13963	Kg
W_Fuel_Reserve	655	Kg
WH_0(Heaviness at Take off)	16046	Kg
WH_1(Heaviness at Landing)	2083	Kg
Buoyant Lift	102072	Kg
Zero Fuel Weight	103500	Kg
Operative Empty Weight	53500	Kg
Landing Weight	104155	Kg

SYSTEMS WEIGTH				
Fabric and gasballoons Weight	18514	Kg		
Gas balloon Lenght	16.29	m		
Gas Balloon Diameter	32.24	m		
Gas balloon volume	13294	m^3		
Tot framework weight	6437	Kg		
	Main frame grid	Ring	21	N°
		Longit.	7	N°
	grid intra_main frame	Ring.	0	N°
		Longit.	7	N°
Rigid Tail Weight	3190	Kg		
Gondola Weight	8528	Kg		
Propulsion System Weight	9696	Kg		
AVIONICS & ELECTRONIC WEIGHT	1605	Kg		
ELECTRIC WEIGHT	987	Kg		
LANDING GEAR WEIGHT	507	Kg		
Crew and Passenger Accomodation Weight	680	Kg		
UNUSABLE FLUID & EMPTY WEIGHT MARGIN	3356	Kg		

Propeller		
Efficiency Coefficient	0.729	
Propeller Diameter	7.74	m

The second worksheet is First Design, which includes all calculations of the following data:

- aerodynamics
- performances
- geometrics
- propulsive system
- propeller system

The next worksheet is Weight Definition, which includes and implements all equations analysed in chapter 8.

This and the previous worksheet represent the heart of the program for a preliminary analysis because they provide raw data for airship sizing. The following worksheets are:

- Tail Preliminary Design - provides the value of the horizontal and vertical tail surface
- Viscosity - allows for calculating the viscosity value of a fluid depending on its temperature
- Develop Sheet - includes a series of data and tables useful to optimise some parameters and try to achieve the solution convergence for any input value entered by the user. Moreover, provides hints and warnings for some performance values.
- Fuel Reserve - useful to the program to estimate, with only the input data, how much reserve fuel is necessary
- Picture - collects images, graphs, formulas, and data useful to understand the meaning of inputs and outputs

These worksheets improve the result quality, automate the program, and make the value obtained more understandable.

9.2. Solver and Macro

This program utilises the solver and macro instruments to perform, automate, and optimise the analysis. Solver is Excel's add-in, useful to find the minimum, maximum, or optimum value (red box in Figure 9-2), to target value (green box), and to find modifying parameters (blue box) related to it.

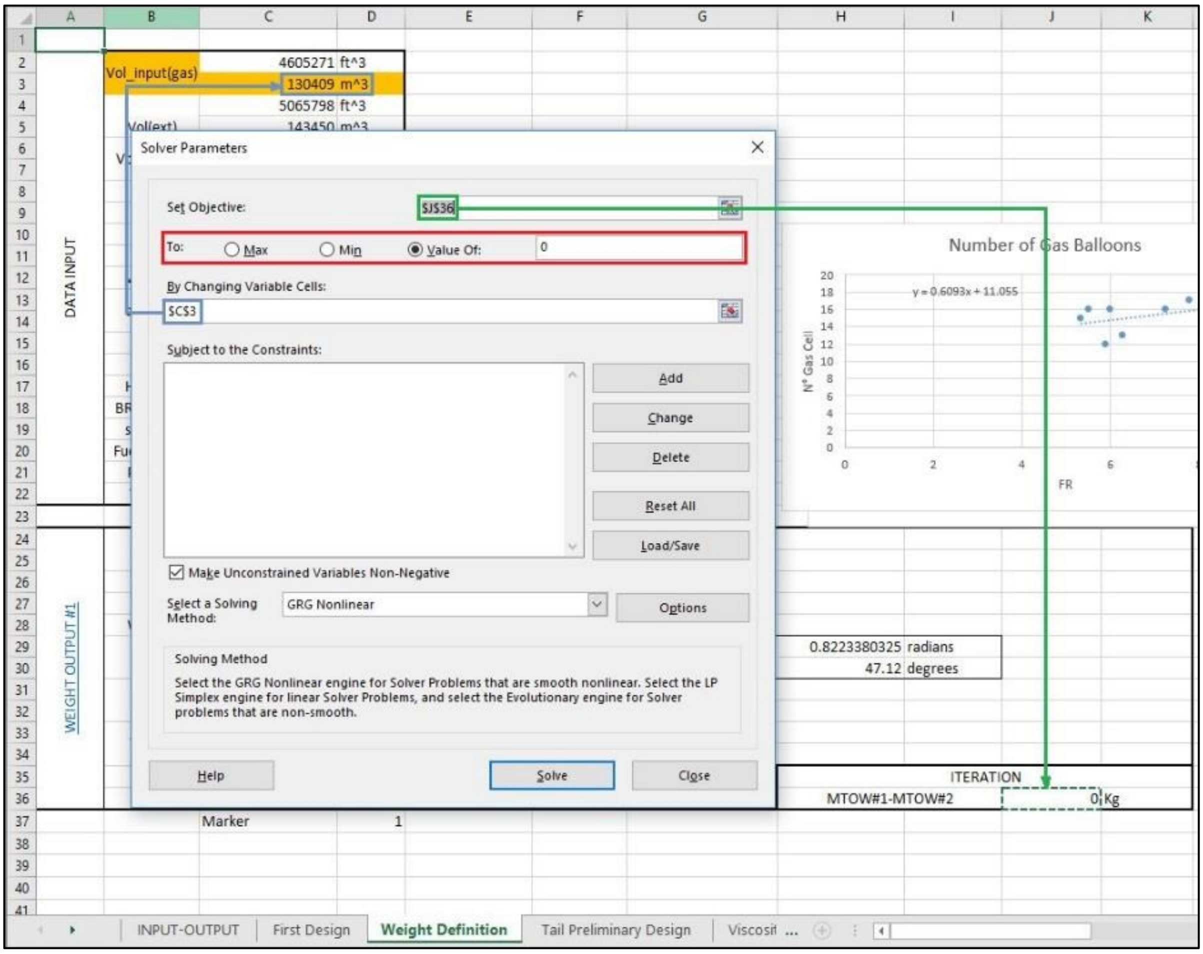


Figure 9-2: Excel Solver

In this specific case, the target cell contains the differences between the MTOW calculated with the two methods described in chapter 8, whilst the variable cell contains volume, as shown in the figure above. Solver works until the objective cell reaches the target value equal to zero.

The other element is macro, which indicates a set of functions performed under appropriate conditions like user interaction with a button. First, it automates the solver launch by pressing the button "solver preliminary design" in the "Input-Output" worksheet; otherwise, to activate solver, the user would have to perform the following steps: open “Weight Definition” worksheet, select the objective cell, expand data in toolbar, open solver in analyse section, and press ‘solve’, ‘OK’, and then ‘close’. The code is in Figure 11-8.

Secondly, macro prevents the divergence of the analysis. Indeed, solver starts with a random value set as an input of the variable cell. Then solver iteratively changes it to obtain the value objective from the target cell. If the initial value of the variable cell is too different from the output result, solver analysis may not converge. Thus, if the user has input values different from those previously present or starts the analysis for the first time, the norm is to press the button “speed up the operation” in the “Input-Output” worksheet to start this macro. In that function of the input, it inserts a value of helium volume coherent enough to start analysis. In this way, the solution converges quickly. The “Develop Sheet” worksheet provides the approximate value of the helium volume through a collection of data output from the program itself, simulating various airship configurations, cruise speeds, and altitudes and changing one parameter at a time to create various charts in the following step.

The first chart below predicts the approximate helium volume depending on payload and altitude for an airship with a fuel propulsion system. Thus, the configuration of the electric propulsion system may have some problems.

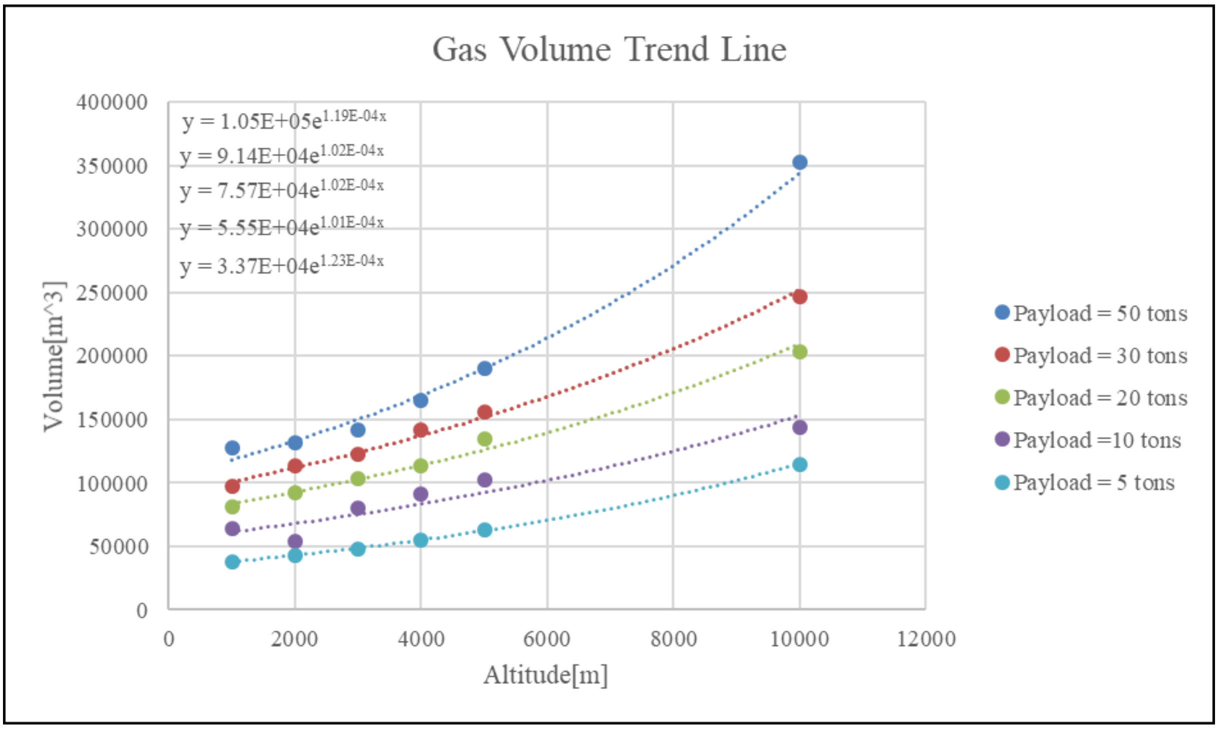


Figure 9-3: Trend line of helium volume depending on payload and altitude

The program evaluates, between two payload curves, which one the input payload falls into. Through (Equation 9-1) it estimates the distance, as a percentage, from the payload curve that acts as the maximum limit:

$$d_{relative} = \frac{W_P - W_{P\ min.limit}}{W_{Pmax.limit} - W_{P\ min.limit}} \qquad \text{(Equation 9-1)}$$

