DSE - Dirigible billboard

Create world's largest dirigible billboard

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Final Report V 2.0

Design Synthesis Exercise

PREFACE

The closing piece of the Bachelor degree of aerospace engineering at Delft University of technology is the Design Synthesis Exercise. In this project, students apply all knowledge acquired in the bachelor phase.

The objective of this report is to provide our client a feasibility study on their idea. The client, United Balloon, desires to create world's largest dirigible billboard. This technical report describes the feasibility study and the preliminary design.

DSE group 18, Diamond of Dubai, worked enthusiastically on this project for ten weeks. The project gave an unique opportunity to get some business experience, as well as training their engineering capabilities. Therefore, a word of thanks goes to United Balloon for providing this extraordinary project.

Finally Diamond of Dubai would like to thank Ir. D. Steenhuizen, the project tutor, and the coaches Dr.Ir. A.C. in 't Veld and Y. Guo MSc, who have contributed to the success of this project.

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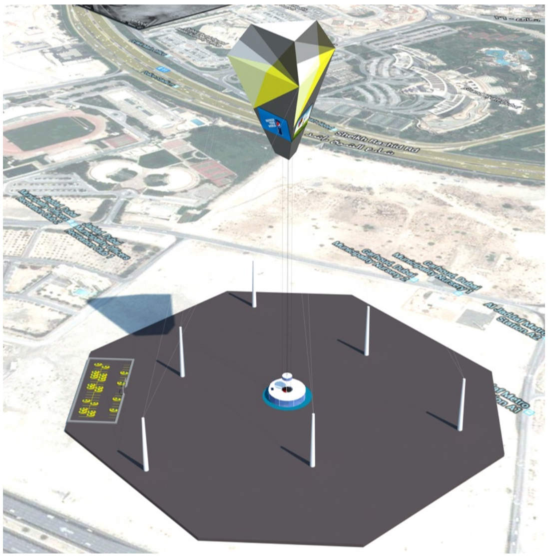
PROJECT SUMMARY

In the spring of 2014, DSE group 18 started the mission to design the world's largest dirigible billboard with a commercial focus, with ten students in ten weeks time. The customer is a company called United Balloon (UB). The need of UB is as follows: to reach a broad audience for advertizing and commercial purposes, a dirigible billboard having large video-displays, positioned at considerable height, providing sightseeing, initially deployed at the Wafi shopping mall in Dubai and viewable from Dubai's airport needs to be developed.

In order to fulfil this need, four reports are produced. In the project plan, the objective and need statements are given and an organogram and a preliminary project planning are made. The baseline report includes inter alia the specific requirements and design option trees. From these options, trade-offs and choices are made in the mid-term report, after which six design configurations are constructed, from which one design choice is made. In the final report this design is worked out in detail and analyzed. During the process, there has always been a lot of contact with the customer (four meetings, e-mails) and the mass, power & cost budget, the market, the technical risks, the RAMS, the design change sensitivity and sustainability are constantly kept track of. The last weeks were used to finish the final report (adding the latest minor improvements and quality checking) and preparing for the final presentation and the symposium.

The final design is a 95 m high inverted tetrahedron with a crown on top called "The Diamond of Dubai". The video-displays are LED curtains on the three sides, all of a size of 18 m x 32 m and a pixel spacing of 50 mm, which ensures good visibility up to a distance of 4 km. These screens are lifted using helium and kept stable on a height of 250 m using a total of 12 cables made of Dyneema, attached to poles on the ground of 50 m height. The internal structure, surrounding the helium balloon, is optimized for weight and made of carbon fiber. The internal structure is protected by an envelope made of Vectran, which is fail safe. A gondola supplies the possibility of sightseeing by bringing 50 people to a height of 200 m four times per hour. When ground wind speeds of >5 m/s occur, the dirigible needs to be lowered to a certain extent to guarantee stability. Ground wind speeds of >12 m/s require a safety mode, which comprises bringing the dirigible to the ground and tighten it strongly. This all results in a commercial and sightseeing spectacle, which costs €5 million and can be in regular operation 6750 h per year (77.1% up-time).



Visual of system parts and layout

CONTENTS

LIST OF SYMBOLS

Symbol	Description	Unit
A	Area	$[m^2]$
C_D	Drag coefficient	[-]
C_L	Lift coefficient	[-]
C_P	Pressure coefficient	[-]
D	Drag	$[N]$
E	Young's modulus	$[GPa]$
F	Force	$[N]$
H	Hellman exponent	[-]
I	Moment of inertia	$[m^4]$
L	Lift	$[N]$
M	Moment	$[Nm]$
P	Power	$[W]$
R	Radius	$[m]$
Re	Reynolds number	[-]
S	Reference area	$[m^2]$
S_f	Sharpness factor	$[P]$
T	Normalized vector	[-]
V	Volume	$[m^3]$
W	Weight	$[N]$
d	Distance	$[m]$
g	Gravitational acceleration	$[m/s^2]$
h	Height	$[m]$
k	Stiffness	$[N/m]$
l	Length	$[m]$
m	Mass	$[kg]$
p	Pressure	$[Pa]$
r	Radius	$[m]$
t	Thickness	$[m]$
v	Velocity	$[m/s]$
z	Vertical distance	$[m]$
α	Angle of attack	$[deg]$
μ	Dynamic viscosity	$[Pa*s]$
ρ	Density	$[kg/m^3]$
σ_y	Yield strength	$[Gpa]$
σ_{ult}	Ultimate yield strength	$[Gpa]$

1
INTRODUCTION

A group of ten Aerospace Engineering students from Delft University of Technology has been offered the chance to actively contribute to the project of developing the world's largest dirigible billboard. This dirigible should be fit to display advertizements to a large radius, as well as acting as a tourist attraction. The goal of the Design Synthesis Exercise (DSE) is to determine the feasibility of this project. This report is meant to provide an insight into the development of a previously chosen concept, by designing all subsystems sufficiently detailed to present a complete preliminary design. This report also presents post-DSE activities and the challenges that the group faced while addressing these tasks.

The dirigible offers a unique possibility for companies to advertize. Being able to produce an effective advertizing campaign can have a huge positive impact on the success of a company or of a specific product. The ultimate goal is to reach as many customers as possible and to capture their attention with new advertizing methods and techniques.

With this objective in mind, the company United Balloon has decided to finance a project to design and develop the world's largest dirigible billboard, which is to be deployed in Dubai. The characteristics of this system would not only allow for a huge visibility of the advertizement, but also attract tourists and potential customers due to the innovative project and the activities it offers, such as sightseeing. In fact, the idea of combining an advertizing purpose with a commercial one allows for this to be a profitable opportunity both for the company renting out the large visual-displays on the blimp and for the company manufacturing it. United Balloon is ultimately planning on developing around 25 of these dirigible billboards in the next ten years, including some smaller in size for easier transportation to events. Nonetheless, the group of Aerospace Engineering students will only focus their research on the design of the first and largest of the aerostats and has decided to name the project "Diamond of Dubai".

Dubai, known as the financial capital of the Middle East, is a very dynamic business center. The company manufacturing the billboard is located in The Netherlands, but deciding to develop a marketing idea in such a global city, the business and cultural hub of the Middle East region, will help the companies involved to grow internationally. Although Dubai's economy was initially built on the oil industry, the ever-developing center now bases its main revenues on tourism, aviation, real estate and financial services. The world's largest dirigible billboard will be a top-notch addition to the list of the ambitious and innovative large construction projects that Dubai has to offer and it will contribute to increase the number of tourists expected by 2015, currently over 15 million [1].

This report, the final report, continues on the mid-term report. In the mid-term report, trade-offs were made for the different design options for all components and subcomponents of the main system. With this info and different combinations of subsystems six design concepts were chosen. A final trade-off was used to determine the final concept. In this report, this concept and the subsystems will be designed in more detail to, in the end, come up with the preliminary design of the aerostat. Next to the designing, it is also important to think about the post-DSE activities, especially since the "Diamond of Dubai" is a real project that should be launched in September 2015. Throughout this report, the terms balloon, blimp, aerostat, billboard and dirigible will be used interchangeably and will all refer to the dirigible billboard.

The report is divided in six parts. The first part specifies the requirements and constraints. In this part the budget breakdown, requirements and preliminary lay-out are discussed as they can be found in previous reports.

The second part covers the design process. Here, the considerations and calculations on the design are treated on the aspects of payload, structures and aerodynamics. At the end of this part one final layout is presented. The following part, part III, describes the specifications of this design. All aspects regarding its characteristics and operation are listed and elaborated upon. Part IV covers different types of analyses, ranging from performance to compliance. These give more insight in the details of the design and how it fulfills the requirements. Part V of the report describes the post-DSE planning. Activities to be performed after the DSE are listed and recommendations on additional research and possibilities are given. To aid in the continuation of the design process, a technical design risk map is created. Finally, in Part VI consists of appendices of the report.

To have an overview of the way in which the entire project was structured from the beginning till the end in a timewise manner, one could take a look at the Gantt charts for the project plan, baseline report, mid-term report and final report, given in appendix B.

2
INITIAL BUDGET BREAKDOWN

Apart from the requirements given by United Balloon and the constraints placed on the design, in the Mid-term report certain values have been estimated regarding mass, finances and power. These values act as upper bound for the distribution of these resources over the project subsystems. These self-placed constraints guide the project into a predictable path.

In this chapter the budget is broken down from a total estimate into separate components and after the design is finished, the budget will be built up and compared to these estimates. Section 2.1 shows a preliminary mass budget, 2.2 a preliminary power budget and 2.3 a preliminary cost budget. Finally section 2.4 shortly discusses the contingencies as stated in the Mid-term report [2].

2.1. MASS BUDGET

At the start of the conceptual sizing of the balloon, a rough preliminary weight estimation was made. Multiple iterations have been undertaken to reach the final weight of the balloon. The weight of the air segment is of major importance in the design of the aerostat. In table 2.1, the masses of all elements of the air segment are listed. The weight of the ground segment has not been estimated, as it is not a constraint in the mission. The total mass of the air segment will approximately be 96000 kg.

Table 2.1: Mass budget breakdown [2]

Element air segment	Mass [kg]	Percentage of MTOW [%]
Screens	19 000	20
Envelope	20 000	22
Structure	35 000	38
Connection cables (8)	3 000	3
People	6 000	6
Cooling system	5 000	5
Electronic cabling	3 000	3
Lighting	2 000	2
Lift & Gondola	3 000	3
Total mass	96 000	100

These estimated values are difficult to validate, as this type of design is the first in its kind, which means that references for this design are severely lacking. The estimations do, however, give more insight into the division of weight amongst the different systems of the aerostat. Because of this large uncertainty in weight, a large contingency value has been chosen, which is further discussed in section 2.4. This will be carefully managed during the design phase.

2.2. POWER BUDGET

In the same way as for the mass, the power budget has been estimated and split up over the separate power consuming components within the system. This distribution is shown in table 2.2.

Table 2.2: Power budget breakdown [2]

Element air segment	Power [kW]	Percentage of total power [%]
Screens	600	80
Lighting	10	1.4
Airconditioning Gondola	10	1.4
Lift/Gondola	100	13.4
Pumps/Compressor	10	1.4
Cable retraction system	7	1
Deployment protection system	1	≈ 0
Control electronics	2	≈ 0
Other systems	10	1.4
Total power	750	100

The power system contains many components, but the screens by far require the largest part of the power supply. This is to be expected, as they are the main payload of the dirigible. The power estimate can be refined once the exact screen size and specific power consumption are determined.

2.3. COST BUDGET

To determine how much the maximum expenditure per subsystem is, the total budget has been determined first. This has been done by adding the turnover for the first three years and subtracting costs as certification, operation costs and insurance. The remainder is distributed for development and production of the aerostat's systems. This distribution is shown in table 2.3. The worst-case scenario has been used, with large development requirements and large amounts of material. The cost of construction materials varies greatly, depending on the material used. For the total cost, the worst case scenario has been used again, which is in this case using carbon-fiber-reinforced polymer (CFRP).

Table 2.3: Cost budget breakdown [2]

Element air segment	Estimate cost [million euros]	Percentage of total cost
Screens [3]	2.5	6
Envelope	2	5
Structure	35(CFRP), 17.5(Glass fiber) or 5.5 (Al)	85
Ground station + control	1	2
Gondola	0.5	1
Gas	0.3	1
Total cost	41.3	100

2.4. CONTINGENCIES

The values previously estimated in sections 2.1 and 2.2 give an idea of the order of magnitude of the weight and total power consumption. Estimation of these values could, however, not be done as accurately as desired, so relatively large contingency values are needed. These contingencies are carefully managed throughout the entire design process, frequently updating current estimates to see if all values still fall within their margins.

Table 2.4: Contingency measures for major parameters [2]

	Contingency %		
Design Phase	Dirigible cost	Take-off Weight	Power consumption
Mid-term conceptual design	40%	20%	45%
Layout design	30%	20%	40%

Especially the contingency for the power consumption is very large. This is mainly due to the low priority that power consumption has for the design, because of the relatively low electricity prices in Dubai. Screens are mainly selected on their specific weight and specific power is regarded less important. This results in a larger allowance regarding power fluctuation and thus a larger contingency.

3 Requirements

In this chapter, all requirements for the DSE project "World's largest dirigible billboard" are listed. Section 3.1 will derive extra requirements that follow from the need for certification and section 3.2 lists all requirements that have previously been discovered.

3.1. Certification requirements

In this section, the extra requirements that follow from certification specifications have been documented. The document used for certification is the CS-31TGB [4], which states the certification specifications for tethered gas balloons. It is assumed that if the balloon is certified according to the strict European CS-31TGB document it can be certified for Dubai. From this document, the requirements which are of importance for the design of the worlds largest dirigible billboard have been stated. As a result, the requirements that will be discussed are on the structures and materials topic.

Since different loading definitions are used in certification, they are shortly elaborated on before certification requirements are stated. Afterwards, the relevant requirements are listed.

3.1.1. Load definitions

The two load definitions used in certification are the limit load and ultimate load. These are defined as follows:

Limit loads are the maximum loads to be expected in service multiplied with a factor of 1.4.

Ultimate load is the limit load multiplied by a safety factor.

3.1.2. Safety factors and constraints

In this section, the safety factors that need to be used are stated and relevant structural requirements are documented. The certification document prescribes a set of safety factors for different structural components, as well as a set of constraints for the dirigible and gondola. The safety factors can be found in table 3.1 and the requirements will be listed afterwards.

Table 3.1: Safety factors to be used in the final design process [4]

	Safety factor
Envelope	5.0
Tethering components (non-metallic)	3.5
Tethering components (metallic)	2.5
Other	1.5

Certification requirements

- CR-001 The minimum mass of a gondola tourist shall be at least 77 kg for all design purposes

- CR-002 The structure shall be able to support limit loads without plastic deformation or other detrimental effects
- CR-003 The structure shall be able to withstand ultimate loads for at least 3 s without failure
- CR-004 The envelope material shall be designed in such a way that when a crosswise slit of 5 cm is present, the damage will not propagate under maximum occurring tension loads
- CR-005 The envelope shall be installed with an automatic overpressure safety valve
- CR-006 During emergency landing of the gondola, the descent speed shall not be higher than 1 m/s, with a maximum occurring load factor of 2

Compliance to these certification constraints is checked after the design is finished in chapter 19. An iteration loop may be initiated when the design does not meet the necessary requirements.

3.2. LIST OF REQUIREMENTS

The following sections will list the requirements for the DSE "World's largest dirigible billboard". These were derived in the baseline report [5]. Also these requirements will be checked in chapter 19. Some of the requirements are 'dropped'. The reason why these requirements are dropped can be found in section 3.2.7.

3.2.1. GROUND SEGMENT REQUIREMENTS (GSR) - PERFORM MISSION TECHNICALLY (PMT)

- GSR-PMT-001: The ground segment shall have attachment points for the air segment for stability of the air segment
- GSR-PMT-002: The ground segment shall provide a means to move the air segment up and down, both for initial deployment and for sheltering
- GSR-PMT-003: The ground segment shall provide space for a possible elevator for people
- GSR-PMT-004: The ground segment shall provide 750 $kWatt$ of power to the air segment
- GSR-PMT-005: The ground segment shall provide sufficient power to itself
- GSR-PMT-006: The ground segment shall have a power backup system that provides 160 $kWatt$ of power
- GSR-PMT-007: The ground segment shall provide a communication system to the air segment
- GSR-PMT-008: The ground segment shall provide a video display connection to the air segment

3.2.2. GROUND SEGMENT REQUIREMENTS (GSR) - PERFORM MISSION WITHIN CONSTRAINTS (PMWC)

- GSR-PMWC-001: It shall be possible to perform maintenance to the ground system during operation
- GSR-PMWC-002: The maximum maintenance time for the ground segment shall be no more than 56 days per year
- GSR-PMWC-003: Dropped
- GSR-PMWC-004: The total cost of the ground segment shall be within 40 000 000 euro minus the cost of the air segment and the control segment
- GSR-PMWC-005: Dropped
- GSR-PMWC-006: The ground segment shall have a probability no higher than 0.1% to cause damage to any humans
- GSR-PMWC-007: The ground segment shall have an operationally deployed ground-area of at most 25x25 m

3.2.3. CONTROL SEGMENT REQUIREMENTS (CSR) - PERFORM MISSION TECHNICALLY (PMT)

- CSR-PMT-001: The control segment shall be able to return the air segment safely back to the ground in case of an emergency
- CSR-PMT-002: The control segment shall be operational at all times
- CSR-PMT-003: The control segment shall provide the elevator for people to go up and down 4 times per hour
- CSR-PMT-004: The control segment the sightseeing mechanism shall be operational from 10h till 00h
- CSR-PMT-005: The control segment shall control the video messages on the advertizement screens
- CSR-PMT-006: The control segment shall receive sufficient power at all times
- CSR-PMT-007: The control segment shall have an emergency power backup
- CSR-PMT-008: The hardware of the control segment shall have a manual control interface
- CSR-PMT-009: The hardware of the control segment shall be installed with displays
- CSR-PMT-010: The hardware of the control segment shall include a data log storage facility
- CSR-PMT-011: The software of the control segment shall have a user friendly interface
- CSR-PMT-012: The software of the control segment shall have an error detection system for system malfunction
- CSR-PMT-013: The software of the control segment shall have an emergency procedure in case of loss of the control segment
- CSR-PMT-014: The control segment shall occupy no more than 20 m^2 of ground area

3.2.4. CONTROL SEGMENT REQUIREMENTS (CSR) - PERFORM MISSION WITHIN CONSTRAINTS (PMWC)

- CSR-PMWC-001: Dropped
- CSR-PMWC-002: Dropped
- CSR-PMWC-003: The total cost of the control segment shall not exceed 40 000 000 euro minus the cost of the air segment and the ground segment
- CSR-PMWC-004: The control segment shall have a backup control computer in case of a control segment loss
- CSR-PMWC-005: The control segment shall have the possibility to accept a software update

3.2.5. AIR SEGMENT REQUIREMENTS (ASR) - PERFORM MISSION TECHNICALLY (PMT)

- ASR-PMT-001: The air segment shall provide sufficient lift to support the entire air segment plus an additional 20% of lift
- ASR-PMT-002: Dropped
- ASR-PMT-003: The air segment shall receive sufficient power for operation
- ASR-PMT-004: The air segment shall support an elevator-like device
- ASR-PMT-005: The air segment shall provide stability for the people and the display
- ASR-PMT-006: The air segment shall support sightseeing

- ASR-PMT-007: The air segment shall have an esthetically pleasing look
- ASR-PMT-008: The air segment shall have a minimum of 350 m of building clearance
- ASR-PMT-009: The air segment shall withstand ultimate load, 1.5x the normal loading, for at least 3 s
- ASR-PMT-010: The video screen of the air segment shall be visible in 360 deg
- ASR-PMT-011: Dropped
- ASR-PMT-012: The video screen of the air segment shall have a sufficient resolution to be visible from 350 m
- ASR-PMT-013: The video screen of the air segment shall be visible out of the terminal of Dubai airport
- ASR-PMT-014: The air segment shall be rain proof
- ASR-PMT-015: The air segment shall be able to withstand the aerodynamic loads acting on it
- ASR-PMT-016: The air segment shall withstand the local thermal conditions
- ASR-PMT-017: The air segment shall withstand a UV index of 12 (daily Dubai weather conditions)
- ASR-PMT-018: The air segment shall be able to resist or be protected against the abrasive sand for a period of 10 years
- ASR-PMT-019: The altitude of the video screens shall be at least 250 m
- ASR-PMT-020: The air segment shall be able to transport a group of 50 persons at once to and from a height of 200 m for sightseeing
- ASR-PMT-021: The air segment shall comply with the EASA CS-31TGB airworthiness regulations
- ASR-PMT-022: The air segment shall be able to get into safety mode for emergency sheltering within 24 hrs.

3.2.6. AIR SEGMENT REQUIREMENTS (ASR) - PERFORM MISSION WITHIN CONSTRAINTS (PMWC)

- ASR-PMWC-001: Maintenance of the air segment shall be possible during lifetime operation
- ASR-PMWC-002: The maximum maintenance time of the air segment shall not take more than 56 days per year
- ASR-PMWC-003: Dropped
- ASR-PMWC-004: The total cost of the air segment shall not exceed 40 000 000 euro minus the cost of the ground and control segment
- ASR-PMWC-005: Dropped
- ASR-PMWC-006: Dropped
- ASR-PMWC-007: Dropped
- ASR-PMWC-008: The air segment shall have a minimum operational life time of 10 years

3.2.7. DROPPED REQUIREMENTS

After consultation with United Balloon, the following requirements have been dropped. It was considered the requirements were no longer applicable.

- GSR-PMWC-003: The mass of the ground segment shall be lower than 113 000 kg
- GSR-PMWC-005: The individual components of the ground segment shall fit in one or multiple sea containers (13.5 x 2.3 x 2.6 m)
- CSR-PMWC-001: The mass of the control segment shall not exceed 113 000 kg
- CSR-PMWC-002: The sizes of the individual components of the control segment shall fit in a sea container (13.5 x 2.3 x 2.6 m)
- ASR-PMT-002: The air segment shall provide <TBD> % power of the total required power
- ASR-PMT-011: The video screen of the air segment shall have a power consumption lower than <TBD>
- ASR-PMWC-003: The total mass of the air segment shall not exceed 100 000 kg
- ASR-PMWC-005: The individual components of the air segment shall fit in one or multiple sea containers of (13.5 x 2.3 x 2.6 m)
- ASR-PMWC-006: The air segment shall be protected from serious damage during transport
- ASR-PMWC-007: The entire project shall be CO2 neutral

4
SAFETY MODE CONCEPT TRADE OFF

After doing research on stability and the input from United Balloon, it was decided to first look into more options before starting with the final design of the safety mode. The initial plan of using a hangar to store the dirigible, as was described in the mid-term report [2], is not an option anymore, because too much space is needed. Different alternative methods explored are a deflatable and collapsible structure, a structure with removable building blocks and the option to make the aerostat life safe. An explanation of the two collapsible structures can be found in section 4.1 and the life safe structure in section 4.2. In section 4.3 the envelope and screen protection can be found and finally a trade-off is made between all options in section 4.4.

4.1. COLLAPSIBLE STRUCTURE

The idea for a collapsible structure is based on the philosophy that the lower the height of the structure is, the lower the wind force is that acts on it. This is true because the wind speed is lower near the ground, and because the frontal area reduces when the structure collapses. Two options are considered to collapse the structure: folding by joints or disassembling by blocks. The former proposes a structure that is foldable by hinges and joints, lowering the height by folding up the bottom of the dirigible. The latter means parts of the balloon (so called 'blocks') might be easily removed to lower the total height of the dirigible.

Collapsing of the dirigible structure is difficult due to five reasons. Firstly, extra weight is needed to add strong joints in the case of collapsing, or to add bolts or other connecting pieces in case of building blocks. Secondly, it is more complex to design, because of the gondola and its platform, which are located under the dirigible. Thirdly, helium needs to be pumped out, which is time-consuming. Fourthly when building blocks are going to be used, compartments with separate helium bags are needed, which add weight to the structure compared to one or two big bags. Finally, when a foldable structure is used, a complex and probably heavy system needs to be designed to control the way the aerostat folds.

Based on these drawbacks, it is estimated that a fully collapsible structure or a structure with a lot of building blocks is infeasible. However, a structure that is partly collapsible or consists out of two building blocks gives a more feasible design, as shown in figure 4.1. The structure lays stable on the ground and just a small part with little helium needs to be folded. Dividing the dirigible into two large building blocks (upper and lower) is not considered since the bottom one is still too big to store. Splitting the dirigible up into more building blocks will make the structure heavier. The good thing about this design is that it lays stable for the hard winds and is easy to anchor. Since this part contains little helium, it takes less time to pump it out. With the most powerful helium pump available on the market, the hostirad TP-800DE [6], and a pumping time of 12 hours, it takes three pumps, costing 23 000 euro each, to take the bottom part down, given that it contains 25% of the helium, which is approximately $120 \cdot 10^3\ m^3$.

4.2. LIFE SAFE STRUCTURE OPERATION

The last option that is considered is to design the dirigible so that it is life safe. This means that it is resistant to all forces and degradation it might encounter over its operational lifetime. Although this would require stronger structural members, it would save weight and complexity on joints and bolts.

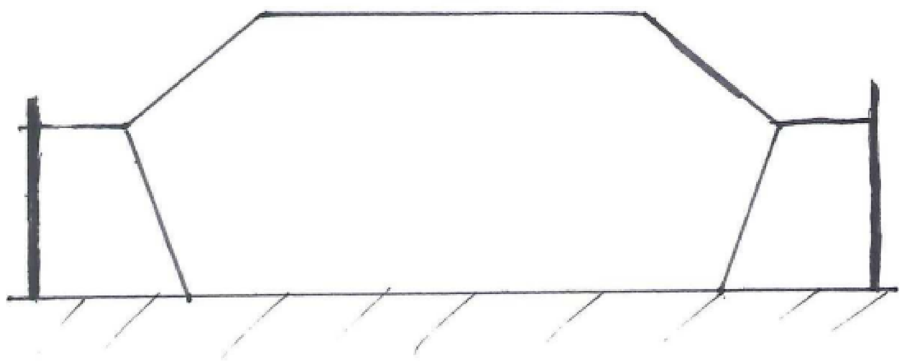


Figure 4.1: Foldable aerostat in safety mode

If the aerostat is able to resist storms without collapsing, it saves for the operations and the needed ground space for storage. On the other hand, a heavier, more expensive structure is needed to withstand the forces that occur during a storm. However it is most likely that a life safe structure is less heavy than a collapsible structure. Stability is important to consider. Two steps that should be performed are lowering the aerostat for less wind force and placing the center of gravity as low as possible for more stability. Next to that, the envelope and the poles should be designed to survive sandstorms.

Lowering of the air segment can be achieved by retracting the cables, pumping out helium, increasing ballast such as pumping up water or air. The last two options are preferable for the stability. Since retracting the cables is by far the easiest way to lower the system, this is going to be done first when entering safety mode. Pumping helium or air takes a long time and if water or air needs to be pumped up, extra space is needed to store it, which makes the structure heavier. Because of this, the best option to stabilize the aerostat when it is down is to pump out a certain amount of helium with the pumps suggested in section 4.1.

4.3. ENVELOPE AND SCREEN PROTECTION

In case a collapsible structure is used, the fact that the structure will be folded should be taken into account when choosing an envelope material. In this case, a flexible, yet resistant material needs to be used for the envelope of the aerostat. In case of a life safe structure, the envelope material does not have to be particularly flexible, as long as it is strong enough to protect the internal structure and helium bags from UV radiation, sand abrasion and water corrosion. When the blimp is lowered to its safety mode configuration and the cables are tensioned, it must withstand winds up to approximately 100 km/h during heavy sandstorms. Long exposure to strong sandstorms can damage the envelope due to friction and abrasion acting on the surface. In order to limit the maintenance interventions, the material chosen will have to provide a good balance between weight, strength and flexibility. A more accurate investigation on these will follow in further chapter 8.

The screens are the most delicate part on the aerostat. Although current outdoor visualization systems are generally waterproof and have thin layers to protect the internal electronics, it is not possible to find screens on the market that can withstand the extreme weather conditions that they would be subjected to in Dubai. The screens would be operative at least 300 days a year and must be operational in temperatures up to 45 degrees Celsius during the summer. In case of a collapsible structure, the screens must be mounted on the aerostat so that the detaching mechanism is relatively easy, in order to facilitate the safety mode procedure. The screens could then be placed in a sheltering location on-site. Otherwise, if a very controlled collapse is allowed, the screens may be left on the blimp. In case the aerostat is made life safe, the screens also need to withstand the mentioned conditions.

Several screen guards are currently on the market and different materials are used for them. The most common material is acrylic, which is also used to manufacture window and roof panels designed to withstand North America's extreme conditions, including perpetual heatwaves, pounding hail, torrential rains, and crushing snowstorms [7]. Although Dubai has the opposite climate, extremely hot, acrylic performs well against UV radiation, as well as sand abrasion. This kind of cover would be mounted on the screens before attaching them to the blimp. This transparent and light panel would constantly be protecting the screens without obstructing visibility [8].

An alternative material choice to cover the screens is to use polyurethane layers similar to the ones used to protect smartphone screens. Such material has high optical transmittance of light, excellent UV-stability, good electrical insulation and it is often used for aerospace application because of its wide range of mechanical properties, from flexible to hard all extremely tough [9]. Thanks to their good adhesion to a large variety of surfaces, these layers could easily be placed on the screens and only occasionally be peeled off one by one, for maintenance reasons. Although the sizes of the screens may be way larger than the ones these products are usually designed for, lots of companies are willing to customize their screen protectors to the client's needs.

4.4. SAFETY MODE TRADE-OFF

Table 4.1: Safety mode trade-off

	Complexity 30%	Cost 10%	Ground area 15%	Speed 25%	Weight 20%	Total 100%
Collapsible by joints	2	1	3	3	2	2.3
Collapsible by blocks	1	3	1	1	2	1.4
Life safe	5	4	5	5	4	4.7

The categories analyzed in this trade-off table are complexity, cost, ground area, speed and weight. The complexity relates to the process required to enter the safety mode configuration. It was given a 30% weight because it is important that the process runs as smooth and controlled as possible. Next, speed had a weight of 25% because of the 24 hours time constraint in which the system needs to enter safety mode. The weight of the safety mode subsystem followed with an impact of 20%. In fact, making the aerostat foldable would for example increase the weight of the internal structure because joints would need to be included. Ground area was given a weight of 15% because United Balloon presented it as a relatively important factor, both for feasibility and financial reasons. Finally, the cost of the safety mode subsystem was evaluated to impact the trade-off by 10%.

From the table, it becomes clear that the life safe design is the best option out of the three design options. The positive side to this concept is that it does not involve a lot of complexity, since only the cables need to be tightened to lower the structure. Besides, this structure is in position relatively fast and it does not need a ground area to lay down.

5 PRELIMINARY LAYOUT

In this chapter, the preliminary layout of the dirigible billboard will be presented up to the stage just after selecting the final design concept, which can be found in the mid-term report [2]. All design decisions that were made up to this point are documented below.

The air segment will be in the shape of a three-sided diamond. The envelope of the aerostat will be reinforced with an internal structure, which will be made out of glass fiber composites. The envelope material is still to be determined. The inside of this envelope will consist of a compartment that will be filled with helium gas to provide lift to the air segment. Stability will be provided by the use of an aerodynamic shape, which will include rounded corners, and by tethering the air segment to the ground with multiple cables. To reduce the ground space, the ground attachment can be done on poles. The safety mode of the air segment is still under investigation, but lowering of the air segment will most likely be achieved through retractable cables, possibly combined with increasing ballast on the air segment.

Advertiszments will be displayed on LED arrays that will be placed on the air segment. Three of these arrays will be placed on the air segment, the size of each of these will be 18 m x 32 m. The sightseeing mechanism will consist of a gondola, suspended by a single cable and stabilized by three extra cables. An engine on the air segment will enable the gondola to move up and down. The gondola will be round. Power to all this will be provided by the grid. Finally, in order to transport this electricity and, among others, gas up to the air segment, one additional, specialized cable will be used.

Figure 5.1 depicts the preliminary layout of the air segment.

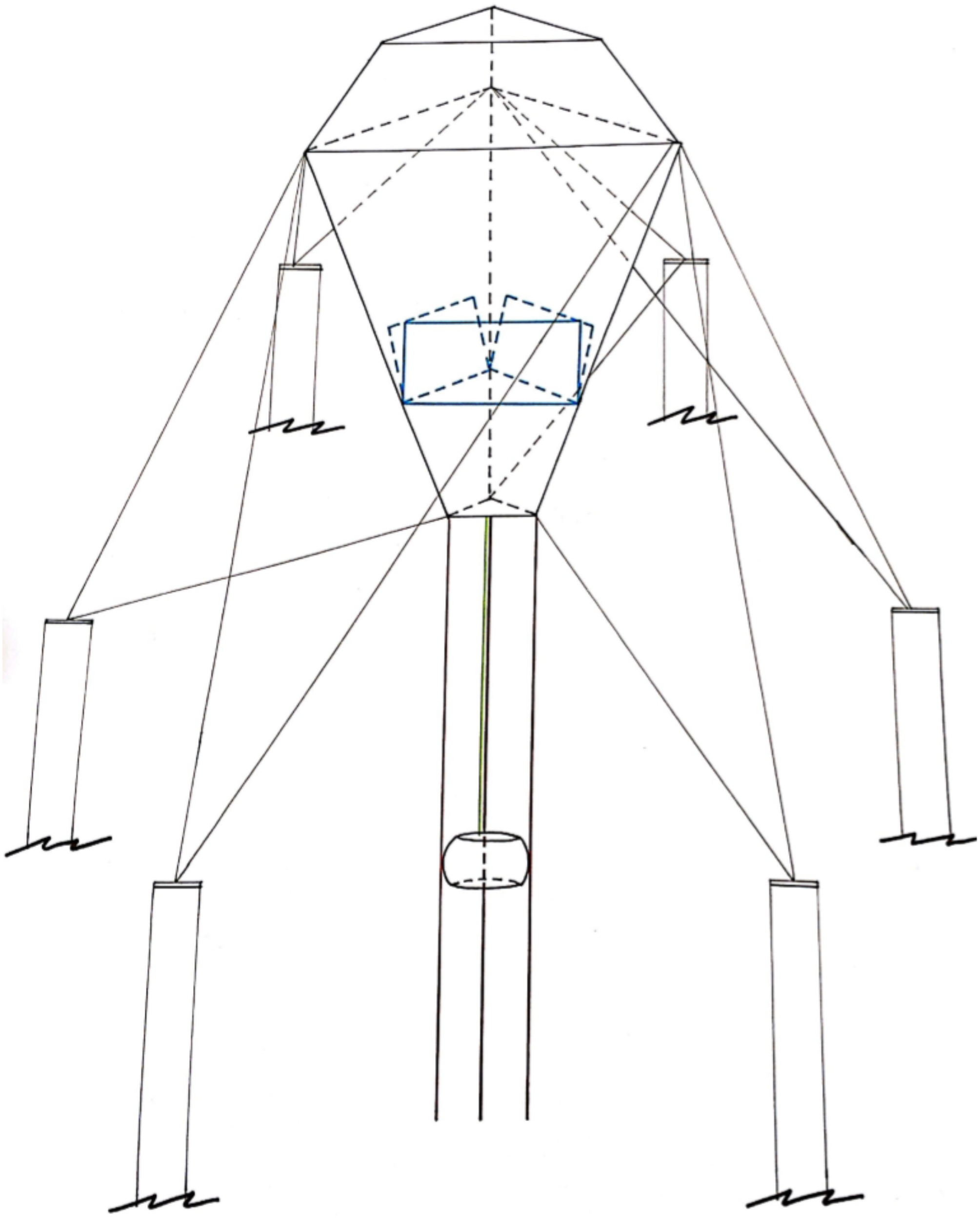


Figure 5.1: Preliminary layout of the air segment

6
PAYLOAD SPECIFICATIONS

The payload consists of a visualization system and a sightseeing system. One of the most important aspects of the mission of "Diamond of Dubai" is to keep these systems in the air. Both systems will impound a large part of the total weight of the system. Therefore, the total amount of payload weight needs to be determined before starting the final design. For both systems a preliminary design is made in this chapter, followed by a weight estimation. This is done in section 6.1 - 6.2 for the visualization system and in section 6.3 for the sightseeing system.

6.1. VISUALIZATION SYSTEM SPECIFICATIONS

This section will address the specifications of the visualization system. First, the effect of the screen size on the viewing distance will be discussed in section 6.1.1. After that, in section 6.1.2, the screen dimensions as determined in cooperation with United Balloon will be stated. Next, the required pixel density will be calculated in section 6.1.3, to make sure the advertizements look sharp. In the last section, the dimensions of the screens and weight of the LED curtains are used to get the weight of the visualisation system.

6.1.1. VISIBILITY AREA

The size, that is the height in meters and the width following from a 16:9 ratio, of the screens affects three things: the viewing distance, the visibility area and the weight of the balloon. The first has a linear relationship with respect to the height of the screen. Twice the screen size is twice the viewing distance. The last two have a quadratic relation with respect to the height of the screen. A problem arises from the relation between the viewing distance and the increase in weight (and size) of the balloon: when the viewing distance is doubled, the weight increases by a factor of 4. It is therefore favourable to select the smallest screen size possible. To be able to do this, three visibility area maps were created, which are shown in figures 6.1, 6.2 and 6.3. The terminal of Dubai airport is indicated by the red line North-East of the dirigible.

The figures are read as follows: the gray area is the maximum distance from which a letter can be read, for example a McDonalds 'M', or a recognizable logo can be seen, for example the BMW logo. The yellow area is the area from which actual text logos can be read, for example the Samsung logo or 'Life's Good' from LG. The green area is the area in which actual text can be read on the screens, for example 'Have a break, have a KitKat'. If required, more about readability of logo's and text can be found in the Mid-Term report [2].

It can be noticed that the area covered increases by a large amount with increasing screen heights, however the particular coverage of Dubai International Airport is not increased by much. In cooperation with United Balloon, the visibility area of figure 6.2 was selected, which has a screen height of 18 m. This corresponds to a radius of the yellow area of 4 km.

6.1.2. VISUALIZATION SYSTEM DIMENSIONS

Since the screens are attached to the balloon under an angle, the apparent size is less when viewed from a direction in which the screens are not directly pointed. This is not about the horizontal viewing angle, as one screen will be pointed towards the airport, but the vertical viewing angle. For example, when the attachment

Figure 6.1: Visibility area for 13.5 meter high screen, outer ring radius of 4.9km

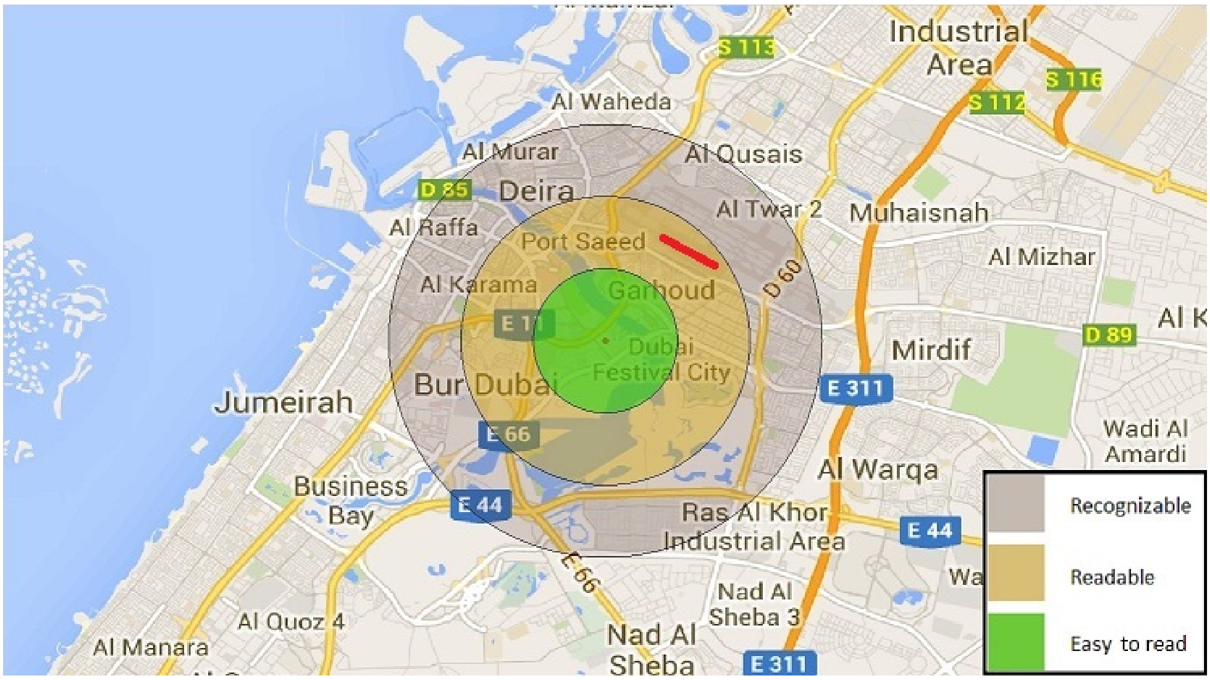


Figure 6.2: Visibility area for 18 meter high screen, outer ring radius of 6.5km

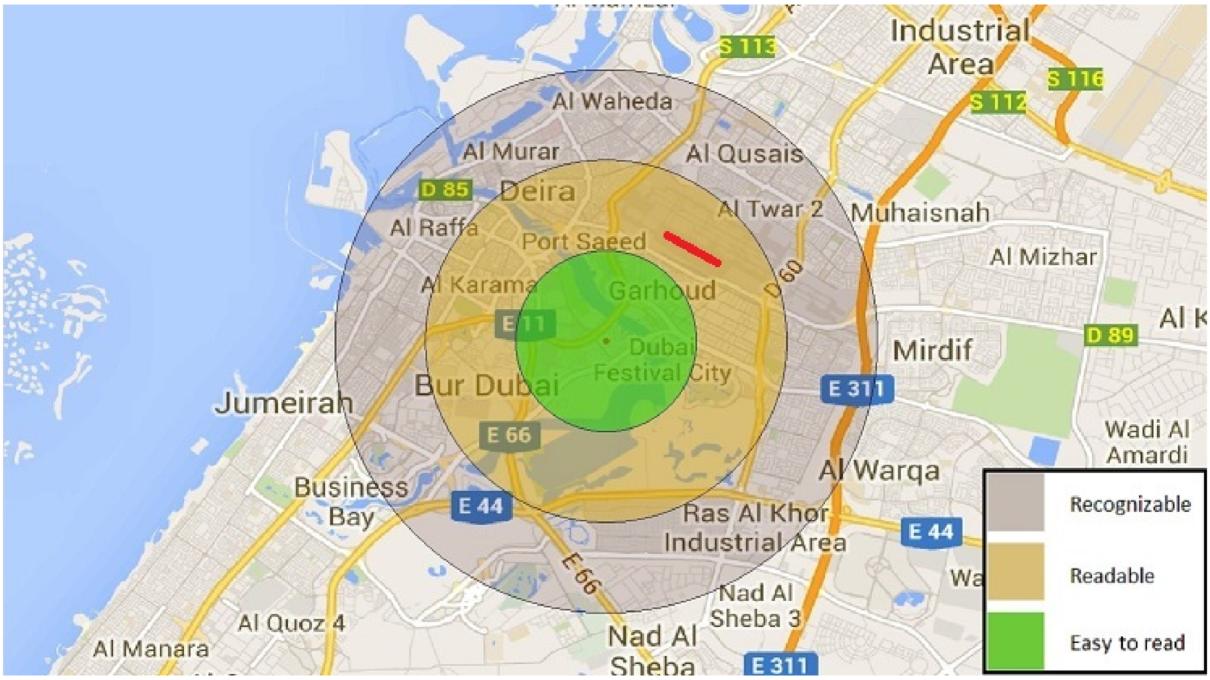


Figure 6.3: Visibility area for 22.5 meter high screen, outer ring radius of 8.1km

angle is 30 degrees, the viewing angle is 26.5 degrees. This is less than the 30 because of the look-up angle of 3.5 degrees when the screens are at a height of 250m at 4km distance. The 26.5 degrees would yield a size perception 10% smaller, which is within the coverage area of Dubai Airport and thus of minor concern.

Next to the reduced perception, another issue to consider are the maximum viewing angles of the screens selected. The type of screens that are selected in section 6.1.4 have a typical viewing angle of 120 degrees [10][11][12]. This means that at 60 degrees above or below the center line, the light intensity is halved. Since the brightness of the screens exceeds the minimum, 1000 candela, by more than a factor of two [10][11][12] and the actual maximum viewing angles are less than 60 degrees, this is not problem.

The width of the screen was determined in cooperation with United Balloon by setting the screen ratio at 16:9, yielding a width of 32 meters. This leads to a total screen area of 1728 m^2, or 576 m^2 per screen, as calculated in equation 6.1. The aspect ratio of the screen was chosen by UB due to the advantages of weight and simplicity, while also being the most convenient ratio for commercials, as those are already created in a 16:9 format.

$$3 \cdot 18 \cdot 32 = 1728 m^2 \qquad [6.1]$$

6.1.3. PIXEL DENSITY

Since the screens are the main attraction of the aerostat, these need to have a very attractive look. Not only does the screen size need to be sufficient to be able to read the letters, any text or logo should look crisp and sharp. The determinant for this is the relative resolution of the screen, which is the resolution of the screen divided by the viewing distance. For example, when a 100 inch, 1080p screen is viewed from 4 meters away, it has half the effective resolution as a 50 inch, 1080p screen viewed from the same distance. Also, a 50 inch screen at 4 meters distance has double the effective resolution as the same screen 2 meter closer.

This means that putting a same size display further away will lower the needed resolution, while increasing the size of a screen at the same viewing distance will increase the needed resolution. To be able to determine how sharp the display will appear at different distances, the sharpness factor S_f with unit P will be defined as the vertical resolution per screen height times the viewing distance. A higher number will yield a sharper perceived image. This follows from the definition of the formula.

As a guidance, a 50 inch, 1080p screen viewed from 4 meters away will be used. This is what the human eye experiences as a sufficiently sharp and crisp image. This yields $S_f = 6.94\ kP$. For a screen 18 meters high at 4 km distance, the needed vertical resolution to yield the same sharpness factor is 31 pixels. To yield the same sharpness as the 50 inch screen at 350 meters distance, which is the minimum distance at which people still have to be able to read the screen, the vertical resolution needs to be 360 pixels. This means that, when a 16:9 ratio is used, a 360p resolution (640px360p) would be sufficient. With 360p and 18 meters screen height, the spacing between the centers of the led lights is 50 mm.

6.1.4. VISUALISATION SYSTEM TECHNOLOGY

Given the required size of the screen and pixel density in section 6.1.2 and 6.1.3, the choice for a visualization system can be made. As mentioned in the mid-term report [2], LED arrays are the most optimal screen technology. Ttwo types of LED arrays used for big screens can be distinguished: tiles and curtains.

Tiles are small panels of a size of 20 - 100 cm with many LED lights installed on a small rigid structure. Tiles are often used in a configuration where many tiles are combined together for a bigger screen. The structure behind the tile strengthens it and by connecting the tiles together, a strong rigid structure is made. Tiles are commonly used for big fixed billboards in cities. However, the structure of the tile causes every tile to be relatively heavy: a weight of more than 30 kg per square meter is common for tiles [13]. For fixed billboards in cities this is not a problem, but connecting them to the aerostat this is not convenient. An example of a tile can be found in figures 6.4 and 6.5.

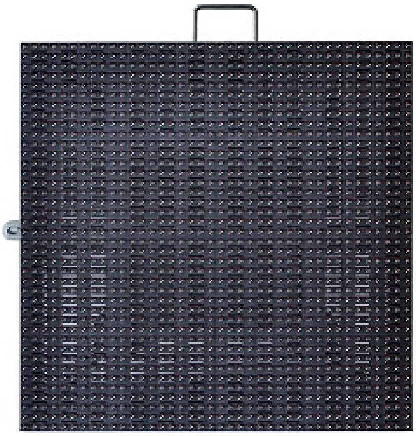


Figure 6.4: Example of a tile, front view [14]

Figure 6.5: Example of a tile, side/back view [14]

LED curtains are flexible systems consisting of a black curtain with interconnected LED lights. An example standard size of a LED curtain panel is 1.44 x 2.4 m. Like tiles, curtains can be combined together to form a bigger screen. A difference is that, due to the absence of a rigid structure, LED curtains must be hung on a structure. LED curtains are commonly used for events or other purposes where transport of the visualization system is important. Because curtains are foldable and light, they function well for this purpose. The curtains used are from PixelFLEX and weigh about 4.0 kg/m^2 [15], when mounting equipment is also taken into account. In figure 6.6 an example of a LED curtain can be found. Since no strength properties are available it is assumed the curtains can withstand the encountered wind forces. As explained in chapter 22 more research on this or the use of a protective layer needs to be performed.

Because curtains are much lighter than tiles, curtains will be used for the visualisation system of the "Diamond of Dubai". Extensive research into possibilities for LED curtains has been done and the LED curtains of PixelFLEX are considered to be high quality LED curtains. The specifications of these particular curtains are used for the estimation of the weight of the visualization system. It is assumed that these curtains are strong enough to withstand the Dubai environment. The weight properties for different LED spacings are given in table 6.1.

In table 6.1 it can be seen that a small decrease of the LED pitch increases the total weight of the visualisation system. The maximum allowed spacing between the LED's is 50 mm as described in section 6.1.3. A smaller pitch would result in better quality of the visuals, but will increase the payload weight to a large extent. Therefore, the choice will be made to use LED curtains with a spacing of 50 mm. This results in a screen payload weight of 6900kg, using these standard available led curtains and adding a small contingency.

Figure 6.6: Example of LED curtain (spacing of 25 mm) [3]

Table 6.1: Weight properties for different LED spacings of PixelFLEX LED curtains [15]

pitch of LEDs $[mm]$	weight $[kg/m^2]$	req. surface / side $[m^2]$	sides $[-]$	total weight $[kg]$
18	13.6	675	3	27556
20	11.8	675	3	23882
25	9.1	675	3	18370
30	5.4	675	3	11022
37.5	4.1	675	3	8267
50	3.0	675	3	6154

6.2. SCREEN SUPPORT STRUCTURE

The payload weight calculated in section 6.1.4 only comprises the weight of the curtains itself. The curtains need to be connected to a structure to fix them. This supporting structure is created from building blocks as shown in figure 6.7, with a back structure as shown in figure 6.8. The building blocks are bolted both together as well as to the back structure to form a sufficiently rigid structure. The assembly, when viewed from the side, is displayed in figure 6.9. The assembly is attached to the balloon on 4 main connection points with 4 bolts per connection point, which are the crossings of the back structure beams. The reason for using panels comes from the need to be able to either remove or replace the screens for maintenance or sheltering. The dimensions of the aluminum building blocks are 3 x 4 m with beam sizes of 30 x 20 mm, t=1 mm and the dimensions of the back structure of the full height and width with beam sizes of 150 x 50 mm, t=4 mm. This leads to a total weight of 710 kg for the support structure per screen, or 1.24 kg/m^2.

