DSE - Final Report

Automated launch, landing and storage of a kite power system

AE3200 - GROUP S01

21 June 2013

TU Delft
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AE3200 - Design Synthesis Exercise

Automated launch, landing and storage of a kite power system

Final report

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Preface

This technical report presents the detailed design of an automated launch, landing and storage system designed for a specific pumping kite system, which uses a $70m^2$ kite. It is written to illustrate the result of a research project commissioned by the Kite Power Group, a subdivision of the wind energy research group (former ASSET group). This research project is performed as part of the Design Synthesis Exercise (DSE). The DSE is intended to be the final project of the bachelor curriculum in Aerospace Engineering in which students will have to combine all competences they have learnt up to this point. It is a group project appointed to nine students over a period of 10 weeks time.

The reader of this report is assumed to have a sound technical background. In the analytical approach (see chapter 4) all relevant equations and methods will be explained for clarity. The most basic theorems of structural analysis and system dynamics are however not included in this chapter. Besides prior technical knowledge it is assumed the reader is familiar with kite power generation. The key terms related to kite power technology are included in the glossary but a basic understanding of kite power terminology will increase the readability of this report.

The reader is referred to the summary on page xiii for a brief overview of the results of the detailed design phase. Chapters 14 and section 12.3 and are of specific interest for those that would like to read about the suggestions and recommendations for further development related to the automation of the launch, landing and storage of the specific pumping kite power system. This report is focussed on presenting all details of the final design. This specific solution followed from an intensive design process. One can consult the baseline report [1] for the results of the preliminary design phase and the mid-term report [2] of group S01 for an elaboration on the conceptual design phase.

This report is written by nine Aerospace Engineering students with guidance and expertise of a number of people. First of all, the group would like to thank the tutor of this project, W. Bierbooms, and the coaches J. Chu and F. Tian, for their assistance throughout the entire DSE. The advice on managerial elements of the DSE have been very helpful and allowed the creation of an efficient and pleasant working environment for the group early in the design process. Furthermore the substantial feedback on the content of the previously delivered reports, evaluations of personal and group performance and general consultation during the weekly team meetings have been of great help in improving the quality of the results. Secondly, thanks go out to all other members of the Kite Power Group of the TU Delft, emphasizing the contribution of R. van der Vlugt, U. Fechner, B. Franca and R. Schmehl. The demonstrations of the current pumping kite system, provision of expert knowledge on kite power (systems), valuable suggestions for improvement and constructive criticism have been highly appreciated. The positive attitude and helpfulness of all members of the Kite Power Group towards our DSE research project has certainly not gone unnoticed. Finally, the group would like to express their appreciation to the general organization of the DSE. The exercise has been very challenging and instructive and will be a worthy conclusion of the bachelor curriculum.

21 June 2013
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Glossary

Bridle system	The complete set of small lines between the CU and the kite.
Control unit (CU)	The control unit is the computer and actuator system which controls the steering and braking lines of the kite.
Depowering	The act of leveling out the kite parallel to the wind vector such that it pulls the least but stays stable.
Driving requirement	These are the requirements defined by the client. These requirements will drive the design more than average.
Drum	The cylinder/spool around which the main tether is coiled up.
Early adopters	Individual or company which starts to use a certain technology before the rest does.
FEM	Numerical modeling tool in which a structure is represented by an appropriate number of finite elements interconnected by nodes.
Killer requirement	The killer requirements are the most important requirements that need to be fulfilled by the final design. If these requirements are not met, the design is driven to an unacceptable extent. From this it follows that if the design does not meet the requirements, the design needs an iteration that results in the fulfillment of those requirements.
Power zone	The general direction in which the kite generates the greatest force. Lies right along the wind vector.
Pumping kite power system	A power system, where the motion of pumping a kite is used to generate electricity. The kite is flown in figures of eight while retracting a cable which is connected to the generator. When the tether is reel out, it is reeled-in in zenith position.
Roughness length	The meteorologic equivalent of an aerodynamic drag coefficient [3].
Swivel	The mechanism which guides the tether out from the drum. The swivel rotates along with the flight of the kite.
Time-to-market	Time it takes for a product from being conceived until it is available for sale.
Zenith	The location where the kite is as far up as possible.

List of abbreviations

AC	Alternating Current
ALLS	Automated Launch, Landing and Storage
AR	Aspect Ratio
ARBO	Arbeidsomstandigheden (working conditions)
CBS	Centraal Bureau voor de Statistiek
CPU	Central Processing Unit
CU	Control Unit
CFD	Computational Fluid Dynamics
CON	Constraints
DC	Direct Current
DLLS	Duration of Launch, Landing and Storage procedure
DR	Driving Requirement
DSE	Design Synthesis Exercise
EC	Energy Consumption
ES	Existing System
EU	European Union
EWEA	European Wind Energy Association
FBD	Free Body Diagram
FBS	Functional Breakdown Structure
FEM	Finite Element Method
FFD	Functional Flow Diagram
GNSS	Global Navigation Satellite System
HAWP	High Altitude Wind Power
HB	Horizontal Beam
IEA	International Energy Agency
IMU	Inertial Measurement Unit
I/O	Input/Output
KNMI	Koninklijk Nederlands Meteorologisch Instituut
KA	Kite Adaption
KR	Killer Requirement
LNC	Launch
LND	Landing
LPC	Levelised Production Cost
MNT	Maintenance
N/A	Not Applicable
OT	Operating Time
PET	Polyethylene Terephthalate
PRU	Pressure Regulation Unit
R&D	Research & Development
RP	Rotating Platform
RAMS	Reliability, Availability, Maintainability and Safety
REG	Regulations
RPT	Replacement
SFT	Safety
SS	Swivel Storage
ST	Storage
SUS	Sustainability
TU	Technical University
TECH	Technical
VALID	Verifiable, Achievable, Logical, Integral and Definitive
V&V	Verification & Validation
VAT	Value Added Tax
VB	Vertical Boom

List of symbols

A	Cross-sectional area	$[m^2]$
A_{circ}	Cross-sectional area of a circle	$[m^2]$
A_f	Frontal area	$[m^2]$
A_{tr}	Pre-adhesive treatment cost	[€]
C	Cost	[€]
C_a	Cost of adhesive	[€]
C_{aw}	Cost of adhesive per kg	$[€/kg]$
C_b	Cost of bolting	[€]
C_{CU}	Cost of the CU	[€]
C_D	Drag coefficient	[-]
C_e	Cost of electrode per meter	$[€/m]$
C_f	Cost of flux per meter	$[€/m]$
C_{GS}	Cost of the ground station	[€]
C_{kite}	Cost of a single kite	[€]
$C_{kite_{repl}}$	Cost of replacing a kite	[€]
C_L	Lift coefficient	[-]
$C_{M\&O}$	Cost of the maintenance & operation	[€]
C_{other}	Cost of other parts needed for the total system	[€]
C_p	Cost of a single perforation	[€]
C_R	Resultant coefficient	[-]
C_r	Cost of riveting	[€]
$C_{rep_{kite}}$	Replacement cost of the kite	[€]
$C_{rep_{tet}}$	Replacement cost of the tether	[€]
C_{sb}	Cost of a single bolt	[€]
C_{sr}	Cost of a single rivet	[€]
C_{sys}	Cost of the system	[€]
C_t	Cost in year t	[€]
C_{tether}	Cost of the tether per m	$[€/m]$
$C_{tet_{repl}}$	Cost of replacing a tether	[€]
C_w	Cost of welding	[€]
C_y	Annual cost of the total system	[€]
D	Drag force	$[N]$
D_{kite}	Drag of the kite acting as a sail	$[N]$
E	Energy	$[kWh]$
E_{loss}	Energy lost of the existing subsystems	$[kWh]$
E_{sys}	Energy used by the system	$[kWh]$
E_t	Energy produced in year t	$[kWh]$
E_Y	Young's modulus	$[Pa]$
E_y	Energy produced annually	$[kWh]$
F	Force (subscripts x,y,z states the axis, the subscript beam indicates the forces at the root of the beam)	$[N]$
F_g	Force due to the weight	$[N]$
F_{mt}	Tether tension force during flight	$[N]$
F_t	Tether tension force	$[N]$
f	Reel factor	[-]
f_{opt}	Optimal reel-out factor	[-]
G	Positive feedback	[-]
$\bar{G}$	Negative feedback	[-]
G_e	De-power status (lift over drag ratio)	[-]
g	Gravitational acceleration constant	$[9.81m/s^2]$
h_{ref}	Reference height	$[m]$
h_{alt}	Altitude at which the wind speed is calculated	$[m]$
I	Moment of inertia (subscript states the axis)	$[m^4]$
I_0	Mass moment of inertia	$[kg/m^2]$
I_{circ}	Moment of inertia of a circle	$[m^4]$
J	Safety factor	[1.5]
L	Lift force	$[N]$
L_w	Length of weld	$[m]$
LPC	Levelised production cost	$[€/kWh]$
l	Length of beam analyzed	$[m]$
l_{beam}	Length of the beam	$[m]$
l_{boom}	Length of the boom	$[m]$
l_{CU}	Length of the CU	$[m]$
$l_{kite0.5}$	Span of half the flat kite	$[m]$
l_{pole}	Length of the pole	$[m]$
l_{stroke}	Stroke length of pumping cycle	$[m]$
l_{swivel}	Maximum length of the swivel	$[m]$
l_{sbeam}	Length of the swivel beam	$[m]$
l_{tet}	Length of the tether to be replaced	$[m]$

M	Moment (subscripts x,y,z states the axis, the subscript beam indicates the forces at the root of the beam)	$[Nm]$
M_{net}	Net moment	$[Nm]$
M_{acc}	Moment required for acceleration	$[Nm]$
M_{launch}	Moment required to launch	$[Nm]$
$M_{packing}$	Moment required for packing	$[Nm]$
M_{dec}	Moment required for deceleration	$[Nm]$
m	Mass	$[kg]$
m_{beam}	Mass of the beam	$[kg]$
m_{boom}	Mass of the boom	$[kg]$
m_{CU}	Mass of the CU	$[kg]$
m_{kite}	Mass of the kite	$[kg]$
m_{pole}	Mass of the pole	$[kg]$
m_{sbeam}	Mass of the swivel beam	$[kg]$
N	Number of	[-]
N_b	Number of bolts	[-]
N_{kite}	Number of kite replacements every year	[-]
N_r	Number of rivets	[-]
N_{tet}	Number of tether replacements every year	[-]
P	Power	$[W]$
P_{av}	Average power produced	$[W]$
P_{crit}	Critical buckling load	$[N]$
P_{in}	Power during reel in	$[W]$
P_{max}	Maximum power	$[W]$
$P_{max_{SP}}$	Maximum power of the storage poles	$[W]$
$P_{max_{SR}}$	Maximum power of the swivel rail	$[W]$
$P_{max_{VBR}}$	Maximum power of the vertical boom rail	$[W]$
P_{motor}	Power required by the motor	$[W]$
P_{out}	Power during reel out	$[W]$
P_w	Power available in the wind	$[W]$
p	Distributed load	$[N/m]$
q	Dynamic pressure	$[Pa]$
q_s	Shear flow	$[N/m]$
R	Addition revenue	[€]
r	Radius	$[m]$
$\mathbf{r}$	Radius vector	$[m]$
r_i	Real rate of interest	[-]
S	Shear force	$[N]$
S_A	Surface area of the kite	$[m^2]$
T	Economic lifetime or payback time	$[years]$
$T_{counter}$	Torque due to the counter moments	$[Nm]$
T_{motor}	Torque required for the motor	$[Nm]$
T_{net}	Net torque	$[Nm]$
T_q	Torque	$[Nm]$
t	Time	$[s]$
t_{in}	Time of the reel in	$[s]$
t_{op}	Operational time	$[s]$
t_{out}	Time of the reel out	$[s]$
t_s	Thickness	$[m]$
V_t	Speed vector tangential to the tether	$[m/s]$
V_w	Wind speed	$[m/s]$
v_{alt}	Wind speed at altitude	$[m/s]$
v_{ref}	Wind speed at reference altitude	$[m/s]$
W_a	Weight of adhesive used	$[kg]$
$x_{c.g.}$	Location of the center of gravity	$[m]$
Y	Von Mises stress	$[Pa]$
z_0	Roughness length	$[m]$
α	Angular acceleration	$[rad/s^2]$
β	Angle of the main tether w.r.t. the horizon	$[deg]$
γ	Boom hinge angle w.r.t. the vertical position	$[deg]$
δ	Angle of deflection	$[deg]$
ζ	Harvest factor	[-]
ζ_{in}	Harvest factor at reel in	[-]
ζ_{out}	Harvest factor at reel out	[-]
η_{gen}	Efficiency of the generator	[-]
η_h	Human efficiency	[-]
θ	Angle traveled by the actuator	$[deg]$
θ_{acc}	Angle required for acceleration	$[deg]$
θ_{launch}	Angle required to launch	$[deg]$
$\theta_{packing}$	Angle required for packing	$[deg]$
θ_{dec}	Angle required for deceleration	$[deg]$
ν	Displacement	$[m]$
ξ	Angle of the swivel rail w.r.t. the horizon	$[deg]$
ρ	Air density	$[kg/m^3]$
ρ_m	Density of material used	$[kg/m^3]$
σ	Normal stress (subscripts x,y,z states the axis)	$[Pa]$
τ	Shear stress (subscript describes which plane)	$[Pa]$
ϕ	Heading angle	$[deg]$
ω	Angular velocity	$[rad/s]$

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Summary

The Kite Power Group of the Wind Energy Department of Delft University of Technology has developed a pumping kite system to harvest high altitude wind energy (HAWP). HAWP technology is one of many renewable energy solutions that are emerging in a time at which Earth's non-renewable energy resources are becoming scarce. The kite power system operates in periodic pumping cycles, alternating between reel-out and reel-in of the main tether from a drum, which in turn drives a generator. Electricity is generated during reel-out and only a small portion of the produced energy is reused during the reel-in process, which gives a positive end result. The current system has a movable ground station and contains all basic elements required to operate the kite in flight. The technology of the kite control unit is still is at an early stage of development and is being further developed and extensively tested at this moment.

The future of the kite power technology depends heavily on the possibility of the kite power system to be fully automated and autonomous. In the current state of development of the system, a ground crew of at least three people is needed to operate the system which makes it highly inconvenient and costly in practice. As part of the Design Synthesis Exercise (DSE) a group of nine students was given the task to develop an automated launch, landing, and storage system for an upscaled version of the specific pumping kite power system which uses a kite of $70m^2$. Automation of the entire operation will enable the technology to be implemented on a larger scale and as such become economically profitable.

Going through a full design process that ended with a detailed design of a launch, landing, and storage system in a period of 10 weeks required a well structured planning. Systems engineering methods were used which divide the design process in three main parts marking their respective completion in specific milestones. The first part covered the entire project planning and the preliminary design phase with a baseline report as the first milestone in the design process. In a highly creative manner a large number of ideas was produced. Subsequently, each one of them was evaluated by means of a trade-off and obvious losers faced immediate elimination.

The second part of the design process was focused on the conceptual design of a limited number of concepts. At the start of this phase all ideas from the first part of the design process were integrated into full-system concepts. The feasibility of each of the integrated concepts was evaluated on a limited number of criteria after which another trade-off was performed. Four different concepts were chosen and were further developed in the remainder of the conceptual design phase. Multiple analyses were performed on topics such as functionality, technical details, sustainability and finance to obtain a good overview of the overall performance of each concept. After extensive research on all four concepts another trade-off was carried out and the final selection of one definite concept was made. At this point the conceptual design phase reached its milestone. Both the clients and kite power experts have confirmed the decision to take this concept into the detailed design phase.

The third and final part of the systems engineering approach is the detailed design phase. In this phase the chosen concept was extensively researched and upgraded to a detailed design over a period of three weeks, and the results are contained in this technical report. Prior to research on the technical properties of the detailed design a detailed design overview was produced. The functionalities of the system were fully explored and put on paper. Furthermore the automated system was divided into subsystems and corresponding mechanisms. This enabled performing detailed research on specific elements of the system in subsequent steps of the design process. At the start of this third phase, pertinent background studies were performed to acquire a thorough understanding of both the aerodynamics and the commercial, environmental, and legal frameworks. The detailed research was first performed on all the subsystems, whereafter the integrated system got a closer look. The analytical approach was hereby always set prior to any calculations. The analysis of the subsystems was divided into structural integrity, energy consumption, actuators and sensors, opera-

tion time and cost. The integrated system analysis comprised research on the operations and maintenance, sustainability, soft- and hardware, and RAMS characteristics as a few examples. During this process many challenges arised. To resolve these challenges and optimize the design an iteration phase was implemented after the research was finished. In this phase the compliance matrix was used as a guide and solutions that improve compliance of the detailed design with the requirements were implemented. The detailed design phase ended with an investigation on post-DSE topics such as a financial analysis including profitability and Return on Investment (RoI), verification and validation and a project design and development logic.

As a final result of the design process a solution for automated launch, landing, and storage of the kite power system has been produced on a detailed level. This system is based on a tall vertical boom of $35m$ (comparable to the length of a Boeing 737) on which a horizontal beam can slide up and down. The kite is launched from and landed upon this horizontal beam, when it is positioned at the top of the vertical boom. Both the horizontal beam and vertical boom can be tilted to put the system at an optimal angle for the launch and landing process. A storage unit has also been designed on a ground level. The horizontal beam can slowly lower the kite into the storage, in which a folding mechanism has been added to prevent entanglement of the tethers and the bridle system. The system has been designed in such a way that it can operate automatically and autonomously for a period of three months; a decision-making tool has been produced that ensures operation only within the kite's operating limits (no lightning and a limited range of wind speeds). The research and development process as described in the above paragraphs have ensured that the detailed design has been explored on a widespread range of topics and has pushed to project group to achieve a sound level of depth within the available resources.

The various results that are produced in this report lead the way for several conclusions. The most important conclusion is that the performance of the automated launch, landing and storage system is considered to be a success. It was shown that the the design can autonomously operate a pumping kite system within the boundaries of the requirements. Furthermore, it was shown that the system can land the kite in a wind speed range of 4 to $25m/s$ and launching can be performed between 5 and $25m/s$. However, this performance fully relies on the capabilities of the control unit. The system was required to not exceed the limit of using 0.1% of the energy produced by the kite for the launch, landing, and storage procedure. As the system uses 0.036% of the average produced energy, it is considered to have met this requirement.

As the team aimed to develop a sustainable design, recyclable materials were implemented. Besides the beam subsystem, steel is used in the design of the automated launch, landing and storage system. Steel is found to be recyclable for 93% and has highly convenient properties in case of structural application as well as costs. As for some parts no renewable materials could be used for structural or durability reasons, the goal to make the system 100% recyclable is not met.The client has stated a maximum cost requirement of €20,000. Unfortunately this requirement is exceeded by 167% as the total estimated costs were estimated to be about €53,500. If the client would reach break even after 20 years of operation, the energy price of $1kWh$ will have to reach an average price of €0.285, which is unfeasible in comparison with the current price of €0.06. The main reason for this is the replacement of the kite and main tether after each three months.

The most important recommendations that follow from the conclusions are related to cost reduction, profitability and funding. The currently designed system increases its cost budget of €20,000, reaching a total of €53,451. It is suggested to use cost estimation relationships for assembly to obtain a more accurate representation of the total cost. A second point of interest is to investigate the need for storage of the kite. Possibly this need can be eliminated or reduced to a partial-cover if the kite and tether durability are increased. The regular kite and tether replacement (every three months) are the largest cost drivers of the entire system and an increase of their durability and lifespan will most certainly help the system to move towards a commercially feasible state. Other recommendations to improve the profitability of the system are related to upscaling the existing model and exploration of an offshore implementation, such that the system can generate more power. The last two propositions on the financial area are focussed on funding. The Kite Power Group is advised to start with the acquisition of subsidies as soon as possible and also look into the prospects of attracting business partners and sponsorships.

A second set of recommendations is related to sustainability. On one hand hand the amount of recycled and/or recyclable materials can be further increased. A second suggestion poses the idea of promoting the kite power system as the true symbol of renewable energy and innovation to increase public interest. The kite power generation could be combined with a wind turbine on top of the tall vertical boom and a storage roof that is covered with solar panels. One final recommendationn follows from the contact with SkySails during this project. At this point such company is already commercially active on the energy market with a kite power system that has comparable features to the proposed detailed design in this technical report. The company has informed that they would gladly support the research with technical feedback and as such it is recommended to keep close contact with this company in further development stages.

1. Introduction

In a world where technologies evolve at a surprisingly fast pace and competition is at an all-time high, it has become of utter importance to push innovation to an even greater extent and break through into the unthinkable. The Kite Power Group of the Wind Energy Department of Delft University of Technology has developed a pumping kite system to harvest high altitude wind energy. However, the future of this technology depends heavily on its possibility to be successfully automated. In the current state of the system, a ground crew of at least three people is needed to operate the system, which makes it highly inconvenient and costly in practice. As part of the DSE a group of nine students was given the task to develop an automated launch, landing and storage system for the upscaled version of the existing pumping kite power system. This version uses a kite of $70m^2$. The project will enable the technology to be implemented on a larger scale and become economically profitable. In cooperation with the clients the project objective statement has been formulated as:

> *"Design a sustainable, automated launch and landing subsystem (onshore) for some specific pumping kite power system, which includes safe storage of the inflatable membrane wing (outside of the kite's operating limits), within a budget of €20,000 by 9 students in 10 weeks time."*

An intensive design process has led to the detailed system design and the final result will be discussed in this report. The preliminary and conceptual design phases are not discussed in this report and the interested reader is referred to the Baseline Report [1] and the Midterm Report [2].

The final design is obtained by using an iterative design process. Initially the dimensions of the design were determined, which served as the basis for the first iteration. When the first iteration came to a conclusion, the design underwent a requirement compliance check. This determined the necessary changed that had to be made in the second iteration. The compliance check was repeated continuously until the design reached an optimal state and could be deemed as final.

The structure of this report is as follows: First the reader is given an overview of the entire system in chapter 2, the existent components and the entirety of the design, finalized with establishing the requirements and functions of the system. In chapter 3 the design process is explained and the context in which the designed system must operate is determined by performing a background study that covers the economic, environmental, technical and legal frameworks. Furthermore, the starting point for the iteration phase is determined by making a resource allocation for the financial, time and energy budgets. chapter 4 elaborates on the different calculation methods used to analyze the subsystems. A distinction is made between different topics such as assumptions, structural analysis, energy consumption, operating time, actuator power, and cost estimation. This chapter is the foundation for the entire analysis and iteration phase. After the analytical basis is formed every subsystem is thoroughly analyzed in chapter 5 through chapter 10, using the aforementioned analytical topics. The different steps within the iteration phase are not discussed and only the final results are given. Following the analysis of the subsystems separately, they are consolidated in chapter 11. This chapter covers the method for integration of the subsystems into a single cohesive system, how it is operated, maintained and what its sustainability aspects. The final cost estimated for the entirety of the design is also given in this chapter along with an argumentation on how this cost ensures an optimal system functionality. Chapter 12 touches up on the performance of the entire system, where it is evaluated by checking its compliance with the requirements and its robustness and sensitivity. Furthermore, a future development plan is drafted and a test setup is proposed and the chapter closes with a financial analysis of the entire pumping kite system including the landing, launch and storage system. The report is finalized by the conclusion and recommendations in chapter 13 and chapter 14 respectively.

2. Detailed design overview

This chapter will present the big picture of the detailed design of the launch, landing and storage system for a specific pumping kite system. The purpose of this chapter is to give the reader a clear sense of the overall design lay-out and system operation, such that following chapters which elaborate on the system and its components in more detail are well understood and can be put in perspective.

In section 2.1 the top and low level requirements are presented. The requirements have been of great importance for the development of the design. The second section presents the details of the kite and tether, including an aerodynamic analysis of the kite's performance. Section 2.3 describes and visualizes the proposed detailed design. The chapter ends with a section that covers the functional analysis of the system by means of descriptions, flow charts and the functional breakdown structure.

2.1 Requirements

At the beginning of the project the client stated the initial requirements for the design. These are called driving requirements and they will guide the design more than average since they form the base of the project assignment as given by the client. Along with the requirements indicated by the client, the project team has identified some additional requirements throughout the design process which will ensure that the final design is the best one possible. Furthermore the requirements for launch, landing and storage have been explored in depth and for these functions low-level technical requirements have been set.

In the complete set of requirements the killer requirements have also been appointed. Killer requirements are the most important to be fulfilled by the final design. If a killer requirement is not met it drives the design to an unacceptable extent. From this it follows that if this requirement is not met the design fails. Therefore this requirement's importance is weighted higher compared to others.

Figures 2.1 to 2.4 give the requirements discovery trees for the top-level and low-level requirements. In the discovery trees a summarized version of the requirements is given along with the requirement identifier codes. A detailed specification of all requirements and the assignment of killer and/or driving status can be found in the first four columns of the tables in Appendix B.

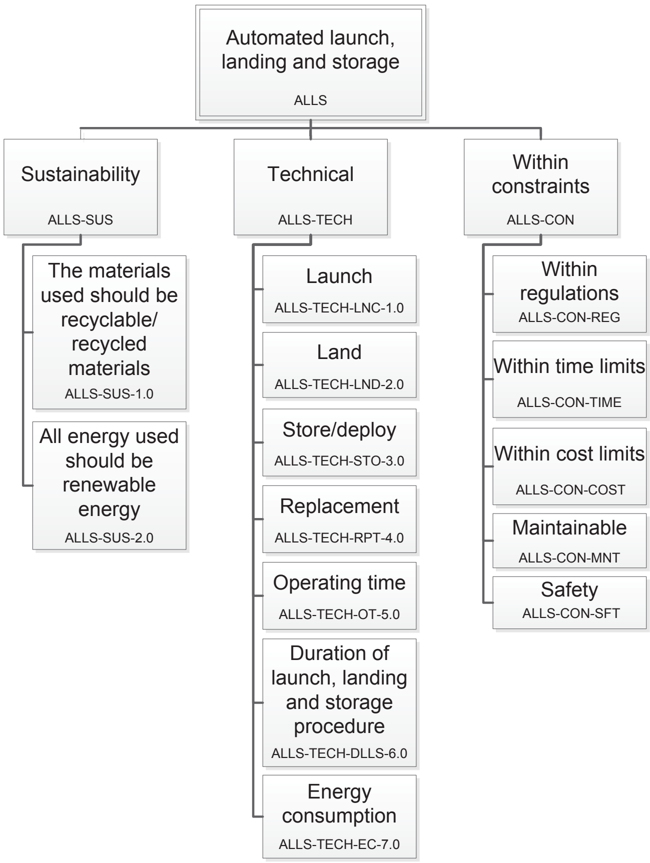


Figure 2.1: Top-level requirements for the launch, landing and storage system

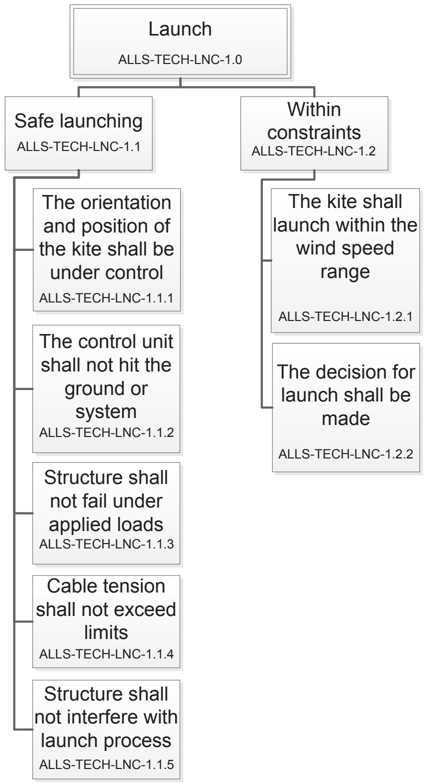


Figure 2.2: Low-level requirements for the launch procedure

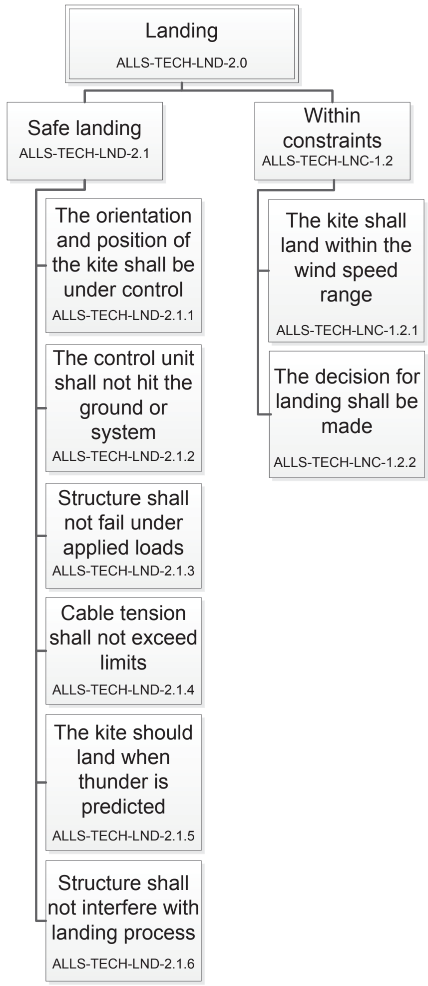


Figure 2.3: Low-level requirements for the landing procedure

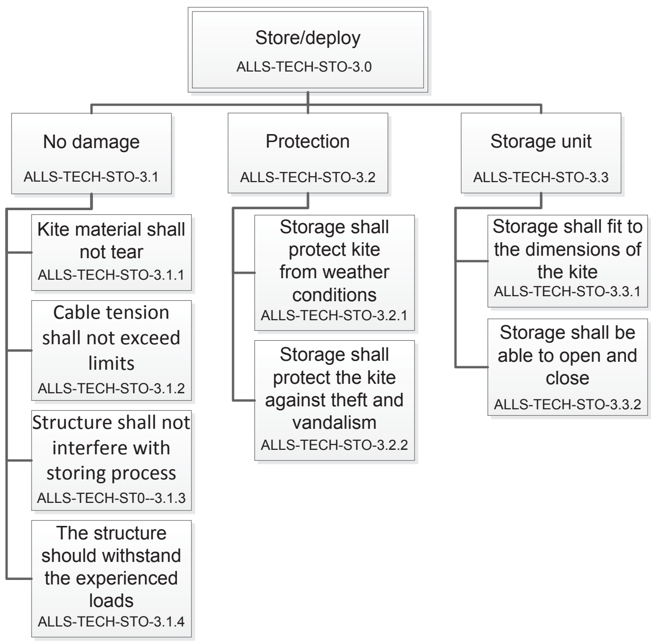


Figure 2.4: Low-level requirements for the storage/deployment procedure

2.2 Kite specification

Understanding the purpose of a design is the first step in carrying out the task successfully and as such it is necessary to introduce an overview of the subject of the design: a $70m^2$ kite used for harvesting wind energy at high altitude. Its physical configuration and aerodynamic properties will be explained in the upcoming sections with the purpose of giving the reader a clear view on the source for dimensions and calculations that will prevail throughout the rest of the report.

Section 2.2.1 gives all details on the power kite, bridle system and tether. The second section discusses the aerodynamic characteristics of the kite.

2.2.1 Dimensions and materials

This subsection elaborates on the dimensions and materials of the kite. The design of the kite has been determined prior to the launch, landing and storage system and therefore it is important to begin the report with this insight. Information used in this section is taken directly from the project guide [18]. It is of utter importance to keep in mind that these dimensions were the basis for a large number of decisions throughout the design phase.

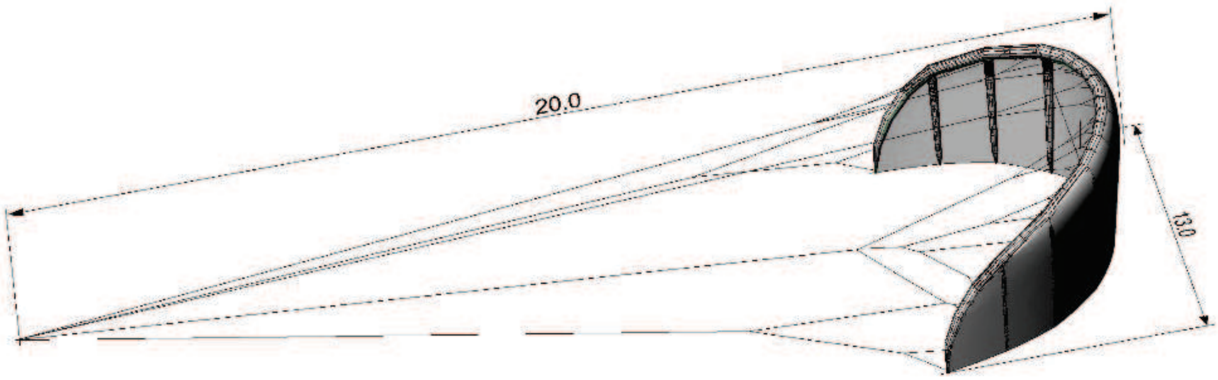


Figure 2.5: The overall dimensions of the kite in meters

The appearance of the kite is shown in Figure 2.5. It consists of an inflated leading edge tube with (inflatable) struts. Between the struts is a lightweight membrane. As this is a lightweight material the mass of the kite is only $45.5kg$. Notice the discrepancy between the wingspan of $13m$ and $13.91m$. For the purpose of the report the latter will be used. The overall flat area (S_A) of the kite is $70m^2$ where the flat wingspan is $13.91m$ and the height is $4.4m$. The total width of the kite with the curvature straightened (otherwise known as flat wingspan) would become $18.7m$. Below a depiction of this kite configuration is given by Figure 2.6.

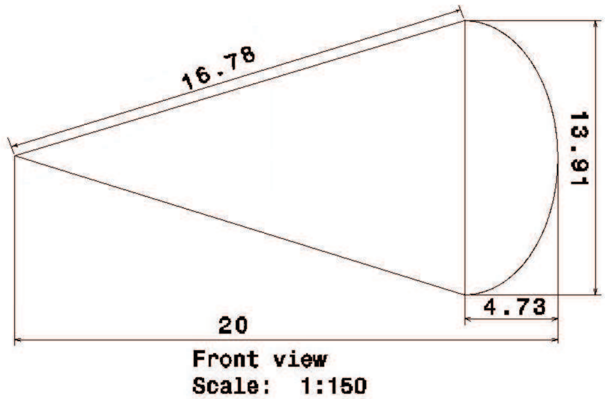


Figure 2.6: The detailed dimensions of the kite in meters

The CU is a $15kg$ component for control of the kite that is suspended from the bridle system at $20m$ from the absolute height of the system. The total length of the bridle system added to half the flat wingspan of the kite is a dimension that plays an important role in the design and a depiction of such state is shown in picture Figure 2.7. In the picture a detaiedl view is provided of the expected bulk height of the kite whilst deflated.

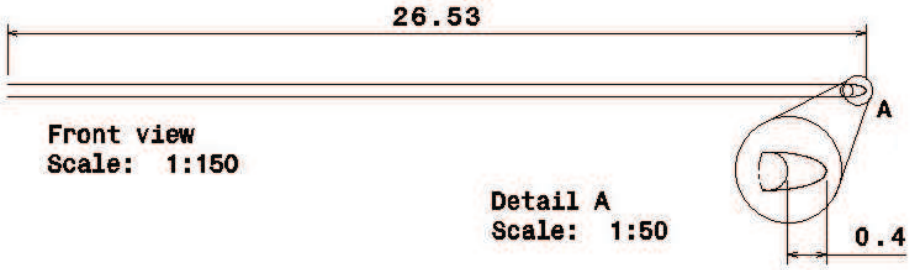


Figure 2.7: The detailed dimensions of the folded kite in meters

Along with the kite, the tether line is another pre-existent component of the system. This line is stored around a spool referred to as drum in the future, located on the ground station. This tether line is made of Dyneema, a lightweight high-strength material with a diameter of $1.2cm$. A more in-depth look at the dimensions of the kite and bridle system is given in Table 2.1 below, obtained directly from the kite power team, complete with parameters that may be useful for further developments on the kite power system.

Table 2.1: All relevant kite dimensions

Parameter	Measure
Flat area (rounded)	$70m^2$
Flat area (real)	$67.985m^2$
No. panels	23
No. struts	8
Flat wingspan	$18.708m$
Flat chord	$4.402m$
Flat AR (rounded)	5
Flat AR (real)	5.243
Projected area	$55.309m^2$
Projected area ratio	79.013%
Projected span	$13.91m$
Projected height	$4.727m$
Projected AR	3.498
Side-view area	$15.809m^2$
Wingtip span	$13.91m$
Upper sail area	$71.466m^2$
Leading edge 3D	$18.911m$
Trailing edge 3D	$18.824m$
Bridle count	82
Bridle length	$184.185m$
Bridle height	$7.57m$
Bridle height percen	40.597%
Canopy tip arc length	40.059%
Bridle-canopy center length	$7.782m$
Bridle-canopy tip length	$5.892m$
Bridle-canopy tip percent	75.713%

2.2.2 Aerodynamic characteristic estimates

In this section the aerodynamic characteristics of the kite are estimated using basic aerodynamic equations and simple simulations. The kite is assumed to be a point mass and the tether to be weightless, prior to modifications necessary for the design. The influences of the modification on the kite are discussed in chapter 5.

The kite can be flown in two general modes: the non-maneuvering mode and the crosswind flying mode. In the non-maneuvering mode the kite is merely reeled in and reeled out and there is no sideways motion of the kite. In the crosswind mode the kite is not only reeled out but also flying sideways, increasing the apparent wind on the kite which in turn increases the lift force and thus the power produced. The flight path resembles an eight figure, from which such a flight pattern derives its name.

In next sections first the aerodynamic forces after landing of the kite are considered. These are followed by an aerodynamic analysis of the kite during the different flight modes. The wind speeds used in the derivatives in this section are always the local wind speeds at the height of the kite.

Aerodynamic analysis of the landed kite
Even when the kite is not flying it can induce aerodynamic forces, which are transferred directly to the structure. There are two large forces considered here, namely:

1. The drag force of the inflated kite after landing.
2. The normal drag force of the deflated kite when catching wind like a sail.

The drag force of the inflated kite is due to the resistance of the kite to wind after landing. This drag force is largest for the strongest wind in which the system is able to land or launch the kite. Using Equation 2.1 and assuming $C_D = 0.2$ and $V_w = 25m/s$, which corresponds to a fully powered kite, a drag force of $5.4kN$ is obtained. In reality the kite will not be fully powered during landing in high winds, however this value is a safe maximum.

The deflated kite may at one point behave like a large sail and catch a lot of wind. This drag force can be calculated by modeling the kite as a flat plate with a surface area half of the full area of the kite. The drag coefficient of a 3D flat plate is assumed to be $C_{D_{plate}} = 1.28$, according to [19]. The wind speed is taken as $V_w = 25m/s$ and the surface area will be $S_{A_{plate}} = 35m^2$. Substitution of all these values into Equation 2.1 yields $D_{plate} = 17.5kN$. For the calculation of the lift Equation 2.2 is used, which is needed further in this chapter.

$$D = \frac{1}{2} \cdot \rho \cdot C_D \cdot V_w^2 \cdot S_A \qquad (2.1)$$

$$L = \frac{1}{2} \cdot \rho \cdot C_L \cdot V_w^2 \cdot S_A \qquad (2.2)$$

Aerodynamic analysis of a stationary kite
The kite will only be able to fly if its lift force is able to counteract the weight of the kite F_g and the tether force F_t. This required lift is achieved only with a certain minimum wind speed. This minimum speed is very important especially for launching, because during this phase the system is not able to increase the apparent wind and thus the lift force by reeling in the kite.