The equation to calculate gas volume is:

$$Vol_{gas} = Vol_{G\ min.limit} + d_{relative}(Vol_{G\ max.limit} - Vol_{G\ min.limit}) \qquad \text{(Equation 9-2)}$$

- W_P = payload weight input
- $W_{P\ min.limit}$ is the curve whose payload weight is less than the input payload weight but is also higher than the payload weight of the other curves.
- $W_{P\ max.limit}$ is the curve whose payload weight is higher than the input payload weight but is also lower than the payload weight of the other curves.
- $Vol_{G\ min.limit}$ is the volume linked to the payload weight curve that acts as the lower limit.
- $Vol_{G\ max.limit}$ is the volume linked to the payload weight curve that acts as the upper limit.
- Vol_{gas} is the gas volume set as the starting input for solver.

Two other graphs also provide information about the maximum range that a user can set as input without incurring the divergence of the solution, for the aerodynamic airship's type . The starting point is the argument of the tangent in (Equation 6-26). Indeed, if it assumes values close to ninety degrees, to which the function asymptote corresponds, the solver solution may not converge. Therefore, the following chart shows the argument value limit for convergence of the solution depending on the altitude and payload:

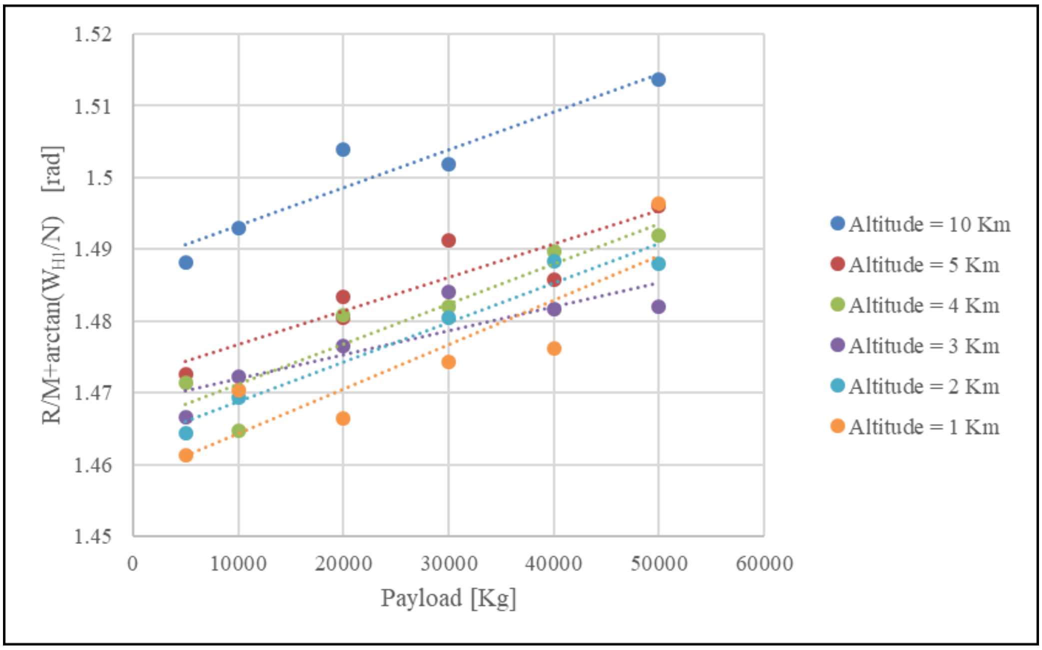


Figure 9-4: Limit argument for solution convergence depending on altitude and payload

The limit argument increases as altitude and payload increase. Therefore, to have the convergence of the simulation, the calculation of the limit argument must take place at the minimum payload (in this case, minimum weight is five tons) depending on the quota, as shown in

Figure 9-5.The lowest altitude dependence is better than payload because its trend is more linear than the payload trend which curve slope is not the same at different.

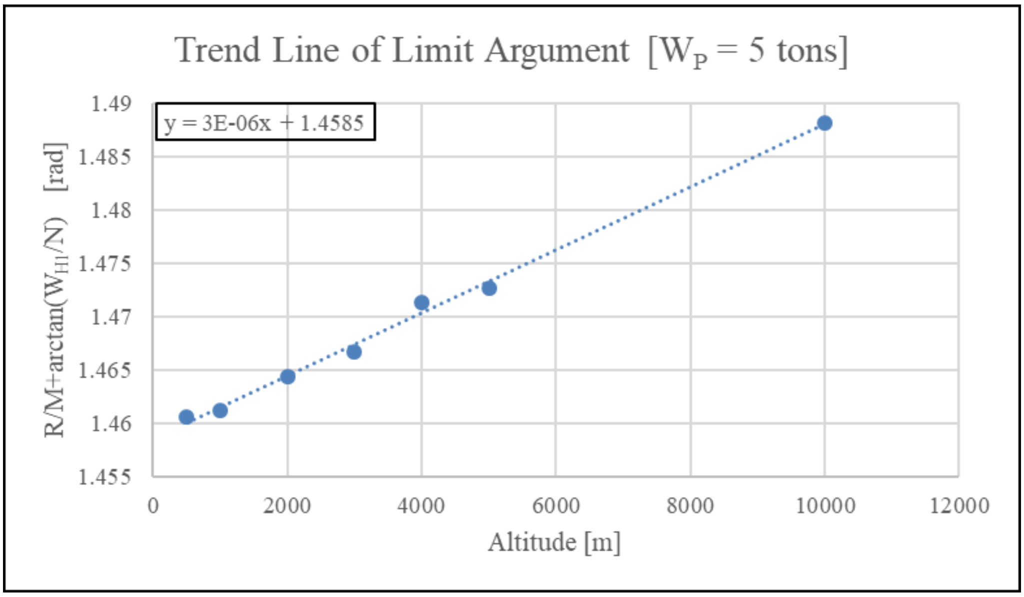


Figure 9-5: Limit argument for solution convergence depending on altitude

Thus:

$$Arg_{\text{lim}} = 3 * 10^{-6}\, Z[m] + 1.4585 \qquad \text{(Equation 9-3)}$$

$$R_{Lim} = M\left(Arg_{Lim} - \tan^{-1}\left(\frac{W_{H1}}{N}\right)\right) \qquad \text{(Equation 9-4)}$$

where M, N, and W_{H1} are the data before making the simulation.

9.3. Program Validation

Program validation is important to verify the reliability of the output data obtained by the analysis. The verification method used involves entering input data from an existing airship, launching the analysis, and comparing the output data with those of the benchmark airship. The program returns reliable data if values fall within the 15 per cent error range. It is a reasonable boundary margin because design phase is preliminary.

Through the website of the Euro Airship Company, one model has a technical data sheet sufficiently detailed to perform the comparison. It is rigid airship DGPA 50 T. The only difference that can slightly distort the values is in the generation of the upward thrust. Indeed, if the software considers aerodynamic airship - hybrid generation of the upward force (buoyant lift and aerodynamic lift) - the company's airships use buoyant gas and thrust vectoring to balance the airship weight. Overall, the situation changes slightly.

Table 14: Program Validation with "DGPA 50 T"

Program Validation with "DGPA 50 T"				
Data Name		Program Values	Airship Data	Error %
Range	R [Km]	2800	2800	/
Payload	W_P [Kg]	50000	50000	/
Cruise Altitude	Z [m]	3000	3000	/
Cruse Speed	V_{Cruise} [m/s]	36.1	36.1	/
Maximum Speed	V_{Max} [m/s]	50	50	/
Fineness Ratio	FR	5.12	5.12*[1]	/
Buoyancy Ratio at Landing	BR_{Land}	0.95	none	/
Propeller efficiency	η_p	0.7	n.r.	/
Crew Members	N_{Crew}	5	5	/
Passengers	N_{Guest}	4	4	/
Gondola Dimensions	$l_g x d_g x h_g$ [m]	26x8.9x4	26x8.9x4*	/
Landing Gear	/	Tricycle	Tricycle*	/
Arm Tail with Gravity Centre	l_t [m]	47% l	(47% l)*	/
Tail Aspect Ratio	AR_t	1	n.r.	/
Maximum profile thickness of the tail	t/c	0.15	n.r.	/
Number of fins	N_t	3	3	/

[1] Data marked with the asterisk are deduced through drawings of the airship and indirect measurement.

Tail Surface Plan (one fin)	S_{el} [m^2]	140	130*	7.29%
Number of Engine	N_{eng}	4	4	/
Total Engine Power	P_R [KW]	8026	8113	1.07%
Airship Length	l [m]	194	169	14.8%
Airship Maximum Diameter	d [m]	38	33	15.1%
Zero Lift Drag Coefficient	C_{D0}	0.227	n.r.	/
Fuel Weight	W_F[tons]	17.13	20	14.3%
Operative Empty Weight	W_{OE} [tons]	56.34	66	14.6%
Maximum Take-off Weight	MTOW[tons]	123.48	136	9.2%
Helium Volume	Vol_{He} [m^3]	132384	130000	1.83%

All values are within the 15 per cent limit except for diameters exceeding the limit of 0.1 percentage points. These results are accurate enough to validate this program for a preliminary design in phases 0 through A. Of course, this value is not sufficiently accurate for subsequent design phases.

9.4. Input, Assumption, and Output

Now that the program works, insert the inputs that come from the requirements table into it and analyse the output. In this phase, the program at the end of analysis could show warnings about some data. Thus, stakeholders, team of designers, and engineers discuss to modify some input data to delete these alerts and have reasonable values to continue the project.