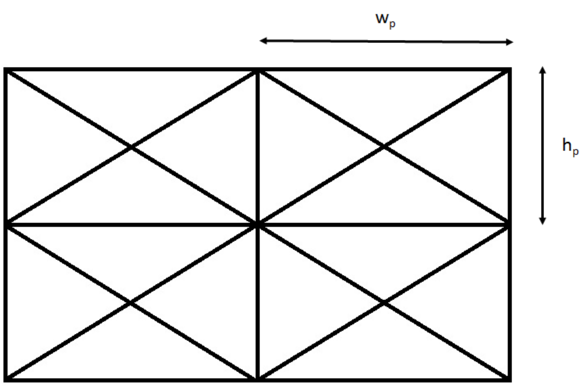


Figure 6.7: Four building blocks of the support structure of the screens

The calculated loads are a maximum bending moment of 4500 Nm, a maximum compressive force of 8000 N and a maximum tensile force of 8000 N. They are derived by decomposing the gravity force on the screen and structure into a compressive and bending component as shown in figure 6.9. With equations 6.2, 6.3

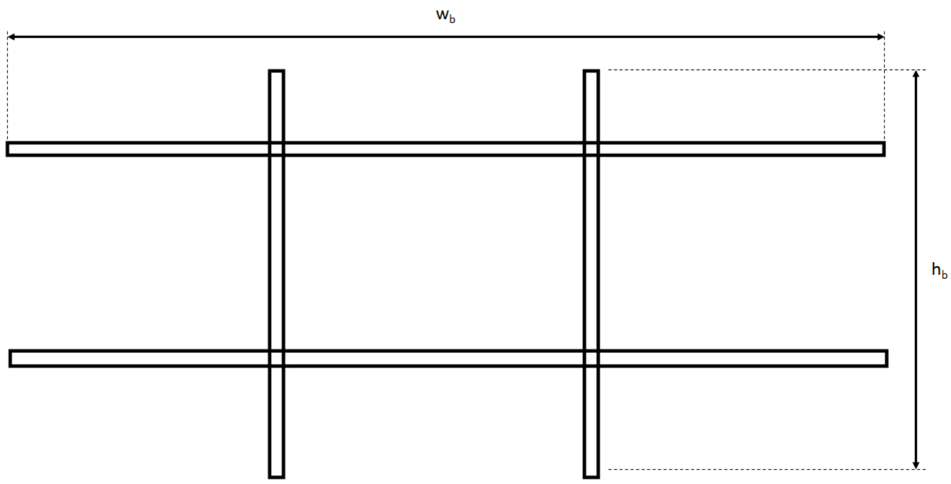


Figure 6.8: Backbone structure of the support structure of the screens

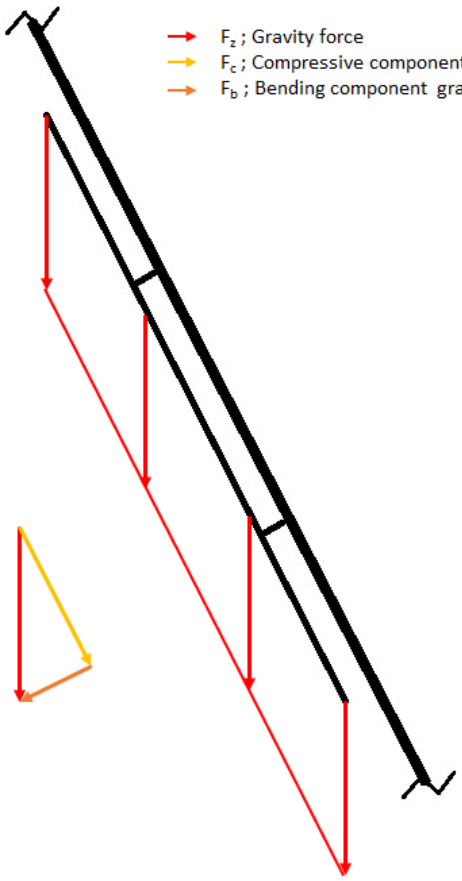


Figure 6.9: Side view of screen attachment

and 6.4 it is calculated that the back structure is able to cope with these loads with a safety factor of 2 for the bending moment, while the buckling and tensile loads are only a fraction of the maximum load the backbone structure can handle. Weight optimization for these dimensions is difficult due to the large bending moment experienced. This large bending moment occurs due to the angle of about 30 degrees at which the screens are attached to the aerostat. In the equations and figures the subscript annotations p and b stand for the panel beams and back structure beams respectively. The reason a quarter of the height is taken, is that the whole screen is 4 panels high, of which one is above the upper horizontal back structure beam and one underneath the lower horizontal back structure beam.

$$F_{tens_b} = \sigma_y A_b \quad [6.2]$$

$$F_{buck_b} = \frac{\pi^2 E I_b}{\frac{0.2 * h_b}{3}^2} \quad [6.3]$$

$$M_{bend_b} = \frac{\sigma_y I_b}{0.25 h_b} \quad [6.4]$$

6.2.1. VISUALIZATION SYSTEM TOTAL WEIGHT

It is expected that due to some optimization for this particular application, the curtains will be lighter than 4.0 kg/m^2. However, a contingency margin has to be added, so the value of 4.0 kg/m^2 is maintained. The result is an estimated maximum visualisation system payload weight of 9000 kg. In table 6.2 it can be seen what the screen payload consists of.

Table 6.2: Weight specifications screens

	Curtains [kg]	Structure [kg]	Total [kg]
One screen	2300	700	3000
All screens	6900	2100	9000

6.2.2. VISUALIZATION SYSTEM COST

The cost of the total visuzalization system is calculated using the cost of a currently existing LED curtain of 6.4 by 3.2 meters [15]. This specific LED curtain costs 14 000 euro, yielding a cost of about 700 euro per square meter of screen. With a total screen area of 1728 m^2 this yields a cost of 1.2 million euro for the screens only. As the screens for the balloon will need to be designed specifically for this application due to the need of being as light as possible, including a screen support structure and having a life time of at least 10 years, including development costs, the total cost is estimated to be 1.5 million euro, with a life expectancy of at least 10 years, which is the operational lifetime of the balloon.

6.3. SIGHTSEEING SYSTEM SPECIFICATIONS

This section will address the weight estimation of the gondola (6.3.1 & 6.3.2), lifting cables (6.3.3) and lifting mechanism (6.3.4). The weight will be based on currently used systems as a reference and adjusted to the needs that arise from the specific requirements. The output of this section will consist of the payload weight of the gondola, the passengers, the cables and the lifting mechanism. The total sightseeing system weight will be addressed in section 6.3.5.

6.3.1. INTERPOLATED GONDOLA WEIGHT

To get an order of magnitude for the weight of the gondola, extensive research into existing gondolas has been done. Gangloff Cabins Switzerland is an important gondola producer, that has designed different types of gondolas [16]. Twelve types of gondola from Gangloff that are similar in capacity and type to the gondola of the "Diamond of Dubai" have been found and these have been investigated. Subsequently, their weight per capacity has been interpolated. For a capacity of 60 persons (50 passengers + 10 crew), a weight of 2222 kg

was found as a result of the interpolation. The weight of the sightseeing system should be reduced as much as possible, so the goal is to design the gondola with a maximum weight of 2222 kg. To give a little extra room for the design, the weight of the gondola is estimated to be 2300 kg.

Passengers are assumed to weigh 77 kg.[4]. Taking into account a contingency margin, which then also accounts for possible small carry-on baggage, results in a total amount of 100 kg per person. 50 passengers and 10 crew members result in an estimated weight of the persons on-board to be 6000 kg. The gondola and passengers together are estimated to have a maximum weight of 8300 kg.

6.3.2. GONDOLA DESIGN

Figure 6.10 shows an overview of the design of the gondola. The gondola's dimensions can be found in figure 6.12. As shown, the gondola has a round shape with a total diameter of 8 m with a central circle of 2 m in diameter for the glass floor. The height of the gondola is 3 m including space for the floor and the ceiling.

The design consists of a full panoramic view with four touchscreen monitors that provide information on the view in that direction. An important feature of the gondola however is the 'sky gate', which is the round glass panel in the center of the floor, as can be seen in figure 6.11. The glass in the sky gate will be made of three layers of tempered glass with a layer of DuPont SentryGlas [17] in between these layers. This material is commonly used in sky floors and therefore the following dimensions are used: the laminate consists of three layers of 0.5 $inch$ glass and two layers Sentryglass for a sky floor of 3.14 m^2, which will have a weight of 308 kg.

To provide some support for passengers looking down, four poles are located around the sky gate. The gondola has on-board air conditioning, which is located on the bottom of the gondola to keep the center of gravity as low as possible. Stability is provided by the three guidance cables on the sides of the gondola. The lifting cable is attached on the pulley which is connected to the central pole of the gondola. Entrance to the gondola is provided by a large sliding door to accommodate people with disabilities to enter the gondola. Illumination is integrated into the roof, being capable of taking any color of the spectrum to be able to create an on-board light show.

The design of the gondola consists of a spiderweb-like top structure to have a look as esthetically pleasing as possible while being as light as possible at the same time. The gondola will mostly be constructed of carbon fiber and aluminum. The panoramic glass panels will be constructed from safety glass with a heat-reflecting foil to ensure both the safety and comfort of the passengers. The weight of the surrounding walls of the gondola is calculated assuming that the material used is laminated glass. Two glass panels of 5 mm each are used for the calculations with a thin PVB layer of 0.5 mm in between, to protect the panels in case of shock. Since the diameter of the gondola is 8 m, the perimeter is calculated to be 25.13 m. The average width of a human body is 50 cm [18], so in theory every person can stand at the window and look outside. However, it is not assumed that all tourists want to be at the window at the same time: they want to walk around and look through the sky gate as well. Therefore, a diameter of 8 m is considered sufficient. The panels are chosen to be as close as possible to 1 m because of manufacturing reasons, hence the final dimensions are 1.2 m in width and 2.8 m in height, referring to figure 6.12. The volume of each component can be calculated, as shown in equations 6.5 and 6.6.

$$V_{glass} = 2.8 \cdot 1.2 \cdot 0.005 = 0.0168 m^3 \quad [6.5]$$

$$V_{PVB} = 2.8 \cdot 1.2 \cdot 0.0005 = 0.00168 m^3 \quad [6.6]$$

Next, the mass of the glass panels and of the PVB layer can be calculated using equation 6.7, 6.8 and 6.9. This results in the total mass of all 21 panels. In fact, the density for the laminated glass layers is 2500 kg/m^3 [19] and the one for the PVB is 1080 kg/m^3 [20].

$$m_{glass} = 0.0168 \cdot 2500 = 42 kg \quad [6.7]$$

$$m_{PVB} = 0.00168 \cdot 1080 = 1.8 kg \quad [6.8]$$

$$m_{TOTAL} = 21 \cdot (2 \cdot 42 + 1.81) = 1802 kg \quad [6.9]$$

The result of these calculations is that using glass would make the gondola heavier than what is expected from literature studies. For this reason, United Balloon might want to investigate further in new types of plastics that have similar characteristics to laminated glass but have a much lighter weight, estimated at about one third of the glass. Nonetheless, plastics do not have good performance with abrasion and hence with sandstorms, so a combination for glass and plastics would provide the best alternative for this specific case.

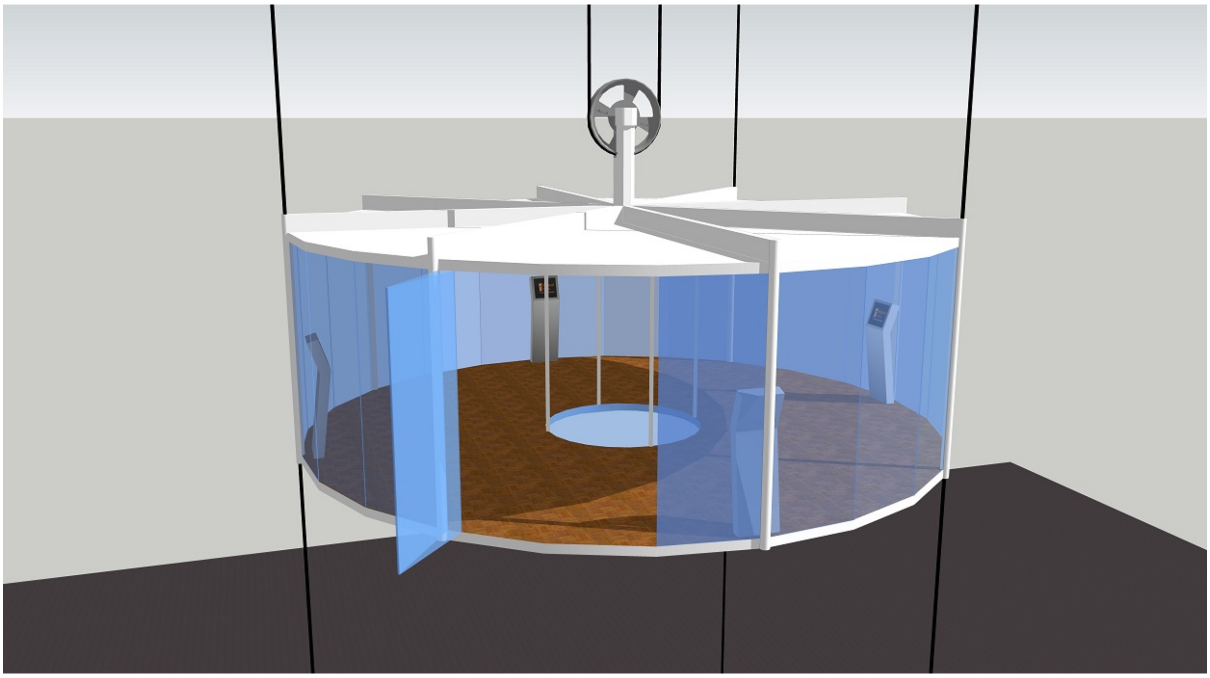


Figure 6.10: Design of the gondola

6.3.3. CABLE SPECIFICATIONS

In order to be able to make a weight estimation for the cables involved in the sightseeing mechanism, the final layout of the sightseeing system has to be explained. The sightseeing mechanism consists of a gondola that is connected to the air segment with cables.

As described in requirement ASR-PMT-020, which can be found in chapter 3, "The air segment shall be able to transport a group of 50 persons at once to and from a height of 210 m for sightseeing". For the sightseeing system, two cable systems are required. One system to lift the gondola and one system to stabilize the gondola. Figure 6.13 depicts this sightseeing mechanism configuration.

The first system is the pulley system. For the pulley system, the cable is connected from the air segment to a pulley on the gondola and then back to a reel for pulling up the gondola, located in the air system and powered by an engine. This cable is the elevator cable and will have a length of 420 m. This cable system must be able to carry the load of the gondola plus passengers. Therefore, a strong cable should be used. The total load to be carried is 8300 kg. In elevators, the commonly used safety factor is 12. This means that the cable must be able to cope with a force of 977 kN. In the mid-term report, the choice for the ground attachment cable material turned out to be Dyneema [2]. Dyneema has a high yield strength of 3.5 GPa and good properties with respect to the environmental conditions (no problems with UV-light or temperature changes). A cable made of Dyneema with a radius of 3.6 cm is sufficient to carry the loads of the gondola [21]. According to this reference, a cable with a diameter of 3.6 cm has a weight of 0.68 kg/m. This yields a weight of 285.6 kg for the cable of the elevator. A more classical alternative for the very modern Dyneema is carbon steel. The weight of the cable using carbon steel has been investigated as well: using carbon steel, the total weight of the cable has been determined to be 870 kg. This is a large difference, so the use of Dyneema is preferred. The used cable can also be split into multiple cables and multiple pulleys. Because the cable then still needs to cope with the same amount of load, the cables will together have the same cross sectional area, which results in the same weight.

The second cable system is a system to stabilize the gondola. This system consists of three cables under slight tension attached to the three sides of the gondola that guide it in the right way. This could be considered as

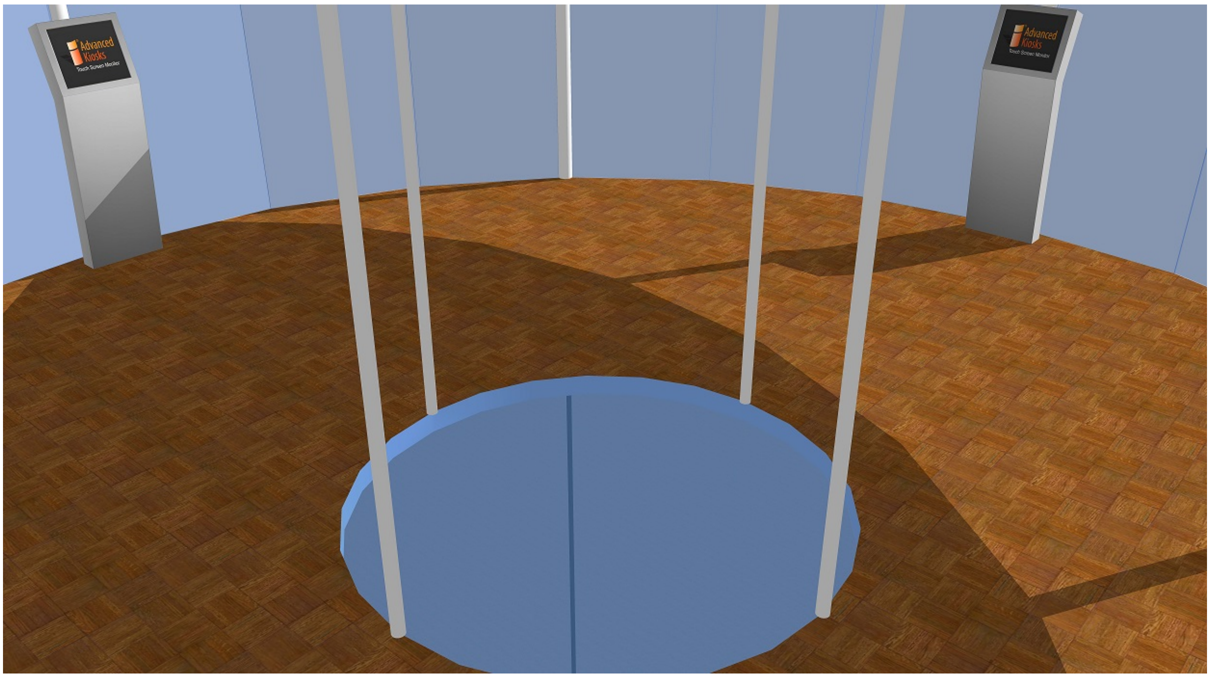


Figure 6.11: Interior of the gondola

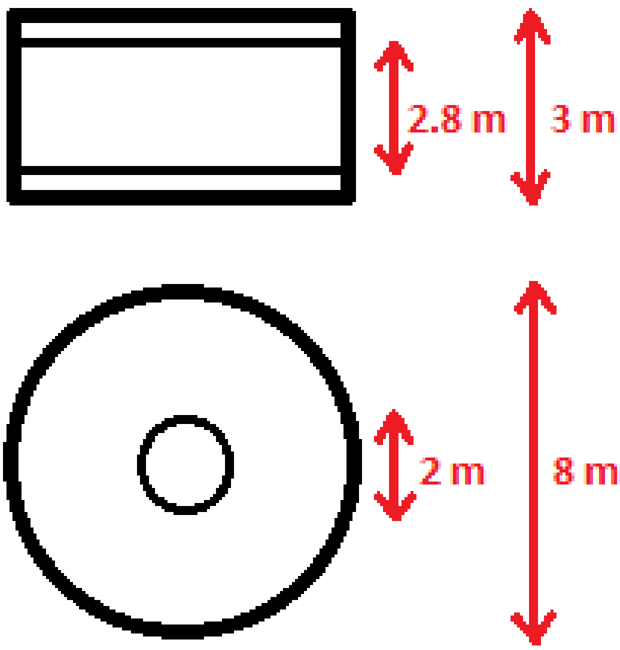


Figure 6.12: Gondola dimensions

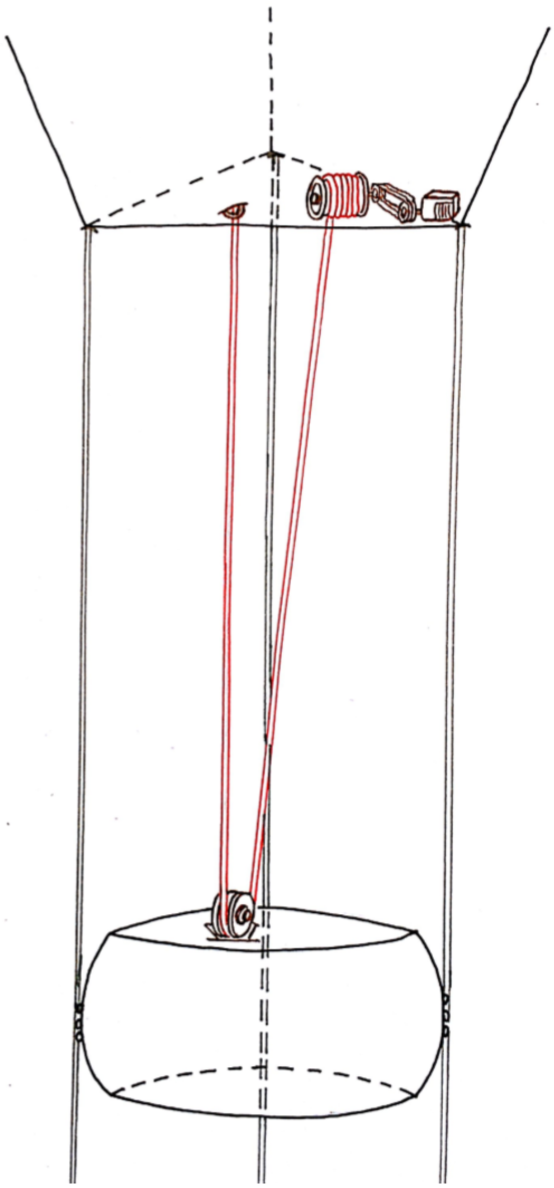


Figure 6.13: Layout of the sightseeing lifting mechanism

rails. These cables will have the same cross section as the ground attachment cables of the aerostat. Assuming the three guiding cables can carry the weight of the gondola togehter, each cable should be able to withstand a load of 326 kN. Three cables with a diameter of 2 cm can be used for this, each with a weight of 0.206 kg/m [21]. This would yield a total weight for the guiding cables of 129.8 kg. A cable length of 210 m was used for this. The total weight of the cables for the gondola lifting and guiding adds up to 415.4 kg if Dyneema is used.

6.3.4. LIFTING MECHANISM SPECIFICATIONS

Since the gondola is suspended by a cable, as specified in subsection 6.3.3, the lifting mechanism for the gondola consists of an engine that will reel in this cable. The estimated weight of the gondola and the passengers is 8300 kg and the estimated weight of the lifting cable is 285.6 kg. Since the gondola has to be brought up to a height of 200 m in a time of 4 minutes, the upward speed of the gondola will be 0.83 m/s. Using equation 6.10, the required engine power can be calculated [22].

$$P = \frac{W \cdot v}{2} = \frac{8585 \cdot 9.81 \cdot 0.83}{2} = 34950W = 35kW \qquad [6.10]$$

To get a weight estimation for an electric engine that can produce this power, research has been done into different electric engines [23] [24] [25] [26]. For a power of 35 kW, a weight of 295 kg was found as a result of interpolation. This is rounded up to give a little extra room for the design, so the estimated weight of the engine is 300 kg.

As this lifting mechanism uses a roller to reel in the cable, the weight of this roller has to be included in the lifting mechanism weight. Normal elevators do not use this kind of system and research has not resulted in any useful findings. Therefore, a weight of 100 kg will be assumed for this rolling mechanism.

6.3.5. GONDOLA STRUCTURE

This subsection shows a preliminary structural design of the gondola. The performed calculation method is exactly the same used in the program for the internal structure of the aerostat. This structure was not completely optimised, but the performed calculations give a rough estimation of the total structural weight as well as the member dimensions. In Appendix H, the data for each structural member can be found. The current estimated structural mass is 1200 kg (without glass etc.). The structure is to be made out of aluminum because this will be light enough and will save costs. The longest members are 8 meters and have a mass of approximately 30 kg. It is important to note that the safety factor used for the gondola structure is 3 to make sure the 'safe life' methodology is satisfied [27].
The calculation methology can be found in section 8.4.3. In figure 6.14, the gondola lay-out is visualized and in figure 6.15 on the right, the structural layout is visualized. The members under an angle of approximately 45 degrees are used to simulate the behaviour of safety glass in the structure. These members can be seen even better in figure H.2 in Appendix H. Extrusion is ideal and thus the proposed manufacturing method to make the aluminum beams for these sizes of beams.

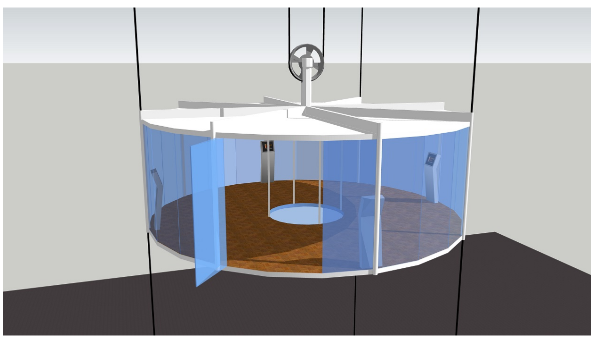


Figure 6.14: Design of the gondola

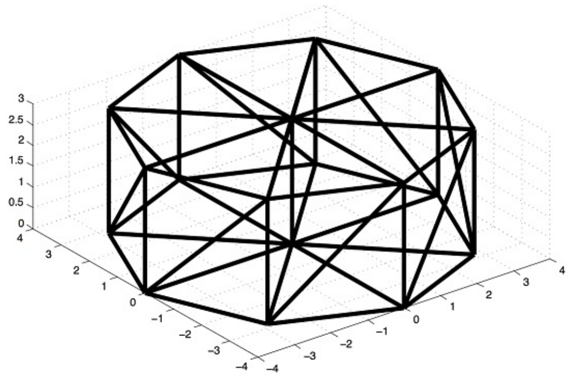


Figure 6.15: Design of the internal gondola structure

6.3.6. TOTAL WEIGHT

Since all the weights for the different components have been estimated, the weight of the entire sightseeing mechanism can be estimated. The weight estimation for empty weight and weight including passengers (total of 6000 kg) are listed in table 6.3. As previously stated in section 6.3.2, the weight of having the window structure fully in glass would result in a large over estimation of the gondola weight. The weight of the gondola found in literature research of 2300 kg is assumed to be a better estimation. Therefore, in table 6.3 a value of 742 kg is given to the gondola glass weight, which results in a total gondola weight of 2300 kg. The value for the gondola glass weight should be regarded as a goal for the design for the windows of the gondola.

Table 6.3: Weight specifications sightseeing system

	Weight [kg]
Gondola structure	1250
Gondola sky gate	308
Gondola glass	742
Gondola operational empty weight	2300
People on board	6000
Gondola maximum weight	8300
Cables	415
Lifting mechanism	400

7
LOAD IDENTIFICATION

In this chapter, all the loads that affect the dirigible are presented. First, in section 7.1, a free body diagram is included, showing all the forces applied on the system. Next, in section 7.2, each force is analyzed separately in terms of distribution and origin. Finally, in section 7.3, the most extreme conditions experienced are introduced together with four ultimate load cases.

7.1. FREE BODY DIAGRAM

In figure 7.1, the free body diagram for the system is shown. All forces applied are included in the figure and these are also the ones considered for structural calculations. The forces are also elaborated on in this section. The position of the cables will not necessarily be as in this configuration, but the goal is to give an idea of what the forces would be and where they would act.

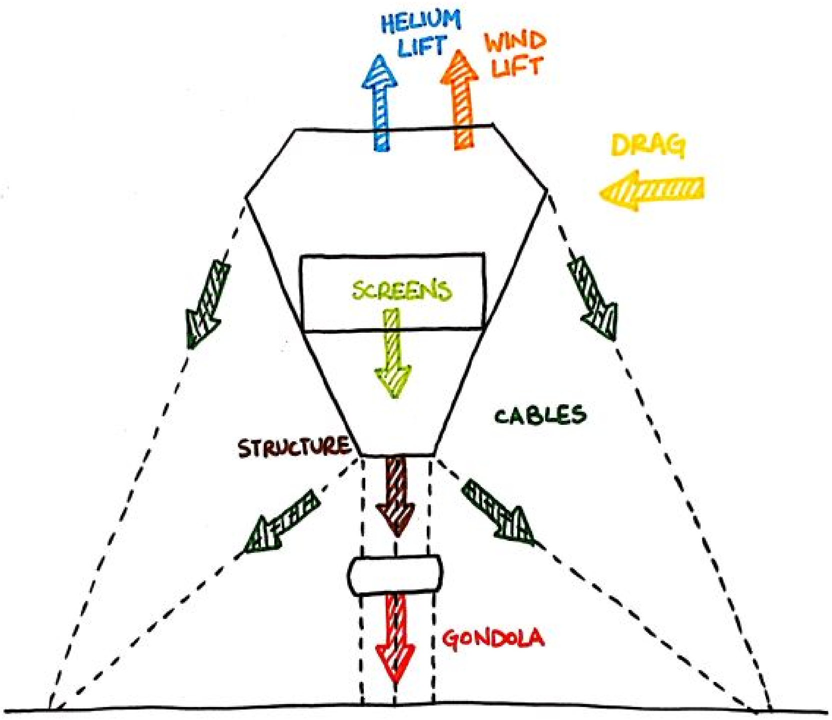


Figure 7.1: Loads applied on the system

7.1.1. LIFT

In order for the blimp to be positioned at a certain altitude, it needs to have a lifting mechanism. The chosen lifting mechanism is a gas: helium. The blimp is designed so that the helium can provide lift for the whole structure and for a minimum of 30% extra lift as a safety margin. However, the helium is not the sole lift generating system; the shape of the dirigble will generate lift when a wind force is acting on it. In figure 7.1, the lift force is indicated by both the orange arrow and the blue arrow at the top of the blimp. The "helium lift" is dependent on the volume of the inner envelope of the dirigible and is therefore constant. The "wind lift" is variable with the wind speed, just as the drag (section 7.1.2). In contrast to the drag, a higher wind speed is favourable for the lift: a higher wind speed results in more lift. When the lift force is concerned, it is the sum of a constant lift force due to helium and a variable lift force due to wind.

7.1.2. DRAG

The drag experienced by the dirigible is a distributed load that varies with wind speed. In fact, such a big structure is subjected to a lot of drag, especially because the screens are positioned at an altitude o 250 m. For this reason, the shape of the aerostat has been optimized following several aerodynamic considerations in order to maintain stability as much as possible, despite the wind. In the Dubai area, winds can get as fast as 93km/h and a passive stabilization was preferred over an active one that would be more expensive and heavy. A better insight on how wind drag has been handled can be found in chapter 9 about aerodynamic stability.

7.1.3. STRUCTURE

The weight of the structure is a distributed load and it is not dependent on the different load cases. In fact, the structure is necessary to contain the bag of helium, and to retain the shape of the aerostat. The total weight, indicated by the brown arrow in figure 7.1, includes both the internal structure and the outside envelope. As will be calculated in chapter 8, a total of 48 round, hollow beams create the internal structure, having a weight of 37 000 kg. The external envelope contributes to the structural weight with 3 000 kg, while the internal one has a weight of 3 000 kg. Including the fishnet cabling system, yields a total weight of 46 000 kg.

7.1.4. SCREENS

The screens are attached to the blimp on four points per screen, meaning that the loads on the structure are point loads. When there is no wind, this force points in the direction of gravity, as can be seen in chapter 6. If there is wind, this exerts a force in the direction of the wind on one screen, while the other screens are assumed not to be affected. The force created by the wind on the screens is assumed to be in the direction of the joints between the screens and the structure, so it will be a compressive force. While this force is present, the structure within the aerostat needs to be able to cope with these forces regardless if there are screens or not, since otherwise the force would be acting on the envelope. Therefore, the force generated by the wind was taken into consideration in the drag section above. That means that the force the screens exert on the structure is 88.3 kN, or 29.4 kN per screen, as was shown in figure 6.9.

7.1.5. GONDOLA

The forces coming from the gondola act in two different conditions: in the first case the gondola is on the ground, hence only the cables and lifting engine have to be supported by the structure of the blimp, in the second case the gondola is in the air with passengers on board. The forces are four point loads, as the gondola is attached to the bottom of the balloon on four points, three for guidance with small load and one for lifting with high loads. The engine and the cables exert a force of 6.3 kN on the structure. If the gondola is in the air with maximum occupancy the force increases to 87.7 kN.

7.1.6. CABLES

The cable forces are multiple point loads, 12 in total. The force and the direction of that force on each individual cable depend on the direction of the wind, the altitude of the balloon and the lift over weight ratio of the balloon. Therefore, the forces indicated in figure 7.1 will be the maximum forces on any single cable. In case of one or two cable failures, other cables need to have sufficient redundancy to account for these loads.

7.2. LOAD CASES

To be able to determine what forces the design has to cope with, four different load cases are considered. These load cases comprise conditions in which it could be expected that ultimate loads are experienced. When the dirigible is operating in the air at low wind speeds, the structure will not be loaded at its maximum allowed force. Two different wind speeds are considered. These are a preliminary assumption of a wind speed at which the dirigible will be in safety mode, which is the case for an encountered wind speed of 17 m/s and the maximum operational wind speed of 12.5 m/s, at which safety mode is not activated. These wind speeds are wind speeds that the air segment will encounter on the height of the screens. For both wind speeds, the system can have two configurations. The load cases are:

1. Max encountered wind speed (17 m/s), maximum gondola occupation
2. Deployment: max operational wind speed (12.5 m/s), no gondola usage, no lift
3. Max operational wind speed (12.5 m/s), no gondola usage , normal operation
4. Possible encountered wind speed (17 m/s) in safety mode, no gondola usage

Table 7.1 shows for all different load cases the resulting forces from the different components acting on the blimp. The values in this table are translated to inputs for the structural calculations. As can be seen in table 7.1, the screen and structural forces remain equal throughout the load cases. This is due to the fact that neither the screens nor the structure will be (partially) removed during the operational lifetime of the blimp. The gondola will either be used with maximum occupancy or stationed on the ground if not operational. The wind force is the force of the wind acting on one side of the aerostat, such that the other sides of the aerostat do not take up part of that force. The force in the cables exists due to the extra lift provided, compared to the weight of the structure, which was around 20 % at the first iteration.

Table 7.1: Resulting forces due to subsystem components

	Wind force [kN]	Structure [kN]	Screens [kN]	Gondola [kN]	Cables [kN]
Case 1	711	348	88	88	20
Case 2	384	348	88	6	20
Case 3	384	348	88	88	20
Case 4	711	348	88	6	20

7.3. LOAD CASES IMPLEMENTATION

In this section, the load cases described in section 7.2 have to be translated into data that can be used in MATLAB. The weights, cable forces and wind forces from table 7.1 all act at certain points on the structure, introducing internal forces into the structural members. These forces are needed to calculate the dimensions of the members and to be able to make the structural design as optimal as possible. As will be elaborated further upon in chapter 8, fourteen points on the structure are defined to be the points at which all loadings can act. The working principle and the way calculations are done are elaborated further upon in section 8.4.3. A drawing showing the points at which the loads act can be found in figure 7.2 and the sign conventions can be found in figure 7.3.

Since the points at which the forces will act are known, it has to be defined on what point each of these forces acts. For example, the screens will not be attached to all points, but only to the convenient ones. An overview of all forces acting on each nodal point in figure 7.2 is given below.

1. No force in x-direction, wind force in y direction, lift force, gondola weight and cable force in z-direction.
2. No force in x-direction, wind force in y-direction, lift force, gondola weight and cable force in z-direction.
3. No force in x- and y-direction, lift force, gondola weight and cable force in z-direction.
4. No force in x-direction, wind force in y-direction, lift force in z-direction.

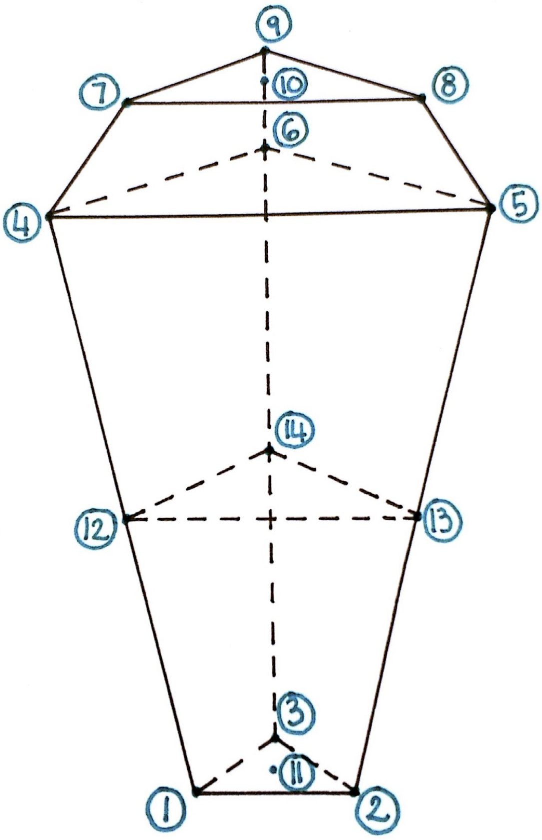


Figure 7.2: Nodal points with their numbering

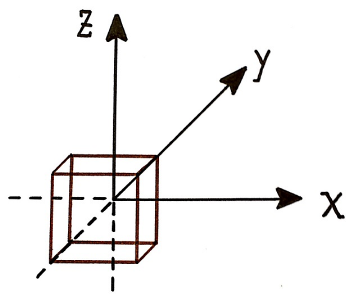


Figure 7.3: Sign and coordinate convention

5. No force in x-direction, wind force in y-direction, lift force in z-direction.
6. No force in x- and y-direction, lift force in z-direction.
7. No force in x- and y-direction, lift force in z-direction.
8. No force in x- and y-direction, lift force in z-direction.
9. No force in x- and y-direction, lift force in z-direction.
10. No force in x- y- and z- direction.
11. No force in x- y- and z- direction.
12. No force in x-direction, wind force in y-direction, screen mass in z-direction.
13. No force in x-direction, wind force in y-direction, screen mass in z-direction.
14. No force in x-direction, wind force in y-direction, screen mass in z-direction.

A few items in the list need some elaboration. When it is stated "wind force in y-direction", it means that only one 6^{th} of the total lift force will act on that point. This is due to the fact that the wind force will be distributed among all six points of the side facing the wind. However, in practice the wind will act on more than one side at the same time and the force will thus be distributed among more than six points. Therefore, the case used for calculations, with force only acting at six points, can be seen as a maximum load.

When "lift force" is mentioned, it means that only one 9^{th} of the total lift force will act on those points, because the lift force will act at nine nodal points in total.

The weight of the gondola will be divided among the three lower points (point 1,2 and 3 in figure 7.2, so when "weight gondola" is mentioned, it means that only one third of the total force will act on that point.

Cable force is assumed to be the generated lift minus the weight of the dirigible and it is distributed among the lowest three points of the structure, point 1, 2 and 3. However, in practice the other cables connected to the ground will also take up some of this force. Therefore, the case when only three cables take up the total extra lift can be seen as a maximum loading case.

These definitions were implemented in MATLAB, which would calculate values for all forces in x,y and z direction at every nodal point. These calculated values are presented in table 7.2. The load cases presented in this chapter will be used to design a structure for the dirigible, capable of withstanding the loads to which the dirigible will be subjected during its lifetime. The table can be read as follows: for all four load cases, the forces [N in all members are given in both Y and Z direction. It was assumed that the wind comes from the y-direction, therefore the forces in x-direction are zero. The four load cases were used as input in MATLAB to do calculations on the structure.

Table 7.2: Forces in kN in y- and z-direction in nodal points

Point	Case 1	Y	Z	Case 2	Y	Z	Case 3	Y	Z	Case 4	Y	Z
1		118	14		64	-2		64	42		118	42
2		118	14		64	-2		64	42		118	42
3		0	14		0	-2		0	42		0	42
4		118	109		64	0		64	109		118	109
5		118	109		64	0		64	109		118	109
6		0	109		0	0		0	109		0	109
7		0	109		0	196		0	305		0	109
8		0	109		0	196		0	305		0	109
9		0	109		0	196		0	305		0	109
10		0	0		0	0		0	0		0	0
11		0	0		0	0		0	0		0	0
12		118	-30		64	-30		64	-30		118	-30
13		118	-30		64	-30		64	-30		118	-30
14		0	-30		0	-30		0	-30			-30

8

STRUCTURAL DESIGN AND MATERIAL SELECTION

In this chapter, the internal structure and material selection will be explained. In section 8.1 the overall design process is stated. In section 8.2 the reader can find the general approach that was taken to design the internal structure. Section 8.3 covers the design iterations. In section 8.4 explanation can be found about the exact steps that were taken to perform the structural calculations, as well as the design configuration, including the iteration process. Furthermore, validation & verification, as well as internal structure material choice, will be treated. In section 8.5, information about the internal and external envelope material can be found. The selection process and the material properties are documented here as well. Finally, the selected layout and design characteristics are summarized in section 8.6.

8.1. OVERALL DESIGN PROCESS

The challenge of stabilizing the aerostat, as will be described in chapter 9, is strongly interconnected with the design of the internal structure of it. In fact, the stability depends on the aerodynamic properties of the shape, which influence the choices for the internal structure. Vice versa, the objective of the internal structure is to withstand the loads applied on the aerostat, which are determined with an aerodynamic analysis of the shape. It is then clear that the structural design process is based on several iterations to optimize both the structure and its resistance to disturbances.

In this report the structural optimization is worked out first and the aerodynamic stability is done afterwards. In reality however, these were done simultaneously with multiple iterations. The dimensions and weights that are included in the aerodynamics and operations chapters are outputs from the structural group, whereas the inputs for forces are the outputs of the aerodynamic stability group. The goal of these chapters together is to optimize the overall design of the dirigible, so all final concepts are chosen in consultation with the entire group.

The flow of the iterative design process is shown in figure 8.1. The results of this process are worked out over chapters 8 and 9, where the design is performed, and chapters 13 and 15 where the performance is determined. The loop is closed in chapter 19, where the compliance to all requirements is checked.

8.2. STRUCTURAL DESIGN PROCESS

In this section the steps that have been taken to come to the final structural configuration will be described. This section only documents a general overview, an elaboration on each specific step that was taken will be found later in section 8.4 .

The preliminary structural design layout of the mid-term report [2] was taken as a starting point for the internal structural configuration. The main goal and target point for the structure was to have an internal volume equal to 120 000 m^3. Assuming that 1 m^3 of helium can lift 1.0377 kg of mass, it would then be capable of lifting the total estimated mass of 100000 kg, including a 1.2 safety factor [2]. However, this safety factor has been changed to 1.4 in a later stage in the project, because it was preferred for the aerodynamic stability. As stated in the mid-term report [2] and explained during the mid-term review, there is a need for an internal structure.

Following the advice of the TU Delft Phd student Yujie Guo, the Diamond of Dubai structures team tried to put the preliminary structural configuration in a finite element method calculation tool called Abaqus CAE. After

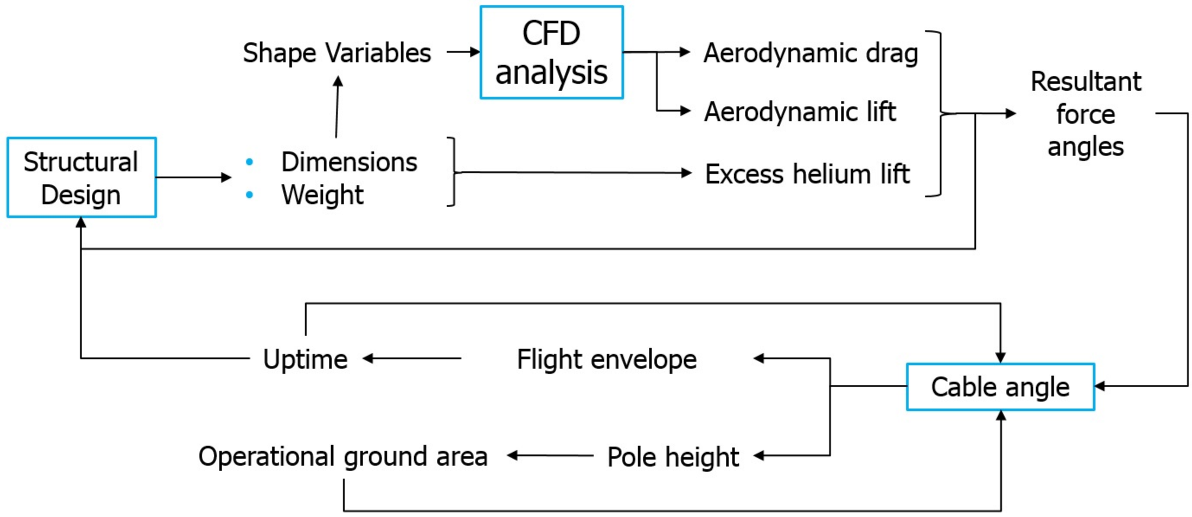


Figure 8.1: Flowchart of iterative design process

struggling a few days in this yet unknown software, a different option was chosen, due to time constraints. MATLAB was chosen as alternative to perform the structural sizing calculations. Once the preliminary structural configuration was put in MATLAB, it was found to be statically indeterminate. As a result, the first step was to change the configuration, until it was statically determinate. Next, the internal forces in each member needed to be calculated. These internal forces are a result of the external applied loads, such as gondola attachment cables or drag on the surface. For sizing, the worst load cases were used. These load cases are defined in section 7.2.

After this, the truss members needed to be sized on their internal load. By only sizing the structure on its internal loads, the total mass was found to be unrealistically low at 1200 kg. Further investigation showed that the buckling of the members would have the largest impact on the structure. Next, a second sizing process was performed to size the members for buckling. These calculations resulted in a required cross sectional area far larger than the first required area. As a result, the structure was now optimally designed for buckling, but a lot overd designed for internal failure. As a consequence of this, the resulting structure would be heavier than required.

The optimum design configuration would be such that the two failure modes occur at exactly the same time. In order to ensure the optimum design, the material area for tensile failure was taken and the cross sectional area was adjusted to change the moment of inertia. This way, both failures would happen at the same time, resulting in a minimum structural weight. Unfortunately, the required diameter of some members exceeded 3.5m, which is not feasible for production. This option was therefore discarded. Another design parameter that could be adjusted was the length of the members. An effective alternative to influence the buckling of the structure was adding members. By doing that, the size needed to be adjusted a little to still have the required internal volume of 120 000 m^3. This resulted in a far too heavy structure which took up nearly 90% of the aerostat's MTOW when using aluminum. Therefore, using aluminium was no longer an option, the only material that was still eligible seemed to be carbon fiber reinforced plastics (CFRP). In table 8.1 the optimized design for the materials aluminum and glass fiber can be found. Manufacturability was also taken into account: realistic maximum member diameters were chosen, as well as minimum manufacturable wall thicknesses. When considering the manufacturing phase of the aerostat, it is found that the structural members of the crown needed to be designed for the manufacturing phase. This was the case, because of the fact that when constructing the aerostat, the crown will be suspended on to a crane to assemble the total internal structure. This process will be explained in detail in chapter 21.

Finally, it was found that the total aerostat produced more lift than required for the chosen screen size. Now the final optimization process can start, which optimizes the structural weight for the required internal volume (and thus the lift).

8.3. DESIGN ITERATIONS

In this section, the reader can find both the original preliminary structural lay-out, as well as the final optimized internal structure. An explanation will be given about the feasibility of the different materials in section 8.3.1. Besides that, the characteristic numbers for the material that will be used will be provided in this section. Next, the optimization process will be clarified using supporting numbers in section 8.3.3. Finally, the optimum structural configuration will be stated and combined with the aerodynamically best configuration.

Figure 8.2 shows the internal structure as it was estimated and documented in the mid-term report [2]. Figure 8.3 shows the total optimised internal structure as it will be advised and presented to United Balloon.

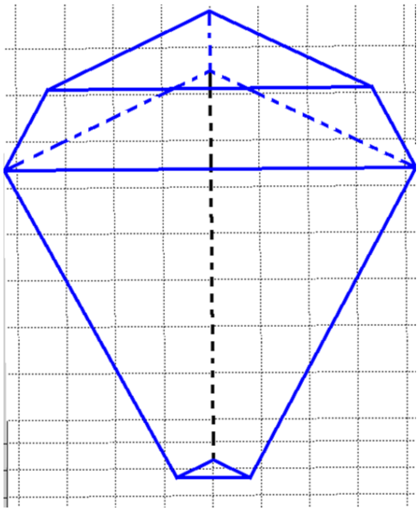


Figure 8.2: Preliminary structural lay-out

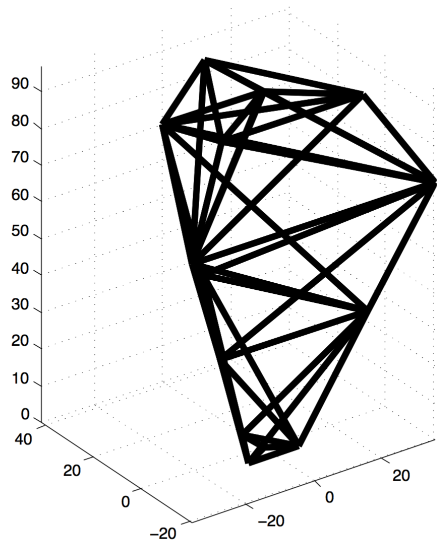


Figure 8.3: Total optimized internal structure, axis shown in meters

8.3.1. MATERIAL FEASIBILITY STUDY

The amount of members that will be used is 48, in order to make the structure statically determined and to minimize the length of the individual members. The entire calculation process can be found in section 8.4.3. At first, the entire structure is sized to have precisely enough lift to lift only the structure and thus, an entire helium 'volume over structural weight' ratio of at least 1 is needed to only get the structure off the ground. This ratio is equivalent with the lift over weight ratio that can be found in table 8.1. First, the structural mass sizing calculation is performed for the aluminum alloy and glass fiber, whose properties can be seen in table 8.1.