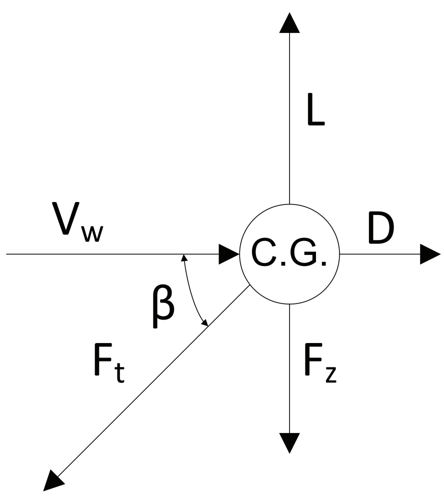


Figure 2.8: The free body diagram for a kite which is considered to be a point mass.

The stationary kite can be modeled using the free body diagram (FBD) as illustrated in Figure 2.8. This model is used to consider the landing and launching behavior of the kite. From this Equation 2.3 and

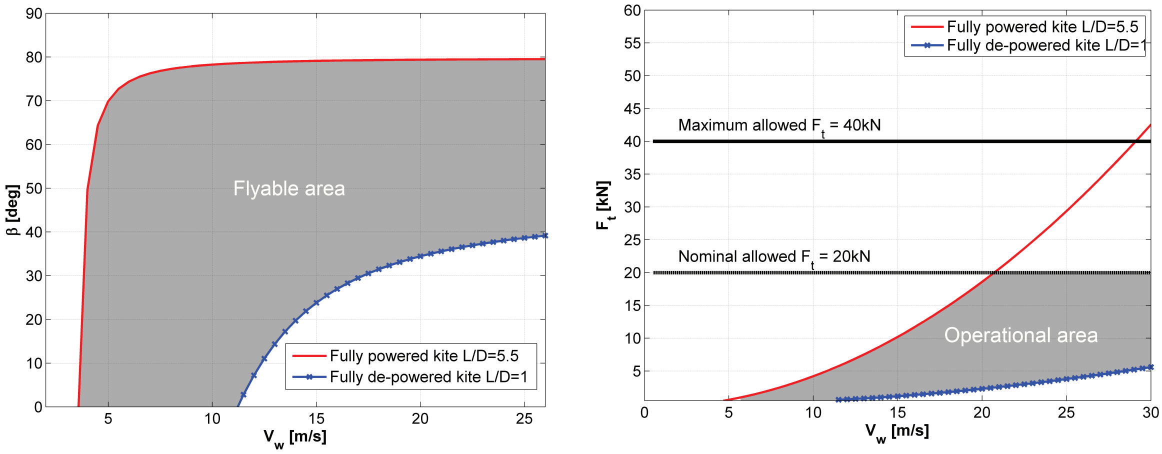
Equation 2.4 can be derived.

$$L = F_g + F_t sin(\beta) \quad (2.3) \qquad D = F_t cos(\beta) \quad (2.4) \qquad F_g = mg \quad (2.5)$$

Rewriting these equations will yield Equation 2.6 for calculating β and Equation 2.7 for calculating F_t.

$$\beta = arctan(\frac{L - mg}{D}) \quad (2.6) \qquad F_t = \frac{D}{cos(\beta)} \quad (2.7)$$

Equations 2.1 to 2.6 will be used to plot β and F_t for different wind speeds, resulting in Figure 2.9. The requirements state that during landing and launching the tether force F_t should not exceed $40kN$. From Figure 2.9b it can be concluded that this requirement is met by using the depower ability of the kite.



(a) The angle between the tether and the wind vector for different wind speeds

(b) The tether force for different wind speeds.

Figure 2.9: Aerodynamic characteristics for the stationary kite

From Figure 2.9 some important conclusions can be drawn: From Figure 2.9a it can be concluded that for stationary flight β is never larger than 80°. However reaching a tether angle larger than 80° can still be achieved by reeling in the kite and letting it overshoot, although it will not stay in place during this situation.

When assessing Figure 2.9b it can be concluded that the kite is able to fly and kept at a stationary location when $V_w = 4m/s$ albeit with a low β (≈ 50). This angle will make landing and launching more challenging. In chapter 5 this will be further elaborated. During the launch the low tether force of $F_t = 100N$ will also pose a possible problem. The kite will only gain altitude very slowly when reeled out and is therefore very sensitive to a sudden drop in wind speed. This will inevitably increase the risks of failing to launch.

Figure 2.9b clearly shows that the tether tension can be kept within its posed limits by depowering the kite. In the case of a fully powered kite the nominal tether tension is reached at $V_w = 20.7m/s$ and the maximum tether tension will be reached at $V_w = 29.1m/s$. The latter is outside of the landing and launching wind range. The curve for the depowered kite stays below both these limits for all required landing and launch wind speeds.

Aerodynamic analysis of non-maneuvering kite

The purpose of the kite is to generate electricity, this is done by letting the kite reel out, which enables a generator to create electrical energy. When the kite is fully reeled out it must be reeled in again in order to retrieve the tether and prepare the kite for a new reel-out phase. During this phase energy is required, which is fortunately less than what is generated during the reel out phase, thus on average energy is produced. The required energy can be minimized by operating the kite in the non-maneuvering mode when fully depowered. During reel-out the kite is operated in crosswind mode to increase the power output.

When operating the kite in non-maneuvering mode it is reeled-out in a straight line upwards. The tether tension (F_t) for the non-maneuvering mode can be calculated according to [20] and [21] by Equation 2.8. Here f is the reel factor which is defined in Equation 2.9. V_t is the speed vector tangential to the tether and is positive for reeling out. G_e is the lift-over-drag-ratio and is given by Equation 2.10, which takes into account the drag force of the tether. C_{D_t} is the drag coefficient of the tether and is assumed to be 1.2 as opted by R. Schmehl (2012) in his Kite Power Theory paper [22]. C_R is the dimensionless coefficient for the aerodynamic resultant force.

$$\frac{F_t}{qS_A} = C_R \frac{[\sqrt{1+G_e^2(1+f^2)}-f]^2}{1+G_e^2} \quad (2.8) \qquad f = \frac{V_t}{V_w} \quad (2.9)$$

Where:

$$G = \frac{L}{D+D_t} = \frac{C_L}{C_D + \frac{C_{D_t} l_t d_t}{4S_A}} \quad (2.10) \qquad C_R = \sqrt{C_L^2 + C_D^2} \quad (2.11)$$

The power produced by the system is given by Equation 2.12, in which P is the power produced by the kite. In order to simplify the calculations the harvest factor (ζ) is used, which is defined in Equation 2.13. Combining Equation 2.8, Equation 2.12, Equation 2.13 and solving for the harvest factor yields Equation 2.14.

$$P = F_t f V_w \quad (2.12) \qquad \zeta = \frac{P}{\frac{1}{2}\rho V_w^3 S_A} \quad (2.13) \qquad \zeta = C_R \cdot f \cdot \frac{[\sqrt{1+G_e^2(1-f^2)}-f]^2}{1+G_e^2} \quad (2.14)$$

Aerodynamic analysis of maneuvering kite

In order to increase the power production during reel-out the kite is flown in crosswind mode. In this mode the kite is not only reeled-out but also flying sideways. This sideways motion increases the apparent wind on the kite and thus increases the lift and tether tension. In this analysis the change in direction needed to keep flying is not taken into account. The maneuvering kite will be flying figures of eight, as illustrated by figure 2.10 and 2.11.

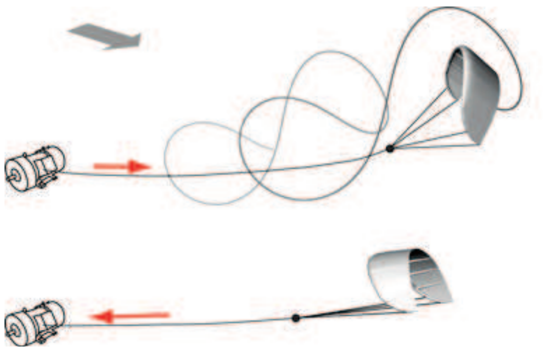


Figure 2.10: Overview of the pumping cycle

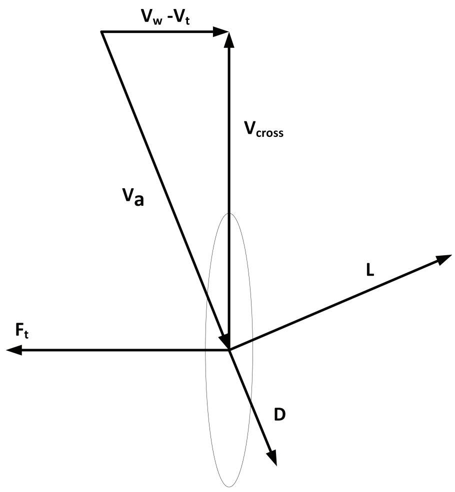


Figure 2.11: Maneuvering kite

According to [20] the increased tether tension can be calculated using Equation 2.15, where ϕ is the heading angle with respect to the wind direction and β is still the tether angle with respect to the ground. Combining this once more with Equation 2.13 and Equation 2.12 yields Equation 2.16 to calculate the harvest factor. A surprising result is the fact that the harvest factor can become larger than 1, even up to 4. This would imply that the kite is harvesting more energy than there is available in the air. Of course the kite is not able to generate more energy than what is available. The cause to this remarkable result is the ability of the kite to extract energy from a much larger area than its own projected area. By flying the figures of eight the kite increases the lift force and subsequently the power produced.

$$\frac{F_t}{qS_A} = C_R \cdot (1+G_e^2)(sin(90° - \beta)cos\phi - f)^2 \quad (2.15) \qquad \zeta = C_R(1+G_e^2) \cdot f \cdot (cos\beta cos\phi - f)^2 \quad (2.16)$$

Power curve of complete system

The complete pumping cycle consists out of a reel-out phase in which in the kite is preferably in crosswind mode, followed by the reel-in phase, in which the kite is in the non-maneuvering mode. There is also a transition phase between the two, but this phase is neglected in this analysis.

The kite is assumed to be operated on a tether angles of $\beta > 20°$ which would take in account the height of any object. $\beta = 20°$ would be an optimum according to [20]; however because the generator is not able to cope with the available energy this angle is increased during the simulation.

The kite is assumed to be operated with a heading angle of $\phi = 0°$ which is measured with respect to the wind vector. In order to optimize the power output of the system the reel-in factor and the operating tether angle is changed. The tether angle will in turn determine the optimal reel-out factor by Equation 2.17. A simulation is used in order to estimate a power curve, which calculates the best reel-in factor and reel-out factor for every wind speed. The simulation should also prevent the tether force from becoming too large. This is handled in the first place by changing the depower status and secondly by increasing the reel out speed away from the f_{opt} value. The depowering is simulated by decreasing the lift over drag ration (G).

In order to calculate the power produced during the reel out phase the influence of the generator has to be taken into account. This is done with the assumptions of a generator efficiency of $\eta_{gen} = 0.9$ and by not producing more than $50kW$ power.

$$f_{opt} = \frac{1}{2}cos\beta \tag{2.17}$$

During the reel-out the kite is operated in the crosswind mode, thus the simulation uses Equation 2.16 to calculate the harvesting factor (ζ_{out}) and substitutes it into Equation 2.18 to obtain the power produced, where P_w is the power available in the air. The power required to bring the kite back down is calculated with Equation 2.14 where P_w is again the power available in the air. During reel-in the kite is assumed to be in non-maneuvering mode and a negative reel factor is chosen. Again the generator has to be taken into account and this is done by using Equation 2.19.

$$P_{out} = \zeta_{out} P_w \eta_{gen} \tag{2.18}$$

$$P_{in} = \frac{\zeta_{in} P_w}{\eta_{gen}} \tag{2.19}$$

$$P_w = \frac{1}{2}\rho V_w^3 S_A \tag{2.20}$$

The average power the system delivers can be calculated by Equation 2.21, where t_{out} is the time required to reel out the kite and t_{in} is time required to reel in the kite as defined by Equation 2.22. Finally, l_{stroke} is the stroke length of the pumping cycle. The average power is optimized by choosing appropriate values for the reel-out and reel-in speed while keeping all values with their boundaries.

$$P_{av} = \frac{P_{out} t_{out} + P_{in} t_{in}}{t_{out} + t_{in}} \tag{2.21}$$

$$t = \frac{l_{stroke}}{V_w f} \tag{2.22}$$

The simulation assumes the wind speed to be constant during the entire power cycle, thus the wind distribution because of height is not taken into account. The influence of tether drag is taken into account during this simulation and assumes a tether length of $300m$. After running the simulation the power curve of the system can be estimated and which is given in Figure 2.12. When looking at the power curve it is striking how fast the line depicting the generated power reaches its maximum. This is due to the fact that the alternator cannot generate any more electricity, even if the kite would pull harder.

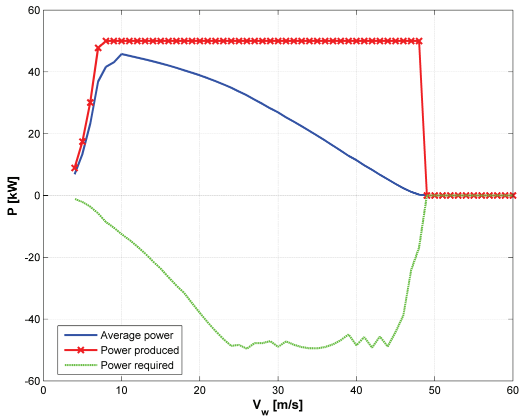
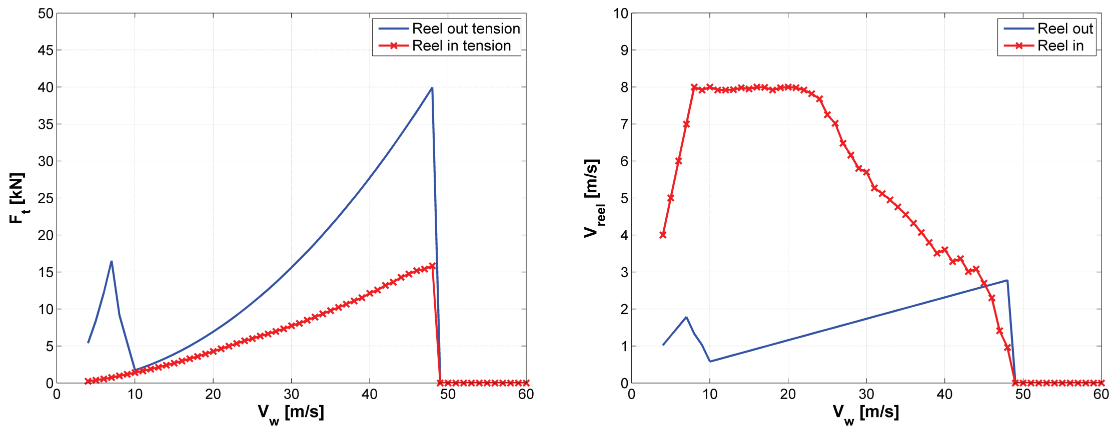


Figure 2.12: The power curve of a $50kW$ $70m^2$ kite system.

Verification

Although the above calculations and simulation are very crude and contain many simplifications they still should be verified. The simple FBD in the first section is in accordance with [22] and the equations in the other sections are from [20] and are in line with [21]. In order to verify the proper working of the simulation the tether tension F_t and the reeling characteristics are also investigated. From Figure 2.13a it becomes clear that the system is able to keep the tether tension within its limits and that the maximum reeling speeds does not exceed the limit of $8m/s$. The behavior of the tether tension is also as expected because it increases with wind speed and is leveled out when it reaches the nominal tension, this is done by changing the reel out speed and by depowering the kite.

From Figure 2.13b it becomes clear that for low wind speeds the systems tries to reel in the kite very fast in order to reduce the reel-in time. The tether tension is very low thus reducing the reel-in time will increase the average power (P_{av}). For larger wind speeds the system has to reduce the reel-in speed in order for the generator to be able to get the kite back. It becomes clear that this is the most limiting factor for the system to operate in high wind conditions.



(a) The tether force F_t during reel out phase (b) The reeling speeds for reeling out and reeling in

Figure 2.13: The results from the simulation

2.3 Detailed design configuration

This section covers the configuration of the detailed design of the launch, landing and storage system by means of clarifying descriptions and pictures. A good understanding of the general configuration will help the reader to better understand the following topics in their entirety.

For the convenience of the design the system has been split up into six main subsystems. These subsystems collaboratively perform the tasks of launch, landing and storage. For the design process, two types of subsystems can be distinguished, namely existing and designed subsystems. Existing subsystems are already used in the current setup of the Kite Power Group of the TU Delft and have not been redesigned. Designed subsystems have been worked out in detail within this project. In Figure 2.14 the system is represented visually, where the six subsystems that have been designed are also pointed out:

- Kite adaptation
- Horizontal beam
- Vertical boom
- Rotating platform
- Swivel storage
- Storage

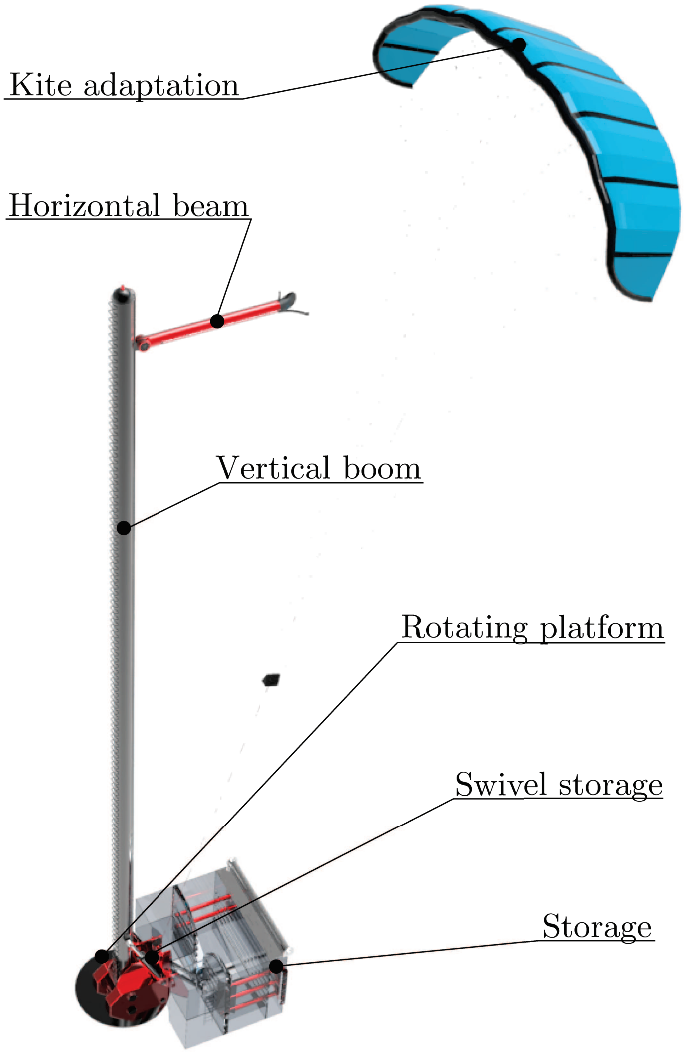


Figure 2.14: Overview of the automated launch, landing and storage system with all subsystems

In subsection 2.3.1 the existing subsystems are described, followed by a short description and illustration of the designed subsystems in subsection 2.3.2.

2.3.1 Existent subsystems

In the current setup of the kite power system the ground station is centered around a truck and there is no fixed ground station. This subsection describes the core elements of the current system that will be implemented in the design without any major adaptations. As stated in assumption M01 in section 4.1, it is assumed that these subsystems can be scaled to accommodate the $70m^2$ kite and require no major changes for implementation in the design of the launch, landing and storage system. The existing subsystems that are defined in this section can have a different location within the newly designed system, but their core functionalities and setup will not change. Small adaptations are discussed in chapter 5.

Drum

In the existing kite power system the main tether is wound on a drum which drives the generator during operation (see Figure 2.15). The drum can both reel in and reel out the tether line and receives its commands from the CPU. At this moment the speed of rotation of the drum can already be adapted which is most certainly required for accurate kite control during landing, storage, deployment and launch.

Figure 2.15: Drum of current kite power system [4]

Weather stations

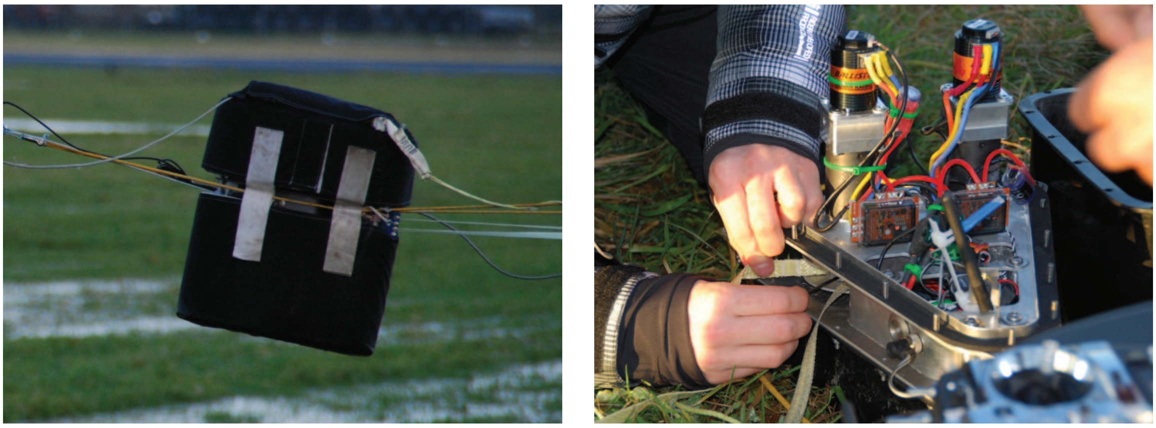
The current power system has two weather stations. One is a ground-based system that determines the weather conditions at a few meters from the ground. The second is a small weather station mounted on the kite to measure wind conditions at the altitude of flight. The primary task of the weather stations is the determination of the wind speed and direction, which are vital parameters for the operation of the kite. These two wind parameters also influence the required orientation and/or deflection of the structural elements of the system during landing and launch.

Weather forecasts also need to be imported and processed to ensure optimal kite operation, only within its operating limits. These forecasts help reduce the risk of damage by ensuring that the kite is already landed and stored when a thunderstorm takes place in close proximity of the kite power system. The weather stations will provide real-time data, while forecasting belongs to the CPU. Further elaboration on the weather-dependent operating limits can be found in subsection 3.2.2.

CU

The technology of the CU is still quite immature and requires some additional development. The CU itself will not be redesigned or further developed within the scope of this project, but the project will produce a list of requirements regarding CU performance (see subsection 4.1.3). These will fulfill the landing and launch with the newly developed system described in this technical report. With these requirements the Kite Power Group of the TU Delft will have a solid base for further development/improvement of the CU.

As defined in subsection 2.2.1 the CU will hang $20m$ below the $70m^2$ kite and it is the connection point between the main tether and the bridle system. The weight is given to be $15kg$ and it has a waterproof casing [18]. It is connected to the kite with four lines of which two are used for steering. The other two change the lift of the kite (powering and depowering) [5]. Additionally a renewable energy source will have to be added (e.g. propeller, solar panel) to provide power to both the CU itself and an additional PRU which will be attached to the kite. The PRU is further explained in chapter 5. This energy source on the CU is also assumed to be present (see assumption CU01) and the additional power requirements due to the PRU are given to Kite Power Group as input for further CU development.



(a) Packed CU (b) Steering belts of CU

Figure 2.16: CU of the current kite power system [5]

CPU

The CPU is the data processing unit of the kite power system and is located at the ground station. It receives data such as weather forecasts and feedback information from all of the system's mechanisms. The CPU comprises a decision-making tool and, based on all inputs, is able to send out control commands to all of the mechanisms to ensure proper functionality of the entire system. The CPU will also be the platform for human interaction with the system to allow staff members to manually control the system during maintenance or failures.

The CPU in the existing kite power system setup is a set of regular computers of which the screens can be seen in top left of Figure 2.17. The CPU for the $70m^2$ is assumed to be more developed and to have at least a (wireless) internet connection for receiving forecasts, proper communication wiring to all ground-based mechanisms, a transmission antenna for interaction with the CU and can be remotely controlled (see assumption M08).

Figure 2.17: Ground station of the current kite power system [6]

Power system

The power system takes care of the energy transfer from the drum to the generator, the distribution of power towards all the mechanisms on the ground station and contains the electricity grid including proper wiring and a power management system. The CU is a self-powered mechanism and is therefore not included in the power system. The design, costs and further specification of the power system are out of the scope of this project and thus the newly designed launch, landing and storage system will implement the existing power system. However, to clarify the power needs of the specifically designed launch, landing and storage system an electrical block diagram is produced (see subsection 11.3.3).

2.3.2 Designed subsystems

This section will give a high-level overview of all the subsystems and mechanisms that have been designed. Each section will represent a subsystem and every subsystem is made up the several mechanisms which are defined in an accompanying table. All the subsystems and their mechanisms are further explained and worked out in detail in chapters 5 up to 10.

Kite and tehther adaptation

The designed launch, landing and storage system will require one large adaptation to the kite: the PRU. Table 2.2 gives a short description of the PRU mechanism. Figure 2.18 visualizes the mechanism and its position with respect to the overall design. In this picture the safety line and identification mark are also shown. These minor kite adaptations are further elaborated in chapter 5.

Table 2.2: Description of the mechanism of the kite adaptation

Mechanism	Description
PRU	The PRU will be positioned in the center of the kite right behind the leading edge. The PRU enables compact storage of the kite.

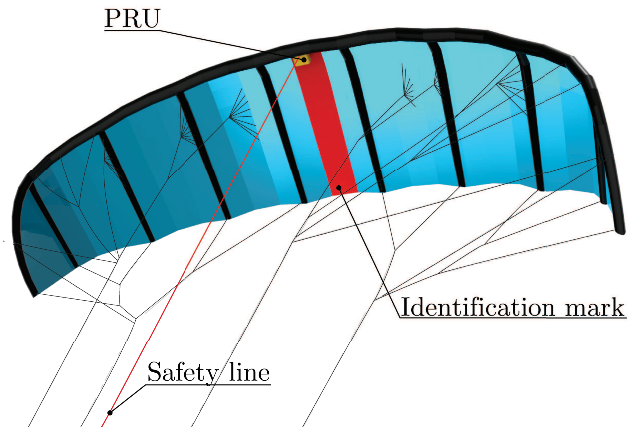


Figure 2.18: Overview of the kite adaptations

Horizontal beam

The horizontal beam subsystem consists of multiple elements and plays a vital role in the launch, landing and storage procedures. Table 2.3 gives a short description of the mechanisms for this subsystem, while they are visualized in Figure 2.19.

Table 2.3: Descriptions of the mechanisms of the horizontal beam

Mechanism	Description
Beam	The kite is landed at its center on top of the horizontal beam and is two-folded over the beam once deflated by the PRU.
Beam hinge	The beam hinge is located at the root of the horizontal beam at the connection with the vertical boom. The beam hinge allows the beam to hinge up- and downwards to suit the optimal launch/landing angle.
Gripper	The gripper has an arm which guides the safety line towards the flippers. The gripper captures the safety line such that this line can be used to guide the kite.
Gripper rail	The gripper rail is located on the side of the horizontal beam and accommodates the movement of the gripper along the length of the horizontal beam when guiding the kite.
Ridge	The ridge is located at the tip of the beam and provides a resistance when the kite is ruffled by sliding the gripper back towards the tip.

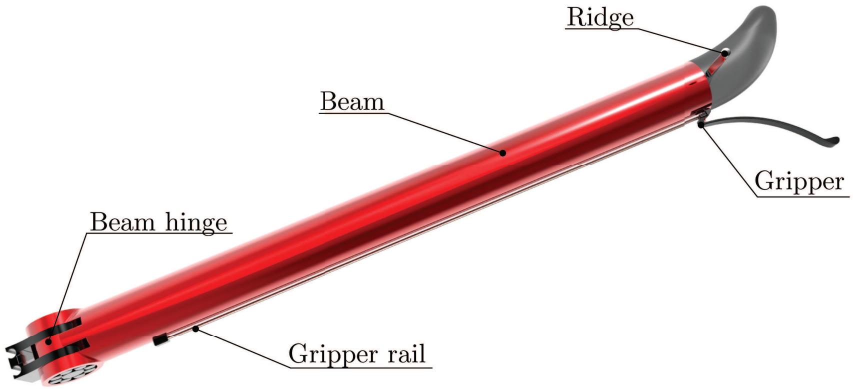


Figure 2.19: Overview of mechanisms within the horizontal beam subsystem

Vertical boom

The vertical boom is the largest component of the designed system and consists of three main mechanisms which are described in Table 2.4. Figure 2.18 gives the visual representation of this subsystem and its mechanisms.

Table 2.4: Descriptions of the mechanisms of the vertical boom

Mechanism	Description
Boom	The vertical boom has a height of $35m$ to create enough altitude for the kite to catch wind (providing the possibility to reel-in) and ensures that the CU will not hit the ground during the landing procedure.
Boom hinge	The boom hinge is located at the root of the vertical boom and allows a tilt angle for the vertical boom to place the kite in the optimal position for landing/launch.
Vertical boom rail	The vertical boom rail runs along the front of the vertical boom and allows an up- and downward movement of the horizontal beam for storage and deployment purposes.

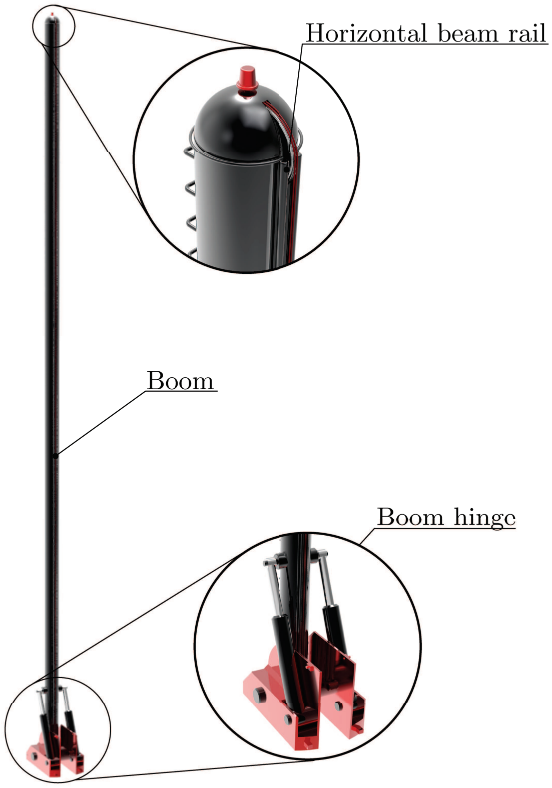


Figure 2.20: Overview of mechanisms within the vertical boom subsystem

Rotating platform

The rotating platform forms the base of the entire structure and allows a 360° rotation of the system. Table 2.5 gives a short description of its two mechanisms which are also illustrated in 2.21.

Table 2.5: Descriptions of the mechanisms of the rotating platform

Mechanism	Description
Bearing	The bearing of the rotating platform is located underneath the ground station and makes it possible to align the vertical boom and horizontal beam with the direction of the wind.
Platform cover	The platform cover is connected to the bearing and all the elements such as the boom and CU storage are mounted on the platform cover.

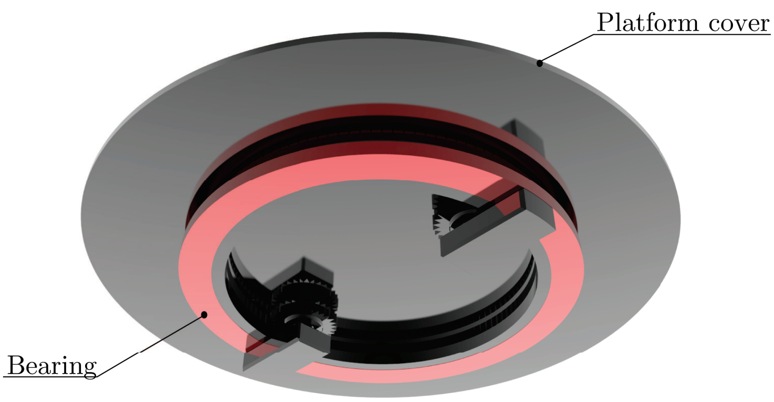


Figure 2.21: Overview of mechanisms within the rotating platform subsystem, seen from below

Swivel storage

This section gives the big picture of the swivel storage. Table 2.6 describes the three mechanisms that together form the swivel storage subsystem. The mechanisms are also pointed out in 2.22.

Table 2.6: Descriptions of the mechanisms of the swivel storage

Mechanism	Description
Swivel	The swivel moves down the swivel rail and rotates during the slide. The currently existing swivel does not allow this rotation and therefore a custom swivel is designed where the tether runs through four wheels.
Swivel beam	The swivel is mounted on a swivel beam, which can run along the swivel rail with two carts. The swivel and CU will need to be positioned directly underneath the kite during storage to prevent entanglement of the lines. The swivel cannot remain within the storage as the main tether would then interfere with the walls of the storage during flight for which reason this mechanism was developed.
Swivel rail	The swivel rail consists of two parts. One part is located on the rotating platform and the second part is located inside the non-rotating storage unit. The swivel rail accomodates the slide of the swivel beam towards the bottom of the storage.

Figure 2.22: Overview of mechanisms within the swivel storage subsystem

Storage

The last subsystem comprises the storage in which the kite is contained outside of the operating limits. The storage subsystem consists of four mechanisms which are shortly described in Table 2.7. Figure 2.23 gives a visual representation of the storage unit.

Table 2.7: Descriptions of the mechanisms of the storage

Mechanism	Description
Storage structure	The storage structure consists of two main parts: a movable section mounted on the rotating platform and a static section. The static section starts approximately $2m$ underground and continues above ground. The storage will keep the kite and CU safe from vandalism/theft and weather conditions that are outside of the kite's operating limits.
Storage cover	The storage cover is a rolling shutter and is located at the top of the storage structure. During the flight of the kite the shutter only covers the non-rotating part of the storage structure. It is completely closed in the case where the kite is contained inside the storage.
Folding poles	The folding poles are located on the sides of the storage unit. The folding poles are placed alternating sides and are used to fold the kite and bridle system in a zig-zag manner while slowly sliding down the horizontal beam with the kite on top.
Lock-in device	The lock-in device is located in the static part of the storage unit and is used to ensure correct alignment of the two parts of the storage structure. The lock-in device pushes a tight-fit pin through an alignment hole to lock the storage unit in place.

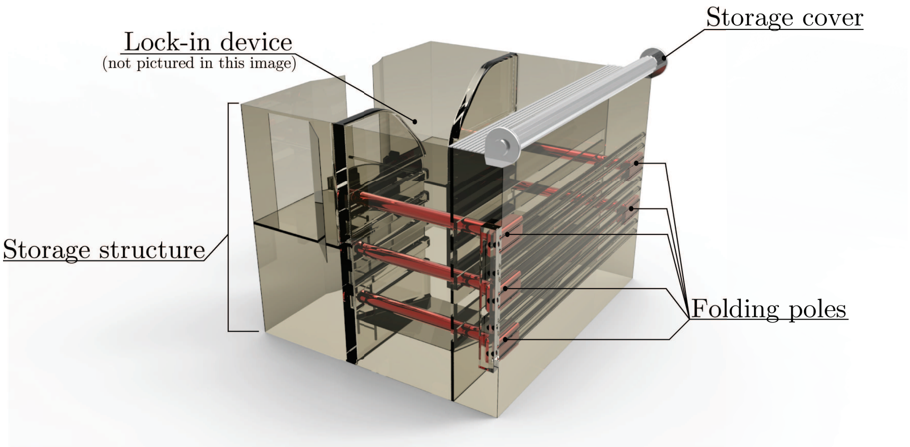


Figure 2.23: Overview of mechanisms within the storage subsystem

2.4 Functional specification

This section will present the results of a functional analysis in which the course of the four main functions of the system (consisting of launch, landing, storage and deployment) has been mapped. Subsection 2.4.1 describes the general process of the main functions. The following two subsections illustrate the functional flow by means of a flow diagram and breakdown structure.

2.4.1 Functional description

In this section the landing, storage, deployment, and launch procedures will be consecutively clarified in a descriptive manner.

Landing procedure

The CPU continuously keeps track of the weather conditions and forecasts from data gathered by the weather station and can initiate landing of the kite in case conditions becomes inappropriate for flying. In case landing is required, the kite will be taken to the lowest point of the pumping cycle at approximately $100m$ height, which is the starting point of the landing procedure. During this maneuver a number of measurements and calculations have to be performed. The wind direction and strength are measured and the shortest turn of the rotating platform to align it with the wind direction is calculated. Based on the wind data also the approach path of the kite towards its landing spot on the horizontal beam and the optimal tilting angle for the vertical boom are determined.

Once the kite has reached approximately $100m$, the structure needs to be prepared for landing. The rotating platform is turned in the right direction and the vertical boom is tilted to the previously determined angle. Simultaneously the horizontal beam is railed upwards to the top of the vertical boom and is hinged downward. The horizontal beam must be completely horizontal at the moment the vertical boom has tilted to its optimal angle. Both the horizontal beam and vertical boom are locked in their correct positions, such that the driving actuators can be released. Finally, the gripper flippers are unlocked.

The structure is prepared for landing in this stage and the kite can be controlled to continue its descent along the approach path. A safety line running from the centre of the leading edge of the kite towards the CU plays an important role in the landing procedure. Once the CU is just below the horizontal beam, the safety line of the kite gets within reach of the arms of a gripper. The kite is slowly lowered into its specific landing position by reeling in the main tether and the safety line will continue to slide in between the arms of the gripper towards the flippers. As soon as the safety line has passed the flippers, these will be locked. The safety line runs through the gripper and thus there are no limitations on its up- or downward movement. Its sideways motion is limited as the line is contained within the gripper's cavity.

The safety line has been secured at this point and only a few meters of descent of the kite remain. The main tether is reeled in further and at the same time the gripper is slid back one quarter of the horizontal beam's length towards the vertical boom to give room for the leading edge to land. The instant the kite touches the horizontal beam, the main tethers stops reeling in and the gripper slides further back up to the end of the gripper rail close to the vertical boom. At this point the ridge will come up which is needed during the storage procedure to ruffle the kite.

As the final two steps of the landing procedure the vertical boom is tilted into its vertical position and the horizontal beam is adjusted accordingly such that it remains in its horizontal position. Both the horizontal beam and vertical boom are again locked against any further movement.

Storage procedure

The storage procedure has the end state of the landing procedure as an input. The boom is completely vertical and the horizontal beam with the kite is locked in horizontal position.