Entering in the program the data in Table 4, the main output value and output with warning are:

Table 15: Initial Requirements Input Data

Initial Requirements Input Data		
Maximum Take-off Weight	MTOW[tons]	53.8
Helium Volume	Vol_{He} [m^3]	48414
Propeller Efficiency	η_p	0.5
Airship Incidence at Take-off	α_{max} [°]	44.5
Buoyancy Ratio at Take-off	$BR_{Takeoff}$	0.77

Where propeller efficiency derives from the analysis made by the program and for this combination of input data, it is less low than propeller efficiency assumed. In addition, airship incidence at take-off and buoyancy ratio at take-off are more different than their limit values.

The table below shows the modified requirements. It is the result of a long iterative process of modifying input data to obtain reasonable output data. Moreover, some requirements are the result of the compromise between the aesthetic and engineering teams.

Table 16: Requirements and Constraints Modified

Requirements Modified		
Payload Weight	7.5	ton
Range	3500	Km
Maximum altitude	2000	m
Maximum Endurance	1.84	days
Cruise Speed	22	m/s
Minimum Endurance	1.56	days
Maximum Speed	26	m/s
Crew	8	People
Guess	8	
Mission Flight Strategy	Constant Speed	/
BR (landing)	0.99	/
FR	5	/
Propeller Efficiency	0.7	/
Gondola Dimensions	Length [m]	28
	Width [m]	8
	Height [m]	6
Airship Configuration	Rigid Structure$^+$	/
	Body of Revolution$^+$	/
	Fuel Propulsion$^+$	4 Engines
	Luxury Yacht Arrangement$^+$	/
Tail Configuration	Number of Fins	4
	Fins Configuration	X
	Aspect Ratio	1

Thus, entering these data in the program, the outputs are:

Airship Dimensions			
(Equation 3-5)	External Envelope Volume	Vol [m^3]	48427
(Equation 3-9)	Reference Surface	$Vol^{2/3}$[m^2]	1329
(Equation 3-7)	External Surface	S_{ell} [m^2]	8777
(Equation 3-8)	Surface plan	S_{plan} [m^2]	2747
(Equation 3-6)	Airship Length	l [m]	132
	Airship Maximum Diameter	d [m]	26

Zero Lift Drag Coefficient Data			
(Equation 4-8)	Body	C_{D0_body}	0.01507
	Tail	C_{D0_tail}	0.00159
(Equation 4-14)	Gondola	$C_{D0\_gondola}$	0.00217
(Equation 4-18)	Engines	C_{D0_engine}	0.00402
(Equation 4-20)	Cables	C_{D0_cables}	0.00187
(Equation 4-19)	landing gear	C_{D0_LG}	0.00027
(Equation 4-21)	Interference	$C_{D0\_interf.}$	0.00057
(Equation 4-8)	Total	C_{D0}	0.02557

Airship Trim			
(Equation 4-27)	Airship Incidence at Take-off	α_{max} [°]	9.86

Tail Design			
(Equation 5-6)	Angle of Fin elements Compare to Horizontal Plan	θ[°]	40.24
(Equation 5-5)	Tail Surface Plan (one fin)	S_{el} [m^2]	47

Performances			
(Equation 6-7)	Maximum power required to the shaft	P_R [KW]	901

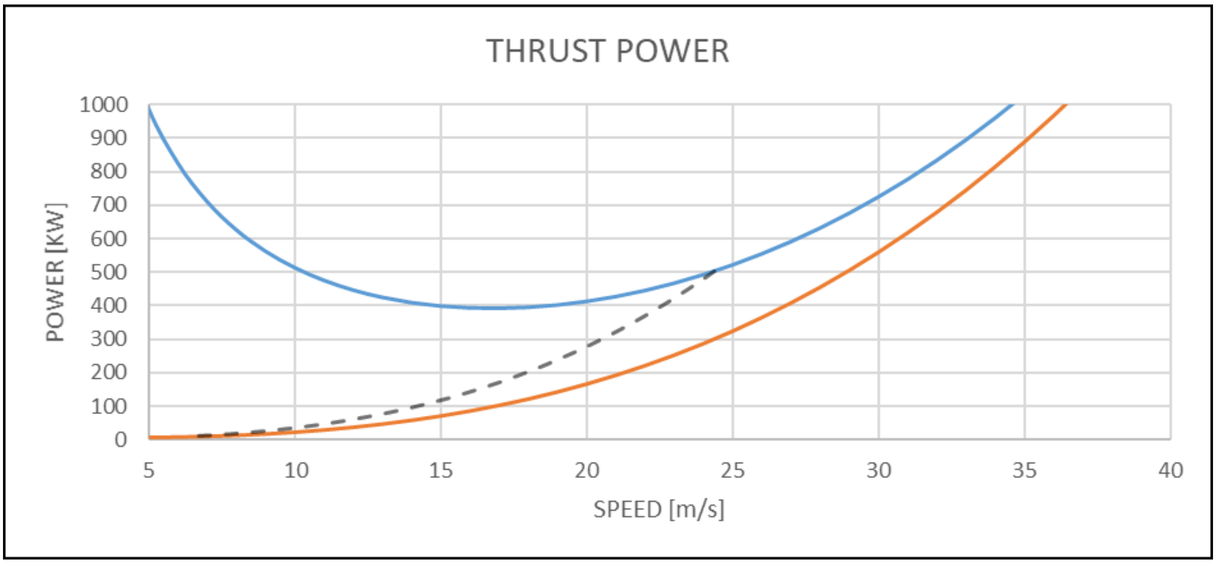


Figure 9-6: Chart of Thrust Power

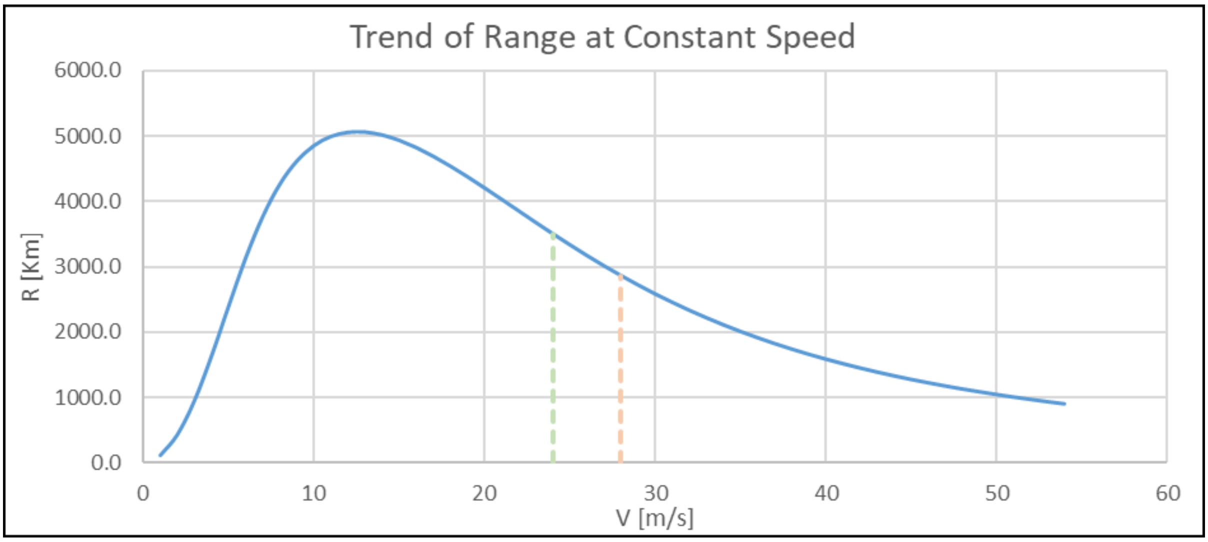


Figure 9-7: Trend of Range at Constant Speed

Take-off and landing Analysis			
(Equation 6-27)	Take-off Speed	V_{TO} [m/s]	23.76
/	Take-off Angle	α_{TO} [°]	10
(Equation 6-28)	Ground Roll Distance	S_G [m]	425
(Equation 6-34)	Rotation Distance	S_R [m]	71
(Equation 6-35)	Climb Out Distance	S_C [m]	172
(Equation 6-37)	Total Take-off distance	S_{to} [m]	668
(Equation 6-41)	Approach Distance	S_A [m]	291
(Equation 6-42)	Free Roll Distance	S_F [m]	55
(Equation 6-43)	Breaking Distance	S_B [m]	62
(Equation 6-44)	Total Landing Distance	S_L [m]	679

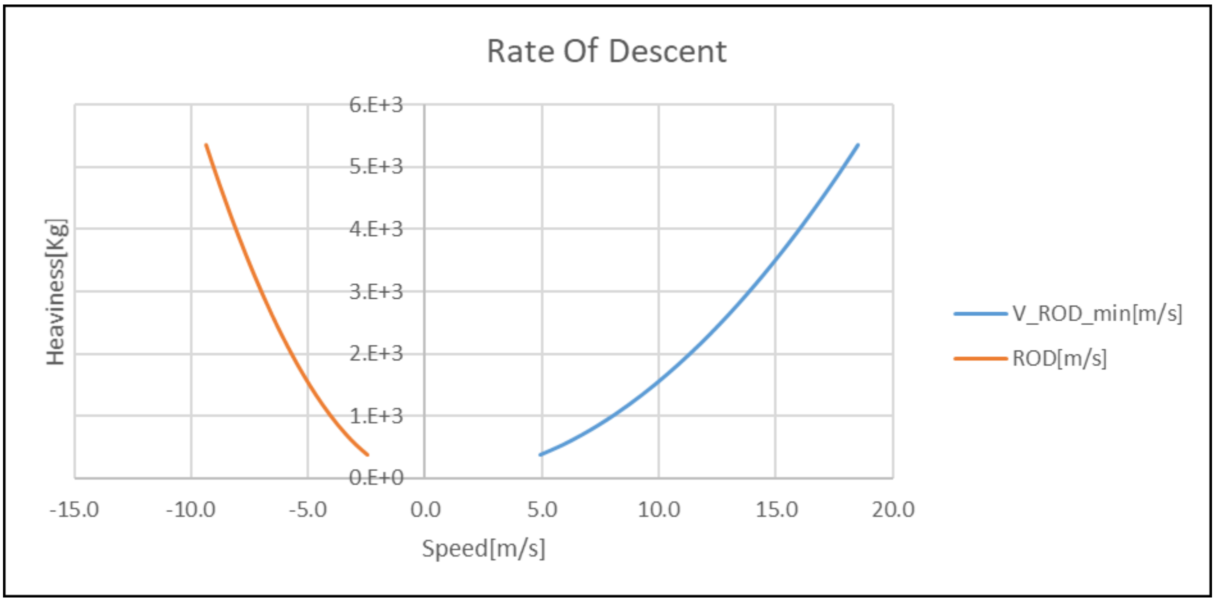


Figure 9-8Rate of Descent

Propeller Design			
(Equation 7-25)	Propeller Diameter	D	5.22
(Equation 7-24)	efficiency coefficient	η_P	0.723