In table 8.1, the best possible designs for aluminum and glass fiber are demonstrated, higher values for 'lift from volume/mass structure' could not be found. These design were found after multiple iterations, by changing the dimensions and optimizing for the applied forces. Thus it can be concluded that for the current chosen structural lay-out, glass fiber and aluminum are not feasible. Another high performance material must thus be looked at: carbon fiber might be a good solution, because of its high specific stiffness.

The important conclusion to be drawn from this section is that aluminium and glass fiber are not feasible for the structural design. In section 8.3.3 the material carbon fiber will be used and multiple iterations will be performed to arrive at the optimal solution for the structural design. The process used to perform the iterations and come up with these final numbers for aluminium and glass fiber are done in exactly the same way as for carbon fiber. This process will be clarified in section 8.3.3

8.3.2. ASSUMPTIONS FOR STRUCTURAL DESIGN

In order to come up with calculations for the structure, multiple design assumptions have to be made. A short list will be presented. It can be said that all the made assumptions will result in a conservative design.

Table 8.1: Design characteristics for the optimum aluminum design and optimum glass fiber design (used names are clarified in figure 8.11)

	Aluminum		Glass fiber	
	Value	Unit	Value	Unit
Height lower pyramid	75	[m]	80	[m]
Height crown	20	[m]	30	[m]
Total height of balloon	95	[m]	110	[m]
Width lower pyramid	75	[m]	85	[m]
Volume lower pyramid	60892	$[m^3]$	83427	$[m^3]$
Volume crown	38622	$[m^3]$	66575	$[m^3]$
Total volume balloon	99515	$[m^3]$	150003	$[m^3]$
Mass main structure	136182	[kg]	165041	[kg]
Lift from volume/mass structure	0.73	[-]	0.91	[-]

- Forces acting on the envelope will only act at the four corners of one side and the two mid points of the vertical beams of one side. The envelope will thus be connected to those points only, for calculation purposes.
- The E modulus of a unidirectional CFRP is equal to the E modulus of a realistically manufacturable CFRP
- The entire structure is made out of one and the same material
- There are no stress concentrations in the envelope material due to connection holes
- 1 m^3 of helium can lift 1 kg
- The weight of the screens is introduced to the structure in the form of point loads
- The volume of the aerostat can be used with a 95% efficiency to fill with helium
- There is no cooling system required for the screens
- The average mass of a passenger visiting the gondola is 100 kg
- The envelope has been assumed spherical to perform the stress calculations
- The internal pressure of the balloon equals the local atmospheric pressure
- Lift acts only at each corner point of the aerostat
- All forces introduced by the stability cables act purely horizontally (results in a conservative computation)
- Connecting the separate CFRP beams does not add weight to the system

8.3.3. OPTIMALIZATION PROCESS FOR CARBON STRUCTURE

In section 8.3.1 it is determined that a carbon structure should be used. Moreover, the geometry of the structure must be optimized so that it has a minimum mass over volume, but such that it is still capable of handling the loads and of lifting the entire system. The starting point for this iteration process is the baseline configuration from the baseline report [5]. 'Carbon 1' and 'Carbon 2' are intermediate configurations that lead to the optimum structural design called 'Carbon 3'. In table 8.2, the geometry and the structural weight of each configuration can be found. The mass budget change due to the iterations can be found in table 8.3. How the iteration process was performed and how the snowball effect played a role in this is visualized in figure 8.4. It will be further elaborated upon later in this chapter

Figure 8.4 illustrates the loop that was used to optimize the carbon internal structure. As a starting point, the preliminary estimated mass was used. This mass requires a volume to store helium to lift the entire aerostat. In order to have such a volume, the structure requires a certain geometry. In the loop to optimize the structure

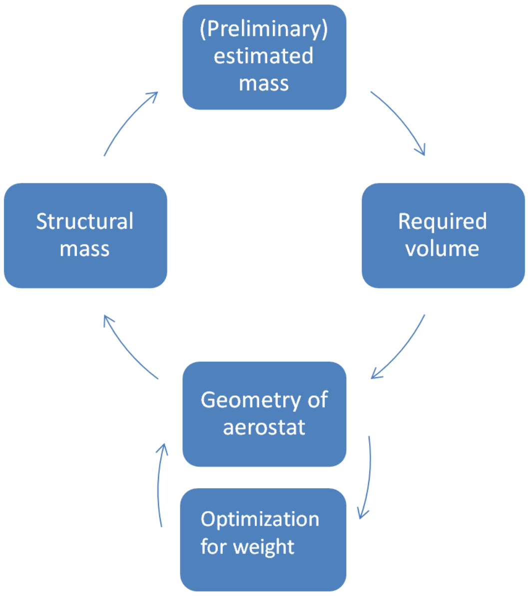


Figure 8.4: Iteration process demonstrated: snowball effect

for weight, the sizes of the structure and the sizes of individual members were optimized for weight for the shape structural concept. In order to come to a concept as light as possible, the dimensions of the structure and the dimensions of the individual members were used to iterate with. So basically the entire structural size was optimized first and then the individual members were optimized for weight, starting the loop over again starting with optimizing the entire structural dimensions and then going back to the sizing of individual members again. Of course, different geometrical configurations can make up the same volume, but they don't necessarily have the same mass. So in the block off 'optimization for weight', the lightest concept for the chosen volume was selected. This new structural mass was then updated in the mass budget in table 8.3. Because the total mass is now less than what was previously estimated, other subsystems can also be scaled down such as the envelope and the stability cables. All these reduced subsystems add up to a new lower total estimated mass. This mass is then used to complete the new cycle. When repeating this process, the MTOW of the 'Carbon 3' design converged to a certain value, which is documented in table 8.3. The process of optimization and thus weight reduction can be seen in figure 8.5. The blue line represents the total mass of the whole aerostat. The yellow line shows the mass of the entire internal structure. The purple line indicates the mass of the non-structural components such as electronics and people payload. Finally, the green line shows the mass of the screens. Once the screen size was fixed to be $32m$ by $18m$, its mass and its related electronics did not change anymore, as can be seen in figure 8.5.

In the calculation, a minimum ratio of 1.3 for the lift/MTOW is required for stability and safety reasons. This will be explained in chapter 9. The total lift from the helium was calculated with equation 8.1. This gives the lift in kN. The factor 0.95 is used because 5% of the internal volume cannot be used for helium storage. This is the case because the subsystems and the structure also take up space. The lift/MTOW ratio values for the iterations can be found in table 8.3.

$$L = \frac{total\ volume\ balloon \cdot 0.95 \cdot 1.0377 \cdot 9.81}{1000} \quad [8.1]$$

In the stage of the baseline, cooling systems for cooling the screens were considered but in a later stage it was discovered that cooling them was no longer needed. Therefore the mass of cooling systems were discarded.

Table 8.2: Design iterations for the carbon material

	Carbon 1		Carbon 2		Carbon 3	
	Value	Unit	Value	Unit	Value	Unit
Height lower pyramid	75	[m]	70	[m]	70	[m]
Height crown	20	[m]	25	[m]	25	[m]
Total height of balloon	95	[m]	95	[m]	95	[m]
Width lower pyramid	75	[m]	75	[m]	72	[m]
Volume lower pyramid	60892	$[m^3]$	56832	$[m^3]$	52377	$[m^3]$
Volume crown	38622	$[m^3]$	44310	$[m^3]$	40105	$[m^3]$
Total volume balloon	99515	$[m^3]$	101143	$[m^3]$	92383	$[m^3]$
Useful total volume balloon	94540	$[m^3]$	96085	$[m^3]$	87764	$[m^3]$
Total helium lift	962	$[kN]$	978	$[kN]$	893	$[kN]$
Mass main structure (no hinges)	35424	[kg]	32079	[kg]	30308	[kg]
Lift from volume/mass structure	2.81	[-]	3.15	[-]	3.05	[-]

Table 8.3: Mass budget changes due to iterations

Part	Baseline [10^3 kg]	Carbon 1 [10^3 kg]	Carbon 2 [10^3 kg]	Carbon 3 [10^3 kg]
Screens (32mx18m)	19	9	9	9
Envelope internal	10	3	3	3
Envelope external	10	3	3	3
Structure internal + hinges	35	35 + 5	32 + 5	31 + 5
Fishnet cabling	1.5	3	3	3
Connection cables	1.5	2	2	2
Entire structure	58	51	48	42
People payload	6	6	6	6
Cooling system	5	0	0	0
Electronic wiring	3	3	3	3
Lighting	2	2	2	2
Lift & Gondola	3	3	3	3
Non structural mass	19	14	14	14
Total mass	96	74	71	70
Lift/MTOW	-	1.32 [-]	1.40 [-]	1.30 [-]

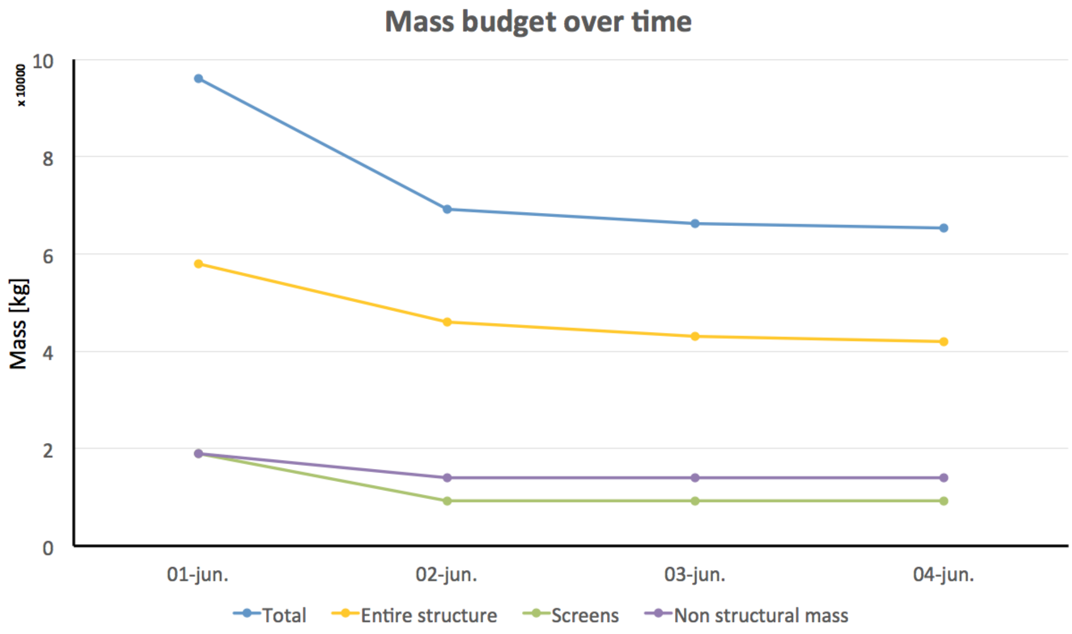


Figure 8.5: Mass budget over time iteration process of table 8.3 visualized

As can be seen in table 8.2, the 'Carbon 3' design has the lowest mass and still has a lift/MTOW of 1.3, which can be seen in table 8.3. When only considering structures, the 'Carbon 3' design would be selected, however, for stability reasons, another option might be better. In section 9.6.2, it is explained why a larger value for the lift/MTOW is beneficial for stability and in sections 9.3 and 9.5, the aerodynamic forces influencing the stability are explained. In section 9.3, it becomes clear that the 'Carbon 2' design generates more aerodynamic lift than the other designs, which is favourable for the overall stability. Besides that, 'Carbon 2' is only slightly heavier than 'Carbon 3' and has the highest lift/MTOW, which is also preferred by the aerodynamics department of the Diamond of Dubai. Considering the weight payment of only 1000 kg with respect to 'Carbon 3', the 'Carbon 2' design was selected. Thus, 'Carbon 2' has a better performance than 'Carbon 3', while only being 1000 kg heavier. More detailed information on the dimensions and masses of individual members can be found in Appendix D.1 for 'Carbon 1', in Appendix D.

8.4. DESIGN OF INTERNAL STRUCTURE

This section covers the design of the entire internal rigid structure. In section 8.4.1, the nodal connection points will be discussed, in section 8.4.2, the fishnet cabling to provide support for the external envelope will be discussed. Section 8.4.3 demonstrates the calculation process for the structure, section 8.4.4 demonstrates the verification of the calculations and section 8.4.5 summarizes the material characteristics.

8.4.1. HINGES IN THE CORNERS

For easier calculations, it is assumed that the joints do not experience any moments. This assumption can be validated if the joints used allow free rotational movement. The first difficulty is the amount of beams that have to be connected in the connection points. In some points, as many as 9 beams come together. For this structure, some kind of block will be used with 11 surfaces, of which 9 are perpendicular to the incoming beams. The first extra surface is for a connection with the envelope. It still has to be determined what type of connection this is going to be. The second one is an open surface. When assembling these connection points rivets or Hi-loks need to be placed from one side and the most suitable location to do that is within the block. A figure of the connection points is given in figure 8.12. Figure 8.15 and 8.16 show the actual beams. To make it more clear, table 8.4 shows the amount of beams that have to be connected in each of the nodal points. This results in a total amount of 96 joints.

The second difficulty is the type of joint or bearing that is going to be used. A first thought immediately went out to ball and socket joints, as shown in figure 8.6, since they enable the beam to rotate in all directions. For this project, they need to be custom made, but as an indication, ball and socket joints capable of handling the same forces were compared. From this data, it was estimated that these type of joints will weigh approximately 300 kg each. A total number of 96 joints results in a weight of 28,800 kg, the use of these joints is infeasible. A second idea came from the existence of hingeless rotorblades for helicopters. They also have moments and torsional forces that should be zero at the rotorhead. A combination of several elastomeric parts, see figure 8.7, makes it possible to absorb these forces. Since these materials are low stiffness elastomers, they do not bend, up to a certain angle, but handle bending loads by shearing. Since the rotorblades are only in tension, the application is different and another configuration needs to be found. The application is approximately the same as for the bearings used in buildings and bridges to absorb the forces of earthquakes. Here, cylindrical bearings made out of elastomer rubber or neoprene are used. For reference, the bearings of the company VSL are used. The most suitable one is the 'Type BS rounded reinforced bearing with a 400 mm diameter' found on page 14 of the company catalogue, see appendix F [28]. It is able to withstand a compressive force of 1.9 MN, which means there is a safety factor of 1.5. The weight of each bearing is 41 kg, which results in a total mass of 3936 kg. This is feasible and integrated into the mass budget rounded to 5000 kg to be on the safe side. The catalogue does not tell the tensile strength, but the BS type differs from the others, because it has bolts going through to make sure the horizontal forces do not make the beam slip from the surface. This is important, but another advantage is that these steel bolts can take tensile loads. If it is assumed that the 4 bolts are made of a common type of steel the yield strength will be about 250 MPa or higher [29]. With the given bolt diameter of 19 mm this means that the pins are able to withstand tensile loads of 284 kN. The loads are going up to 850 kN, but if bolts with a diameter double the given one are used, loads up to 4 times as big can be withstood. This can be custom made for this project. Two rendered figures of how the block at node 11 will look like are found in figure 8.8 and 8.9. More details and CATIA drawings of this block can be found in appendix G.

Table 8.4: Amount of beams coming together in each nodal point

Nodal point	Amount of beams
1	6
2	6
3	6
4	9
5	9
6	9
7	6
8	6
9	6
10	6
11	3
12	8
13	8
14	8

In this section the used theoretical concept has been explained and possible solutions for the hinge points have been stated. In fact, it is assumed that the moments in the connection points can be neglected, because they will be very small. As a result, it might be possible to interchange the hinged connection points with fixed ones during manufacturing without large consequences.

8.4.2. FISHNET CABLING

From the structural dimensions, it becomes clear that just covering the structure with the external envelope might introduce large out of plane deformations of the envelope. These deformations might occur when wind forces become large. To minimize these deformations of the external envelope and keep the preferred aerodynamic shape, the internal structure will be covered entirely in a cabling net. This cabling net, made of Dyneema, won't allow the external envelope to deform towards the inside of the balloon and thus this fishnet cabling will make sure the planes will keep their shape. In the future, more research is advised on this topic. The total area of the balloon to be covered in cabling is $14700m^2$ and using cabling of 200 grams per

Figure 8.6: Ball and socket joint

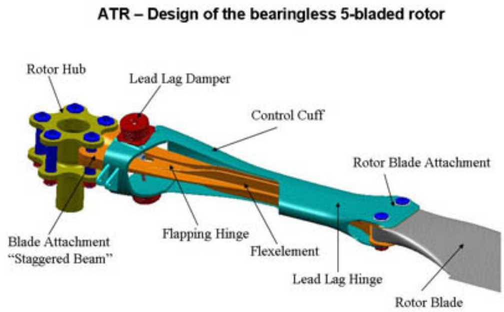


Figure 8.7: Hingeless rotorblades

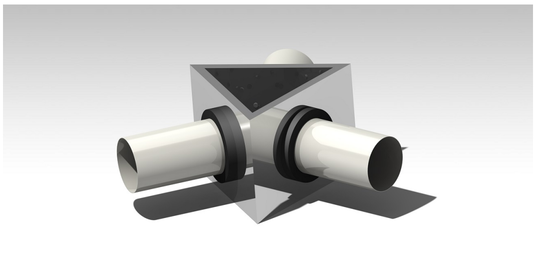


Figure 8.8: Isometric view connection block at node 11

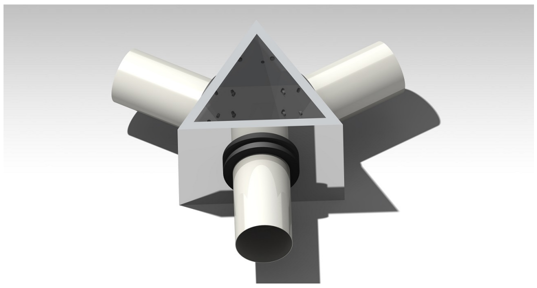


Figure 8.9: Isometric view connection block at node 11 from the other side

m^2 [30]. For now, the weight of the entire fishnet covering for the aerostat can be assumed to be 3000kg at a maximum, including connections to the structure. An example of such a net can be seen in figure 8.10.

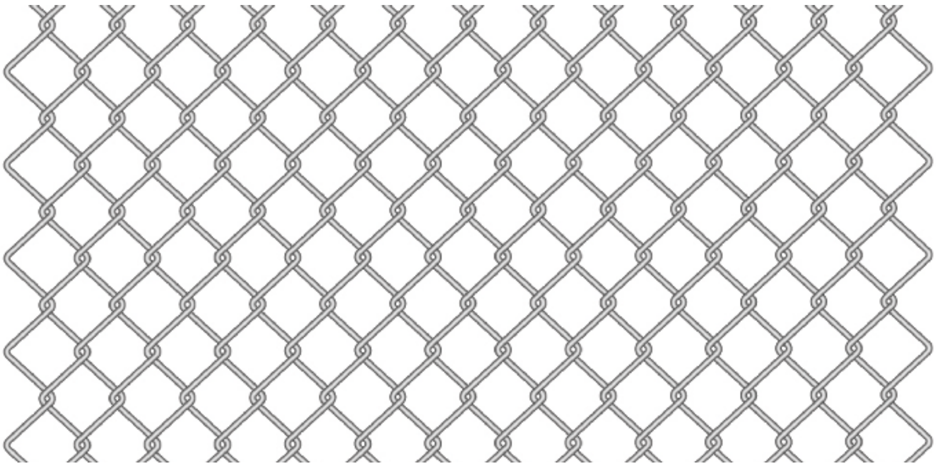


Figure 8.10: Example of a cable net configuration

8.4.3. CALCULATIONS ON THE INTERNAL STRUCTURE

The structure outlining the shape of the balloon was determined in the midterm report. To be able to start optimizing the structure and the dimensions of the balloon, it is necessary to create a program that is able to calculate all dimensional sizes, including members lengths, the internal forces in all members for different load cases, the optimal cross sectional areas/radii/thicknesses and the mass of the entire structure.

A MATLAB script was created to optimize the structure on the topics mentioned above. The script outline can be summarized in a total of 9 steps. In this section, these steps will be elaborated upon [31].

STEP 1: Calculate the dimensions, internal volume and determine the position in cartesian coordinates of the nodal points

In figure 8.11, it can be seen that the shape of the structure consists of two pyramids put on top of each other, both with the point cut off. The program uses the so-called "height of lower pyramid", the "height of the "upper pyramid" and the 'maximum width' of the structure as input values. The dimensions and the names to which they are referred are visualized in figure 8.11. The program calculates the exact size of the structure, the internal volume and the location of the nodal points with respect to the origin. These coordinates will be used in step 2, in order to connect the points in space and to visualize the structural layout in step 3. It is important to keep track of the nodal points. In figure 8.12, the location and numbering is made clear. The sign convention for the coordinate system is also important: the positive Z-axis points upwards, the positive Y-axis points into the paper and the the positive X-axis points to the right. This is visualized in figure 8.13.

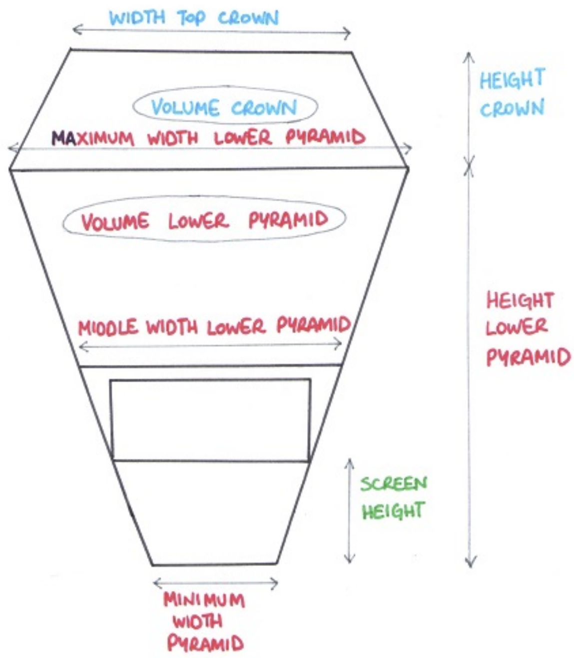


Figure 8.11: Dimensions of the aerostat and their corresponding names

The dimensions of the structure are calculated using basic geometry. The internal volume can be calculated by computing the volume of multiple pyramids (as seen in figure 8.14), followed by subtracting them from each other. For example: the volume of the lower pyramid missing its top can be calculated by first obtaining the volume of the pyramid with its top and then subtracting the volume of the smaller pyramid. This can be repeated for the upper pyramid. The volume V of the pyramid in figure 8.14 can be calculated with equation 8.2.

$$V = \frac{1}{3}\left(\frac{1}{2}bh\right)H \qquad [8.2]$$

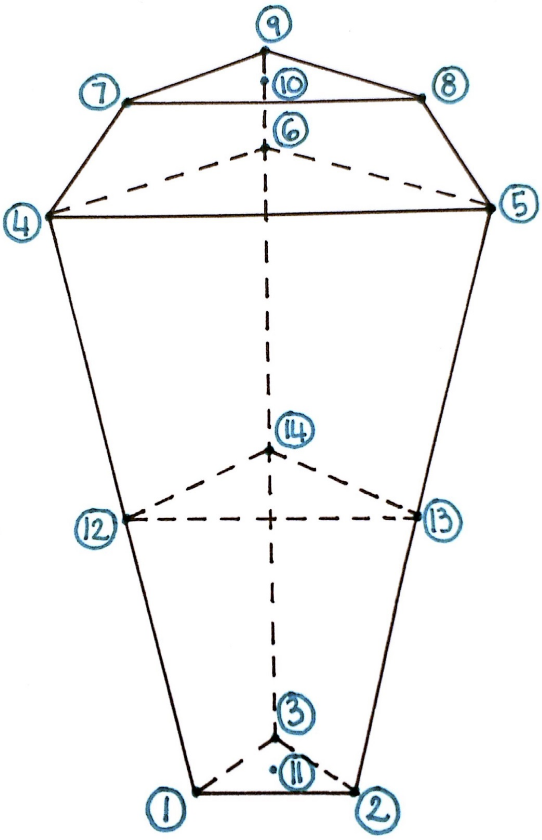


Figure 8.12: Nodal points with their numbering

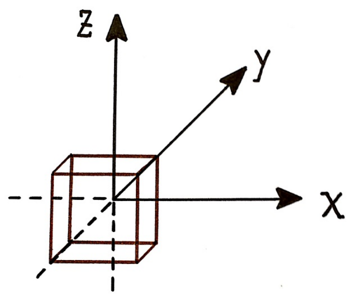


Figure 8.13: Sign and coordinate convention

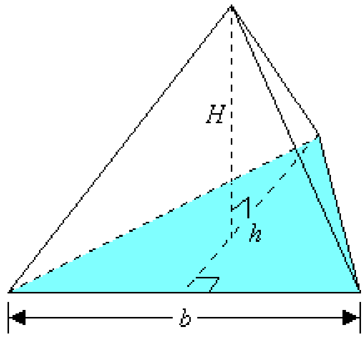


Figure 8.14: Pyramid calculation visualization

STEP 2: Connect the nodal points, set the degrees of freedom and calculate the length of the members
In step 2, some of the coordinates need to be connected to each other. In this step, the program connects the nodes that need to be connected. Besides that, it is necessary to fix some of the nodes to be able to perform calculations. For all calculations, all nodes on the lowest surface have been fixed to the ground. In a later stage, the mass has to be calculated and therefore the length of each member is calculated using the cartesian coordinates. E.g. the length spanned between point $A(A_x, A_y, A_z)$ and $B(B_x, B_y, B_z)$ can be calculated using equation 8.3.

$$l = \sqrt{(B_x - A_x)^2 + (B_y - A_y)^2 + (B_z - A_z)^2} \quad [8.3]$$

This step generates a n-by-2 matrix with n connections and rows that correspond to the connected nodes. In other words, a row [1 7] means that there is a member running from node 1 to node 7. A m-by-3 matrix is generated, where m is the amount of points that each represent a node and the rows correspond to [1 1 1] fixed or [0 0 0] not fixed. A n-by-1 vector contains the lengths of all members.

STEP 3: Put different load cases into the program
It is obvious that different load cases will result in different internal forces and thus different optimized designs for these cases. It is important to consider all possible load cases and to derive the maximum internal forces from them for each individual member. The load cases considered can be found in section 7.3.

For the load cases, a safety factor of 1.5 is used. All load cases are thus multiplied with a factor of 1.5 and then applied to the structure. This value was chosen by the because it is a common safety factor value in the aerospace industry.

In the MATLAB program, loadings can be applied to the nodal points only. The format is as follows: when it is required to apply a load of 100 N in Z-direction on point 10, for example, then the force should be entered as follows: [0 0 100]. It is thus possible to add different load cases in MATLAB to calculate the internal forces and optimize the structure in later steps.

STEP 4: Visualize the structure by plotting it in 3D
During the calculations it is of great importance to verify whether or not the structural design that was expected to be in the code is really there. A visualization of the nodes and the members is thus very helpful. This is obtained by plotting them in 3D. This will also make it possible to visualize the dimensions and to have a feeling whether or not the dimensional ratios are esthetically pleasing. Two examples of the 3D visualization plots can be found in figures 8.15 and 8.16.

STEP 5: Calculate the internal forces in all members and the reaction forces acting on the fixed nodal points
An important step in the structural sizing is the calculation of the internal forces in all members for the different load cases. As stated already, one member is defined by two nodal (cartesian) points. To be able to calculate the internal forces, the program sets up a normalized vector between the two nodal points. E.g. for the points $A(A_x, A_y, A_z)$ and $B(B_x, B_y, B_z)$ this would be done with equation 8.4.

$$T = \frac{[B_x - A_x; \quad B_y - A_y; \quad B_z - A_z]}{\sqrt{(B_x - A_x)^2 + (B_y - A_y)^2 + (B_z - A_z)^2}} \quad [8.4]$$

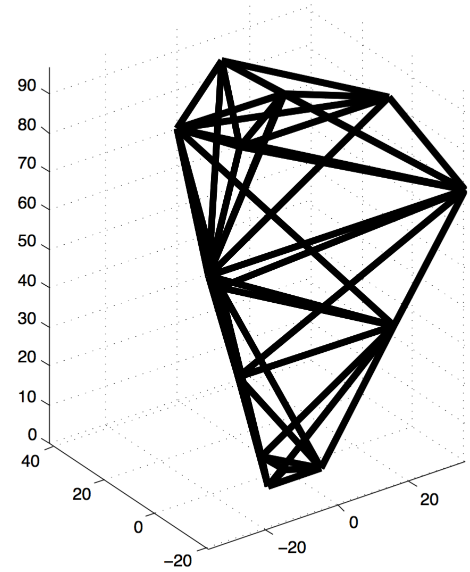


Figure 8.15: 3D view MATLAB generated plot, axis shown in meters

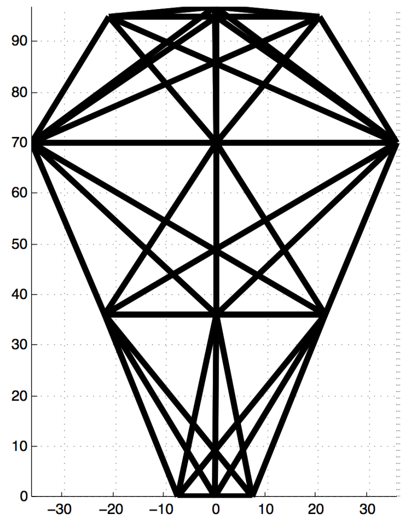


Figure 8.16: Front view MATLAB generated plot, axis shown in meters

In the next step, the direct product, also known as tensor product, (T) of this normalised vector is calculated.

$$TT^T = \begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix} \begin{pmatrix} T_x & T_y & T_z \end{pmatrix} = \begin{pmatrix} T_xT_x & T_xT_y & T_xT_z \\ T_yT_x & T_yT_y & T_yT_z \\ T_zB_x & T_zT_y & T_zT_z \end{pmatrix} \quad [8.5]$$

In the following step, the Young's modulus and cross-sectional areas are used for the calculation. However, it is not needed to know the values of these and it is possible to assume values for these properties. This is possible, because these properties will be undone again in a later stage of the calculation, in calculating the internal forces. Thus assuming values (with the exception of zero) does not affect the values of the internal forces. This has been successfully verified.

To start with, the values of the cross-section and the value of the Young's modulus can be assumed to be 1, as they do not affect the internal forces. When the deflections of the members are required, the proper values must of course be used. Hooke's law has been used, because it enables the use of space vectors in calculating the internal forces in all members. Hooke's law can be found in equation 8.6. In this equation, k is the stiffness or the stiffness tensor and T is the relative directional displacement vector from node A to B.

$$F = kT \quad [8.6]$$

First, the stiffness k can be defined using equation 8.7. In this equation, E is the Young's modulus, A is the cross-sectional area and l is the length of the member.

$$k = \frac{EA}{l} \quad [8.7]$$

The next step is to calculate the force using equation 8.6, using the stiffness obtained from equation 8.7 and the vector T from equation 8.4. Filling this in results in equation 8.8.

$$F_{AB_{partial}} = \frac{EA}{l}\vec{T} \quad [8.8]$$

The program saves all partial forces $F_{partial}$ of each member in one matrix and saves all tensor matrices, like AB's, from equation 8.5 in one other large matrix. Finally, MATLAB solves the large system of linear equations using the built-in MATLAB solver 'mldivide'. The only thing left to be done is to sum up all partial forces that act in each member and making sure the Young's moduli and cross-sectional areas do not influence the internal forces. The same can be done for the reaction forces on the fixed nodal points.

STEP 6: Determine the required area for the internal tension and compression forces (without buckling)
The cross-sectional area required for pure tension and/or compression (no buckling assumed) can be calculated by using equation 8.9 and the yield strength from table 8.6. For carbon and glass-fiber, the ultimate strength should be used. The program now creates a vector where every required area for each member will be stored.

$$A = \frac{F}{\sigma} \qquad [8.9]$$

STEP 7: Determine the cross-sectional area to prevent buckling, optimize radius and skin thickness
The next step is to calculate the moment of inertia for each member. This value is needed to prevent buckling of the members. This is done for all members by using equation 8.10. In equation 8.10, F corresponds to the internal force in the member, l is the length of the member and E is the Young's modulus. The Young's modulus is a material property.

After the calculation of the required moment of inertia, a preliminary wall thickness of 5 mm is assumed. This is a preliminary starting value and it will be changed later on by means of an iterative process performed by MATLAB.

$$I = \frac{Fl^2}{\pi^2 E} \qquad [8.10]$$

Since the moment of inertia I and the wall thickness t are known, the radius of the circular hollow beam R can be computed. An example of the beams cross-section with the definition of the thickness can be found in figure 8.17. The required radius for the fixed moment of inertia and the wall thickness can be computed using equation 8.11.

$$R = \sqrt[3]{\frac{I}{t\pi}} \qquad [8.11]$$

Equation 8.11 does not automatically take into account manufacturability and thus a minimum radius of 15 cm and a maximum radius of 40 cm is assumed. After this calculation, the program calculates the new required thicknesses of the members by using equation 8.12. The program incorporates a loop, make sure the wall has a minimum thickness of 2 mm for manufacturability. A new radius can then be calculated from the moment of inertia and the wall thickness using equation 8.11. The question that might arise is: 'why isn't the radius maximized as much as possible and the thickness as low as possible?'. The answer to this question is four sided: First of all, members with a large radius will take a large part of the inner volume of the balloon, reducing the amount of helium that can be used. Secondly, members with larger radii are more difficult to produce and will thus be more costly. Thirdly, the members need to be connected in nodal points and the larger the radius, the more difficult it will be to do so. Finally, the smaller the radius, the likelier it will be to find off the shelf carbon members.

The members would be optimally designed when the failure in the normal mode and buckling mode are simultaneous. However, this would mean that the radius of the members would go up above 40 cm and that is not preferable as mentioned previously.

$$t = \frac{I}{\pi R^3} \qquad [8.12]$$

The cross-sectional area of all members can now be calculated for the specific load cases by equation 8.13.

$$A = 2\pi R t \qquad [8.13]$$

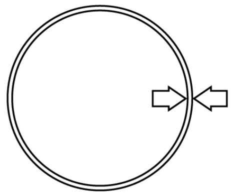


Figure 8.17: Cross-sectional view of the members with the arrows pointing out the wall thickness

Intermezzo: problem by using asymmetrical loading
When looking at the obtained data, it could be seen that when the structure is loaded asymmetrically, which will be the case for all worst load scenarios, the program optimizes all members for that specific loading. This means that members 1 to 12, 3 to 14 and 2 to 13 in figure 8.12 have different optimal cross-sectional dimensions for a specific load case. The maximum cross-sectional area and dimensions must thus be used for all of these members, as the exact same load case could also act on one of the other two sides of the balloon. This is also incorporated into the program.

STEP 8: Compare required area for buckling and for pure compression/tension only
The required cross-section for the normal mode and the required cross-section for the buckling mode are checked in MATLAB and the largest required dimension were used in all further calculations. It can already be said that the failure mode will likely be due to overal buckling of the long members.

STEP 9: Use properties of different materials to calculate and optimize for mass
To optimize the structure for the mass for fixed dimensions, different material properties are used from table 8.6. Aluminum, glass fiber and carbon fiber are used to calculate weights. The performance number 'the entire volume (lift) over the structural mass' is used to compare different materials and dimensions. The program calculates the mass of all members and sums them up to get the structural weight.

8.4.4. VERIFICATION & VALIDATION

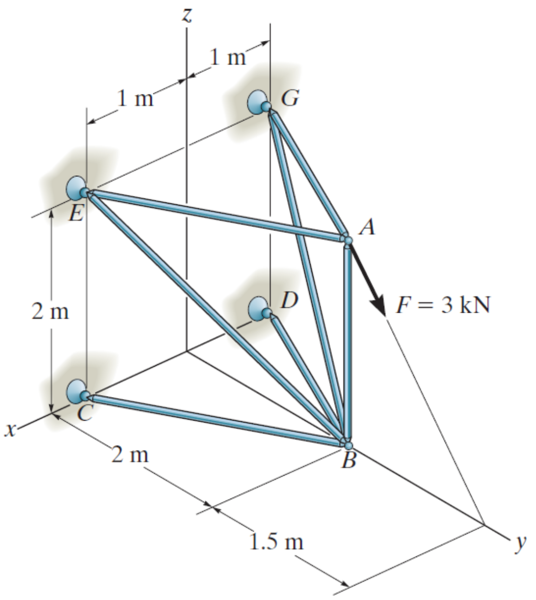
The process of verification and validation in the field of software engineering is a way of testing whether or not the developed software meets the proposed requirements. This is a crucial step in the software development phase, because in this way, it is possible to ensure to the client that the computer model represents the real world within the required accuracy. The way to perform a verification test is compare the programmes results with hand calculations. The way to perform a validation test is by checking the program output with real test data.

To verify the developed computer tool, a 3D truss structure exercise of a statics handbook [32] was chosen. This problem was calculated by the model and afterwards it was compared with the worked out solutions of the handbook. As can be seen in figures 8.18, 8.19, 8.20 and table 8.5, both outcomes are nearly the same, therefore it can be said that the program is verified successfully. The small discrepancy is due to small rounding errors, which were introduced by manually calculating the X,Y and Z components of the introduced load. If those hand calculations were done with more significant digits, the program would come up with the exact solution. The rest of the program consists of failure calculations due to tension, as well as buckling. This was verified by small and simple hand calculations based on equations 8.10, 8.11, 8.12 and 8.13. Now that the program is verified, it can be used to do the required calculations for the internal structure.

To perform a validation test, the results of a structural destructive test should be compared with the predicted failure by the program. To fully verify the model, a scale model of the structure must be produced and tested. Due to the time constraints of this DSE project, it was not possible to perform this test. Only if the program is validated, it is possible to guarantee the costumer that the right product has been built.

8.4.5. MATERIAL SELECTION AND MATERIAL PROPERTIES

In this section, the material choice for the internal structural will be investigated. First, some material characteristics will be listed in table 8.6 and afterwards the interpretation will be demonstrated.



Prob. 6–55

Figure 8.18: Verification exercise 6.55

6–55. $F_{BC} = F_{BD} = 1.34$ kN (C), $F_{AB} = 2.4$ kN (C)
$F_{AG} = F_{AE} = 1.01$ kN (T), $F_{BG} = 1.80$ kN (T)
$F_{BE} = 1.80$ kN (T)

Figure 8.19: Verification exercise 6.55 solution

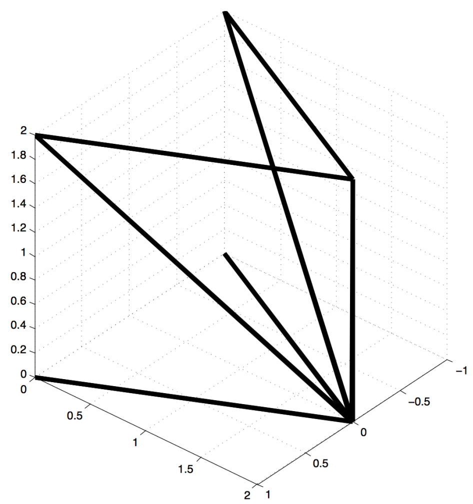


Figure 8.20: Verification exercise 6.55 matlab figure

fist node	seconde node	Force [kN]
1	2	-2.4
1	6	1.0062
1	5	1.0062
2	3	-1.3416
2	4	-1.3416
2	5	1.8
2	6	1.8

Table 8.5: Internal member forces calculated by the program

Table 8.6: material properties

	E [GPa]	$\rho [kg/m^3]$	σ_{ult} [MPa]	E/ρ [10^6 Nm/kg]	$\sqrt[3]{E}/\rho$ [10^6 $mm^{7/3} N^{2/3}$]
Aluminium 7075 T-6 [33]	71.7	2810	503	$255 \cdot 10^5$	1.48
Carbon fiber (70% fiber)[34]	181	1500	1600	$1206 \cdot 10^5$	3.77
Glass fibre (epoxy matrix) [35]	50	1800	1500	$278 \cdot 10^5$	2.05

To properly compare the possible materials, it is necessary to compare both their physical performance characteristics and their density. The ratio of Young's modulus over density was calculated. This ratio should be used to judge materials for rods and members that will be loaded under pure tension. On the other hand, when it is needed to compare materials for rods/members that will be loaded under compression, the bending stiffness is important, the ratio then becomes the 3rd power root of the young's modulus over its density [27].

In both the loading cases, it can be clearly seen that carbon fiber is the best option as a material choice. Although carbon fiber was considered to be the worst option considering cost, after discussing this issue with the material department of the faculty of Aerospace Engineering at the Delft University of Technology, it seemed that this is not necessarily the case. There is a large possibility that the cost of for example glass fiber will be higher, because more material would be needed to withstand the loads. In other words: the price of CFRP is higher per kg, but the price of the total carbon fiber structure can compete with that of a glass fiber structure. The cost estimation for the carbon structure can be found in chapter 18. It should be noted that the cost for an aluminum or glass fiber structure has not been calculated since it would result in a too heavy structure making the design infeasible.

8.5. ENVELOPE DESIGN AND MATERIAL SELECTION

In this section, the design of the envelope and material selection of the envelope will be clarified. The section will be split up into two parts, one describing the internal envelope and the other describing the external envelope. First, the material selection for both envelopes is explained, combined with some calculations on stress inside the fabric.

As said before, the envelope configuration of the aerostat will consist of two balloons, made out of two materials. The main reason for using two balloons, is the fact that the external envelope will need to have holes to attach cables and screens to the internal structure. Via these holes, helium would escape, this thus excludes the possibility of using one single envelope. A second reason for using two balloons can be found in safety: using only one envelope would increase the risk of failure, since if a hole or tear is introduced, by any matter, there is no back up to guarantee the safety of passengers on board of the aerostat or gondola. To ensure their safety, a second configuration was designed.

This configuration consists of an internal envelope containing the helium, which will provide the lift. This envelope will be placed inside the structure. On the outside of the structure, the external envelope will be placed. The outer envelope will consist of a material that can withstand the harsh conditions of the climate of Dubai. The outer envelope will be mounted onto the structure, but space will be left in between the inner and outer envelope to make sure there is space for cabling, maintenance and other systems. In the next two sections, the inner and outer envelope will be further elaborated on.

8.5.1. INTERNAL ENVELOPE

The internal envelope will hold the helium, as explained earlier. Helium loss can have a large economical and logistics impact, so this needs to be prevented as much as possible. A possible solution is selecting a material that can contain the helium inside, minimizing the helium passage through the membrane of the envelope. The internal envelope should be able to withstand the stresses induced by the pressure inside and outside the balloon. A safety factor of 5 should be applied as mentioned in section 3.1.

Many suppliers and manufacturers for these materials can be found. The company willing to provide DSE group 18 with information on those materials is Lamcotec Inc [36]. Lamcotec Inc. is a manufacturer of urethane laminated textiles, which can be used for aerostats. The company provided information on 15 different materials, among which there were nylon, nylon ripstop, polyester and vectran. These materials differ in weight, strength and helium permeability. For the internal envelope, which does not have to withstand the harsh conditions of the external environment, a lightweight material was required, which limits helium passage as much as possible. Looking at the material properties of the 15 materials, it became clear multiple vectran configurations and one nylon configuration had low permeability of helium. The 30 denier nylon ripstop material was found to be the lightest, yet strong material for the internal envelope. The material consists of nylon fibers with a polyurethane matrix. Characteristics can be found in table 8.7. Furthermore, to decrease the permeability to helium, an ethylene vinyl alcohol (EVOH) coating will be used because of its superior gas barrier properties [37] [38].

Table 8.7: 30 denier nylon ripstop properties from Lamcotec Inc.(excluding coating) [36]

Weight	Thickness	Breaking strength	Permeability helium
37 g/m^2	0.1397 mm	7880 N/m	0.615 L/m^2/24h

With the helium permeability value for the nylon material and the area of the aerostat given, the helium loss per day can be approximated. The total area is 14761m^2, so the helium loss per day will be 9078L, which is 9.08m^3. Comparing this to the total volume of the envelope, which is 101143m^3, the helium loss is calculated to be 0.0089% per day. If the aerostat would be refilled once a year, this could be done since the helium loss is very small, the amount of helium to be pumped into the envelope is 3233m^3, which costs 9699 euro with a helium price of 3 dollars per cubic meter [5]. In other words, helium loss is not a major operational cost increasing factor.

To calculate the stress in the nylon fiber, some assumptions should be made to make calculations possible. It is assumed that the bag of helium is spherical inside the aerostat. This way, the stress in the envelope can be calculated using the hoop stress formula in equation 8.14.

$$\sigma_E = \frac{(p_i - p_a)r}{2t} \qquad [8.14]$$

In equation 8.14, p_i is the internal pressure, p_a is the aerodynamic pressure from outside on the envelope, r is the radius of the balloon and t the thickness of the envelope material. In the calculations, the forces due to aerodynamic pressure p_a can be assumed to be the static air pressure of the surrounding air.

To calculate the internal pressure, one should calculate buoyancy forces. The buoyancy force can be calculated using equation 8.15 [39].

$$F_b = \int_{body} (p_2 - p_1) dA \qquad [8.15]$$

The buoyancy equation in equation 8.15 can be used to come up with an equation to calculate the internal pressure at a certain point above or below the equator of the balloon. This equation is found in equation 8.16. In this equation, g is the gravity acceleration and z_e the vertical distance from the equator of the balloon to the point at which the internal pressure is calculated. The last value to be explained is $\bar{p}$, which is the internal overpressure compared to the outside environment. In the case of the world's largest dirigible billboard, the pressure inside and outside of the balloon will approximately be the same, so the difference can be set to zero when compared to the pressure due to the density difference between air and helium.

$$p_i = \bar{p} + (\rho_{air} - \rho_{he}) g z_e \qquad [8.16]$$

Finally, equation 8.15 and equation 8.16 can be combined to come up with an equation to calculate the stress in the fibers of the envelope at a certain point along the vertical axis. Of course, maximum and minimum values of this stress can be expected at the top and bottom of the balloon. The equation can be found in equation 8.17.

$$\sigma_E = \frac{(\rho_{air} - \rho_{he}) g z_e r}{2t} \qquad [8.17]$$

In equation 8.17, multiple variables are stated, one being the thickness of the envelope. Knowing this value is thus essential to calculate the stress in the envelope. Lamcotec Inc. provided these values, so useful calculations could be performed. The thickness was added in table 8.7. To be able to fill in equation 8.17, first the radius of the envelope sphere should be known. Knowing the volume of the envelope, 101143 m^3, a corresponding radius of 28.9 m was calculated. For the maximum stress to occur, z_e should be as large as possible, which is if z_e equals the radius, so maximum stress occurs at the top of the balloon. Filling in the equation with $(\rho_{air} - \rho_{He}) = 0.94$ [5], a maximum stress of 27.6 MPa was found.

To see if the internal envelope material would be able to withstand these forces, the maximum stress before failure was calculated. Using a breaking strength of 7880 N/m as mentioned in table 8.7, and dividing by the thickness, a maximum stress of 56.4 MPa was found. This implies the safety factor for the internal envelope is 2.04. To fulfil the requirement of a safety factor of 5, a triple internal envelope can be used. The weight of one single envelope is approximately 546 kg, using a total area of 14761 m^2. When a triple envelope is used, the weight increases to 1638 kg. However, for structural calculations an initial weight of 3000 kg for the internal envelope was used, to account for attachments to the structure and a safety factor.

8.5.2. EXTERNAL ENVELOPE

The external envelope will have a totally different function than the internal envelope. Where the internal envelope is designed to keep it's contents inside, the external envelope is designed to keep the environment outside. It needs to protect the structure and the internal envelope from UV-radiation, sand, water and wind. Therefore, the material needed will be much thicker than that of the internal envelope. However, the external envelope should be able to hold helium as well, for example when a leakage occurs in the internal envelope. The helium will leak out of the internal envelope, but will still be inside the external envelope. The lifting force of the helium is thus preserved, and the dirigible can be safely lowered to the ground for maintenance. The external envelope acts as a redundant envelope, minimizing the risk of accidents for passengers. The external envelope should be able to withstand the forces of the wind the envelope is subjected to. For those calculations, a safety factor of 5 should be applied as mentioned in section 3.1.

Again, Lamcotec Inc. was the company who provided information on its different envelope materials and a comparison could therefore be made. In this case, helium permeability is not the most important factor, since the internal envelope was designed to hold the helium. Strength, weight, UV resistance, water resistance and rip-stop capacity are thus the factors of importance. After comparison, it was clear the 400 denier vectran with a urethane laminate has the highest strength over weight ratio and it is also water and air tight. Properties of this vectran material can be found in table 8.8. When looking at UV-radiation, it was found that urethane resists UV-degradation very well and is commonly used as a coating on other materials [40] [38]. Since the vectran has a urethane laminate, it will not be necessary to coat the envelope with some extra protective material, as the urethane laminate will provide the protection against UV degredation.

Table 8.8: 400 denier vectran properties from Lamcotec Inc. [36]

Weight	Thickness	Wound tear	Breaking strength	Permeability helium
108 gr/m^2	0.3048 mm	2313 N	2189 N/25mm	0.577 L/m^2/24h

Calculations have to be made to be able to make sure the external envelope can withstand the forces induced by the wind. As will be explained in section 9.3, the drag forces acting on the dirigible in operation can get as large as 711kN for the second configuration. Assuming this force is divided only over one of the three largest sides of the dirigible, which all have an area of 3244m^2, the force per square meter becomes 219 Pa.

This means by defenition that the maximum force the wind introduces per square meter is 219N. This force will have to be partially taken up by the vectran fibers, as the fibers will be loaded in tension. For calculations to be conservative, it is assumed that the total wind force is taken up by the envelope. The maximum tensile force the material can withstand was tested by Lamcotec Inc. and included under 'breaking strength'. When looking at the properties of the 400 denier vectran in table 8.8, vectran has a breaking strength of 2189$N/25mm$. This corresponds to a breaking strength per meter of 88kN. It can be said the external envelope will thus not fail in tension, since there is a safety factor of 400. At first thought, one could say the external envelope is overdesigned. However, the strength of the material will also be needed to withstand the forces of sand, and withstand UV degredation.