In the storage procedure the kite is first deflated by the PRU, which will cause the kite to hang downwards and fold over the horizontal beam. As the tips of the kite hang downwards the tension in the bridle system is released, which will cause the CU to lower. To allow this downward movement of the CU the safety line will be reeled out. To make sure that the bridle system remains under small tension the main tether will be rolled in simultaneously with the deflation process. If the kite is fully deflated the PRU is turned off, the drum stops reeling in the main tether and the safety line is not reeled out further. During the deflation procedure the shortest turn of the rotating platform towards the non-rotating part of the storage unit is also determined. Furthermore the cover of the storage unit is opened.

Thereafter, the kite is ruffled into itself to reduce the frontal area of the kite and position it in such a way that it fits within the storage. The ridge which was already turned upwards during the launch procedure provides resistance when the gripper is slid back towards the tip again. As the gripper moves towards the tip of the horizontal beam the drum will have to slightly reel out part of the main tether, while ensuring enough tension to slide the kite via the gripper. Once the kite is ruffled into itself, the rotating platform is turned such that the rotating part of the storage unit is aligned with the non-rotating part of the storage unit. To ensure an accurate alignment and prevent further movement a lock-in device is used to lock the rotating part to the non-rotating part. If both parts of the storage unit are well aligned the swivel beam is lowered via a rail into the storage unit such that the swivel is positioned underneath the centre of the kite as it is brought into the storage and folded. Sliding the swivel down along the swivel rail requires that the main tether is reeled out while remaining in constant tension.

As soon as the swivel reaches the end of the swivel rail in the centre of the storage unit and is locked in place, the CU is lowered towards the ground by reeling in the main tether and lowering the horizontal beam. If the CU reaches the swivel the folding procedure can start, which is based on a set of alternating poles inside the storage unit. As the horizontal beam rails further downward the bridle system will start slacking. To prevent entanglement of the bridle system the lowest pole in the storage will slowly start to move towards the opposite side of its current position. As the lowest pole approaches the wall of the storage structure, where it will end its movement, a second pole will start to slide to the opposite side, folding the next layer of the bridle system and kite. All the following poles keep interchanging their direction of movement until the bridle system and kite are completely packed. The instant the horizontal beam enters the storage represents the end of the packing process. The rail speed of the horizontal beam and speed of the poles are highly dependent on each other and have to be well aligned to prevent tearing of the kite.

Once the kite and bridle system are fully contained within the storage, the storage cover closes and the storage unit is locked. At this point a process of continuous weather checking and forecasting will determine the right time to deploy and launch the kite as soon as weather conditions become favorable for flight again.

Deployment procedure
The kite will be deployed and prepared for launch if weather conditions are favorable for flying the kite. As a first step the storage cover is unlocked and opened. At this point the horizontal beam can be unlocked and raised in accordance with the speed of the folding poles. These poles will now slide in opposite direction similarly to the storage process in order to slowly release the kite and its bridle system as the horizontal beam moves upward. Once all folding poles have been put on alternating sides the horizontal beam is raised and the main tether is reeled out. This is done to prevent the bridle system from getting stuck behind the walls of the storage unit. When the horizontal beam is at the top of the vertical boom the drum stops reeling out the main tether and the swivel is slid along the rail towards the root of the vertical boom. To ensure tension the drum simultaneously reels in the main tether.

Since there will be large forces on the swivel during operation the the swivel beam is locked as it reaches the end of the swivel rail. In parallel the cover over the non-rotating part of the storage unit is closed. During the unpacking process the system will also determine the wind direction.

In the next phase of the deployment procedure the wind direction will be used to turn the rotating platform into the right direction and position. Once the kite is in the correct position the gripper is slid towards the vertical boom to unruffle the kite. When the gripper is at the vertical boom the ridge is retracted into the horizontal beam. The main tether must be slightly reeled in to maintain tension. Next, the kite is inflated by means of the PRU. During inflation the lengths of the main tether and safety line are adjusted accordingly to compensate for the fact that the tips of the kite will move upwards as the kite takes on its inflated, curved shape.

Launch procedure
The launch procedure has the inflated kite at the top of the vertical boom as a starting point. To correctly position the system for launch the system measures the wind conditions. Based on the wind data the optimal angle for the horizontal beam and vertical boom are determined. The vertical boom is tilted downward and locked when it reaches the optimal angle. Hereafter the gripper is slid to the tip of the beam, while the power lines are reeled in slightly to power the kite and as such enhance a smooth slide. The horizontal beam does not compensate for the tilt angle of the vertical boom and is therefore also at an angle with relation to the horizontal. This will help the gripper and kite to easily slide down the horizontal beam.

As the gripper reaches the tip of the horizontal beam the kite will reach its fully powered status. At the same time the horizontal beam is tilted upwards towards an almost vertical position with the safety line of the kite still contained by the gripper at the tip. By tilting the horizontal beam upwards the kite is brought to a greater height with higher wind speeds, which increases the probability of a successful launch. Furthermore the chance that the CU hits or gets damaged by the horizontal beam is reduced to great extent since the horizontal beam is now aligned with the direction of the kite during take-off.

When the kite has enough lift force and the horizontal beam is tilted to the optimal angle, the gripper is unlocked. The kite will be steered away from its zenith position in the direction of the power zone. In the meantime the horizontal beam is tilted into the fully vertical position and locked. As soon as the CU of the kite is lifted above the vertical boom, the kite can be flown up to $100m$ where it can start with the power cycles. One of the last steps of the launch procedure concerns tilting the vertical boom back into its vertical position to reduce the forces on the actuators. Also the horizontal beam is slid downward over the rail up to the point where the height of the tip is equal to that of the tip of the vertical boom. The launch procedure has ended at this point and the structure will remain in this state during the flight of the kite.

2.4.2 Functional flow diagram

Functional flow diagrams (FFD's) are produced to give a clear overview of all the steps which need to be performed in order to successfully complete the mission and includes actions and decision blocks. The FFD will be the visual representation of the procedures discussed in the functional description given in subsection 2.4.1.

The top-level FFD for this design is shown in Figure 2.24. The functions landing, store, deploy and launch will consist of several lower-level functional steps, which differ for every concept. The function 'kite replacement' is also shown for sake of completeness, but is not elaborated any further within the FFD. This report will contain a proposal for the kite replacement procedure, but its functional steps however will not be worked out in detail. Finally there are four decision blocks shown in Figure 2.24. Two checks are performed to evaluate the weather conditions. These make sure the kite lands when weather conditions are not favorable and launches as weather conditions are again within limits. The checks on operation time ensure the flight hours of the kite do not exceed the three months operating limit. After performing the replacement procedure of the kite the entire process starts again with the kite in storage, waiting for the right conditions to start the deployment phase.

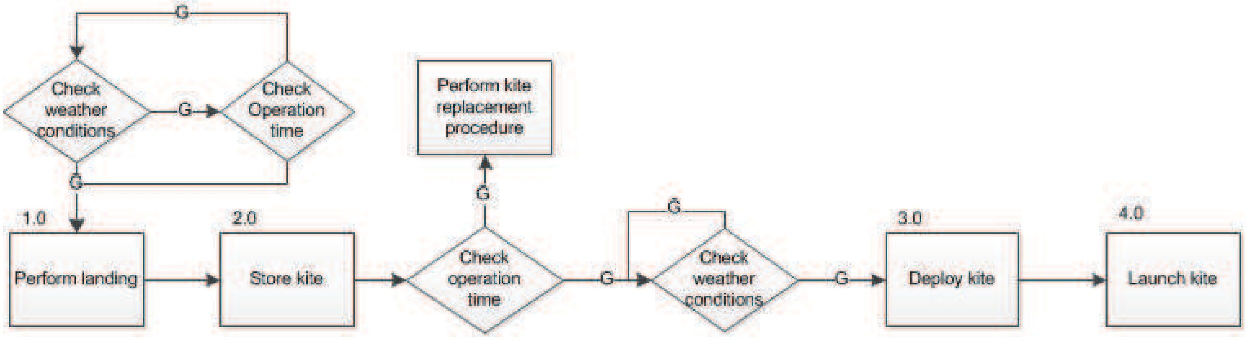


Figure 2.24: Top-level functional flow diagram

The functional block diagrams with all low-level functional steps of the four key functions of the detailed design are given in Appendix A.

2.4.3 Functional breakdown structure

As opposed to the FFD of the system, the functional breakdown structure (FBS) provides a clear overview of the tasks the system must be capable of performing for each function. This is given in the form of an AND-tree structure, taking each FFD as the main input for the functions and lists all the tasks that must be carried out during each function thereby from the specifications within the FFD itself. Appendix A.5 contains the FBS for the launch, landing and storage system.

3. Outline of the detailed design phase

This chapter will cover all topics that have been important in the approach and execution of the detailed design process. The information in this chapter will show the way of working throughout the project and will help the reader to understand certain decisions and additions to the design in subsequent chapters.

The first section describes the most important steps of the detailed design process in a concise manner. Section 3.2 gives the results of an environmental analysis, where environmental is considered in a broad sense. The sustainable development strategy that has been pursued throughout the design process is given in section 3.3. Thereafter, section 3.4 gives an overview of the development risks that have been defined at the start of the detailed design process. The last section of this chapter explains the way contingency management has been embedded in the detailed design process and gives the resource allocations.

3.1 Detailed design process

After a design was chosen from the conceptual design phase, the detailed design phase followed with the intent of working out the chosen concept into detail. To be able to properly design every part and to designing multiple parts simultaneously, the total system was divided into five subsystems. These subsystems are the horizontal beam, vertical boom, rotating platform, CU storage, and storage. These subsystems were then, for some of the analyses, divided into several mechanisms.

In the detailed design phase, the first design segment served to carry out preliminary calculations about the weight of the main components. To do this, the group was divided into three. The first group was assigned to design every component into detail. The second group would then use this detailed design to do a preliminary structural analysis to determine the core properties. The third group had the task of looking at a wide variety of actuators which could be used, such that when the exact moments due to the weights were known, the most optimal actuator could be chosen from a list. To be consistent in the way of calculating and the way of reporting of every subsystem an analytical approach was first made. In it the assumptions made are described along with the method to approach the structural analysis, energy consumption analysis, operating time estimation and cost estimation.

When the first design phase was completed, a second would start in which the group was divided into two different groups. The first group worked on the cost, structures, and materials. The second group took care of the actuators, sensors, energy consumption and operating time. Following this second phase, there was be a third and last one in which general diagrams over the design were be made. After this, an iteration could be considered in order to optimize the design. It was found out that during the first segment a lot of iterations were done due to the interdependence of all the parameters. For example, it was decided that the kite would first be ruffled to almost a third of its normal length to prevent large forces acting on the system from a sail-like effect. This had a very large impact on the structures of the horizontal beam, vertical boom and storage. Therefore more time was taken for the second phase before continuing to the final one, after which other small iterations were made.

3.2 Background study

At the start of the detailed design process a background study was performed in which the market, weather and legislation were analyzed in more depth. The results of these three topics are presented consecutively in the following subsections. The purpose of the background study is to gain a better insight into the environment in which the automated launch, landing and storage system will have to operate, namely the commercial, climatic and legal environment.

3.2.1 Market analysis

In order to assess the commercial viability of the product a market analysis is performed by examining the number of potential clients and competitors in the field as well as their past and current performance. The market analysis is focused in both a general and specific sense for the kite power system: the market in general for clean sources of energy within Europe and the Netherlands, and more specifically those that focus on energy harvesting through kite power systems. In this market analysis the complete pumping kite system is being considered and not only the launch, landing and storage system.

The pumping kite system generates electrical energy. To estimate the size of the potential market the energy consumption in the Netherlands is analyzed in the first subsection. Next to the potential market it is important to understand which competitors are involved in the energy market. In case of the pumping kite system the competitors are divided into two categories:

1. High Altitude Wind Power (HAWP) technology competitors
2. Energy source competitors

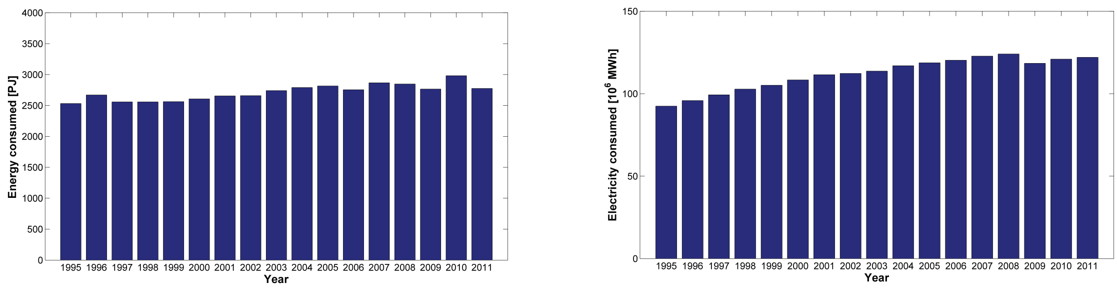
HAWP is still a novel technology and a lot of similar concepts exist. The pumping kite system is one of those concepts. The state of development of these HAWP concepts is investigated in the second subsection. To make the pumping kite system commercially viable, it also has to be able to compete within the current energy market. This competition is mainly based on the price per kWh. In the last subsection about energy generation competitors an overview is given of all major energy sources in the energy market and the historical development of the energy prices.

Energy market potential

The purpose of the pumping kite system is to generate electricity in an environmentally friendly manner and sell this energy on the energy market. The size of the market can be estimated by the amount of electricity that is being consumed in the Netherlands. The potential growth of this market can be estimated by comparing the amount of electricity consumption to the total energy used in the Netherlands. The total energy consumption also comprises the use of other energy carriers, such as gas, coal and other fuels.

The CBS is a statistics agency in the Netherlands and among others keeps track of the energy use. It can be seen in Figure 3.1 that the total energy consumed in the Netherlands has increased only slightly in the last decade. However, the share of electricity within the total energy has increased during the last decade substantially. Henceforth it can be concluded that the potential market for electricity producers is growing. A strongly growing demand for electricity is also expected on a worldwide base. The IEA predicts that the worldwide electricity demand will grow with an average of 2.4% each year until 2035.

The growth of the energy demand results mainly from the population and economic growth from countries such as China and India. Secondly fossil fuels are becoming scarce. As a final consideration, if greenhouse gases and other hazardous emissions do not decrease to the levels they had around 1990, it is expected that their negative consequences will endanger the world's climate [23].



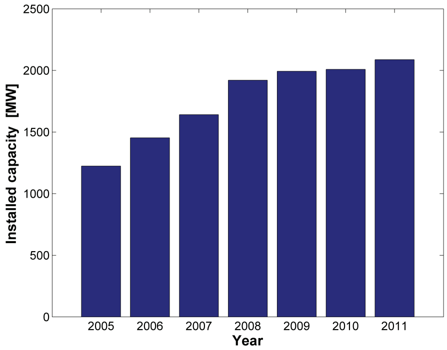
(a) Total energy consumed within the Netherlands expressed in PJ (includes all types of energy)

(b) Total amount of electricity consumed in the Netherlands expressed in 10^6 MWh

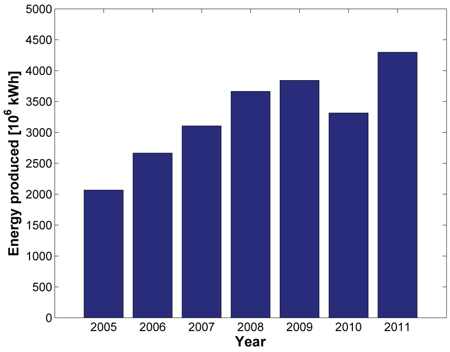
Figure 3.1: Energy consumption in the Netherlands from 1995 to 2011 [7]

There is a fierce debate going on about the sustainability of the current energy sources and their consequences on the environment. The goal is to increase the share of renewable energy sources. This trend can be seen when looking into the share of wind turbines. As can be seen in Figure 3.2 the installed wind turbine capacity has grown substantially in the last decade. The pumping kite system is also considered to be a wind power energy source and thus such a system can also take advantage of this growth.

One major drawback of the wind turbines is their size and dominant appearance within in the landscape. This is the cause for many public debates against wind energy. The pumping kite system could be a solution for these issues, as the sight of a kite is much more appealing, less intrusive and thus can help to increase the public goodwill to invest in wind power.



(a) The installed, onshore wind turbine capacity in the Netherlands in MW



(b) The annual energy production by onshore wind turbines in the Netherlands expressed in 10^6 kWh

Figure 3.2: Total onshore wind turbine capacity and the total electricity generated by wind turbines in the Netherlands from 2005 to 2011 [8]

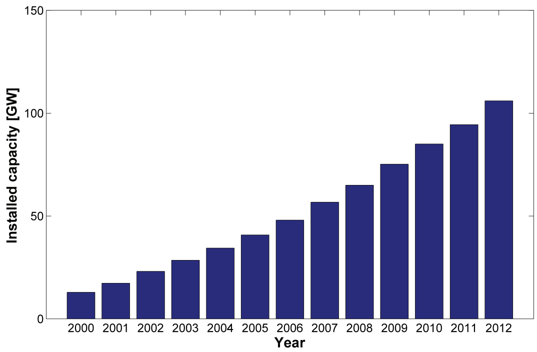


Figure 3.3: Installed wind turbine capacity in the European Union as calculated by the EWEA. [9]

From Figure 3.3 it can be seen that the growth of wind energy within the European Union is even larger, which is favorably influencing the commercial opportunities for the pumping kite system.

HAWP technology competitors

The current wind power systems are mainly based on wind turbines. In addition to the previously mentioned drawback of their gigantic size they also have an inability to harvest the wind on higher altitudes. These winds are more consistent and more powerful. In order to gain access to these high-altitude winds, HAWP concepts are developed. The pumping kite system of the Kite Power Group of the TU Delft is one example of a HAWP concept.

Other HAWP concepts are considered to be technological competitors, though a complete descriptive overview of all concepts is outside the scope of this analysis. Instead Table 3.1 gives a compact overview of some of the most important HAWP competitors of the Kite Power Group of the TU Delft. For more information about the individual HAWP concepts, the reader is referred to the corresponding references. This list is not considered to be complete and does not contain all the different research groups or companies active in the HAWP field.

Table 3.1: Overview of the most important competitors in the HAWP R&D field and their state of development

Name	Current state of development	Reference
Makani power	A company taken over by Google with plenty of resources available. It has a successful autonomous system for all flight modes and uses a small tethered airplane. They have some issues with upscaling the concept.	[24]
Altaeros energies	Small company founded by students. It has ample resources and has just developed a prototype. It uses a large tethered, floating, inflatable wind turbine.	[25]
Joby energy	Medium size company with a staff of 50 employees founded in 2008. Currently it only has very small scale prototypes.	[26]
Sky windpower	Small company which has only small scale prototypes. The prototype consists of a small tethered quadrocopter.	[27]
Amphyx power	Company was founded in 2008 and consists of a staff of seven people. The company has many sponsors and partners. The concept consists of a tethered glider.	[28]
SwissKitePower	SwissKitePower is a collaboration of four universities in Switzerland and some industrial partners. The system is comparable to the TU Delft pumping kite system.	[29]
Wind ward energy	Wind ward energy is a development group located at the TU of Munich. It uses a similar system as the TU Delft pumping kite system. It is still in a very preliminary phase.	[30]
Enerkite	Enerkite is a small company with a staff of seven people located in Germany. It was founded in 2010. It has many sponsors and partners and has developed a working, medium scale prototype which has proven to be able to operate automatically for one hour. It uses a comparable concept as the pumping kite system of the TU Delft.	[31]
Sky sails	Sky sails is a medium size company which is located in Germany. It has about 40 employees and is already commercially active. It sells kite power systems to provide additional propulsion for large ocean freighters. This system is already fully developed and operating. It is now also researching an offshore version of the pumping kite system.	[32]
Windlift	Windlift is a small company which targets a specific off-grid, remote location power system using kites. It is currently still in a development stage, but has a working full scale prototype.	[33]

Energy generation competitors

In order for the pumping kite system to be competitive within the current energy market the price per kWh has to be as low as possible. The launch, landing and storage system is not the only contributor to the kWh price; the costs of the ground station, kite and tether also add up to the total costs. However, the contribution of the automated system must be kept as small as possible in order to ensure success of the complete pumping kite system.

An overview of the kWh prices for different energy sources in the UK in 2012 is given in Table 3.2. This table gives an insight in the prices of different energy sources relative to each other.

Table 3.2: An overview of the kWh prices in the UK in the year 2010 for different energy sources (converted to € from £ using an exchange rate of 1.17) [16]

Resource	Price [€ $cents/kWh$]
Onshore wind power	9.4 – 12.9
Offshore wind power	17.6 – 24.6
New nuclear power	9.4 – 12.3
Biomass	7 – 14
Natural gas without CO2 capturing	6.4 – 12.9
Natural gas with CO2 capturing	7 – 15
Coal	11.7 – 18.1
Solar farm	14.6 – 21
Tidal power	18.1 – 45.6

In Figure 3.4 it becomes apparent that the price of electricity in the Netherlands has more than doubled over a period of almost 20 years, while the price in other EU countries has only increased with approximately 20%. Half of the increase is due to a higher base price, while the other half can be traced back to higher taxes.

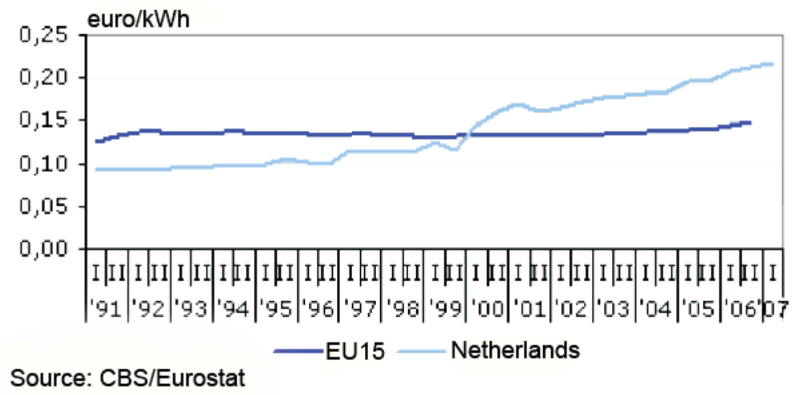


Figure 3.4: Development of electricity price in €$/kWh$ over the period of 1991 to 2007 in the European Union and the Netherlands [10]

In 2012/2013 the price of single tariff electricity power is on average €0.22 per kWh. Of this value, on average €0.07 is related to the power itself, almost €0.04 cents for VAT, and €0.11 is due to all sorts of energy taxes. The price of environmentally friendly, 'green' power is similar to that of non-sustainable power [34].

At this point the expectation is that 70% of all investments in electricity (up to 2035) will go towards development and implementation of renewable energy sources. At this point renewable energy sources are still considerably more expensive per kWh and the IEA [23]predicts that also in the future the costs of these renewable energy sources will certainly be higher than the cost of the conventional energy sources. The combination of these statements lead to the conclusion that the trend of a growing electricity price as shown in Figure 3.4 is expected to continue.

3.2.2 Weather analysis

Weather plays another major role in the success of the design. To complete the requirements on the deployment time and energy consumed one has to determine the total performance of the entire kite system. After consulting experts on the matter, the main reasons determined as to why the kite should land is lightning and boundary wind speeds. Lightning is discussed firstly, followed by the reasoning for the extreme wind speeds is explained. When these two conditions are considered the actual energy and deployment time available for the launch, landing, and storage system can be calculated. Next to that the orientation of the system is discussed.

Lightning

Lightning poses a risky environment for the kite as any strike will not only damage the material itself but also the electrical equipment. Historical data concerning the proximity of lightning is available on the KNMI site [35]. If this data is analyzed one can determine downtime due to the lightning storm. Additionally an extra approximation has to be made: the kite should be stored one hour before and one hour after the lightning. When lightning has passed the wind conditions should also be checked. The explanation for this is given in the part on wind influence. Data for Valkenburg is available starting from 1951 until the current date. At this point data up to June 8th is used. The total number of lightning storms is counted during the period. The amount of landings during a three month period is obtained by dividing the total number of landings by the number of three month periods in the data available. According to the data the kite should land 1,515 times due to lightning. As the data is given for a period of 62.5 years the kite should be able to land 6 times in three months. The total number of hours down time due the lightning is 6,357, which is on average 25 hours in three months.

Wind influence

From the top-level requirements it can be seen that the kite has to be launched and landed based on the wind speeds of $4m/s$ until $25m/s$. These speeds are assumed to be at the altitude of the kite in the subsystem. The height at which the kite lands is $35m$ (see subsection 7.2.1). The available wind data is given for an altitude of $10m$ height. To be able to calculate the wind speeds a relation for winds at different altitudes has to be used [36]. This relation can be seen in Equation 3.1. In this equation v_{alt} indicates the wind speed at the requested altitude, v_{ref} is the wind speed at the reference height, h_{ref} is the reference height, h_{alt} is the altitude at which the wind speeds are required, and z_0 is the roughness length. For more information on the roughness length, consult [36].

$$v_{alt} = v_{ref} \cdot \frac{ln\left(\frac{h_{ref}}{z_0}\right)}{ln\left(\frac{h_{alt}}{z_0}\right)} \tag{3.1}$$

The wind speed range of 4 to $25m/s$ at $35m$ height corresponds to a wind speed range of 3 to $18.7m/s$ at $10m$ height. The wind distribution retrieved from the KNMI and corrected for a height of $35m$ can be seen in Figure 3.5.

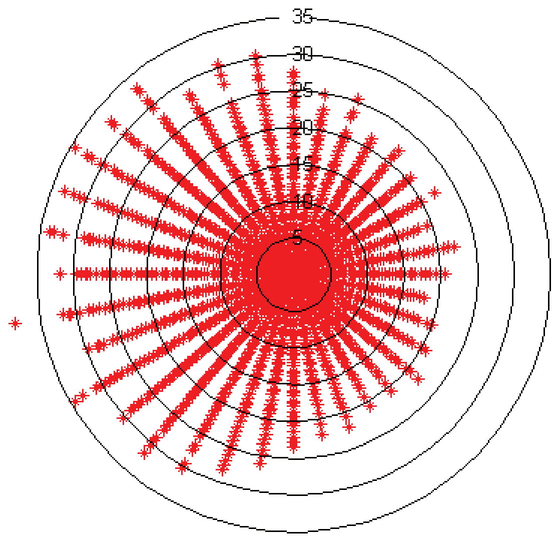


Figure 3.5: The wind distribution at Valkenburg from 1951 onwards, corrected for $35m$ height

The lower limit for the launching is challenging. To be able to design the subsystem as a robust system this limit has to be increased slightly. The lower limit is increased from 4 to $5m/s$ for reasons explained in subsection 2.2.2. The effect of this increase in lower limit is shown here.

Before discussing the effect of the increased lower boundary one more addition to the wind speed range should be added. When the wind speed approaches the lower landing limit the team has chosen that a check has to be done. The check is added to improve the availability of the system by flying the kite in conditions below the minimum landing wind speed. This check determines, based on a weather forecast, if the kite should land at that point. The decision is based on the expected presence of lightning and of wind conditions below the minimum landing speed. It is done on a maximum period of three days, or on the period until the occurrence of wind speeds in range with the landing requirements, whichever is lowest as can be seen in Figure 3.6. When using this check an extra risk is created, but even when wind speeds are too low the kite can be landed using a gliding approach. This approach was proposed by the expert but care should be taken that this involves more risk during landing. Some of the added risks include slamming the kite on the beam instead of a soft landing, or due to the slacking CU missing the beam and landing softly on the ground. The use of this style of landing should be kept at a minimum. By simulating this check in the data only 12 emergency landings had to be performed during 62.5 years. This is the convincing factor to include this check and improve the availability and power generation dramatically.

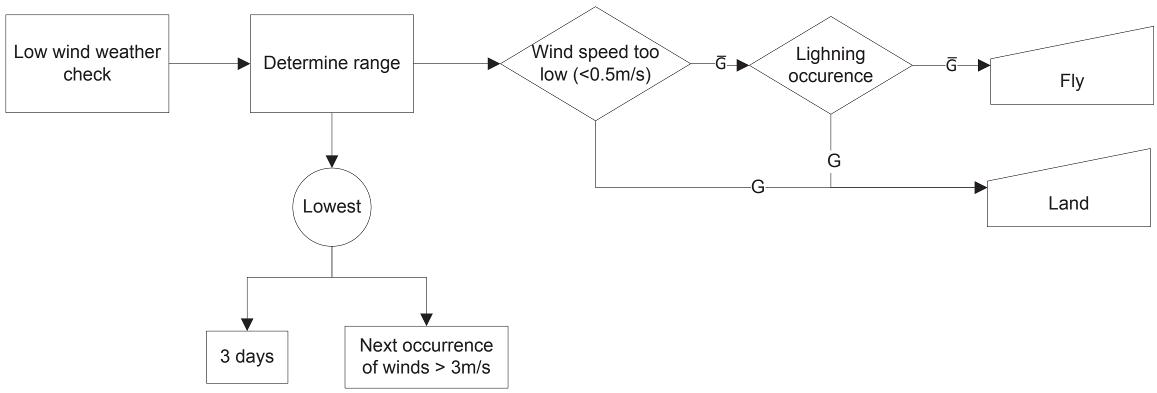


Figure 3.6: Weather check for low wind occurrence

When using the aforementioned wind speed range, including the check, the kite has to be landed 4,374 times due to the wind considerations. Spread over the period of 62.5 years this is on average 18 times every three months. The total number of hours down time due to wind is 79,742, which is on average 320 hours in three months.

To prove that this approach is valid a comparison with the original situation can be made. From the requirement it follows that the kite should be landed every single time the wind speed drops below $4m/s$ or above $25m/s$. In this case the kite has to be landed 26,434 times in 62.5 years, or 107 times every three months. By comparing the number of landings required for this case (107) to the number of landings required for the proposed case (24) one can immediately see that the current approach from the design team results in a higher availability. The increased availability is achieved by fewer and shorter landings. This improved availability is the convincing factor to accept the increased risk for emergency landings.

Conclusion on time and energy

When combining the amount of times the kite has to land due to wind and lightning the total number of landings in three months can be obtained. By using the equation for power determination in relation to the wind velocity (subsection 2.2.2) one can determine the actual energy produced by the system. Using these two parameters, the time and energy available can be calculated. From the requirements it follows that the subsystem can not use more than 5% of the total uptime. The total uptime (in three months) is 1,820 hours. 5% of this values is 91 hours. As the total number of landings in three months is 24 times, the time available for one cycle is 3.8 hours. The requirements also state that no more than 1% of the energy produced can be used by the launch, landing and storage system. The energy generated in those three months is $6.6 \cdot 10^4 kWh$. 1% of this value is $6.6 \cdot 10^2 kWh$. Using 24 landings, the energy available for one cycle is $27.4kWh$.

Crosswind evaluation

The requirements state that the kite should be landed with an upper wind speed limit of $25m/s$. As the fatigue loads should be minimized to lower the structural load the orientation can be optimized to lower the effect of winds.

As can be seen later in this report, the storage plays an important role in sizing the boom, especially the moment imposed on the boom by the deflated kite on the beam. This moment is determined by the wind speeds which are perpendicular to the kite. It can be calculated by multiplying the magnitude of the wind speed with the sine of the angle difference. This angle is the difference of the orientation of the storage to the wind direction. The calculation can be done for the data used in the wind analysis. The result of this calculation can be seen in Figure 3.7. This figure shows the effect when orientating the storage at 280°. It can be noted that the crosswind speeds are much lower than the absolute wind speeds. Using this approach the fluctuating load can be lowered which minimizes the fatigue load on the structure.

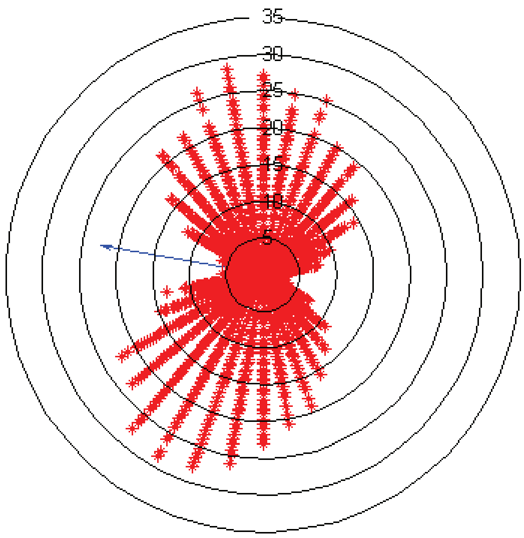


Figure 3.7: The crosswind distribution with ground station orientation of 280° from North at Valkenburg, data from 1951 onwards, corrected for $35m$ height

Verification

To be sure that the code works as intended it must be verified. This is done for the parts considered in the subsection. Firstly the code for the lightning downtime is discussed, followed by the the code for the downtime of extreme wind speeds. After that the code for the energy and time available is examined. The last part considered is the crosswind calculations.

The Matlab script used to calculate the total number of lightning strikes and the number of hours the kite has to be stored is verified using a dummy file and by checking the code by another team member. The dummy file has the same layout as the actual data used. The data available in the dummy file consists of approximately 30 time steps. These data entries can easily be changed so the behavior of the Matlab class can be checked. A special test case was the occurrence of lightning followed by low winds. In this case the kite first has to be stored due to the lightning. If the kite can be launched due to the ceasing of lightning the kite has to be stored because of the wind. During the test one lightning followed by one low wind condition was the input. The result was three hours of storage which is as expected. It was confirmed that the script works as expected for various cases like sequential lightning strikes and multiple occurrence of lightning strikes closely together.

The Matlab script used to calculate the storage time and landings due to wind speeds is checked again as for the lightning conditions: a dummy file is used and an independent person checks the code. The dummy file was executed with known cases as input and the outcome was examined. It was confirmed that the script works as expected for various cases like wind speeds below the minimum landings speed but above the emergency landings wind speed.

This last Matlab script is verified by checking the code and calculating an order of magnitude. The code was checked for correct usage of programming attributes like loops. The equations used where also checked for consistency with literature. The numbers can also be estimated by determining the maximum available. The maximum time available in three months is 2160 hours (assuming 30 days in a month). 5% of this value is 108 hours. Taken into account that the availability is high, 91 hours available for the subsystem is acceptable. The energy generated can be estimated by knowing that the system operates on average at 40% of the power. This number was verified by the expert. When combining 2,160 hours and $20kW$, the result is $4.3 \cdot 10^4 kWh$. The power generated calculated by the Matlab script is $6.6 \cdot 10^4 kWh$ as discussed before. This number is higher because the average power produced is larger. By dividing the power generated according to the Matlab file by the total number of hours an average power of $30kW$ was determined. This larger power explains the higher number of energy generated. This number is still considered valid because the generator is assumed to be able to operate at an average of 60% of its rated power.

The plot of the crosswind speeds was checked by using the dummy value used in previous verification parts. The dummy value is filled with data entries in which the wind speed directions and magnitudes can be chosen. By comparing the result on the graphs and the input values one can make sure that the graph shows the intended data.

3.2.3 Legislation analysis

When designing a new system, it is important to know what legislative boundaries and requirements need to be taken into account. Kite power systems are a relatively new source of energy so no specific laws and regulations exist yet. Nevertheless, it is crucial not to overlook special situations that apply to the system in question as non-compliance with laws could result in partial or total shutdown.

Research on legislations that would, in a broad manner, apply to the launch, landing and storage system yielded requirements that have to be addressed. Specifically shadow flicker and noise levels that would cause intrusion in the environment where the system is located. The Environmental Activities Rules and Regulations mention the following article excerpts:

Article 2.17-2.22 ”For management of an industrialized zone, the competent authority may require an acoustic survey within four weeks after a noise complaint [. . .] The standards apply to the facade of nearby buildings and adjacent areas [. . .] The maximum noise level of the standard is $70dB$ on the facade and $55dB$ indoors [. . .] If the company is located in an industrial zone, a norm distance of 50 meters from the boundary is established for noise-sensitive objects [. . .] The norm distance does not apply for wind turbines and an acoustic survey must be carried out on the facade of nearby buildings.”

In order to comply with this article, the maintenance of the system must be kept strictly so as to ensure the mechanisms are well lubricated and in top condition to reduce noise emission. Since the majority of the potential noise originating from the system happens during storage and packing (as more mechanisms are required) rather than during flight, as long as maintenance takes place it will be assumed that the legislation is met.

Article 3.13-3.15 ”[. . .] an annoying shadow effect is caused by the change in brightness on a window or residential place. An expert will check a wind turbine annually. If there is an unwanted situation (shadow passing frequencies between 2.5 and $14Hz$) the turbine will immediately be stopped until necessary measures are taken.”

The shadow effects of the kite power system must be monitored to avoid non-compliance with this regulation. It is expected for the kite power system to have a lower shadow effect and since this is an effect that takes place whilst the kite is in flight, compliance with this article is out of the scope of the design. As the exact location of the kite power system including the launch, landing and storage system is not determined in this technical report, the assumption is made that the system is positioned far enough from residential areas (see assumption M12).

3.3 Sustainable development

As the kite power project is inherently environmentally friendly, great effort must be put into developing an eco-friendly launch, landing and storage system for this specific pumping kite system. The environmental impact will be monitored exhaustively throughout the whole design process, paying special attention to the type of materials used for manufacturing. In the preliminary and conceptual design phase the sustainable possibilities of each concept have been explored but the core of the matter lies in the detailed design phase in which for example materials are selected, actuators are chosen and the energy consumption is set.

In subsection 3.3.1 the results of a general sustainability analysis are presented. The second subsection gives an overview of the development strategies that have been determined for this project. The last subsection elaborates on the actual implementation of sustainable development in the design process. In the entire section the main focus is on the detailed design phase.

3.3.1 Sustainability analysis

This subsection covers the exploration of the drivers for sustainability and the clarifies the role that sustainability plays throughout the entire design process.

Project drivers for sustainability
The following drivers for sustainability have been identified:

- Environmental bottom line of kite power systems enhances the need to be sustainable in every aspect.
- Achieve compliance with the sustainable vision of the TU Delft and of project developers.
- Establish a standard among other initiatives to set sustainability as a core factor.

Set a vision
Develop the kite power system as a fully automated, yet environmentally friendly system.

- Reduce harmful waste and emissions originating from manufacture and operations.
- Reduce the use of non-renewable resources for development and manufacture of the system.
- Reuse waste materials and energy.
- Aim to develop a self-providing system.
- Recycle old scrap material, which is useful for manufacture of the launch, landing and storage system.

Set objectives
Based on the previously set vision for this project and the research that has been performed during the preliminary and conceptual design phase, the vision has been slightly updated. The following objectives hold throughout the design process:

- Reduce environmental impact of system manufacture by setting natural or recycled (materials) as the project's first choice.
- Develop a launch, landing and storage system which requires a return of no more than 1% of the generated electricity during flight of the kite into the system for operation.
- Develop a self-providing system which uses 100% renewable energy produced by the kite or by additional renewable energy sources (in case the energy demand exceeds the 1%).

3.3.2 Sustainable development strategy

The following four strategies have been determined to ensure that sustainability is thoroughly covered via a wide range of activities throughout the design process:

Strategy I - Reduce energy needs
Monitor the energy need for the functions of launch, landing and storage and reduce that need as much as possible in order to make it feasible for it to run on electricity solely generated by the kite and other renewable energy sources if necessary.