Weight			
(Equation 8-7)	Fuel Weight	W_F [Kg]	4981
(Equation 8-6)	Fuel Reserve Weight	W_{FR} [Kg]	487
(Equation 6-26)	Heaviness at Take-off	W_{H0} [Kg]	5359
(Equation 8-8)	Heaviness at Landing	W_{H1} [Kg]	378
(Equation 8-4)	Buoyant Lift	B_{lift} [Kg]	37423
(Equation 8-2)	Zero Fuel Weight	W_{ZF} [Kg]	37314
(Equation 8-3)	Landing Weight	W_{land} [Kg]	29814
(Equation 8-5)	Operative Empty Weight	W_{OE} [Kg]	37801

Systems Weight			
(Equation 8-12) + (Equation 8-22)	Outer Skin and Gas Balloons Weight	$W_{ES} + W_{GB}$ [Kg]	9486
(Equation 8-20)	Internal Framework Weight	W_{IF} [Kg]	1931
(Equation 8-13)	Number of Ring Elements	N_R	25
(Equation 8-18)	Number of Longitudinal Elements	N_L	16
(Equation 8-28)	Rigid Tail Weight	W_T [Kg]	1523
(Equation 8-35)	Gondola Weight	W_G [Kg]	9955
(Equation 8-40)	Propulsion System Weight	W_{PS} [Kg]	1835
(Equation 8-54)	Avionics and Electronics Weight	W_{Av} [Kg]	894
(Equation 8-55)	Electric System Weight	W_{El} [Kg]	733
(Equation 8-56)	Landing Gear Weight	W_{LG} [Kg]	202
(Equation 8-58)	Crew and Passenger Accommodations Weight	W_{serv} [Kg]	1412
(Equation 8-63) + (Equation 8-64)	Unusable Fuel and Empty Weight Margin	$W_{uf} + W_{margin}$ [Kg]	1844

Main Outputs			
(Equation 8-1)	Maximum Take-off Weight	MTOW [Kg]	42782
/	Helium Volume	Vol_{He} [m^3]	44024

Chapter 10

10. Aesthetic Design Development

The design team worked without precise values during the first preliminary phase of the project, taking care only of the aesthetic aspect of the airship. At the same time, the engineering team collected data and information related to the topic to model it and provide valid data. Thus, initially, the engineering group and stylistic group worked separately. The problem for the latter group was to provide a renewed image of the airship, and benchmark model DGPA 50 T provided data to start drawing. The result is a beautiful style exercise that, however, has many gaps in structure, aerodynamics, and manoeuvrability. Indeed, the main critical points highlighted by the technical table are:

Gas balloons—Thirty-four gas balloons to contain the buoyant gas are too many. Indeed, they add excessive weight without making any advantage.

Unconventional hull shape—Although this makes the airship more appealing, it has some aerodynamic and structural disadvantages. Firstly, the hull symmetry does not allow aerodynamic lift generation. Then the sudden change in the shape's direction and the presence of sharp edges generate a remarkable increase of shape and friction drag. Moreover, the realisation of a structural grid that follows this articulated shape is complicated and has criticalities because the strain distribution will not be uniform.

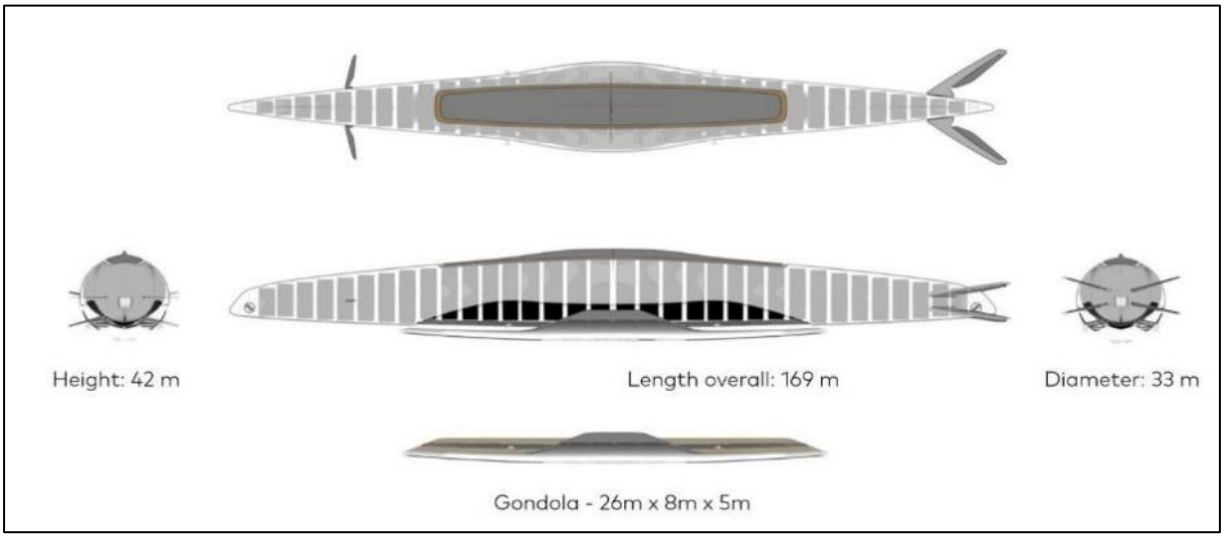


Figure 10-1: Technical table of the initial design process

Figure 10-2: First rendering of initial model [9]

Figure 10-3: Second rendering of initial model [10]

Of course, in a multidisciplinary project like this, compromise plays a fundamental role since the engineering design process has too-rigid theoretical bases to respect, aimed at the realisation of a performance object at the expense of its aesthetics, whilst the opposite case is true for the aesthetic design process. The exchange of data and opinions was important to converge into a single nice and functional design, as shown from the technical figure below.

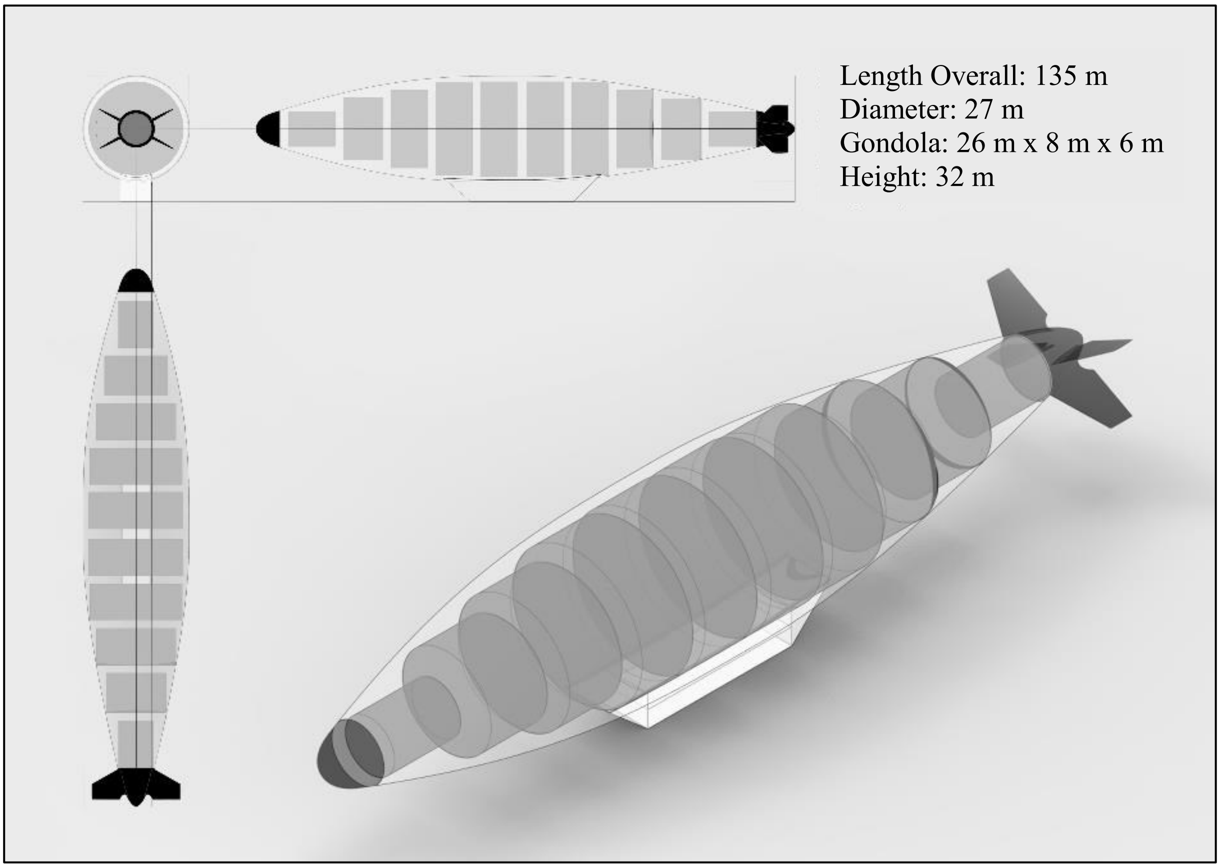


Figure 10-4: Technical Table [11]

References [12], [13] and [14] belongs to the author (Grisales)

Chapter 11

11. Conclusion and Future Works

Design and implementation of an aeronautical vehicle require a great use of resources and knowledge because it is a complex system. Numerous disciplines and many people are involved; thus, a perfect management of all these resources is essential. Given the vastness of the topic, this paper covers the preliminary design phase. Recent tools like WBS, study logic, timelines, and others help the study manager to handle and optimise resources. Yet in the context of preliminary design of an airship, the tools are the same as those used in the early ’40s because during those years, the decline in the airship as a transportation method reduced people’s interest in developing new tools. Currently, computers allow the designer to get results of a preliminary analysis quickly by implementing into a program the formulas useful to model the system. Thus, the purpose of this thesis is to show all formulas and logical steps implemented in the Excel program RAsDEx 1.1 to get a preliminary description of airship dimensions and performances, aerodynamic data, propulsion system, weight estimation, and gas volume required. With a maximum error of about 15 per cent on some results, the program becomes a valuable tool to get first estimates and data on a new model of rigid airship, allowing the aesthetic team to make a more accurate design than before and to proceed with the next project phases.