Furthermore, information about shear strength was not provided by Lamcotec Inc. The properties and maximum shear stresses can therefore not be calculated yet. More investigation is needed, to make sure the envelope can also withstand those loadings. However, looking at the safety factor of 400 for loading in tensile direction, it is assumed the envelope can withstand forces in shear. On the other hand, calculations on tensile strength when a hole is introduced in the envelope were performed, and discussed in the next paragraph.

The calculations performed on the wind force acting on the envelope assume the envelope does not have any inconsistencies on its surface. However, for multiple reasons it is possible that a hole or multiple holes are introduced onto the external envelope. One reason for the holes is to create a connection between the external envelope to the structure on the inside. Also, the LED arrays will have to be connected from the outside to the internally placed structure. This will introduce holes in the external envelope as well. A third reason is the possibility of an accident causing a hole in the external envelope. Lamcotec Inc. also performed testing on the vectran material with an incision covering 16% of the length perpendicular to the pulling direction. In table 8.8, a wound tear strength of $2313N$ is given, after testing a specimen of $75mm$ wide, with an incision of $12mm$. Thus, a one meter wide vectran envelope with a hole or incision of $16cm$ wide should be able to withstand a force of $31kN$. This is still a much higher force than the force the wind will introduce on the envelope, which was 219 N/mm. This implies a safety factor of 142. As said before, the high safety factor is convenient since the envelope will also have to withstand abrasive sand and UV degradation.

Using a total area of 14761 m^2, the total weight of the external balloon is calculated to be 1594 kg. Similar to the internal balloon, in calculations for the structure a value of 3000 kg was assumed, to account for a safety factor and attachment points to the structure.

8.6. FINAL STRUCTURAL DESIGN AND DESIGN CHARACTERISTICS

In this section, a summary is provided for the final structural configuration, as can be seen in figure 8.22 and 8.21, as well as the envelope material. The final configuration that was chosen is 'Carbon 2', this was done in cooperation with the aerodynamics and stability department of the Diamond of Dubai group. This choice is explained and documented in section 9.6.
Dimensions of the aerostat can be seen in table 8.9. Furthermore, the mass budget is documented in table 8.10 and visualized in a pie chart in figure 8.23.

The envelope material selection has resulted in two balloons, an internal and an external envelope. The internal envelope is made out of 30 denier nylon ripstop, covered with a EVOH coating to decrease helium permeability. The external envelope is made out of 400 denier vectran, to withstand the harsh environmental conditions in Dubai. The total area of the envelope is 14761 m^2, with a total mass of 2140 kg. The volume of the envelope is 101143 m^3.

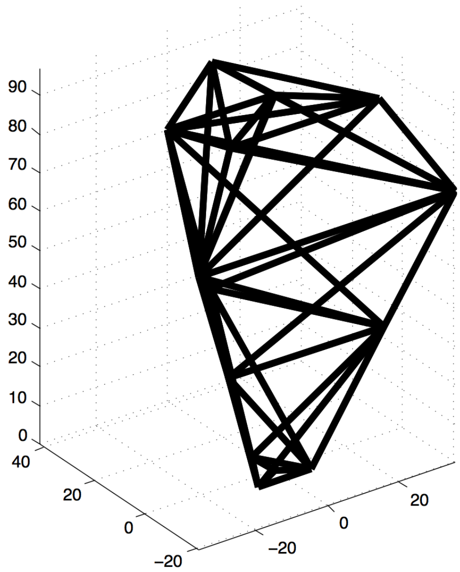


Figure 8.21: 3D view MATLAB generated plot, axis shown in meters

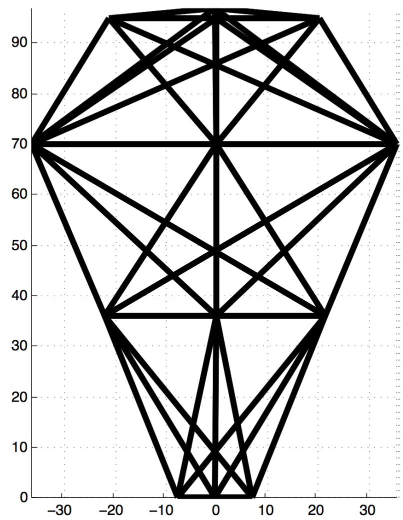


Figure 8.22: Front view MATLAB generated plot, axis shown in meters

To be able to predict the interaction between vortices and the structure, the eigenfrequency of the entire diamond needs to be determined. The Diamond of Dubai group recommends more research in this area. This will be further elaborated upon in chapter 22.

Table 8.9: Structural dimensions of the selected design 'Carbon 2'

	Carbon 2	
	Value	Unit
Height lower pyramid	70	[m]
Height crown	25	[m]
Total height of balloon	95	[m]
Width lower pyramid	75	[m]
Volume lower pyramid	56832	[m^3]
Volume crown	44310	[m^3]
Total volume balloon	101143	[m^3]
Useful total volume balloon	94540	[m^3]
Total helium lift	978	[kN]
Mass main structure (no hinges)	32079	[kg]

Table 8.10: Mass budget breakdown of the selected structural design

Part	Carbon 2 [kg]
Screens (32mx18m)	9000
Envelope internal	3000
Envelope external	3000
Structure internal + hinges	32000 + 5000
Fishnet cabling	3000
Connection cables	2000
Entire structure	48000
People payload	6000
Electronic wiring	3000
Lighting	2000
Lift & Gondola	3000
Non structural mass	1 4000
Total mass	71000
lift/MTOW	1.40 [-]

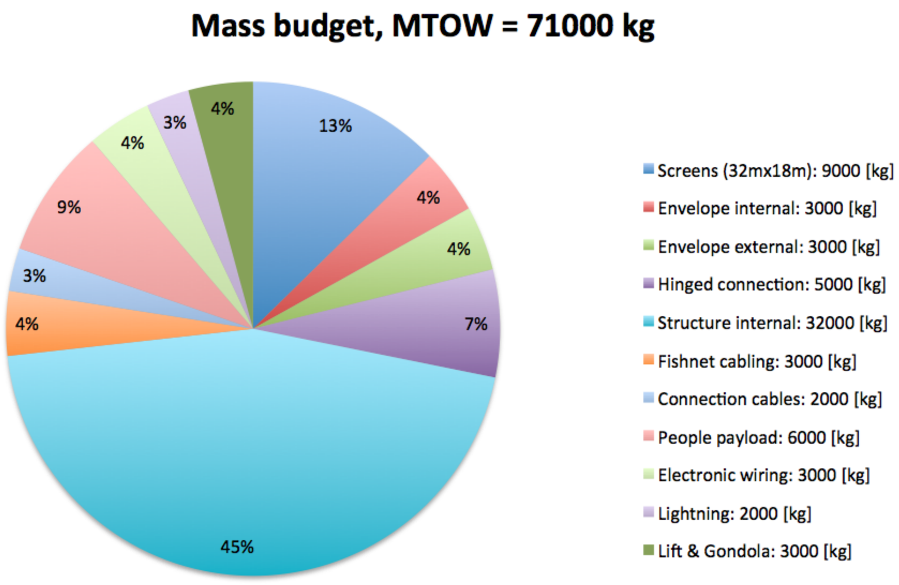


Figure 8.23: Pie chart of the mass budget for the selected structural design configuration

9
AERODYNAMIC STABILITY

One of the biggest challenges in designing the world's largest dirigible is to keep it in stable operation in the air. The final report continues on the work done in the mid-term report [2]. In the chapter on stabilization in that report, apart from discarding the infeasible stabilization options, it is stated that further investigation on stability is of very high importance. For that reason, both the concept of stability and control and aerodynamic design will be discussed here. Section 9.1 describes why the system is not stable by itself and what disturbances act on the system and section 9.2 discusses the Reynolds number of the aerostat. Section 9.3 covers the aerodynamics of the chosen shape and includes a discussion on the aerodynamic pressures on the air segment. Section 9.4 shows the calculations of important geometrical points. Section 9.5 discusses vortices. Section 9.6 describes the stabilization systems that will be used on the air segment, and in section 9.7 temperature considerations are mentioned. Finally, section 9.8 covers the stabilization during safety mode.

9.1. DISTURBANCE OF STABILIZATION

Before coming up with systems for stabilizing the air segment, it must be determined what needs to be stabilized. The biggest destabilizing factor is the wind. In this section, the following question is answered: in what way do wind forces disturb the stabilization of the air segment? The answer can be split into three parts: displacement (9.1.1), rotation (9.1.2) and vibrations of the aerostat (9.1.3).

9.1.1. DISPLACEMENT OF AEROSTAT

The aerostat has a diamond shape with three large surfaces, as can be seen in chapter 5. When wind force is acting on the aerostat, this will result in a large drag force. The drag force can be computed using equation 9.1.

$$D = C_D \frac{1}{2} \rho v^2 S \qquad [9.1]$$

Another force acting on the aerostat is the lift force. The lift force consists of lift force due to the lifting gas and lift force due to the wind. The latter can be computed using equation 9.2.

$$L = C_L \frac{1}{2} \rho v^2 S \qquad [9.2]$$

The drag force is pointing in the direction of the wind and the lift force is perpendicular to the wind direction. The combination of the drag and the lift force gives a resultant force. If only one cable is connected to the aerostat, the aerostat will be displaced as can be viewed in figure 9.1. The aerostat will be displaced until the tethered cable is parallel to the resultant force.

In figure 9.2, the consequence of a drag force on the aerostat connected to multiple cables is illustrated. In the case of multiple cables, one cable will be in tension and one cable in compression. This cable in compression will thus hang loosely.

In a configuration with multiple cables, the cables are under a certain initial angle. When wind acts on the balloon this angle may increase by an angle β. This angle β, seen in figure 9.2, will be a lot smaller than angle α

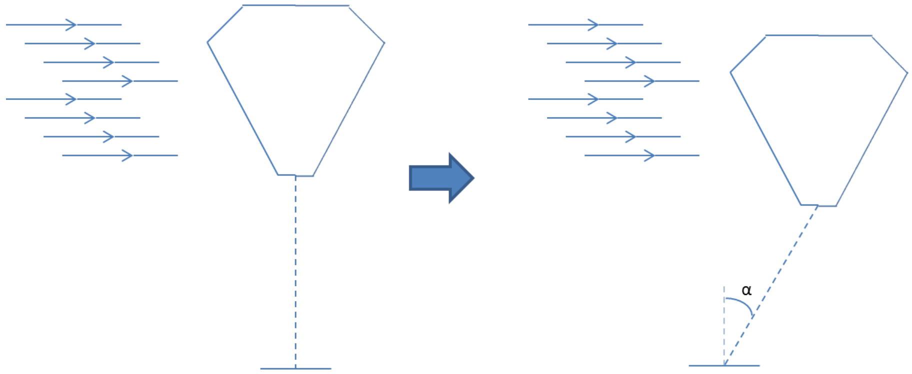


Figure 9.1: Result of drag force acting on the aerostat with one cable

in figure 9.1. This results in less displacement of the aerostat when multiple cables are used, which is desired. An issue when using multiple cables, however, is the loose hanging cable when such displacements occur. This cable will swing and vibrate due to the wind. Therefore, in such a case a system to retract the cable must be implemented to solve the problem of the loosely hanging cable. This is described in section 9.6.3.

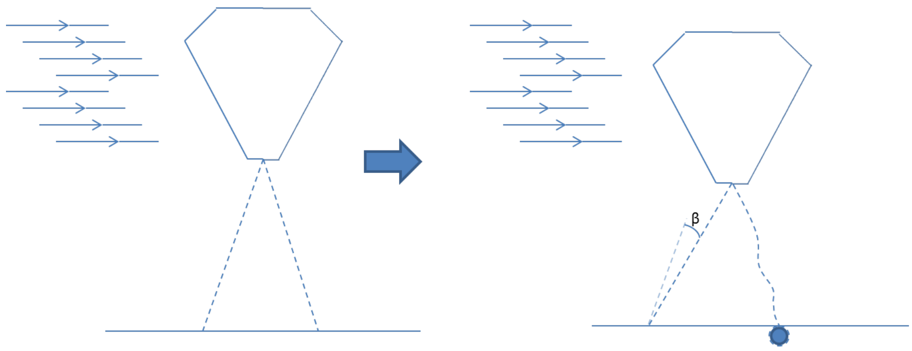


Figure 9.2: Result of drag force acting on the aerostat with multiple cables

To ensure a small variation of the angles of the cables in all possible directions of wind disturbances, at least three cables are necessary. Adding more cables would further decrease the tendency to displace, but the ground space as well as connection points on the aerostat need to be taken into account.

Loosely hanging cables can be seen as ballast for the balloon, as they do not add anything to the stability and are susceptible to aerodynamic vibrations. To counteract these effects, the ground system of the cables will be equipped with a retraction system. The working of the retraction system will be as follows: when wind causes the dirigible to displace, the rolling systems will retract the cables to the extent that swinging and vibration of all loosely hanging cables is minimized. In effect, this would make the length of the cables variable.

It can be concluded that the wind results in a drag force on the air segment, which results in displacement of the aerostat. This can be minimized using multiple cables. The disadvantage of multiple cables is that not every cable is in tension. These loosely hanging cables will be tightened using a retraction system. The exact drag forces on the aerostat due to the wind will be discussed in section 9.3.

9.1.2. ROTATION OF AEROSTAT

The asymmetric shape of the aerostat has the consequence that wind forces might cause a rotation of the aerostat. When the center of pressure (through which the resultant of the drag force acts) is on a different location than the center of gravity, the force times the arm causes a moment. This moment can be the cause of a rotation. Another reason that might cause the aerostat to rotate, is that it naturally tends to turn into the direction in which it experiences the least drag. Either way, rotation of the areostat is undesired and should be prevented.

The shape of the aerostat is asymmetric in two planes, so the wind can cause rotations around two axes. The two types of rotation can be best described using a side view and a top view. A visualization of this is found in figure 9.3 and 9.4.

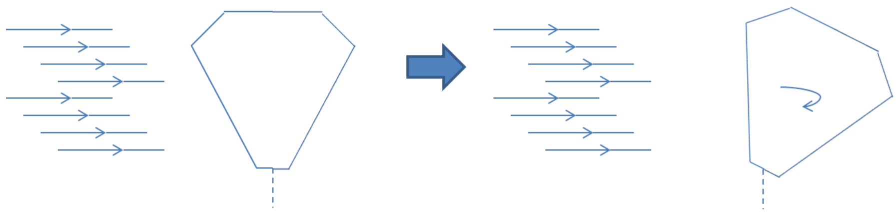


Figure 9.3: Side view, degree of freedom for rotation of aerostat

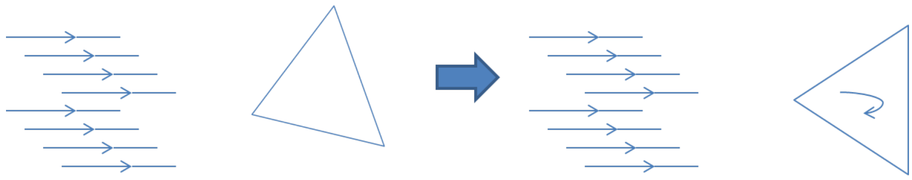


Figure 9.4: Top view, degree of freedom for rotation of aerostat

As described in section 9.1.1, movement of the aerostat will be prevented using cables. When properly located, cables can also be used to prevent rotation by introducing counter-moments.

Rotation as described in figure 9.3 is the result of a difference of the location of the center of pressure and the center of gravity. Because of this arm, the resultant of the lift and drag pressure will cause a moment around the center of gravity of the aerostat. The location of the center of pressure and the center of gravity will be computed in section 9.4. Using these two geometric points, the resulting moment around the center of gravity can be computed. This moment can cause a rotation. This rotation can be prevented by a counter moment. A force that has an arm with respect to the center of gravity should be applied, so that the rotation can be compensated. Cables can apply this force. I.e. if a cable under slight tension is connected to the top of the aerostat, and the top moves away from this cable due to the rotation, the cable gets under extra tension. The cable will then exercise a larger force on the aerostat, which results in a stabilizing moment. Because it is difficult to predict if the aerostat will rotate clockwise or counter-clockwise as a reaction on a wind force, it is good to connect a cable to both the top and the bottom corner points of the aerostat. More details about this configuration can be found in section 9.6.

The rotation as described in figure 9.4 can be prevented by using a sufficient amount of cables. An example of a good configuration is connecting two cables from different locations on the ground to the same connection point on the aerostat. If this is done on all corners, the “top view rotation” is prevented in clockwise and counter-clockwise direction. This has been tested using a weighted balloon hanging from a ceiling in this configuration. When applying a torque it turned out to be difficult to rotate the balloon. More about preventing rotation can be found in section 9.6.

It can be concluded that cables, if properly placed on the aerostat and directed to the ground, can prevent the air segment from rotating by applying a moment.

9.1.3. VIBRATIONS OF AEROSTAT

The wind might introduce vibrations in the aerostat. When the wind flows along the surface of the aerostat, two vortices are created at the two corners of the surface that is tangential to the flow. These vortices have opposite directions of rotation and will shed alternately, creating the flow pattern depicted in figure 9.5. This flow pattern is called a Von Kármán vortex street [41]. The alternate shedding of these vortices introduces alternating loads on the structure, resulting in vibrations. Another phenomenon that may occur is galloping. This occurs when a change in angle of attack results in an exciting force, creating a growing up and down motion. Section 9.5 elaborates on these phenomena.

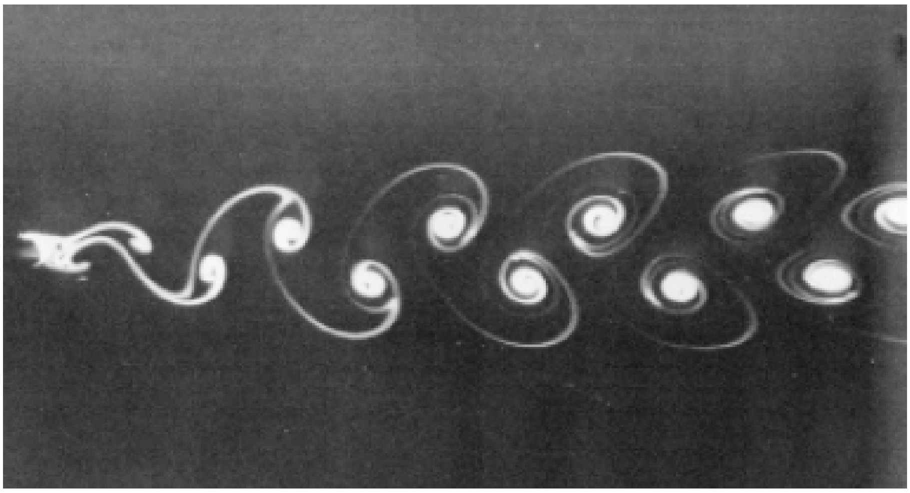


Figure 9.5: Von Kármán vortex shedding [42]

9.2. REYNOLDS NUMBER

9.7 The Reynolds number is an important number governing aerodynamical coefficients such as C_D. Knowing the Reynolds numbers for the design gives insight in the flow patterns around it, and allows adapting the design to optimize for these parameters. How Reynolds number and drag coefficient interact for a triangular shape is shown in figure 9.6.

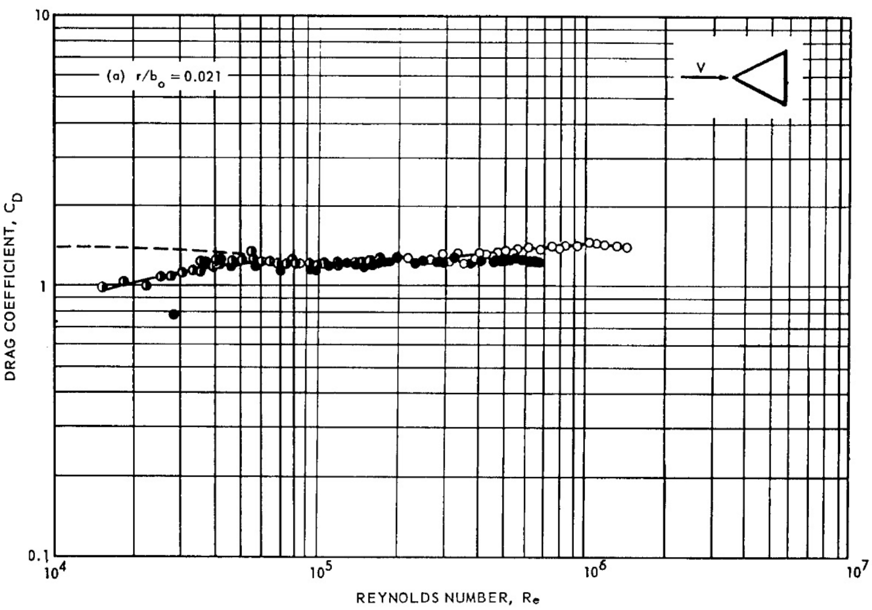


Figure 9.6: Reynolds number versus drag coefficient for triangular cross-section [43]

To compute the Reynolds numbers, equation 9.3 is used. [39]

$$Re = \frac{\rho \cdot v \cdot l}{\mu} \qquad [9.3]$$

In this equation, the air density ρ, the airspeed v and characteristic length l all vary with altitude. Finally, the airspeed variation is given by [44]

$$v = v_{ref} \cdot \left(\frac{altitude}{reference\ altitude} \right)^H \qquad [9.4]$$

The reference speed v_{ref} is the airspeed at reference altitude, which is in our case 10 meters high. Reference velocities used are the daily average, daily average maximum, and 90% of days maximum wind speeds [45]. The Hellman exponent H describes the environment in which the reference airspeed was measured and is in this case equal to 0.16.

The air density variation over height is small and the airspeed variation is reasonable in size. However, the characteristic length variation over height is large, and will thus dominate this equation to make the variation approximately linear. The variation of the Reynolds number is shown in figure 9.7.

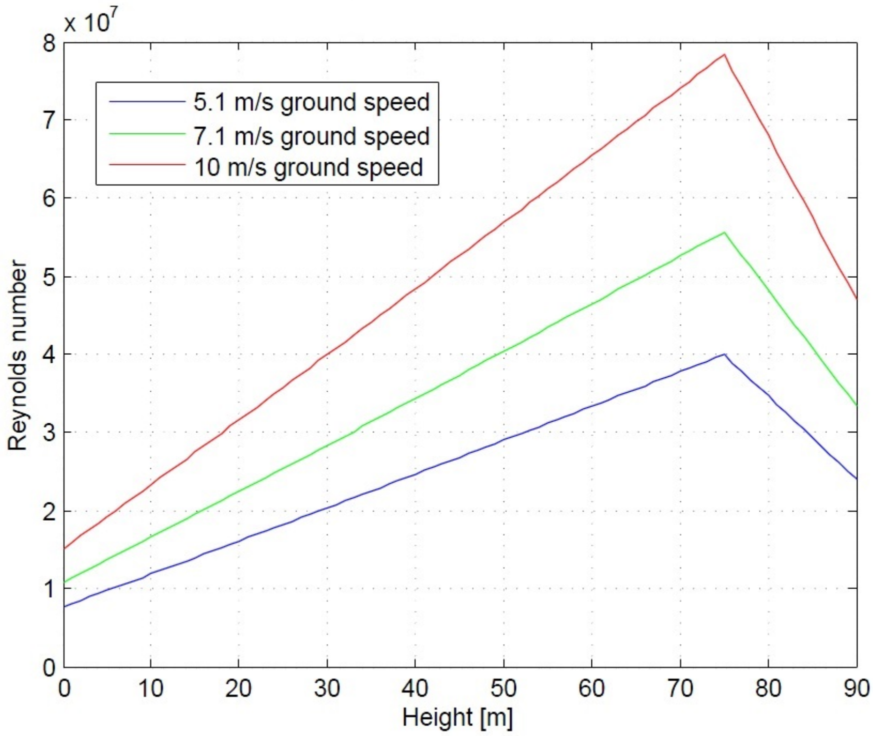


Figure 9.7: Reynolds number distribution over the aerostat

As can be seen, the Reynolds numbers vary over the height of the balloon in the order of 10^7. For these Reynolds numbers, the flow generally separates from the body quickly and forms a turbulent wake. Unfortunately, coverage of current literature hardly discusses Reynolds numbers of 10^6, let alone 10^7. Extrapolation of figure 9.6 would suggest that there are no secondary effects of the Reynolds number on the drag coefficient. This is however an assumption, and for full validation suggestions for research are included in the post-DSE planning.

9.3. AERODYNAMICS OF SHAPE

To determine the aerodynamic characteristics of the dirigible, the SolidWorks Flow Simulation Computational Fluid Dymaics (CFD) has been used [46]. The validation for this software can be found in appendix C. This tool is capable of simulating a flow around an object and computing the forces and moments acting on it. Two model orientations were used in analyzing these forces. In the first case, the three-sided diamond shaped model was pointed with one of the side faces towards the wind. In the second case, one of the corners of the model was pointed in the direction of the wind. This allowed to analyze the different wind drag conditions and determine the shape with the most optimal characteristics in terms of dimensions and corner rounding. These two configurations were applied to four dirigible designs, each with different dimensions provided from the structures team within the Diamond of Dubai. Only one parameter at the time was changed and then it was assumed that it would have the same effect on each of the four designs. These four configurations are derived from the simultaneous progress made by the structures team and the aerodynamics team. Hence, they represent four stages in which new improvements to the structure and adjustments to the dimensions were implemented. Four parameters have been varied in the CFD model: orientation of the dirigible in the wind (section 9.3.1, rounding of the corners (9.3.2), height of an additional top offset (9.3.3) and variation of the wind speed (9.3.4). The four different design configurations can be seen in figure 9.8. These configurations correspond to the 'Baseline', the 'Carbon 1', 'Carbon 2', and 'Carbon 3' configurations in chapter 8.

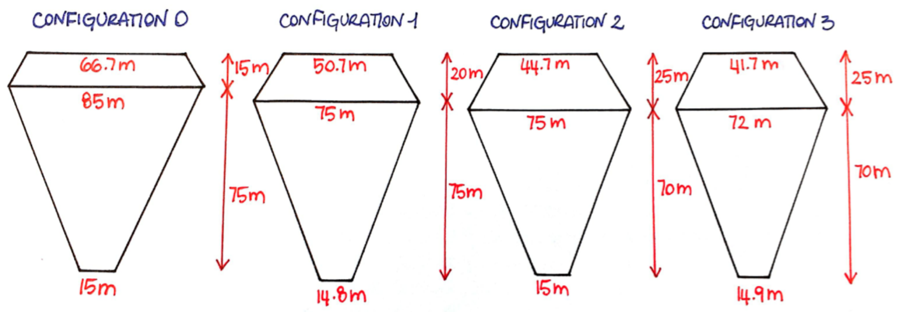


Figure 9.8: Dimensions of dirigible configurations

9.3.1. DIRIGIBLE ORIENTATION

As mentioned before, the model has been tested in two different orientations, one with a side face pointed towards the wind and one with one of the corners facing the wind. For this analysis, it has been assumed that all values for the lift and drag coefficient will be in between the values for these two cases, as they are the extremes. The next step is to see which of these two cases is the critical orientation, meaning the orientation in which the drag is at a maximum.

Table 9.1: Lift and drag coefficients for different dirigible orientations

	Lift Coefficient	Drag Coefficient
Flat side in wind	0.343	0.865
Point in wind	0.232	0.541

In table 9.1, the results of the Computational Fluid Dynamics analysis for different orientations can be found. In this analysis, the dimensions of the aerostat are those of configuration 0. It can be seen that the highest drag occurs when the aerostat has a side face that is facing the wind. Analyses on different configurations yield similar results, this can for example be seen in section 9.3.3. Since this orientation is the critical case, it is used for other analyses to identify the maximum loads.

9.3.2. CORNER ROUNDING

Because a diamond shape was selected, corners will be present on the aerostat. Research into flow characteristics around corners has shown that rounding the corners of a two-dimensional triangle in a wind flow has a beneficial effect on its drag coefficient [47]. When the corners are rounded, the flow stays attached to the surface longer, which reduces drag. The effect of rounded corners on the flow around a square cylinder is visualized in figure 9.9. It can be seen clearly that corner cut-offs are able to reduce the wake size behind a shape in a wind flow. Figure 9.10 shows the drag coefficient for wedges in different orientations and with different corner rounding [43]. Rounding of the corners also decreases the frontal projected surface. This results in an overall decrease in drag on the aerostat.

Rounding the corners of the aerostat has drawbacks as well. When the corners are rounded, the surface of the area where the screens can be attached is reduced. The consequence of this is that the screens have to be placed higher on the aerostat, resulting in a higher center of gravity and this will negatively influence the stability of the aerostat. Another drawback of rounded corners is the effect on the vortex shedding of the aerostat. When rounded corners are present, the location of vortex shedding varies. This causes a Von Kármán vortex street to develop, as explained in section 9.1.3. Finally, less frontal area will cause less air to be deflected downward by the leading surface. This smaller downwash also lowers the generated lift.

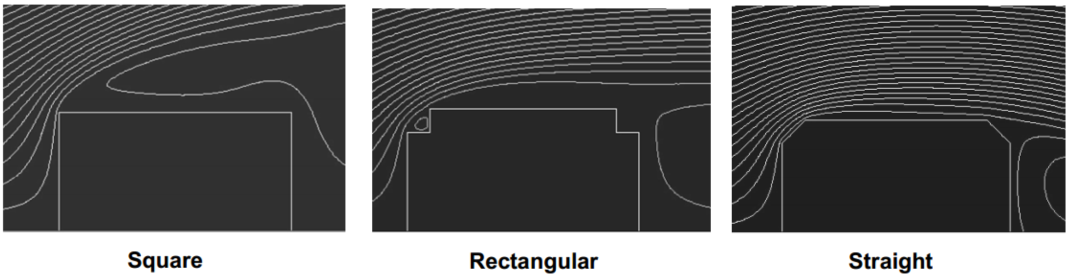
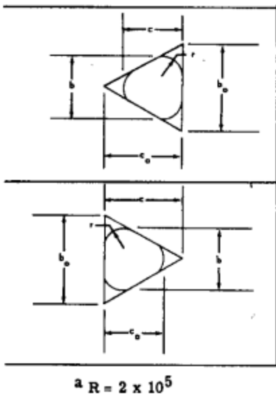


Figure 9.9: Flow around square cylinders with different edges



(All dimensions in inches)
(NACA-TN-3038)

Flow direction	Fineness ratio, (c_o/b_o)	Corner-radius ratio, (r/b_o)	Nominal size	b_o	b	c_o	c	r	C_D at $R = 10^5$
	1:1	0.021	12	12.00	11.69	12.00	11.69	0.25	
	1:1	0.021	4	4.00	3.90	4.00	3.90	0.08	1.2
	1:1	0.021	1	1.00	0.98	1.00	0.98	0.021	
	1:1	0.083	12	12.00	10.77	12.00	10.77	1.00	1.3 [a]
	1:1	0.250	12	12.00	8.29	12.00	8.29	3.00	1.1
	1:1	0.250	4	4.00	2.78	4.00	2.76	1.00	
	1:1	0.021	12	12.00	11.69	12.00	11.69	0.25	
	1:1	0.021	4	4.00	3.90	4.00	3.90	0.08	2.0
	1:1	0.021	1	1.00	0.98	1.00	0.98	0.021	
	1:1	0.083	12	12.00	10.77	12.00	10.77	1.00	1.9 [a]
	1:1	0.250	12	12.00	8.29	12.00	8.29	3.00	1.3
	1:1	0.250	4	4.00	2.76	4.00	2.76	1.00	

[a] $R = 2 \times 10^5$

Figure 9.10: Drag coefficient of wedges

Table 9.2: Lift and drag coefficients for different corner radii

	Lift coefficient	Drag coefficient
No rounding	0.343	0.865
0.083 rounding radius	0.308	0.919
0.1 rounding radius	0.294	0.878

As can be seen in table 9.2, the drag coefficient first increases as a small rounding is applied, but it decreases with a larger rounding. This effect is caused by the change in Reynolds number that applying the rounding causes. What can also be seen is that the lift decreases drastically when rounded corners are applied. As rounding the corners would only result in reduction of drag at a large rounding radius and this would result in a large decrease in dynamic lift, the choice has been made to apply no rounding to the corners of the aerostat.

9.3.3. TOP OFFSET HEIGHT

This next analysis was done by adding a small top to the crown of the diamond. This top will be made by heightening the middle of the top surface of the dirigible. This can be seen as increasing the height of point 10 in image 8.12. Three configurations are used: one without a top added to the crown, one with a 2 m top and one with a 4 m top. The location of the top is shown in figure 9.11.

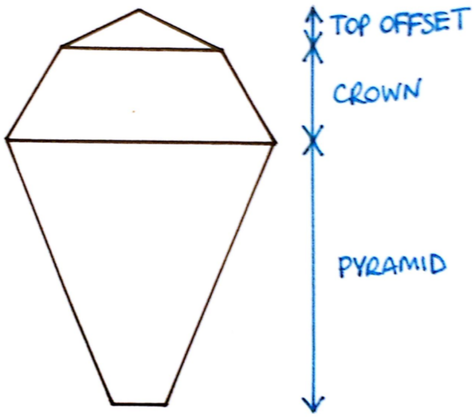


Figure 9.11: Location and dimension of dirigible top offset (2D)

For each of these options, the lift and drag coefficient were calculated, both in case the model was pointed with a corner towards the wind and in case one of the flat sides was in the direction of the wind. The results for this analysis are listed in table 9.3. The first result of this analysis is that when a corner is in the wind, the drag coefficient is much lower than when the flat side is pointed towards the wind, as expected. For this reason, the lift coefficient needed is lower when the corner is pointed in the wind and the drag coefficient values are mostly constant. Though the overall values of the lift coefficient are higher for the case of the flat side in the wind, they tend to decrease when the top is enlarged. This is not beneficial for the blimp because with higher values of drag, higher values of lift coefficient are needed. Hence, the aerostat will be designed for the case of flat side in the wind with highest lift coefficient, which occurs in the "no top" configuration. In fact, the blimp will then be sure to have enough lift even with high values of drag.

Table 9.3: Lift and drag coefficients for different hat heights

	No top		2m top		4m top	
	CL	CD	CL	CD	CL	CD
Point in wind	0.120	0.501	0.197	0.512	0.178	0.516
Flat side in wind	0.173	0.831	0.149	0.848	0.134	0.854

9.3.4. CFD RESULTS FOR DIFFERENT WIND VELOCITIES

Table 9.4 shows the results of the CFD analysis on the four different configurations from figure 9.8 of the aerostat for four different wind speeds. The wind speeds considered are wind speeds at the height of the center of pressure of the dirigible. All these tests have been performed with one of the side faces pointed towards the wind, as this is the worst situation the aerostat will encounter, which was explained in section 9.3.1. In this case, the drag and lift forces are compared, because in these configurations only the dimensions changes of the aerostat, not the coefficients. Another reason for choosing the forces over the coefficients is that these forces are needed for structural calculations.

Table 9.4: Results of the CFD analysis

Wind speed	Force	Configuration 0	Configuration 1	Configuration 2	Configuration 3
8.5 m/s	Lift	47 kN	29 kN	18 kN	18 kN
	Drag	184 kN	185 kN	177 kN	173 kN
12.5 m/s	Lift	101 kN	62 kN	39 kN	39 kN
	Drag	397 kN	393 kN	384 kN	375 kN
15 m/s	Lift	145 kN	89 kN	56 kN	56 kN
	Drag	573 kN	566 kN	553 kN	539 kN
17 m/s	Lift	187 kN	115 kN	71 kN	72 kN
	Drag	736 kN	777 kN	711 kN	693 kN

9.4. COMPUTATION OF IMPORTANT GEOMETRIC POINTS

The lifting force of the helium and the wind force are assumed to act in the center of pressure. They will generate moments around the center of gravity of the system. In order to keep the system stable, the ground cables must counteract these forces and moments. To determine the moments and forces, the center of pressure and the center of gravity are needed, which are calculated in sections 9.4.1 and 9.4.2 respectively. In these sections, only the position in the z-direction is determined, because of the symmetry of the balloon in the x,y-plane.

9.4.1. CENTER OF PRESSURE

The wind force on the balloon will result in a lift and a drag force. These forces will act in the center of pressure of the wind. The helium has a center of pressure as well, the lifting force acts here. Together, these result in one center of pressure for the whole balloon. The center of pressure due to the cables and the gondola are neglected since they are small. The best method to calculate the center of pressure of the wind, (cp_{wind}), is with a CFD model, validated by windtunnel tests. This will be done in the post DSE phase as is described in chapter 22. Because the center of pressure is important, an estimated center of pressure is used. This is done by calculating the geometrical center point of the side of the balloon. Equation 9.5 is used to calculate the center of pressure in the z-axis.

$$cp_{wind} = \frac{\sum(A*d)}{\sum A} \qquad [9.5]$$

In equation 9.5, A is the frontal area and d is the distance of geometrical center point of the respective area to the bottom of the aerostat. The center of pressure of the wind is calculated to be at 55.23 m from the bottom.

The center of pressure of the lifting force of the helium is determined with the 3D model, which can be seen in appendix C. The center of gravity of this 'solid' model is assumed to be the center of pressure of the helium (cp_{helium}), which is at 59.9 m on the z-axis.

This results in a total center of pressure, which is calculated with equation 9.6. In this equation F_{lift} is the lift generated by the helium and the wind force and cp is their respective position.

$$cp_{total} = \frac{\sum(F_{lift}*cp)}{\sum F_{lift}} = 59.73m \qquad [9.6]$$

9.4.2. CENTER OF GRAVITY

In order to calculate the center of gravity with respect to the bottom of the system, the center of gravity of the subsystems is calculated first. This is done for the structure, envelope, gondola, screens, wiring and lighting subsystems. The mass of cables is neglected, because this mass is small and the cable length is not determined yet. For the calculation of the center of gravity, equation 9.7 is used.

$$cg = \frac{\sum(m * d)}{\sum m} \quad [9.7]$$

For center of gravity of the structure in equation 9.7, m is the mass of each beam and d is the distance from the center of gravity of the beam with respect to its respective axis. For the envelope, the center of gravity is calculated by taking the center of gravity of each panel. It is assumed that the inner and outer envelope and the fishnet structure are equally distributed over the surface. In the same way as for the structure, its center of gravity is calculated with equation 9.7. The center of gravity of the gondola depends on the altitude of the gondola. The height of the gondola is variable from 0 to 210 m with respect to the ground. The center of gravity in the cases where it is at its maximum altitude and just before it is connected to the ground will be calculated. In the case where the gondola is resting on the ground, the gondola will not affect the center of gravity of the system. With the center of gravity of the subsystems, the total center of gravity is calculated and can be seen in figure 9.12.

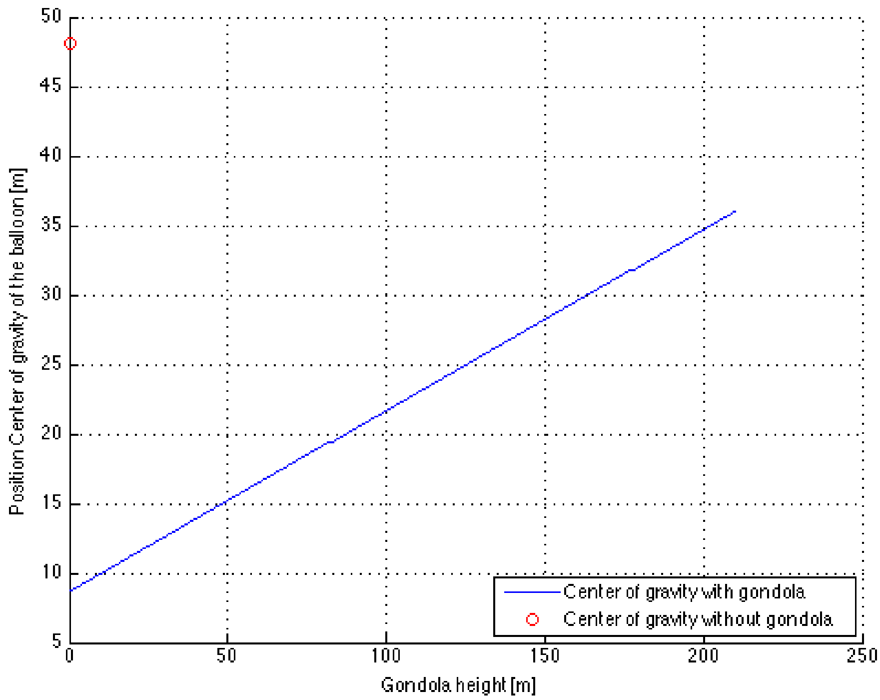


Figure 9.12: Position of center of gravity

9.5. VORTEX GENERATION

This section covers two of the main concerns on vortex generation, as discussed in section 9.1.3. As the wind flows along the surface of the aerostat, vortices will be created when the flow detaches at the corners. Section 9.5.1 discusses galloping and section 9.5.2 discusses vortex shedding.

9.5.1. VORTEX INDUCED GALLOPING

Vortices along the aerostat will cause vertical, low-frequency vibrations (<1 Hz), often with an amplitude in the order of meters. This so called 'galloping' will cause the effective angle of attack of the dirigible to vary while moving either up or down.

Galloping forms a problem when this change in angle of attack results in an exciting force, causing a vertical oscillation of growing amplitude. This is undesirable, as it will cause a loss of control of the aerostat. This can be avoided when the lift slope of the aerostat is positive, since a downward movement of the dirigible (and thus higher effective angle of attack) would cause a greater lift, thus weakening the downward movement.

Figure 9.13 shows the lift slope curve for aerostat configuration 2. As can be seen, the lift slope is positive: $\frac{\delta C_L}{\delta\alpha} = 0.0088$. Galloping will therefore not form a problem on the aerostat, since the motion will damp itsself.

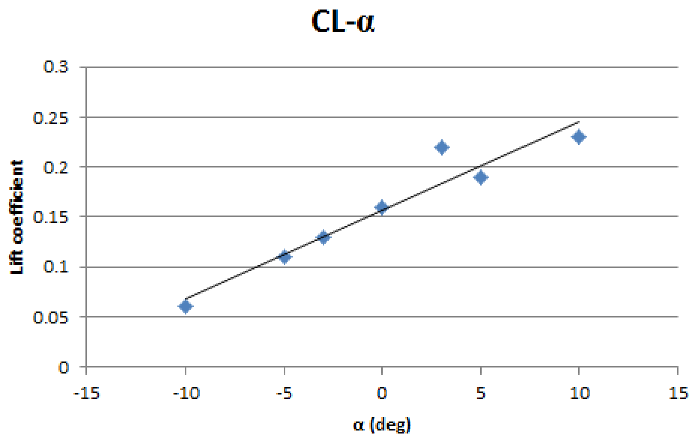


Figure 9.13: Lift slope curve

9.5.2. VORTEX SHEDDING

As described in section 9.1.3, the aerostat will cause the formation of a von Kármán vortex street. When the frequency of this vortex shedding approaches the natural frequency of the aerostat, resonance will occur. This will cause loads way beyond the structural capacity and should thus be avoided. The frequency of vortex shedding can be calculated with equation 9.8, where v is the airspeed in m/s and r is the radius in m. As the aerostat is tapered, the radius varies along the height of the aerostat. The wind speed will vary as well.

$$f = 0.2\frac{v}{2r} \tag{9.8}$$

To identify the critical cases, the minimum and maximum wind speed and radius need to be determined. As there can be days without any wind, $v_{min} = 0\ m/s$. The maximum wind speed at which the aerostat needs to be operational has been set at $v_{max} = 17\ m/s$. The maximum radius of the aerostat that the flow will encounter is $r_{max} = 37.5\ m$ and the minimum radius is $r_{min} = 0.15\ m$. The minimum frequency of vortex shedding theoretically occurs at the minimum wind speed of $0\ m/s$. The minimum vortex shedding frequency therefore approaches $0\ Hz$. The maximum vortex shedding frequency occurs at the maximum wind speed and the minimum diameter of the aerostat. This results in a maximum vortex shedding frequency of $11.3\ Hz$, as can be seen in equation 9.9. All vortex shedding frequencies that the aerostat will encounter will be in between 0 and $11.3\ Hz$. To avoid resonance, the eigenfrequencies of the aerostat should be higher than these vortex shedding frequencies.

$$f_{max} = 0.2\frac{v_{max}}{2r_{min}} = 0.2\frac{17}{0.3} = 11.3Hz \tag{9.9}$$

9.6. STABILIZATION SYSTEMS

This section describes the different stabilization systems that will be used on the aerostat. In section 9.6.1, the stability concept will be described. This section elaborates on a concept to cope with the disturbances, as described in section 9.1. It is followed by section 9.6.2, in which the configuration of the used cables in the concept is further elaborated on. In section 9.6.3, it will be described how the cables are connected to the ground and in section 9.6.5, the use of guide vanes will be discussed. Finally, in section 9.6.6, the gondola stability will be discussed.

9.6.1. STABILITY CONCEPT

In this section, the concept that is used to ensure stability is covered. In the section about disturbances of the stability (9.1), preliminary suggestions of ensuring stability are given. In this section, a description is given on how these preliminary suggestions will be used in the final design. The exact configuration of the cables (read: angles with respect to the ground and location of ground connection) will be further worked out in section 9.6.2.

As mentioned in section 9.1, cables will be used to prevent displacement and rotation. With the use of cables, a balance needs to be found. The more cables, the more stable the system. However, the more cables, the more ground space required, which is undesired. In the end, full stabilization must be ensured with the least ground space required.

Firstly, the solution to the displacement due to the wind will be treated. The tetrahedron has three corners. These corners are structural nodes and are therefore strong points. This structural argument, which is further elaborated upon in chapter 8, is the reason that the cables will be connected to the three corners.

The next step is determining how the cables need to be directed to prevent destabilization. Inspired by a recently published master thesis [48], it was concluded that pointing three cables in the three directions of the corners was not sufficient. Two of the three cables would be hanging loosely and one cable would have to cope with all forces. A better configuration to cope with wind force from one side and directly prevent rotation to a certain extent, was to have one cable in the direction of the wind and two other cables, connected to the other corners, pointing diagonally into the direction of the wind. A visualization of this concept can be found in figure 9.14.

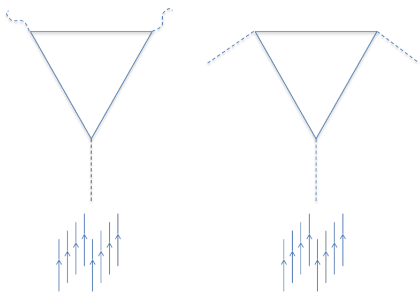


Figure 9.14: Visualization of cable configuration for one wind direction, top view

Wind is unpredictable and can originate from all possible directions, as can be seen in figure 9.15.

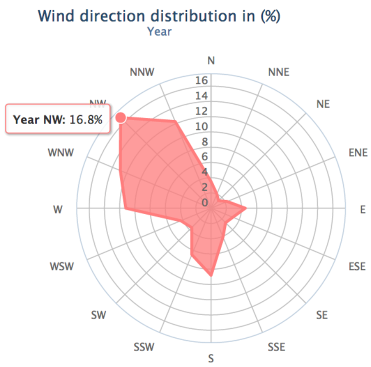


Figure 9.15: Yearly average wind direction distribution Dubai[49]

From figure 9.15 it can be concluded that, altough one wind direction jumps out, the cables should be able to cope with drag forces in all directions.

The concept of figure 9.14 is a good way of coping with wind forces and can be applied for all three corners. A top view visualization of this concept can be found in figure 9.14. This concept solves for displacement as well as for "top view rotation" as described in figure 9.4. To reduce the amount of required ground connections, every two diagonal cables are connected to one ground station. These cables are the primary cables and are indicated with '1' in figure 9.16. The secondary cables are indicated with '2'.

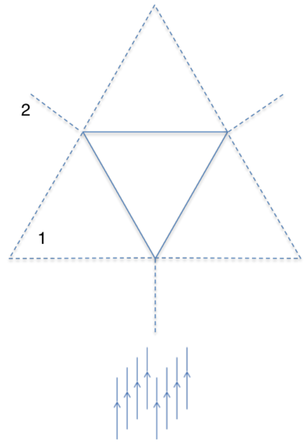


Figure 9.16: Visualization of complete cable configuration concept, top view

As can be found in figure 9.17, there is one direction from which the wind comes most often (16.8 %): north-west. As described in section 9.3, the aerostat experiences the least drag when one of the points is directed into the wind. Therefore one corner will be pointed into the north-west (315 °). Because of the isosceles triangle, the other points are directed in east (75 °) and south-south-west direction (195 °). Because of small peaks in the two latter directions, this placement is optimal. This configuration is also preferable since one of the screens is pointed to the terminal of Dubai's airport. Only when wind comes from the west, where a small peak can be found, this will not be acting on one of the points of the aerostat.

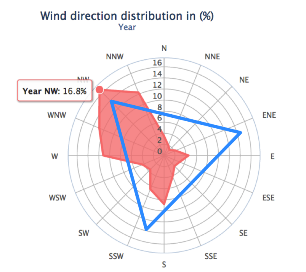


Figure 9.17: Pointing of dirigible with respect to wind direction

Once the localization of the cables from the top view is determined, one dimension is still not determined. The next issue to be addressed is the attachment height of the cables. This problem can be solved by looking at the rotational stability, as described in figure 9.3. The cables can exert a force to compensate for the moments generated by the wind disturbances. For structural reasons 8, there are four possible connection points for the cables: on the top of the crown and on the top, middle, or on the bottom of the pyramid part of the aerostat. As described in section 9.1, the resultant of the lift and drag pressure times an arm generates a moment around the center of gravity. The arm in this case is the distance between the resultant of the lift and drag force and the center of gravity. In figure 9.18 this is visualized for the side view with the right side of the drawing being a point that is directed into the wind (therefore the center of gravity is on 1/3 of the width of the drawing).

The cables can be connected to the ground closer to the aerostat when the cables are connected at a lower point on the aerostat. However, as can be viewed in figure 9.18, the higher on the aerostat the cables are connected, the larger the arm of the compensating moment. Therefore, it must be determined to what extent the cables can be connected on a low connection point.

When there is no wind force, there is no drag, which means no rotation, so no difference for the placement of the cables. The stronger the wind force, the stronger the rotational moment, because of a larger force and also a larger arm of the resultant force. Therefore, the height of the cable connection on the aerostat should be determined for the most extreme resultant force. As will be described in section 9.6.2, the smallest angle that the total resultant force will make with the ground is 59.19 °. This is when the aerostat is with its flat side in the wind. (Further elaborated upon in section 9.6.2). Using this, the direction of the pulling cables under the most extreme resultant force can be determined. The tensile force in the cable is as big as the resultant force, because of equilibrium. Therefore, to compensate for the rotation, the arm of the cable force should be larger than the arm of the resultant lift force. It has been determined whether or not this is the case for all three possible connection points in the drawing on scale in figure 9.18.