Strategy II - Innovative solutions exploration
Explore the opportunities of using innovative sustainable solutions like solar cells, small wind turbines and environmental friendly materials to optimize the durability and sustainability of the design.

Strategy III - Green material design
Reduce the waste and harmful materials or materials manufactured by environmental unfriendly processes as much as possible during the desing process. Additionally, natural/biological materials that are not harmful to the ecosystem or humans will be prioritized.

Strategy IV - Cradle-to-cradle design
Design the automated system from reusable and recyclable materials as much as possible such as those obtainable from bike and car junk yards. Furthermore, the team will aim to use materials that will be reusable and/or recyclable after usage.

3.3.3 Implementation of sustainable development

Implementation, monitoring and improvement of the sustainable strategy are on-going processes that will be carried out throughout the entirety of the design period and the responsibility to do so befalls every team member. In the detailed design phase a tremendous difference can be made if the sustainable development strategy is fully put into practice, however a possible impact on the quality and durability of the design must always be considered. In this subsection the action plan is discussed. The action plan is a short list of simple yet effective precepts for the detailed design phase.

The project will incorporate sustainability aspects from the start of the detailed design phase but special effort in this regard is put in during the iteration phase, in which the design will be improved. A list of steps is given below to ensure the implementation of the sustainable strategy.

1. Allocate the energy budget at the start of the detailed design phase which specifies the energy consumption [kJ] by every mechanism.
2. Determine per mechanism which parts can be reusable, recyclable, and/or made out of natural/biological materials.
3. Perform research on existing sustainable solutions throughout the detailed design process to enhance the use of innovative, sustainable design solutions.
4. Take sustainable solutions as a first choice throughout the design process if their possible disadvantages in costs, maintainability or availability do not affect the overall feasibility of the design; make a quick trade-off before implementation.
5. Calculate the total energy [kJ] required at the end of the design of a mechanism.
6. Calculate and evaluate the total energy consumption of the integrated system and go back into the iteration phase if the requirements/demands are not met.

In section 11.2 a review is given on these steps using the four development strategies as a guideline.

3.4 Technical risk assessment

To have an estimate which part of the design is hardest to design a risk map is made. Which can be used to assign certain resources to a part in the design. The risk included in the risk map is the technical risk, defined as the risk of not being able to complete the design within limits of cost, schedule or technical information and it should be kept in mind that mechanisms with larger technical risk require more resources to complete the design within constraints. The risk levels of the different mechanisms are explained in this section and can be used in the next section for the resource allocation.

The risk levels for all mechanisms are shown in Table 3.3. An explanation for these levels is given below the table. This grading of the scales is chosen so the classification of the risks can be done with least confusion on the definition of the grades. The vertical scale indicates the risk that the design can not be complete within the constrains set for the project. The horizontal scale indicates the consequence in case the design team fails to design the mechanisms within the limits for the project. To further minimize the discussion the definitions of the grading are given here. *Catastrophic to mission* indicates that there is severe damage where parts need immediate repairs or replacement. *Mission failure* indicates that there is no severe damage to the system, however the mission is unable to proceed. This could mean that the kite has missed the horizontal beam and has landed elsewhere. *Marginal damage* indicates minimal damage that can be repaired during the next maintenance period. *Negligible damage* indicates possible damage but hardly any consequence.

Table 3.3: Risk levels of the mechanisms

Risk of occurrence →	Feasible in theory			ST03	
	Working laboratory model				
	Practically working in another field	HB03, HB04, ST04	SS03, ST01, ST02	RP01, KA01	HB01, HB02, VB01, VB02, VB03, RP02, RP03
	Practically working in our field	ES04	HB05	ES01, ES05	ES02, ES03, SS01, SS02
		Negligible damage	Marginal damage	Mission failure	Catastrophic to mission
		Consequence →			

The codes in Table 3.3 correspond to the codes in the tables below. The explenation for the different risk levels are also shown below. The risk levels for the existing systems are shown in Table 3.4, for the beam in Table 3.5, for the boom in Table 3.6, for the rotating platform in Table 3.7, for the swivel storage in Table 3.8, for the storage in Table 3.9, and for the adaptations to the kite in Table 3.10.

Table 3.4: Technical risks for the existing systems

Identifier	Mechanism	Explanation
ES01	CPU	The CPU already exists in the current system. If the computing power is not sufficient, a possible consequence is that the kite might miss the beam. This is a mission failure, as no severe damage to the system is done.
ES02	Weather station	The weather station already exists, however it should be able to receive information from the KNMI to predict the occurrence of lightning as lightning is one of the most prominent reasons for landing. If this system is not designed properly, it is catastrophic to the kite, as the kite and CU may be damaged by lightning strike.
ES03	Power system	The elaborate power system for the concept is not available in the current system. It is however existing in our field. If it is not possible to design the power system properly within the given resources, a consequence such as a short circuit or the generator burning is catastrophic to the mission.
ES04	Drum	The drum already exists in the current system but hardly needs any adjustments for this concept. There is for consequence of not being able to design the drum.
ES05	CU	The CU already exists in the current system, however the amount of commands which can be sent through the CU needs to be upgraded. If this can not be done the commands may be insufficient for the required maneuvers. One such maneuver is landing on the beam. If the kite misses the pole, it may land on the ground. There is no severe damage to the system, however human intervention is required which indicates mission failure.

Table 3.5: Technical risks for the beam

Identifier	Mechanism	Explanation
HB01	Beam	The horizontal beam is a common structure, however is so far not used in our field of application. If the beam can not be designed properly within our resources, it could buckle or break during operation. This is catastrophic to mission.
HB02	Beam hinge	The beam hinge is available in various technologies outside of our field. If the beam is not designed properly, it may not be able to withstand the loads experienced on it. Or it may not be able to turn with enough speed. If the hinge is unable to withstand the loads and collapses as a result, the consequence is that the hinge needs replacement. Moreover the kite/CU could damage which indicates catastrophic to mission.
HB03	Gripper	The technology predominantly exists in robotics. If it is not possible to design the gripper properly the consequence is that the gripper may not be responsive within the time to secure and fasten the safety line. If the gripper lets the safety line escape due to a possible large delay time, multiple tries are permissible which indicates negligible damage.
HB04	Gripper rail	The rail technology on the beam already exists. If there is not enough resources available for proper design, the rail mechanism could be too fast or too slow, however this has a negligible consequence to the overall operation.
HB05	Ridge	The ridge mechanism is already used in other technology to keep a certain item in place. When this ridge is not designed properly the kite could fall off the beam. If the safety line is still holding the kite there would be negligible damage as the wind can put the kite back on the beam.

Table 3.6: Technical risks for the boom

Identifier	Mechanism	Explanation
VB01	Boom	Booms exist in many applications. However if it is not designed properly, it can structurally fail throughout numerous failure modes (buckling, deflection, etc.). The consequence is catastrophic to the mission.
VB02	Boom hinge	Hinge technology is available in other disciplines, however if not designed properly the hinge is not able to withstand loads and may cause the boom the collapse under the applied loads which indicates catastrophic to mission.
VB03	Vertical boom rail	The risk of occurrence is equal to the gripper rail (HB04). However the consequence is higher as incorrect speed of the vertical boom rail could rip apart the kite. Another possibility occurs when the tether lines are not tightened. In that case the kite can flap around. This can induce high fatigue loads which are catastrophic to the kite. This indicates catastrophic to mission.

Table 3.7: Technical risks for rotating platform

Identifier	Mechanism	Explanation
RP01	Bearing	Bearing technology is very widespread. However if not designed properly for this application, the bearing may not be able to turn into the right direction. This requires human intervention to lubricate the bearing more or to check for more damage which indicates mission failure.
RP02	Platform cover	Covers that work as mounts of structure to carry heavy loads exist in fields other than kite power. If this structure is not designed properly and fails due to applied loads, the whole structure collapses which indicates catastrophic to mission.
RP03	Foundation	Foundations are commonly used in all civil engineering application. However if not designed properly, it is catastrophic to the structure above it.

Table 3.8: Technical risks for swivel storage

Identifier	Mechanism	Explanation
SS01	Swivel	The swivel already exists in the current system but it needs to be redesigned for the current system. If the swivel does not work properly, the tether could get damaged and the kite could be blown away which is catastrophic for the mission.
SS02	Swivel beam	The beam on which the swivel is mounted is a simple beam which is already being used in kite power applications: to support a certain load. If this swivel beam would fail the subsystem would not be able to operate and immediate human intervention is needed for repairs. This makes the consequence catastrophic.
SS03	Swivel rail	The swivel rail technology is predominantly available in train tracks. If the swivel rail is not designed properly, the system retries to align the tracks numerous times until the tracks are aligned. The consequence is marginal and can wait until the next maintenance period.

Table 3.9: Technical risks for storage

Identifier	Mechanism	Explanation
ST01	Storage cover	The storage cover technology exists from swimming pool covers and garage doors. If the storage cover is not designed properly and can not close properly, this can be treated during the next maintenance phase which indicates marginal damage.
ST02	Storage structure	The structure for storage has to keep the kite safe, has to withstand all the loads acting upon it and has to keep the humidity down to a certain level. If it is not designed properly, there is no immediate damage done to the kite, so the repair can wait until the next maintenance period which indicates marginal damage.
ST03	Folding poles	This mechanism has not been done before. Therefore it is feasible in theory. If we are not able to design this mechanism properly, the mission fails, hence human intervention is needed to come and store the kite which indicates mission failure.
ST04	Lock-in device	The lock-in device is available in existing technology, if it is not designed properly there are only negligible consequences.

Table 3.10: Technical risks for kite and tether adaptation

Identifier	Mechanism	Explanation
KA01	PRU	The PRU exists in other fields of engineering, if the PRU is not designed properly and fails to pump the kite, the consequence is that human intervention is required which indicates mission failure.

3.5 Resource allocation

The project has a limited amount of resources which can be used to design the system. To be able to monitor these scarce resources an allocation has to be made before the design progresses. This assigns a certain budget, time and amount of energy to each subsystem in the design. In this section the different budgets are discussed. After that a classification of mechanisms is given which is helpful when allocating the budget. Next the resource allocation itself is discussed in which the reasoning for some choices are given.

The budgets which need to be taken into account are based on the requirements. The requirements state that the subsystem can use a limited amount of money, time, and energy. These budgets are chosen because if they are not tracked properly throughout the design the risk of not meeting the requirements is increased. The maximum values used in the budgeting for the deployment time and energy available can be seen in subsection 3.2.2. The maximum value for the finance part is retrieved from the project guide [18]

In order to be able to distribute the budgets over the different mechanisms they should be ranked. The ranking makes sure that an overview is maintained. This ranking is based on the technical risk assessment. The grade a mechanism receives is the number of boxes the mechanism is away from the origin. The box with its corner in the origin is defined as grade 1. For example a mechanism which is classified as *Practically working in our field* and *Marginal damage* would get a grade of 2. Although a grade is given this is not a hard figure to determine the budget available.

3.5.1 Result

In Table 3.11 the resource allocation is given together with the actual values obtained from the design. At first sight it is clear that the cost budget was overshot by over 100% (267% of the initial budget of €20,000). This is mainly due to the cost of the storage and rotating platform subsystems. All other subsystems are cheaper than or right on target of their aloocated budget. Pleas note that the sum of the prices of all the subsystems does not add up to the total value simply because the final assembly and overhead cost are not listed.

The deployment time does not go over 50% of the allocated time. All subsystems except for the PRU perform their task considerably faster than was initially estimated. In the designed column a zero means this mechanism is working while another lengthier task is performed.

On top of this, the system also uses only a little over 3% of the allowed amount of energy to execute the mission. In some rows a zero occurs in the last column while there is a value present in the column before, this simply means that the energy consumed by this mechanism was deemed negligible. The PRU does consume a reasonable amount of energy for inflating the kite. However, the value in the table is zero because this energy is generated by a stand-alone power generator which also powers the CU.

Please note that the swivel mechanism has no values because there was no intention of designing it at the start of the detailed design phase. During this phase it was redesigned to make the system function properly but for cost it is assumed to be part of the existing ground station.

In previous reports the contingency percentage for this design phase was set at 95% of the maximum. This is to prevent going over the actual value. For this fraction the conclusion stays the same: Cost is too high while energy consumption and operation time are nowhere near the limit value.

Table 3.11: Resource allocation for the project

Subsystem	Mechanism	Risk Map	Finance allocation	Designed	Deployment time allocation	Designed	Energy consumption allocation	Designed
		[]	[€]	[€]	$[s]$	$[s]$	$[kJ]$	$[kJ]$
Horizontal beam	Beam	5	1,000	660	N/A	N/A	N/A	N/A
	Beam hinge	5	1,000	1,672	N/A	N/A	4,000	46.4
	Gripper	2	600	123	1	0	400	0
	Gripper rail	2	200	638	50	9	1,000	31.9
	Ridge	3	200	75	8	0	600	0
	Total	3.4	3,000	3,168	60	9	6,000	78.3
Vertical boom	Boom	5	6,000	4,158	N/A	N/A	N/A	N/A
	Boom hinge	5	2,000	4,147	30	50	9,000	348
	Vertical boom rail	2	2,000	2,965	600	140	25,000	908
	Total	4	10,000	11,269	630	190	34,000	1256
Rotating platform	Bearing	4	1,000	3,413	180	120	24,000	495
	Platform structure	5	1,000	2,574	N/A	N/A	N/A	N/A
	Total	4.7	2,000	5,987	180	120	24,000	495
Swivel storage	Swivel	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Swivel beam	4	500	388	N/A	N/A	N/A	N/A
	Swivel rail	3	750	752	N/A	N/A	5,000	77.7
	Total	3.7	2,000	1,140	10	0	5,000	77.7
Storage	Storage structure	3	1,000	1,176	N/A	N/A	N/A	N/A
	Storage cover	3	500	1,650	300	48	3,500	0.6
	Folding poles	6	800	5,808	600	0	10,000	706
	Lock-in device	3	200	110	10	0	500	0
	Total	3.8	2,500	8,744	910	48	14,000	706.6
Kite adaption	PRU	4	300	124	600	600	500	N/A
	Total	4	500	248	600	600	500	N/A
Total value		3.8	20,000	53,451	2,190	997	83,500	2,614

4. Analytical approach

The subsystems and their mechanisms have been analyzed in detail. This chapter will present the analytical approach of these analyses, such that the content of chapters 5 to 10 follows logically from the analytical background introduced within this chapter.

Section 4.1 lists all the assumptions has been made in the process towards the final design. The second section describes the equations and methods used for the structural analysis calculations. The third section gives the analytical theory related to the energy consumption, while section 4.4 gives the details on actuator power calculations. Finally, in the last two sections of this chapter the analytical approach of the estimation of operating time and costs and manufacture are discussed.

4.1 Assumptions

In this section all assumptions made throughout the project will be stated. The first subsection will discuss the main assumptions which are related to the entire system. The second subsection describes the requirements related to the aerodynamic, while the fourth section specifically focusses on the CU. Subsection 4.1.4 elaborates on the assumptions made in the weather analysis. The fifth subsection states the assumptions considered for the energy, operation time and power consumption calculations and the subsection 4.1.6 describes the assumptions made for the structural integrity calculations. The section ends with all assumptions on the manufacturing process and cost.

4.1.1 Main assumptions

In the list below, the main assumptions about the entire system can be seen. These are the assumptions on which the design is based.

M01 All existing subsystems as defined in subsection 2.3.1 are scaled to accommodate the $70m^2$ kite.
M02 The drum is already designed.
M03 The generator is already designed.
M04 The motor accompanying the generator is already designed.
M05 The kite carries a wind sensor.
M06 The ground station has a fixed location.
M07 The main tether and kite have to be replaced every three months.
M08 The CPU has a wireless internet connection for receiving forecasts, proper communication wiring to all ground-based mechanisms, a transmission antenna for interaction with the CU and can be remotely controlled.
M09 The minimum angle which the main tether makes with respect to the horizon is assumed to be 15 deg.
M10 The pump is positioned in such a way that it does not change the stability of the kite during flight.
M11 There is sufficiently small delay time between the hardware such that the gripper is able to grab the kite.
M12 The kite power system is established far enough from a residential area to prevent shadows on windows or residential buildngs.

4.1.2 Aerodynamic assumptions

The aerodynamic assumptions are stated in this subsection. The assumptions are referred to in the text when made.

A01 The upstroke and downstroke are assumed to be two equidistant steady straight line motions.
A02 The net effect of the kite mass on power output is assumed to be negligible, i.e. kite mass is assumed to be zero and we have a massless point model kite.
A03 The wind profile is assumed to be constant with altitude and time (no gust).
A04 The kite is assumed to feature good depower qualities.
A05 $C_{L_{up}} = 1.1, C_{L_{down}} = 0.11, (L/D)_{up} = 5.5, (L/D)_{down} = 1$
A06 The tether is assumed to follow straight lines and have zero mass.
A07 The tether is assumed to have zero drag.
A08 Steady flight.
A09 The drag coefficient of a flat plate is 1.28
A10 The kite is assumed to operate at tether angles $\beta > 20°$ and at heading angles of $\phi = 0$.
A11 During reel-in the kite is assumed to be in non-maneuvering mode.

4.1.3 CU assumptions

The CU assumptions are stated in this subsection. The assumptions are referred to in the text when made.

CU01 The CU is self-powered by means of renewable energy and can provide enough power for the PRU.
CU02 The CU is assumed to have a GNSS and IMU.
CU03 The CU has a wireless transmitter to send in for the ground station.
CU04 The CU is able to control the orientation of the kite within three degrees of freedom for orientation and three degrees of freedom for position during launch and landing. Hence the required actuators are established in the CU.
CU05 The CU is able to control the kite with enough accuracy to perform reel in and out from and to $100m$ in zenith position.
CU06 The CU is able to control the kite such that the horizontal beam is able to enter in the bridle gap of $26m^2$.
CU07 The CU is able to control the kite with an accuracy of $1m$.
CU08 The bridle system and main tether can be easily removed from and reattached to the CU.
CU09 The response time of the CU is sufficient to ensure accurate control during launch and landing.

4.1.4 Weather assumptions

In the following list, the assumptions used during the weather analysis are shown. The assumptions are referred to in the text when made.

WE01 The kite should be landed due to lightning.
WE02 The kite should be landed due to winds above $25m/s$ measured at the altitude at which the kite lands.
WE03 The kite should be landed due to winds below $4m/s$ measured at the altitude at which the kite lands unless the decisions program decides otherwise.
WE04 The kite should not be landed for reasons other than stated in WE01, WE02 or WE03 hence no landing is required for hail, heavy rain, etc
WE05 The kite can not be launched when there is lightning present.
WE06 The kite can not be launched when the wind speed is above $25m/s$ measured at the altitude at which the kite launches.
WE07 The kite can not be launched when the wind speed is below $5m/s$ measured at the altitude at which the kite launches.
WE08 The kite can be launched during all conditions except those describes in WE05, WE06 or WE07 hence launchs is not stopped for hail, heavy rain, etc

4.1.5 Energy consumption assumptions

The energy consumption assumptions are stated in this subsection. The assumptions are referred to in the text when made.

E01 The system is assumed to be free from heat and sound energy losses.
E02 The mass in the system obeys the law of conservation of mass. Therefore the wear on equipment is neglected.

4.1.6 Structural assumptions

The structural assumptions are stated in this subsection. The assumptions are referred to in the text when made.

S01 Shear forces are assumed to go through the shear center.
S02 In cases of torque, pure torsion is assumed. Hence warping is not considered and $\frac{d\theta}{dz} = 0$.
S03 For the calculation of plane stress the beams are assumed to be clamped at one end.
S04 The neutral axis acts through the centroid of the cross sections considered.
S05 For the calculation of buckling the beams are assumed to be simply supported.
S06 For buckling, there are no eccentricities.
S07 Buckling occurs in the first mode.
S08 The structure is assumed to experience only plane stress.
S09 The swivel rail is designed using thin-walled assumptions. This implies that the stresses are constant through the thickness and t^2 or higher are neglected.
S10 The swivel beam is modelled as being two separate beams since the force exerted by the swivel is acting in the middle.
S11 The lock in device for the rotating platform is assumed to only experience shear stress.

4.1.7 Manufacturing process and cost assumptions

The manufacture process and cost assumptions are stated in this subsection. The assumptions are referred to in the text when made.

MP01 The quotes obtained from [37], [38], [39], [11] and [40] are correct and represent the true value of the components.
MP02 Shipping costs are included in the quote for each component from the providers above.
MP03 Assembly costs of the elements of a subsystem will add up to 10% of their total purchase and manufacture cost.
MP04 Assembling subsystems together will cost 10% of the manufacture, purchase and assembly costs of all subsystems.
MP05 Employee salary to adjoin all components and subsystems will add up to 5% of the total manufacture, purchase and assembly costs of the entire system.
MP06 Overhead costs add up to 100% of the total direct labor costs (assembly and employee salary) and fits within the range given by [17].
MP07 Human efficiency for assembly is taken as 45%. [17] suggests 65% as a top-level efficiency for human labor.

4.2 Structural analysis

This section will discuss the approach to size the structure to withstand the maximum loads experienced. The purpose is to provide the reader with the steps taken and equations used to size the structure and size the actuators. The equations in this section are retrieved from [41].

In subsection 4.2.1 the forces and moments experienced by the structure will be discussed and in subsection 4.2.2 the formulas for stress calculation are given. Subsection 4.2.3 discusses the buckling load equation and the deflection of the structure after which subsection 4.2.4 will discuss the optimization procedure used. Subsection 4.2.5 will discuss the reference frame used throughout the calculations. Finally the verification of the code is presented in subsection 4.2.6.

4.2.1 Forces and moments

For the analysis of the design the worst case scenario is considered. The worst case considered for this design is wind speeds of above $25m/s$ and where the wind is perpendicular to the storage. At this point, the kite will be deflated and hanging as a large sail in the perpendicular direction of the wind. The drag force of this sail will cause a load on the horizontal beam of $8.6kN$ in both the $z-$ and $y-$direction since the a similar force downwards will be needed to keep the lines and kite into tension this force is also stated as F_t. This drag force was calculated using Equation 2.1 in subsection 2.2.2.

Other forces which are applied to the structure are the drag force on the structure and the weight of the kite. This drag load is also determined using Equation 2.1 in subsection 2.2.2. All these forces and moments caused by these forces described before are multiplied by a safety factor of $J = 1.5$.

In this structural analysis all subsystems are analyzed separately and the analysis is going to start where the loads are applied. The subsystems will all be analyzed as being separate structures and are analyzed as being simple beams where possible. The forces and moments experienced at the root of every separate subsystem are passed onto the next subsystem(s). This is visualized in a simple way in Figure 4.1.

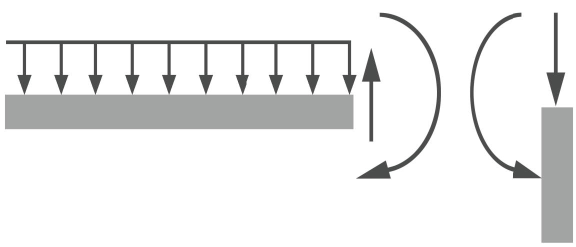


Figure 4.1: Load transfer

4.2.2 Materials and stresses

For the analysis of the stresses two materials will be used. This is because for some mechanisms the weight needs to be lower to minimize actuator cost. The materials used can be seen in Table 4.1.

Table 4.1: Specifications of the materials considered

Material	Type	Yield Stress $[MPa]$	Young's Modulus $[GPa]$	Density $[kg/m^3]$
Aluminum	6061-T6	275	68.9	2700
Steel	API 5L X65	448	200	7800

The structures will be designed to have Von Mises stresses just under the yield stress of the material chosen. The Von Mises stress equation is given by Equation 4.1.

$$Y = \sqrt{\frac{1}{2}\left((\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\right) + 3\tau_{xy}^2 + 3\tau_{yz}^2 + 3\tau_{xz}^2} \tag{4.1}$$

In this equation σ is the normal stress parallel to the subscript axis in Pa and the τ is the shear stress on the plane of the subscript axes. Since only stress in one direction and pure shear will be considered, Equation 4.1 can be reduced to Equation 4.2.

$$Y = \sqrt{\sigma_z + 3\tau^2} \tag{4.2}$$

The normal stress in Equation 4.2 is the sum of the bending stress and the compressive stress. The bending stress can be determined using Equation 4.3 and the compressive stress is determined using Equation 4.4. The shear stress is determined by Equation 4.5.

$$\sigma_z = \frac{I_{xx}M_y - I_{xy}M_x}{I_{xx}I_{yy} - I_{xy}^2}x + \frac{I_{yy}M_x - I_{xy}M_y}{I_{xx}I_{yy} - I_{xy}^2}y \tag{4.3}$$

$$\sigma = \frac{F}{A} \tag{4.4}$$

In Equation 4.3 the I being the moment of inertia in m^4, M is the bending moment in Nm and x and y are the distances from the centroid in x- and y-direction, they are both in m. In Equation 4.4 the A is the cross-sectional area of the structure analyzed at the location at which it is analyzed.

$$\tau = \frac{q_s}{t_s} \tag{4.5}$$

In this equation, q_s is the shear flow in N/m and t_s the thickness of the sheet/part analyzed. The equation for the shearflow due to a shear force q_s is given by Equation 4.6.

$$q_s = -\frac{I_{xx}S_x - I_{xy}S_y}{I_{xx}I_{yy} - I_{xy}^2}\int_0^s tx\,\mathrm{d}s - \frac{I_{yy}S_y - I_{xy}S_x}{I_{xx}I_{yy} - I_{xy}^2}\int_0^s ty\,\mathrm{d}s \tag{4.6}$$

S is the shear force in N and s is the path of the piece of a cross-section analyzed. There can also be a shear flow caused by a torque on the structure given by Equation 4.7.

$$q_s = \frac{T_q}{2A} \tag{4.7}$$

4.2.3 Buckling and deflection

While the entire structure is designed using these equations, the buckling force must still be analyzed all along. The critical buckling load is given by Equation 4.8, this is the buckling equation for a simple supported case in the first buckling mode and is used since this is the worst case buckling mode.

$$P_{crit} = \frac{\pi^2 E_Y I}{l^2} \tag{4.8}$$

In the formula above l is the length of the beam determined in m and E_Y is the young's modulus of the material used in Pa. For this equation, a simply supported beam is assumed.

Next to that it must not fail under bending, shear, compression and buckling, the structure should not deflect too much at the tip. The structures are designed to have a deflection not more than 2% of its own length. The deflection at the tip due to a singular load is given in Equation 4.9. The deflection of a distributed load is given in Equation 4.10.

$$\nu = \frac{FL^3}{3E_Y I} \quad (4.9) \qquad \nu = \frac{pL^4}{8E_Y I} \quad (4.10)$$

Where p is the distributed load in N/m. In some cases the load will not act at the end of a beam, in this case the angle of deflection is calculated at that part of the beam and the extra part is simulated as a linear beam over the remaining beam part. This angle is calculated using Equation 4.11.

$$\delta = \frac{FL^2}{2E_Y I} \quad (4.11)$$

4.2.4 Optimization

The ideal structure has the lowest possible weight and can still withstand the forces experienced. To get to this an optimization program was written in Matlab. This optimation program uses as input a certain range of radii and thicknesses. The program iterates for all possible combinations of radii and thicknesses the stresses experienced as explained in subsection 4.2.2 and the buckling load and deflection as explained in subsection 4.2.3. For most cases circular cross-sections will be used since these are better resistant against torque and have no sharp edges which cause wear on the kite or the tethers. The cross-sectional area of a circle is calculated by Equation 4.12 and the moment of inertia of a circle is calculated using Equation 4.13.

$$A_{circ} = \pi(r^2 - (r-t)^2) \quad (4.12) \qquad I_{circ} = \frac{\pi}{4}(r^4 - (r-t)^4) \quad (4.13)$$

In Equation 4.12 and Equation 4.13 r is the radius of every iteration. The weight in each iteration is determined using Equation 4.14.

$$m = AL\rho_m \quad (4.14)$$

In this equation ρ_m is the density of the chosen material. The structure will be optimized to weight. Since the assumption was made that weight is almost equal to cost.

4.2.5 Reference frame

The reference frame considered for the calculations can be seen in Figure 4.2. The x-axis is along the horizontal beam and the z-axis along the vertical boom.

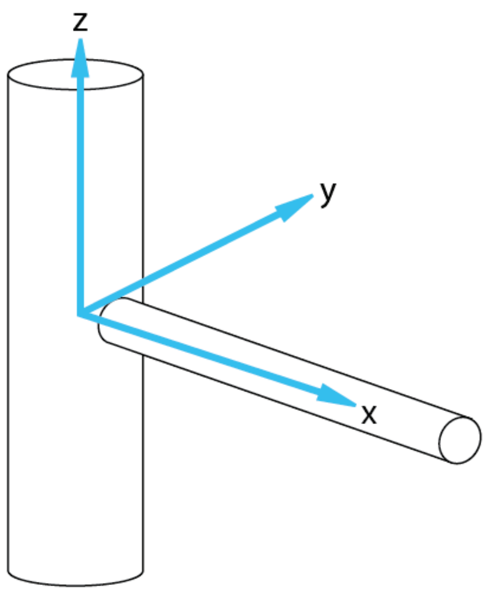


Figure 4.2: The reference frame for calculations

4.2.6 Verification

To verify the program written for the optimization of the structure, the unit blocks of the system were all tested separately. In the program functions will be written to calculate the shear and bending stress in the cross section. The results will be checked visually if they make sense. Furthermore the entire code of the written program will be checked by one of the other students to make sure that no errors exist in equations and determining of forces and moments.

4.3 Energy consumption analysis

In this subsection the outline for the calculation of the energy required to perform the dynamics of the mechanisms is given. Their energy consumption is used to make sure the system does not consume too much energy to operate. When considering all the mechanisms the total energy consumption can also be calculated.

The energy required for the actuators is determined by the load estimation and the distance for each actuator. When these estimates are known the energy required can be calculated using Equation 4.15 and Equation 4.16. The energy calculated at this point is the output energy for the actuator. If one takes into account the efficiency for the actuator the energy input is determined. When the actuators are sized their own weight can be used for the next iteration phase in the structures analysis.

Energy for a linear actuator:

$$E = \int_{x_1}^{x_2} F(x)dx \tag{4.15}$$

Energy for a rotational actuator:

$$E = \int_{\theta_1}^{\theta_2} M(\theta)d\theta \tag{4.16}$$

Note that for most mechanisms we assume that the energy needed to accelerate is negligible except for the rotating platform, the boom hinge, the beam hinge and the vertical boom rail. For these respective mechanisms the force or moment to accelerate to a chosen ω (angular velocity) or velocity v is also taken into account as shown in Equation 4.17. This is done because the large and heavy structures result in a large moment of inertia, hence the acceleration phase cannot be ignored.

$$M = I_0\alpha \tag{4.17}$$

Energy needed for the sensors is easier to calculate. They operate for a certain amount of time. When their power is known the energy needed follows from those two values with the following equation.

$$E = Pt \tag{4.18}$$

4.3.1 Verification

The energy consumption for all the respective subsystems was calculated by means of a Matlab code which must be verified. Even though the formulas that are used are straight forward, the code has been checked for correctness multiple times. It will be shown by means of an equation array that the code block *horizontal beam hinge for launch* is correct. In the code the numerical version of an integral was used as shown in Equation 4.19.

$$E = \sum M_i \delta\theta_i \tag{4.19}$$

To calculate the energy of the beam hinge during launch, we consider 4 different phases; when the beam is accelerating, launches the kite, retracts, and decelerates. During these four phases the hinge experiences four different moments. They are the following: $M_{acc}, M_{launch}, M_{packing}$ and M_{decc}. The beam accelerates up to $6deg/s$ in $0.2s$, that means it has an angular acceleration of $30deg/s^2$. Taking the reference as the horizontal or 90° to the vertical boom, the acceleration angle is 0.6° calculated using Equation 4.20.

$$\theta = \frac{1}{2}\alpha t^2 \tag{4.20}$$

The maximum angle at which the beam will have to hinge upwards to launch the kite is 60°. The angle at which the beam hinge decelerates is 89.4° and the angle at which the horizontal beam stops is 90°.

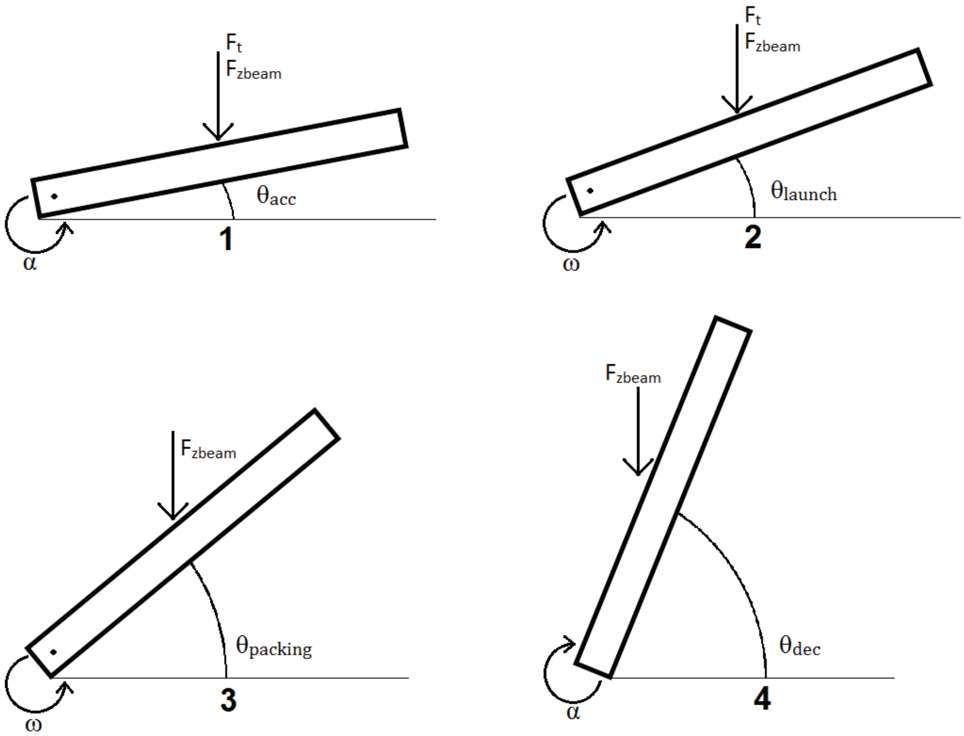


Figure 4.3: the four respective phases required for the *Horizontal Beam Hinge for Launch* energy calculation

The first phase is when the kite is on the horizontal beam and the horizontal beam accelerates to ω (angular velocity). When the kite is on the beam the normal force on the beam $F_{z_{beam}}$ and the tension on the main tether keeping the kite in place F_t are considered. The second phase is when the kite proceeds with constant angular velocity up to the angle at which the horizontal beam is launched (θ_{launch}). Note that the kite is still on the beam so the forces F_t and F_{zbeam} are still considered to simulate the worst case scenario. After the kite has launched, the horizontal beam needs to be packed. It is packed in an upright position so the beam keeps on travelling upwards with no tension force from the tether up to a deceleration angle θ_{dec}. During deceleration the horizontal beam moves to the upright position. To calculate the total energy required the moments needed to actuate the motion are considered as a function of θ as shown in Equation 4.21.

$$E = \int_0^{\theta_{acc}} M_{acc} d\theta + \int_{\theta_{acc}}^{\theta_{launch}} M_{launch} d\theta + \int_{\theta_{launch}}^{\theta_{dec}} M_{packing} d\theta + \int_{\theta_{dec}}^{\frac{\pi}{2}} M_{dec} d\theta \tag{4.21}$$

The moments present in each phase and the moment of inertia are stated below.

$$I_{horizontalbeam} = \frac{mL^2}{2} \tag{4.22}$$
$$M_{net} = I\alpha \tag{4.23}$$
$$M_{acc} = M_{net} + (F_{z_{beam}} + F_t)x_{c.g.}cos(\theta) \tag{4.24}$$
$$M_{launch} = (F_{z_{beam}} + F_t)x_{c.g.}cos(\theta) \tag{4.25}$$
$$M_{packing} = (F_{z_{beam}} x_{c.g.}cos(\theta)) \tag{4.26}$$
$$M_{dec} = (F_{z_{beam}} x_{c.g.}cos(\theta)) + M_{net} \tag{4.27}$$

Given that the normal force of the beam is $15.4kN$, the tension on the tether $8.5kN$, the $x_{c.g.}$ is $2.3m$, the mass of the boom $126.42kg$ and the length of the boom $35m$ one can calculate the total energy for the beam to launch to be $57.4kJ$, whereas the Matlab code gives $57.7kJ$. The reason for this is because the values used in the Matlab code are more exact than the values used in the above calculation. Each code block was verified using unit testing and the method described above, therefore the code is verified.

4.4 Actuator power

Before an actuator can be chosen for a specific mechanism the required power needs to be calculated. A typical movement with an actuator consists of three phases: acceleration, constant-speed and deceleration. The maximum power a motor needs to deliver takes place right before the end of the acceleration phase. At that moment the product of force and velocity or torque and angular velocity is the greatest. The analytical calculation of the required power for a rotational actuator is given below. The same calculation is valid for linear actuators by replacing the angle, angular velocity etc. with position, velocity etc. To find the motor power first the desired angular velocity ω and acceleration time t_{acc} are set. With these values the angular acceleration α can be found through division of the two. The next step is to estimate the mass moment of inertia I_0 of the object in motion. The general formula for this can be found in Equation 4.28.

$$I_0 = \int_V \rho_m(r) r^2 dV \tag{4.28}$$

Next follows the calculation of the net torque T_{net} that the object should experience to accelerate at the specified value α.

$$T_{net} = I_0 \alpha \tag{4.29}$$

Then the torque required from the motor T_{motor}can be found by adding all counteracting torques like friction and wind.

$$T_{motor} = T_{net} + \sum T_{counter} \tag{4.30}$$

With this torque the power P_{motor} can be found by multiplying with the angular velocity ω

$$P_{motor} = T_{motor} \omega \tag{4.31}$$

4.4.1 Verification

The code used for the energy consumption is the same as that used for power as they are interrelated. The respective code block is *Horizontal Beam Hinge for Launch.* For the elaboration on moments and forces refer to Equation 4.27. The maximum power needed is found for the purpose of sizing the battery required for the system. In this case the maximum power occurs in the acceleration phase of the horizontal beam. In the Matlab code, the function *max()* is used to find the maximum power during operation. In this verification, it is shown that using the analytical method of differentiation, the same result is obtained.

$$P = M_{acc} \omega \tag{4.32}$$

$$\frac{\delta P}{\delta \theta} = -sin(\theta) x_{c.g.} (F_{z_{beam}} + F_t) = 0 \tag{4.33}$$

In Equation 4.32 the power required for acceleration is given. The objective of the next equation is to find the angle at which the power is maximized, hence the power equation is differentiated and equated to zero. Since $F_{z_{beam}}$, F_t and $x_{c.g.}$ are constants they can not equal zero, hence $sin(\theta)$ is zero. Note that the moment is obtained from Equation 4.27.

$$sin(\theta) = 0 \implies \theta = 0 \tag{4.34}$$

$$P(\theta = 0) = (M_{net} + x_{c.g.}(F_{z_{beam}} + F_t))\omega \tag{4.35}$$

$$P_{max} = 5.82kW \tag{4.36}$$

In Equation 4.35 the angle at which maximum power is achieved is zero. This value is put back into the power equation and the maximum power is found. For the values in the calculations please refer to subsection 4.3.1. The results from the equations above and from the code block are the same. The other code blocks were verified in the same manner and therefore the code is verified.