Some requirements initially defined have undergone substantial modification, linked to engineering aspects and to reach compromises with the design team on the aesthetic aspect. Range is one of these; indeed, its value is almost halved, and the cause is related to the airship model analysed, namely the rigid airship with hybrid lift generation. Indeed, this type shows the same disadvantages typical of aerodyne, such as total drag increase of the aircraft due to induced drag from aerodynamic lift and therefore the range reduction and the need to have a non-zero feed rate to generate the required aerodynamic lift to balance airship weight. This implies that it is unable to make a vertical take-off and landing. However, the advantages are significant, such as better manoeuvrability, weight reduction, and less constructive difficulty. Whilst, in the case of gas, heavy and complex mechanisms of gas balloons and volume management are present, they are also present in the model of hybrid lift generation airships but in a less pronounced way. Moreover, one way to mitigate these disadvantages is reducing the aerodynamic lift contribution by assigning the task of balancing an additional amount of fuel to increase range. Thus, through these considerations and the data obtained from analyses, it emerges that if the intercontinental range is the main requirement of the airship, the lift generation through only buoyant gas is the most opportune configuration to use. For international range, hybrid lift generation is a great solution.

However, the work does not end now because the program is still at the embryonic stage. Future research will have new automation and conditions to prevent analysis divergence, an increase of structural materials and fuel engine databases, the ability to do the analysis on hybrid and nonrigid airships, a new and improved graphic interface, and a better comment about all results to help the user and to try making data values more accurate. Thus, the next step for this project is the detailed analysis of the airship subsystems.

Annex

A1. Pinifarina Extra

"In Pininfarina Extra the design culture interacts directly with the industrial research aspect, in an organisation which features all the stages of the creative process: from the concept to engineering, from prototyping to cost and feasibility analyses. Styling no longer means just the external embellishment of a function. It is an aesthetic and functional solution for collective and individual needs, representing lasting values and performance. We believe that the design process must focus on the users of the product, their experiences, dreams and limits. The winning product is the product which best responds to the desires, needs and user experience which consumers seek."

A2. Euro Airship

The Euro Airship company designs and manufactures rigid airships. It commissioned Pininfarina to realise a new project based on their airship, taking care to make a functional but also nice model.

There are three main airship models that the company offers:

- Corsair 1-8 T - The target of this aircraft is tourism and surveillance of large regions at low cost compared with typical surveillance aircraft. Moreover, the aircraft guarantees a mission duration up to two weeks. The technical sheet is:

CORSAIR 1-8T
payload

Airship CORSAIR crew :
1 pilot, 1 copilot and 1 engineer
or as drone with no crew

Payload capacity	8T
Helium charge max	29,000 m³
Cruising speed	108 km/h
Cruising altitude max	2,000 m
Maximum speed	130 km/h
Power 2 TURBOMECA ARIEL engines 2C / 600 Kw /SHP 800 x 2	1,600 SHP
Ballasting engines	2 micro turbo 100 Kw
Range : speed 108 km/h	2,000 km
Maximum weight at take-off	12 T
Ferrying range	2,800 km
Fuel weight	2 to 5 T max
Weight (unloaded)	10 T

Other features
Vertical and vectorial take-off
Amphibious / All terrain / All weather
Adjustable double external envelope
Complete de-icing of the external envelope
Stable thermal conditions for helium
Lateral and 360° manoeuvrability
Crew quarters for long flights

Specifications	
Length	139 m
Diameter	23 m
Height	28 m
Internal helium envelope	29,500 m³
Maximum altitude (1T)	7,000 m
Maximum altitude (8T)	2,000 m
Helium expansion envelope	29,000 m³

Figure 11-1: Model (Airship, Corsair 1-8 T) [15]

- DGPATT 50 T—The target is the transport of large quantities of goods and passengers for long routes. Technical data are:

DGPA 50T
50 tonne capacity jumbo airship

DGPA 50T crew :
2,3,4 persons based on flight duration
2 pilots, 2 copilots or 1 engineer.

Payload capacity	50T
Helium charge max	130,000 m³
Cruising speed	130 km/h
Cruising altitude max	3,000 m
Maximum speed	180 km/h
Bow and steering fans	2
Power 4 TURBOMECA engines 2,700 SHP x 4	10,800 SHP
Ferrying range	> 10,000 km
Maximum weight at take-off	136 T
Range: speed 130km/h	2,800 km
Fuel weight	20T
Weight (unloaded)	66T

Features
Vertical and vectorial take-off
Amphibious / All terrain / All weather
Adjustable double external envelope
Complete de-icing of the external envelope
Stable thermal conditions for helium
Lateral and 360° manoeuvrability
Crew quarters for long-distance flights
Tools and first degree spare parts storage for inflight maintenance

Dimensions	
Length overall	169 m
Height	42 m
Diameter	33 m
Cargo compartment	26 x 8 x 4 m Vol. 680 m³

Figure 11-2: Model (Airship, DGPATT 50T) [16]

- DGPATT 250 TO 400 T—Future models will have capacities extending from 250 to 400 tonnes.

A3. Project Phases

A spatial project can be divided into several different phases that affect the whole system life cycle. ESA has defined a standard in which it divides the project into seven phases that, with appropriate modifications, can be applied to other areas. The phases are as follow:

- Phase 0 is the preliminary analysis phase of the project, where the SHA and NA are the main activities to be carried out. The output of this phase is the MS.
- Phase A is the feasibility analysis of the project in terms of technologies and production timing. Various concepts must be developed to be able to make the trade-off.
- Phase B consists of preliminary design of the concept obtained in the previous phase.
- In Phase C, the systems and subsystems are developed in detail, and a draft of the user manual is produced.
- In Phase D, the qualification, verification, and production of the systems are carried out.
- Phase E is related to the operative life of the system and its maintenance activity.
- Phase F represents the disposal phase of the system.

A4. Stakeholders Classification

SHs can be classified into four different categories:

- Promoters have much interest in and influence on the mission. Indeed, it is very important to satisfy most of their requirements.
- Latent stakeholder have much influence but low interest in the mission. For this reason, this category must be considered.
- Defender indicates a category that although it has much interest in the mission, its influence is poor.
- Apathetic stakeholders have low interest and influence but could evolve into defenders or latent.

A5. Dimensions of the Gondola: Internal Space Analysis

The data and project confidentiality did not allow the uploading of images, sketches, and data of fifty-metre-length super yachts; thus, the three bridges with the interior spaces subdivisions have been schematised through CAD modelling software, as shown in the image below:

- Lower Deck:
  - Gym and Toy Room
  - Engine Room
  - Garage for Tenders and Toys
  - 2xVip Cabin

- Guest Cabin
- Galley
- Laundry
- Crew Mess
- 8xCrew Cabin

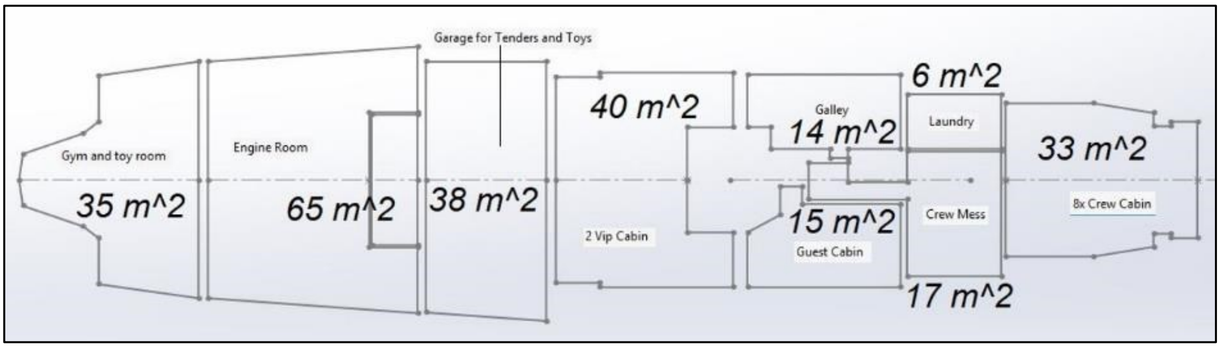


Figure 11-3:Yacht lower deck diagram (fifty meters model)

$$Area_{LowerD.} = 263\ m^2$$

- **Main Deck**
  - External Part 1
  - External Part 2 & Swimming Pool
  - Main Saloon
  - Dining Area
  - Guest Lobby & Storage Artwork
  - Main Lobby & Day Head
  - Entrance & Tech Space
  - 2x Guess Cabin
  - Food Storage
  - Owners Cabin
  - Rescue Boat Room

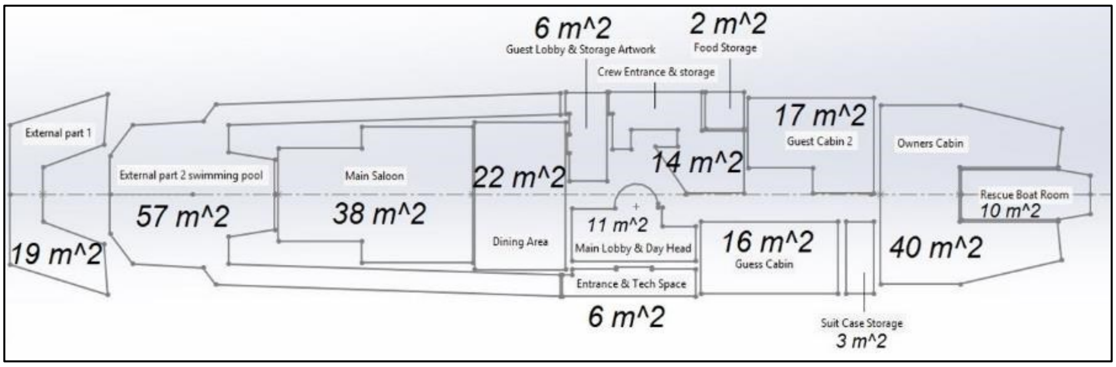


Figure 11-4: Yacht main deck diagram (fifty-metres model)

$$Area_{MainD.} = 261\ m^2$$

- **Upper Deck**
  - External Part 3
  - Tech Space
  - Upper Saloon Cinema
  - Wine Cellar
  - Bar
  - Storage
  - Pantry
  - Captain's Cabin
  - Electric Panel and Control Room