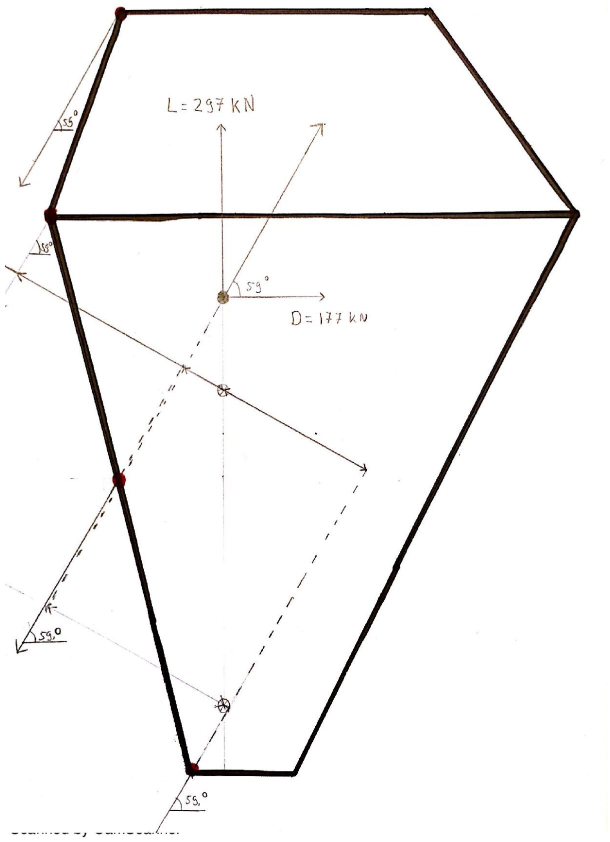


Figure 9.18: Arm of center of pressure and three connection points with center of gravity

In figure 9.18 the cable forces are drawn for four different connection points. The arms for all forces are presented and furthermore, the arms of the lift and drag forces can be seen. Finally, two centers of gravity can be seen: the low center of gravity is for the case when the gondola is just above the ground, the high center of gravity is when there is no gondola attached (or the gondola is fully supported by the ground).

It is clear that the arm of the lowest connection point can not compensate for the rotation, because the force does not generate a counter moment. For the middle connection point holds that the generated counter moment by the cable is just enough to keep the aerostat from rotating. However, if the aerostat is brought down because of extreme conditions, the cable will have a smaller angle with respect to the ground. This will result in a larger arm between center of pressure and center of gravity than between the connection point and the center of gravity. It can be concluded that the middle connection will be a proper point during normal operation, but when the aerostat needs to be brought down, another solution should be found. The top of the lower pyramid and top of the crown are the only remaining possibilities for cable connection. Both have a large arm to the center of gravity and both are positioned higher than the center of pressure. This means that, regardless of the height of the aerostat, there will be a counter moment that is large enough. The most optimal decision for saving ground space is choosing the top of the lower pyramid as connection point.

However, only connecting the cables to the top of the pyramid can cause another rotational problem. The pulling force of the cables and the resultant force form a couple, which causes rotation as well. Therefore it is suggested to connect cables to the bottom of the lower pyramid to counteract the generated couple. Three cables is sufficient to prevent rotation around every corner. These cables will be called the lower secondary cables. These cables can be in the same direction as the upper secondary cables and can be connected to the same ground attachment as the upper secondary cables are. There is no requirement on the angle that the lower secondary cables need to make with respect to the ground, because these only cover rotational stability.

A visualization of the cables can be found in figure 12.1.

9.6.2. STABILITY CABLES CONFIGURATION

In the previous section, the concept for the stability is determined and a decision has been made for the connection of the cables to the aerostat. Knowing this concept, the final stability configuration can be made by determining where the cables will be connected to the ground and computing the required angles.

The principle that will be used for determining this is the following. The helium in the aerostat, together with the aerodynamic shape of the aerostat, will generate a certain amount of lift. Furthermore, the big shape of the aerostat will generate a large drag force as well. The lift force in combination with the drag force will generate a resultant force that has a certain angle with respect to the ground. The aerostat will be pulled into this direction and can in this case be compared to a kite. If the aerostat is connected to the ground using only one cable, this cable will have the same angle with respect to the ground as the resultant force has. As described in section 9.1.1, the use of multiple cables will reduce the change of the angle with respect to the ground. If a small wind force acts on the aerostat, the angles in which the cables are placed will not be changed. However, if the wind force, and thus the drag force, is large, the resultant force will have a smaller angle with respect to the ground. If this angle is smaller than the angle that the cables have with respect to the ground, there will be a displacement of the aerostat. This principle is visualized in figure 9.19.

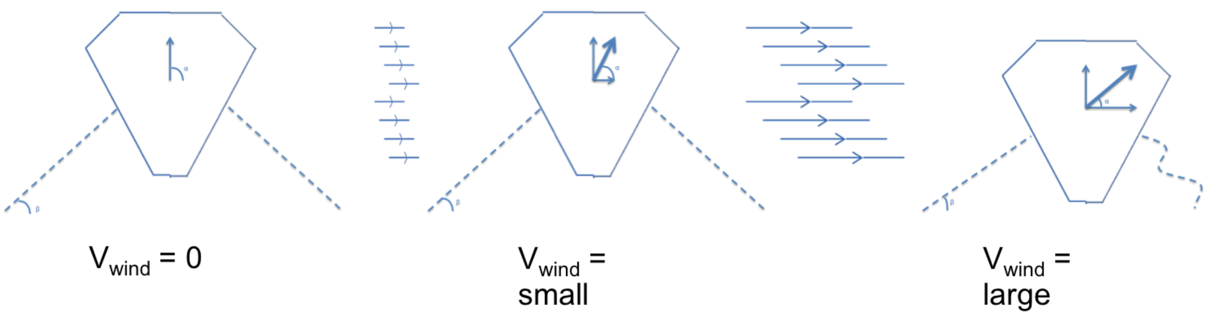


Figure 9.19: Visualization of displacement of aerostat due to wind

As can be seen in figure 9.19, no wind force means no drag force, hence no displacement. The lift force is handled by the cables in tension. A small wind force will result in a small drag force. If the resultant force has a larger angle with respect to the ground (α) than the cables have (β), there will be no displacement either. All cables are still in tension to handle the relatively large lift force. However, the cable with the ground station that is directed into the wind will be in more tension than the others. If the wind force becomes even larger, the drag force becomes larger, which results in a small α. If this angle is larger than the original angle of β, the aerostat will displace and β will be smaller. Assuming that the cable will be completely straight, β will be exactly the same angle as α (compare to a kite). Some other cables will be no longer in tension any more and will hang loosely. As described in section 9.1, this cable will be pulled into small tension using a retraction mechanism.

From the previous paragraph, it can be concluded that the cables need to have a certain angle with respect to the ground to cope with the wind disturbances. The smaller the angle, the bigger the wind and thus drag forces can be. However, because of the required screen height of 250 m, a small angle with respect to the ground will require large cables hence a large ground space. An optimum needs to be found for this.

The most extreme resultant force will be considered. This is the case when the flat side is pointed into the wind. For the resultant force, the lift force from the helium, the weight, the lift force from the aerodynamic shape and the drag force must be known. The latter two are computed in section 9.3 for different wind speeds.

For the lift force from the helium and the weight, three options (named Carbon 1, Carbon 2 and Carbon 3) are generated in chapter 8. All values are combined in table 9.5.

Table 9.5: Total lift and drag forces for different wind speeds

Wind speed	8.5 m/s	12.5 m/s	15 m/s	17 m/s	8.5 m/s	12.5 m/s	15 m/s	17 m/s
	Lift [kN]	Lift [kN]	Lift [kN]	Lift [kN]	Drag [kN]	Drag [kN]	Drag [kN]	Drag [kN]
Carbon 1	263	295	322	348	184	393	566	727
Carbon 2	297	318	335	350	177	384	555	711
Carbon 3	222	243	260	276	173	375	539	693

In table 9.5, the total lift force is the total lift generated by helium and aerodynamic lift minus the weight of the dirigible. Assuming the drag to be parallel to the horizon and the lift force straight up, the angle of the resultant force with respect to the ground can be computed. The angle of the resultant force with respect to the ground for the different wind speeds and different structure types can be found in table 9.6. In this table, the horizontal distance of the ground attachments from the aerostat are alsogiven as. For this computation, a height of 210 m for the bottom of the aerostat has been used. Using this height, the top of the screens are on a height of 250 m. The cables are connected to the top of the lower pyramid of the aerostat (70 m higher) and the cables are assumed to have the same angle with respect to the ground as the resultant force. Furthermore, the forces are assumed to act on a point mass on the center of pressure at a height of 270 m.

Table 9.6: Required angle of cables and horizontal distance for different wind speeds

Wind speed	8.5 m/s	12.5 m/s	15 m/s	17 m/s	8.5 m/s	12.5 m/s	15 m/s	17 m/s
	Angle [°]	Angle [°]	Angle [°]	Angle [°]	Dist. [m]	Dist. [m]	Dist. [m]	Dist. [m]
Carbon 1	55.03	36.95	29.67	25.55	196	372	492	586
Carbon 2	59.19	39.62	31.20	26.23	167	338	462	568
Carbon 3	52.07	32.97	25.75	21.75	218	432	580	702

As can be seen in table 9.6, the structure "Carbon 2" results in the largest required angle with respect to the ground. This implies that structure 2 has the least required ground space. This is the case due to the large available volume for helium in this structure. The structure is heavier than "Carbon 3" and suffers from more drag, but the larger amount of lift from the helium compensates for this. Therefore, "Carbon 2" will be the chosen structure.

It table 9.6 can be seen that the cables need to make an angle of 26.23 ° with respect to the ground if the aerostat must remain stable in air during wind speeds of 17 m/s, which results in a ground attachment distance of 568 m. In a densely populated city like Dubai, this amount of ground space is hardly feasible. Therefore, a choice needs to be made: either having a large ground space, or lowering the aerostat at moderate wind speeds.

A more feasible ground space can be obtained when the ground attachment has a horziontal distance of 167 m from the aerostat. Using this configuration, the cables will have a angle with the ground of 59.19 ° and the aerostat will not displace up to wind speeds of 8.5 m/s. Staying stable in winds of 8.5 m/s at a height of 280 m means staying stable when there is a wind of 5 m/s on the ground in the city of Dubai. This is exactly the average wind speed in Dubai [49]. If the winds are stronger, the aerostat needs to be brought down a little in order not to displace. To what extent it needs to be brought down will be elaborated further upon in the explanation of the flight envelope in chapter 13.

When the wind is directed perpendicular to a flat side of the aerostat, the largest drag force will be acting on it. This drag force will mostly be counteracted by the primary cables. It is assumed that every cable must be able to withstand the total drag force. This is because the wind can come from every direction and the wind flow is not laminar, but dynamic. The primary cables are designed for the case with the largest drag force. When the aerostat is pointed in the wind, the aerodynamic drag and lift are different. At windspeed of 8.5 m/s the values for aerodynamic drag and lift computed by the CFD is 110 kN and 14 kN respectively. This results in a angle of 69.43 ° for the secondary cables. This is beneficial for the secondary cables, since this large angle reduces the required horizontal distance to 105 m. When the wind is not directed perpendicular to the flat side nor a pointed side of the balloon, but in between, the drag will be counteracted by primary and secondary cables. The drag force on the aerostat in this case is smaller than the drag force when the aerostat is pointed with its flat side in the wind. The result of this is that the primary cables, together with the secondary cable, are able to withstand the drag force and the applied moment. The dimensions can be found in figure 9.20.

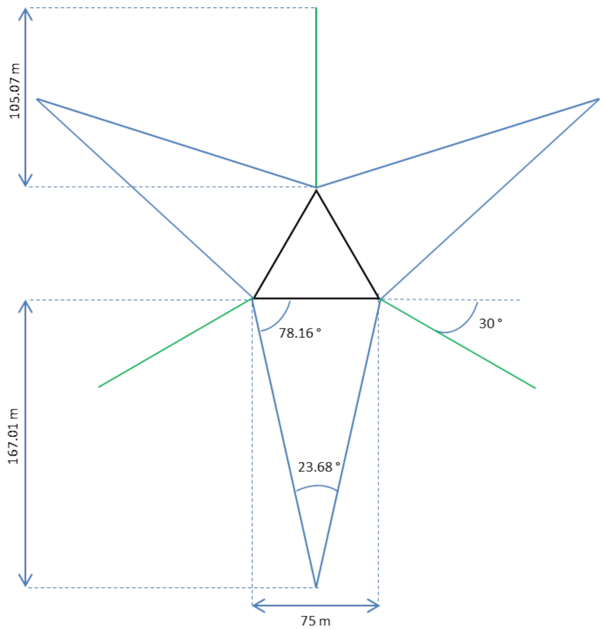


Figure 9.20: Dimensions of cable configuration

Using the configuration as described in section 9.6.1, six ground connections need to be on a distance of 167 m of the aerostat. To compute the ground space, a circular ground space is used. The radius of this circle is the distance of the ground connection from the dirigible, plus the distance of the cable attachment on the dirigible to the center of mass of the dirigible (21.65 m). This means that a circular ground space of 112 000 m^2 is required. This is a rather large amount of ground space and another solution has therefore been thought of. This solution can be found in section 9.6.3, which covers the ground attachment of the cables.

9.6.3. GROUND ATTACHMENT

The primary and secondary cables will connect the aerostat to the ground for stability. The cables can be connected directly to the ground, or they can be connected to poles. If the cables are not attached to the ground itself, but to poles which are standing on the ground, there are two advantages: on one hand the cables can be shorter and on the other hand, it is still possible to use the space beneath the aerostat, because there will be no cables at a low height. The suggested solution is to make six poles with a height of 50 m. These kind of poles are commonly used for wind turbines. Different kind of poles can be used: the best options are the conical tubular pole tower (tower of a modern wind turbine) or a lattice truss tower (mostly used for electricity cable poles). Conical tubular poles are preferable, because of their esthetics. Conical tubular pole towers of this size will cost approximately 50 000 euro each [50]. Larger poles can be used, but the costs of larger poles increase exponentially. For the 50 m poles, the cables need to have a horizontal distance of 137.19 m for the primary, and 86.31 m for the secondary cables to cope with a wind force of 8.5 m/s at a height of 280 m. The dimensions can be found in figure 9.21. Using these dimensions, the angle with respect to the ground for the lower secondary cable can be determined to be 67.17 °.

The design of the poles depends on their height. The pole needs to be able to withstand the tension forces of the stability cables. The higher the poles the higher the moment in the poles will be. Since the tension force of the cable will always be in one direction, the poles needs to be specific designed for the force in this direction. When the preferred height is determined by the client, a specific design for the poles can be made in the post-DSE phase. In this stage of the design, the assumed configuration of the poles are windturbine poles, since they are able to withstand high load. On top of these poles a retraction system needs to be placed for retracting the cables.

If circular ground space is assumed again, the ground space beneath the cables has a total area of 80 000 m^2.This is 29 % less than the configuration without poles. The space under the cables can also be used, since the cables are not located at a low altitude.

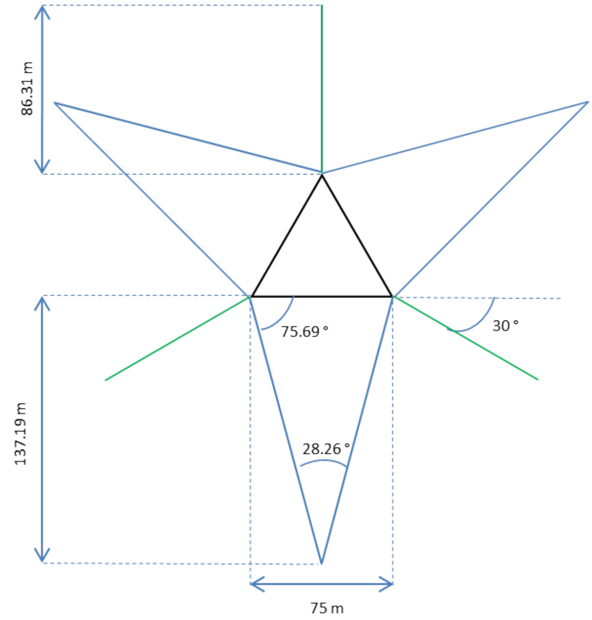


Figure 9.21: Dimensions with poles (2D)

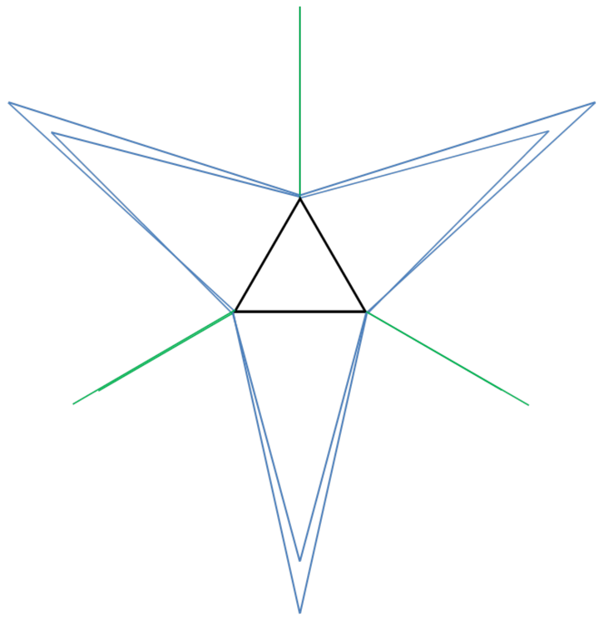


Figure 9.22: Comparison of dimensions with and without poles (2D)

The use of poles depends on the price of the ground. Using no or smaller poles results in a larger ground space, but in a less complex configuration. It should be taken into account that the costs of these kind of poles grows exponentially with height [50]. It is up to the client to decide what is preferable for them. In figure 17.3 a graph can be found in which the horizontal ground distance and the required ground space are plot against the pole height, so a proper choice can be made.

To calculate the ground space a circular area is used. However, ground space can be reduced if a more specific ground area can be used. In figures 9.23, 9.24 and 9.25 three different configurations with their approximate ground space are given. Figure 9.23 describes the circular ground space and is assumed to be the maximum ground space. In figure 9.24 a more compact ground space is given. If it is possible to use this ground space it will reduce the area by 32.5 %. If an even more extraordinary ground area can be used, as can be seen in 9.25, where a ground space of 5 m from every cable is used, it will reduce the ground space by 52.5 %. However, it might be difficult to rent/buy such specific shape of ground area. Pleas notice that these figures are not constructed on scale.

The cables for the stability of the gondola will be connected to the ground station. These cables and all the stability cables will be equipped with a retraction system. These systems will be installed on the ground and on the poles and will be able to change the altitude of the balloon when required.

The power for the cable engines has been calculated with the use of equation 6.10. The use of this equation yields a total power of 350 kW. This power has to be divided over the nine cables that will be involved in lowering the aerostat. This results in an engine power of approximately 40 kW for each of these nine engines. The weight of a 35 kW engine has been determined in chapter 6. As the cable retraction engines have to be slightly bigger than the gondola lifting engine, the weight of this engine is estimated to be 350 kg.

9.6.4. CABLE DESIGN

The length and loads on the cables are determined. These are the inputs for the design of the cables. In this section about the cable design, the loads on and the size of the cables are analyzed and their material is chosen.

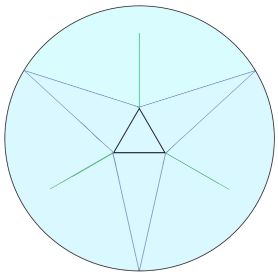


Figure 9.23: Circular ground area, 80,000 m^2, Not to scale

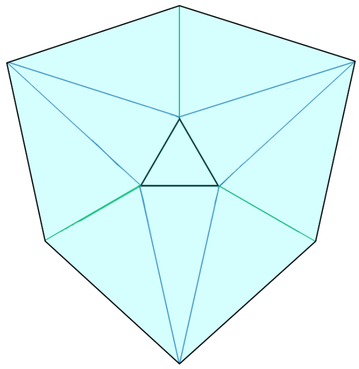


Figure 9.24: Compact ground area, 54,000 m^2, Not to scale

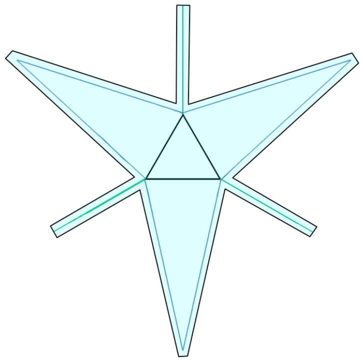


Figure 9.25: Minimum ground area, 38,000 m^2, Not to scale

It is complicated to predict what the maximum forces in each cable will be. Wind, causing drag force, from one direction, is compensated for by different cables. The tensile forces in every cable are hard to predict, so proper sizing of the cable is tough. Therefore, firstly a maximum of the sizing of the cables is determined.

To compute for the maximum boundary of the weight of the cables, all cables are designed to be able to cope with the maximum tensile force that will act on the cables. Since the system will be put into safety mode from a wind speed of 12 m/s (17 m/s in air), the cables are designed to cope with the forces at a ground wind speed of 12 m/s. The chosen safety factor for non-metallic tethering components is 3.5 (table 3.1). The conditions and properties of the cables are summarized in table 9.7

Table 9.7: Conditions and properties of stability cables

Lift $[N]$	710690
Drag $[N]$	350240
Total force $[N]$	792306
Safety factor $[-]$	3.5
Required strength $[N]$	2773070
Material	Dyneema
Tensile strength $[GPa]$	3.5
Density $[kg/m^3]$	970
Surface area $[m^2]$	$7.92 \cdot 10^{-4}$
Radius $[cm]$	1.59

As described in this chapter, there are three different types of cables. For all types of cables the size and weight has been determined in table 9.8

Table 9.8: Specifications of cables per type

Cable type	Primary	Secondary lower	Secondary upper
Horizontal distance $[m]$	137.19	86.31	86.31
Height $[m]$	280	210	280
Cable length $[m]$	311.8	227	293
Volume $[m^3]$	$2.47 \cdot 10^{-1}$	$1.8 \cdot 10^{-1}$	$2.32 \cdot 10^{-1}$
Mass $[kg]$	239.63	174.49	225.18
Amount of cables $[-]$	6	3	3
Total mass $[kg]$	1437.79	523.48	675.55

Using six primary cables, three lower secondary cables and three upper secondary cables, the total cable weight will be 2636.81 kg

However, these numbers are obtained theoretically using the tensile strength of 3.5 GPa. To check whether such cables would also be available on the market, investigations were done on what cables are available at manufacturing companies around the globe. Only limited information was available, but it was found that a cable with breaking strength of around the needed 2 773 070 N would require a diameter of 68 mm and approximately have a weight of 2.41 kg/m [51] [21]. Combining the length of all necessary cables, a total length of 3430.95 m is obtained, resulting in a weight of 8268.60 kg. This is 5632 kg different from the theoretical weight.

To estimate the cost of these cables, the costs of a 10 mm dyneema cable [52] was found and extrapolated to 70mm. The cable would cost than 42 euro per meter. Since 3430.8 meter was needed, the costs would add up and be rounded off to 150 000 euro.

As mentioned, this is a maximum constraint and it was assumed the total force of lift and drag could act on just one of the attachment cables. In practice, there are always at least two primary cables, and two secondary cables that can take up a part of these forces. Therefore, the cables are over designed. To come up with more accurate numbers on thickness, weight and cost, more detailed research and calculations should be performed on the dynamic behaviour of the aerostat subjected to high wind speeds. The resources available during the DSE do not allow for such calculations, and thus it should be planned for after the DSE. Once the calculations are done, each cable can be designed more accurately and will probably reduce the weight and costs.

For completeness, an example of how much weight this might reduce will be given. Because of symmetry of the dirigible, it can be cut through half to compute the forces in two cables. The remaining force is half of the original total resultant force. This force need to be conteracted by the two cables. In figure 9.26 the top view of the system cut through half.

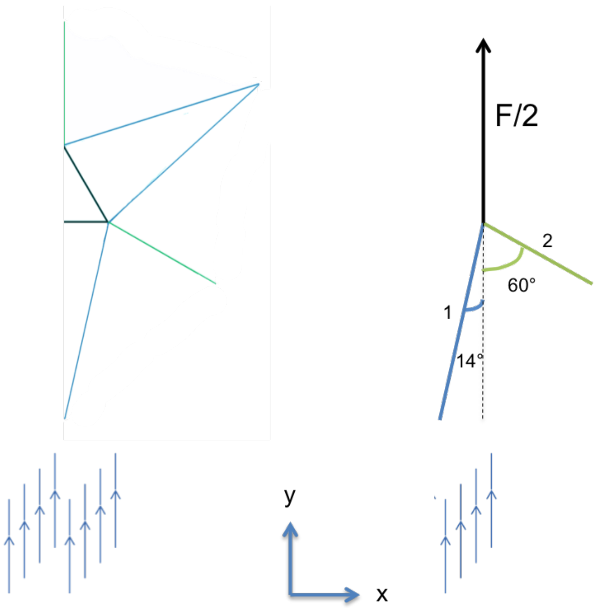


Figure 9.26: Cable force computation: vector subdivision

Because of symmetry, the force acting on the dirigible is only half of the total force (F/2). For simplicity a point mass is assumed on which the two remaining cables are attached. These cables need to be able to counteract F/2. Their x-components of the forces need to cancel each other out, and the y-components of the forces must be F/2 in total. It is computed that, using a safety factor of 3.5, the primary cable needs to be able to withstand a tension force of $1.25 \cdot 10^6 N$, and the secondary cable a tension force of $3.52 \cdot 10^5 N$. For the primary cable, this would result in a cable diameter of 40 mm and a weight of 85.1 $kg/100m$. This results in a cable weight of 265.34 kg per cable. The tension in the secondary cable is very low in this configuration. This means that using this tension force would result in an under estmation of the cable weight of the secondary cables. Assuming a diameter of 40 mm for all cables seems more feasible. In this case, the upper and lower secondary cables have a weight of respectivily 249 kg and 193 kg. This results in a total cable weight of 2920 kg, which is a feasible cable weight.

It can be concluded that, using cables that are all capable of withstanding the maximum force on the dirigible, theoretically a cable weight of 2637 kg can be obtained, which is acceptable. In practice however, the cables can have a maximum weight of 8269 kg. By doing experiments the cables can be resized for the exact force acting through each separate cable and be made less over designed. A preliminary resizing resulted in a cable weight estimation of 2920 kg for all cables combined.

9.6.5. Guide vanes

In order to reduce drag and vortex shedding, the use of guide vanes has been considered. This option was brought to the attention of the team by experts in the aerodynamics department of the TU Delft. Guide vanes are plates that can be placed along corners and edges. Guide vanes usually have an airfoil shaped cross-section and are commonly used in turbines, in wind tunnels, in airconditioning systems and on bridges. When the flow encounters a guide vane of this shape, it is naturally deflected along the airfoil, resulting in less turbulence around the corners. Due to the airfoil shape, guide vanes are only effective if the flow encounters it in a set direction. However, the decision has been made to fix the aerostat in place, so the direction of the flow will vary. Therefore the use of guide vanes is not an option anymore, because there is no set direction in which the guide vanes could be mounted.

9.6.6. Gondola stability

As the gondola will carry passengers, it is important that stability is guaranteed. As described in chapter 6, the gondola will be stabilized with the use of three guide cables. As the gondola will be round, a von Kármán vortex street will likely develop behind the gondola and introduce vibrations. At this point, it is unknown to what extent the stabilization cables will disturb this flow. Further investigation into the stability is needed and will be accounted for in the post DSE planning in chapter 22. The shape of the gondola is not yet fixed and changing it to possibly reduce the effects of wind-induced vibrations is possible if necessary.

9.7. Temperature considerations

When temperature changes, it has an effect on the aerodynamic properties of air and the densities of both the air and the helium. At this moment, it is known that an increase in temperature results in a lower drag, but also in a lower lift from the shape and a lower lift from the helium. Since the used CFD methods are conservative and not validated for these calculations, it is recommended to research the effects in wind tunnel tests. If the different densities are known, the helium lift can be calculated with equation 9.10[53].

$$L = \rho_{air} \cdot V \cdot g \left(1 - \frac{\rho_{he}}{\rho_{air}}\right) \tag{9.10}$$

The lift of the shape should then be added and the weight of the structure subtracted. The change in this lift should be compared with the change in drag to know whether or not the system is still stable.

9.8. Safety mode stability

When the aerostat is lowered for the safety mode, stability must still be guaranteed. Lowering of the aerostat will be achieved by retracting the cables that stabilize it. This introduces extra loads on the cables, that have been taken into account in the sizing of the cables. Next to this, it must be ensured that all cables are retracted at the same speed, as any differences result in tilting of the balloon, which is undesirable.

The maximum wind speed during a storm is 30 m/s, measured at a height of 10 meters [54]. This is a wind speed that occurs approximately once every fifty years. Because of the height of the aerostat, the maximum wind speed will be at a altitude of 90 m. Using equation 9.4, the maximum wind speed during safety mode can be calculated [45].

The absolute maximum wind speed the aerostat has to endure in safety mode is approximately 44 m/s. When the air segment has been lowered in the way described above, all cables will be tightened. Due to the higher angle between the aerostat and the cables, the system will be able to resist higher wind speeds. This will ensure that the aerostat is stable in safety mode. A more elaborate description of the safety mode design can be found in chapter 10.

10
SAFETY MODE DESIGN

In this chapter, the safety mode design will be presented. As can be seen in chapter 4, the safety mode of the aerostat will consist of lowering it to the ground and holding it in place. Section 10.1 describes the lowering of the aerostat and section 10.2 covers the ground attachment of the aerostat.

10.1. LOWERING OF AEROSTAT

When the ground wind speed exceeds the operational limit of 12.0 m/s, the aerostat has to be lowered to the ground. When lowering is initiated, the gondola must be resting on the ground. In order to lower the aerostat, all stability cables, including the gondola stability cables, must be retracted. The retraction speed of these cables must be coordinated in such a way that the aerostat remains in an upright position and remains stable during lowering. During the lowering of the aerostat, the gondola lifting cable must be retracted as well to ensure that it does not detach from the pulley on top of the gondola.

When entering safety mode, the dirigible must be lowered a maximum distance of roughly 250 meters. Based on the elevation speed of the gondola subsystem, a conservative estimate of the lowering speed can be made. This maximum lowering speed is taken to be 0.5 m/s. This means the air segment can be lowered to ground level in less than 10 minutes.

10.2. GROUND ATTACHMENT

This section covers the ground attachment of the aerostat during safety mode. Section 10.2.1 discusses the ground attachment that will be used. Subsection 10.2.2 covers the additional reinforcement cables that will be attached during high wind forces.

10.2.1. BOTTOM ATTACHMENT

When the blimp has been lowered to the ground, the bottom will be attached to the ground. For stability, it is important to fix the lower surface of the aerostat to the ground structure. Different methods can be used to attach the bottom. One option is to clamp the bottom beams. Another option is to use three attachment pins that will be located at the bottom hinges of the balloon. When the aerostat is lowered, these pins will slide into a connection point on the ground station and they will be fixed. This way, the large moments that are generated by the wind on the aerostat can be transferred into a ground based structure that will be able to handle these loads. The exact bottom attachment has to be designed into more detail, because more insight is needed in the architecture of the ground station. The structure of the aerostat is designed in such a way that the ground attachment can transfer 800 kN of drag load in lateral direction according to chapter 8. This excluding the safety margin of 1.5 as is described in section 8.4.3. This means that the ground attachment must be able to transfer these loads.

10.2.2. ADDITIONAL REINFORCEMENT CABLES

Forces and moments in the aerostat are transferred to the ground via a supporting structure as is described in section 10.2.1. The main loads in safety mode are handled by the cables that are used for stability in normal operation. This means that the main function of the ground attachment is to form a stable base to keep the dirigible from moving. The amount of cables and their placing depends on the wind force acting on the blimp. In table 10.1, the drag forces on the aerostat when the it is attached to the ground can be found.

Table 10.1: Drag forces and attachment flight envelope

Wind speed in ground [m/s]	<12.5	>15	>20	>25
Aerodynamic drag [kN]	648	932	1653	2565
Number of attachments	4	6	8	8+(amount post DSE)
Attachment points in figure 10.1	1, 2, 3, 4, 5, 6	1, 2, 3, 4, 5, 6, 12, 13, 14	1, 2, 3, 4, 5, 6, 12, 13, 14, A, B	1, 2, 4, 5, 12, 13, A, B + skin/beams

One side of the structure of the balloon can handle 800 kN of the drag forces, excluding a safety factor of 1.5 for wind gusts (and thus 12 000N for ultimate loading)8. As can be seen in table 10.1, the drag force at 15 m/s is already larger than what the structure can handle (the structure has a limit load of 800 kN) when the balloon is with its flat side in the wind. This means that when the drag force exceeds this 800 kN, extra cables needs to be attached to handle the loads. The exact amount of cables, however, can not be calculated, because the exact behaviour of the forces in the beams can not be determined to sufficient detail at this stage of the project. A more detailed design is therefore needed in the post DSE phase.

The primary and secondary stability cables will transfer drag forces. When the balloon is attached to the ground, the angle of the cables with the ground and/or poles is smaller. The tension in the cables can be much larger than the tension in the cables when the aerostat is in the air, as the tension in is not restricted by the lift of the aerostat. When the drag force becomes larger, extra stability cables must be attached to the balloon. For example a crane or platform can be used to do so. In table 10.1, the amount of cables at a certain wind speed is given from one side . It is assumed that the drag forces will be equally distributed over the used attachment points. In figure 10.2 an example of the drag distribution with its drag components is given when the primary and secondary cables are used with additional stability cables attached at 12, 13 and 14. It would be favourable to attach as much cables as possible, in order to distribute the drag forces. However, for practical reasons and the time consraint of 24 hours before a sand storm, a minimum amount of cables to be installed is preferred. The smallest amount of cables that is needed to keep the structure stable is considered with their attachment points in table 10.1. These cables will be connected to the structure at specific attachment points. Up to a wind speed of 25 m/s, the structure and the stability cables must handle the drag force. Above this wind speed, the internal structure would not withstand the drag force and other options are therefore needed. Two options are considered.

The first option is to divide the drag load on the structure even more. Stability cables will not only be connected to hinge points of the structure, but also to points on the beams, reducing the amount of drag force that goes through the beams. The exact number of extra cables can only be calculated in a more detailed design.

Another option is to prevent the drag force from going through the structure. This means that cables will be connected to the envelope to counteract the drag force. The drag force will then be divided over multiple small cables. The number of cables needs to be large since the envelope can not withstand large point forces.

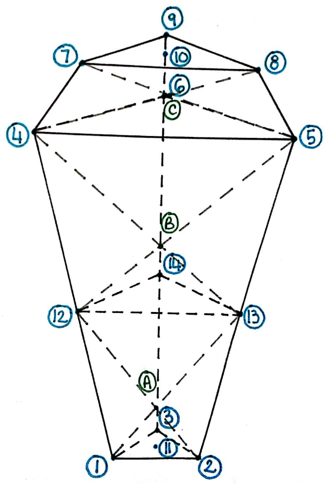


Figure 10.1: Attachment points

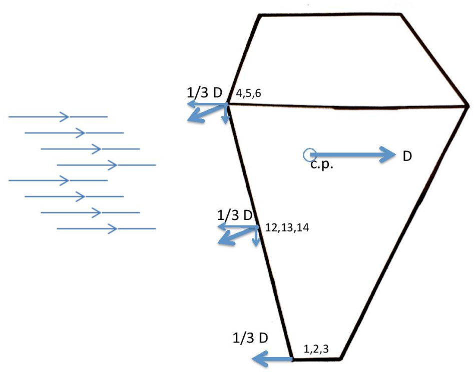


Figure 10.2: Drag force distribution with 1,2,3,4,5,6,12,13 and 14 as used attachment points

11

SUSTAINABILITY DESIGN

Following the meeting with United Balloon of May 22nd 2014, new information was obtained on the sustainability of the system. The initial requirement was for the whole system to be CO_2-neutral, which means that it would have net zero carbon emissions. This would derive from the system balancing the amount of carbon released in the atmosphere by using an equivalent measured amount located offset or by buying enough carbon credits to adjust the difference. United Balloon stressed the importance of realizing the project even if this requirement may not be fully met. On the other hand, TU Delft is much concerned with being involved in 'green' projects and with the preservation of the environment, hence the following solution is chosen: the sustainability part of the design is completely optional. If one would like to be CO_2 neutral, this chapter should be considered, while if one does not have the need for it, the chapter can be discarded. First, there will be a quick look at what the meaning of sustainability is in section 11.1 and then a more detailed explanation is given on how to apply this concept to the system in sections 11.2, 11.3, 11.4, 11.5 and 11.6.

11.1. ETHICS

According to an ethical approach to sustainability, society has an obligation to limit wasteful uses of resources, while providing economic development and maintaining environmental resource protection. The concept of sustainability is based on preserving the resources available and only limiting the use of these to the minimum necessary. A relatively simple definition of sustainability is: "meeting the needs of the present generation without compromising the ability of future generations to meet their needs." [55] Sustainability ethics is concerned with the moral aspects of the relationship that humans have with other contemporaries, nature and future generations [56]. This idea clearly does not match with the consumerist and materialistic view that the city of Dubai applies to the creation of new buildings and attractions. In fact, most new projects in Dubai follow the principle "bigger is better", without too much concern for the environmental impact of this. In the last years though, the government has been working on supporting projects that are sustainable, giving prizes to companies that manage to achieve CO_2 neutrality. This is one of the reasons why United Balloon was initially set on making this dirigible an environmentally friendly project. Nonetheless, the cost of making the system CO_2 neutral would be high in terms of mass, ground space and financial figures. This is true for the simple fact that extra solar panels or wind turbines increase the weight, required ground space and cost.

11.2. MATERIALS

As the project is rather large, a lot of material has to be used. It will have a major impact on the environment if non-sustainable materials are used. For instance, aluminum can be recycled, both for constructing the balloon and after its life, which is not the case for carbon or glass fiber reinforced polymers. Where possible, recycled aluminum will be used to reduce the environmental footprint of the project, while the use of glass and carbon fiber is minimized. For a project this large, being CO_2 neutral for the material usage is costly to achieve. Minimizing the use of pollution materials is therefore the most viable option. Carbon offsetting may be considered for marketing purposes.

The ground station will be built using local building materials, using recycled materials where possible. Roofs will be covered with sun shielding to provide a naturally cool atmosphere, minimizing the need for air conditioning. The buildings will be constructed to be just viable for their intended use, to save on material usage.

Again, being CO_2 neutral at this point is too costly, though minimizing the impact of the materials will contribute greatly to a reduction in CO_2 emissions.

11.3. MANUFACTURING

Not only the used materials need to be sustainable, but the way in which the aerostat is manufactured is also of large influence on the environmental impact. For instance, if a lot of material is wasted during manufacturing, if pollution is not captured and filtered or if non-renewable energy is used, this has a negative influence on the CO_2 footprint. The biggest savings would come from proper engineering: in that way the amount of material needed is minimized, which also minimizes the amount of manufacturing. It is a goal to manufacture as much of the project as possible within the area of deployment to give a boost to local economy. The manufacturing processes used will all account for their CO_2 emissions by using carbon offsetting, either by themselves or by buying emission rights.

11.4. ENERGY

To have no CO_2 emissions for the energy use of the aerostat, the average net usage of non-sustainable energy should be zero. This is accomplished by either placing a solar panel park or placing a medium to large wind turbine nearby in the desert, on a convenient location. On-site neutrality is not feasible due to the limited space available and the high prices of ground within the city perimeters. Costs for having a fully CO_2 neutral energy cycle range between 2.5-10 million euro, depending on the type of energy generation and the chosen location [2]. For instance, when the power is generated more efficiently in another part of the country, or a different country entirely, the net effect would be the same, but at a lower cost.

11.5. DAILY OPERATIONS

The main system that needs to be sustainable, or 'green', is daily operations. One can build something using the greenest materials and by means of the most sustainable manufacturing technologies known, if the daily operation generates huge amounts of waste, it is not CO_2 neutral. The biggest factor during daily operations is the energy usage. As described in the previous section, this is already accounted for. Another factor to consider is the release of helium. Some of the helium inside the aerostat might have to be released into the atmosphere in emergency situations. As this is a non-renewable gas, once released, it is lost into space. Therefore, the amount of gas released should be minimized and whenever possible it should be pumped out and stored. Next to purposely releasing gas, there is also the problem of gas leakage due to the nature of helium. The amount of gas lost during leakage is minimized by using a specially coated envelope material.

To save as much energy as possible, the brightness of the screens will be adjusted to the minimal level needed for clear images during whatever time of the day: brighter by daylight, dimmed during night time. The gondola will use heat shielded glass to reduce the amount of air conditioning needed, while staff will be trained to not waste any material or energy. All these small contributions will, together with the self generated energy, yield CO_2 neutral daily operations.

11.6. END OF LIFE DISPOSAL

At the end of life, the system has to be disposed. To both protect the environment and to give something back to society, the envelope material can be used to make emergency tents for third world countries. The envelope material is strong enough to withstand virtually all weather conditions. Furthermore it is light-weight, making it suitable for quick transportation to emergency locations. Because the gondola structure is made of aluminum it can be completely recycled and used for other purposes. This also holds for all electronic wiring and components. CFRP can also be recycled and used for less performance demanding applications. The contentious fibers can be milled in to short fibers and together with a new matrix make a new carbon composite. Furthermore CFRP waste can be used as a light-weight filling material.

The ground station can be reused for any kind of purpose. Shops, office space and catering facilities are some of the possible options.

12

FINAL LAYOUT

This chapter describes the final layout of the system. Figure 12.1 shows an overview of the final layout of the total system. For clarity, all subsystems are numbered and a short description of each subsystem is given in table 12.1. Note that, for the sake of clarity, not every part in the final layout drawing is numbered. For example, the stability cable engine is present on each tower. To have a good overview of the number of times each subsystem is present, the second column in table 12.1 shows how many times the subsystem is used within the total system. In figure 12.2, the final dimensions of the aerostat can be seen. The dirigible will have a total height of 95 meters and a maximum width of 75 meters.

Table 12.1: Description of all subsystems within the final layout drawing

Part #	Amount	Description
1	6	Tower for stability cables attachment
2	9	Stability cables for preventing rotational motion
3	3	Stability cables for preventing tilting motion
4	3	Guidance cables for the gondola
5	1	Lifting cable for the gondola
6	1	Gondola
7	3	Screens
8	1	Aerostat
9	1	Gondola lifting engine
10	6	Stability cables engine
11	1	Ground station gondola
12	1	Control center
13	1	Power supply

In chapter 8, the internal layout of the dirigible has been determined. From the inside to the outside, the dirigible will consist of an internal envelope, the internal structure, fishnet cabling and an external envelope. The function of the internal envelope is to contain the helium and to withstand any pressure differences. The internal structure will ensure that the aerostat retains its shape and it handles the loads that act on the aerostat. The fishnet cabling will ensure further retainment of the shape, by ensuring that the external envelope cannot bend towards the inside of the aerostat. The function of the external envelope is to protect the components inside the aerostat from the harsh environmental conditions.

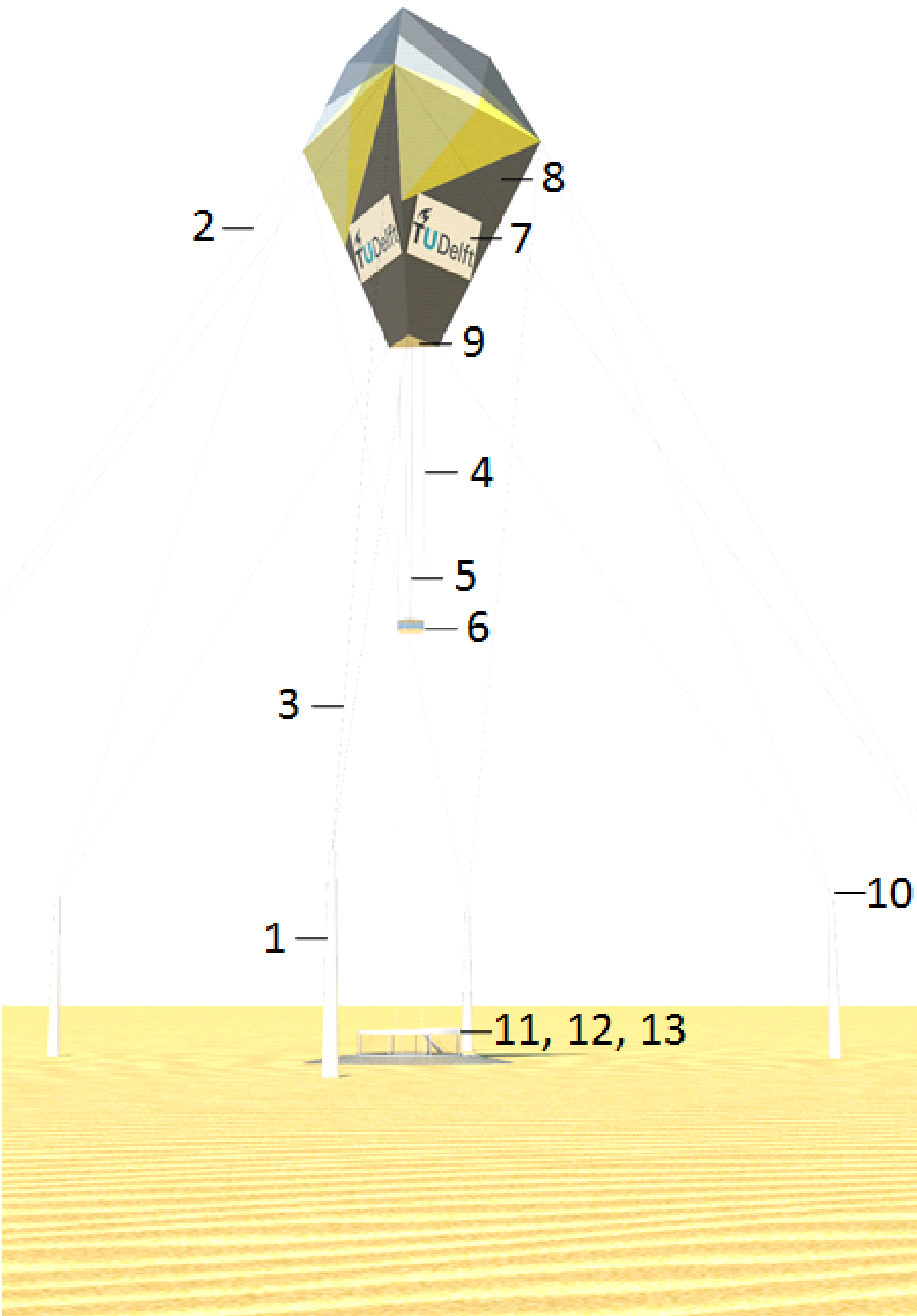


Figure 12.1: Overview of the final layout of the total system

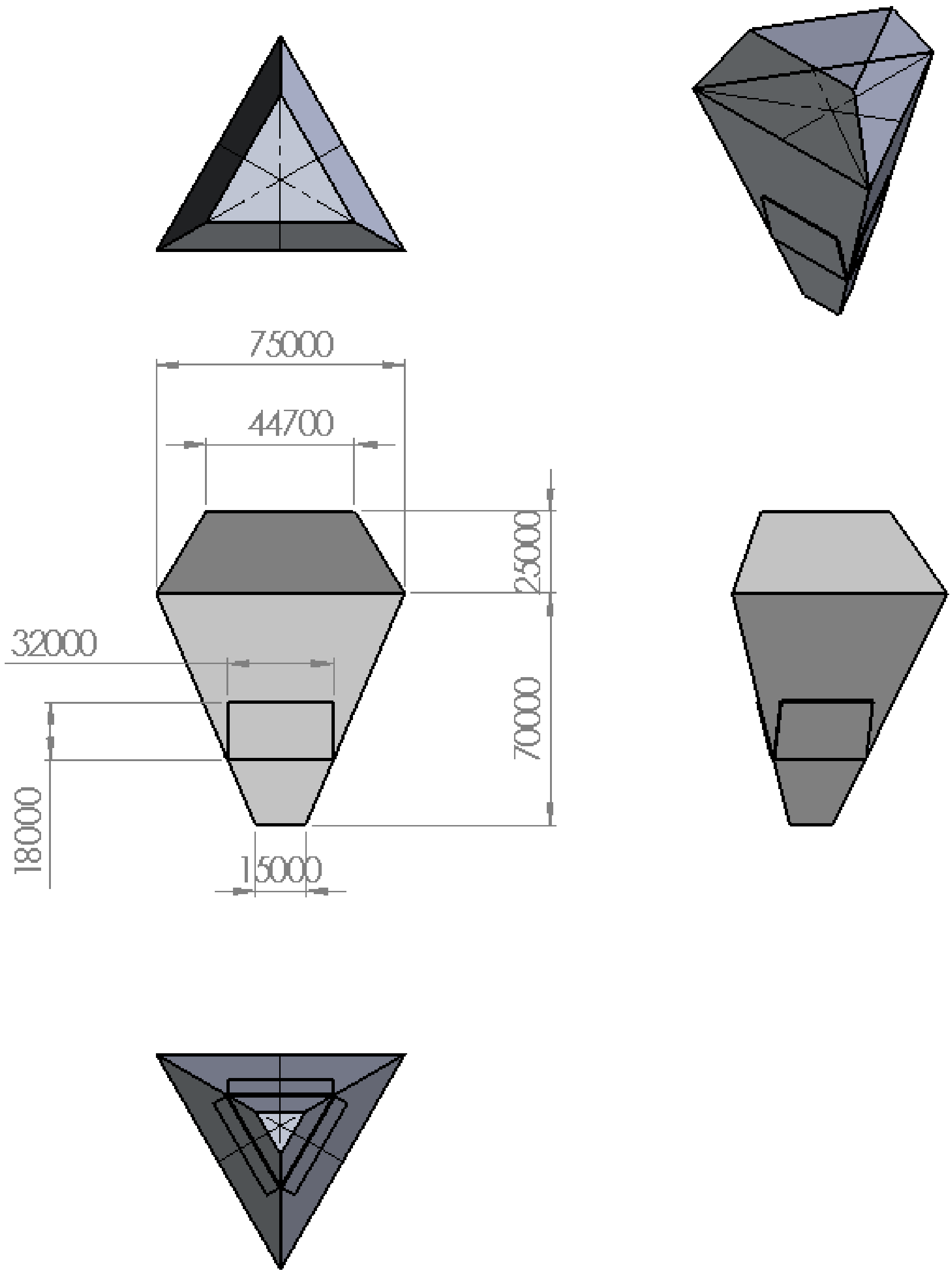


Figure 12.2: Overview of the final dimensions of the aerostat

13 Characteristics

This chapter will address the aerostat system, aerodynamic, structural, stability and control and material characteristics. All characteristics follow from the requirements as stated in chapter 3. Section 13.1 covers the system characteristics of the aerostat and section 13.2 describes the aerodynamic characterystics of the aerostat. In section 13.3, the stability characteristics of the aerostat will be described and section 13.4 covers the structural characteristics. Finally, in section 13.5, the material characteristics are described.