4.5 Operating time estimation

Estimating the operating time is important to ensure that the addition of this system to the existing pumping kite does not hinder the energy efficiency too much. The calculation for this is given by Equation 4.37.

$$t_{op} = \sum_{i=1}^{n} v_i \Delta x_i + \sum_{j=1}^{m} \omega_j \Delta \theta_j \tag{4.37}$$

In which:

- t_{op} The operation time
- n The number of linear actuators
- v_i The speed of linear actuator i
- Δx_i The distance for actuator i
- m The number of rotational actuators
- ω_j The angular speed of rotational actuator j
- $\Delta \theta_j$ The angle for actuator j

The equation above is applicable to each subsystem as well as the entirety of the system. When doing the latter, one has to takes special care in not counting simultaneous actions. If two processes occur at the same time only the longest must be accounted for.

4.6 Cost estimation

Estimating costs is a lengthy and complicated process as it consists of not only researching and quoting the price of the off-the-shelf elements, but also of extra custom-made components that will serve as the junction and connections between mechanisms as well as those parts that are specific to the design and thus cannot be obtained in the market. In the upcoming chapters about design of each subsystem, costs of material and manufacturing are considered whereas assembly methods will be taken into consideration in section 11.5 to obtain the total cost of the whole automated launch, landing and storage system.

In order to allocate the cost of each subsystem as accurately as possible for each subsystem, the price of the off-the-shelf components will be researched online and compared among supplier websites in order to obtain a realistic average. Sometimes the cost of these components may not be readily available so contacting the company will be required in order to get a quote.

In case a component must be custom-made to accomodate the dimensions and uses of the subsystem, possible manufacturing processes will be explored and budgeted as accurately as possible. This is prior knowledge obtained from the class AE2207 Production of Aerospace Systems and in order to reassure that the cost for custom production is accurate, the opinion of a mechanic specialist was obtained. For each custom manufactured part a cost will be estimated taking into account the price and volume of material used factored to the complexity of the process in order to get an accurate estimation of the cost.

For the connections of elements within each subsystem, the costs of assembly were found to be quite intricate and undefined at this point of the design such that a 10% of the total manufacturing and purchase cost will be taken into account for assembly. In section 11.5 these costs will be added to those of manufacturing or purchase of the elements and the final assembly costs to obtain a cost estimation for the whole system. The final assembly costs consist the process to ensemble all the subsystems together (both assembly material and process cost as well as man-hours) as well as overhead costs that are considered in every product that goes into the market. If the design of the system goes through and a more accurate representation of costs is needed, and the relations stated in Table 11.4 can be used as a basis for the renovated pricing strategy.
It is important to keep in mind that all these costs are subject to the volatility of the market and thus may not accurately represent the achievable cost: prices can be brought down by discount opportunities, cooperations and agreements with manufacturing companies, partnerships, sharing of facilities and manufacture equipment among others. A strong recommendation for the future of this design is to explore these options so as to make the overall system more affordable.

5. Design: Kite and tether adaptation

In order to launch and land the kite one large adaptation has to be made to the kite. A Pressure Regulation Unit (PRU) is needed to automatically inflate and deflate the kite. This PRU is attached behind the leading edge of the kite and is powered by the CU. Besides the PRU, three other small adaptations are required.

The first small adaptation is the relocation of the safety line attachment point (a safety line is already present on the kite with an offset of $25cm$ from the center). The safety line must be moved to the leading edge of the kite at the very center. Another second small change is related to sensors that will measure the tension in the bridle system and in the main tether, which will be mounted on the CU. A final adaptation is the addition of an identification mark on the kite. A red line will run along the center of the kite from the leading towards the trailing edge. The identification mark will help the ground crew during kite replacement (see subsection 11.6.3). The safety line and identification mark are considered to have a negligible impact on the system and are therefore not included as a mechanism. The effect of the tension sensors on energy consumption and costs is considered within this chapter, but as the sensors are such a small component of the entire system they are also not stated as a separate mechanism.

This chapter will discuss the actuator and various sensors needed for the PRU in section 5.1. The time and energy it takes to inflate and deflate the kite is discussed in 5.2. Section 5.3 gives the details off the additional cost of the PRU and sensors. The affected aerodynamic performance due to the PRU and the forces experienced by the system due to the kite are discussed in the last two sections respectively.

5.1 Actuators and sensors

The main functions of the PRU are to inflate the kite for launch and to deflate the kite after landing. It is located behind the leading edge in the center of the kite . The best solution to inflate and deflate the kite is the use of a volume pump (see Figure 5.1). These pumps are able to achieve a large mass flow of air, but are not able to attain high pressure. This does not pose a problem to inflate the kite as it is only pressurized to $1.55bar$. The pump should include a barometer in order to check the pressure in the leading edge of kite. This allows the PRU to compensate for pressure losses during flight operation.

Some research on pumps resulted in a $12V$ volume pump to be the most suitable candidate. Since specific parameters for such pumps are hard to find a specific $12V$, $20W$ volume pump (with a mass flow of $240l/min$) is scaled linearly in order to have a proper idea to decide on a specific pump. The volume pump under consideration is the Brüder Mannesmann 12V volume pump [11].

Figure 5.1: Brüder Mannesmann $12V$ volume pump [11]

Additionally to the PRU and as it was mentioned in the prior section, certain sensors and actuators will be adapted onto the kite. During landing, launch and operation, it is useful to know the tension on the steering lines, the safety line and the main tether line. There are four rope tension sensors mounted on the CU which communicate with the CPU conveying the required information. Secondly, When the kite is deflated the safety line needs to be elongated in order to keep the bridle system under tension. This is done by an additional actuator which should be mounted in the CU. Finally, on the swivel there is a angle sensor which monitors the angle at which the kite travels with relation to the ground.

5.2 Energy consumption and operation time

The PRU has to be able to fill the kite to the desired pressure within the required inflating time. Using the provided CATIA drawing the volume of the kite is calculated to be $2.4m^3$. The available time to pressurize the kite is $5min$ and assuming a pressure inside the leading edge of $1.55bar$ the required mass flow the pump has to deliver is $744l/min$.

In order to achieve the required mass flow the pump as described in the previous section is scaling up to a mass flow of $744l/min$, this would result in a $62W$ pump. The powering of the pump is done by the CU and is considered to be outside the scope of this project as stated in assumption CU01.

5.3 Manufacturing process and cost

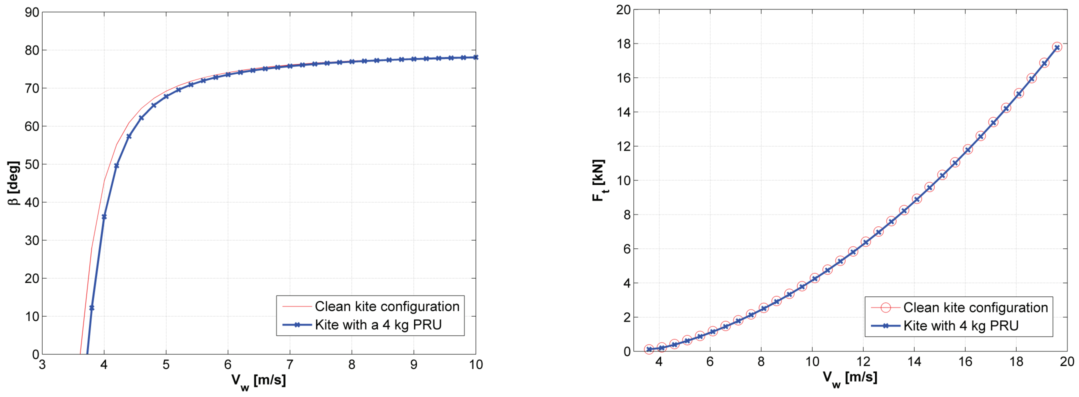
The PRU is considered to be an off-the-shelf product, where it is assumed that the price scales linearly with mass flow. Scaling up the Brüder Mannesmann 12V $240l/min$ volume pump [11], to a $744l/min$ pump would imply a price of €62, however it is assumed that the costs for including a valve system which has to be added to the pump doubles the costs to €124. There are 2 tension sensors mounted on the CU which cost €100. The angle sensor mounted on swivel costs €24. Taking all these costs into account, the total cost of the kite adaption subsystem comes up to €248. The manufacturing process is not considered because it is an off-the-shelf component.

5.4 Aerodynamic analysis

Adding a pump to the kite will affect its flying behavior. A full aerodynamic investigation using CFD-modeling is outside the scope of this project, thus only the influence of the added weight is being investigated. It is assumed that the pump is positioned in such a way that it does not change the stability of the kite during flight.

A volume pump can be a very lightweight machine because it does not require high pressures to operate. Hence it is safe to assume that the weight of the volume pump will be less than $4kg$. The influence of the safety line on the performance of the kite is already taken into account when the performance characteristics of the kite have been calculated, because it is already part of the kite. The change in locating will not influence any flight characteristics of the kite.

In order to investigate the change in aerodynamic performance due to the PRU the same free body diagram and assumptions as in subsection 2.2.2 are used to calculate the minimal tether angle and tether tension. This time the weight of the PRU is also taken into account. The result is compared with the results in subsection 2.2.2 as is shown in Figure 5.2. For these analysis the following parameters where used: the kite has a projected surface area $S = 70m^2$ and is assumed to fly fully powered with a $\frac{L}{D} = 5$. Where $C_L = 1.1$ and $C_D = 0.2$.



(a) The maximum tether angle β for different wind speeds

(b) The tether force F_t for different wind speeds

Figure 5.2: The influence of a PRU of $4kg$ compared with a clean kite configuration

Figure 5.2 clearly shows that the influence of the weight of the PRU is negligible for the tether tension and hence has a negligible effect on the power output of the system. The PRU has a bigger influence on the tether angle, but still the influence is still rather marginal.

However this marginal difference can have some large consequences for the design because of the steepness of the curve. From Figure 5.2a it becomes very clear that launching the kite in wind speeds of $V_w = 4m/s$ the kite will be at an angle of $\beta \approx 30°$, which will require the horizontal boom to tilt forward for 60° in order to get the kite in a stable position. This large angle can be reduced by accepting a larger wind speed in which the kite can be launched. By only increasing this speed with $1m/s$ to $V_w = 5$ the tether angle will increase to an acceptable $\beta = 68°$, which only requires a tilting of approximately 30°. The effect of this change on the performance of the complete system is further elaborated on in subsection 3.2.2.

These graphs are only valid as long as the PRU does not change the pressure distribution over the wing of the kite.

5.5 Structural Analysis

This section describes the forces experienced by the fabric of the kite and the main tether during the packing procedure. The fabric is able to withstand a load of $8.6kN/m$ [42] but since the total drag is only $8.6kN$ and the length of the kite is $4.2m$, the load on the kite will not exceed $2.0kN/m$ during the packing procedure. Therefore no adjustments to the kite will have to be made in order to make it stronger. The tensile force in the main tether does also not exceed the maximum given force of $40kN$.

6. Design: Horizontal beam

This chapter will give further insight in the horizontal beam subsystem. The purpose of this chapter is to provide the reader with a more detailed explanation of the horizontal beam subsystem, what mechanisms it contains, and through which actuators and sensors these mechanisms perform their task.

In section 6.1 the subsystem will be described into detail. The second section will discuss the structural analysis with the dimensions and weights. In section 6.3 the actuators and sensors required to actuate certain mechanisms of the horizontal beam are stated. In the next section the energy consumption and operation time used by these actuators and sensors will be given. The last section of this chapter will discuss the manufacturing process and cost of all described mechanisms.

6.1 Detailed description

The horizontal beam subsystem comprises five mechanisms:

- Beam
- Beam hinge
- Gripper
- Gripper rail
- Ridge

These five mechanisms ensure that the horizontal beam can execute all its required functions. The following subsections give a detailed description of the lay-out of each mechanism. An important consideration in the entirety of the horizontal beam design is that all elements have to be blunt. Any sharp edges can damage the kite as it rests on top of and/or slides over the horizontal beam subsystem.

6.1.1 Beam

In Figure 6.1 a drawing is given of the beam mechanism. The beam is the core element of this subsystem and all other mechanisms are mounted onto this beam. The beam consists of an aluminum part and an additional plastic nose cone.

The aluminum part has a circular, hollow shape. The circular shape is chosen since the beam will experience torques and this shape can withstand these forces better than other cross-sections. The exact dimensions of the beam are elaborated in section 6.3. The aluminum beam has a total length of $4.6m$. This length is mainly based on the kite's flat chord at the centre which is equal to $4.4m$ (as stated in Table 2.1). The additional $0.2m$ is reserved as a safety margin of approximately 5% on the root of the horizontal beam. As the kite is pulled towards the vertical boom by the gripper, the gripper should have enough clearance from the vertical boom, such that the kite does not get entangled with the vertical boom rail.

At the tip of the horizontal beam there is a blunt, plastic nose cone. This nose cone is at an angle of 45° to the left of the horizontal beam in the horizontal plane (considering a top view). Its absolute width and length are both equal to $0.5m$ The purpose of this nose cone and reasoning behind the dimensions/angle are explained in the detailed description of the gripper later in this section.

Figure 6.1: Detailed drawing of the beam mechanism

6.1.2 Beam Hinge

In Figure 6.2 a detailed drawing is given of the beam hinge mechanism. The beam hinge allows the horizontal beam to rotate both upwards and downwards and makes use of a rotary actuator which produces a torque. The rotary actuator is preferred over the use of a hydraulic cylinder since the horizontal beam has to have a large range of rotation, even including a full vertical position, which is hard to achieve with a hydraulic cylinder. More information on the rotary actuator can be found in section 6.3.

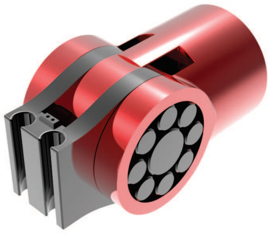


Figure 6.2: Detailed drawing of the beam hinge mechanism

6.1.3 Gripper

In Figure 6.3 a detailed drawing is given of the gripper mechanism. The gripper is added to the horizontal beam to capture the safety line and thereby ensure a proper landing and launch of the kite. An important consideration is that the gripper only encloses the safety line and does not tightly hold it.

From the CATIA drawing it follows that the kite has a gap of approximately $4m$ wide between the control lines. The safety line is attached to the centre of the leading edge and hangs in the middle of this gap towards the CU. Based on assumption CU07, which states that the CU can be controlled with an accuracy of $1m$, a reach of $1m$ wide has been determined for the gripper arms.

One of the gripper arms is in fact the plastic nose cone at the tip of the horizontal beam. The second gripper arm has the same dimensions, both width and length are equal to $0.5m$. This arm is connected to the gripper itself and its angle in the horizontal plane is mirrored to that of the nose cone. The gripper arms will guide the tether line to the gripper. This arm is made of a flexible material such that it can bend towards the beam. This is necessary to fold the kite around the beam.

The gripper captures the safety line in a small cavity with openings at top and bottom using flippers which are located at the mount of the gripper arms. The flippers both have one hypothenuse (on opposing sides) and can only rotate in one direction. The flipper with the hypothenuse will always guide the line towards the other flipper which can rotate in such a way that the line is pushed through. Sensitive springs will allow the line to pass the flippers easily, but ensures a return in the original position after capture or release. As soon as the safety line is captured, the flippers are locked.

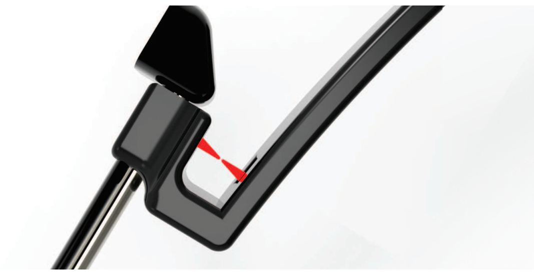


Figure 6.3: Detailed drawing of the gripper mechanism

6.1.4 Gripper rail

In Figure 6.4 a detailed drawing is given of the gripper rail mechanism. In order to fulfill its function the gripper will have to be able to slide along the horizontal beam by means of a rail system. The rail system has a length of $4.4m$ based on the flat chord of the kite. It will start $0.2m$ from the root of the horizontal beam and run towards the tip.

The rail mechanism used is called a linear slide which can be used to precisely move an object along a single axis. The movable object is in this case the gripper system including the flippers and gripper arm. The gripper system will be transported by means of a lead screw which is driven by an electric motor at the root of the vertical boom. The lead screw hangs just below the linear slide and rotation of the lead screw causes movement of a wedge which in turn enables the slide of the gripper system.

The rail system will be mounted on the outside of the aluminum, horizontal beam such that it has little to no effect on the structural integrity of the beam. From a top view the rail is attached on the rightmost edge of the circular beam.

Figure 6.4: Detailed drawing of the gripper rail mechanism

6.1.5 Ridge

In Figure 6.5 a detailed drawing is given of the gripper mechanism. The ridge is mounted within the horizontal beam to act as a resistance when the kite is ruffled. It is moved upwards as the gripper reaches the end of the gripper rail. The ridge ensures the kite does not slide off the horizontal beam as the gripper slides back towards the tip of the horizontal beam to ruffle the kite. The ridge has a right angle on the tip and an absolute height of $0.4m$ (see Figure 2.7 in subsection 2.2.1). This is estimated to be sufficient to hold back the kite when the gripper is slid back.

Figure 6.5: Detailed drawing of the ridge mechanism

6.2 Structural analysis

In this section the structural analysis of the horizontal beam is described. As described in the analytical approach the structure is analyzed to handle the worst case scenario. The only mechanism which is analyzed structurally is the beam; for the other mechanisms just dimensions and weights are given.

6.2.1 Beam

The material used for this beam is 6016-T6 aluminum because the weight of the beam must be minimal in favor of a weaker actuator. To size the structure the forces and moments on the beam are needed which were calculated using the worst case scenario described in section 4.2. The forces and moments calculated can be seen in Table 6.1.

Table 6.1: Forces and moments experienced at the root of the beam

Force/moment	Equation	Value	Unit
F_x	$-$	0	kN
F_y	$J \cdot D_{kite}$	13	kN
F_z	$-J \cdot (F_t + m_{kite} \cdot g + m_{CU} \cdot g + m_{beam} \cdot g)$	-16	kN
M_x	$J \cdot D_{kite} \cdot l_{kite0.5} \cdot y_{act}$	45	kNm
M_y	$J \cdot ((F_t + m_{kite} \cdot g + m_{CU} \cdot g) \cdot l_{beam} \cdot x_{act} + m_{beam} \cdot g \cdot \frac{l_{beam}}{2})$	-52	kNm
M_z	$J \cdot D_{kite} \cdot l_{beam} \cdot x_{act}$	44	kNm

In these equations F_t is the tether tension force pulling the kite downwards in N, $l_{kite0.5}$ is the length of half the kite in m, and x_{act} and y_{act} is the ratio of the total length of the section were the force is acting on.

Knowing these moments and forces a circular cross-section was chosen, since a circular cross-section is more resistant against torque and is smoother for the kite to slide over. Using the forces and moments determined as input for the optimization process described in subsection 4.2.4 an optimal radius and thickness were found which minimizes the weight and still withstand the forces and moments experienced. The optimal specifications can be seen in Table 6.2.

Table 6.2: Specifications of the horizontal beam

Specification	Value	Unit
Length	4.6	m
Radius	91	mm
Thickness	2	mm
Weight	126	kg

6.2.2 Beam hinge

The torque to hinge the beam was calculated using the masses of the beam, gripper rail and the weight, the weight of the kite and the weight of the CU. These masses were then multiplied by the distance they are from the root of the horizontal beam and this gave the maximum torque to hinge. This is true since the beam will only be hinged when the kite is fully inflated and just resting on the beam. The maximum torque to hinge this beam was found to be $5.2kNm$. This hinge will be described further in section 6.3 and the weight of this hinge was found to be $50kg$.

6.2.3 Gripper

The element of the gripper attached to the end of the beam will be made out of plastic and the element attached to the rail will be made of steel. Since the gripper is too much of a detail to structurally analyze, the weight of the gripper and its actuator were estimated, which resulted in a total weight of $5kg$. The length of the gripper will be $0.4m$, this to have a big enough span where the safety line can be caught.

6.2.4 Gripper rail

This mechanism will be explained in section 6.3. The gripper rail is $4.4m$ long. Since the weight per meter was found to be $9.8kg/m$ as can be seen from the provider's website given in Table 6.3 in section 6.5, the total weight of the gripper rail is therefore $45kg$ and is made of steel. The weight of the actuator to move the gripper over the gripper rail is $20kg$.

6.2.5 Ridge

The ridge as described in subsection 6.1.5 is again a structure which is too much of a detail to structurally analyze. Therefore the weight of this mechanism was estimated again. The ridge mechanism will be made of steel and the total mechanism including its actuator is assumed to weigh about $5kg$. The length of the ridge is determined to be $0.4m$ the reason for this can be seen in subsection 2.2.1.

6.3 Actuators and sensors

The actuator for the beam hinge will consist of an electric motor (see Figure 6.6) and a gear system. The providers chosen for these actuators and sensors can be seen in Table 6.3.

Figure 6.6: Electric motor used for the beam hinge [12]

The actuator will have to maintain a constant speed of $6.02deg/s$ up to a launch/landing angle, which depends on the wind conditions. Hence information on the deflection angle and angular speed is given through a rotary position sensor Cherry Switches GS101201 and a rotary encoder speed sensor GHS38 to the CPU and the servo of the motor. The servo controls the speed and position of the horizontal beam. It controls the speed of the horizontal beam by adjusting the power, hence torque given to the beam, keeping the angular speed constant. The gear system incorporates a locking system, where the horizontal beam is locked into place when movement is not required, this is done to reduce power consumption. The motor will have to deliver at most $5.8kW$ of mechanical power in order to hinge the beam upward in the worst case scenario, due to the fact that the power required varies with the deflection angle. This value is computed using the method in section 4.4. See that section for a detailed explanation. The $4.5kW$ of mechanical power will be generated with an MS 132L-6 electric motor which has a maximum power of $7.5kW$. This motor has a mass of $50kg$.

Figure 6.7: Balscrew mechanism

The actuator for the gripper rail will consist of an electric motor and a ball screw (see Figure 6.7) with a platform attached to the gripper. The position of the gripper needs to be closely monitored as its main function strongly depends on the alignment of the control tether position and the position of the gripper. There is a rotary position sensor Cherry Switches GS101201 on a rotating shaft which communicates to the CPU. The speed of the gripper is set to a constant value of $0.5m/s$, to maintain this speed, the speed is monitored by a rotary encoder speed sensor GHS38 which communicates with the servo of the gripper motor. The gripper itself is a mechanical system that does not require any sort of electrical actuator except for a locking sensor and actuator. When the control tether is locked into place a locking actuator and sensor needs to be present to ensure that the control tether will not escape. When the gripper reaches its required destination at the end of the beam, there is a contact sensor for the purpose of recalibration of the position sensor which acts on a rotary basis, to reduce the errors that may grow over time. The gripper motor will have to deliver at least $750W$ of mechanical power to move the gripper and kite.The $750W$ of mechanical power will be generated with an MS 100L2-8 electric motor which has a maximum power of $1,100W$. The weight of this motor is $19.5kg$.

The actuator for the ridge consists of a motor, a gear and a locking actuator. The locking actuator consists of a small pin that secures the ridge into place when required.

6.4 Energy consumption and operation time

The energy used by all mechanisms on the horizontal beam is computed with the method in section 4.3. The beam hinge consumes $58kJ$ when tilting upwards prior to launch. This equals $16.1Wh$. Tilting downwards after the kite is launched consumes only $2.5kJ$ which equals $0.7Wh$. The gripper rail needs $13.5kJ$ ($3.75Wh$) to slide over the beam with the powered kite attached.

The speed at which the beam hinge rotates was chosen to be $6deg/s$. It needs to move over a total of 90° so the operation time of this mechanism becomes $15s$. The gripper rail speed was set at $25cm$ per second. Combined with the length of the beam ($4.6m$) results in an operation time of $18.4s$.

6.5 Manufacturing process and cost

In this section, the manufacturing process, assembly of mechanisms and cost estimation of each element is given as was established in section 4.6. Each mechanism of the horizontal beam is broken down into its core elements, establishing the origin of each (whether it must be custom-made or readily available off-the-shelf) and an approximated quote or cost. This includes every single component, from core structural ones to actuators and sensors. Certain costs, mostly from custom-made parts require an explanation which will be given under Table 6.3 for clarity with the reader.

Table 6.3: Production of elements of the horizontal beam components

Mechanism	Element	Product code	Origin: provider/process	Quote obtained
Beam	Hollow aluminum beam	8SCH40 $20ft$	metalsdepot.com [[39]]	€600
Beam hinge	Hinge cylinder bearing	NU30/670EMA	timken.com [[40]]	€800
	Horizontal beam motor	MS 132L-6	electramo.com [[12]]	€500
	Horizontal beam servo	SBW-10	alibaba.com [[37]]	€100
	Angle sensor	AN920031	conrad.nl [[11]]	€40
	Angular speed sensor	N/A	alibaba.com	€80
Gripper	Flippers (hinges+springs)	N/A	Any hardware store	€20
	Plastic gripper arm	N/A	Custom: mould casting	€40
	Metal gripper arm	N/A	Custom: bending	€25
	Position sensor	GS101201	conrad.nl	€23
	Locking actuator & sensor	CFBMC001	alibaba.com	€2
	Contact actuator/sensor & sensor	CFBMC001	alibaba.com	€2
Gripper rail	Main rail (3cm diameter)	N/A	dogarulman.com.tr [[38]]	€119
	$3cm$ rail guide	N/A	dogarulman.com.tr	€36
	Threaded rod	N/A	Any hardware store	€50
	Gripper speed rotary sensor	GHS38	alibaba.com	€80
	Gripper motor servo	SBW-10	alibaba.com	€100
	Gripper motor	MS 100L2-8	electramo.com	€195
Ridge	Ridge steel bar	N/A	Custom: bending	€25
	Electric motor	MS 561-47	electramo.com	€43
Subtotal				€2,880
10% Assembly cost				€288
Total				€3,168

The provider metalsdepot.com can only supply a beam of $10ft$. or $20ft$.. Since $4.6m$ are required, the $20ft$ beam was chosen. The plastic gripper arm will be made of a cheap but durable plastic casted from a mould that can be simply made, thus production and material costs are quite low. Recycled PET is an option for material due to its availability and ease of re-processing. The metal gripper arm can be made of a reused flat steel bar, only bent as required which is a simple process. An extra addition to the cost is made for cutting it into the desired dimensions and for mounting it atop the gripper. The same process goes for the steel ridge bar that will stop the kite from sliding off when ruffled.

7. Design: Vertical boom

This chapter will show the vertical boom subsystem into more detail. The purpose of this chapter is to provide the reader with a more detailed explanation of the vertical boom subsystem, what mechanisms it contains, and by which elements these mechanisms are actuated and which sensors the mechanisms use.

In section 7.1 the subsystem will be divided into the mechanisms and described into detail. The second section will show the dimensions and weights of all mechanism of which some are retrieved from the structural analysis. In section 7.3 the actuators and sensors needed to actuate certain mechanisms of the vertical boom are stated. In section 7.4 the energy consumption and operation time used by these actuators and sensors will be given. The last section of this chapter will discuss the manufacturing process and cost of all described mechanisms with their elements.

7.1 Detailed description

The vertical boom comprises three mechanisms:

- Boom
- Boom hinge
- Vertical boom rail

These three mechanisms ensure the vertical beam can perform its tasks. The following subsections give a detailed description of the lay-out of each mechanism.

7.1.1 Boom

In Figure 7.1 a drawing is given of the boom mechanism. The vertical boom is the largest element in the entire launch, landing and storage system. The boom will have a length of $35m$. This length makes sure the CU has some clearance from the ground during landing and launch and is based on three parameters. Firstly, if the kite is folded over the horizontal beam at its centre, both tips of the kite will be lowered approximately $9m$ below the horizontal beam (as stated in Table 2.1). Secondly, the distance between the control lines at the tips and the CU is equal to $16.5m$ (see subsection 2.2.1) which is the maximum distance the CU will hang below the tips of the folded kite. Finally, an additional $10m$ is included to ensure the distance between the kite and the ground station is sufficient for kite control.

The vertical boom has a circular, hollow cross-section to be able to cope with both bending forces and torques. Industrial steel is selected due to combination of its high strength characteristics and its relatively affordable pricing. An elaboration on the exact dimensions and material selection is presented in subsection 7.2.1.

The impressive length of the boom requires manufacturing and assembly in sections. The boom has ladder steps on the outside to improve the ease of inspection and maintenance. Since the system is developped to be installed nearby Schiphol airport, there is a red light installed at the top of the boom to warn low-flying air traffic.

Figure 7.1: Detailed drawing of the boom mechanism

7.1.2 Boom hinge

In Figure 7.2 a drawing is given of the boom hinge mechanism. The boom hinge allows the boom to be tilted forward. As described in Figure 2.9a in subsection 2.2.2 the kite is not able to stay at a perfect zenith position. For low wind speeds the tether angle with respect to the ground can be as low as 36° for a wind speed of $4m/s$ in case the PRU is mounted to the kite. During landing this small angle can be increased by reeling the kite in, this would make the landing more difficult to achieve but still feasible. To launch the kite in such low wind conditions while keeping control of it without tilting the beam forward is practically impossible. The kite needs to be positioned in a stable position. Taking in account the weight of the PRU the maximum tilting angle must be 30°, as can be seen in Figure 5.2a in section 5.4.

The designed boom hinge is inspired by the conventional hydraulic boom cranes, often mounted on a truck, in the construction industry. The vertical boom will only have to hinge into one direction due to the fact that there is a rotating platform. However, the swivel and swivel rail are located directly underneath the hinge direction. Therefore the two hydraulic actuators need to be positioned along the sides of the vertical boom. At the root of the vertical boom two curved clamps will attach a circular, hollow beam to the vertical boom to create the point of rotation. A solid bar will run through the hollow beam which has a bearing to accommodate a smooth rotation. The two ends of the bar will be connected to a triangular hinge structure. The two hydraulic actuators will be positioned in compression and are attached to two support pins including bearings on both sides of the vertical boom. The root of the hydraulic actuators are attached to the rotating platform, also via a hinge. The exact position of the attachment points of the actuators and more information on the hydraulics and bearings can be found in section 7.3.

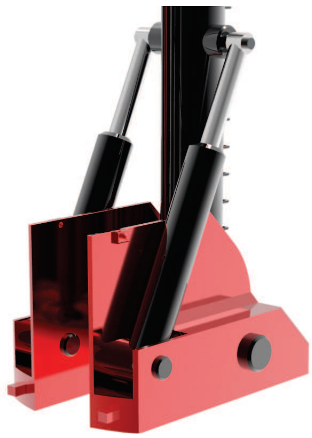


Figure 7.2: Detailed drawing of the boom hinge mechanism

7.1.3 Vertical boom rail

In Figure 7.2 a drawing is given of the vertical boom rail mechanism. The movement of the horizontal beam along the vertical boom plays an important role in the storage and deployment procedure. A cable mechanism is used to transport the beam along the boom. This transport mechanism will be mounted on the outside of the boom structure instead of integrating it into the boom, to prevent interference with the structural integrity of the boom. In order to handle the moments on the horizontal beam, it is placed on two linear slides. These linear slides ensure a proper stability of the horizontal beam.

The applied transport system is based on an elevator system. In the vertical boom a counterweight is placed within the boom that is connected with two cables to the horizontal beam by a pulley at the top of the vertical boom. After the horizontal beam the two cables run into a drum at the root of the vertical boom. If the horizontal beam needs to go up the drum reels out the two cables, which causes the counterweight to go down and the horizontal beam to be pulled up. If the horizontal beam must go down the drum is reeled in.

(a) Top of boom where the cables run through a pulley

(b) Drum at the bottom of the vertical boom

(c) Rail attachement to beam hinge

Figure 7.3: Detailed drawing of the vertical boom rail mechanism

7.2 Structural analysis

This section discusses the results found in the structural analysis of the vertical boom. The loads and moments found at section 6.2 were used further in this analysis. The boom is the only mechanism which will be structural analyzed. For the other mechanisms just the dimensions and weights are discussed.

7.2.1 Boom

The material used for this vertical boom is chosen to be steel in order to make the boom as strong as possible and minimize its the cost. The radius of the vertical boom is made constant, since making the boom tapered would increase the cost compare to keeping a constant radius. To size the structure the forces and moments on the boom are needed which were calculated using the worst case scenario described in section 4.2. The forces and moments calculated can be seen in Table 7.1.

Table 7.1: The forces and moments experienced at the root of the boom

Force/moment	Equation	Value	Unit
F_x	$-$	0	kN
F_y	$J \cdot (D_{kite} + D_{boom})$	32	kN
F_z	$-J \cdot (F_t + m_{kite} \cdot g + m_{CU} \cdot g + m_{beam} \cdot g + m_{boom} \cdot g)$	-98	kN
M_x	$J \cdot (M_{x_{beam}} + D_{kite} \cdot l_{boom} + D_{boom} \cdot \frac{l_{boom}}{2})$	850	kNm
M_y	$J \cdot (M_{y_{beam}} + m_{boom} \cdot \frac{l_{boom}}{2} \cdot sin(\gamma) + F_{z_beam} \cdot l_{boom} \cdot sin(\gamma))$	-362	kNm
M_z	$J \cdot M_{z_{beam}}$	67	kNm

In these equations D_{boom} is the drag on the boom calculated using Equation 2.1 in subsection 2.2.2 and γ is the boom hinge angle.

Having these moments and forces a circular cross-section was chosen, since a circular cross-section is more resistant against torque. Using the forces and moments determined as input for the optimization process described in subsection 4.2.4 an optimal radius and thickness were found which minimizes the weight and still withstand the forces and moments experienced. The optimal specifications can be seen in Table 7.2.

Table 7.2: Specifications of the vertical boom

Specification	Value	Unit
Length	35	m
Radius	0.47	m
Thickness	7	mm
Weight	5625	kg

7.2.2 Boom hinge

The maximum torque to hinge this beam is calculated using the weights of the boom, the entire horizontal beam subsystem, the weight of the kite and the weight of the CU. These loads are then multiplied by their respective distance on the x-axis to the root of the boom. This distance is measured at the maximum tilt angle of 30°. The maximum torque to hinge this beam was found to be $472kNm$. This hinge will be described further in section 7.3 and the weight of this hinge was found to be $108kg$.

7.2.3 Vertical boom rail

This mechanism will be described in section 7.3. The length of the rail is $34m$, the material used is steel and since the weight per meter is $5.58kg$, as can be seen on the provider's website shown in Table 7.3 in section 6.5, the weight is found to be $380kg$. The actuator needed to move the horizontal beam along the rail is found to be $50kg$. The diameter needed for the steel cable is $6.4mm$ and the weight of the cable is found to be $12kg$. The weight of the counter weight should be at least as high as the normal force on the horizontal beam times the safety factor. This weight is $1,600kg$.

7.3 Actuators and sensors

The actuator for the boom hinge will consist of two hydraulic cylinders, a pump and a motor. To ensure a smooth operation and minimize the effects of fatigue to the structure, the angular velocity of the hinged boom is kept constant at a value of $1deg/s$. As a result, during operation the speed of the hydraulic actuator is $0.026m/s$. The speed is monitored by using a servo and a rotary encoder speed sensor GHS38. Depending on weather conditions the boom will have to be tilted to facilitate launch and landing. Moreover, the angle depends on the wind speed. The boom tilt angle is monitored by a rotary position sensor Cherry Switches GS101201 that communicates with the CPU. In the worst case scenario the hydraulic cylinders will have to deliver $5.2kW$ of mechanical power and $85kN$ each to tilt the boom from 25° deflection from zenith to zero deflection. The maximum stroke of this hydraulic cylinder 0.636m. The power value is computed using the method in section 4.4. See that section for a detailed explanation of how this value was calculated. The total $5.2kW$ of mechanical power will be generated with two electric pumps of $3kW$ each.

Figure 7.4: Hydraulic cylinder used in the boom hinge mechanism

The actuator for the beam rail will consist of an electric motor, a drum system and a rail. The motor is attached to a drum system, the cable is pulled down by a counteracting weight. The speed of the horizontal beam is kept constant at a value of $0.5m/s$, hence the speed is monitored using a rotary encoder speed sensor GHS38 which communicates with a servo that ensures constant speed by controlling the power received by the motor. To indicate the position of the horizontal beam, a rotary position sensor Cherry Switches GS101201 is located on the gear and communicates with the CPU and servo, such that the horizontal beam can decelerate when arriving at required altitude. To save power, the horizontal beam is locked in place when it reaches its required position using a locking actuator. There is a contact sensor on top of the beam which indicates that the beam has reached the top of the boom for purposes of recalibration to reduce the effect of accumulated errors. The horizontal beam motor will have to deliver at most 8.1kW of mechanical powering during the worst case scenario to raise the beam to the top of the boom. The 8.1kW of mechanical power will be generated with an Y3-132M2-4 electric motor which has a maximum power of 11kW. This type of actuator weighs 50kg.

7.4 Energy consumption and operation time

The energy required for operation of the vertical boom was calculated with the method explained in section 4.3. The energy required for tilting the boom from 25 degrees deflection to straight up was found to be 83kJ. This equals 23.1Wh. The boom rail actuator requires 572kJ or 159Wh to move the beam all the way up.

The time needed for the boom to go from 25° to straight up is 25s. This follows from the angular speed of 1deg/s. The horizontal beam moves upward at a speed of 0.5m/s. From the boom length of 35m then follows that it takes 70s to get the beam all the way from the ground to the top of the boom.

7.5 Manufacturing process and cost

In this chapter Table 7.3 specifies the main elements that make up every mechanism of the vertical boom subsystem. Their origin and approximated cost can be seen in the last two columns. For the side railings of the vertical boom rail, a brief explanation is given below to make clear how such cost was obtained.

Table 7.3: Production of elements of the vertical boom components

Mechanism	Element	Product code	Origin: provider/process	Quote obtained
Boom	Hollow steel boom	N/A	alibaba.com	€3,500
	Steel boom steps	N/A	Custom: steel bending	€280
Boom hinge	Bearing	640260-B	timken.com	€1,500
	Hydraulic Cylinders	N/A	alibaba.com	€2,000
	Boom tilt angle sensor	GS101201	alibaba.com	€15
	Angular velocity sensor	GHS38	alibaba.com	€80
	Cylinder servo	SBW-15	alibaba.com	€175
Vertical boom rail	Side railing x2	N/A	dogarulman.com.tr	€1,618
	Rail guide x2	SBR 30UU	dogarulman.com.tr	€72
	Electric motor	Y3132M2-4	electramo.com	€800
	Motor servo	SBW-10	alibaba.com	€100
	Hor. Beam location sensor	GS101201	alibaba.com	€23
	Hor. Beam speed sensor	GHS38	alibaba.com	€80
	Hor. Beam locking sensor	CFBMC001	alibaba.com	€2
Subtotal				€10,245
10% Assembly cost				€1,024
Total				€11,269

The side railings which will serve as guides for the horizontal beam mount to slide up and down the boom were budgeted according to costs of Cromsteel Industries. From [38], bars of 30mm diameter were chosen with a length of 34m, each meter costing €23.80. Two rail guides (SBR 30UU) were chosen, each with a cost of €36.