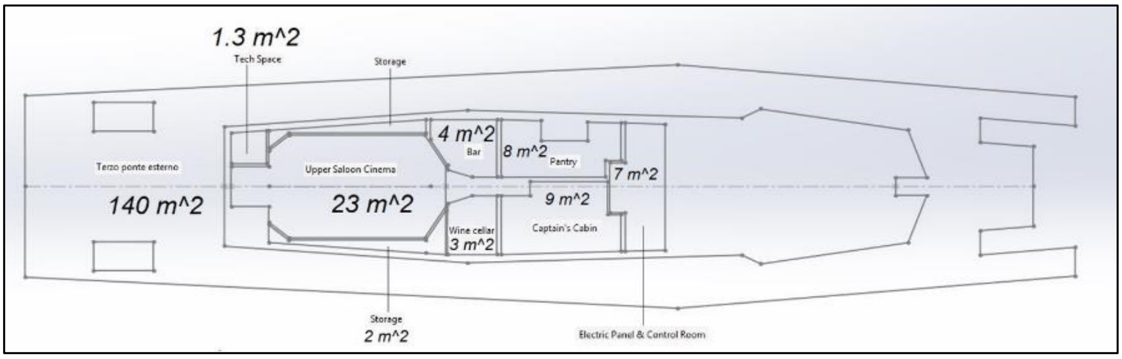


Figure 11-5: Yacht upper deck diagram (fifty-metres model)

$$Area_{UpperD.} = 197.3\ m^2$$

Thus, the total area is:

$$Area_{TOT} = Area(LowerD. + MainD. + UpperD.) = 721.3\ m^2$$

The image below (Figure 11-6) shows the gondola installed on the reference airship model, made by the Euro Airship Company.

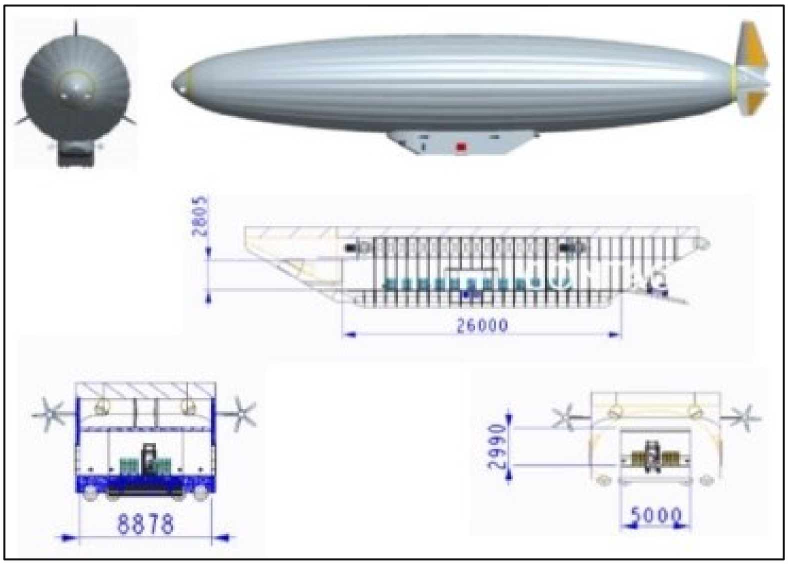


Figure 11-6: Gondola (Airship, DGPATT 50T)

The parallelepiped is the easiest way to schematise the DGPA 50-T gondola. The walkable surface of a two-flor gondola with dimensions shown in Figure 11-7 is:

$$Area_{gondola} = N_{flor}(26 * 8) = 416\ m^2$$

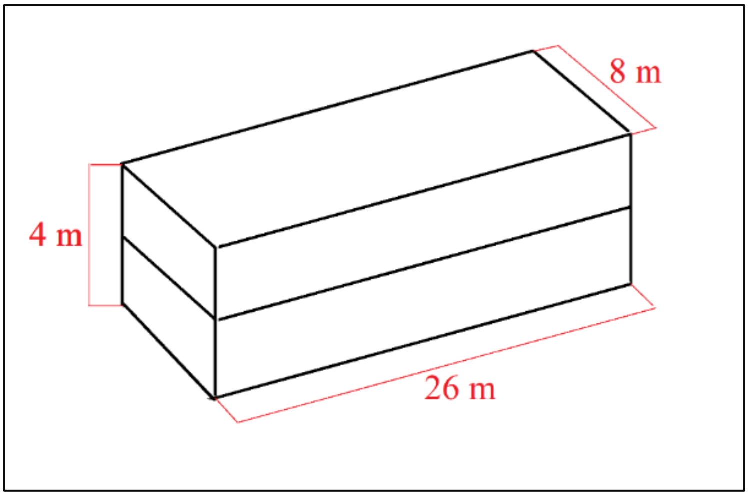


Figure 11-7: Gondola schematisation

A6. Tables of Conversion and Physical Quantities

Table 17: Table of Conversion

CONVERSION		
1 ft	0.305	m
1 m	3.281	ft
1 Km	0.539	nm
1 nm	1.855	Km
1 Kg	2.205	lb
1 lb	0.454	Kg
1 m^3	35.314	ft^3
1 ft^3	0.028	m^3
1 ft/s	0.305	m/s
1 m/s	3.281	ft/s
1 Kn	0.514	m/s
1 m/s	1.946	Kn
1 KW	1.341	HP
1 rpm	60	rps
1 HP	550	ft*lb/s
1 lb/ft^3	16.018	Kg/m^3
1 rad/s	0.159	rps
1 m^2	10.76	ft^2
1 ounce	0.028	Kg
1 yarda	0.914	m
1 m	0.000539	nm
1 ft	0.000164	nm
1 rad	57.296	deg

Table 18: Useful Physical Quantities

USEFUL PHYSICAL QUANTITIES		
g	9.81	m/s^2
R	287.05	J/Kg*K
γ	1.4	
T_0	288.16	K
ρ_{SL}	1.22	Kg/m^3
	0.00238	$slug/ft^3$
	0.1244	$Kg\ s^2/m^4$
He Force	0.0646	lb_f/ft^3
He density	0.1785	Kg/m^3
H_2 Force	0.0711	lb_f/ft^3
H_2 Density	0.0899	Kg/m^3

Table 19: Fuel Density

Aviation Grade 100LL Fuel			
ρ_F	6.01	lb/US Gal	15 Celsius
	0.721	Kg/l	
	6.41	lb/US Gal	-40 Celsius
	0.769	Kg/l	

A7. Atmospheric Data

At varying altitudes, parameters of temperature, pressure, dynamic viscosity, and air density vary. Some formulas that refer to standard atmosphere allow one to define the profile of temperature, pressure, and air density at a given altitude.

The following formula allows for calculating temperature, expressed in K:

$$T[K] = T_0 - 6.5\ Z(Km) \qquad \text{(Equation 11-1)}$$

To calculate air density:

$$\rho[Kg/m^3] = \rho_0 \sigma \qquad \text{(Equation 11-2)}$$

Where σ indicates ratio of the air density to altitude and the air density at sea level, the equation is:

$$\sigma = \left(\frac{T_0 - 6.5\,Z(Km)}{T_0}\right)^{4.2561} \quad \text{(Equation 11-3)}$$

The table below shows parameters of temperature air density and σ at the altitude variations.

Table 20: Temperature of Air Density and σ at the Altitude Variation

Z(Km)	σ	ρ	T(Z)
0	1	1.22	288.16
0.1	0.9904347	1.20833	287.51
0.2	0.9809397	1.196746	286.86
0.3	0.9715144	1.185248	286.21
0.4	0.9621585	1.173833	285.56
0.5	0.9528717	1.162504	284.91
0.6	0.9436537	1.151257	284.26
0.7	0.934504	1.140095	283.61
0.8	0.9254224	1.129015	282.96
0.9	0.9164084	1.118018	282.31
1	0.9074618	1.107103	281.66
1.1	0.8985821	1.09627	281.01
1.2	0.8897691	1.085518	280.36
1.3	0.8810223	1.074847	279.71
1.4	0.8723415	1.064257	279.06
1.5	0.8637263	1.053746	278.41
1.6	0.8551763	1.043315	277.76
1.7	0.8466912	1.032963	277.11
1.8	0.8382707	1.02269	276.46
1.9	0.8299144	1.012496	275.81
2	0.8216219	1.002379	275.16
2.1	0.813393	0.99234	274.51
2.2	0.8052274	0.982377	273.86
2.3	0.7971245	0.972492	273.21
2.4	0.7890842	0.962683	272.56
2.5	0.7811061	0.952949	271.91
2.6	0.7731899	0.943292	271.26
2.7	0.7653351	0.933709	270.61
2.8	0.7575416	0.924201	269.96
2.9	0.7498089	0.914767	269.31
3	0.7421368	0.905407	268.66
3.1	0.7345249	0.89612	268.01
3.2	0.7269728	0.886907	267.36