13.1. Aerostat system characteristics

This section covers the system characteristics of the aerostat. These characteristics can be seen in table 13.1. The screen power, size and weight and the gondola engine power have been calculated in chapter 6 and the cable engine power has been calculated in chapter 9. Table 13.2 shows the power budget for the aerostat. It must be noted that the cable engines do not require power constantly, but only need power when the height of the aerostat is adjusted.

Table 13.1: Aerostat system characteristics overview

Power screens (total)	86.4 $[kW]$
Screen size	32x18 $[m]$
Screens weight (total)	3000 $[kg]$
Gondola engine power	35 $[kW]$
Cable engines power	350 $[kW]$
Gondola dimensions	8x8x3 $[m]$
Gondola empty weight	2300 $[kg]$
Gondola payload	6300 $[kg]$
Gondola capacity	50 $[p]$

Table 13.2: Power budget breakdown

Element air segment	**Power [kW]**	**Percentage of total power [%]**
Screens	86.4	16.9
Lighting	10	2
Airconditioning Gondola	10	2
Lift/Gondola	35	6.6
Pumps/Compressor	10	2
Cable retraction system (maximum)	350	68.3
Control electronics	2	0.2
Ground station	10	2
Total power	513.4	100

13.2. AERODYNAMIC CHARACTERISTICS

Table 13.3 shows the aerodynamic characteristics of the aerostat. All values in this table have been calculated at a wind speed of 12.5 m/s. This wind speed is not a ground wind speed, but an actual wind that the aerostat will encounter in flight. The lift and drag values and coefficients have been calculated at an angle of attack of zero degrees and the heights of the center of pressure, center of gravity and aerodynamic center are measured with respect to the bottom of the aerostat. Figure 13.1 shows the variation of lift and drag coefficient with α. Calculations and explanations for all these values can be found in chapter 9.

Table 13.3: Aerodynamic characteristics overview

Frontal projected surface area	4541 $[m^2]$
Top projected surface area	2435.7 $[m^2]$
Static lift	978 $[kN]$
Dynamic lift (point in wind)	29.3 $[kN]$
Dynamic lift (flat side in wind)	39 $[kN]$
Drag (point in wind)	236 $[kN]$
Drag (flat side in wind)	384 $[kN]$
Lift coefficient (point in wind)	0.12 $[-]$
Lift coefficient (flat side in wind)	0.16 $[-]$
Drag coefficient (point in wind)	0.52 $[-]$
Drag coefficient (flat side in wind)	0.84 $[-]$
Center of pressure	59.73 $[m]$
Center of gravity (maximum)	48 $[m]$
Center of gravity (minimum)	9 $[m]$
Aerodynamic center	59.7 $[m]$
Vortex shedding frequency (minimum)	0 $[Hz]$
Vortex shedding frequency (maximum)	11.3 $[Hz]$
Reynolds number (minimum)	$8 * 10^6$
Reynolds number (maximum)	$7 * 10^7$

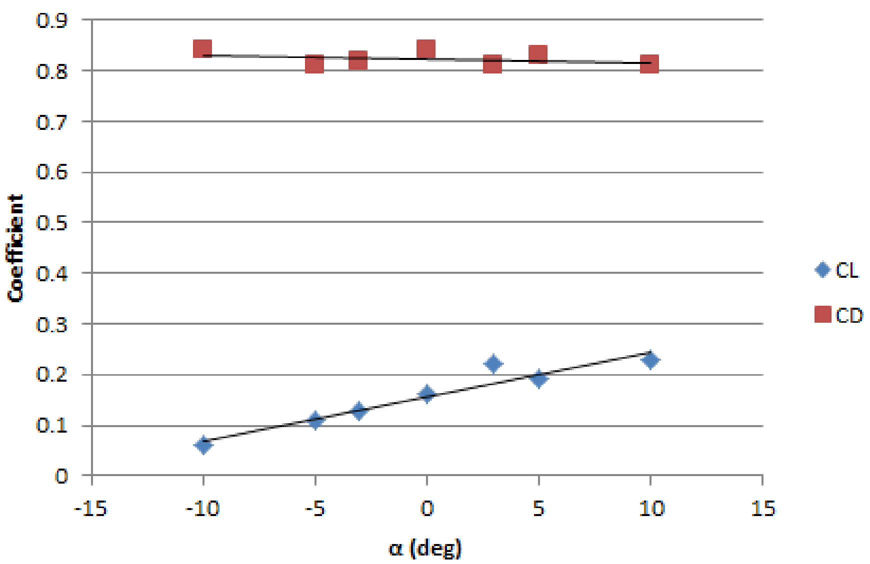


Figure 13.1: The lift and drag coefficient of the aerostat with varying angle of attack

13.3. STABILITY CHARACTERISTICS

The description of the stability characteristics is divided into two parts. Firstly, the characteristics of the stability are summarized in a table in section 13.3.1. Section 13.3.2 describes the flight envelope, which is a result of the structural, aerodynamic and stability investigations.

13.3.1. STABILITY CHARACTERISTICS SUMMARY

Using the right amount of cables, rotational stability can be ensured. When the cables are placed at the right distance from the dirigible, they have an angle with respect to the ground at which displacement is prevented as well. However, as will be described in section 13.3.2, this is true up to a certain maximum wind speed. This maximum wind speed is higher when the gondola is not used. The maximum wind speed without safety mode is also determined in section 13.3.2. The stability characteristics are summarized in table 13.4. Calculations and explanations for all these values can be found in chapter 9.

Table 13.4: Stability and control characteristics overview

Primary cables, amount	6 [−]
Upper secondary cables, amount	3 [−]
Lower secondary cables, amount	3 [−]
Primary cables, weight / cable	265 [kg]
Upper secondary cables, weight / cable	249 [kg]
Lower secondary cables, weight / cable	193 [kg]
Primary cables, angle w.r.t. ground	59.2 [°]
Upper secondary cables, angle w.r.t. ground	69.4 [°]
Lower secondary cables, angle w.r.t. ground	67.2 [°]
Primary cables, ground distance	137.19 [m]
Secondary cables, ground distance	86.31 [m]
Pole height	50 [m]
Total cable weight	2637 [kg]
Max. wind speed, regular operation with gondola	5 [m/s]
Max. wind speed, regular operation without gondola	5.8 [m/s]
Max. wind speed, operation	12 [m/s]

13.3.2. FLIGHT ENVELOPE

As described in section 9.6.2, the maximum wind speed in this cable configuration is 8.5 m/s in air, which corresponds to 5 m/s wind speed on the ground. The resultant lift and drag force due to different wind speeds is computed using CFD. With a ground wind speed of 0 - 5 m/s, normal operation is possible. Above a wind speed of 5 m/s, the aerostat needs to be lowered. Using computational fluid dynamics and regression lines, figure 13.2 has been constructed.

Figure 13.2 shows the relation between wind speed and the altitude of the dirigible. The stated altitude is the height of the connection point of the primary cables and the upper secondary cables (at the top of the lower pyramid). Depending on the altitude, the wind speed changes and that influences the up-time for the subsystem. In figure 13.2, the blue line indicates the envelope for normal operation conditions. The curved line is a powered trend line through the data that has been generated using CFD. Using CFD, the lift and drag force has been computed for different wind speeds, which, combined with the lift force due to helium, forms a resultant force with a certain angle with respect to the ground. As explained in section 9.6.2, for every wind speed there is a maximum angle for which stability of the aerostat can be ensured. The higher the operational height, the higher the angle, so for certain wind speeds there is a maximum height. This has been iterated for six different wind speeds, which are the data points in figure 13.2. For these data points, the wind speed at the particular height has been used. It has been decided that the aerostat will be brought into safety mode if the ground wind speed is 12 m/s or higher. This is the case, because the risk of harmful sandstorms with high wind peaks is very high and the possible height is not much more than 100 m, which is not a relevant operational height.

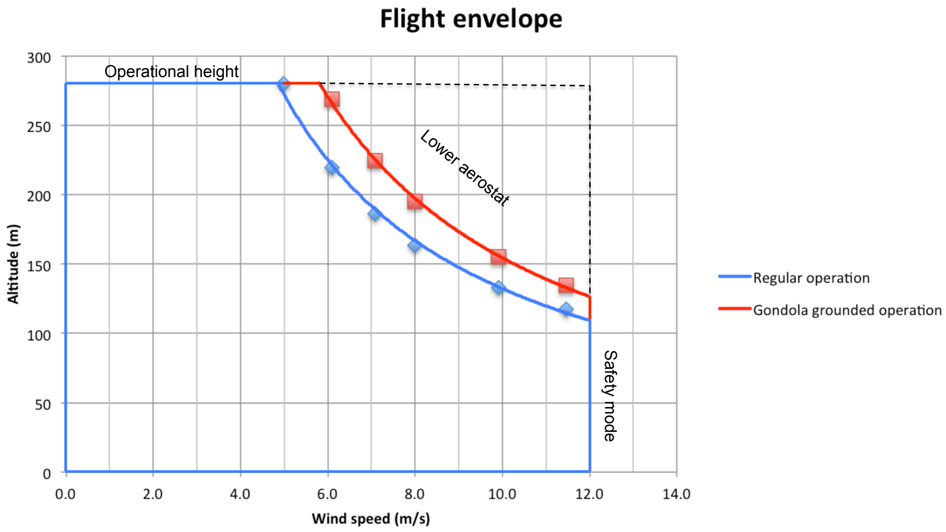


Figure 13.2: Flight envelope aerostat of altitude vs windspeed

The red lines cover the maximum height where stability can be ensured when the gondola is detached or when the weight of the gondola is supported by the ground. For this configuration, CFD has been applied. The other borders are the operational height of 280 m and the maximum wind speed of 12 m/s as already described.

More about the mission envelope can be found in section 15.4.

A very important note is that these restrictions are computed with all knowledge that is available for the DSE group. Clearly, the exact conditions in Dubai are not known. Therefore, the system should be deployed at calm conditions and needs to be checked for stability very frequently during the first operational moments. The same holds for the safety mode wind speed. It might be possible that safety mode is not required at a wind speed of 12 m/s, but at a lower or higher wind speed.

Another important remark is that the flight envelope can be considered as rather conservative. The wind is assumed to act perpendicular to the flat side of the aerostat, which results in the largest force. Furthermore, the CFD computations can be considered conservative as well, as explained in Appendix C.

It can be concluded that the flight envelope as described in this section should be used as a guide line and that good measurement systems are necessary for the practical operation.

13.4. STRUCTURAL CHARACTERISTICS

This section covers the structural characteristics of the aerostat. Table 13.5 lists the dimensions of the final design and table 13.6 contains the mass budget for the final design. All values in these tables have been determined in chapter 8.

Table 13.5: Structural dimensions of the selected design carbon 2

	Carbon 2	
	Value	Unit
Height lower pyramid	70	$[m]$
Height crown	25	$[m]$
Total height of balloon	95	$[m]$
Width lower pyramid	75	$[m]$
Volume lower pyramid	56832	$[m^3]$
Volume crown	44310	$[m^3]$
Total volume balloon	101143	$[m^3]$
Useful total volume balloon	94540	$[m^3]$
Total helium lift	962	$[kN]$
Mass main structure (no hinges)	32079	$[kg]$

Table 13.6: Mass budget breakdown of the selected structural design

	Carbon 2 [kg]
Screens (32mx18m)	9000
Envelope internal	3000
Envelope external	3000
Structure internal + hinges	32000 + 5000
Fishnet cabling	3000
Connection cables	2000
Entire structure	43000
People payload	6000
Electronic wiring	3000
Balloon lighting	2000
Lift & Gondola	3000
Non structural mass	14000
Total mass	71000
Lift/MTOW	1.40 [-]

13.5. MATERIAL CHARACTERISTICS

This section lists the characteristics of the materials that will be used on the aerostat. Table 13.7 lists the characteristics for the material that will be used for the internal structure. Table 13.8 lists the internal envelope material characteristics and table 13.9 lists the external envelope material characteristics. All values in these tables have been determined in chapter 8.

Table 13.7: Internal structure carbon fiber material characteristics

Material type	Carbon fiber (70% fiber +epoxy)
Maximum stress	1600 $[MPa]$
Young's modulus	181 $[Gpa]$
Density	1500 $[kg/m^3]$
Safety factor for internal structure	1.5 $[-]$

Table 13.8: Material characteristics of internal envelope

Material type	30 denier nylon ripstop
Breaking strength	7.88 $[N/mm]$
Mass	0.037 $[kg/m^2]$
Helium permeability per day	0.615 $[L/m^2]$
Safety factor for envelope	5 $[-]$

Table 13.9: Material characteristics of external envelope

Material type	400 denier Vectran
Breaking strength	87.56 $[N/mm]$
Mass	0.108 $[kg/m^2]$
Helium permeability per day	0.577 $[L/m^2]$
Safety factor for envelope	5 $[-]$

14

Dirigible operation and logistics

In this section, the daily operational aspects of the dirigible are discussed. Topics covered are the functional flow diagram, a functional breakdown structure, helium refilling of the aerostat, a data handling diagram and an electrical block diagram. All communications between hardware systems, software systems, staff and the environment are discussed. First, an operation and logistics concept is presented in the form of a functional flow diagram in section 14.1. Second, a functional breakdown structure is given in section 14.2 to indicate which functions the dirigible should execute. To visualize the way inputs and outputs within the system are connected, section 14.3 contains a communication flow diagram. After that, a data handling method is presented in section 14.4, along with an electrical block diagram in section 14.5 to indicate what kind of power all systems will use and how the systems will interact. Afterwards the hardware connections are discussed and shown in a hardware block diagram in section 14.6. In the end, the method of transporting data, electricity and helium from the ground to the aerostat will be discussed in section 14.7 and a preliminary software design for the cable retraction system will be made in section 14.8.

14.1. Operation and logistics concept

In order to determine the functions the aerostat has to perform, a functional flow diagram was made. In this diagram, a clear overview is given of all functions during the lifetime of the aerostat. A first set-up has been made in an earlier stage of the design process and is included in the baseline report [5]. For the final design, this functional flow diagram was reviewed and aspects of the diagram which could be worked out in further detail were changed. Since better knowledge on the whole design was available, certain processes in the functional flow diagram were changed. The final functional flow diagram can be found in figure 14.1, 14.2, 14.3 and 14.4. The figure was split into multiple sections due to its size. Within the figures the letter g means the next step will only happen when previous step is performed, whereas $\tilde{g}$ means that it will only happen when the previous task is not performed.

The main operations are: transport, pre-operational inspection, deployment, operation, maintenance and disarrangement. A short description will be given for each step in the process.

The transport is the process in which the system is brought from production location to the location of operation. To do this the correct transportation method, for example containers, has to be selected. If a method is chosen in which the system is divided amongst multiple containers, the amount of conainers must also be determined. The next operation starts when the aerostat has been transported from production site to deployment site.

This next phase is the pre-operational inspection, in which it is ensured that the system is ready for operation. During production, mistakes can be made so that parts of the dirigible are of a incorrect size, damaged or are just missing. These parts should therefore be replaced or repaired. It should be ensured that all parts are present before the system is assembled.

Then the aerostat can be deployed. When the conditions allow it, the balloon can be filled with helium and take off. It can then be turned on. Before filling the balloon with helium completely, the balloon will first be filled partially, after which a check will be performed to see whether any leakages are present. If any are present, the leakages should be fixed before continuing the deployment of the dirigible. If the aerostat has been filled, all components should be checked before ascending the balloon to the desired altitude.

When the aerostat has been deployed, the main operation starts: displaying the videos, providing sightseeing, and monitoring for problems. The last one is necessary, because the aerostat needs to be lowered if critical structural problems or weather hazards are present. When lowered, the dirigible can be put into safety mode for maintenance. If a structural problem is found, but it is classified as not critical, it will not be lowered to the ground but the problem will be fixed during scheduled maintenance. If no problem is found at all, the system can continue operating.

As stated in the previous paragraph, scheduled maintenance is needed during operation. This consists of checking all main systems and repairing or maintaining where needed. If a critical problem is found, one which can not be solved while in operation, the dirigible will have to be lowered to the ground when possible and the problem will have to be fixed on the ground.

After operation, which is expected to be after a minimum of 10 years of service, the system will be taken out of operation and is lowered to the ground. There, the system needs to be disassembled. The parts of the system that can be used for other purposes have to be recycled, while parts which can not be used are disposed of. The ground segment will also have to be given a new purpose or be broken down otherwise.

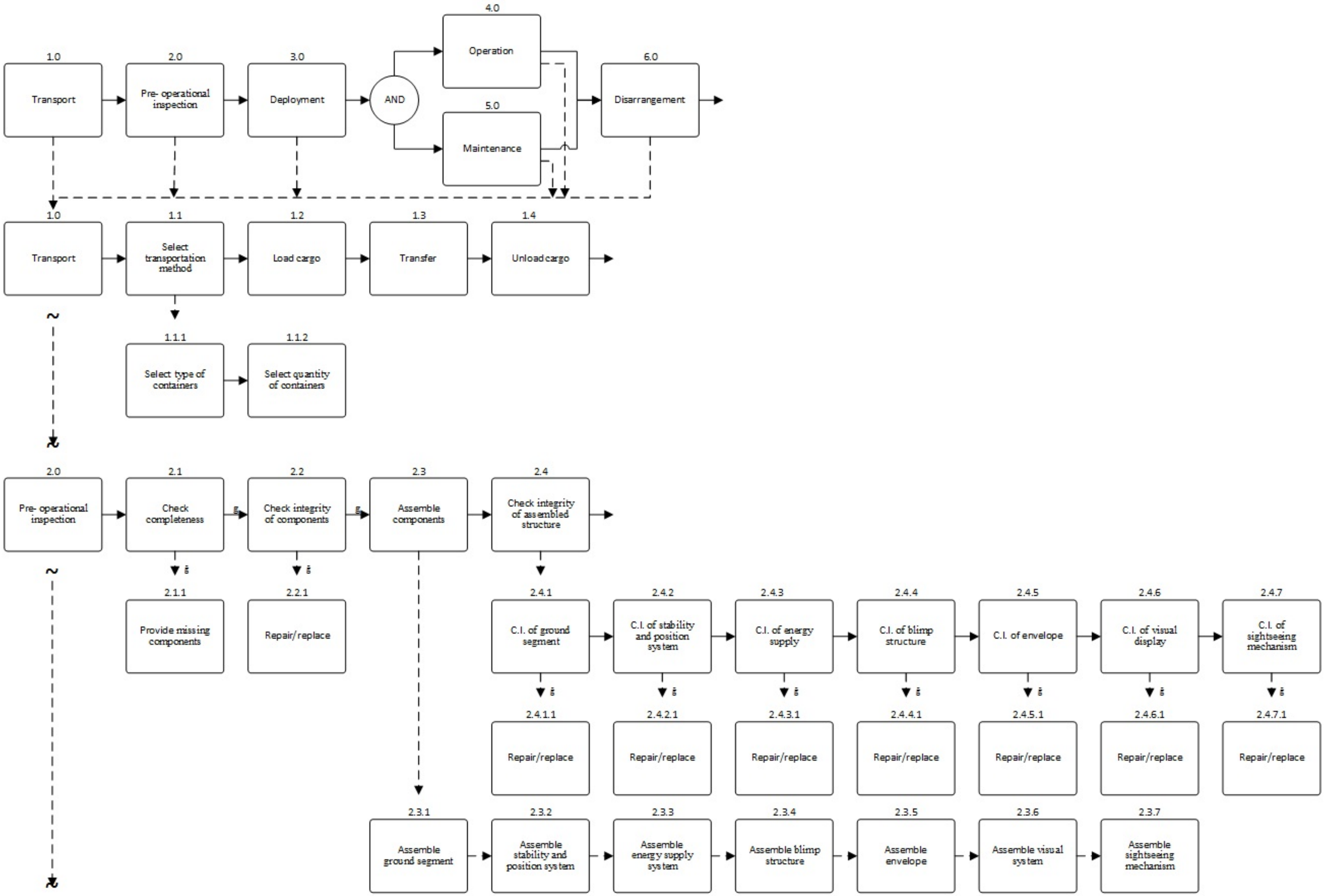


Figure 14.1: Functional flow diagram part 1

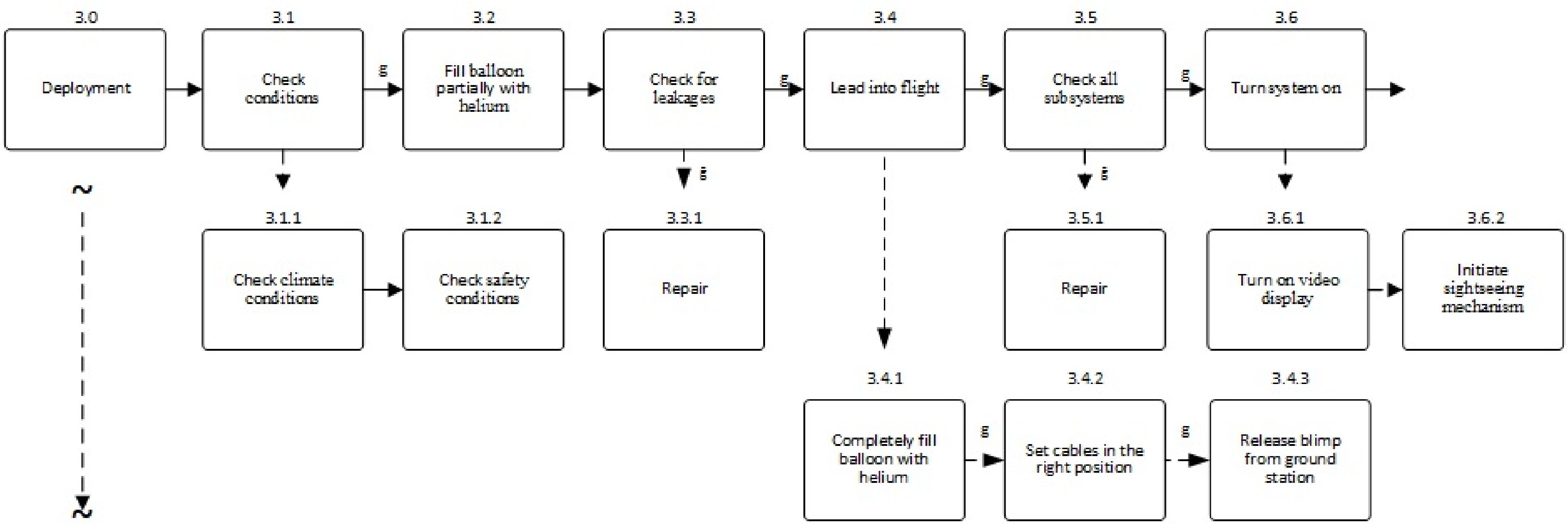


Figure 14.2: Functional flow diagram part 2

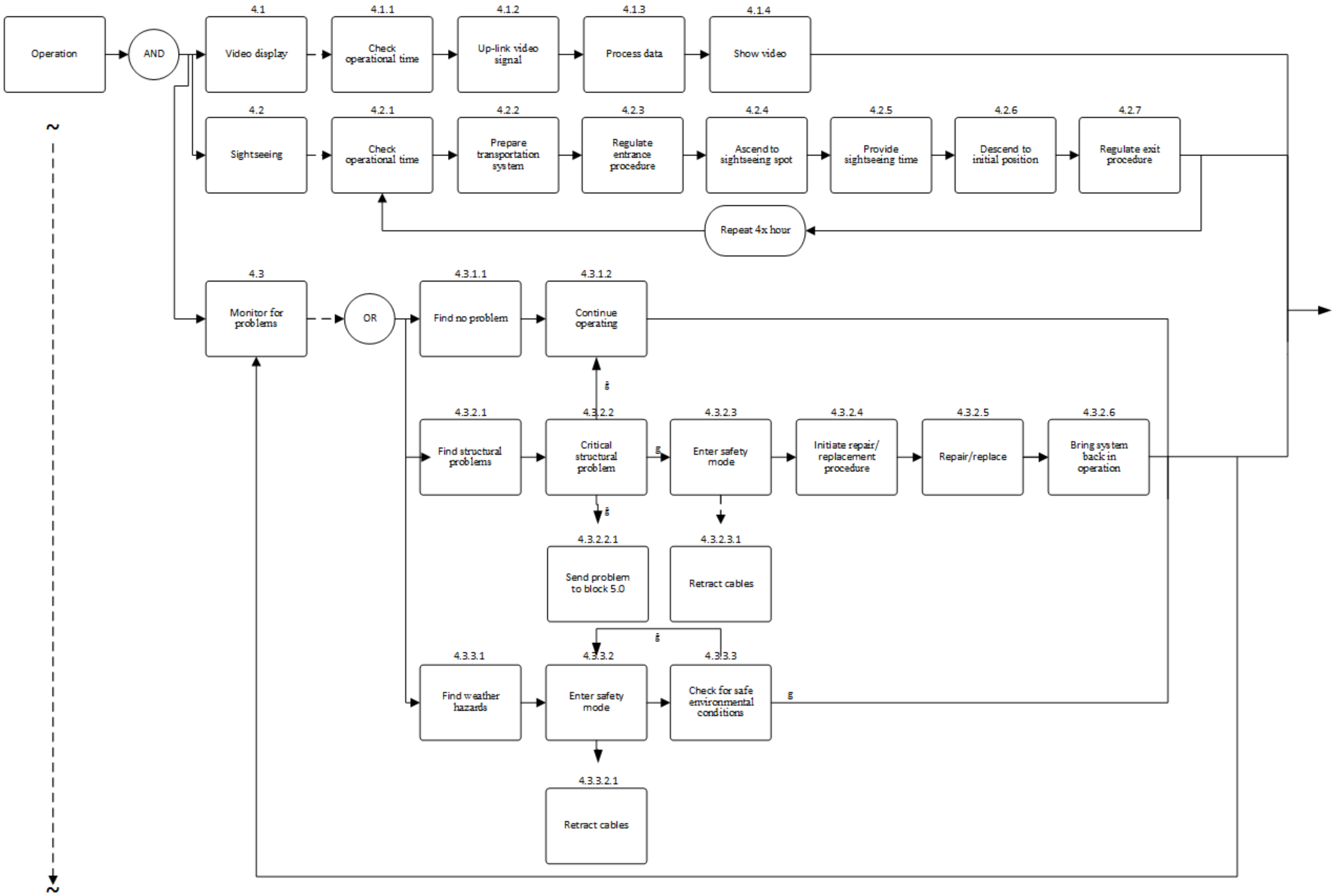


Figure 14.3: Functional flow diagram part 3

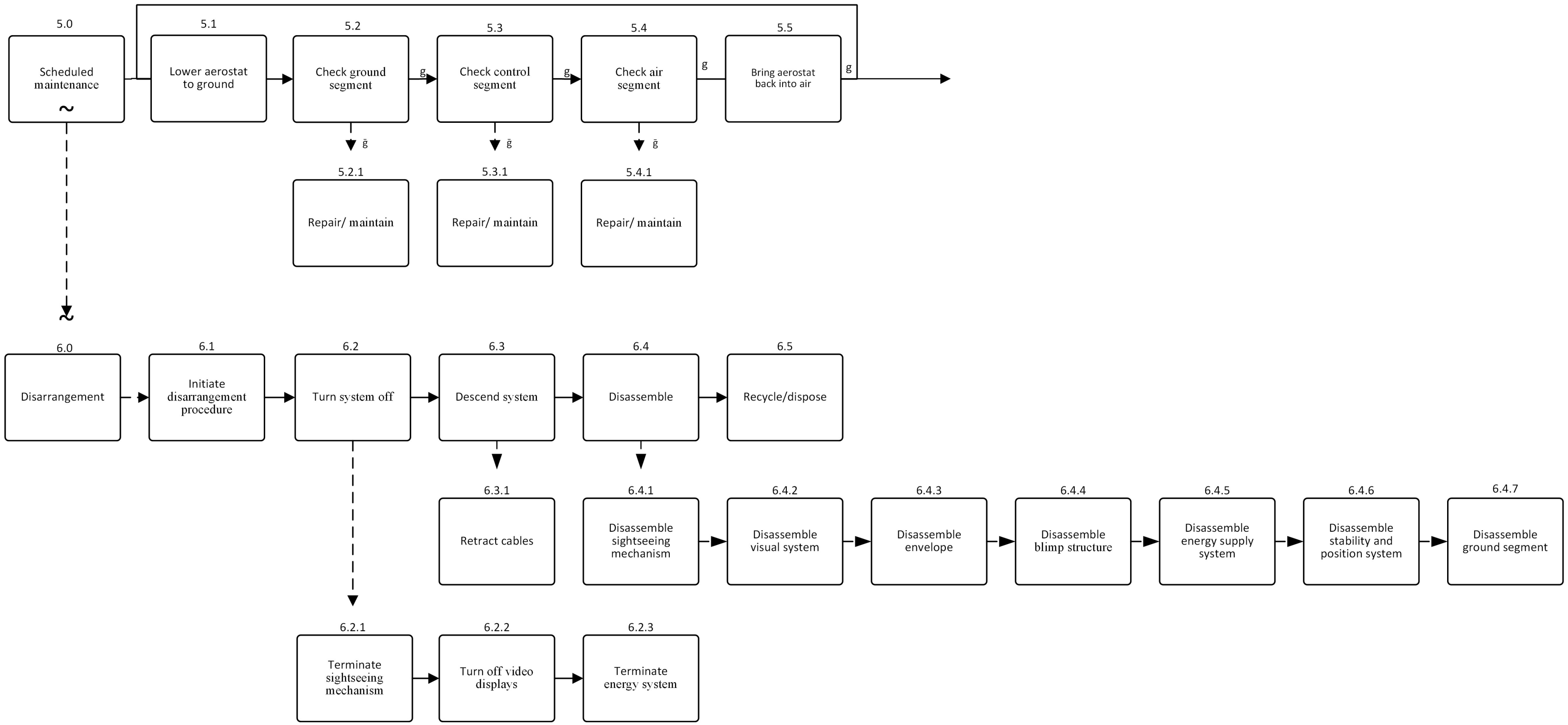


Figure 14.4: Functional flow diagram part 4

14.2. FUNCTIONAL BREAKDOWN STRUCTURE

A functional breakdown structure displays the functions that the system to be designed should be able to perform. These functions were defined during the development of the functional flow diagram in section 14.1. The functional breakdown structure can be found in figure 14.5.

In the functional flow diagram the functions are given is a chronological order. In the functional breakdown structure, the basic functions of the system are split up into 'sub-functions' of this basic function. The sequence is no longer chronological, the basic function consists of all the sub-functions added together. The breakdown structure is a so called AND-tree.

Of course, performing the mission is the main function during the lifetime of 'World's largest dirigible billboard'. Performing the mission can be split up into six basic functions, which are: provide transport, provide power, perform flight, provide video-display, provide sightseeing and provide safety mode.

Providing transport contains every function the system needs to have to make transportation of the billboard possible. This mainly includes the organized assembly and disassembly of the whole structure and everything that comes with that. When the structure has been disassembled, it can be transported easily. Providing power describes the system's function to provide the power the subsystems need to perform correctly. When the grid power enters the system, it should be distributed to all subsystems in either alternating current (AC) or direct current (DC). Section 14.5 elaborates on this topic. Performing flight is all about getting and keeping the dirigible in the air. Providing lift, control and stability are essential to this end. Providing video-display is about the advertizing function of the dirigible billboard. Properly working screens are of course essential to this. Providing and processing data and continuously providing power to the screens are vital parts of the function. Providing the sightseeing possibility consists of getting the customers inside and outside of the gondola and moving the gondola up and down. For this part maintenance plays an important role. Providing the safety mode comprises the ability to protect the system from harm. The two possible harmful situations are structural problems and environmental problems. If there are critical structural problems or environmental threats, the system should be able to switch to safety mode.

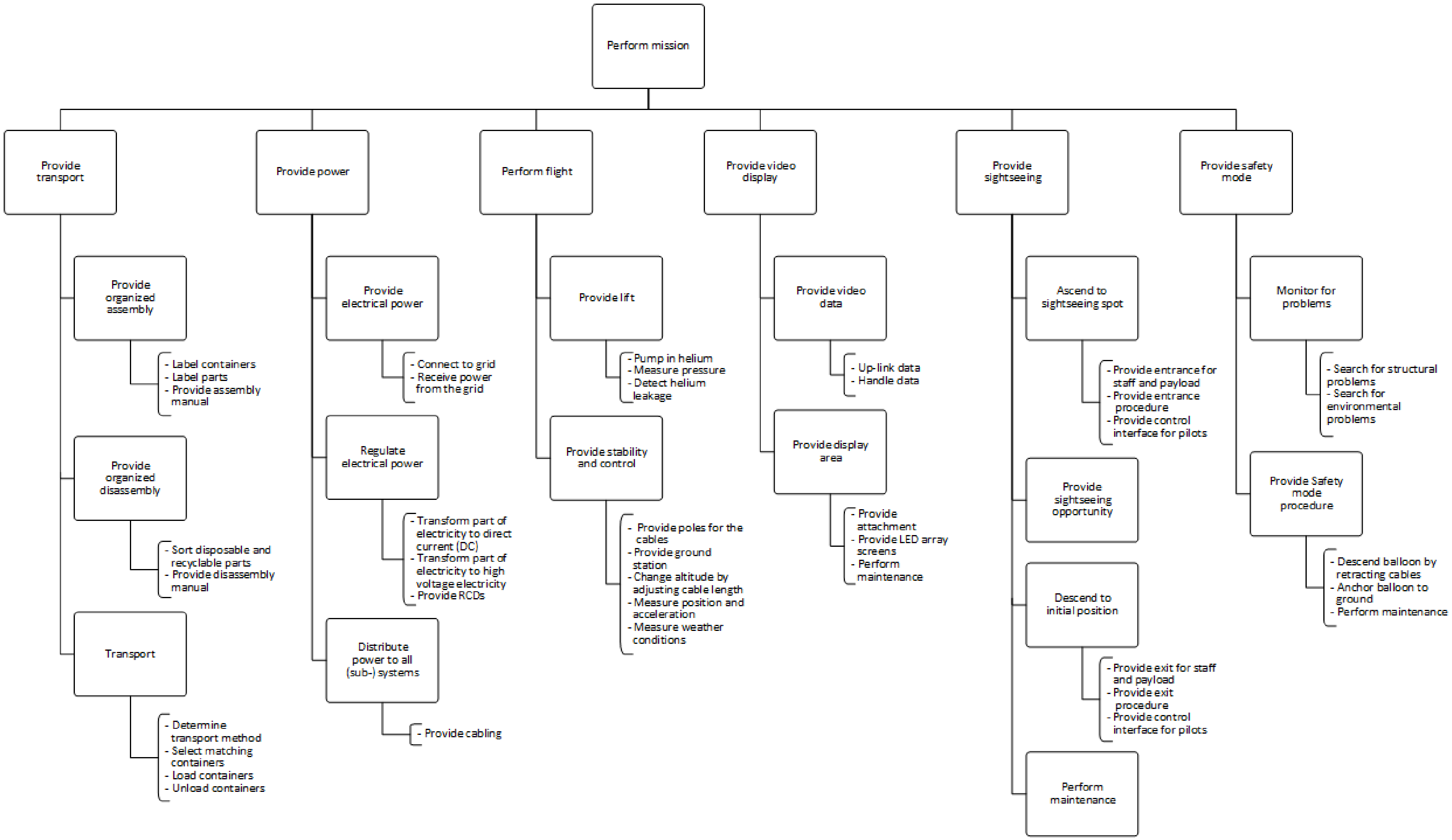


Figure 14.5: Functional breakdown structure

14.3. COMMUNICATION FLOW DIAGRAM

To understand how the system is controlled in the way described by the functional flow diagram, a communication flow diagram is made. A lot of measurements are taken on the aerostat as well as on the ground, to keep track of the status of the dirigible and the environmental conditions. This is important for controlling for example the altitude of the aerostat, if wind speeds rise above the determined limits. To give a clear overview of all measurements taken, combined with the subsystems that respond to those measurements, the communication flow diagram which is found in figure 14.6 is made. In other words, it shows how data flows through the system from input to output. Since the connection of inputs and outputs is not clearly defined in figure 14.6, because all signals come together in the main processor, a table was made to indicate what inputs are connected to what outputs, and vice versa. This table is found in table 14.1. In this section, the multiple inputs and outputs which can be found in figure 14.6 are explained in more detail in subsections 14.3.1 to 14.3.10.

The inputs in figure 14.6 are divided into four groups: environmental input, internal input from both the aerostat and the gondola, input from the gondola controller and input from the ground control center (GCC). For this last group, the exact input specifications are not given. This is due to the fact that the GCC controller can ask for any desired output (except the ones ending in the control center) and stating all of these would not make the picture clear. Explanation on these inputs can be found in subsection 14.3.3 to 14.3.6. In the processing part, the ground control has overriding power on the autonomous main and back-up computer. Explanation is found in subsections 14.3.1 and 14.3.2. The outputs are divided in four groups, which are found in subsections 14.3.7 to 14.3.10. The groups are the display related outputs, the aerostat outputs, the gondola outputs and the outputs in the control center.

14.3.1. GROUND CONTROL CENTER

In the control center, the main processor is controlled. The control center should be able to override automated processes at all times in case of a failure or accident. Staff should therefore be present in the control center.

14.3.2. MAIN PROCESSOR

The main processor is the heart of the data handling system. This computer will process all data coming from measurements from the dirigible, the gondola and the environment. It will process this data and send signals as output to systems on the aerostat, the gondola and the control center. The output signals for the control center are used as feedback. The systems on the aerostat and gondola will be discussed later.

14.3.3. INTERNAL MEASUREMENTS

Internal measurements are the measurements taken on the aerostat itself, as well as ground systems directly linked to the aerostat as the stability cable connection poles. This data will be processed and sent to the control center. The measurements performed are on the helium pressure, to check for leakages or overpressure; strain gauges for measuring loads on the structure; a screen check to make sure advertizing is working properly. Next to those measurements, there are measurements of aerostat position, acceleration and vibration, which are important for the stabilization of the aerostat. The cable tension and vibration are also measured. In the gondola, the temperature, vibrations and air quality are measured. Air quality consists of O_2, CO_2, CO and smog measurements.

14.3.4. GONDOLA CONTROLLER

The gondola controller is a staff member assigned to control the gondola. This person will be present in the gondola while transporting passengers to and from the sightseeing spot and indicates the desired gondola altitude and speed. Communication with the ground control center should be established at all times. The controller can also adjust the temperature in the gondola, since gondola temperatures can change during the day. For evenings, the controller can also adjust illumination in the gondola. Safety mode should be activated or deactivated by the controller when an accident happens or wind speeds get above the specified limits.

14.3.5. ENVIRONMENT

Environmental conditions are measured to give the ground control center a clear view on the operational circumstances of the dirigible. Among these measurements are temperature, wind speed, solar brightness, atmospheric pressure and a power supply check. The solar brightness is important, because the screen brightness needs to be adjusted such that visibility is assured. Solar brightness measurements will be taken on every side of the dirigible, as a different screens brightness can be applied for every screen, according the the position of the sun. Wind speed is very important for determining whether or not the dirigible should be lowered or enter safety mode, which is further explained in detail in the flight envelope in section 13.3.2. A power supply check is performed to make sure power is received from the grid.

14.3.6. GENERAL CONTROLLER

The general controller is the person controlling the system at the ground station. The controller is based in the ground control center, and is able to monitor all inputs and outputs on screens. Furthermore, the possibility of taking over all autonomous processes should be provided to the controller. Therefore, everything the gondola controller can change and control, can also be changed and controlled by the general controller.

14.3.7. AEROSTAT

The first set of outputs in the communication flow diagram are the systems on the aerostat. Helium pumps will be activated when the envelope is refilled with helium. Since helium losses are only 9 m^3 per day (as determined in section 8.5.1), refilling will not be performed every day, but during maintenance on the ground. The second system that is controlled is the cable winch system, which is used to change the altitude of the aerostat. This system is vital for safely operation, since lowering the aerostat is important for stability of the aerostat. Finally, the anti-collision lights can be turned on or off by the general controller.

14.3.8. GONDOLA

There are multiple systems in the gondola that are controlled. First, the airconditioning and ventilation system can be adjusted according to the number of passengers in the gondola, air temperature and the O_2 and CO_2 measurements. The gondola illumination can be turned on in the evenings. Furthermore, since the gondola controller should have a control desk or screen in the gondola, those screens should display feedback from other systems. The communication from ground to gondola is also an output in the gondola. Finally, the lifting mechanism to lift the gondola up and down is controlled.

14.3.9. DISPLAY

The display can be controlled in two ways. First, there should be content such as video or pictures to be displayed, which is provided by the control center. Secondly, the brightness can be changed according to the position of the sun.

14.3.10. CONTROL CENTER

In the ground control center, multiple systems act as output of the communication system. All data, inputs and outputs, should be logged in a processor logbook. All feedback from the systems in other parts of the dirigible should be displayed in the ground control center, to enable the controller to respond to the data. It should also display errors or warnings, for example when wind speeds reach a certain level or when the gondola lifting mechanism does not work. Furthermore, in case of power loss, a back up power supply should be activated. This back up consists of a back up generator, which will have to be started to provide power. Until the generator is running, a back up battery will provide the power necessary.

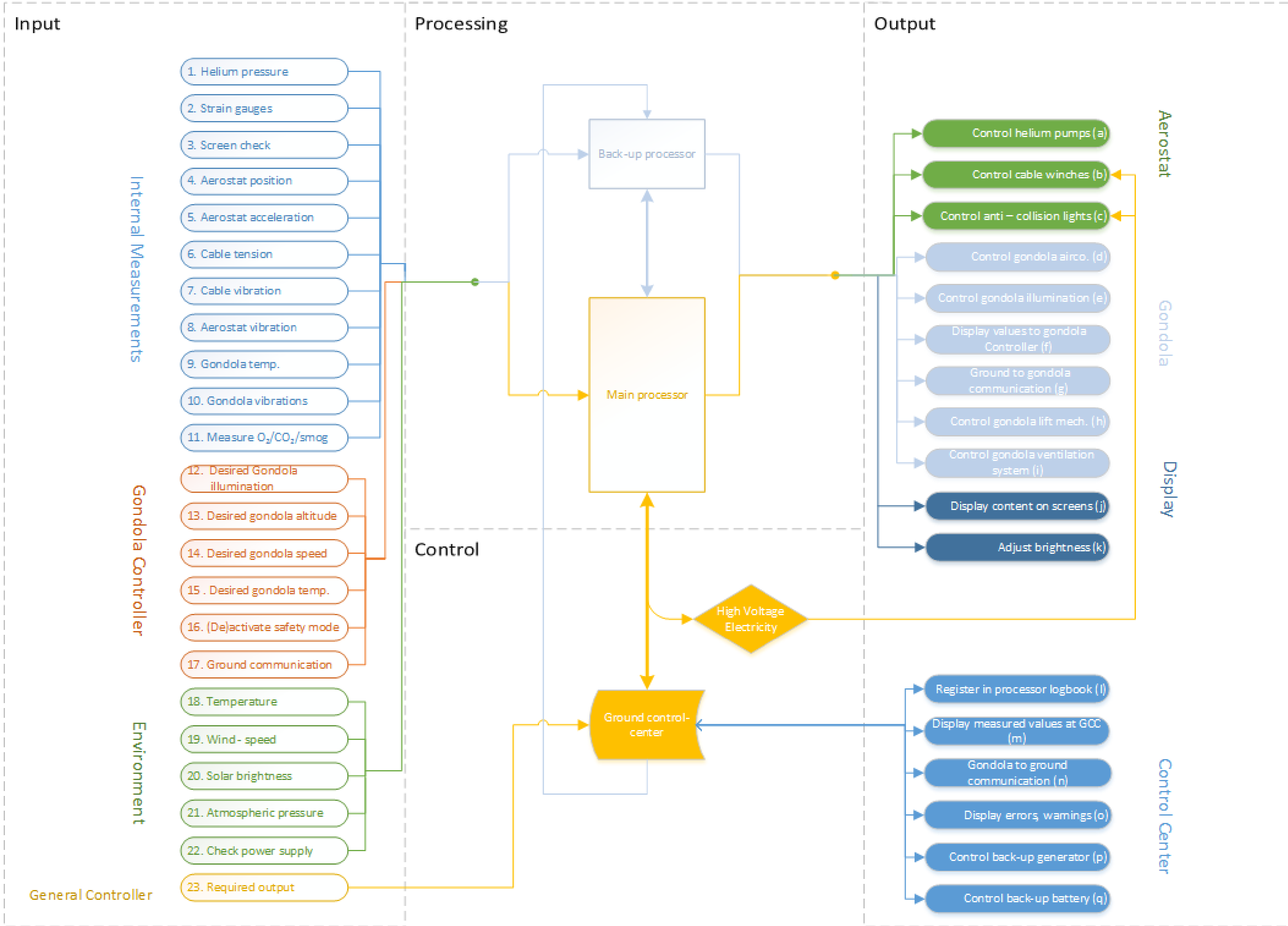


Figure 14.6: Communication flow diagram

Table 14.1: Communication flow diagram dependency table

	Inputs		Output		Outputs per input		Inputs per output
1	Helium pressure	a	Control helium pumps	1	b, l, m, o	a	23
2	Strain gauges	b	Control cable winch	2	b, l, m, o	b	1, 2, 4, 5, 6, 7, 8, 19, 23
3	Screen check	c	Control anti - collision lights	3	l, m, o	c	23
4	Aerostat position	d	Contr. gon. airconditioning	4	b, l, m, o	d	9, 15, 18, 23
5	Aerostat acceleration	e	Contr. gon. illumination	5	b, l, m, o	e	12, 23
6	Cable tension	f	Display values to gon. controller	6	b, l, m, o	f	9-16, 19, 23
7	Cable vibration	g	Ground-gondola communication	7	b, l, m, o	g	11, 23
8	Aerostat vibration	h	Contr. gon. lift. mechanism	8	b, l, m, o	h	10, 13, 14, 16, 19, 23
9	Gondola temperature	i	Gondola ventilation system	9	d, f, l, m, o	i	11, 23
10	Gondola vibrations	j	Display content on screens	10	f, h, l, m, o	j	23
11	Measure O2/CO2/smog	k	Adjust brightness	11	f, i, l, m, o	k	20, 23
12	Desired gondola illumination	l	Register in processor logbook	12	e, f, l, m, o	l	1-16, 18-22
13	Desired gondola altitude	m	Display measured values at GCC	13	f, h, l, m, o	m	1-16, 18-22
14	Desired gondola speed	n	Gondola-ground communication	14	f, h, l, m, o	n	17
15	Desired gondola temparature	o	Display errors, warnings	15	d, f, l, m, o	o	1-16, 18-22
16	(De)activate safety mode	p	Control back-up generator	16	f, h, l, m, o	p	22, 23
17	Gondola-ground communication	q	Control back-up battery	17	n	q	22, 23
18	Temperature			18	d, l, m, o		
19	Wind speed			19	b, f, h, l, m, o		
20	Solar brightness			20	k, l, m, o		
21	Atmospheric pressure			21	l, m, o		
22	Check power supply			22	l, m, o, p, q		
23	Required output by controller			23	a-k, p, q		

14.4. DATA HANDLING DIAGRAM

In table 14.1, an overview is given of the several inputs of the communication flow diagram and the outputs of this diagram. This diagram represents the flow of data through the system and the way this data is handled. Since a particular output is only dependent on some of the inputs, it is useful to know which output depends on which input, and vice versa. This dependencies can be found in the third and fourth columnin table 14.1. The inputs have been given a number and the outputs have been given a character. In the table, these numbers and characters are combined to represent the relation between a specific set of input(s) and output(s). Table 14.1 can be seen as a zoom of the main computer found in figure 14.6. Within this computer, every input is connected to an output, or multiple outputs.

Another important design aspect to keep in mind are the type of cables that will be used for data transport. For data transport, there is a choice between cables that send data in one or two directions, cables that only send data or cables that also receive feedback. For every input system, except for number 17, the data is sent only towards the GCC, since these devices do not need any control and only send their data. Input system 17 is the gondola to ground communication and there it is useful to have a feedback signal, since the signal will need to flow two ways to make communication possible. If there is no feedback signal, the alarms go off that the system is down. This also happens when an input signal stops.

As said before, the data will be transported via cabling. The video-data for the screens could for example also be sent wireless from the ground station to the screens. However, a wireless connection is harder to secure and using cables was therefore considered a better option. A cable transporting the data will thus run from the ground to the aerostat. This cable will be guided by one of the gondola cables.

14.5. ELECTRICAL BLOCK DIAGRAM

Another important aspect are the electricity cables. All systems work on a different voltage and therefore have a transformator build within. It is however important to deliver the right voltage to the transformator. Also some systems are continuously receiving electricity, while other systems need active control. In this design, all input systems are passively controlled with a continuous amount of electricity. For the output systems, this only holds for systems c, f, g, i, j, l, m, n, and o. The systems a, b, d, e, h and k are actively controlled by only sending electricity when needed. There are two systems that do not need energy, namely p and q, the backup generator and the backup battery. These systems only need a data signal that makes starts them when the grid fails. Because the cable winches and the gondola lifting mechanism need a lot of power, it is decided that high voltage electricity of 400 V is send to the cable winches and the systems on aerostat. Be aware that the electric cabling is not shown in the communication flow diagram of figure 14.6, since this only represents the data flow. To give a clear view on how the electric cabling should look like in the final design, figure 14.7 was produced to indicate what sort of cables and electrical supply systems would be needed.

In figure 14.7, power is received from the grid (220 V). The control station distributes electricity at the grid voltage of 220 V to the control center and to the transformer. The transformer enlarges the voltage to 400 V and sends it to the cable winches and the aerostat systems. When the grid power is lost, both a backup generator and backup batteries can be used to provide sufficient power until grid power supply is restored.