The steel boom steps can be manufactured out of a simple steel bar. Because these steps must span the whole height of the boom, 4 steps per meter were considered each made by cutting the steel bar and bending it. A cost of €2 per step yield a total of €280 for all the steps.

8. Design: Rotating platform

This chapter will present a detailed description of the rotating platform subsystem. The purpose of this chapter is to give the reader a description of how this subsystem works. It will be described what mechanisms the rotating platform contains and what elements actuate the system along with the sensors used.

The first section will give the detailed description of the rotating platform and of what mechanisms it consists. In section 8.2 the dimensions and weights of the mechanisms and the loading on the structure will be discussed. The third section will describe the actuators and the sensors needed to perform the systems tasks correctly. section 8.4 will discuss the energy consumed and time spent by the mechanism performing its task.

8.1 Detailed description

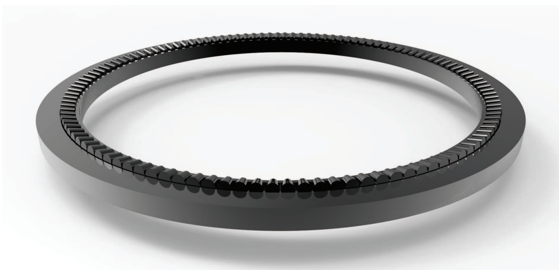
The rotating platform comprises three mechanism:

- Bearing
- Platform cover
- Foundation

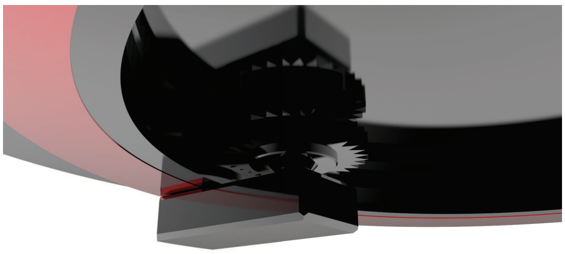
Since the foundation will highly depend on the soil that is built on, this mechanism is not further elaborated on. The following subsections will give a detailed design of the lay-out of the bearing and the platform cover mechanism.

8.1.1 Bearing

In Figure 8.1 a drawing is given of the bearing mechanism. The bearing consists of two circular rotating rings, which rotate on top of each other. The lowest ring is mounted onto the foundation and the upper ring is mounted below the platform cover. This allows the boom to rotate 360°. In order to ensure that the rotating platform will rotate smoothly with respect to the foundation, cylindrical rollers are put in horizontal and vertical position on the lowest ring (Figure 8.1a). On the inside of the upper ring a gear cut out is attached, which enables an actuator to rotate the upper ring (Figure 8.1b).



(a) The bearing of the rotating rings



(b) Actuator and saw tooth structure of the bearing

Figure 8.1: Detailed drawing of the bearing mechanism

8.1.2 Platform cover

The platform cover is a circular steel plate that is deep-drawn to allow the mounting on the bearing. It is the main rotating disk on which the whole structure is mounted. It has a diameter of $4m$ and can be rotated 360°. On the platform cover the drum, CPU, generator, boom hinge and swivel beam are located. Due to its simplicity a visual representation is not included.

8.2 Structural analysis

The structures of the mechanisms of this subsystem were not analyzed but only sized to fit the whole system. The outer radius of the rotating platform was found to be $2m$.

8.2.1 Bearing

The radius of the bearing is $1.57m$, the thickness of the bearing is $0.18m$. The weight of this bearing will be $1,200kg$. The weight of the actuator rotating the structure is $50kg$. The bearing will be made of steel.

8.2.2 Platform cover

The cover over the bearing was sized to be $2m$ in radius and will be made of steel. On the platform cover, the drum and generator of the system are mounted. The thickness of this cover is $50mm$. This cover was not structurally analyzed and is just over-designed to be able to cope with all loads.

8.2.3 Foundation

The designing of the foundation for this system is out of scope. However the moments and loads it must carry are given. For the loads and moments on the rotating platform the worst case scenario is considered as well as the weight of the subsystems and mechanisms on the rotating platform. The moments and loads experienced by the rotating platform are shown in Table 8.1. These moments are retrieved of the maximum moments on the subsystems. All but one are from the boom mechanism described in subsection 7.2.1 execpt for F_x which is retrieved from the swivel beam described in subsection 9.2.2.

Table 8.1: Loads and moments on the foundation

Load/moment	Value	Unit
F_x	77	kN
F_y	32	kN
F_z	-98	kN
M_x	850	kNm
M_y	-362	kNm
M_z	67	kNm

Since the drum and generator are also on the main platform, the loads caused by the weight of these subsystems have to be added. The weight of these subsystems combined is estimated to be $2,000kg$. This weight will cause an extra normal force F_z of about $20kN$ which will add up to a total normal force on the foundation of $117kN$.

8.3 Actuators and sensors

The actuator that will rotate the platform on the ball bearing is an electric motor combined with a gear. The platform is accelerated up to speed in $0.5s$, after which the actuator will have to sustain an angular velocity of $3deg/s$. To do this there is a rotary encoder speed sensor GHS38 attached to the gear which communicates with the servo. To enable the rotating platform to stop at the correct position there is a rotary position sensor Cherry Switches GS101201 which communicates with both the CPU and the servo. The rotating platform motor will have to deliver $3.5kW$ of mechanical power in the worst case scenario to accomplish this. This value is computed using the method in section 4.4. See that section for a detailed explanation.

The $3.5kW$ of mechanical power will be generated with a MS 132M1-6 electric motor which can deliver a maximum power of $4kW$. The mass of this motor is $50kg$ which is taken into account in other calculations such as the structural analysis.

8.4 Energy consumption and operation time

The energy consumed by the rotation motor for a turn of $180°$ is equal to $210kJ$ or $58.3Wh$. This value was found with the method explained in section 4.3. The time it takes to cover this turn is exactly one minute. This follows from a chosen rotation speed of $3deg/s$ which was chosen.

8.5 Manufacturing process and cost

The rotating platform consists of fewer components for its functionality. However due to the high forces acting on this subsystem, each element must be sized appropriately to prevent failure and to require the least amount of maintenance during its lifetime. The approximated costs for these components is established in the table below.

Table 8.2: Production of elements of the rotating platform components

Mechanism	Element	Product code	Origin: provider/process	Quote obtained
Bearing	Main bearing	F/3067/C	timken.com	€2,500
	Electric motor	MS132M1-6	electramo.com	€400
	Motor servo	SBW-10	alibaba.com	€100
	Angle sensor	GS101201	alibaba.com	€23
	Angular velocity sensor	GHS38	alibaba.com	€80
Platform structure	Metal plate	N/A	Custom: steel, deep drawn	€2,340
Subtotal				€5,443
10% Assembly cost				€544
Total				€5,987

The metal plate that will serve as the platform structure is obtained from a steel plate of $6m$ x $6m$ with an increased price for the cutting and deep drawing process in order to mould it into the desired shape. A $1.5cm$ thick steel plate of the required size may be obtained for €1,800 which after a cutting and deep-drawing process elevates the cost to €2,340.

9. Design: Swivel storage

This chapter will present a detailed description of the swivel storage subsystem. The purpose of this chapter is to provide the reader with a description of how this subsystem works. It will be described what mechanisms the swivel storage contains and what elements actuate these mechanisms along with the sensors used. The chapter also provides the reader with the consumption of the system with respect to cost, energy and time.

The first section will give the detailed description of the swivel storage subsystem and of what mechanisms it consists. In section 8.2 the dimensions, cross-section used and weights of the mechanisms will be discussed. The next section will describe the actuators and the sensors needed to perform the systems' tasks correctly. Section 8.4 will discuss the energy consumed and time spent by the mechanism performing its task.

9.1 Detailed description

The storage comprises three mechanisms:

- Swivel beam
- Swivel rail

The two mechanisms stated above will be used to move the swivel to the bottom of the storage during the storage phase. Their respective roles are thoroughly explained in the following subsections.

9.1.1 Swivel

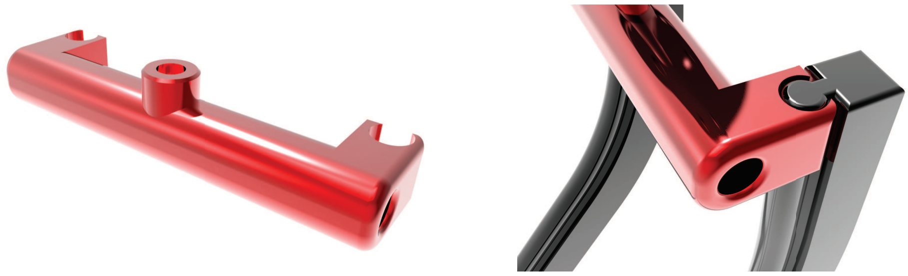
In Figure 9.1 a drawing is given of the swivel mechanism. The swivel is used to guide the main tether from the drum to the CU and is mounted on top of the swivel beam. The swivel needs to go into the storage, which is the reason why some adaptions needed to be made to the existing swivel. If the swivel is moved into the storage it will rotate 90° towards the horizontal boom from its upright position (see Figure 9.1). This will cause the main tether to be in a different inclination when the swivel is in the storage. Therefore a system is used with four wheels that is capable of guiding the main tether when the swivel is at the top of the swivel rail as well as in the storage.

(a) Swivel during operation (b) Swivel at the bottom of the storage

Figure 9.1: Detailed drawing of the swivel mechanism

9.1.2 Swivel beam

In Figure 9.2 a drawing is given of the swivel beam mechanism. The swivel beam is a cylindrical rod on which the swivel is mounted. In order to move the swivel towards the bottom of the storage the swivel beam is mounted on two carts that run on the swivel rail. These carts consist of two smaller wheels that lock the cart into the rail and a larger gear that runs on a sawtooth track on the bottom of the rail. The swivel beam is moved towards the bottom of the storage by rotating the gear on the sawtooth track. This is done by an actuator which drives the gear. The swivel beam has to cope with large loads during flight due to the pull of the main tether on the swivel. To ensure that it can do so the swivel beam is locked at the top of the swivel rail. This way the swivel beam is capable of carrying all the loads. For further calculations on the structural behavior see section 9.2.



(a) Swivel beam with swivel attachment point (b) Swivel beam connection to swivel rail

Figure 9.2: Detailed drawing of the swivel beam mechanism

9.1.3 Swivel rail

In Figure 9.2 a drawing is given of the swivel rail mechanism. The swivel rail guides the swivel beam over a vertical distance of $4m$ to the bottom of the storage. Since the rail has to cover a fairly large vertical distance the wheels on the swivel beam are locked in the rail. Thereby a sawtooth track is added to the center of the rail such that the gear can move the swivel beam up and downwards. Since the storage consists of a rotating and non-rotating part the swivel rails need to be aligned during storage. To make sure the rails are aligned a lock-in device is used (as described in subsection 10.1.4).

Figure 9.3: Detailed drawing of the swivel beam mechanism

9.2 Structural analysis

This section discusses the mechanisms in the swivel beam subsystem. The swivel beam and swivel rail are both structurally analyzed.

9.2.1 Swivel

The structure which will transfer the loads of the wheels in the swivel will be made from steel; the weight of this mechanism is not estimated.

9.2.2 Swivel beam

The worst case scenario considered for this swivel beam is different, since this swivel beam needs to be able to cope with the maximum forces in flight of the kite, being $80kN$. The minimum angle with respect to the horizon is assumed to be 15°. Since the forces are acting in the middle a value of $0.5m$ was picked for the swivel height. This value is considered to be the maximum height at which the swivel can be. The material used for the swivel beam is steel to minimize the cost of this mechanism. To size the structure the forces and moments on the beam are needed which were calculated. The forces and moments calculated can be seen in Table 9.1.

Table 9.1: Forces and moments experienced at the root of the beam

Force/moment	Equation	Value	Unit
F_x	$J \cdot F_t \cdot cos(\beta)$	58	kN
F_y	$-$	0	kN
F_z	$J \cdot F_t \cdot sin(\beta)$	60	kN
M_x	$J \cdot F_t \cdot cos(\beta) \cdot \frac{l_{sbeam}}{2}$	14	kNm
M_y	$J \cdot F_t \cdot cos(\beta) \cdot l_{swivel}$	18	kNm
M_z	$J \cdot (F_t \cdot sin(\beta) \cdot \frac{l_{sbeam}}{2} - m_{sbeam} \cdot g \cdot \frac{l_{sbeam}}{4})$	14	kNm

In these equations F_t is the tether tension force in the main tether during flight in N, l_{swivel} is the maximum length of the swivel assumed in m.

Having found these moments and forces a circular cross-section was chosen, since a circular cross-section is better resistant against torque. Using the forces and moments determined as input for the optimization process described in subsection 4.2.4 an optimal radius and thickness were found which minimizes the weight and still withstand the forces and moments experienced. The optimal specifications can be seen in Table 6.2.

Table 9.2: Specifications of the swivel beam

Specification	Value	Unit
Length	0.72	m
Radius	49	mm
Thickness	15.5	mm
Weight	15	kg

The weight of the motor to actuate the movement over the swivel rail is $3.2kg$. The actuator is further described in section 9.3.

9.2.3 Swivel rail

The cross section considered for the swivel rail is shown in Figure 9.4. This is a simplified model of the one used on the swivel rail.

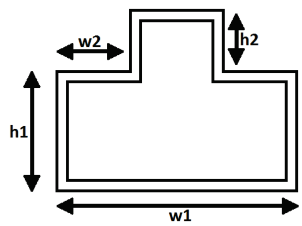


Figure 9.4: The cross-section of the swivel rail

The material chosen for the rail is steel, this to minimize the cost of the rail. Since this cross section is of such complexity the only stress determined are the bending and compressive stresses given by Equation 4.3 and Equation 4.4 in section 4.2. The moments and forces experienced by the swivel rail are given in Table 9.3.

Table 9.3: Forces and moments experienced at the root of the swivel rail

Force/moment	Equation	Value	Unit
F_{ax}	$J \cdot \frac{F_t}{2} \cdot cos(\xi)$	58	kN
F_{per}	$J \cdot \frac{F_t}{2} \cdot sin(\xi)$	0	kN
M	$J \cdot F_{mt} \cdot sin(\beta)$	60	kN

In these equations F_{ax} is the axial loading of the swivel rail and F_{per} is the force perpendicular to the swivel rail both in N. ξ is the angle of the swivel rail with respect to the horizontal in degrees. This angle is calculated by using the height of the storage and the distance from the swivel rail to the start of the folding poles, this distance is $1.5m$.

For this structure no optimization was applied, values were chosen and a large margin was kept to be able to withstand the shear forces, since shear forces were not taken into account. The dimensions and the weight for the swivel rail can be seen in Table 9.4.

Table 9.4: Specifications of the swivel rail

Specification	Value	Unit
Length	5.3	m
w1	0.15	m
w2	0.05	m
h1	0.1	m
h2	0.05	m
Thickness	2	mm
Weight	37	kg

The weight given is for a single rail so the total weight is $74kg$. This weight is divided into $20kg$ of rail on the rotating platform and the rest in the fixed storage. The weight of the actuator to move the rail is found to be $5kg$ it will be described in section 9.3.

9.3 Actuators and sensors

The actuator for the swivel rail will be an electric motor and a gear system . The speed of the swivel rail is kept at a constant of $0.2m/s$. The velocity is monitored by a rotary encoder speed sensor GHS38 which communicates with the servo and the CPU. This speed sensor is given in Figure 9.5.

Figure 9.5: Rotary encoder sensor [13]

Whilst in operation the speed of the horizontal beam and the swivel rail will have to be synchronized in such a way that the tension in the tether is kept constant. To facilitate the initiation of packing, the indication of the position of the swivel is crucial, hence a rotary position sensor Cherry Switches GS101201 is situation on the gear. For the purpose of recalibration, a contact sensor is situated at the end of the swivel rail. Whilst in operation, the largest load acting on the swivel rail is the tension on the tether, as that needs to be kept constant and is equal to the drag on the kite. In the worst case scenario the swivel rail motor will have to deliver $1.5kW$ of mechanical power in order to slide the CU and swivel. This value is computed using the method in section 4.4. See that section for a detailed explanation. The $1.5kW$ of mechanical power will be generated with a motor similar to an MS 562-4 electric motor which has a maximum power of $1.5kW$. This motor has a mass of $3.2kg$ which is also taken into account in calculations.

9.4 Energy consumption and operation time

The energy used by this mechanism is calculated using the method explained in section 4.3. The energy consumed by the swivel rail to slide from one side to the other is $33kJ$. This equals $9.16Wh$. The operation time of this this mechanism is not accounted for as this process takes place simultaneously with raising the beam. The latter takes longer which makes the former insignificant.

9.5 Manufacturing process and cost

The swivel storage is a fully custom developed subsystem and as such, the costs were quite flexible. Most of the components may be obtained from hardware stores and the few custom-made could be chosen from materials that are not too expensive. Few adaptions are required to interconnect these elements but the cost from these can be appointed purely to the assembly phase.

Table 9.5: Production of elements of the swivel storage components

Mechanism	Element	Product code	Origin: provider/process	Quote obtained
Swivel rail	Railing x2	N/A	Custom: extrusion + bending	€350
	Guide x2	N/A	Any hardware store	€40
	Motor x2	MS562-4	electramo.com	€94
	Motor servo x2	SBW-10	alibaba.com	€200
Swivel beam	Swivel	N/A	Custom: steel plates and pulleys	€150
	Main steel bar	N/A	Any hardware store	€100
	Beam location sensor	GS101201	alibaba.com	€23
	Speed sensor	GHS38	alibaba.com	€80
Subtotal				€1,037
10% Assembly cost				€103
Total				€1,140

The railing for the swivel bar may be extruded from steel as it is an easily recyclable material. The dimensions are 15cm x 10cm with a length of 5.3m which will be extruded and bent as desired. Steel has an average price of 0.15€/kg, and because of the production process and die required, the total cost for both rails comes up to €350.

10. Design: Storage

This chapter will present the detailed design of the storage subsystem. The purpose of the chapter is to provide the reader with a detailed explanation of the subsystem and its functionality. It will be made clear what mechanisms the storage subsystem contains and how the different mechanisms are actuated. Furthermore will insight be given to the consumption with respect to energy, time and cost.

Section 10.1 will give the detailed explanation of the storage subsystem. The next section will discuss the dimensions and weights retrieved out of the structural analysis. In section 10.3, the actuators and sensors needed to let all mechanisms work will be stated and explained. Section 10.4 gives insight into the energy consumed and the time taken by the task which the mechanisms need to perform. The last section will give the cost and the manufacture manner of all the mechanisms and their elements.

10.1 Detailed description

The storage comprises four mechanisms:

- Storage cover
- Storage structure
- Folding poles
- Lock-in device

The four mechanisms stated above will work in conjunction and cohesively with the rest of the system to carry out the tasks of packing, storage and unpacking as necessary. What their role is in these tasks is explained in the following subsections, where a thorough explanation of each mechanism is given.

10.1.1 Storage structure

In Figure 10.1 a drawing is given of the storage structure mechanism. This structure is the core element of the storage subsystem and consists of 2 main parts: a movable section mounted on the rotating platform in front of the boom and a static section right next to the rotating platform.

The movable section will serve as a mount for other subsystems such as the swivel storage, the drum and generator. The distance between each wall on the rotating platform is $0.80m$ (to allow for tilting of the boom) and will span from the root of the boom to the edge of the rotating platform, essentially being approximately $2m$ long. These walls will have a matching curvature to the rotating platform which, when rotated into place, will fit perfectly in the non-rotating storage section.

The non-rotating section of the storage will have a height of $2m$ above ground and will be dug $2m$ below the surface. It will have a length of $4.8m$ from the rotating platform. The first $1.5m$ from the rotating platform will allow space for the swivel rail of the swivel storage subsystem to run down to the bottom, the following $2m$ will be occupied by the folding poles. The last meter will allow the mounts and railings of the folding poles to be placed and on the very edge, the rolling shutter of the storage cover will be placed.

Figure 10.1: Detailed drawing of the storage structure

10.1.2 Storage cover

In Figure 10.2 a drawing is given of the storage cover mechanism. The storage cover will perform the simple task of safeguarding the entire storage subsystem both while the kite is stored as well as when the kite is fully deployed and the storage is not being used. It is a simple mechanism consisting of a rolling shutter made up of thin, 5.2m wide plastic plates that are rolled up when not in use and stored at the end of the storage opposite to the boom.

When the storage needs to be closed, this rolling shutter will be pushed along rails on each side of the storage towards the boom. These rails are mounted with a slope of 1° such that it allows rain water to slide down away from the rotating platform. The shutter will be powered by an electric motor mounted right on the side axis atop the storage on the side opposite to the boom.

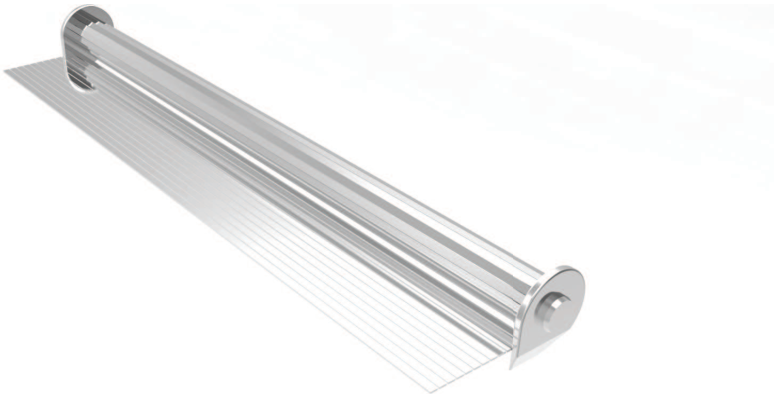


Figure 10.2: Detailed drawing of the storage cover mechanism

10.1.3 Folding Poles

In Figure 10.3 a drawing is given of the storage structure mechanism. The folding poles will be the main mechanism to pack the kite within the storage in a zig-zag configuration from pole to pole. There will be five poles that slide from one side of the storage to the other in an alternating manner. The first pole starting from the bottom will be mounted at a height of 1m from the bottom. Its length is 2.5m, of which 2m will work to push the deflated kite to either side of the storage and the remaining 0.5m will serve for the mounting on the railings that enables the motion.

From the top of the first pole there will be a distance of 0.21m to the bottom of the following pole, and these distances will remain consistent for all five elements. From the top pole there will be a distance of 0.40m to where the bottom of the horizontal beam will be once it is lowered and stored. Once one takes into account the 0.18m diameter of the horizontal beam, the remaining space from the top of it to the storage cover is 0.40m. Since the kite is ruffled this space is needed to store the kite.

The mechanism that moves the poles from side to side will be a railing mounted along the width of the storage, where a turning screw will push the pole mount back and forth a total distance of 4.6m.

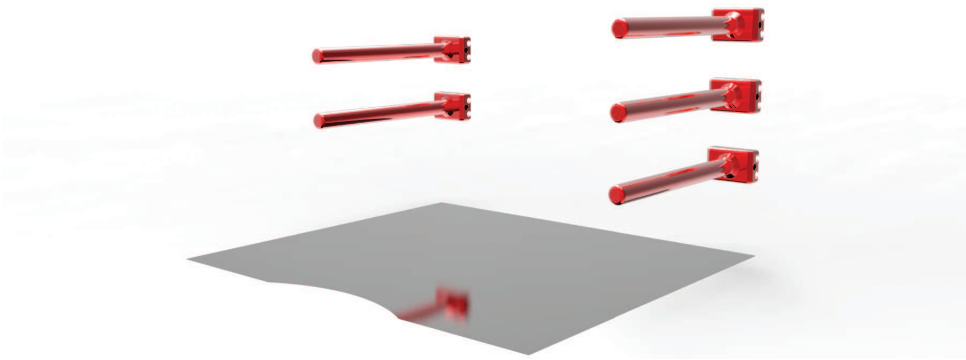


Figure 10.3: Detailed drawing of the folding poles mechanism

10.1.4 Lock-in device

In Figure 10.4 a drawing is given of the storage structure mechanism. The lock-in device of the storage will be located mainly within the non-rotating section of the storage, next to one of the walls that will be aligned with the rotating side of the storage. These walls will have a hole of $0.15m$ perfectly aligned with each other, through which a tight-fit pole will be pushed by an electric motor.

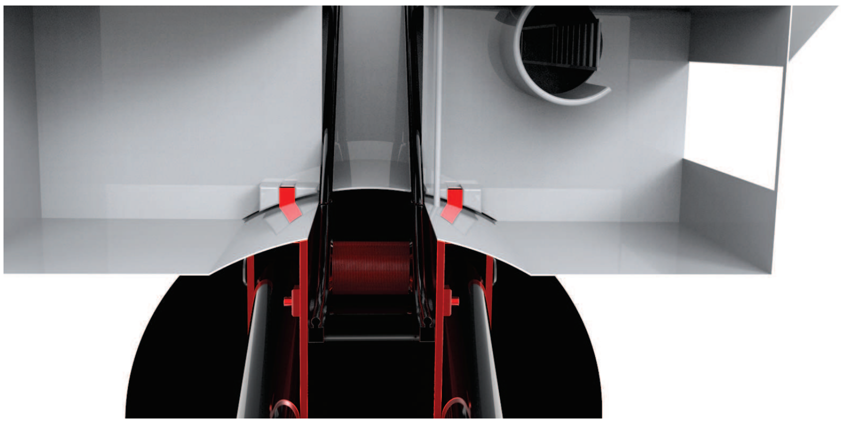


Figure 10.4: Top view detailed drawing of the lock-in device mechanism

10.2 Structural analysis

In the structural analysis for the storage, two mechanisms are analyzed, being the folding poles and the lock-in device. For the rest of the storage the dimensions and weights are given.

10.2.1 Storage cover

This mechanism will be described in section 10.3. The dimensions of the cover are length of $4.8m$ and width $5.2m$. The weight of the storage cover is determined to be $240kg$. The storage width follows from the analysis of the folding poles in subsection 10.2.3. The length comes from the distance from the back of the storage to the vertical boom.

10.2.2 Storage structure

The structure of the storage was not analyzed since it will be just a casing with sheet metal as walls of the storage. The dimension of the storage are: length of $4.8m$, width of $5.2m$, and a height $4m$. The height of the structure is determined in the section below.

10.2.3 Folding poles

The material used for the folding poles is chosen to be steel, due to the need to be as strong as possible and minimize their cost and size. To size the structure the forces and moments on the folding poles are needed which were calculated using the worst case scenario described in section 4.2. The forces and moments calculated can be seen in Table 10.1.

Table 10.1: The forces and moments experienced at the root of the boom

Force/moment	Equation	Value	Unit
F_x	$-$	0	kN
F_y	$J \cdot 2 \cdot F_t$	26	kN
F_z	$J \cdot (F_t - m_{pole} \cdot g)$	13	kN
M_x	$-$	0	kNm
M_y	$J(F_t - m_{pole} \cdot g) \cdot \frac{l_{pole}}{2}$	16	kNm
M_z	$J \cdot 2 \cdot F_t \cdot \frac{l_{pole}}{2}$	32	kNm

For the folding poles, a circular cross-section was chosen since the poles can not have any sharp edges that could damage the bridle system and the kite. Using these forces and moments in the optimization described in subsection 4.2.4, an optimal radius, thickness and weight were found. These optimal dimensions are shown in Table 10.2.

In this analysis the amount of poles, which gives the storage the ideal height and width, was determined. This was done using the deflated flat span of the kite and divide it by the amount of poles. The amount of poles were then iterated, to get a storage width which is in proportion with its length. The height of the storage was determined by adding the diameter of all five poles, the clearance between them, the CU height and the diameter of the horizontal beam. Values needed for this calculation are given in Table 10.2. The results are already given in section 10.3.

Table 10.2: Specifications of the folding poles

Specification	Value	Unit
Length of to be packed kite	26	m
Vertical clearance between poles	0.2	m
Horizontal distance between poles	4.8	m
Length	2.5	m
Radius	0.132	m
Thickness	1.5	mm
Weight	24.1	kg

This weight is only for one folding pole and as five is the ideal number of poles, the total weight will be $121kg$. The weight of the motor to actuate the movement of the folding poles will be $50kg$ for each, so a total of $250kg$.

10.2.4 Lock-in device

This mechanism will be made out of steel. The structure of the lock device was analyzed assuming there is only a shear force on it. This shear force was calculated by using the maximum torque on the vertical boom and dividing it by the radius of the rotating platform. The maximum shear force was found to be $50kN$. Using this shear force the shear stress can be calculated using the shear stress equations described in subsection 4.2.2. This was done by iteration by hand and by slightly overdesigning the bar. The shear stress was calculated to a Von Misses stress by simplifying Equation 4.2 in subsection 4.2.2 even further to Equation 10.1.

$$Y = \sqrt{3 \cdot \tau^2} \tag{10.1}$$

A radius and thickness were chosen from which the weight resulted. The result of the analysis can be seen in Table 10.3. This device is described in section 10.3. The actuator for this mechanism is just a small electrical motor and the weight of it is assumed to be $1kg$.

Table 10.3: Specifications of the lock-in device

Specification	Value	Unit
Length	0.4	m
Radius	0.05	m
Thickness	0.01	mm
Weight	1	kg

10.3 Actuators and sensors

The actuator for the storage cover will be an electric motor combined with a storage cover drum (shown in Figure 10.2). The storage cover drum resembles that of a swimming pool. The speed of the storage cover has been determined to be $0.25m/s$, the only force that the storage has to overcome is the friction caused by its own weight. The speed and position is monitored by a rotary encoder speed sensor GHS38 and a a rotary position sensor Cherry Switches GS101201 respectively, both of which communicate with the servo. There is a locking contact sensor when the storage closes. Moreover there is an alarm system coupled to this contact sensor. The storage cover motor will have to deliver at most $10W$ of mechanical power in order to slide the cover over the storage. This value is computed using the method in section 4.4. See that section for a detailed explanation. The $10W$ of mechanical power will be generated with an MS 561-4 electric motor which has a maximum power of $60W$. It has a mass of $3kg$.

The actuators for the storage poles will consist of electric motors and a ball screw. The speed of the packing poles as the travel horizontally are determined to be $0.2m/s$. The speed and position of the packing poles need to be monitored and controlled along with the horizontal beam by the CPU as their speeds need to be synchronized in such a way that the tension in the tether stays constant. The speed and position of the packing poles are monitored by a rotary encoder speed sensor GHS38 and a rotary position sensor Cherry Switches GS101201 which communicate with both the servo and CPU. There is a contact sensor at the end of each rail for the purpose of recalibration of the position sensors. Each of the storage poles will have to deliver $3.43kW$ of mechanical power to fold the kite in the storage. The $3.43kW$ of mechanical power will be generated with an MS 132M1-6 electric motor which has a maximum power of $4kW$. This type of motor has a mass of $50kg$.

When required the rotating platform is turned to the non rotating storage. To indicate alignment, there is a magnetic contact sensor. The rotating and non-rotating storage are secured into place using a lock-in actuator consisting of a small pole that is linearly actuated by a small motor and gear. There is also a small angular sensor that gives feedback on the position of the pole.

10.4 Energy consumption and operation time

The energy consumption of the storage cover is $0.1kJ$ ($0.028Wh$) per operation (opening or closing). This value was found with the method explained in section 4.3. The speed of the storage cover was set to be $0.25m/s$. Combined with a distance of $6m$ this results in an operation time of 24 seconds. The energy consumption of the storage poles is $600kJ$ ($166Wh$) per operation (opening or closing). This value was found with the method explained in section 4.3. The speed of the storage poles are $0.2m/s$. The operation time of the storage poles are not taken into consideration, as they act when the horizontal beam is descending or rising.

10.5 Manufacturing process and cost

The storage provides a big opportunity to make use of recycled material due to it not carrying intensive loads. This way the entirety of the structure can be made from common items found in hardware stores or reused parts as the table below states.

Table 10.4: Production of elements of the storage components

Mechanism	Element	Product code	Origin: provider/process	Quote obtained
Storage cover	Rolling shutter w/motor	N/A	Certain hardware stores	€1,500
Storage structure	Lateral wall x2	N/A	Custom: 5x4 cargo container cut-out	€535
	Pole guide wall	N/A	Custom: 5x4 cargo container cut-out	€267
	Posterior wall	N/A	Custom: 5x4 cargo container cut-out	€267
Folding poles	Steel pole x5	N/A	metalsdepot.com	€1,700
	Guide x5	N/A	dogarulman.com.tr	€180
	Threaded rod	N/A	Any hardware store	€250
	Electric motor	MS132M1-6	electramo.com	€2000
	Motor servo	SBW-20	alibaba.com	€250
	Position sensor x5	N/A	alibaba.com	€500
	Speed sensor x5	GHS38	alibaba.com	€400
Lock-in device	Pole lock	N/A	Reused steel pole	€50
	Electric motor	N/A	electramo.com	€50
Subtotal				€7,949
10% Assembly cost				€795
Total				€8,744

The inner and outer walls are manufactured out of a reused $40ft$ cargo container. This cargo container provides a total of $146.4m^2$ and costs approximately €1,950. Cutting and welding processes are the only production methods required to make the overall shell of the storage, with certain stiffening elements strategically placed but that will only affect minimally the overall price for the walls.

A final element that can be mentioned is the pole lock. This is simply a short pole mounted to an electric motor that will prevent misaligment from the two storage sections when the kite must be stored. Therefore any scrap section of a pole can be used if mounted properly into the storage subsystem.

11. Analysis of the integrated system

This chapter will present analysis of the integrated system. In previous chapters the specifics of every subsystem were presented individually whereas this chapter aims to provide the properties of the entire system.

In section 11.1 the overall energy consumption and operation time are presented. The second section presents the sustainable review to show that the design fulfills the sustainability goals. Section 11.3 describes the manufacturing process. In section 11.4 the information and communication diagrams are discussed. The section thereafter contains the breakdown of the cost. Section 11.6 discusses the operations, maintenance and logistics of the system. The chapter ends with a section that covers the RAMS (Reliability, Availability, Maintainability and Safety).

11.1 Energy consumption and operation time

In this section the energy consumption and operation time of the integrated launch, landing and storage system are presented. Subsection 11.1.1 summarizes the energy consumption of all actuators per cycle. In subsection 11.1.2 the overview of the operation time is given.

11.1.1 Energy Consumption

One of the requirements of the system is that it consumes less than 1% of the total energy generated by the pumping kite. Therefore it is important to carefully analyze the energy consumption of each subsystem and make adjustments if necessary. The breakdown of the energy consumption can be found in Table 11.1.

Table 11.1: Summary of the energy consumption and percentage of the total

Subsystem	Actuator	Energy consumption per system cycle [kJ]	Percentage of the total [%]
Kite adaptation	N/A	N/A	N/A
Horizontal beam	Gripper rail	27	0.7
	Beam hinge	60	1.6
Vertical boom	Boom hinge	168	4.6
	Vertical boom rail	1,145	31.5
Rotating platform	Rotation bearing	418	11.5
Swivel storage	Swivel rail	66	1.8
Storage	Folding poles	1,200	33
	Storage cover	0.5	0.01
Integrated system including efficiency		3,632	100

The total energy consumption of the system during one system cycle (land, store, deploy and launch) equals $1,009Wh$. In subsection 3.2.2 it was found that the maximum amount the system may use in three months is $660kWh$. Since the kite will most likely land around 24 times in this period the system only uses 3.6% of the maximum amount it can use in the requirement. It uses only 0.036% of the total energy produced in one cycle.

11.1.2 Operation time

The operation time has been determined by calculating the time needed for the actuators to perform their task. To do this a speed has been predetermined. The predetermined speed is also included for the power consumption. Note that not for all actuators a time is given as some actuators act simultaneously, hence there are some time overlaps. This is taken into consideration in the operation time calculation.

Table 11.2: The operation time for launching

Mechanism	Speed	Includes operation time of	Time (s)
Storage cover	0.25 m/s	N/A	24
Vertical boom rail	0.5 m/s	The folding poles retracting, the swivel rail elevating	70
Rotating platform	3 deg/s	N/A	60
Kite inflation	N/A	N/A	300
Gripper rail	0.5 m/s	N/A	9
Boom tilt	1 deg/s	Beam tilting the same angle	25
Beam rotation	6 deg/s	N/A	15
Total launch time			503

Table 11.3: The operation time for landing

Mechanism	Speed	Includes operation time of	Time (s)
Boom tilt	1 deg/s	Beam tilting back to the horizontal is fully retracted	25
Gripper Rail	0.5 m/s	N/A	9
Kite deflation	N/A	N/A	300
Rotating platform	3 deg/s	N/A	60
Beam rail	0.5 m/s	The packing poles retracting, the swivel rail elevating	70
Storage cover	0.25 m/s	N/A	24
Total landing time			494

The total operation time is found by taking into account that the kite lands 24 times in 3 months, hence the total time the kite must operate equals $6,531,840s$ (84% of the total time available in 3 months). The total time of operation in one cycle is $997s$. This means that for 24 operation cycles only 0.37% of the total operation time of the kite producing power is used for landing, launch and storage.

11.2 Sustainable review

In section 3.3 an approach to the sustainable development strategy was given for the design of the launch, landing and storage system. In this section a review is given on the strategies stated in that section. First a review is given on the energy consumption of the various subsystems based on section 11.1 and sustainable strategy I. Next, the used materials are evaluated on their sustainable properties per subsystem based on sustainable development strategy II and IV. Finally, sustainable solutions on the results of the review are discussed in the the last subsection.

11.2.1 Energy consumption

As stated in sustainable development strategy I, in section 3.3, the team aims to reduce the need of energy for this launch, landing and storage system. In this subsection a short review is given on the achieved results on sustainable design with respect to energy consumption. Every subsystem is briefly discussed on energy consumption and efficiency in the following subsubsections, for which the values from Table 11.1 are used.

Kite adaptations

The energy consumption of the kite adaptations subsystem mainly consists of the PRU. The PRU is powered by the CU which in its turn is assumed to be self-powered in assumption assumption CU01. Therefore this subsystem is considered as not consuming any energy.

Horizontal beam

The horizontal beam contains several small actuators and sensors to catch and retrieve the kite. The two main energy consumers are the beam hinge and the gripper rail. The energy consumption of these actuators take up 2.8% of the total energy consumption. Both actuators are electrical and therefore relatively energy efficient.

Vertical boom

The largest energy consumer of the automated launch, landing and storage system is the vertical boom. The vertical boom rail hoists the beam up and down, while the beam hinge tilts the the complete vertical boom subsystem. Together these actuators consume 42.5% of the total energy consumed. The vertical boom rail is an electrical engine which pulls the beam down while lifting a counter weight inside the boom. The reversed process does not consume energy as the beam and kite are lifted by the counter weight inside the boom. The beam hinge actuator consists of two hydraulic pumps forcing the hydraulic fluids into the load carrying pistons. The pumps will have an efficiency of about 90% [43] and are therefore relatively energy efficient.

Rotating platform
The rotation of the structure is powered by the rotation platform. Two electric actuators turn the boom in the right direction. The rotating platform actuators use 13.6% of the total energy consumption. These actuators are also electrically powered and therefore relatively efficient in energy usage.