3.3	0.7194803	0.877766	266.71
3.4	0.712047	0.868697	266.06
3.5	0.7046726	0.859701	265.41
3.6	0.6973568	0.850775	264.76
3.7	0.6900992	0.841921	264.11
3.8	0.6828995	0.833137	263.46
3.9	0.6757575	0.824424	262.81
4	0.6686727	0.815781	262.16
4.1	0.6616449	0.807207	261.51
4.2	0.6546738	0.798702	260.86
4.3	0.647759	0.790266	260.21
4.4	0.6409002	0.781898	259.56
4.5	0.6340971	0.773598	258.91
4.6	0.6273493	0.765366	258.26
4.7	0.6206567	0.757201	257.61
4.8	0.6140188	0.749103	256.96
4.9	0.6074354	0.741071	256.31
5	0.6009061	0.733105	255.66
5.1	0.5944306	0.725205	255.01
5.2	0.5880087	0.717371	254.36
5.3	0.5816399	0.709601	253.71
5.4	0.5753241	0.701895	253.06
5.5	0.5690609	0.694254	252.41
5.6	0.56285	0.686677	251.76
5.7	0.556691	0.679163	251.11
5.8	0.5505838	0.671712	250.46
5.9	0.544528	0.664324	249.81
6	0.5385232	0.656998	249.16
6.1	0.5325692	0.649734	248.51
6.2	0.5266658	0.642532	247.86
6.3	0.5208125	0.635391	247.21
6.4	0.5150091	0.628311	246.56
6.5	0.5092553	0.621291	245.91
6.6	0.5035508	0.614332	245.26
6.7	0.4978954	0.607432	244.61
6.8	0.4922887	0.600592	243.96
6.9	0.4867304	0.593811	243.31
7	0.4812202	0.587089	242.66
7.1	0.4757579	0.580425	242.01
7.2	0.4703431	0.573819	241.36
7.3	0.4649756	0.56727	240.71

7.4	0.4596552	0.560779	240.06
7.5	0.4543814	0.554345	239.41
7.6	0.449154	0.547968	238.76
7.7	0.4439728	0.541647	238.11
7.8	0.4388374	0.535382	237.46
7.9	0.4337475	0.529172	236.81
8	0.428703	0.523018	236.16
8.1	0.4237035	0.516918	235.51
8.2	0.4187487	0.510873	234.86
8.3	0.4138383	0.504883	234.21
8.4	0.4089722	0.498946	233.56
8.5	0.4041499	0.493063	232.91
8.6	0.3993712	0.487233	232.26
8.7	0.3946359	0.481456	231.61
8.8	0.3899437	0.475731	230.96
8.9	0.3852942	0.470059	230.31
9	0.3806873	0.464439	229.66
9.1	0.3761227	0.45887	229.01
9.2	0.3716	0.453352	228.36
9.3	0.3671191	0.447885	227.71
9.4	0.3626796	0.442469	227.06
9.5	0.3582814	0.437103	226.41
9.6	0.353924	0.431787	225.76
9.7	0.3496073	0.426521	225.11
9.8	0.345331	0.421304	224.46
9.9	0.3410948	0.416136	223.81
10	0.3368985	0.411016	223.16

A8. Data Tables

Table 21: Historical Rigid Airship Database

HISTORICAL RIGID AIRSHIP DATABASE					
	Payload [ton]	Fuel [ton]	OEW [ton]	MTOW [ton]	He Volume [m^3]
ZODIAC TYPE	2	2	16	20	12800
LZ4	4.5	2.5	12	19	16000
LZ10	7	1.4	13.6	22	17800
HM	0.6	1.4	19.9	21.9	18800
S.L.1	4.5	1.1	19.3	24.9	19000
LZ24	9.2	4	16.9	30.1	25000
S.L.2	8	4	21	33	25000
LZ120	10	2.4	13.2	25.6	29000
CORSAIR	8	4	10	22	29500
LZ38	11.2	4.8	21	37	39000
LZ62	32.4	6.2	31.4	70	55000
NAVAL AIR	29.6	6.6	35.1	71.3	61000
LZ112	36.5	12	24.5	73	79000
LZ126	32	16	42	90	117220
DGPA 50T	50	20	66	136	130000
ROYAL AIRSHIP	62	30	90	182	141500
ZRS-4/5	80	60	110	250	209000
LZ129 HINDEMBURG	102	65	130	297	228561

Table 22: Surface Plan of Tail Element (Y-Configuration): Mathematical Passages

Surface Plan of Tail Element (Y-Configuration) Mathematical Passages	
START	$\begin{cases} S_{VT} = A + a_1 + a_2 \\ S_{HT} = b_1 + b_2 \\ A = \sqrt{b_1^2 + a_1^2} \\ a_1 = a_2 = a \\ b_1 = b_2 = b \end{cases}$
1 STEP	$\begin{cases} S_{VT} = A + 2a \rightarrow a = \frac{S_{VT} - A}{2} \\ S_{HT} = 2b \rightarrow b = \frac{S_{HT}}{2} \\ A = \sqrt{\frac{S_{HT}^2}{4} + \left(\frac{S_{VT} - A}{2}\right)^2} \end{cases}$
2 STEP	$A^2 = \frac{S_{HT}^2}{4} + \frac{S_{VT}^2}{4} + \frac{A^2}{4} - \frac{S_{VT}A}{2}$
3 STEP	$A^2 - \frac{A^2}{4} + \frac{S_{VT}A}{2} - \frac{1}{4}(S_{HT}^2 + S_{VT}^2) = 0$
4 STEP	$A^2\left(1 - \frac{1}{4}\right) + \frac{S_{VT}A}{2} - \frac{1}{4}(S_{HT}^2 + S_{VT}^2) = 0$
5 STEP	$A^2 + \frac{2}{3}S_{VT}A - \frac{1}{3}(S_{HT}^2 + S_{VT}^2) = 0$
END	$A_{1/2} = -\frac{2}{3}S_{VT} \pm \sqrt{\left(\frac{2}{3}S_{VT}\right)^2 + \frac{4}{3}(S_{VT}^2 + S_{HT}^2)}$

Table 23:Power as a Function of Speed: Mathematical Passages

Power as a Function of Speed: Mathematical Passages	
START	$\begin{cases} q = \frac{1}{2}\rho V^2 \\ g\,W = L_{aero} = q\,Cl\,Vol^{2/3} \\ P = q(C_{D0} + KCl^2)Vol^{2/3}V \end{cases}$
1 STEP	$Cl = \frac{g\,W}{q\,Vol^{2/3}} \rightarrow Cl = \frac{g\,W}{\frac{1}{2}\rho V^2 Vol^{2/3}}$
2 STEP	$P = C_{D0}qVol^{2/3}V + KCl^2qVol^{2/3}\,V$
3 STEP	$P = C_{D0}\frac{1}{2}\rho V^2 Vol^{2/3}V + K\left(\frac{g\,W}{\frac{1}{2}\rho V^2 Vol^{2/3}}\right)^2 \frac{1}{2}\rho V^2 Vol^{2/3}V$
END	$P = \frac{1}{2}C_{D0}\rho Vol^{2/3}V^3 + \frac{2K(gW)^2}{\rho Vol^{2/3}V}$

Table 24: Maximization of Ratio between Aero Lift and Drag: Mathematical Passages

Maximization of Ratio between Aero Lift and Drag: Mathematical Passages	
START	$\begin{cases} L_{aero} = C_{Laero}qVol^{2/3} \\ D = C_D qVol^{2/3} \end{cases}$
1 STEP	$\frac{L_{aero}}{D} = \frac{C_{Laero}qVol^{2/3}}{C_D qVol^{2/3}} = \frac{C_{Laero}}{C_{D0} + KC_{Laero}^2}$
2 STEP	$d\left(\frac{f(x)}{g(x)}\right) = \frac{f'(x)g(x) - f(x)g'(x)}{\left(g(x)\right)^2} = 0$
3 STEP	$\frac{1(C_{D0} + KC_{Laero}^2) - C_{Laero}(2KC_{Laero})}{(C_{D0} + KC_{Laero}^2)^2} = 0$
4 STEP	$C_{Laero} = \sqrt{\frac{C_{D0}}{K}}$

5 STEP	$\left(\frac{C_{Laero}}{C_D}\right)_{max} = \frac{\sqrt{\frac{C_{D0}}{K}}}{C_{D0} + K\frac{C_{Do}}{K}}$
END	$\left(\frac{L_{aero}}{D}\right)_{max} = \frac{1}{2\sqrt{C_{D0}K}}$

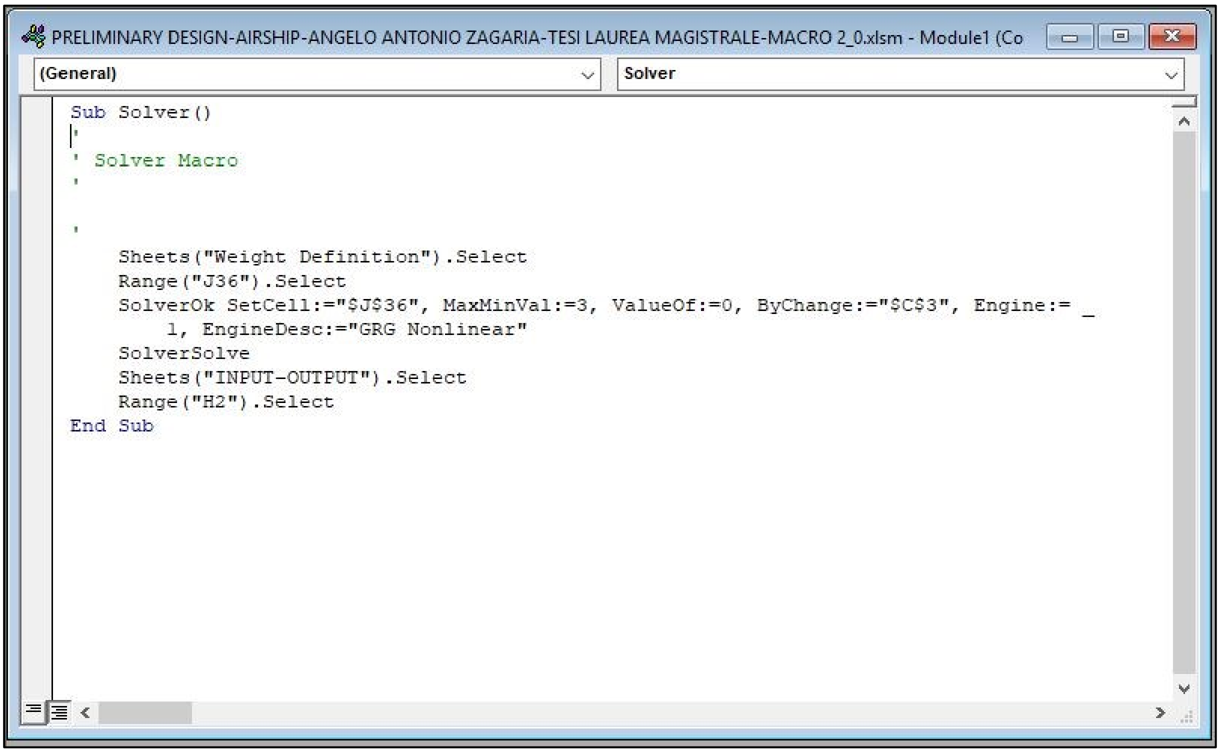
Table 25: Constant Speed for Minimum Drag: Mathematical Passages