Since data and electric cables are very vulnerable to environmental hazards such as water and lightning, the cables should be designed such that protection against these hazards is optimal. In the dirigible itself, cables are attached to the internal structure, since the structure can guide the cables to any part of the aerostat. For the connection from the ground to the aerostat, one high voltage cable is used to transport electricity to the main receiver on the aerostat. The cable will be guided along one of the connection cables, to make sure it is stable and is not obstructing for the gondola. Since a data cable also runs from ground to aerostat, the electricity cable could be combined with the data cable, all running via a gondola attachment cable.

14.6. HARDWARE BLOCK DIAGRAM

To have a clear picture of how all subsystems within the total system interact, the hardware block diagram of figure 14.8 was created. It can be seen that all systems finally come together in the aerostat, which is the center of the total system. The arrows coming from the power supply indicate energy transport, while the control center arrows are bi-directional, both for sending control data as receiving input from sensors. The arrow from

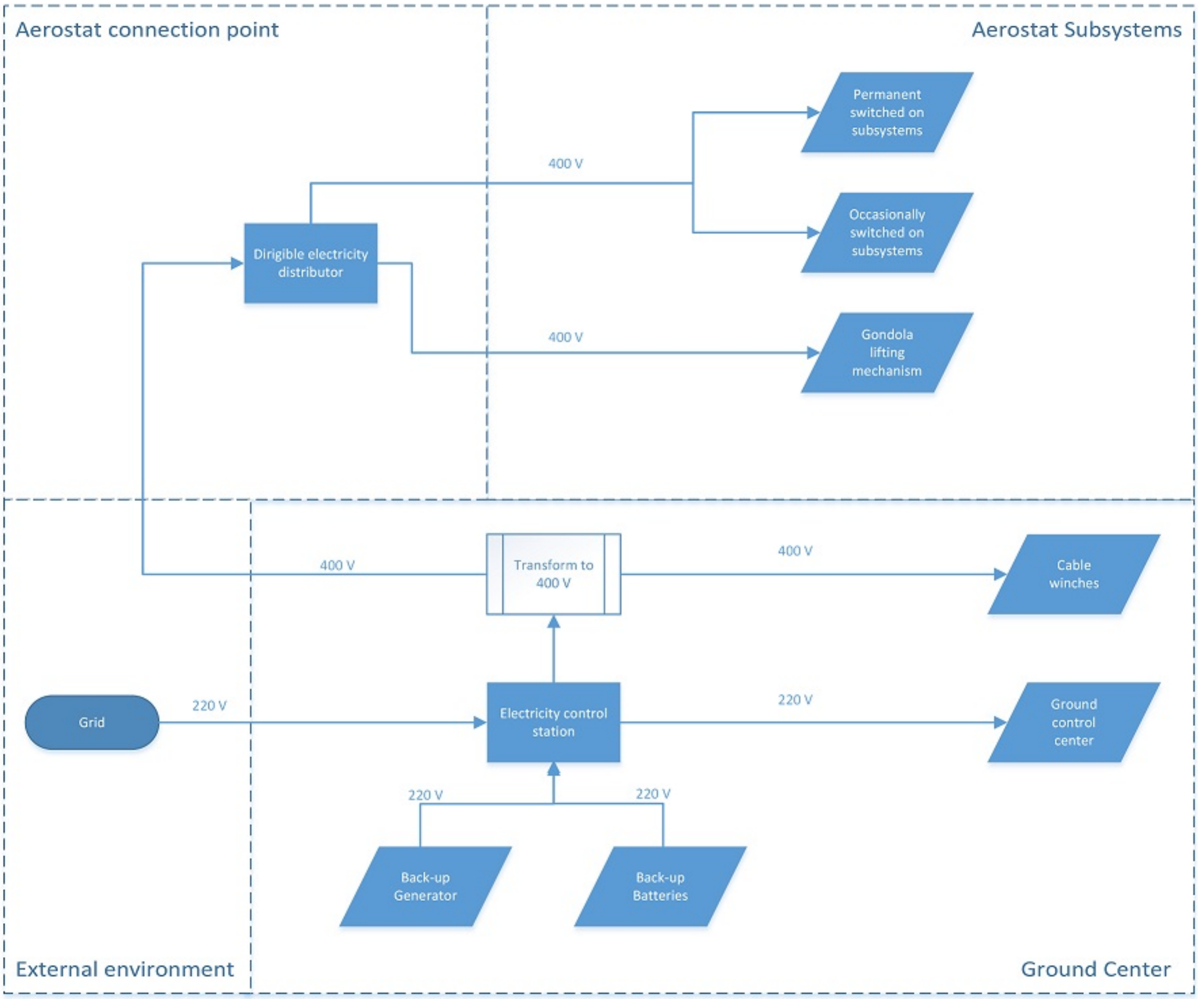


Figure 14.7: Electrical block diagram

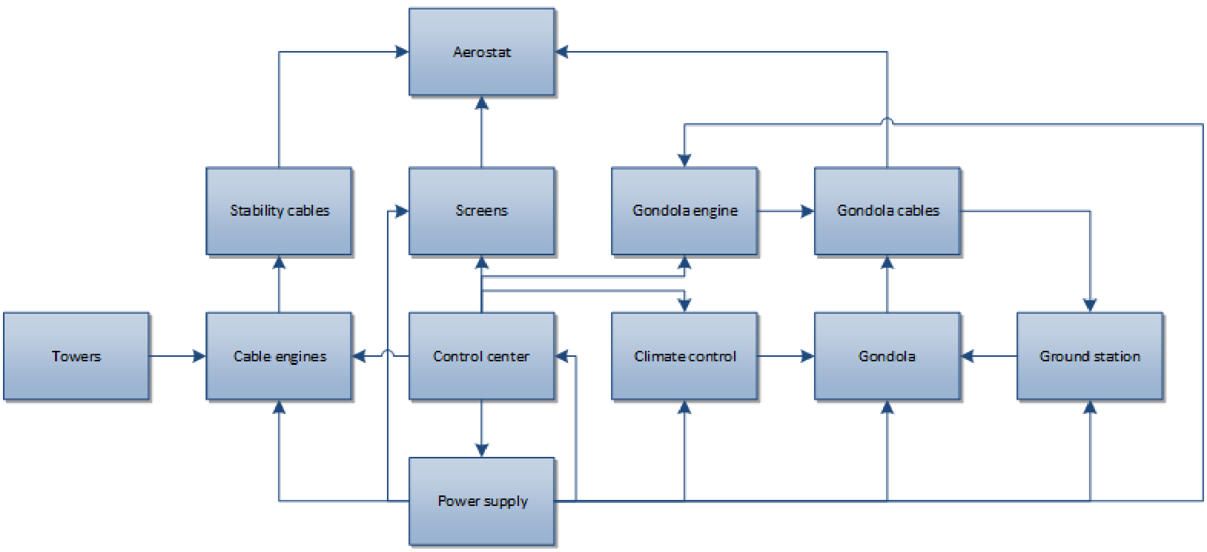


Figure 14.8: Hardware block diagram

climate control to the gondola represents cooled or heated air, depending on the time of day. All other arrows represent (control) forces, either from gravity, wind or engines.

14.7. INTERNAL ENVELOPE REFILL

As discussed in section 8.5, the internal envelope loses about 9 m^3 of helium per day. As a consequence, the balloon should be refilled on a regular basis. Since the loss is small, it will not be necessary to refill every day. Statistically, wind speeds will force the aerostat to be lowered to the ground at least once a month. Refilling during this safety mode will be sufficient, since helium losses per month are to small to be of great influence to the stability of the aerostat.

Furthermore, the balloon will be regularly maintained according to the functional flow diagram 14.2. This regular maintenance is a convenient moment in time to refill the balloon as well. The aerostat will be lowered to the ground, after which maintenance takes place. The helium containing envelope can be connected to helium pumps through a valve [6], which can refill the balloon to the desired quantity. The helium pumps are connected to a helium storage, to ensure helium is present in case emergency refilling is needed. The valve will already be present in the internal envelope, since it is also used for filling the envelope with helium when the aerostat is assembled.

14.8. PRELIMINARY CABLE ENGINE SOFTWARE DESIGN

This section describes a preliminary design for the cable engine software. The Unified Modeling Language (UML) class diagram in figure 14.9 shows this preliminary design. The software system uses the observer design pattern. Every cable will be equipped with a strain gauge. This gauge will constantly measure the strain in that specific cable, with which the tension can be determined. When the tension in the cable gets above or below certain values, the method notifyObservers( ) will be called, alerting the cable engine. Depending on the value of the tension, the method update( ) of the cable engine will retract or extend the cable slightly. When this has been done, the strain gauge checks the strain value again, repeating the process in case of too high or too low tension.

The setMode( ) method of the strain gauge enables switching between different operation modes. These modes are normal operation, lowering to a certain height and safety mode. When the aerostat is being lowered, the tension values in the cables will be different than those during normal operation. The boundaries on the method notifyObservers( ) will have to be adjusted in this case, to allow the aerostat to be lowered.

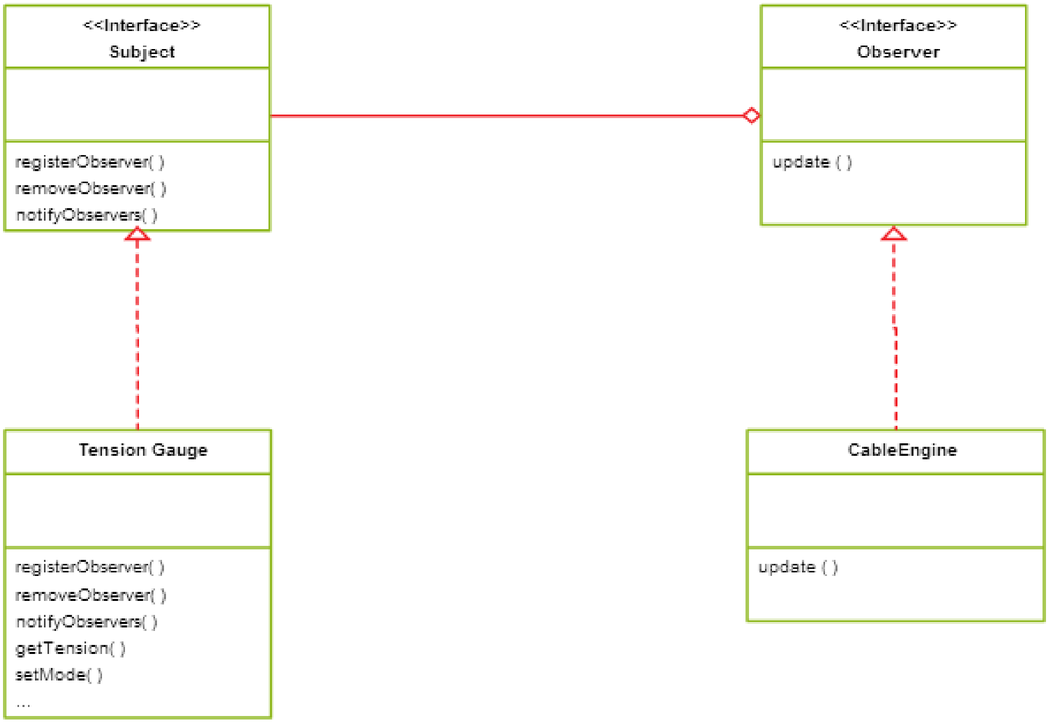


Figure 14.9: Preliminary software design

15

PERFORMANCE ANALYSIS

In this chapter multiple criteria are discussed to measure the performance of the dirigible. The criteria are already stated in the mid-term report [2]. Before analyzing the final design, the criteria are reviewed on their relevance and new criteria are thought of during the design phase. Since this dirigible is a new concept, it is not clearly stated what parameters indicate a good performance. Therefore, the Diamond of Dubai group comes up with parameters specifically of importance to the design of the dirigible, which is discussed and clarified in this chapter.

In table 15.1 all performance characteristics are stated, along with their values. Following, a short description for each characteristic is given in section 15.1 till 15.5.

Table 15.1: Performance characteristic numbers

Performance characteristic	**Value**	**Unit**
Screen weight/MTOW	0.13	[-]
Passenger weight/MTOW	0.085	[-]
Screen size/OEW	3.15	[m^2/kN]
Lift by helium/mass entire structure	2.32	[-]
Lift/MTOW	1.40	[-]
C_L (at $\alpha = 0$)	0.16	[-]
C_D (at $\alpha = 0$)	0.84	[-]

15.1. PAYLOAD WEIGHT/TOTAL WEIGHT

It was important to keep track of the (payload weight/total weight) ratio during the design process. This ratio was maximized, since the extra weight that is needed to carry the payload should be as low as possible in this case. The payload generates the income for the dirigible project, so minimizing the cost of carrying the payload will maximize the profit. Both the weight of the payload, defined as the passengers and the screens, (15000 kg) and the total weight (71000 kg) were calculated during the design. The calculated ratio can be looked up in table 15.1.

15.2. LIFT/MTOW

The performance (lift over maximum take-off weight) ratio is important for the stability of the aerostat. The higher the number, the more 'efficient' lift is generated, basically, the higher the number, the less structural mass is required for the same amount of lift. As can be seen in table 15.1, the Lift over MTOW is 1.40 for the chosen design. This means that the aerostat generates 40% more lift than required, which is required for the stability as can be seen in chapter 9.

15.3. LIFT AND DRAG COEFFICIENTS

In chapter 9, all aerodynamic properties of the aerostat have been examined. Figure 13.1 shows the lift and drag coefficient of the aerostat at different angles of attack. The lift and drag coefficients of the aerostat are important, because they represent the aerodynamic forces that act on the system and therefore have an influence on the stability. The stability influences the flight envelope, which on its turn is the main input parameter of the mission envelope and up-time as described in section 15.4.

15.4. MISSION ENVELOPE & UP-TIME

As described in section 9.6.2, the aerostat needs to be brought down at wind speeds higher than 8.5 m/s at an altitude of 280 m, which is at 5 m/s on the ground. In figure 15.1 it can be found that 5 m/s is the daily average ground wind speed in Dubai.

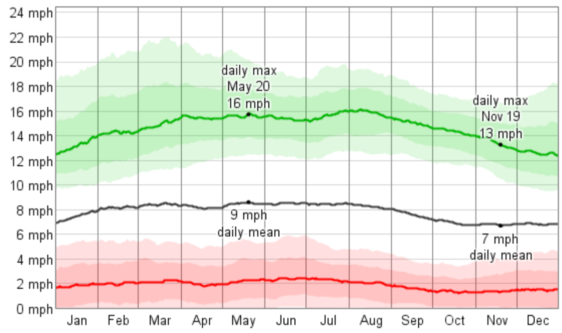


Figure 15.1: Average wind speed in Dubai in a year

An example of the distribution of the daily average wind speed can be found in figure 15.2.

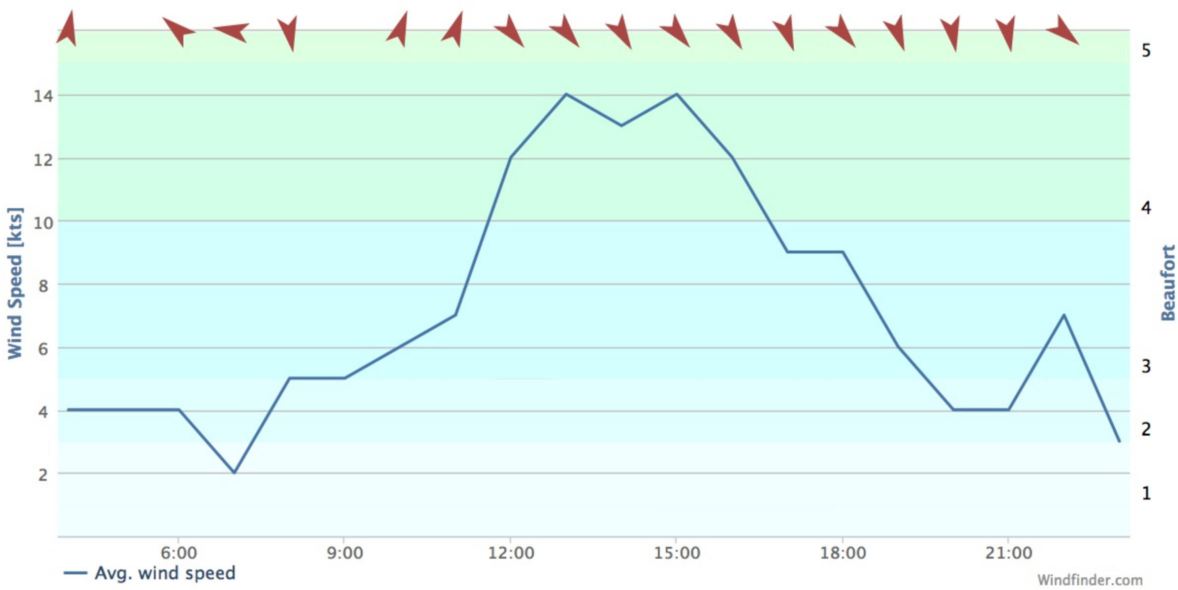


Figure 15.2: Example of daily wind speed (3 June 2014) [49]

In figure 15.2, it can be found that on almost 75 % of a random day, the wind speed remains below 5 m/s. This means that the "Diamond of Dubai" can be in normal operation at optimal height most of the day. However, as the temperature rises between 12:00 and 16:30, the wind speed increases as well. This means that the aerostat needs to be lowered to be stable in the air. The total up-time, in hours per year (h/y), is an indication of the total up-time the dirigible will have per year. The specific design can withstand wind speeds up to a certain level, after which it has to be lowered to remain stable in air. For even higher wind speeds, the system needs to be taken out of operation. The total up-time affects the amount of time advertisements can be displayed on the screens. If more time is available, the revenue of the advertisements will increase.

In figure 13.2 in section 13.3.2, a flight envelope is constructed. In this flight envelope, the maximum operational height for different ground wind speeds, varying from 0 - 12 m/s, is given. For ground wind speeds higher than 12 m/s, the system should get into safety mode. Using the flight envelope graph and the daily wind speed distribution in figure 15.2, figure 15.3 is made. In this figure, the height of the dirigible is plotted against the time for 3 June 2014.

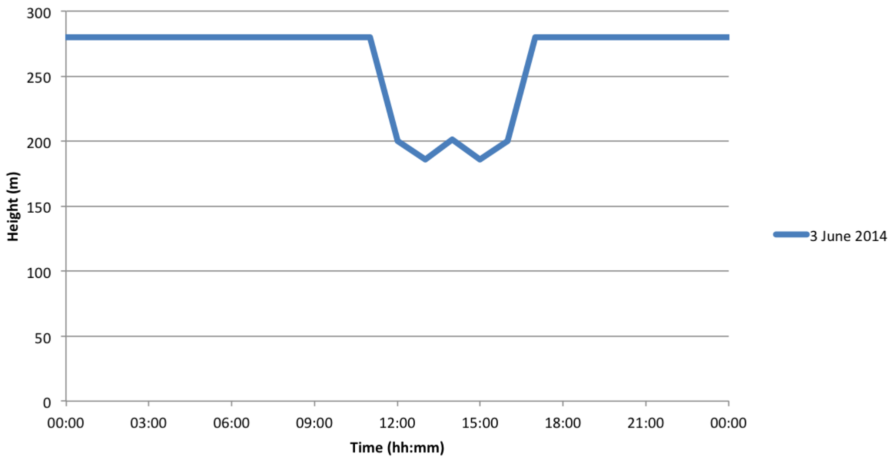


Figure 15.3: Maximum dirigible height over time on 3 June 2014

June 3^{rd} is a typical operational day for the Diamond of Dubai. Between 11:00 and 17:00, the dirigible (with operational gondola) needs to be lowered, but the rest of the day regular operation is possible. 3 June 2014 is only one day, so another height to time plot is produced for the wind data of one entire week in June (10 - 6 June 2014) in figure 15.4.

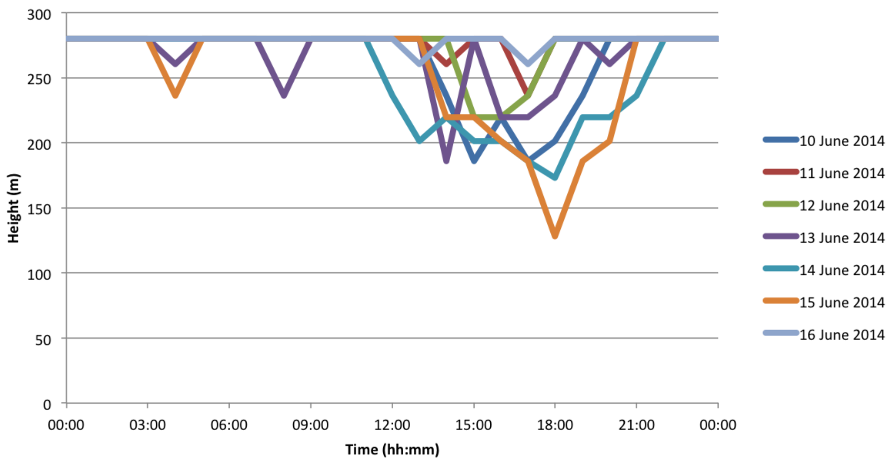


Figure 15.4: Maximum dirigible height over time on 10 - 16 June 2014

In the week in figure 15.4, there are some good days on which the balloon almost does not need to be lowered (11 and 16 June) and some bad days (14 and 15 June) where a lot of lowering is required. It should be noted that June is one of the months with the strongest wind and that these are the maximum constraints; operation without gondola would result in more favourable graph in terms of balloon height as can be seen is 13.2

Three estimations can be made for the total up-time per year. The first estimation is the amount of time per year that the dirigible is able to operate at original design operational height in regular operation, that is with gondola. This value has been filled out in table 15.1, because it is the desired operation. The second estimation is the same as the first operation, but then without the gondola connected. The final estimation is the amount of time per year that the dirigible is able to stay in the air, either lowered or on original operational height. For this estimation, no distinction can be made for operation with or without gondola, because in both cases the maximum wind speed for operation is 12 m/s. However, for this report, this estimation can not be done because of a lack of information on environmental conditions. In table 15.2, the estimations can be found. It should be noted that these are first order estimations. These estimations have been made using wind data of one week in June, which is one of the months with the heaviest winds as mentioned before. Once the dirigible is deployed in Dubai, the practical experience should supply a more accurate up-time determination.

Table 15.2: Up-time estimations

	Max ground wind velocity (m/s)	Up-time (hr/year)	Up-time (%)
Estimation 1	5	6750	77.1
Estimation 2	5.8	7500	85.6
Estimation 3	12	Post-DSE	Post-DSE

15.5. VISIBILITY AREA

Visibility of the dirigible is one of the most important design drivers for United Balloon. For the screens to be visible from 4 km distance, a screen size of 18x32 m was selected. To give a clear picture on from what distances these screens would be visible and readable, a visualization of the visibility area was created in chapter 6. In that chapter, this visualization was created for multiple screens sizes and the area for the chosen screen size is found in figure 6.2. With the use of this visibility area, the customer can easily check whether or not the design performs properly on this design requirement.

16
RAMS ANALYSIS

This chapter covers the RAMS (reliability, availability, maintainability and safety) analysis of the aerostat. In section 16.3, the critical functions for safe operations are listed. In section 16.1, the expected reliability and availability of the system are discussed. Section 16.2 describes both the planned and unplanned maintenance. Finally, in section 16.3.1 the safety critical functions of the system will be addressed.

16.1. RELIABILITY AND AVAILABILITY

The study of reliability is based on an analysis of all systems that could fail. As, for example, the internal structure, the envelope, all attachment cables, the screen attachment and the gondola structure have been designed with corresponding safety factors, it is expected that these components are reliable. When proper maintenance is done on these parts, failure should not occur. Systems on board of the gondola, the engine that moves the gondola and the screens are for example considered to be reliable, because these are proven working designs in operation. With proper maintenance, as described in section 16.2, failure of these systems should not occur often. Other systems on the aerostat fall in either of these categories and should thus not fail (often).

The study of availability of the system is based on the flight envelope shown in figure 13.2 and is further worked out in the performance analysis in chapter 15. The system is available to work to the best of its capabilities up until a ground speed of about 5 m/s, which corresponds to 8.5 m/s in flight. When the wind is lower than this speed, the performance of the system is optimal and both the aerostat and the gondola can maintain their standard altitude. This condition occurs for 77.1% of the yearly operational time. With an increase in the strength of the wind, the aerostat should be gradually lowered to ensure stability and visibility of the screens. Finally, when the wind speed approaches 12 m/s on the ground, the system should be prepared to enter safety mode, to account for the protection of both the system and the passengers.

The concept of redundancy is important in case of a large structure. In fact, lots of factors have to be controlled simultaneously and if one of the components fails or needs maintenance, the system should be able to still function at least long enough to ensure a safe recovery. This kind of philosophy usually means a slightly over designed system in order to account for unexpected loads and/or subsystem failures. One of these safety measures applied to the system is related to the ground segment. Backup computers have been introduced among the instrumentation to control the screens and all other operations related to the blimp and to the sightseeing mechanism in case of a control segment loss. The ground and control segment has also been provided with a power backup system, able to generate emergency power. The next redundancy measure applies to the poles with which the aerostat is kept in place and stable. In fact, six poles have been included in the design, to make sure that every possible wind direction is covered. Furthermore, every cable carries part of the tension, but are all designed to withstand the total maximum load. The cables at the top of the blimp will prevent the aerostat from top view rotation of the aerostat. Even if the center of pressure is shifting above what is considered as the maximum height, the cables would be able to counteract the moment created by this change (see section 9.4.1). Extra cables have also been added to the bottom of the lower pyramid of the dirigible, so that possible side view rotation of the aerostat can be avoided. Another redundancy measure taken relates to the envelope. To make sure the helium does not escape into the atmosphere, it will be protected by both an internal and an external envelope. The latter has also been designed to be life safe as an extra safety measure. Finally, the structure that constitutes the internal skeleton of the aerostat is made of more beams than structurally needed. For example on each side there are two cross members which are only included for redundancy, since one would be sufficient to withstand the load. This way the structure is fail safe.

16.2. MAINTAINABILITY

For scheduled maintenance, the aerostat has to be lowered to the ground, in order for mechanics to access the systems on the air segment. Scheduled maintenance is performed on fixed dates and these do not necessarily coincide with occasions on which the system has to enter safety mode. All systems that need scheduled maintenance are listed below:

- Sightseeing mechanism
  - Engine
  - Airconditioning
  - Electrical systems
  - Structure
  - Cables
  - Other tourist appliances
- Stability system
  - Poles
  - Retraction system
  - Cables
  - Cable attachment points
- Aerostat
  - Structural inspection
  - Envelope inspection
- Visualization system
  - Screens
  - Screen attachment
  - Electrical wiring
- Envelope
- Backup power unit
- Software system

The only unscheduled maintenance that will be performed is refilling of the aerostat with helium. This will be done whenever there is a possibility since the daily leakage is small. For example when the aerostat is down for regular maintenance or has to enter safety mode.

16.3. SAFETY

Safety critical functions are introduced into a system to prevent or stop the development of an accident. Safety critical functions may range from simple physical barriers to complex systems including software. Accidents can be of technical nature, but often administrative controls and human actions are included. [57]. This section covers all safety critical functions of the aerostat. Section 16.3.1 covers safety factors. In section 16.3.2, the envelope will be discussed and section 16.3.3 discusses the safety mode. Finally, section 16.3.4 covers the other safety margins.

16.3.1. SAFETY FACTORS

An important means of incorporating safety critical functions in the aerospace industry is the use of safety factors. Safety factors will be used in most components of the aerostat. Table 16.1 lists the safety factors that have been used in the design of the aerostat.

Table 16.1: Safety factors used in the final design process [4]

	Safety factor
Envelope	5.0
Tethering cables	3.5
Structure	1.5
Lifting cable gondola	12.0
Stability cables gondola	12.0
Support structure screens	2.0
Other	1.5

16.3.2. ENVELOPE

The envelope is a vital part of the aerostat, as it holds the lifting gas. A broken envelope results in a crash and cause a disaster. A good envelope design is therefore of importance. The decision has been made to use two envelopes, an inner and an outer one. This ensures that lift will be partially preserved in case of a leak. When a leak occurs, the aerostat has to be lowered and repaired as soon as possible. The inner envelope material has rip-stop capabilities, ensuring that a small hole in this envelope does not cause the entire envelope to rip open. Even without a hole inside the inner envelope, helium will slowly leak out. In order to reduce this leakage, an extra coating will be applied to the inner envelope. The material of the outer envelope is eleven times stronger than that of the inner envelope, because this material needs to withstand the harsh environmental conditions in Dubai.

16.3.3. SAFETY MODE

As the wind speed during sandstorms exceeds the operational limits, the aerostat will be lowered to the ground during a sandstorm. The description of the entire safety mode can be found in chapter 10. Taking the aerostat out of operation at high wind speeds ensures a safe environment during extreme environmental conditions.

16.3.4. OTHER SAFETY MARGINS

When performing the CFD analysis, a safety margin of 10% was used for the calculation of the drag coefficients. Furthermore, the stability department designed the cables holding the aerostat in place so that they would be able to withstand the highest possible force occurring in safety mode. Both these measures make the system over designed in case the aerostat were to experience more aerodynamic drag than expected. Another extra safety margin that has been used is a passenger weight of 100 kg for the gondola passengers, whilst the minimum required design passenger weight is 77 kg due to regulations [4].

17
SENSITIVITY ANALYSIS

The sensitivity analysis is a study on how the system performs if certain major parameters of the design are modified. The behaviour and dimensions of the system needed to fulfill the same requirements change when important parameters are affected. The variables examined are divided in three sections. In section 17.1 the influence of the number of passengers in the gondola on the maximum take-off weight and the total volume is treated. Next, in section 17.2, the influence of the size of the screens to display the advertisements on the same parameters is covered. Finally, the concequences of changing the configuration of the cables used to stabilize the aerostat and changing the size of the ground area available is discussed in section 17.3.

17.1. NUMBER OF PASSENGERS

In this section, it is investigated what the influence of the amount of passengers in the gondola would be on the total required volume and the maximum take-off weight (MTOW) of the entire aerostat. This research is done in order to provide the client with an idea of how these parameters could interact. As can be seen in figure 17.1, the interconnection is quasi-linear with a R^2 value of 0.9994. To draw this graph, some assumptions are made. In fact, the only factors changing when increasing or decreasing the number of passengers are considered to be the mass of the internal structure and the mass of the gondola. So the extra weight of the envelopes and the cables are neglected. As a result of those assumptions, the graph of the real life case would either be steeper or have a more quadratic shape. Nonetheless, this graph is a good approximation. An important issue to consider is that this trend line is only to visualize the weight increase and not the absolute values. This is due to the fact that for this graph the required 30 % extra lift was not taken into account. This will only influence the height of the graph but not the shape and thus also not the relation.

17.2. SIZE OF THE SCREENS

For the influence of the screen mass on the MTOW and volume, the same reasoning as in section 17.1 applies. The value for R^2 is now 0.9985. In this case, the mass of the internal structure and the mass of the screens, including the related electronics are the changing factors when increasing or decreasing the mass of the screens. As in section 17.1, the weight fluctuation of the envelopes and of the cables is neglected when compared to the weight of the other components. The graph can be seen in figure 17.2.

17.3. CABLE CONFIGURATION AND GROUND AREA

As described in chapter 9, the number of cables used and the angle at which they are inclined influence the stability of the blimp. To guarantee top - and side view rotation, the minimum amount of connection points on the dirigible is six, and the minimum amount of cables connected to the ground is twelve. When this amount of cables is reduced, rotational stability can not be fully guaranteed. If the lower secondary cables are removed, side view stability is not ensured, while reducing the amount of primary - or upper secondary cables results in no guarantee of top view stabilization.

The angle of the cables with respect to the ground plays an important role in the displacement. Depending on the angle, a different amount of lift is required to guarantee stability. A large angle of the cables with respect to

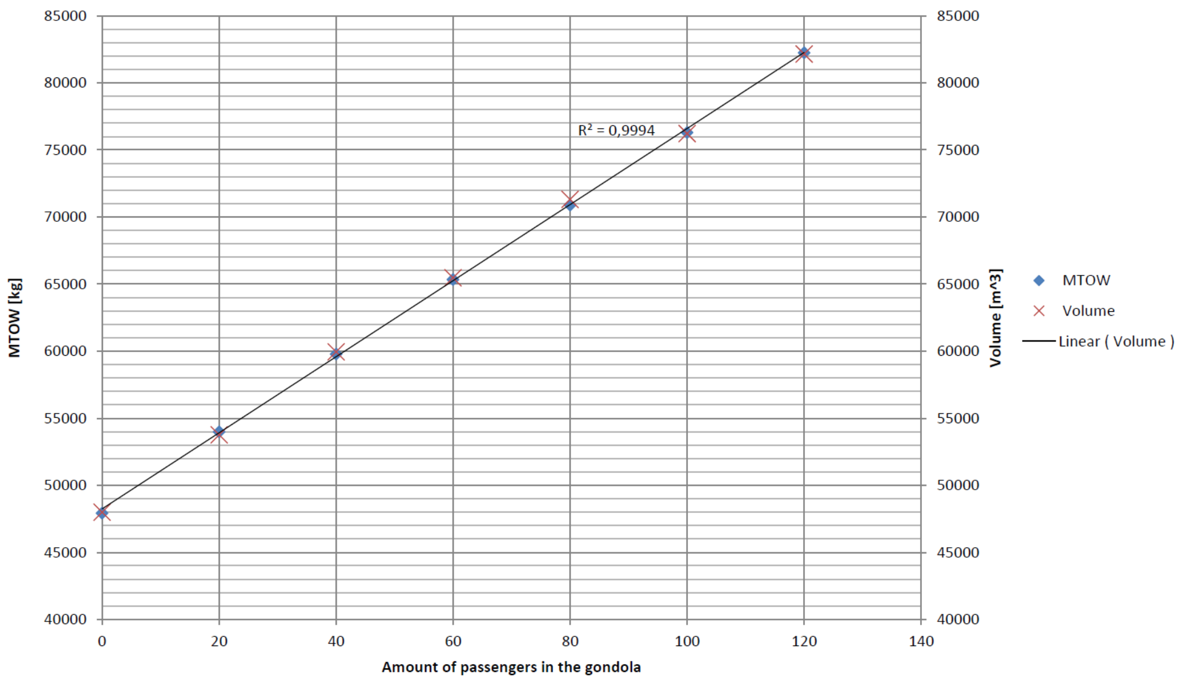


Figure 17.1: The influence of the amount of passengers on the MTOW and the total volume

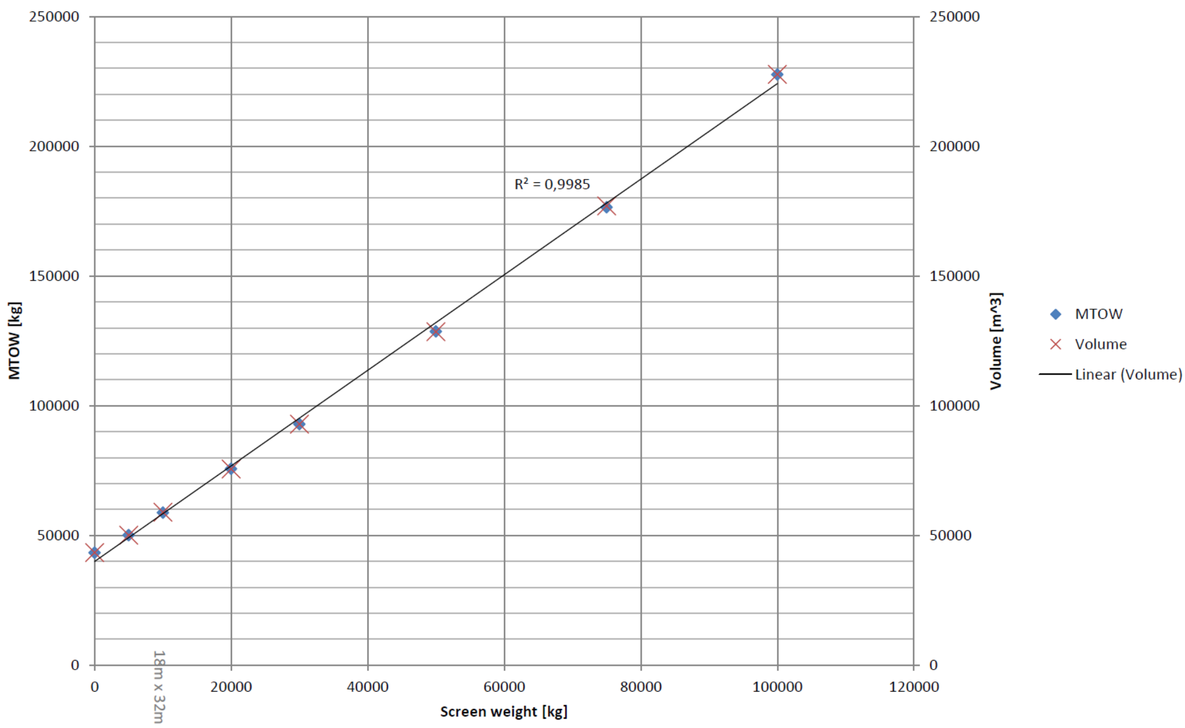


Figure 17.2: The influence of the screen mass on the MTOW and the total volume

the ground reduces the ground space. However, a large angle of the cables with respect to the ground results in displacement with low wind speed. If the cable configuration is changed by modifying the angle of the cables, the only way to prevent displacement would be to increase the lift force by an amount large enough. This will have the consequence that the effects of the drag on the resultant force on the dirigible are negligible. In table 17.1, two different cable configurations are considered, both under strong wind condition.

Table 17.1: Aerodynamic characteristics for two cable configurations

	V ground [m/s]	V air [m/s]	Drag [kN]	Angle 1 [°]	Angle 2 [°]	Lift [kN]	n. of cables
Config. 1	5	8.5	177	59.1	69.4	297	12
Config. 2	5	8.5	177	85	-	2100	1

Configuration 1 represents the one selected from the aerodynamics investigation, as shown in chapter 9. This one includes twelve cables and six connection points to the ground. This configuration is considered stable up to a ground wind speed of 12 m/s. High wind speeds, that cause a drag force which would cause displacement of the dirigible, are compensated for by lowering the dirigible, as described in section 15.4. In table 17.1 it can be found that a ground wind speed of 15 m/s results in a required cable angle for the primary cables of 59.1 ° and 69.4 ° for the secondary cables.

Configuration 2 is analyzed after consulting the client, who had the desire of using only one cable. This one cable, perpendicular to the ground when there is no wind, is there only to prevent the dirigible from floating away. The drag force due to wind is the same as in configuration 1. This configuration is considered stable up to an angle change of 5 °. Larger angle changes result in a too large displacement. To ensure this stability up to a wind speed of (only) 5 m/s, the lift needs to be 2100 kN, which is more than seven times larger than the lift required for stability in configuration 1. This kind of lift increase would require a volume seven times larger, in the order of $7 \cdot 10^5$ m^3, for the same lifting gas. At this stage in the design, changing the lifting gas is not an option, knowing that hydrogen is not a feasible alternative because of safety reasons. To ensure such an increase in volume, the structure needs to be designed a lot bigger as well. This means that the current calculations for the internal structure are no longer valid, so a complete redesign is necessary to prevent buckling of the beams. The maximum take-off weight will then be strongly affected by the change in configuration. This design is very likely to be infeasible due to its huge dimensions. Moreover, the solution of increasing the lift and redesigning the structure for this will only help prevent displacement. Because of the lack of cables, top - and side view rotation will still be a big issue for the aerostat, which is undesired for visibility reasons.

The required ground area depends on the angle at which the cables are installed. As previously mentioned, the required angles influence the stability of the blimp. This characteristic has a direct impact on the amount of up-time of the aerostat. If the available ground area is decreased, the angles between the ground and the cables will necessarily become larger, which will result in a less stable aerostat. Consequently, the aerostat will have lower in altitude to remain stable or enter safety mode at lower wind speeds than what was initially planned. Another option is further increasing the height of the poles (but high costs) or a smaller internal structure and smaller screens would need to be built to reduce weight and drag. Table 17.2 shows the relation between wind speed and ground space needed to have the angle necessary to keep the aerostat stable.

From a financial point of view, a smaller ground area and hence a shorter up time will generate less income from advertizements and sightseeing. On the other hand, buying less ground area will benefit the budget of the project. Ultimately, a trade-off would have to be made between pushing the break-even point further away in time or saving money on ground surface. Nonetheless, if United Balloon can get a good deal for the ground area from the Wafi Mall, as they expect, this will not be an issue and all angles will have to be adjusted accordingly. If stability was not a main concern for this project, an alternative would be to accept the consequent extra vibrations and displacements, although this will impact the visibility of the screens. Finally,

Table 17.2: Relation between wind speed and ground space

Wind speed, ground [m/s]	5	8	10	11.5
Wind speed, air [m/s]	8.5	12.5	15	17
Angle [°]	59.19	39.62	31.20	26.23
Ground distance [m]	167	338	462	568

changing the available ground area may not allow meeting certain key requirements that have initially been set by the client. To avoid the problem of a very large ground area, poles would be installed below the aerostat so that the cables can have a smaller angle without necessarily impacting the surroundings. In figure 17.3, the horizontal ground distance from the dirigible connection to the ground attachment and the required ground space are plotted against the pole height.

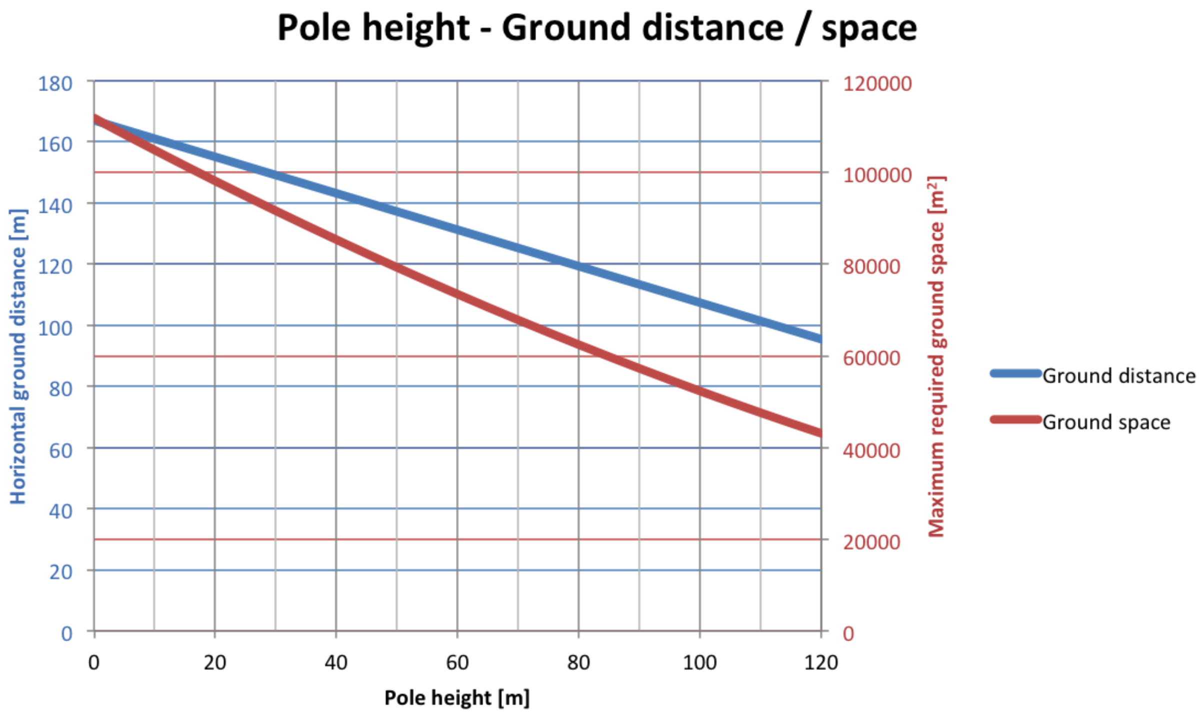


Figure 17.3: Influence of pole height on horizontal ground distance and ground space

18

FINANCIAL ANALYSIS

This chapter describes the finances of the project. Section 18.1 shows the cost breakdown structure. In section 18.2, an overview of the total budget is given. Section 18.3 contains the market analysis and finally, section 18.4 covers the return on investment.

18.1. COST BREAKDOWN STRUCTURE

In the baseline report [5], the total cost of the aerostat was estimated to be 40 million euro. This number was the maximum amount of money the aerostat was allowed to cost, considering an earnback period of 3 years. In this final phase of the DSE, another approach has been taken. Since all subsystems are designed and investigated in more depth, a cost prediction of each subsystem can be made. Adding up all these values gives the total cost of the entire aerostat.

As a start, a cost breakdown structure was made. In the cost breakdown structure, all costs are grouped in multiple activities during the lifetime of the aerostat. The structure can later be used to easily identify all costs. Four main groups are defined: Design & Project management, Production, Operation and Post-Operation. These topics are then split up into more detail, after which all separate costs are defined.

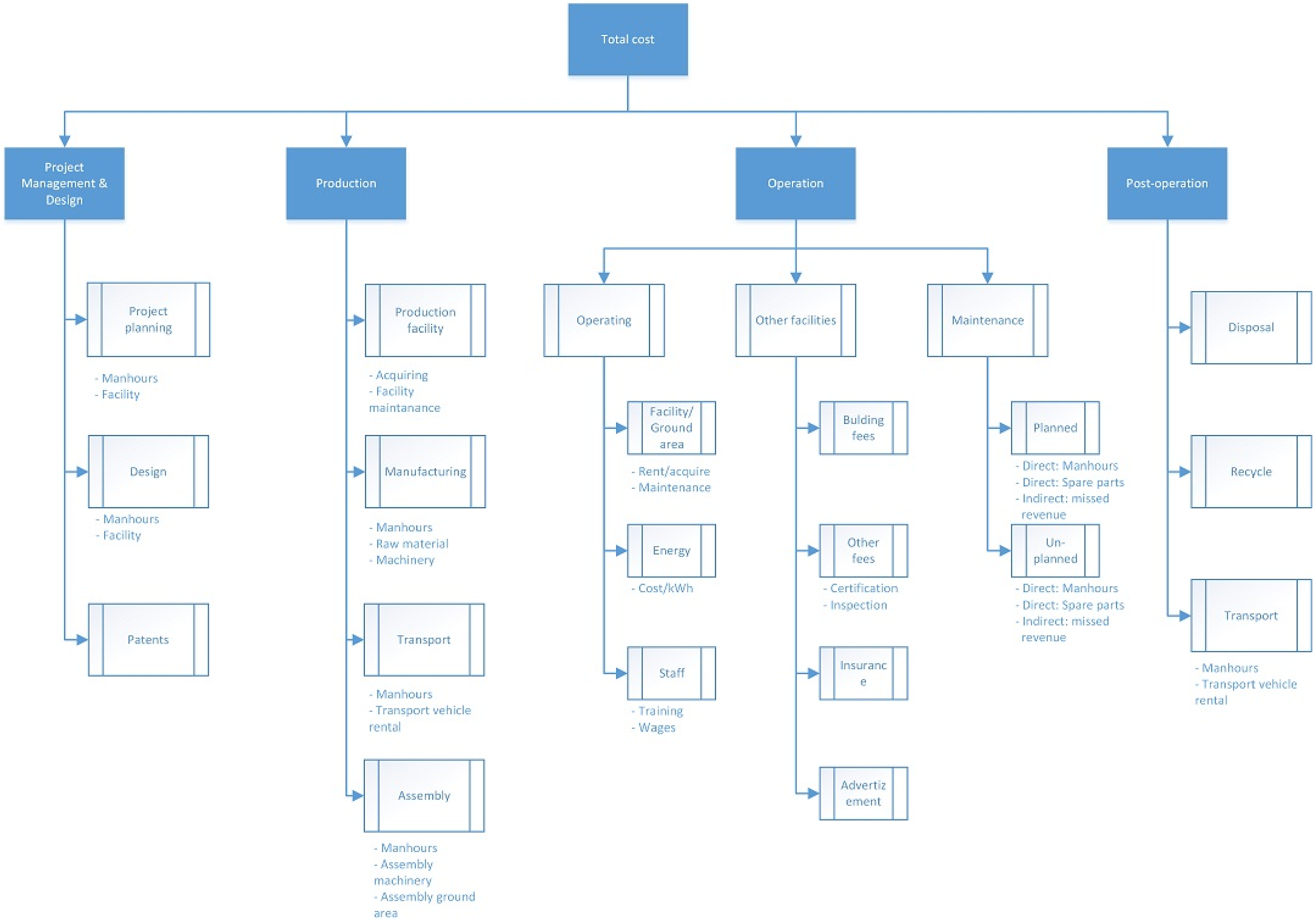


Figure 18.1: Cost breakdown structure

18.2. BUDGET OVERVIEW

Table 18.1 shows an overview of development and production costs for different subsystems of the dirigible, ground station and operational equipment. These budgets are added and afterwards used to estimate a return on investment time. Table 18.2 shows an overview of the operational costs. The content of the tables 18.1 and 18.2 will be explained afterwards, zooming in on important matters such as the internal structure cost and the gondola cost.

Table 18.1: Development and production costs

	Initial costs
Screens [6]	€1 500 000
Gondola [6]	€500 000
Cables [9]	€150 000
Cable towers [9]	€300 000
Cable retraction engines	€50 000
Internal structure	€2 196 000
Internal envelope	€100 000
External envelope	€100 000
Helium	€300 000
Ground station	€800 000 - 4 800 000 (UB)
Total	**€6 000 000 - 10 000 000**

Table 18.2: Operational cost breakdown per year

	Operational cost per year
Power Usage (excl. cable retraction)	€92 000
Cable retraction power usage	€49 000
Helium refill	€10 000
Staff	€3 492 000
Maintenance	€50 000
Office rent	€36 000
Advertizement	UB
Insurance	UB
Inspection/Certification	€1000
Total	**€3 000 000 - €5 000 000**

In table 18.1, all costs for production and development are stated. The screen costs are extrapolated from existing products. However, the choice of screens will be made in cooperation with the client, United Balloon. Once a screen is chosen, a better cost prediction of the screens can be made. It is assumed that all subsystems can operate for at least the operational lifetime of 10 years. For maintenance €50 000 per year is reserved, which is considered to be sufficient to make sure that all subsystems operate properly during the entire lifetime. This means that all subsystems, such as the screens, the gondola and the cable and cable retraction engines, are expected not to require complete replacement in the operational lifetime.

The costs for the internal and external envelope were provided by a manufacturing company, Lamcotec Inc. Costs for cables and cable towers can be found in section 9.6.4. Helium costs were estimated at 3 euro per cubic meter and with the volume of 100 000 m^3, this becomes a total of 300 000 euro. As described in section 8.5.1 in chapter 8, helium losses are very small, in the range of 9 m^3 per day. This comes down to a helium refill cost of around 10 000 euro per year. For the engines for cable retraction, electrical engines were compared.