Swivel storage
The swivel storage mainly consist of the rail system guiding the swivel to the floor of the storage. The actuator of this system is a small electrical motor attached to a gear inside the swivel beam. This actuator uses about 2.1% of the total energy used.

Storage
The storage subsystem is the third largest energy consumer of this launch, landing and storage system. Five poles fold the tensioned bridle system such that entanglement is prevented. To enable this movement, five electrical motors drive screws ball on which the five poles are moved and slid along rails. These electrical motors consume about 39.4% of the total energy consumption and are relatively energy efficient.

Concluding, there are two main energy consuming subsystems i.e. the vertical boom and the storage, which are responsible for 70% of all energy consumed. All actuators use electrical motors which are relatively energy efficient in comparison with other solutions on creating a rotation motion of equal torque.

11.2.2 Materials

As stated in sustainable development strategy III and IV, the team aims to design the automated system from reusable and recyclable materials and to reduce the waste and harmful materials used in the design and processes as much as possible. In the following subsection the materials and their impact on the sustainability of the design of each subsystem are discussed.

Kite adaptations
The kite material is ripstop nylon, which is a thermoplastic (like all nylon fabrics). Therefore the kite can be reprocessed after usage and thus the kite is recyclable. The Dyneema tethers can easily be recycled so environmental pollution from product and process is minimal [44]. However, in the process of fabricating plastics environmental unfriendly chemicals are used. As the tether and kite are out the scope of this design process no further research is done on alternative materials.

Horizontal beam
The horizontal beam consists of two parts: the aluminum beam and the plastic cone and gripper at the tip. The aluminum beam is recyclable as it can be remelted and reused for other purposes. The plastic cone at the tip of the beam and the gripper require to have a very high durability, recyclable thermoplastic with uv-protection additions can be used. Therefore the plastic cone at the tip meet the sustainability development strategy.

Vertical boom
The vertical boom requires the largest amount of material in comparison with the rest of the subsystems. For structural and cost purposes, the vertical boom mainly consists of steel. Steel is easily recyclable and therefore meets the sustainable development strategy. However, the process of manufacturing the 35m steel boom is highly unfriendly to the environment [45]. No other material meets the structural and cost requirements besides steel and therefore no other solution is considered.

Rotating plat form
The rotating platform subsystem is fully made out of steel for the same reasons as were stated for the vertical boom i.e. cost and structural properties. Therefore also for the rotating platform no other materials are considered.

Swivel storage
The swivel, swivel beam, and swivel rail are all manufactured out of steel for cost reasons. As discussed in the subsubsection on the vertical boom, the process of manufacturing steel products is highly environmentally

unfriendly. With a higher budget materials with environmental friendlier manufacturing processes must be considered.

Storage
Equal to the reasoning on the swivel storage, also the storage subsystem is fully manufactured from steel. Environmentally friendlier materials like concrete for the walls should be considered when a larger budget is available. Furthermore a large part of the storage subsystem is the folding system. Five steel poles are used to fold the bridle system which could easily be replaced with environmental friendlier materials of equal strength, when one is in possession of a larger financial budget.

Concluding, the kite is recyclable as well as the tether and all steel and aluminum parts. Steel is used extensively for cost and structural reasons, however its manufacturing process is utterly environmental unfriendly. Therefore other materials should be considered when a larger financial budget is available. Still, many materials used are recyclable when the system is decommissioned at the end of its life. The steel parts are recyclable for almost 93% and therefore it is recommended to do so in future elaboration of this design.

11.2.3 Sustainable solutions trade-off

From sustainable development strategy II the team aims to explore opportunities of using sustainable solutions. In this section several sustainable solutions are discussed for every subsystem and the eventual choice is explained.

Kite adaptations
As the PRU requires power as well as the CU, a new source of energy must be found. Two energy generating systems were considered: a small turbine or a solar panel attached to the CU. Both systems use sustainable energy sources to generate electricity used by the CU and PRU. However, the turbine will have a higher energy potential as wind speed is available at all times (during flight) in comparison to the solar panel which uses daylight. Therefore the wind turbine attached to the CU will be more convenient for this particular system.

Horizontal beam
The horizontal beam uses a non-recyclable plastic cone which could be replaced by a recyclable material like polished wood or a recyclable plastic. However these materials are less durable and the cone will need replacement after a certain timespan. Furthermore, less durable materials will be more expensive as replacement requires the manufacturing of new parts.

The beam itself could be replaced by a much lighter, evenly strong material like carbon fiber composites. The weight reduction will result in a lower energy consumption of the vertical boom rail and the beam hinge. However, a carbon fiber composite beam will be extremely expensive in comparison to the increase in energy efficiency it will obtain. Furthermore, carbon fiber composites are non-recyclable.

Vertical boom
The vertical boom subsystem has the largest mass of the launch, landing and storage system due to its $35m$ steel boom. To reduce energy consumption a lighter material could be used like aluminum or carbon fiber composites. However, using a carbon fiber composites would drive the costs to an extreme level and thus it is considered as unfeasible. Furthermore, steel tubes like the vertical boom are recyclable for 93% and therefore meet sustainable development strategy IV [46]. Aluminum could reduce the weight to a certain extent, but as aluminum loses a lot of its properties after recycling, steel is considered as the best choice for the launch, landing and storage system.

Rotating platform
The rotating platform uses relatively energy efficient actuators and is manufactured out of steel. Reducing the weight will not significantly decrease the energy consumption. Furthermore, as the rotating platform requires to be very stiff, strong and durable, metal will be the only suitable material for this subsystem. For cost reasons steel is the most convenient choice.

Swivel storage
The swivel storage is a subsystem made completely of steel. No recycled materials can be used for this system due to fatigue reasons as it will have to manage the cycling forces on the tether.

Storage
The storage is a full steel structure. Materials like concrete could easily replace the walls of the storage subsystem as they do not carry any loads besides the weight of the cover. The folding poles can be replaced

by polished wooden bars as the cover will protect the wood against environmental conditions. However, for financial reasons steel is chosen as the most convenient material for the storage.

11.3 Assembly and integration

Integrating the subsystems that make up the entirety of the launch, landing and storage platform for the kite is an important process as it must ensure full cohesiveness and synergy in every aspect. This will span from a proper physical assembly of the components, intelligent setup for functions of the hardware and proper communication between the mechanisms and the CPU. In this section all these aspects will be discussed at length with the goal of providing clarity to the reader about the process of integrating and unifying the subsystems into one fully functional system.

In subsection 11.3.1 the assembly process is discussed and in subsection 11.3.2 the physical interaction is described in the hardware block diagram. The section ends with the electrical block diagram which shows the electrical interaction.

11.3.1 Assembly process

In order to come up with solutions to the issue of interconnecting each subsystem, research was done on the most common methods of assembly and their uses. The most appropriate method will be chosen from Table 11.4 below. The cost of each assembly process among the subsystems will be, for the sake of simplicity, taken as 10% of the total cost up to this point. This decision was made in order to keep consistency with the pricing method in section 4.6.

Finally assembly methods will come down to the processes used to put parts together, whether they are adhered, welded, riveted or bolted, and the amount of material used for these processes. Suggestions for assembly of the overall system are given, along with cost estimating relationships in Table 11.4.

Table 11.4: Main assembly methods

Assembly method	Description	Cost estimation
Riveting	Only transfers shear stress. Used more commonly for single-side assembly, disassembly can be carried out although it is not encouraged due to weakening of the rivet hole.	$C_r = \frac{(C_{sr}+C_p)N_r}{\eta_h}$
Bolting	Transfers shear stress and tension. Easiest method for disassembly, but tolerances are low to avoid unexpected stress concentrations.	$C_b = \frac{(C_{sb}+C_p)N_b}{\eta_h}$
Adhesive	Transfers shear stress only. Pretreatment of the surfaces must be carried out and disassembly is nearly impossible. Expensive method.	$C_a = \frac{(C_{aw}W_a)+A_{tr}}{\eta_h}$
Welding	Transfers shear and normal loads. Used for uniform and smooth connections. Heat-treated materials must not be welded as it changes microstructure configuration.	$C_w = \frac{(C_e+C_f)L_w}{\eta_h}$

The constants and variables for the cost estimation can be found in Table 11.5.

Table 11.5: Variables for cost estimation of each assembly method [17]

Riveting	Bolting
C_r: Cost of riveting [€]	C_b: Cost of bolting [€]
C_{sr}: Cost of a single rivet [0.15€]	C_{sb}: Cost of a single bolt [0,3-0,8 €/m]
C_p: Cost of a single perforation [0.20€]	C_p: Cost of a single perforation (& threading) [0,9 €/m]
N_r: Number of rivets	N_b: Number of bolts
η_h: Human efficiency [0.45]	η_h: Human efficiency [0,45]

Adhesive	Welding
C_a: Cost of adhesive	C_w: Cost of welding [€]
C_{aw}: Cost of adhesive per kilo [23.7 €/kg]	C_e: Cost of electrode per meter [0.097 €/m]
W_a: Weight of adhesive used [kg]	C_f: Cost of flux per meter [0.147 €/m]
A_{tr}: Pre-adhesive treatment cost [€]	L_w: Length of weld [m]
η_h: Human efficiency [0.45]	η_h: Human efficiency [0.45]

These assembly methods are common ground in engineering designs and the Kite Power Team should decide upon what the most optimal course of action is regarding the assembly of the subsystems.

11.3.2 Hardware diagram

In this section the hardware diagram is discussed. The hardware diagram gives an overview of all the subsystems and how they work together. Although all the subsystems only work together with the CPU, it is still very useful to have an overview which subsystem interacts with other subsystems in order to accomplish a certain task.

The actual hardware diagram can be found in Appendix D. To keep the hardware diagram clear the interactions with the CPU and power system have not been included. All subsystems, except for the PRU and CU (these are self-powered), require power from the power system and are thus connected to, it. Furthermore, the CPU is omitted in the hardware diagram because all subsystems connected in the hardware diagram are connected to each other by means of the CPU. Including the CPU would clutter the diagram without adding value.

All interactions in the hardware diagram are numbered and further explained in Table D.1, which can also be found in Appendix D.

11.3.3 Electrical diagram

In this subsection the electrical block diagram will be elaborated. The actual diagram can be found in Appendix E. The purpose of the electrical block diagram is to illustrate how electricity is produced and distributed amongst the respective electric devices. Note that the filled lines represent power lines and the dotted dark blue lines represent signals.

The generator used is a 3-phase synchronous generator. A synchronous generator is chosen over an asynchronous generator, due to its higher efficiency. Although the angular velocity of the drum is not constant, the AC/DC converter controls the frequency and voltage output. The voltage output of the generator is monitored as it can not go above $400V$. This is done by sending feedback from the AC/DC converter to the I/O (input/ output port which is connected to the control computer) about the torque experienced. The I/O also gives a set voltage that the AC/DC converter can take. When the torque is above a threshold value the I/O sends a signal to the field coil which influences the impermanent magnet of the generator, lowering the voltage and current output. Between the I/O port and the field coil there is an amplifier that is powered by the rechargeable battery. The amplifier is needed as the power of the signal sent to the field coil is insufficient, hence needs amplification such that it can become a power line.

The rechargeable battery is powered both by the generator and the grid. There is a bi-directional inverter connected to the grid which receives input from the I/O port. The bi-directional inverter has three functions; it is a switch controlled by the control computer, an AC/DC converter and a DC/AC converter. When the batteries need charging the bi-directional inverter acts as an AC/DC converter. When the batteries are full and the generator is producing excess power, it acts as a DC/AC converter yielding $230V$ at $50hz$.

The power from the batteries is distributed between two main categories; the CPU (which comprises the control computer and the I/O port) and the actuators. Note that the power input to the CPU is constant whereas the power input to the actuators varies with time. The control computer can not process more than $24V$, therefore a DC/DC converter is required. The I/O port sends signals to the servos of each respective motor. There is a power signal that is also connected to each of servo's. The servos control the amount of power the motors receive and thereby their behavior. Note that most actuators need to perform three phases; constant acceleration up to certain velocity, constant velocity and constant deceleration. In Figure 11.1 the power required to actuate the horizontal beam at constant velocity is given. It is favorable to keep the velocity of the respective components at constant velocity because this highly reduces the effects of fatigue.

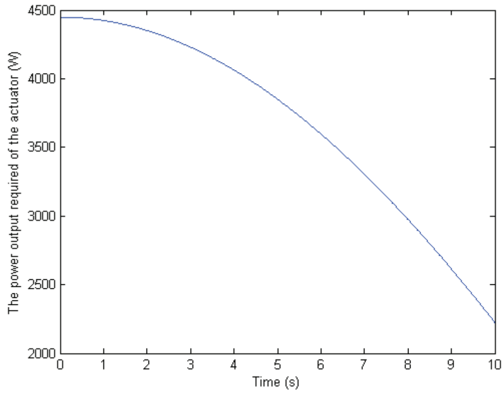


Figure 11.1: The change of power required of an actuator over time

The change in power required over time stems from the fact that the loads that the actuator has to counteract changes along with the position and orientation of the mechanism that it actuates. To maintain constant velocity or acceleration, the power output of the actuator needs to vary, this is controlled by the servo. Each actuator has multiple sensors sending feedback to both the servo and the I/O port. Signals are sent to the I/O port as well because some mechanisms have to co-operate with and/or depend on each other. Some motors are controlled by the same servo; the hydraulic actuators and the storage poles. Not all actuators work at the same time. However the power that the battery can deliver should be designed, hence the power budget table 11.6 has been made.

Table 11.6: Power budget of the respective motors

Mechanism	Maximum power required $[kW]$	Motor/pump rated power $[kW]$
Gripper	0.736	1.1
Swivel rail	1.5	1.5
Beam hinge	5.8	7.5
Rotating platform	3.5	4
Storage cover	0.005	0.06
Vertical boom rail	8.3	11
Boom hinge	2.6	2.6
Storage pole	3.4	4

The most power intensive interval is when the kite is rising on the vertical boom $P_{max_{VBR}}$, the last storage pole is moving $P_{max_{SP}}$ and the swivel rail moves up $P_{max_{SR}}$. This requires a power input from the battery of $13kW$, this is shown in the equation below.

$$P_{max} = P_{max_{SR}} + P_{max_{VBR}} + P_{max_{SP}} \tag{11.1}$$

Hence the power that is required from the battery is $13kW$. Note that the power for the motors can not come from the I/O port with an amplifier, this would cause a loss of power as the amplifier can cause power losses. Moreover the motors require a 3-phase power input.

11.4 Information and communication

This section describes the communication between the subsystem and the CPU. The purpose of this section is to provide the reader with the detailed communicative interaction between the subsystems. This is done by giving a communication flow and data handling diagram and a software block diagram.

In subsection 11.4.1 the communication flow and data handling diagram gives the communication and the information of the data sent between the subsystems. The software block diagram described in subsection 11.4.2 further describes the software code required to execute the commands given in the communication flow and data handling diagram.

11.4.1 Communication flow and data handling diagram

In the communication flow and data handling diagram, the communication between subsystem is shown. In the case of this system, all information is sent to the CPU, processed by the CPU and sent forward to another or the same subsystem. The diagram shows what data is retrieved from which sensors and is communicated towards the CPU. The data is processed by the CPU after which it is sent back. In the diagram can also be seen what data is sent back towards the actuators of the subsystems. The diagram can be seen in Appendix F.

In some of the boxes of the sensors a star is shown. These sensors are used to calibrate the position of the mechanism since using only angular sensors and integrating the information over time, will have errors. For example, every time the gripper rail reaches the end of the rail (tip of the horizontal beam) the position of the gripper on the rail is reset.

11.4.2 Software diagram

Software diagrams are used to visually show the structure of a program. If these diagrams are built properly they can be used to start building the source code to the system. When using Unified Modeling Language-programs the diagram can be used to automatically generate a base for the code.

The diagram used to illustrate the base of the software is a class diagram. In object-oriented programming languages classes are defined as the base unit. Every item (for instance in programming jargon) is of a certain class. When these classes are defined the very beginning of the programming is fixed. The classes are accompanied by their attributes (properties belonging to the class) and their methods (actions which the class can perform). If the link between the classes is shown in the class diagram it can be a clear base to start programming.

The software diagram which shows the base for the programming of the Automatic Launch Landing Subsystem (ALLS) can be seen in Appendix G. The classes are indicated by rectangular boxes with boldface class names. Below the header are the attributes shown under which the methods are shown. The figure shows the main class 'ALLS' in center. All classes except 'ALLS' are put into packages to structure the code with respect to the subsystems. These packages include one main subsystem class while the other classes in the package represent the mechanisms required for that subsystem. The whole system can be started by running 'ALLS's 'initialize()' method. The 'ALLS' instance runs the main class in the package which invokes the mechanisms required for the subsystem.

When the 'ALLS' is commanded to start a function the corresponding method should be activated. The commands required to perform the function are passed on from the 'ALLS' to the main subsystem class which activates the actual mechanism. This approach is based on the interface segregation principle used in software engineering. If one mechanism is changed, only the interface (the main subsystem class) should be changed. No changes are required in the 'ALLS' class. This makes adaptations to the system more foolproof and easier to perform.

11.5 Cost breakdown

This chapter will focus on the final costs regarding the purchase and manufacturing, assembly, employee salaries and other overhead costs. In the design chapters, a cost estimation process yielded the necessary investment to completely assemble each of the subsystems independently. By the end of this chapter the final design cost will be given that will represent the necessary amount of investment to put the system in the market. Finally, subsection 11.5.2 will explain the reasons why the system may have surpassed the allocated budget.

11.5.1 Final design cost estimation

The subsystem design chapters yielded the cost for each of these to be purchased or manufactured and assembled. Now the costs of adjoining each of these together must be considered, taking the 10% over the added value of all subsystems, referred to as 'final assembly costs'. After this has been done, a 5% 'employee salary cost' over the total of the subsystems plus final assembly was taken which will serve to cover the man hours used during the entirety of the assembly process.

Finally 'overhead costs' must be considered. These are ongoing costs during the whole process of construction of the system and will cover wages of the Kite Power Team, accounting, taxes, advertising, among others. Their article [17] suggests to use 50%-400% of direct labor rate which is in this case the added values for subsystem and final assembly as well as employee salary. As this design is the prototype of an enterprise still in development, overhead costs are taken as 100% of the labor rate. This is because salaries for high positions, taxes, expenditures in advertising must be kept at a minimum if one wants to see the project be successful.

In the end, the total cost may not fully reflect all the expenditures that will be made. Unexpected costs, shortcomings, failed processes and redo's will bump the price up. For this reason a buffer budget of 10% over the total cost is added which will hopefully provide enough to tackle these unwanted situations. Adding this 'uncertainty cost' to the total cost will yield the final design cost.

A table containing the cost breakdown for the final design of the launch, landing and storage system is given below in Table 11.7:

Table 11.7: Final design cost breakdown

	Assembly & partials	Cost
Kite adaption	-	€248
Horizontal beam	€288	€3,168
Vertical boom	€1,024	€11,269
Rotating platform	€544	€5,987
CU storage	€103	€1,140
Storage	€795	€8,744
Subsystem assembly	€2,754	
Subtotal 1		€30,556
Final assembly	€3,055	
Subtotal 2		€33,611
Employee salary cost	€1,680	
Direct labor	€7,490	
Overhead cost	€7,490	
Total cost		€48,591
Uncertainty cost addition	€4,859	
Final design cost		€53,451

11.5.2 Cost-budget discrepancy

It is now evident that the final cost of the system is 167% higher than the budget allocated for the design. It comes as no surprise since the sheer dimensions required for a structure that supports a $70m^2$ kite are quite large, which in turn increases the demands for strong and reliable components and hefty production costs. Despite having kept assembly and overhead costs at a plausible minimum it became quite clear that the chosen concept for the system cannot be developed within the budget of €20,000 without compromising its optimal functionality.

It can be argued that the design was made such that an immense structure was needed and had this not been the case, the overall cost could be lowered. Or had cheaper reused materials be used for the most expensive components, downpricing would have ensued. Arguments like this are not uncommon and while they may hold a certain truth to them, it is difficult to carry out such changed without compromising the driving and killer requirements that were stated in section 2.1.

Nevertheless, this overshoot in price does not go inadverted and its effects on the Return on Investment are explained in section 12.4.

11.6 Operations, maintenance and logistics

This section discusses the plan regarding operations, maintenance and logistics which has been worked out to ensure proper functioning of the system. The characteristics of the system that ensure the actual maintainability are treated in section 11.7 on RAMS.

The first subsection elaborates on the maintenance strategy that has been chosen for the kite power system, specifically focusing on the launch, landing and storage system. The following section shows and describes the high-level operational flow diagram. Subsection 11.6.3 and 11.6.4 discuss the kite replacement procedure and maintenance checks and activities.

11.6.1 General maintenance strategy

The maintenance strategy that been chosen for the kite power system is visualized in Figure 11.2.

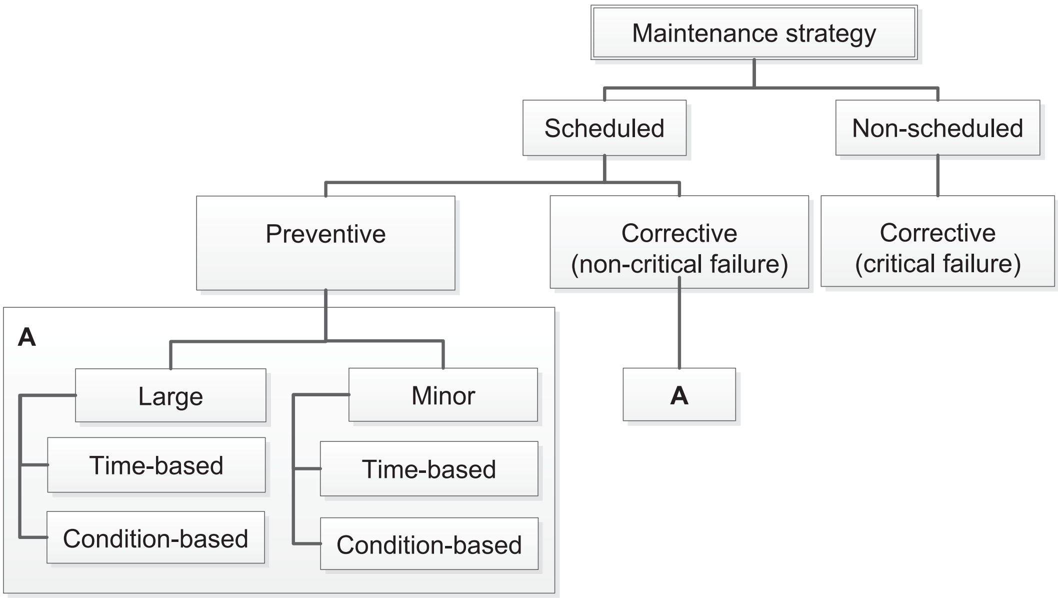


Figure 11.2: Maintenance strategy

The maintenance strategy for the launch, landing and storage system is mainly based on scheduled, preventive maintenance on the left side of the option tree. In this type of maintenance the equipment is repaired and serviced before failure occurs. The frequency of this type of maintenance activities is pre-determined by schedules. Inspection takes on a crucial role in the chosen preventive maintenance strategy. Components are inspected for corrosion and other damage at planned intervals, in order to identify preventive action before failures occur. Most of the checks and activities will be scheduled. However there is always a risk that non-scheduled maintenance has to be performed. This type of maintenance is caused by critical failure of the system, which has a corrective character; the failure has already occurred and the system requires a repair.

The kite power system's maintenance is divided into two categories: minor and large maintenance. The minor activities and checks are mostly less complex and time-consuming, while large maintenance can include additional, more difficult elements such as parts replacement or a complete system check. The chosen maintenance strategy defines two types of maintenance: minor and large maintenance. The first type is time-based which means that the activity or check is always performed at fixed moments in time, regardless of the condition of the (sub)system or mechanism at that time. The second type is condition-based and follows from inspection. The ground crew could make a decision to preventively replace or repair a part based on its current condition.

The scheduled, preventive maintenance will diminish the chances of failure, although the possibility that the ground crew encounters the consequences of non-critical failures during maintenance can never be completely ruled out. During maintenance several checks and inspections are executed which can bring non-critical failures to light. Therefore corrective maintenance on non-critical failures is also part of the scheduled maintenance. Corrective maintenance is always condition-based as it follow from inspection and occurs unexpectedly.

A maintenance strategy with a strong focus on preventive actions performed at regular intervals will usually result in reduced failure rates and a safer system [47].

11.6.2 Operational flow diagram

In Figure 11.3 the operational flow diagram is shown. The core functions within the operational flow diagram of the kite power system include the regular operation of the kite, minor and large maintenance checks/activities and the kite replacement procedure.

After three months the kite material and tether will be worn-out and will have to be replaced (see assumption M07). Complete automation of the kite replacement procedure is out-of-scope for this project, but a replacement plan has been produced. The process is rather complex and requires a ground crew on site. The kite replacement plan could serve as a general guideline for the crew.

As the ground crew already visits the system every three months for the kite replacement, these moments can directly serve as the base for scheduled maintenance checks and activities. It is suggested to integrate maintenance into the kite replacement procedure. The old kite can first be removed, whereafter maintenance can take place. As the final step the new kite can be positioned and attached. By applying this order of executing the steps, the new kite has the least risk of getting damaged. The maintenance checks and activities can have a minor or large character. Minor maintenance is performed every kite replacement, thus every three months. Once every four kite replacements large maintenance checks and activities will have to be performed (once each year). Of course, it might also be the case that minor maintenance directly results in large maintenance in case critical damage or errors are found.

Finally, the emergency stop has been included. In principle, the system should be able to run without human intervention for a period of three months. However it happens that the system encounters damage or a fatal error during its operation span, which immediately results in minor/large maintenance, depending on the nature of the emergency stop.

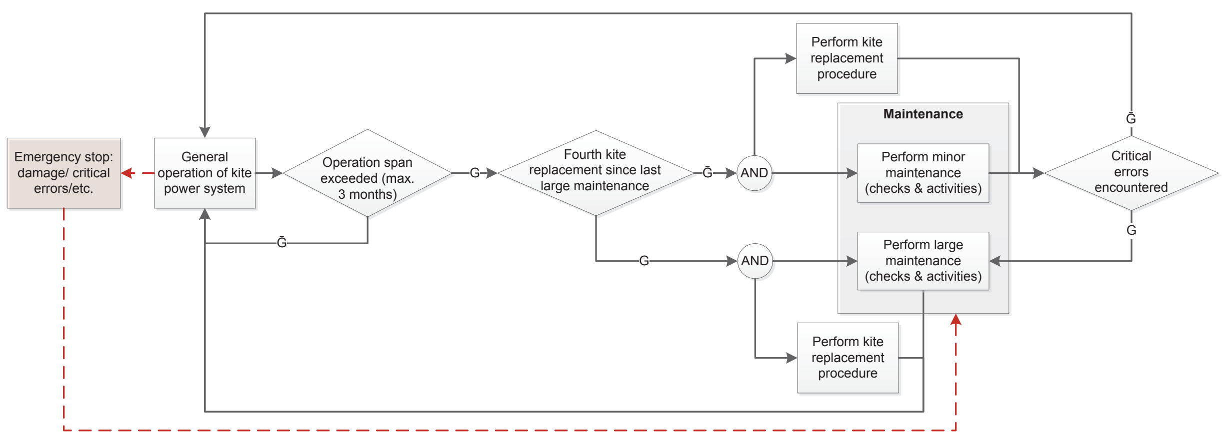


Figure 11.3: Operational flow diagram

11.6.3 Kite replacement procedure

The kite material and main tether deteriorate during operation by exposure to UV-light and weather conditions and have to be replaced after three months of operation. As the kite is very large with a surface area of $70m^2$, replacement is not that straightforward. The steps that have to been taken for the kite replacement are given in Appendix C. The replacement procedure has a stored kite as the starting point. If the kite is flying at the moment of arrival of the ground crew, the crew will first have to give the commands for landing and storage. A few elements of the procedure will be further clarified in the following paragraphs.

The horizontal beam is approximately $2.5m$ above ground at its lowest point and therefore the ground crew will require that a higher platform is positioned underneath of the beam. A liftbed truck can for example serve as the platform (see Figure 11.4). To create enough space for the kite replacement and positioning of the movable platform, the rotating platform will have to rotate away from the static part of the storage into the replacement range. This range starts at least $90°$ away from the regular storage position in both directions. The kite replacement procedure also requires two maintenance drums: one to coil up the old main tether and one which carries the new tether. These maintenance drums should be able to rotate automatically to increase the efficiency of the tether replacement.

Figure 11.4: Example of a liftbed truck required for the kite replacement procedure [14]

During the replacement the kite has to be lifted by the ground crew. The Dutch ARBO allows a maximum manual lifting load of $23kg$ per person and a load of maximum $50kg$ to be moved manually [48]. The kite has a weight of $45kg$ and therefore this will not pose any problems. However, to ensure health and safety of the ground crew and to able to cope with the size of the kite it is recommended to perform the replacement procedure with a crew of three people. This crew will lift the kite onto the horizontal beam and position it on the beam in such a way that no errors will occur during the regular folding procedure. To ensure correct attachment to the horizontal beam, the kite will have an identification mark on the fabric. This identification mark can be mapped onto the horizontal beam. The final steps that require some additional explanation are the reattachment of the PRU and CU. These parts will be reused and are designed in such a way that easy removal and reattachment is garanteed (see chapter 5 and assumption CU08).

In general the kite replacement procedure requires manual operation of the system. This can be done by connecting a computer to the CPU. Once the kite and tether have been replaced, a small test is performed in which the horizontal beam is slid to the top of the vertical boom and inflated. The automated operation is reactivated after a successful test run and can result in execution of the storage or launch procedure depending on the weather conditions.

As a final remark, the kite replacement procedure can only be performed in moderate wind conditions. High wind conditions will increase the risk of damage or incorrect positioning of the kite and the time required to execute the procedure. A maximum wind force of level 4 on the scale of Beaufort can be taken as the guideline for the ground crew (max. $8m/s$) [49].

11.6.4 Maintenance

Maintenance activities and checks are integrated in the kite replacement schedule and will thus be performed every three months. Regular maintenance will increase smooth operation of the system until the next kite replacement. In general these activities will be of minor character. Minor maintenance is less time-consuming and complex than large maintenance and is mainly based on general cleaning and visual inspection. During large maintenance elements such as lubrication, parts replacement and full-system checks are included. In Table 11.8 maintenance is worked out in further detail. The several checks and activities are listed and classified as part of minor and/or large maintenance.

Table 11.8: Classification of minor and large maintenance checks and activities

Check/activity	Description	Minor	Large
Check 1	Electronic operation check: all required in-/outputs, outlying data, abnormal behavior. This check has to be performed prior to the system visit, such that the reason for abnormalities can be found and repaired.	X	X
Check 2	Visual inspection of the structure on rust, wear and damage. During minor maintenance checks will be performed on-ground, large maintenance also includes visual inspection of the top of the boom.	X	X
Check 3	Mold/moist check of the storage.	X	X
Check 4	Complete system check: maximum load tests, observation of short flight cycle, etc.		X
Activity 1	Cleaning the storage.	X	X
Activity 2	Lubrication of the critical movable parts (e.g. rail systems, hinges).		X
Activity 3	Upgrade system (software/hardware)		X
Activity 4	Thorough cleaning of the entire system		X

To guarantee employee safety a maintenance protocol will be written. During periodic maintenance the vital components which could cause the largest danger for the employee should be checked first. This means that the employee should start at the boom hinge and the components that are at height (during large maintenance). If the employee would start at the storage, a large and heavy element such as the vertical boom could cause unnecessary danger during the maintenance checks and activities. Furthermore a list of safety regulations should be established and strictly followed by employees.

11.7 RAMS

This section will assess the design on the performance on the four RAMS topics. In subsection 11.7.1 the reliability of the system will be evaluated. Subsection 11.7.2 will describe the availability of the system in the sense of uptime versus downtime. The third subsection will assess the ease of maintenance and the fourth and final subsection gives details on the evaluation of the safety of the entire sytem.

11.7.1 Reliability

The reliability of a system is the probability that the system performs in a satisfactory manner for a given period of time under specified operating conditions. In this subsection the reliability of the system is evaluated with respect to the operation time of three months. For the design of the mechanisms two different approaches are chosen, namely fail safe and safe life. Fail safe engineering ensures that if one part of the system fails, there is an alternate success path, such as a backup system. This can also be seen as the mechanism or subsystem being redundant. Safe life design on the contrary ensures that a component will not fail during a specific design lifetime. To accomplish this a safety factor of 1.5 is used for the design of these parts.

Due to the fact that making the vital components (vertical boom, horizontal beam, beam hinge, boom hinge) more redundant will drive the cost of the system to an unacceptable extent, all the mechanisms are designed using the safe life approach. Since the vertical boom rail (subsection 7.1.3) performs a crucial role for the system and could cause serious damage to the other subsystems it is designed with a fail safe approach. This is done by using two cables instead of one. If one of the cables breaks the other cable is still capable to operate the total system.

For the selection of all the components used in the system most parts are off-the-shelf. This has multiple advantages since these components are tested many times and have proven their reliability. Thereby are the customized parts minimized and mostly used at positions that do not harm the operation.

Another important factor for the reliability is the probability that the kite has to perform an emergency landing. From the weather analysis in subsection 3.2.2 it follows that the kite would only have to perform six emergency landings in 60 years. This means that in an operation period of three months the probability of a emergency landing is very low.

From the above it can be concluded that the system is reliable and that the probability of hazards are kept as low as possible.

11.7.2 Availability

A determinant factor for the system is the amount of time the system can operate. This uptime for the system can influence the financial profitability. Therefore a higher availability is preferred. This ratio can now be determined.

In the previous paragraphs down time was mentioned due to the lightning and boundary winds. The total time available can be retrieved from the data set. The amount of data entries represents the amount of hours the system can operate. The availability can be determined by the ratio of the time the system is operating and the total time available.

From subsection 3.2.2 it follows that the uptime for the system is 1,820 hours and that the downtime due to lightning and boundary winds is 340 hours. From this it can be concluded that the availability of this system is 84%. These numbers are given for a period of three months but are based on the average of the data available (which is for a period of 62.5 years).

11.7.3 Maintainability

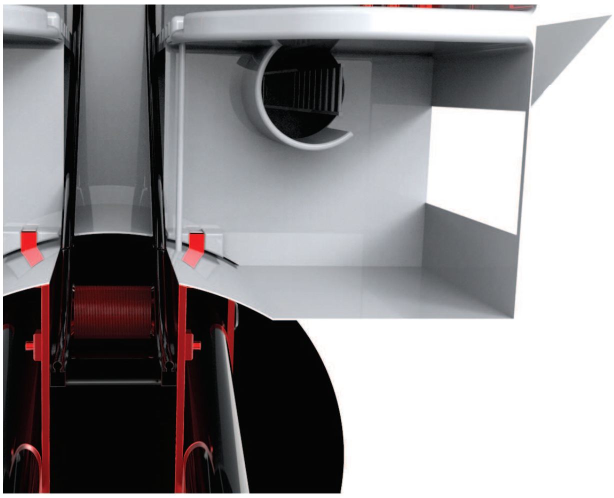
In section 11.6 the approach with respect to operations, logistics and maintenance has been presented. This subsection will assess the ease of these maintenance activities. Maintenance on the system has been continuously kept in mind throughout the design process and as such multiple elements have been added to improve the maintainability and the ease of the kite replacement procedure. This section will treat the core components of the system that are related to maintenance.

The most notifiable addition to the system are the steps that have been added on the entire backside of the vertical boom. These steps allow a maintenance crew to reach the top during maintenance checks and activities. During the climb the maintenance crew will always have to be anchored to the stairs; a person will have to wair a harness and attach himself/herself with carabiners. At the top of the boom an additional ring has been added which will allow a crew members to hook the carabiners to this ring and thereby enable an all-around inspection of the boom. Figure 11.5 shows an example of inspection of a wind turbine using this method. The steps and ring on top of the vertical boom are shown in Figure 11.6. As the horizontal beam can slide up and down along the vertical boom rail this element can be inspected on the ground.

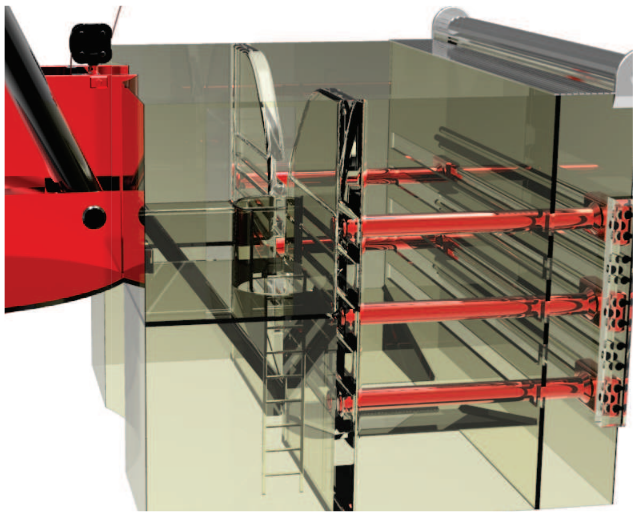
Figure 11.5: Example of maintenance on a wind turbine [15]

Figure 11.6: Steps and ring on the vertical boom

The storage also has some features that enhance the maintainability of the system. A separate access door has been made for entrance of personnel. Furthermore the storage unit has been designed to have sufficient walking space. On ground level the crew also has access to the drum. Stairs have been included to allow inspection of the basement. A barrier has been placed around the stairs to prevent the chance of falling in the stairwell during activities and checks on a ground level. The basement has a height of $2m$ and the maintenance crew can stand up during inspection. The access door and stairs are shown in Figure 11.7.



(a) Top view



(b) Side view

Figure 11.7: Access door and stairs in the storage unit for maintenance

A final consideration in the assessment of the ease of maintenance is the possibility to remotely control the system. In assumption M08 and subsubsection 2.3.1 it was already assumed that the CPU will have a wireless connection and possibility of remote control. This wireless connection will allow to monitor the system in an externally located operation room. Analysis of the data and behavior prior to a system visit will reduce the time required for maintenance and repair on site. In subsection 11.6.4 it was also stated that a laptop can be attached to the system to allow manual operation.

The aforementioned additions to the system lead to the conclusion that the launch, landing and storage system is maintainable.

11.7.4 Safety

Safety is defined as the degree of freedom from hazard to equipment and humans. First of all it can be stated that the system makes use of a lightweight kite, which does not cause a large impact if it crashes into the ground for the community and the system itself. The most important components that could cause problems are the mechanisms that are at a certain height. This is due to their potential energy, which could cause damage to the lower mechanisms in case of a failure. These mechanisms are:

- Vertical boom
- Vertical boom rail
- Horizontal beam
- Beam hinge

For the design of these components a safety factor of 1.5 is taken into account to ensure that failure of these components is minimized. As described in subsection 11.7.1 the vertical boom rail is made redundant since failure of this mechanism could cause major damage to employees and the system itself during maintenance. In Addition a red light is added to the 35m vertical boom to ensure that no hazard is caused to low-flying airtraffic.

Apart from the design considerations with respect to safety, the risk of injury of employees during maintenance is also minimized as much as possible. Subsection 11.6.4 describes the measures taken on this topic.