Constant Speed for Minimum Drag: Mathematical Passages	
START	$\begin{cases} Cl = \frac{W_H}{q\,Vol^{2/3}} \\ D = qC_D Vol^{2/3} \end{cases}$
1 STEP	$D = q(C_{D0} + KCl^2)Vol^{2/3}$
2 STEP	$D = q\left(C_{D0} + K\frac{W_H^2}{q^2(Vol^{2/3})^2}\right)Vol^{2/3}$
3 STEP	$D = qVol^{2/3}C_{D0} + qVol^{2/3}\frac{KW_H^2}{q^2(Vol^{2/3})^2}$
4 STEP	$D = \frac{1}{2}\rho V^2 Vol^{2/3}C_{D0} + \frac{KW_H^2}{\frac{1}{2}\rho V^2 Vol^{2/3}}$
5 STEP	$\frac{dD}{dV} = 0 \rightarrow \frac{2}{2}\rho V\,Vol^{2/3}C_{D0} - \frac{2KW_H^2}{\frac{1}{2}\rho V^3 Vol^{\frac{2}{3}}} = 0$
6 STEP	$\frac{dD}{dV} = 0 \rightarrow \frac{1}{2}\left(\rho Vol^{2/3}\right)^2 V^4 C_{D0} - 2KW_H^2 = 0$
END	$V^4 = \frac{4KW_H^2}{(\rho Vol^{2/3})^2}$

Table 26: Sunrise and Sunset of Main City in 2018[1]

Sunrise and Sunset of main city at 2018										
			Daylight time hours[4-gen]				Daylight time hours[4-Jul]			
#	City	Latitude [°]	Sunrise[hh:mm]		Sunset [hh:mm]		Sunrise [hh:mm]		Sunset [hh:mm]	
1	Moscow	55.8	8	58	16	11	3	52	21	15
2	London	51.5	8	6	16	6	3	50	20	20
3	Paris	48.9	8	43	17	6	4	52	20	55
4	Rome	41.9	7	38	16	52	4	40	19	49
5	New York	40.7	7	20	16	42	4	30	19	31
6	Tokyo	35.7	6	51	16	40	4	30	19	1
7	Los Angeles	34.1	6	59	16	57	4	47	19	8
8	Cairo	30.1	6	51	5	8	4	58	19	0
9	Miami	25.8	7	8	17	44	5	34	19	16
10	Hong Kong	22.3	7	4	17	53	5	44	19	11
11	Mexico City	19.4	7	12	18	12	6	3	19	19
12	Bombay	18.9	7	13	18	15	6	6	19	20

[1] (ESRL, s.d.) - Source of this data is NOAA ESRL: https://www.esrl.noaa.gov/gmd/grad/solcalc/sunrise.html




```
Sub Solver()
'
' Solver Macro
'

'
    Sheets("Weight Definition").Select
    Range("J36").Select
    SolverOk SetCell:="$J$36", MaxMinVal:=3, ValueOf:=0, ByChange:="$C$3", Engine:= _
        1, EngineDesc:="GRG Nonlinear"
    SolverSolve
    Sheets("INPUT-OUTPUT").Select
    Range("H2").Select
End Sub
```

Figure 11-8: Instruction of Solver Macro

A9. Viscosity Estimation

A valid method to determine dynamic viscosity depending on the temperature is through Sutherland's law. The expression is:

$$\mu = \frac{ST^{\frac{3}{2}}}{X + T} \quad \text{(Equation 11-4)}$$

where S is Sutherland's constant that contains data of gas analysed and X is Sutherland's temperature. The table below shows these parameters for some gases.

Table 27: Sutherland's Constant and Temperature for Some Gases

	S	X
Aria	1.46E-06	110
CO	1.4E-06	109
CO2	1.55E-06	233
CH4	9.8E-07	155
Freon-12	1.48E-06	317
H2	6.5E-07	71
He	1.52E-06	98
N2	1.39E-06	102
NH3	1.89E-06	684
O2	1.65E-06	110

For the air, dynamic viscosity trend described by Sutherland's law is visible in the graph below, and is the same trend of each other gas.

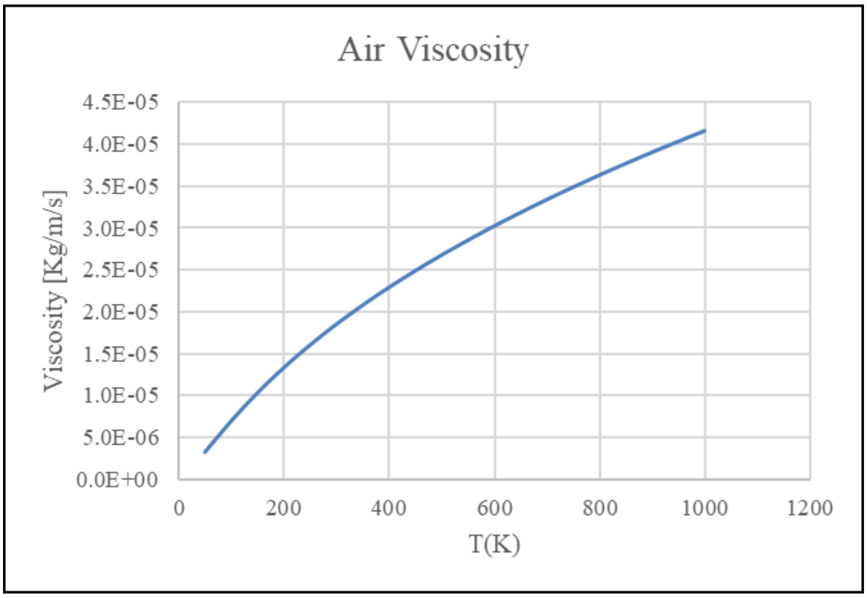


Figure 11-9: Air viscosity graph

BIBLIOGRAPHY

Airship. (n.d.). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Airship

Airship, E. (n.d.). *Corsair 1-8 T*. Retrieved from Euro Airship: http://www.euroairship.eu/index.php/corsair/

Airship, E. (n.d.). *DGPATT 50T*. Retrieved from Euro Airship: http://www.euroairship.eu/index.php/dgpatt/

Andrea, G., & Antonio, Z. A. (2018, May 3). Air Ship. Turin, Piedmont, Italy.

Carichner, G. E., & Nicolai, L. M. (2013). *Fundamental of aircraft and airship design. Volume 2-Airship Design and Case Studies.* (A. E. SERIES, Ed.) Blacksburg, Virginia, United State of America: American Institute of Aeronautics and Astronautics, Inc. 1801 Alexander Bell Drive, Reston, VA 20191-4344.

cmglee, N. (2015, 07 01). *Wikipedia*. Retrieved from Wikipedia: http://visibleearth.nasa.gov/view.php?id=73580

ESRL, N. (n.d.). Retrieved from : https://www.esrl.noaa.gov/gmd/grad/solcalc/sunrise.html

Grisales, A. (n.d.). *Airship Renders.* Turin.

Pasquerella, G. (1937, 05 6). *Wikipedia*. Retrieved from Wikipedia: https://commons.wikimedia.org/wiki/File:Hindenburg_burning.jpg

Richy. (2003). *Wikipedia*. Retrieved from Wikipedia: https://commons.wikimedia.org/wiki/File:SkyLanternRichy01.jpg

variantmarketresearch.com. (2017, April). *Airship Market*, Overview. Retrieved from Variant Market Research: https://www.variantmarketresearch.com/report-categories/defense-aerospace/airships-market

Wikipedia. (n.d.). Retrieved from https://en.wikipedia.org

RINGRAZIAMENTI

Ringrazio la mia relatrice, la professoresa Maria Cinefra per avermi seguito pazientemente lungo tutto il processo di sviluppo e realizzazione dell'elaborato. Ringrazio anche il corelatore, professor Erasmo Carrera e le aziende Pininfarina Extra e Euro Airship, poiché senza la loro presenza e il loro consenso l'elaborato non sarebbe mai esistito. A tal proposito ringrazio i tutori aziendali, l'ingegnere Francesco Lovo e Dan Mattanò per la grandissima disponibilità dimostratami in questi mesi.

Un traguardo così importante non vale niente se non vi è la gioia di condividerlo con le persone davvero importanti, che da sempre e in particolare per questo percorso universitario mi sono state accanto.

Un grazie infinito va alla mia famiglia sempre presente, in qualunque circostanza. Ringrazio i cugini, gli zii e i nonni a cui voglio loro un grandissimo bene. Ringrazio Tea, Matteo, Fonte, Nicola, Nino, Lidia, Angelo, Betti e Rita, persone meravigliose che con il loro supporto e la loro presenza reputo a tutti gli effetti membri della mia famiglia. Ringrazio le mie due fantastiche sorelle, Anna Pia e Gloria per il loro grande affetto anche quando ero scontroso. Non ci sono parole e azioni per dimostrare la mia gratitudine nei confronti dei miei "immensi" genitori, disposti a tutto pur di vedere realizzato questo obiettivo. Sarò sempre riconoscente per i mille sacrifici, le mille rinunce e le mille preoccupazioni che questo percorso vi ha inflitto.

Un grazie immenso va a Sabrina, la mia stupenda ragazza e fidata consigliera, a cui è toccato l'arduo compito di sopportare tutte le mie ansie, le mie preoccupazioni, i momenti di rabbia e di tristezza con un'impareggiabile capacità di ascolto.

Dico grazie agli amici di una vita come Antonio, Matteo e Giulia, pronti a rispondere anche dopo mesi di assenza e grazie anche a quelli più recenti, che hanno reso più facile l'ambientazione in una grande realtà come Torino e il Politecnico, quindi dico grazie al gruppo "Puglia e Basilicata", e ringrazio anche Alberto che ha reso il corso di Spazio in questi due anni più leggero. Tra questi un ringraziamento speciale a due grandi punti di riferimento come Leo e Cosimo. Per finire cito i due Cerignolani con cui questa avventura ha avuto inizio, grazie Sergio e Umberto.

In fondo è grazie a voi se il puzzle di questa fantastico percorso è completo. Davvero un grazie infinito.