The costs of the internal structure is elaborated on in section 18.2.1. The only remaining unknown is the ground station costs, since these costs will depend on the plans United Balloon has for the ground station. Therefore, the total initial cost of the aerostat are at least 6 000 000 euro, but this number may increase. To be on the safe side for a return on investment estimation, a total cost development and production of 10 000 000 euro was assumed.

It is assumed that all parts

18.2.1. INTERNAL STRUCTURE: MATERIAL, LABOR AND CONSTRUCTION COST

As can be found in chapter 21, the hollow structural carbon members will be manufactured using the production method filament winding. The cost per kg carbon fiber can be found in table 18.3 [58]. Since the total carbon structure has a weight of 32 000 kg, the material cost can be obtained.
For the production cost of the members an online tool called 'filament winding calculator' is used to calculate the production cost [59]. An example of the online calculation program can be found in Appendix E. The production cost is estimated to be 400 000 euro. In chapter 21, the timestamps for the production, sub-assembly and final assembly can be found. For the sub-assembly, it is assumed that 20 people work 2 weeks in a row, 8 hours a day and that each worker costs 60 euro per hour. For the final assembly, it is assumed that 20 people work 8 hours a day for 8 weeks, with a cost of 35 euro per hour. For the assembly, four large cranes must be hired. Besides that, assembly requires much tooling equipment. The costs are estimated to be 500 000 euro. For the hinges and the cabling net, 75 000 euro has been reserved. This results in the total cost demonstrated in table 18.3. As a sanity check, the cost estimation for the internal structure has been verified using the tool 'filament winding calculator' [60].

Table 18.3: Materials & manufacturing costs

	Cost [€]	**Remark**
Materials	896 000	28 €/kg
Manufacturing of members	400 000	Filament winding
Subassembly	100 000	-
Assembly	225 000	-
Machinery for final assembly	500 000	4 Cranes + tooling equipment
Hinges	50 000	-
Cable net	25 000	-
TOTAL	2 196 000	-

18.2.2. GONDOLA COST

The cost for building the gondola specified above is a preliminary estimated value, since specifications of any miscellaneous systems, as well as costs for the glass and structure, are unknown. These detailed research on these costs were considered not to be inside the scope of the feasibility study, and the cost will be determined in the post DSE phase in section 22.1.

To come up with a value, the cost estimation for the gondola has been extrapolated from what could be found for existing gondolas. Including a relatively large contingency margin (>15%) to cope with the unknowns, this cost is estimated to be around 500 000 euro. This includes engineering, production and assembly.

18.2.3. OPERATIONAL COST

In table 18.2, an overview of the yearly operation cost is found. Power usage costs were calculated using the power budget and a current electricity rate in Dubai of 8 eurocents per kWh. Office rent was calculated comparing multiple offices available in Dubai. An average of 36 000 euro per year for an office of 100 square meter was found, which should be sufficient for all office work during operation. Furthermore, the costs of advertizement and insurance will have to be provided by United Balloon, since expertise is needed. This is indicated with 'UB' in table 18.2.

The largest part of the operational cost is taken up by the staff. To come up with a number for this topic, a closer look at the plans of United Balloon was taken. It was found out that around 12 managers would be working during operation, together with 54 support staff members. For the engineers and managers, a monthly wage of 13 000 euro was assumed, which is common for engineers in Dubai. For the support staff, a wage of 2 500 euro was used. On a yearly basis, this would add up to 3 492 000 euro.

Adding all costs, except for the numbers that still need to be provided by United Balloon, a yearly operation cost between 3 000 000 and 5 000 000 euro was found. This number, together with the initial cost is used to calculate and visualize the return on investment graph, which can be found in section 18.4.

18.3. Market analysis

In the market analysis, the attractiveness and dynamics of a special market, within a special segment, are analyzed. An important part of the market analysis is the global environmental analysis, the PEST analysis, which is explained in section 18.3.1. After the PEST analysis, a SWOT analysis is performed in section 18.3.2, to investigate the strengths, weaknesses, opportunities and threats. In section 18.3.3, the Porter five forces analysis is performed, as a framework for the business strategy. Section 18.3.4 addresses the revenue forecast generated by both tourism and advertizing.

18.3.1. Political, economic and social analysis

This section documents the performed research on the political, economical and social aspects. This research has been done, because these factors influence the success of an entrepreneurial project to a large extent.

Political analysis

Dubai is part of The United Arab Emirates, which is an absolute monarchy. The controller of Dubai is Khalifa bin Zayed Al Nahyan, the Prime Minister of the United Arab Emirates. He is also the current head of government (2014). The fact that the political power is centralised can be an advantage or a disadvantage. If the prime minister is a proponent of the project, a lot will be possible. The opposite applies as well. Some further research in this field and the field of environmental law is required as described in section 22.1.

Economic analysis

Although the general economical state of the western world is decreasing, the market of advertizing grows year after year and has become a very important part of United Balloon's strategy. World leading brands are therefore searching for more spectacular and new ways of advertizing their products to the world. The fact that United Balloon is planning to get their budget from investors and give them free advertizing time in return, instead of renting money from a bank, ensures that the interest rates are of minor importance only. The currency United Balloon is planning to use is the euro. With current exchange rates, the high value of the euro is an extra advantage, although the exchange rates are highly fluctuating and may be totally different by the time the balloon is operational.

Social analysis

Dubai is a young city. This results in an environment with a low level of culture and history. Dubai is known for its extravagance. Due to this, the general idea of United Balloon fits nicely in the thoughts of the Dubai inhabitants. An important issue to be considered is the fact that the United Arab Emirates is a practicing Muslim country. This should be taken into account when selecting advertizers. Additional research is required to avoid offending their religion section (22.1).

18.3.2. SWOT product analysis

The SWOT analysis (figure 18.2) consists of the internal factors, which consist of strengths and weaknesses, and the external factors, which consist of opportunities and threats.

Strengths: List the characteristics of the product/project that are favourable over others, in which B2B is business to business and B2C is business to consumer.
Weaknesses: List the characteristics that are unfavourable over others.
Opportunities: Options that the product/project could exploit to its advantage.
Threats: Elements that could bring the product/project in danger.

Figure 18.2: SWOT analysis overview

18.3.3. PORTER FIVE FORCES ANALYSIS

To determine the overall industry profitability, one can use the analysis framework of Porter. In this framework, the five forces which drive the profitability of a market, both by internal and external sources, are graphically described. As can be seen in figure 18.3, the threats to the profitability to new entrants come from existing ballooning and advertizement companies, who have the knowledge or budget to create a similar aerial advertizement with public attraction capabilities. If there are many (high potential) threats in any of the 5 areas, this might pose a danger to the profitability. However, these threats are manageable due to patent applications and the required time and budget to design a similar solution, therefore allowing United Balloon to be the first to enter the market.

When the substitutes are considered for the tourism part, balloon and helicopter flights are possibilities. For the advertizement part blimp and airplane advertizments are possibilities. At the moment of designing, existing competitors are airport and highway advertizement by traditional (digital) billboards, the Burj Khalifa and the Dubai Eye. These are all conventional competitors, which will not offer the same experience and are thus thought to be able to coexist.

Major threats come from suppliers, which have a strong bargaining position. An important part of the business plan is to have the operation fully funded by different suppliers and partners. However, if one supplier wants to get out of the program, while part of the design is based on their specific product, that supplier has a high bargaining power. The same logic holds for the Wafi Mall, which should provide the location and the Dubai Tourism center, for providing a large share of the visitors.

Threats coming from the customers are considered minor threats, as due to the unique nature of the product, both tourists and advertizers will be highly interested. A threat can be that tourists get used to the attraction and advertizers are looking for something new after a while.

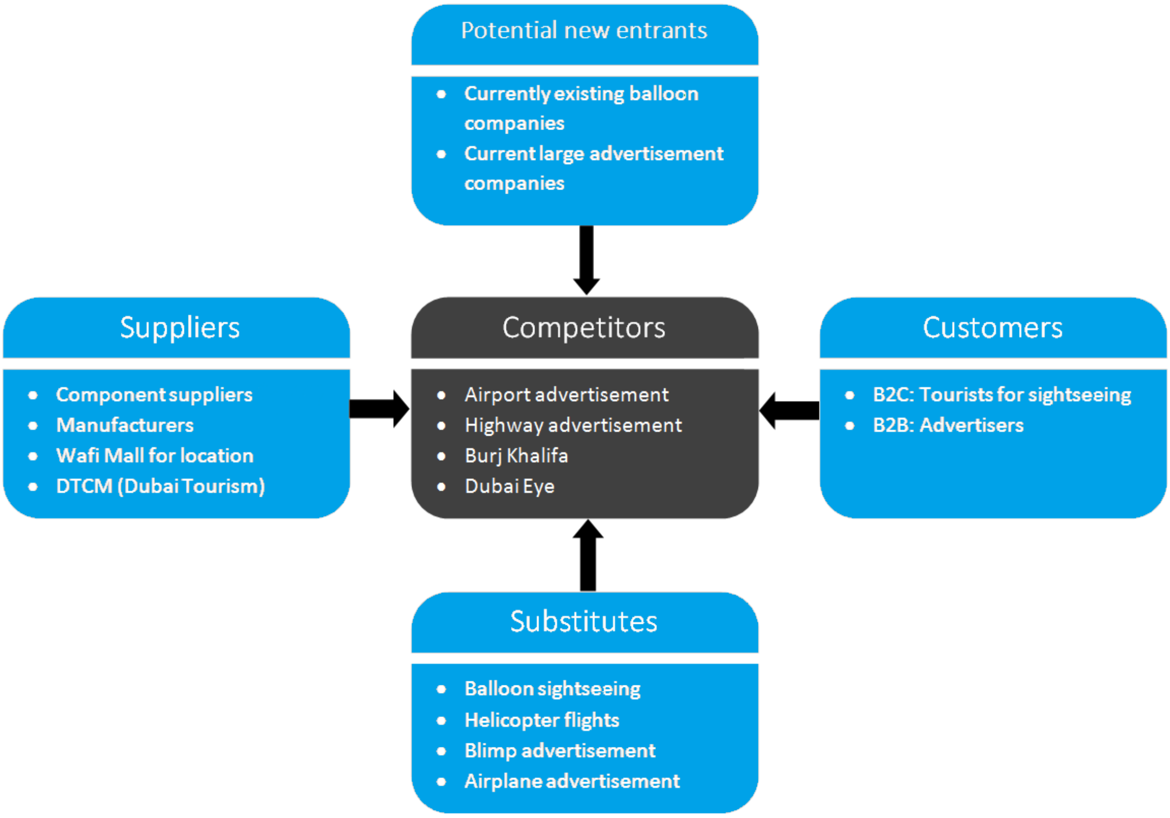


Figure 18.3: Porter's five forces

18.3.4. REVENUE FORECAST

The previous sections have shown where the possibilities for profit are and where the threats come from. Most important however, is what their effect is in terms of generated revenue. Table 18.4 shows the expected number of passengers for the first five years, combined with their average spending on the ticket, ground attractions and merchandising together. The two of these multiplied yield the last row, which is the expected revenue generated by passengers. The information was obtained in cooperation with United Balloon, as it was described in the earnings model [61].

Table 18.4: Revenue forecast passengers for the first five years

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Passengers (thousands)	582	611	642	642	642
Avg. spending	€15.39	€16.93	€18.62	€20.49	€22.54
Revenue (millions)	€8.96	€10.35	€11.95	€13.15	€14.46

Table 18.5 shows the available screentime for the first five years, together with the average expected cost per minute. The available screen time is calculated based on a required screen time of 21 hours a day, for 300 days a year. Screen time available for advertizers will increase the first four years, due to both more efficient time allocation and less time needed for investor screen time. The prices will rise in the first three years due to expected high demand. The last row is the expected revenue generated by the advertizement business.

Adding the revenues from tables 18.4 and 18.5 yields the total expected revenue for the first five years of deployment, which can be seen in table 18.6. It goes without saying that this table, together with the targeted return on investment and payback time, are the major constraints for the available budgets for construction, operations and maintenance.

Table 18.5: Revenue forecast advertizement for the first five years

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Available screentime	9000h	10000h	11000h	12000h	12000h
Cost/minute	€10	€11	€12	€12	€12
Revenue (millions)	€5.40	€6.60	€7.92	€8.64	€8.64

Table 18.6: Total revenue

	Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Total revenue (millions)	€14.36	€16.95	€19.87	€21.79	€23.10

18.4. RETURN ON INVESTMENT

After the cost and revenues have been calculated, a return on investment graph can be produced. The cost subtracted from the revenue is the profit per year. At some point, all costs will equal the total revenue. Looking at the graph in figure 18.4, this point is located just after one year of operation.

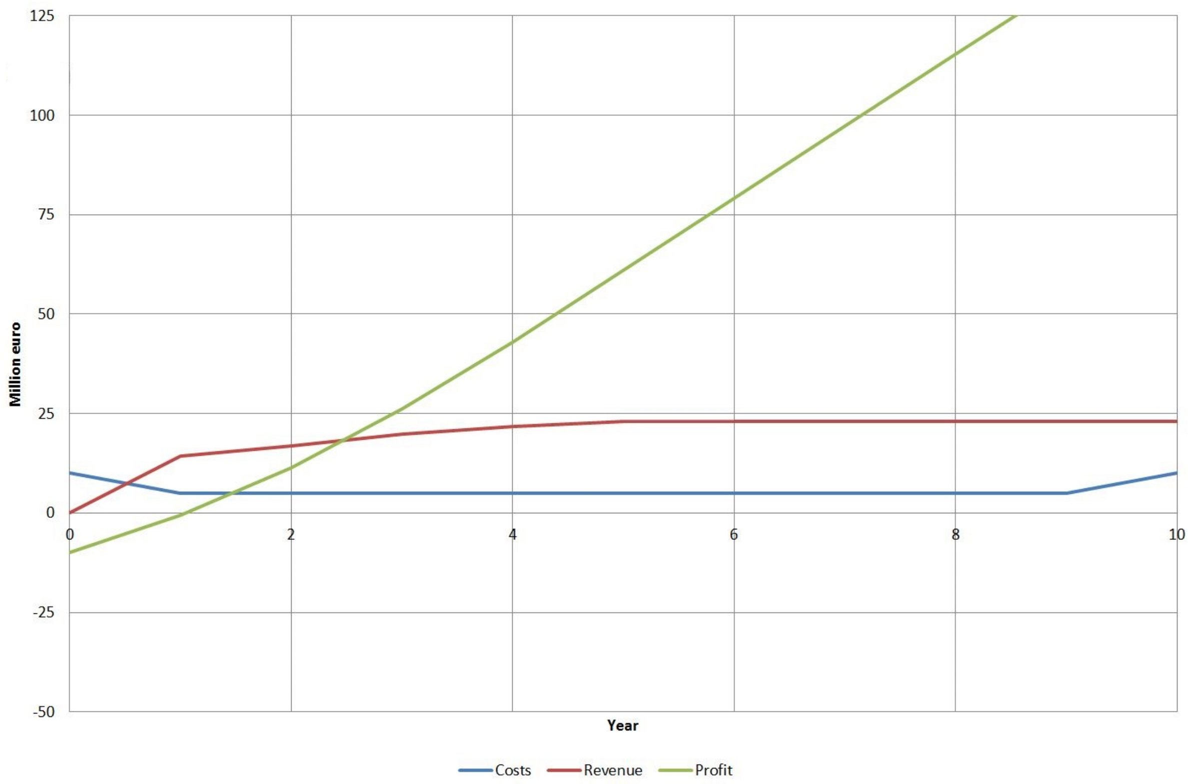


Figure 18.4: Cost vs revenue plot for the operational lifetime

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COMPLIANCE MATRIX

In this chapter, in order to see if the final design meets the requirements, the final design is checked with the requirements. A full list of all requirements can be found in chapter 3. A checkmark indicates that a requirement has been met, whereas a cross indicates that a requirement has not been met. Section 19.1 gives the air segment compliance matrix, section 19.2 gives the control segment compliance matrix and section 19.3 the compiance matrix for the ground segment. Any requirements that have not been met are discussed in the appurtenant section.

19.1. AIR SEGMENT

Table 19.1 contains the air segment requirement compliance matrix for 'perform mission technically' and table 19.2 contains 'perform mission within constraints' requirements.

Table 19.1: Air segment requirement PMT compliance matrix

Requirement	Status
ASR-PMT-001	✓
ASR-PMT-002	✓
ASR-PMT-003	✓
ASR-PMT-004	✓
ASR-PMT-005	✓
ASR-PMT-006	✓
ASR-PMT-007	✓
ASR-PMT-008	✓
ASR-PMT-009	✓
ASR-PMT-010	✓
ASR-PMT-011	✓
ASR-PMT-012	✓
ASR-PMT-013	✓
ASR-PMT-014	✓
ASR-PMT-015	✓
ASR-PMT-016	✓
ASR-PMT-017	✓
ASR-PMT-018	✓
ASR-PMT-019	✓
ASR-PMT-020	✓
ASR-PMT-021	✓

Table 19.2: Air segment requirement PMWC compliance matrix

Requirement	Status
ASR-PMWC-001	✓
ASR-PMWC-002	✓
ASR-PMWC-003	✓
ASR-PMWC-004	✓
ASR-PMWC-008	✓

19.2. CONTROL SEGMENT

Table 19.3 contains the control segment requirement compliance matrix for 'perform mission technically' and table 19.4 contains 'perform mission within constraints' requirements.

Table 19.3: Control segment requirement PMT compliance matrix

Requirement	Status
CSR-PMT-001	✓
CSR-PMT-002	✓
CSR-PMT-003	✓
CSR-PMT-004	✓
CSR-PMT-005	✓
CSR-PMT-006	✓
CSR-PMT-007	✓
CSR-PMT-008	✓
CSR-PMT-009	✓
CSR-PMT-010	✓
CSR-PMT-011	✓
CSR-PMT-012	✓
CSR-PMT-013	✓
CSR-PMT-014	✗

It can be noted that requirement CSR-PMT-014 "CSR-PMT-014: The control segment shall occupy no more than 20 m^2 of ground area" is not met. As is described in 9.6 the control segment, the entire area needed to control the aerostat, shall provide stability to the aerostat. Therefore six poles and a ground station right beneath the aerostat are needed. The ground area to control the aerostat is described in 9.6. As can be seen 9.6 the required ground space to control the aerostat depends if the ground under the stability cables can be used. This ground space will exceed the prescribed 20 m^2 in all cases .

Table 19.4: Control segment requirement PMWC compliance matrix

Requirement	Status
CSR-PMWC-001	✓
CSR-PMWC-003	✓
CSR-PMWC-004	✓
CSR-PMWC-005	✓

19.3. GROUND SEGMENT

Table 19.5 contains the ground segment requirement compliance matrix for 'perform mission technically' and 19.6 contains the 'perform mission within constraints' requirements.

Table 19.5: Ground segment requirement PMT compliance matrix

Requirement	Status
GSR-PMT-001	✓
GSR-PMT-002	✓
GSR-PMT-003	✓
GSR-PMT-004	✓
GSR-PMT-005	✓
GSR-PMT-006	✓
GSR-PMT-007	✓
GSR-PMT-008	✓

Table 19.6: Ground segment requirement PMWC compliance matrix

Requirement	Status
GSR-PMWC-001	✓
GSR-PMWC-002	✓
GSR-PMWC-003	✓
GSR-PMWC-004	✓
GSR-PMWC-006	✓
GSR-PMWC-007	✗

Ground segment requirement GSR-PMWC-007 "The ground segment shall have an operationally deployed ground-area of at most 25x25m" is not met due to the size of the dirigible. The size of the balloon already exceeds this area, and the stability system requires even more ground space. The operationally deployed ground area also depends if the area under the stability cables can be used. Furthermore, in 'Revenue forecast year 1 to 5' of our client it was stated that the total estimated ground area is 6000 m^2 and the ground area of the size of balloon plus the safety area is 2500 m^2. This exceeds the initially required ground area of 25x25 m^2.

20 CERTIFICATION

This chapter covers the certification of the aerostat. In section 20.1, the compliance matrix of the final design certification requirements is shown and in section 20.2, a further plan for certification is outlined.

20.1. CERTIFICATION REQUIREMENTS

In section 3.1, the certification requirements have been listed. In table 20.1, the compliance of the final design with these requirements has been checked. A checkmark indicates that a requirement has been met, whereas a cross indicates that a requirement has not been met.

Table 20.1: Certification requirements overview

Requirement	Status
CR-001	✓
CR-002	✓
CR-003	✓
CR-004	✓
CR-005	✓
CR-006	✓

20.2. PLAN OF ACTION FOR CERTIFICATION

It is recommended to start certification procedures as quickly as possible. If certification procedures are started later on in the process, there is a chance that some parts that have already been designed do not meet certification standards. This results in a redesign of these parts, which increases development cost and delays the project. When certification procedures are started early on in the project, the design can be developed in cooperation with the certification agency, which reduces the risk of having to redesign parts of the system. Next to this, it is important to carefully document design decisions, calculations, etc., in order to prove compliance with the certification requirements. In this report, it has been assumed that the aerostat can be certified under the EASA CS-31TGB certification specifications[4]. These specifications are sufficiently strict that they allow the aerostat to be certified in Dubai as well. The timeframe needed for certification is, as of yet, unknown.

21

MANUFACTURING ASSEMBLY AND INTEGRATION PLAN

The MAI Plan (manufacturing, assembly and integration) is a time ordered outline of activities required to construct the product from its individual parts. Firstly, in section 21.1 an explanation on the manufacturing method is given, followed by an explanation on the connection of all invidual members in section 21.2. In section 21.3 the entire production and assembly plan is visualized and explained. This chapter ends with section 21.4 about the required ground area for the on site assembly of the balloon. This chapter focuses on the production of the aerostat and not on the related stability poles nor the ground station. The reason for this is that the stabilizing poles most likely are off the shell products and the ground station needs to be designed by civil engineers, which is outside the scope of the DSE project.

21.1. MANUFACTURING METHOD USED FOR THE STRUCTURE

The manufacturing method for the structural members should be considered very carefully. The manufacturing method directly determines quality, material and structural characteristics, time span of the manufacturing and cost. To manufacture the hollow members made from carbon fiber, four different manufacturing processes can be distinguished: braiding, tape winding, extrusion and pultrusion. Each of these methods has its pro's and con's. Braiding, extrusion and pultrusion are relatively cheap, but the specific stiffness properties of the end product are lower than those of tape winded members. The drawback of tape winded members are the long manufacturing time, the expensive production process, the maximum member length of 12 meter and the limited amount of companies that can produce the members.

Nonetheless, the high specific stiffness is absolutely required for the structure and therefore the best manufacturing method would be tape (filament) winding. Products made using filament winding have a high tensile strength and a high strength over weight ratio.

Filament winding is an open mould process in which the reinforcement (yarns, tapes, roving) is wound onto a mould (mandrel), which rotates on a lathe. The reinforcements are stored on a reel and before it is wound onto the mandrel, it goes through a bath of resin for impregnation. To allow impregnation, the material needs to be pre-tensioned. The angle with respect to the rotational axis is called the rotational angle (0° is polar winding, 90° is hoop winding, the rest is helical winding). During curing, the product should be rotating to make sure the resin stays evenly spread. There are three limits on the producibility of products: the length of the member is limited by the length of the mandrel, the mandrel should be able to be removed after curing (using tapered shapes, soluble mandrels, divisible mandrels or use the mandrel as a part of the product) and thirdly, the reinforcement tapes must stay on the mandrel during the process. To reduce the cost, it is preferred to use an epoxy resin (thermoset) that cures at room temperature, but not too fast, as the entire product must be made before curing. Otherwise curing must take place in an autoclave, which is expensive (starting at 500,- euro per hour at Airborne Composites). In figure 21.1, the filament winding process is visualized and in figure 21.2 an example product is shown.

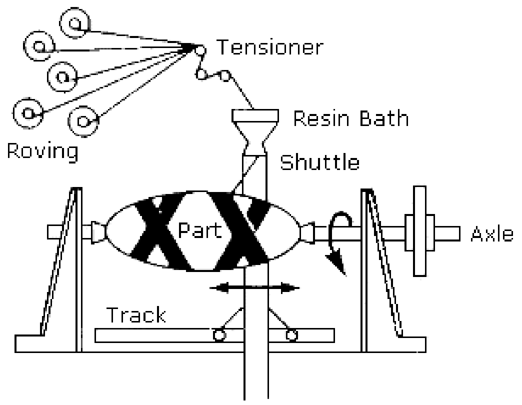

Figure 21.1: Production process setup for filament winding [62]

Figure 21.2: Large circular product made using fiament winding [63]

21.2. CONNECTING CFRP BEAMS

In this section, an explanation will be given on how to connect two CFRP tubes. This is necessary because the longest tube that exists in the design of the internal structure is 75 m long. The longest manufacturable CFRP tube found in literature [64] is 12 *m* long. As a result, the long members need to be built up from several other members. Different joining techniques have been considered such as mechanical bonding, adhesive bonding and welding. Clearly, adhesive bonding is the best and most feasible option when weight and complexity are considered, it is assumed that the weight impact of this connection method can be neglected in this stage of the design. A brief action plan will be given, including some illustrations. The general idea of connecting two tubes to each other is to put a 3rd tube inside the two and bond them together as can be seen in figure 21.3 and 21.4.

Figure 21.3: Clarifying picture for epoxy adhesive bonding [65]

Figure 21.4: Clarifying picture for epoxy adhesive bonding [65]

21.3. PRODUCTION PLAN

In figure 21.5, the time ordered manufacturing, assembly and integration plan is demonstrated. In this section, figure 21.5 will be explained in more detail.

The light green block represents the design period that comes before the actual production. The light blue blocks represent the manufacturing of all individual parts. The dark blue blocks represent the assembly of the entire aerostat.

At the start of the 1st month, the production of all structural hollow carbon members will start. The production of these members will last 4.5 months when 2 winding machines are used. Using only 1 machine will thus delay the production by 4.5 months. For the manufacturing, multiple companies should be contacted and it might be wise to look for companies worldwide. The company manufacturing the members is preferably situated as close as possible to the deployment site, but the total cost must be taken into account. Together with the main members, the production of the hinged connection points for the corners, the manufacturing of the internal and external envelope and the manufacturing of all subsystems can start. The required Dyneema cables can be ordered at specialized fiber cable companies such as . For the production of the inner and outer balloon, a specialised 'lighter than air fabric company' should be contacted and thus the production should be outsourced. Contact with the company Lamotec Inc. resulted in a supply of the necessary data.

The subsystems to be made are the following:

- Gondola
- Screens plus support structure
- Lifting mechanism gondola
- Helium refill system
- Electrical system
- Ambilight system
- Connection points for the stability cables
- Sensors
- Ground station
- Poles

When the first structural members are made, the members can be prepared for connection to other members. This process can start after approximately 2 months and will continue untill the 5th month. From the 5th month onwards, the sub-assembly of the internal structure and the sub-assembly of the subsystems can be performed. In the sub-assembly of the internal structure, some small members can be connected and the hinged connection nodes can be attached to the members. In the sub-assembly of the subsystems, all subsystems are finished and ready to be installed.

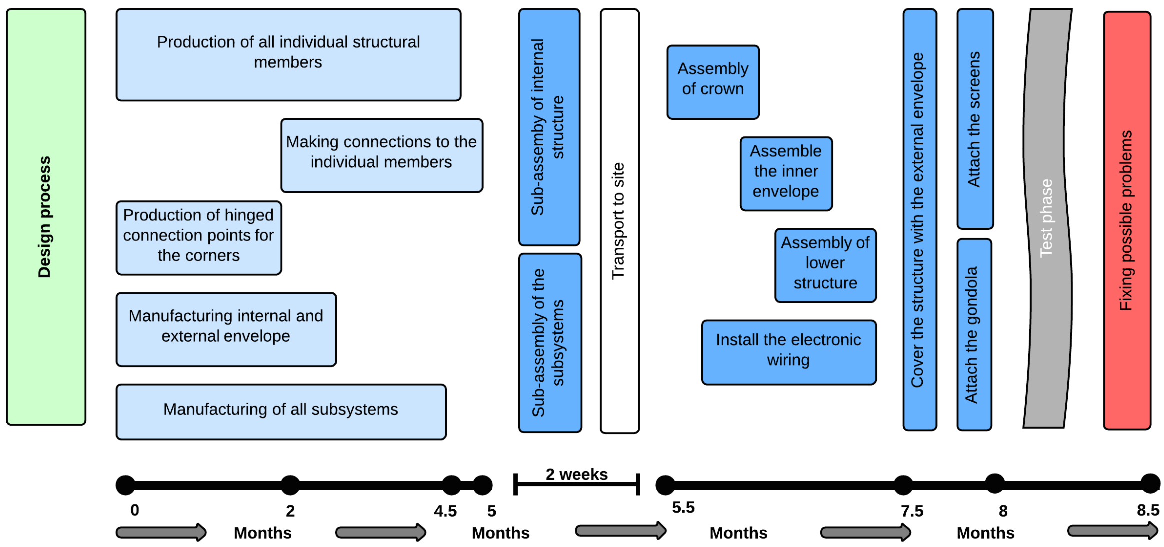

Figure 21.5: MAI time line for the entire aerostat

After the transportation to the deployment site, the longer members can be assembled and the final assembly of the entire aerostat can start. This will take a maximum of 3 months. The dark blue blocks in figure 21.5

represent the assembly of the entire aerostat. This assembly is demonstrated in figure 21.6, the following step-by-step plan supports the production plan. During assembly, four cranes will be used. Three of these cranes will be used to lift the partially finished structure, whilst the fourth crane will be used to lift structural members up to the partially finished structure.

(1) At first, the crown must be assembled completely and the external envelope must be positioned on the crown, so that it can be lowered (like blinds) in a later phase. The cables that need to be attached for operation should immediately be attached and can be used for lifting the entire structure. (2) Next the crown must be lifted by three cranes, bringing the structure to a height of approximately 40 m. After the assembly of the crown, the electronic wiring installation can already start and will continue up to the point where the structure is covered in the external envelope. (3) The inner envelope can be attached to the crown. (4) Then the first layer of structural members can be added to the structure. (5) The inner envelope should partially be filled with helium so that the structure can support itself and the cranes can be removed. The lower structural members should be added to the structure. When all members are assembled and the wiring and internal subsystems have been installed, the (6) external envelope can be lowered from the crown. Finally, the screens (7) and the gondola (8) can be attached to the aerostat. In the last step (9) the aerostat should be completely filled with helium and the entire system can be tested for problems. In the time plan there is half a month reserved for testing and solving problems that might arise. The layer division described in figure 21.6 is visualized in figure 21.7.

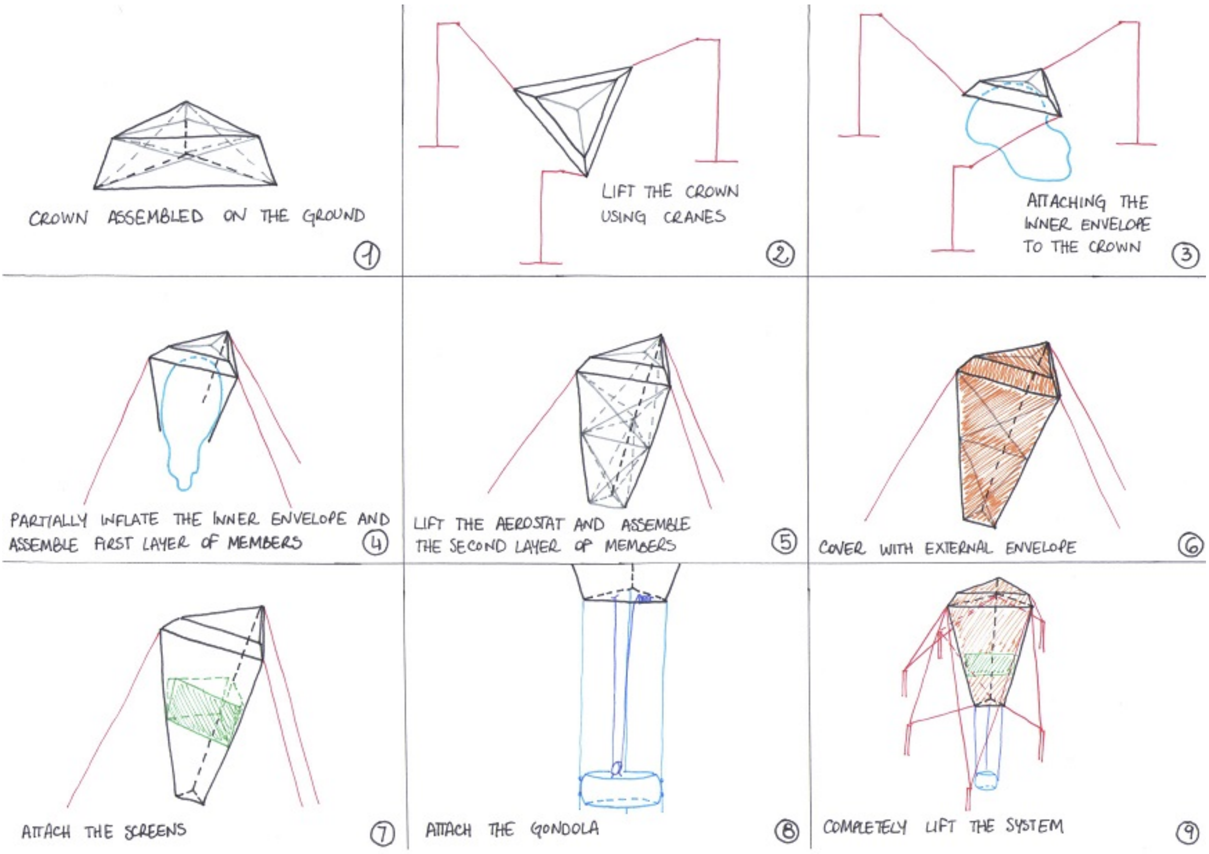

Figure 21.6: Story line of final assembly of structure

21.4. REQUIRED GROUND AREA FOR THE ON SITE ASSEMBLY OF THE BALLOON

For the assembly of the entire balloon, the required ground area will be larger than the area covered by the balloon in daily operations. In figure 21.8, the dimensions of the minimum ground area are demonstrated. It is important to note that the drawing is not to scale.

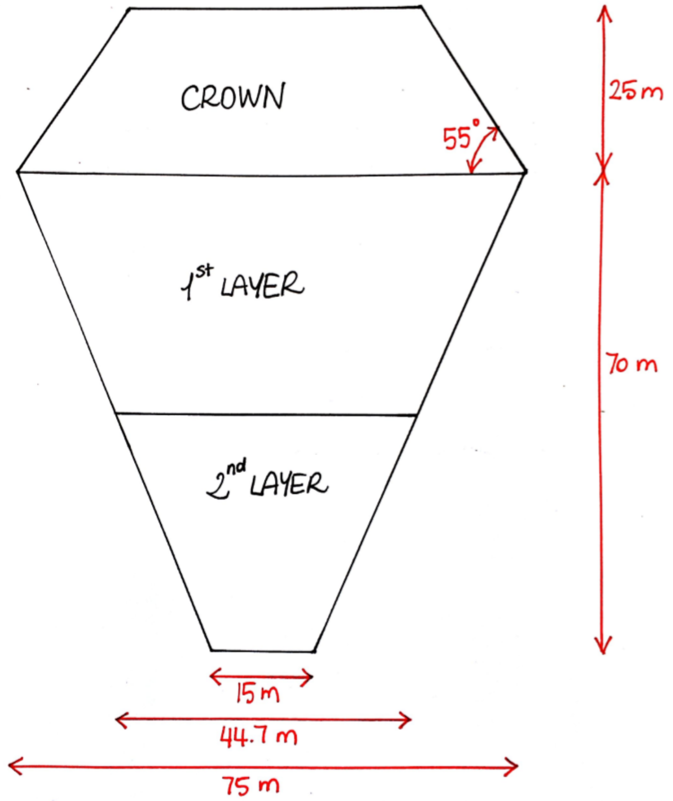

Figure 21.7: Overview of the final layout of the total system

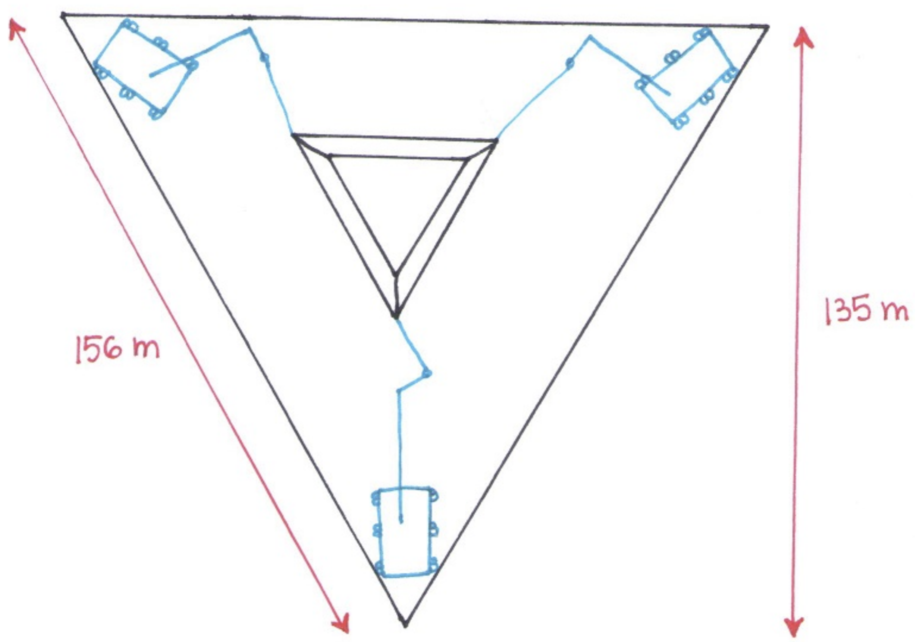

Figure 21.8: Visualization of required ground area for on site assembly of dirigible

The required ground area for assembly consists of the ground area required for the aerostat itself and the required space taken up by the 3 lifting cranes. For the crane size, the dimensions of a Liebherr LTM-Mobilkrane are taken [66]. These cranes were not selected on their lifting capacity, but on the maximum height (114m [66]) they can reach. In figure 21.8, a drawing illustrates the minimum ground area with a width of 156 *m* and a height of 135 *m*.

22
POST-DSE ACTIVITIES

In this chapter, the activities for the the project after the DSE are discussed. The Gantt-chart of UB, which can be found in appendix B, shows a lot of the tasks that still have to be finished before the entire system can be operational. This chapter contains all the the activities that concern engineering and production. First, an estimation is done on the timeline of the post-DSE activities in section 22.1. The details on engineering can be found in section 22.2.

22.1. PROJECT DESIGN AND DEVELOPMENT LOGIC

The activities discussed in this chapter are a more elaborate description of tasks that are already in the planning of UB. The engineering on the detailed design is done in the period between August and November 2014, with a more detailed analysis. The plans about the maintenance and manuals for operation should also be considered at this point. Then there is time to make a complete production plan and subsequently build the parts of the balloon between February and May 2015. The shipping and the assembling, executed in June and July, should be in the production plan as well. All these activities are shown in the work flow diagram in figure 22.1. Some phases already contain more detailed activities. It is expected that these will need to be performed, but they might require some planning and preparations.

22.2. DETAILED DESIGN

For the detailed design, it is necessary to do a more detailed analysis on certain topics and perform tests both to research on the design and to validate it. First, the suggestions for further research will be listed in section 22.2.1 and a list of tests that have to be performed will be given afterwards in section 22.2.2.

22.2.1. SUGGESTIONS FOR FURTHER RESEARCH

- Investigate if the design can become lighter if the beams of the internal structure have stiffeners (Helix or straight) on the inside, so the thickness and diameter can be reduced.
- Possibly, it is lighter to make the structure out of a sandwich panel instead of full carbon.
- Another possibility that is not researched yet is to use only an envelope without an internal structure of beams or to only use a partial reinforcing structure.
- The eigenfrequency of the structure needs to be determined in order to calculate the vibrations due to vortex shedding. If this is not possible, tests will be needed to measure the vibrations.
- For dynamic calculations, the CFD model should be improved to make it capable to compute the aerodynamic properties more precisely and predict vortex shedding.
- From wind data, CFD analysis and wind tunnel tests, the shock loading on the cables can be determined. It must be ensured that the cables are capable of handling these loads.

- The gondola has to be designed in more detail. It needs to be made sure that the structure can withstand the loading of payload and that a lighter material than glass is found for the windows. After the gondola is designed, the cost for the gondola can be determined more accurately.
- Research into local customs in the field of law and religion should be performed, since it can influence the progress of the project.
- As described in section 9.6.4 the cables are overdesigned and all designed to cope with maximum forces. A preliminary research on this topic is started in this section and should be continued in the detailed design.
- As is described in section 9.6.3 a detailed design of the poles needs to be made. This includes, but is not limited to, sizing, choice of material and production plan.
- The ground space available must be further determined and more information about the location must be obtained.
- The gondola attachment to the ground station in case of a safe mode should be further investigated.
- An emergency procedure for the gondola should be made. For example if the lifting engine gets stuck, there should be a procedure to evacuate the tourists.

22.2.2. SUGGESTIONS FOR TESTS

- The wind and aerodynamics are difficult and bring a lot of uncertainties. A lot of the suggested tests are on this topic and will be summed up underneath this bullet.
  - Wind speed tests at different heights were the blimp is going to be would be very useful and should start as soon as possible. The wind speed is measured at 10 m height and is calculated at the desired altitude with a general equation, so it could differ in reality. Especially the urban environment, with the extreme high buildings, can cause changes to the wind speed and direction.
  - Tests on the influence of temperature on the aerodynamic properties of the wind and the lifting capacity.
  - Research if Reynolds numbers above 10^7 have secondary effects on the drag coefficient.
  - Windtunnel tests for validation of the (dynamic) CFD models.
  - Windtunnel tests to validate the final model with a scale model.
- Some subsystems might need to be tested in a simulated environment. The dutch company NLR has experience with all kinds of environmental simulations. It is recommended to think of the subsystems that need to be tested soon and make an appointment with NLR to discuss the possibilities for testing.
- Some components might need to be tested for their lifetime. If it is known how often they break, it is also known how to implement replacement in the maintenance schedule.
- For the safety mode, extra cables will be attached to the structure and/or envelope material at a ground windspeed of more than 25 m/s. In order to know how much the structure/envelope can handle and how many extra cables need to be attached, testing is required. The patches on the envelope must be tested, as well as the influence of adding extra connection point to the beams.
- It is highly recommended to perform a small scale test of the entire aerostat to check all of its sub components, and thus validate the complete design.
- It should be tested if the led-curtains can handle the wind force or if a protective layer is needed.

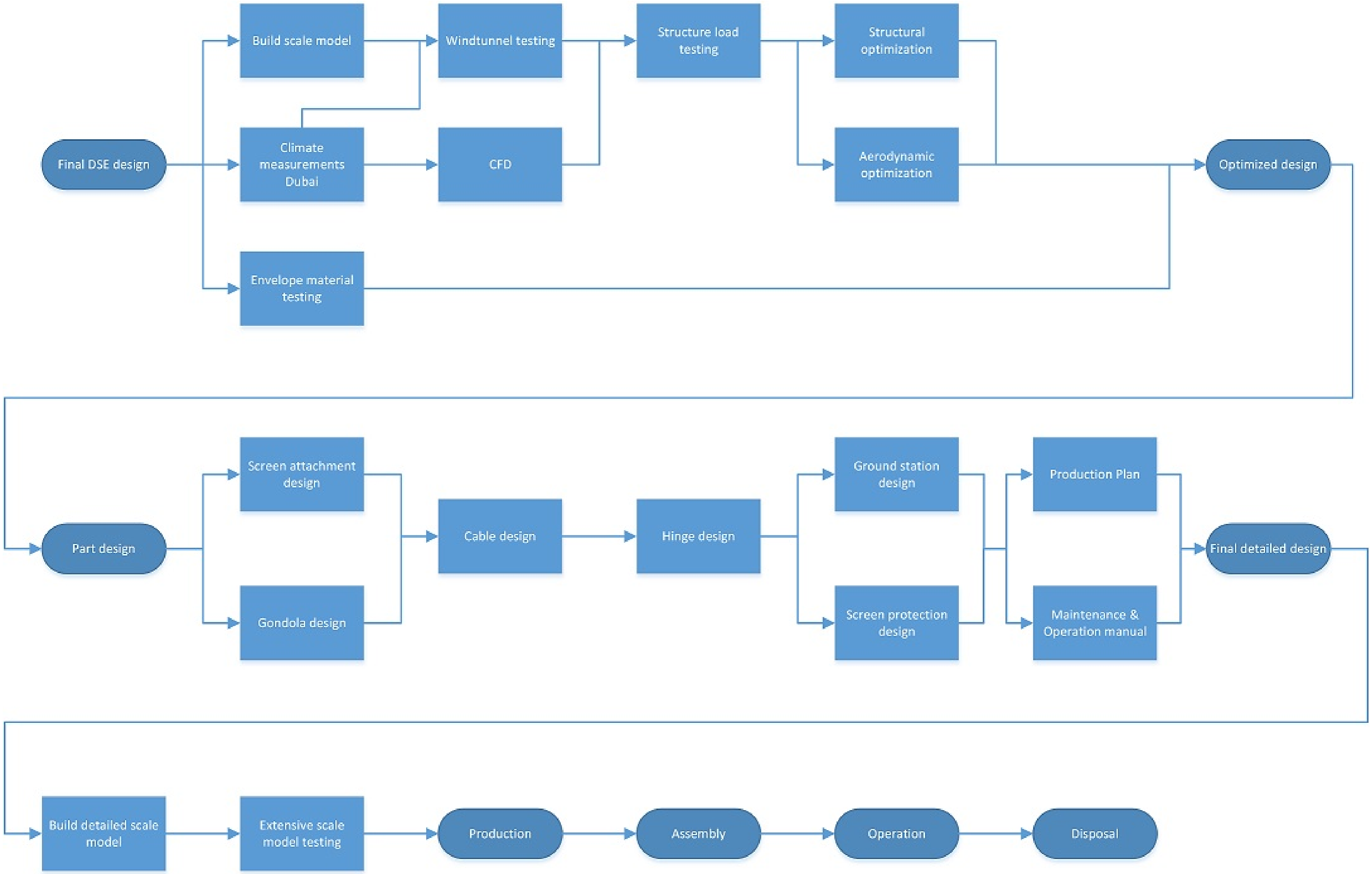

Figure 22.1: Post-DSE work flow diagram

23 Technical design risk map

Technical design risk determines the amount of resources necessary to perform a certain design task. These resources are mainly, but not limited to, engineering hours and design budget. It is important to research design risk before starting a more detailed design, since it can be a useful tool to divide resources in the continuation of the design process.

To get more insight into the different total technical design risks involved in the design, the development risks of the different subsystems are assessed. This is done by placing all subsystems in a technical risk map. In this risk map, the subsystems are ranked according to risk probability and consequence.

The risk probability is determined by the systems current level of development. The development of systems that can be extrapolated from current designs (either in-flight or not-in-flight) has a smaller risk probability than designing a system from a theoretic model.

The other component in determining risk is consequence. The consequence factor is determined by assessing the level of the consequences that occur when failing to design a certain subsystem. This consequence scale ranges from negligible to catastrophic, indicating either a very small or a huge impact respectively.

The subsystems are represented by numbers, categorized in four categories. The numbers belonging to the categories stability, sightseeing, structure or operations can be found in tables 23.1, 23.2, 23.3 and 23.4 respectively. The risk map assessing the risks of different subcomponents is presented in table 23.5.

Table 23.1: Risk map legend: Stability

1	Pole design
2	Vortex handling system
3	Cable vibration handling
4	Cable dimensioning
5	Cable retraction system

Table 23.2: Risk map legend: Sightseeing

6	Gondola structure
7	Gondola aerodynamic stability
8	Gondola lifting mechanism
9	Ground station

Table 23.3: Risk map legend: Structure

10	Internal structure
11	Internal envelope
12	External envelope
13	Screen attachment
14	Hinge design
15	Fishnet design
16	Cable attachments
17	Safety mode attachments

Table 23.4: Risk map legend: Operations

18	Data and electricity transport system
19	Refilling valve
20	Pumping system
21	Screen protection
22	Operational software
23	Backup power unit
24	Ambilights
25	Lightning system

Table 23.5: Subsystem technical design risk map

Feasible in theory	-	22	10,13,24	-
Working laboratory model	-	15	-	2, 7
Based on existing non-flight engineering	-	18	5, 14, 21	8, 17
Extrapolated from existing flight design	9	1, 4, 11	6, 12	3, 16
Proven flight design	19, 20, 23, 25	-	-	-
	Negligible	Marginal	Critical	Catastrophic

24 CONCLUSION

In this report, a team of ten Aerospace Engineering students from Delft University of Technology, who have defined themselves as the "Diamond of Dubai" group, conducted a feasibility study and made a preliminary layout of the world's largest dirigible billboard. The dirigible is equipped with a LED visualization system to display advertizements visible up to 4 kilometers, as well a sightseeing mechanism which supports groups of up to 50 tourists.

The most important outcome of this report is that a technical feasibility is confirmed, provided that assumptions made correspond with reality to a sufficient extent. A preliminary layout shows that, with a correct material choice, it is possible to build a structure light enough to lift with helium, yet strong enough to withstand wind forces. Furthermore, calculations into aerodynamics and stability show that it is possible to keep the dirigible stable and upright in the air. Although the required ground space is currently out of bounds, no large redesign is thought to be necessary to resolve this issue. Finally, it has also been found possible to realize the plan of attaching a gondola to the base of the balloon for sightseeing purposes.

The feasibility of this concept has been confirmed by making a preliminary layout complete with dimensions, weights, cost and more. Multiple design iterations have converged to a single, technically coherent design. This design has been presented to United Balloon, the client who put forward the design request. They have approved of the work done, and plan to continue the project to the extent of finally launching the dirigible in Dubai. Ultimately, the concept of this dirigible is to be extend to over 20 other major cities worldwide, as well as constructing smaller versions for festivals and events. To aid United Balloon in this process, a series of recommendations for post-DSE research and tests have been made, and the Diamond of Dubai group plans on staying in touch with United Balloon to determine the possibilities of future collaboration.

When the dirigible is launched, it will offer a truly unique possibility for companies to display their advertisements and trousists to experience Dubai, as nothing quite similar exists worldwide.

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