12. Functionality assurance of the design

This chapter will elaborate on the methods used to make sure the functionality of the system can be guaranteed. The purpose of this chapter is to provide the reader with evidence the design team has put all effort in making sure the design will work as intended. A second goal is to show the amount of work still needed to fully complete the design.

The chapter starts with the sensitivity analysis to show the effect of main system parameters on the design. Section 12.2 elaborates on the verification and validation effort to ensure the validity of the results and design. Thereafter the design effort which needs to be done post DSE is explained in the project design and development logic. Section 12.4 finally examines the financial plausibility of the designed system.

12.1 Sensitivity analysis

This section is about the sensitivity analysis. In the sensitivity analysis the sensitivity of the system to parameters changes will be investigated. This is done by testing the robustness and feasibility of the design. In subsection 12.1.1 the effect of changes made to the top-level requirements will be discussed and in subsection 12.1.2 the correlation between the main functions of the design will be discussed.

12.1.1 Change of the requirements

The client could at any moment desire changes to be made to the requirements set for this design. How these changes affect the design will be investigated next. The four main system parameters which are likely to be changed are considered to be the size of the kite, the wind speed range, the length of the bridle system and the generator size.

Changing the size of the kite
The current system is capable of handling a smaller kite, without any changes required, although the system will be over sized. When designing a system for a smaller kite the entire structure can decrease in size. Every part will decrease into proportion of the decrease in kite area. For this downscaling no adjustment in the manner of actuating of any mechanism will have to be made.

However, scaling up the kite will require more intrusive changes to the system since the entire structure will have to increase in size. A larger kite will require the horizontal beam and the rail on the horizontal beam to be enlarged. This again may pose a problem since the rotary screw to move the gripper along the rail will only be supported at the root and tip of the horizontal beam. Enlarging this system could cause the rotary screw to sag, which will hinder it to function properly. This could result in changing to another actuator system to move the gripper. Since the weight of the entire horizontal beam will increase, this could result in the hinge not being able to cope with the forces. In that case it might be needed that this mechanism is also actuated by a more expensive hydraulic cylinder.

Enlarging the kite will result in the distance between the kite and the CU to be increased. A direct consequence of this will be the need to increase the length of the vertical boom. A larger kite will induce larger forces and thus the structure has to be sized such that it is able to cope with them. This will cause an increase in weight of the horizontal beam structure, which in turn requires the thickness and radius of the vertical boom to be increase.

The rotating platform will have to be sized in relation to the other elements. Increasing the weight and enlarging the horizontal beam and vertical boom will require a bigger and stronger bearing. Because the weight is assumed to be perfectly centered on the rotating platform no change in rotating system is needed.

The swivel rail will have to be adjusted too, since a larger kite normally would induce larger tether tension forces. The way the swivel rail is designed will most likely not need any large changes.

Since a larger kite will be used, the structure of the storage also needs to be enlarged. The number of folding poles might also change. In case the folding poles need to travel a larger distance this might have a consequence for the choice of the actuators. This is due to the same reason as explained for the gripper rail.

Wind speed range

Changing the wind speed range can have an effect on several different parts of the system. A decrease in the minimum launching speed will have a profound influence on the design. From Figure 5.2a in section 5.4 it can be seen that the tether angle will decrease, resulting in the need for a longer beam or a larger possible tilt angle of the vertical boom in order to be able to launch the kite in a controlled way. In turn this will have an impact on several other components. The first thing which it affects is the storage height and swivel placement. In order to have enough clearance for a larger tilt of the vertical boom, either the storage will have to be lowered into the ground even more, or placed further away. Placing the storage further away will mean that the size of the rotating platform needs to be increased. The horizontal beam will also have to be elongated which will have the same cause on the gripper rail and beam hinge as described in the previous section about changing the size of the kite.

If the minimum launch wind speed is increased, it will cause the tilt angle of the vertical boom to decrease as shown in Figure 5.2a in section 5.4. If this minimum wind speed is increased far enough, the vertical boom does not need to tilt at all. This will have a huge influence on the design, since no clearance is needed anymore for the tilting of the boom and no actuator is needed to tilt the boom. Since no clearance is needed anymore, the swivel beam, swivel rail, generator, drum and storage can be moved closer to the vertical boom. Moving the storage closer to the vertical boom will mean that the kite can be ruffled forward instead of backward. This change will cause a decrease of the torque on the vertical boom.

Changing the maximum wind speed to a higher value will cause the forces in the worst case scenario to be higher. This increase in loads will result in a stronger, heavier and more expensive structure. However the chosen types of actuators will not need to change. The only critical actuator is the beam hinge, in case the size of the horizontal beam becomes to large the electrical motors could not be powerful enough to produce the required torque.

Having a lower maximum wind speed will cause the system to have lower loads. This however will only result in the structure to be a little thinner and smaller in radius. This will not cause any actuators to change.

Change in the length of the bridle system

A change in the length of the bridle system will be directly related to a change of the length of the vertical boom. The shortening of the bridle system will result in a shorter vertical boom. However the shortening of the vertical boom will result in a change in wind speed at the kite due to the height difference, albeit marginally.

Increasing the length of the bridle system will require the length of the vertical boom to be increased proportionally to the change. This increases the weight of the boom and that will have a influence on the rotating platform bearing.

Change of the generator

A change in the desired generator will only have a marginally influence on the system. The weight of the new generator will only change marginally and the current system does not operate often under full tether tension, see subsection 2.2.2. Thus the system will be able to handle the larger tether tension required for a larger generator without exceeding the current nominal tether tension of $40kN$ without the need of reinforcing the swivel beam. In case the larger generator does require marginal a larger nominal tether tension this will require a stronger swivel beam and a stronger rotating platform.

Making a larger generator worthwhile could require a higher operating altitude for the kite in order to take the most advantage of the higher winds at altitude. This increases the needed tether length and as a consequence the size and the weight of the drum is increased. However, compared to the weight of the boom the increase of weight will still be very marginal and thus no large changes to the sizing of the rotating platform will be required.

12.1.2 Correlation of the main functions

With the correlation of the main function it is meant how much influence the main function have on each other. The three main functions considered are the landing, launching and storage.

The main functions launch and landing are highly correlated to each other. They both use the same structures and mechanisms. Changing one of them will have a large impact on the functioning of the other one.

In other words, if you change the manner of one function, the manner of doing the other function will have to change.

Storage can be considered separately from the launch and landing function. Storage is only slightly correlated to the launch and landing function, because it is using other structures and mechanisms. Also the orientation of the deflated kite is fixed from launching and landing, since the kite will always be hanging on the horizontal beam. Therefore the storage unit can be completely redesigned without influencing either the landing or launch function.

12.2 Verification and validation

At this point the system is designed based on requirements, using different models and several assumptions. Every item which is used should also be checked to make sure that the design is constructed in a valid manner. The approach for this verification and validation of the system is based on the course on Systems Engineering [50].

The evaluation of this system start with examining the requirements in subsection 12.2.1. When they are confirmed the models used are verified (subsection 12.2.2) and validated (subsection 12.2.3). If the requirements and models used are verified and validated one can be sure that the design is done in a validated manner. The next step is to check whether the system complies with all the requirements during the product verification (subsection 12.2.4). Thereafter the check is done whether it works as intended by the clients during the product validation (subsection 12.2.5). For the validation of the system a test setup is constructed which can be seen in subsection 12.2.6. The final step is to certify the system and present the result to the clients in the flight certification (subsection 12.2.7).

12.2.1 Requirements validation

The requirements used to design the system are partly given in the top-level requirements and partly determined by the design team. The quality of the requirements should also be check to make sure that they can be used to design the system in a correct manner. The validation of the requirements can be done by using the VALID-approach. Every requirement should be stated so it is Verifiable, Achievable, Logical, Integral and Definitive. An overview of the requirement can be seen in Appendix B. These requirements can be checked with the VALID-approach.

From the overview of the requirements it can be remarked that all low-level requirements comply with these criteria. They can be verified by test, analysis, demonstration or review. They all are achievable with the current state of technology. The logic is visible in the numbering of the requirements. All low-level requirements are also integral as they state when something should be done. Last but not least, they are also definitive as they state only one item for every requirements and they have clear wording.

The top-level requirements which can be seen in Appendix B do not follow the VALID-approach as they are not at a detailed level to be able to fully describe what should happen. This is normal to happen when requirements are divided into sub-levels. Therefore these requirements can be kept on the condition that the sub-level requirements are checked.

Some of the driving requirements where stated in the project guide. This includes ALLS-CON-SFT, ALLS-CON-COST (the description of these requirements can be found in section 2.1). The requirements on the safety standard and cost are not stated in compliance with the VALID-approach. Requirement ALLS-CON-SFT as stated in the project guide states that the launch and landing must fulfill safety standards. This is not definitive as multiple safety standards exist. Requirements ALLS-CON-COST as state in the project states that low cost are required for production, transport and maintenance. 'Low cost' in not verifiable as cost can always decrease. That requirement also states "additional costs should be less than €20,000". The 'additional' aspect is not definitive for which more specifications should be included on what costs are included and which are not. If these requirements can be specified more the system can be designed such that the final design is certain to be according to the client's wishes.

Requirement ALLS-SUS-1.0 has been added by the group, but has been stated in such a way that is unachievable. To fulfill this requirement the entire structure had to be made from recycled/recyclable materials. The use of no off-the-shelf components in the entire structure is nearly impossible, especially in combination with other requirements such as those about costs.

One final remark can be made: throughout the design it was noted that the cost increased by a lot, even twice the available budget. After consulting the experts it can be stated that the combination of the wind speeds in the requirements and the available cost budget is rather unachievable. In this design the budget was exceeded as the focus was put on the operational qualities of the design. Further discussion on the cost budget versus the wind range related requirements can be found in chapter 14.

12.2.2 Model verification

In order to make sure that the models and simulations used in the design of the system represent the theory intended they should be verified. The models used in this design are described at either the analytical approach, the weather analysis, subsection 3.2.2, or the aerodynamic analysis, subsection 2.2.2. The verification of the models used is also shown in the corresponding part. The explanation of the verification is placed next to the model itself to ensure that if the model is used, the verification can be included immediately.

12.2.3 Model validation

If the verification is done it can be concluded that the models show the intended theory. The next step is to obtain evidence that the model used to analyze the system reflects the real world as accurately as necessary to support critical decision making. This step is called model validation and is not performed for all models in this report due to time and budget limitations.

Validation can be performed by using the experience of experts, analysis showing the models have correctness, and by comparison with test cases. The last two possibilities are not selected. Test cases are disregarded because they require large amount of time and budget which is unavailable for this project. Analysis is also not done as elaborate analysis of theory would be a lengthy and time-consuming process. Although these steps cannot be performed at this point, it should certainly be recommended that all models are validated using at least one of the possible three approaches.

Validation by experience is done for two models. For this, experts where contacted and the results where proposed. The experts were able to have a critical view on the calculations and using their expertise on the field they could indicate whether the results are plausible. The experts indicated that it could be assumed that the average power would be around 40% of the total generated power, which is $20kW$. The calculations showed that the average power produced was $30kW$ or 60% of the total rated value. These numbers are not close to each other. Therefore one should keep in mind that these average power calculations can be optimistic and the actual value is lower. The expectation is that the efficiency of the kite power systems increase. With this fact the slightly higher average power can be considered valid and used in this report. The other model validated is the wind analysis. The experts indicated that an uptime of 90% should be able to be achieved with a kite power system. The calculations from the weather analysis showed that the uptime for the calculations is 84%. This number is slightly lower but certainly acceptable. Therefore the weather analysis can also be considered as validated.

12.2.4 Product verification

The verification of the product comprises the evalution of the system for its compliance to the requirements (see Appendix B). In general checks can be performed by inspection, analysis, demonstration or testing. Due to time limitations and lack of actual hardware produced, the verification of the requirements is performed by analysis of the results presented in this technical report.

The compliance matrix in Table B.1 of Appendix B shows that most of the top-level requirements are not met, but this is mostly due to the fact that a few low-level requirements are not met. The matrix is built up in such a way that a requirement on a higher level is made up of several low-level requirements and if these are not met, the high-level requirement does not comply. The non-compliant requirements of the compliance check will be shortly discussed in the next paragraph.

The top-level requirement ALLS-SUS-1.0, which states that the materials used for production of the system shall be recycled or of recyclable materials is not achieved. As already mentioned subsection 12.2.1 this statement is actually formulated in an unachievable way. Therefore it is not surprising that this requirement is not compliant. The second notable result is the fact that both the top-level technical requirements of launch and landing are not compliant. In both cases this can be assigned to the low-level requirements related to the wind speed range. These low-level requirements are nearly achieved and a weather optimization program that maximizes uptime has been written. These two arguments allows to disregarded the fact that these wind requirements are non-compliant. The most striking result is the significant non-compliance of requirement ALLS-CON-COST. The fact that the requirement is not strictly defined and rather unachievable (as elaborated on in subsection 12.2.1) will play an important role in the cost difference. The cost breakdown is explained in section 11.5 and discusses the elements that have the largest affect on the cost budget.

Overall it can be assumed the system complies with most of the requirements and the design is quite successful.

12.2.5 Product validation

Validation of the product should be performed to makes sure that the product accomplishes the intended purpose. This validation incorporates four steps: check the connections in between different components, test whether the system can operate in flight-like conditions, test the system in real scenario conditions, and assess the robustness to variations in performance and faulty conditions. It can be noted that during the validation the focus is not on the requirements but on the actual functioning in practice. These four steps are discusses in the following four parts.

End-to-end information system testing
Up to this point in the design most of the subsystems where examined and tested as individual parts. To make sure the overall system can operate the connections in between the different subsystems should be checked. This includes checking the hardware connections (subsection 11.3.1), checking the actual hardware interrelations as shown in the hardware block diagram (subsection 11.3.2), checking the electrical connections according to subsection 11.3.3 and checking whether the software used (subsection 11.4.2) works as intended by the communication and data flow diagram (subsection 11.4.1). The result of this test is to show the compatibility of the project information system and hardware.

Mission scenario test
By performing the mission scenario test it can be shown that the hardware and software can execute mission when in flight-like conditions without a real timeline. This test can involve testing only a single item at a time. Some examples can be testing the hinging of the beam in windy conditions, folding the kite with crosswinds, etc. The lack of a timeline as stated before makes sure that all the individual steps can be performed sequentially but without going from one step directly to the next. One more example can be added: the team wants to be able to demonstrate the most crucial part about the airborne situation: launch and landing on top of the beam. To show that this concept is feasible a test setup is made. The test is to be performed in the period in between the handing in of the report and the Symposium . The description of the test can be seen in subsection 12.2.6.

Operations readiness test
Whereas the previous test was done without timeline this operations readiness test does have a timeline. This test should prove that all the elements work together to accomplish the mission plan. During this test all the events should follow each other as they should when the system is operating as intended. This test can be performed by making a prototype and operating it at suitable places such as Valkenburg.

Stress testing and simulation
The final step in validating the entire system is to asses how the system operates in abnormal situations. As the prototype has already been built for the operations readiness test it can also be used to demonstrate the operation of the system in abnormal situations.

During these tests the limits of the system should be explored. This includes the structural limits (by simulating high load on the horizontal beam or vertical boom), the aerodynamic limits (by operating at the boundary wind speed conditions), control limits (by simulating gusty winds with fans), etc. One special case should certainly be tested: when the kite is flying at wind speeds below the minimal speed required from the top-level requirements and the kite has to be landed. As explained in subsection 3.2.2 the kite has to perform a gliding approach and be reeled in until it is on the horizontal beam. If the system can be proven to remain reliable even in low wind condition this gives extra proof that the weather check is an acceptable decision.

Next to the limits of the system, the behavior of the system in case of a fault conditions should be checked. Tests should be performed to see which damage is still acceptable to operate the system in a safe manner. Situations in which the system cannot operate safe anymore should also be identified. If these cases are found they can be used to program the control and decision system such that it can warn when immediate assistance is required. This helps make the system safer to operate and its surroundings.

12.2.6 Test setup

To prove the concept of landing and launching on top of a tall boom the team is will execute a small-scale test. A $10m^2$ water kite will be used to perform the landing and launch maneuvers. Since this kite will be one seventh the size of the kite for the project, all other parts of the system should also be downsized. This means the boom should be $8m$ tall, the beam $1m$ long and a CU surrogate should be placed at $4m$ below the kite.

Resources

The vertical boom construction will be made of the trusses the Kite Power Group currently uses for their launch and landing system (suspended upside down). Instead of the entire structure, only two or three truss parts will be needed to reach the $8m$ height. The beam will consist of two wooden poles/beams with some space in between. This could also be made from a single piece of wood by milling it into a tall and narrow U-shape. At the ends some extra material will be mounted in a V-shape to simulate the gripper arms. The test kite will be a regular inflatable power kite with certain adaptations necessary to simulate the actual system layout. The first adaptation is a mock CU and safety line hanging from the kite. This will be done by adding a bag filled with sand to simulate the weight of the CU. Attached to this bag is a ring through which the power and steering lines pass. A fifth line simulating the safety line will also be added here. All this will be placed at a fixed distance of $4m$ from the leading edge of the kite.

Another adjustment is the representation of the drum at the bottom of the boom. To simulate this a metal ring will be attached to the foot of the boom where the lines will run through. This allows the person controlling the lines to stand at a distance behind the boom for safety.
The test setup can be visualized in Figure 12.1.

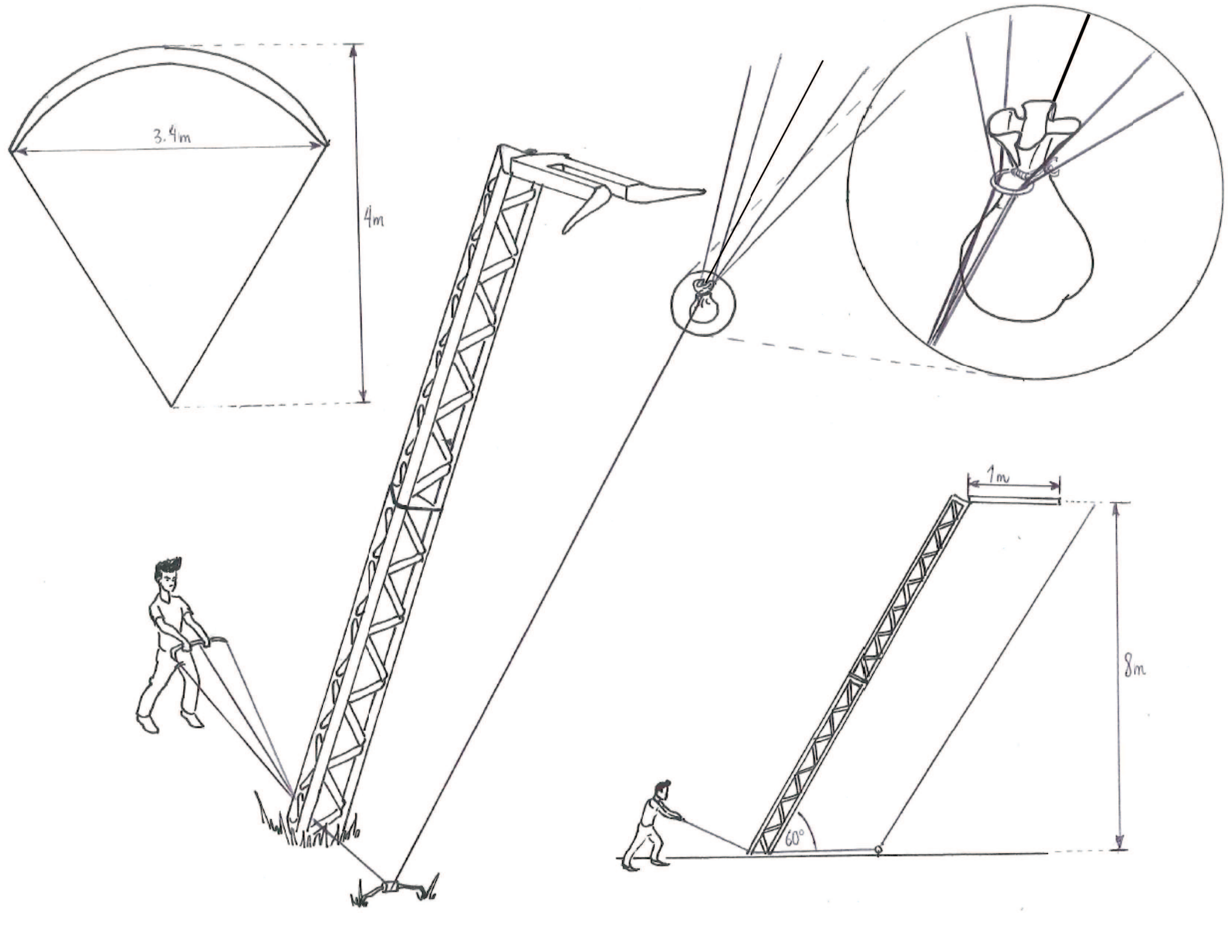


Figure 12.1: The test setup

Test plan

The test should take place at a location such that the wind is as constant as possible. Therefore it will be done at the beach of either Scheveningen or Hoek van Holland. The first part of the day will be spent building and setting up the structures involved in the test. The rest of the day can be spent on the test which consists of three main parts: The first is a general flight test to see if the kite can be controlled through the layout specified above. Depending on how long the setup takes, the flight test can take place simultaneously as only the ground ring and CU ring are required. When it is confirmed that the kite can be controlled or the system is tweaked such that it can, the second test will take place. This involves the full test setup including the boom, beam and gripper arms. The goal will be to aim the safety line between the gripper arms and thus proving that the landing subsystem is valid. The maneuver will be performed several times to ascertain there is no luck involved. After this the third and last test will be executed. To start off the kite will be put all the way over the beam in a depowered state. Depending on the outcome of test two this may or may not have to be done manually. The goal will be to take off with the kite in a controlled way.

If all three parts of the test have a positive outcome the proof of concept will be considered a success. The test will take place sometime between the deadline of this report and the Final Review date. The results will be presented in both the Final Review and the Symposium. It should be noted that the test may be postponed due to bad weather conditions. In this case the results will only be presented at the Symposium.

12.2.7 Flight certification

During the flight certification one main question should be answered: "Is the system ready to fly?" The product validation has already proven that the system works as intended. Even during abnormal situation the operational capabilities were determined. Now the system should go through final series of tests to show the capabilities of the system to both the authorities and to the client. The system should comply to the regulations stated in subsection 3.2.3. If the system demonstrates to operate within limits set by the authorities it can be certified to be distributed on the commercial market. The final system is also demonstrated to the client. As the client was involved in the design of the system it should not be possible the client to disagree with the design at this point. The purpose of this test for the client is to show the final design with all of its functionalities. It serves as a final point to the client which closes of the designing phase of the system. The next phase is starting up production and establishing a position on the market.

12.3 Project design and development logic

This section elaborates on the activities to be executed in post-DSE phases. In subsection 12.3.1 the suggestions for further research on the proposed automated launch, landing and storage system are given. An in-depth analysis on these topics is required to ensure proper operation of the system. Any recommendations related to the commercial implementation of the system and suggestions that are optional to the client are presented in 14. The second section of this chapter gives the post-DSE planning. This planning runs from the DSE symposium up until decommissioning of the system after 20 years of operation.

12.3.1 Prime focal points for further research and development

In this section all suggestions for further research and development are presented. The suggested activities could not be performed during the DSE due to resource limitations, but are required for successful implementation and operation of the system. Suggestion on the topics of structural analysis, aerodynamic and a proof of concept are given consecutively.

Structural analysis
During the detailed design phase initial load calculations have been performed on all critical, structural elements of the launch, landing and storage system. Shear and normal forces, moments and torques have been considered and an optimization program has been written to determine the optimal dimensions e.g. thickness.

Before effectuation of the system, the structural integrity must be completely ensured. Multiple structural aspects that should be explored in more depth, have been excluded in this stage due to their complexity and the project's limited resources. The following topics of structural analysis will therefore require further research and development:

- Impact damage - The structure has been designed in such a way that a collision of the kite or CU with the structure is prevented to large extent. However the risk of collision cannot be completely ruled out and the possible impact of a collision should be investigated.
- Vibrations - The wind conditions may cause dangerous vibrations of the structure and the system's resistance to vibrations and damping characteristics should be analyzed.

- Buckling - The structure has multiple elements of great length which can fail due to buckling. The system design should incorporate the prevention of buckling.
- Wear and fatigue - The structure has several hinges, slides, and other elements that are positioned in open air. The structure should be checked for its ability to withstand wear and fatigue.
- Joint analysis - Production will pose additional challenges to the structural integrity of the design as some parts will not be able to made in one piece. As an example, the vertical boom will be produced in sections and connection methods and their impact on the structural integrity have to be explored in depth.
- Material choice - As the design stands now, it consists of regular steel and aluminum alloys. It may be advantageous to investigate other alloys or even entirely different materials like composites to optimize the design.
- Foundation - The designed system will require a sound foundation that can cope with all forces and moments. The foundation requirements will have to be formulated and the actual design of the foundation will have to be made once the location of the fixed ground station of the kite power system is known.

Structural modeling methods such as FEM can be used to accurately model the loading conditions and their structural impact.

Aerodynamics
Throughout the design process of the automated launch, landing and storage system a certain level of development for the CU has been assumed since the actual flight control is out-of-scope for this project. The assumptions can serve as input for further research and development of the CU and can be found in subsection 4.1.3. Furthermore assumption A03, stating gust winds are neglected, requires additional research and might pose new requirements to the CU in case the effect of gust winds during the launch, landing and storage procedure cannot be neglected. It is also desirable to look into CFD to analyze the effect of the kite adaptations on the kite's performance.

Proof of concept
In the designed system the kite will be launched from and landed on a horizontal beam on top of a tall, vertical boom. A controlled launch and landing procedure is crucial for the successful implementation of this system and these elements should therefore be thoroughly validated and verified before taking the project to the next step. Section 12.2 discusses various verification and validation procedures, including proposal of a test setup in subsection 12.2.6.

12.3.2 Post-DSE planning

A detailed design of the automated launch, landing and storage system is the final result of the DSE. This detailed design gives information on a lot of details of the system, but a long road lies ahead of the Kite Power Group of the TU Delft in order to transform the detailed design into a fully operational and profitable system. Figure 12.2 presents the project flow diagram from research and development up to decommissioning of the system. The project flow gives a high-level overview of the activities that need to be performed in the upcoming years. An estimation of the time span is also given. The fact that kite power technology is still at an early stage of development and that the resources of the Kite Power Group are limited are taken into account. The automated launch, landing and storage system will bring many new challenges on topics such as kite control which will require substantial time and effort. A Gantt chart showing the post-DSE activities is given in Appendix H.

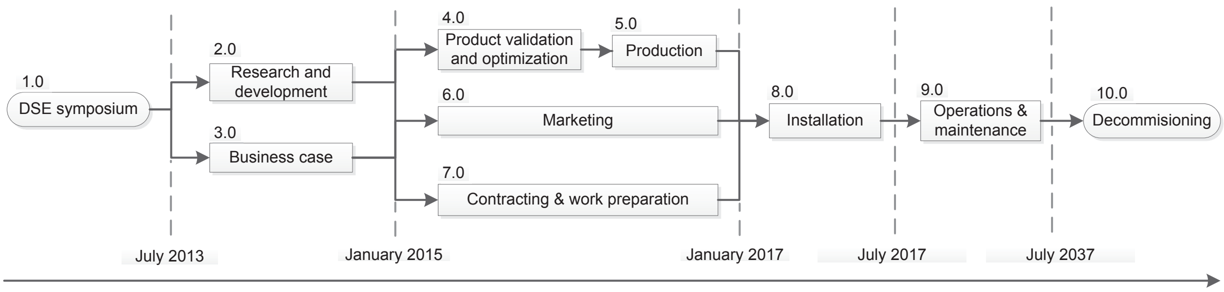


Figure 12.2: Post-DSE project planning up to the decommissioning of the system

In Table 12.1 descriptions of all activities in the post-DSE flowchart are given. For an elaboration on most of the activities the reader is referred to other chapters within the technical report. For some of the activities a substantial description or planning is outside the scope of this project and therefore these are only explained in the following table.

Table 12.1: Detailed description on elements of the post-DSE project planning

Nr	Item	Description	Section
1.0	DSE symposium	The symposium will be the end of the DSE project. At this point the information will be handed to the Kite Power Group for further development.	12.4.3
2.0	Research and development	During DSE the concept has been developed to the level of a detailed design, but limitations on resources will require additional R&D activities prior to actual implementation. Suggestions and recommendations for future development have been listed in this technical report.	12.3.1 + 14
3.0	Business case	The financial analysis of this report has shown that tough challenges exist in the area of finance and profitability of the kite power system as a whole. As a first step towards commercial implementation of the system a sound business case should be made. Also investors and subsidies will need to be consulted during this phase in order to finance the product.	12.4
4.0	Product validation and optimization	At the end of the research and development phase the Kite Power Group will have an automated launch, landing and storage system in which every detail is worked out. This next phase focusses on validation of the performed research and further optimization of the design based on testing and prototyping results.	12.2
5.0	Production	The production phase comprises the making of a production plan, manufacture of all elements and factory assembly.	11.3
6.0	Marketing	During the product realization phases (4.0 and 5.0) attention should also be given to marketing of the product and finding early adaptors. A thorough marketing plan will have to be written prior to exposure such that the right message is communicated.	3.2.1
7.0	Contracting and work preparation	Contracting and work preparation will have to be executed simultaneously with product realization and marketing. This for example comprises the request of building permits, signing construction companies and production of a detailed installation plan. The details on this phase are out-of-scope for the DSE project.	-
8.0	Installation	During the installation of the system, the location is prepared, foundations are built and the final assembly is performed on site. A description of the installation procedure is highly dependent on the final location and is therefore not included in this technical report. The installation phase will have to end with a flight certification test to ensure safe operation.	12.2.7
9.0	Operations and maintenance	The longest phase of all is the actual operation of the system which is estimated to be 20 years. During this phase the system will require regular maintenance. The maintenance approach and system addition to enhance the maintainability are included in this technical report.	12.4 + 11.6 + 11.6.4
10.0	Decommissioning	At its end of life, the system will have to be decommissioned. Sustainability in the form of recycling plays an important role in this phase. The materials of the system are chosen to be recyclable as much as possible.	11.2.2

12.4 Financial analysis

In order to attract investors the system needs to be able make a profit, especially if it must survive in a highly competitive market. Due to the fact that the landing, launch and storage system does not bring about a profit by itself, the entire pumping kite power system will be considered for this financial analysis. Precise cost estimates are difficult to obtain because the system under consideration is still in an early development stage. For this reason research papers of the kite power group of the TU Delft will be taken as a basis for estimations and assumptions.

In subsection 12.4.1 the levelized production cost of the system is estimated in order to obtain a minimum selling price to reach a break-even point within its lifetime, which is assumed to be 20 years (similar to that of the wind turbines). In subsection 12.4.2 the return on investment is estimated and an overview is given of the cost build-up during the lifetime of the system. Finally in subsection 12.4.3 the influence of improving the system and taking into account advancements in production methods and used materials are considered. With thus future application of the system is reviewed.

12.4.1 Levelized production cost

In order to determine whether this system is competitive with other systems, the levelized production cost (LPC) will be determined. This is the cost of the energy produced by the system per kWh required to break even over the lifetime of the system. For the determination of LPC of the designed system, a lifetime of 20 years is taken and the real interest rate of the Netherlands in 2011 is found to be 1% [51]. The formula for the LPC is given in Equation 12.1 [52].

$$LPC = \frac{\sum_{t=1}^{T}(C_t - R_t)(1+r_i)^{-t}}{\sum_{t=1}^{T} E_t(1+r_i)^{-t}} \tag{12.1}$$

In this equation:

- C_t is the cost in year t in €.
- R_t is the revenue in year t excluding the energy sales e.g. subsidy in €.
- E_t is the energy produced in year t in kWh.
- r_i is the real interest rate.
- T is the lifetime of the system.

Since the energy produced can be given as energy produced per year the denominator in Equation 12.1 can be written as described in Equation 12.2, where E_y is the average energy yield during a year.

$$\sum_{t=1}^{T} E_t(1+r_i)^{-t} = E_y \sum_{t=1}^{T}(1+r_i)^{-t} = aE_y \tag{12.2}$$

Where:

$$a = \sum_{t=1}^{T}(1+r_i)^{-t} = \frac{1}{r_i}[1-(\frac{1}{1+r_i})^T] \tag{12.3}$$

The additional revenue is assumed to be zero as this system needs to run without subsidies and does not create substantial value except the selling of electrical energy. For the cost, the same method as the energy can be used. The cost can be given per year and is calculated with Equation 12.4.

$$C_y = \frac{(C_{sys} + C_{other})(1+r_i)}{T} + C_{rep_{tet}} + C_{rep_{kite}} + C_{M\&O} \tag{12.4}$$

Where:

$$C_{rep_{tet}} = N_{tet} \cdot (C_{tether} + C_{tet_{repl}}) \tag{12.5}$$

$$C_{rep_{kite}} = N_{kite} \cdot (C_{kite} + C_{kite_{repl}}) \tag{12.6}$$

$$C_{other} = C_{GS} + C_{CU} \tag{12.7}$$

In this equation the $C_{rep_{tet}}$ is the cost due to replacing the main tether and $C_{rep_{kite}}$ is the cost of replacing the kite, C_{sys} is the cost of the designed system and C_{other} are the other costs of the system which are not included in the system such as the ground station and the CU. N_{kite} and N_{tether} are the number of times the kite and tether need to be replaced each year. Estimates for the costs are obtained from the Master orientation project of Franca (2012) [53] and then scaled for this system. The original system is assumed to have a $16.7m^2$ kite, a $350m$ tether and a $15kW$ ground system. Everything is linearly scaled with respect to the scaling parameter. An overview of this scaling can be found in Table 12.2

The expert within the Kite Power Group of the TU Delft estimates that the costs of producing a kite will be €3,000 and it should be replaced every three months, thus $N_{kite} = 4$. The tether length is calculated using a minimal tether angle $\beta = 20°$, a maximum operating height of $500m$ and an additional tether length which stays on the drum of $100m$. Thus, the tether length will be $1,600m$ and assuming a price of €3.00 per meter this will yield a total tether cost of €4,800. The price for the tether is estimated by halving the current retail price of €6.79 [44], assuming that buying it directly from the suppliers will reduce the price significantly. According to the expert the tether lifetime is a little longer than 3 months; however for maintenance purposes the lifetime is considered to be equal to that of the kite so $N_{tether} = 4$.

Finally the landing, launch and storage system also needs maintenance. Maintenance cost is estimated in the same way as it is done for large wind turbines, by estimating the yearly maintenance cost to be 3% of the total investment cost, which is the sum of C_{sys} and S_{GS}. This results in $C_{M\&O} = €2,926$.

Table 12.2: Scaling of the cost estimates

Symbol	Description	$16.7m^2$ system	Scaling parameter	$70m^2$ system
$C_{tet_{repl}}$	Cost of replacing the tether	500	l_{tether}	€2,900
$C_{kite_{repl}}$	Cost of replacing the kite	1,000	S_A	€4,200
C_{GS}	Cost of the ground station	33,579	P_{rated}	€84,750
C_{CU}	Cost of the CU	8,350	S_A	€35,000
C_{sys}	Cost of landing, launch and storage system	-	-	€53,451
C_{kite}	Cost of the kite	-	-	€3,000
C_{tether}	Cost of the tether	-	-	€4,800
$C_{M\&O}$	Yearly maintenance costs	-	-	€5,196

Using the same principle as Equation 12.2 the numerator of Equation 12.1 can be rewritten as aC_y. Taking also into account that the landing, launch and storage systems uses energy which can not be sold will result in Equation 12.8, where $E_{sys} = 96kWh$ is the energy used by the landing, launch and storage system during one year as can be found in section 11.1. Other systems are also a source of additional losses and are estimated to be $1,000W$ which result in $E_{loss} = 8,760kWh$ a year.

$$LPC = \frac{C_y}{E_y - E_{sys} - E_{loss}} \tag{12.8}$$

Using all the previous values obtained, this will result in a LPC of 0.285€/kWh.

12.4.2 Return on investment and cost overview

As the current energy prices in the market waver around 0.06€/kWh and with the information on the expected LPC of the kite power system, it is not able to compete within the current energy market. Without the help of subsidies or other revenues the system will not make any profit within its assumed lifetime. The foresight is that the system creates a loss of €46,737 every year when selling at the competitive price of 0.06€/kWh and not taking into account depreciation.

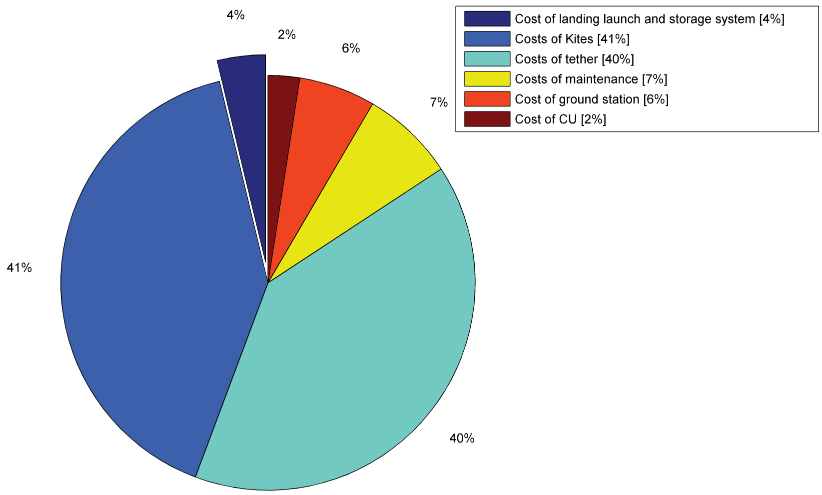


Figure 12.3: Overview of the total cost distribution over the economic life of the system

12.4.3 Feasibility of kite systems in the future

One of the major drawbacks at this moment is the limited lifetime of both the kite and the Dyneema tether. The recurrent replacement procedure that takes place four times each year makes it impossible for the system to make a profit in its current state, because the maintenance costs are already higher than the revenue from selling the energy.

When examining the power curve in Figure 2.12 found in subsection 2.2.2 it becomes apparent that the pumping kite system is not taking advantage of all the wind power available because of the limits of the generator. When increasing the size of the generator to $P_{rated} = 150kW$ the power curve will change. The new power curve is given in Figure 12.4. From the graph it becomes apparent that the largest gain is obtained in higher wind speeds. In order to stay within the higher wind speeds the kite has to be flown at a higher altitude, thus taking advantage of the wind shear. Using the wind data again as discussed in subsection 3.2.2 and assuming an average operating altitude of $500m$ the average power produced by the system will be $P_{av} = 70.85kWh$. This is a large increase in power production without the need of a different kite or landing, launch and storage system.

Repeating the calculations of the previous section again and accounting for the larger generator and longer tether length will result in $LPC = 0.131$ €$/kWh$. This result is in line with the overall thoughts about pumping kite systems, and HAWP concepts alike, that increasing the altitude makes it possible to harness more energy with a relatively small increase in costs. However, there is one important side note to make in this context: the influence of the tether weight is neglected in the above calculations and will in reality have a profound effect on the energy produced if the tether length is increased significantly. In that situation it is not realistic to assume an even higher operation altitude using this analysis, even if it would reduce the LPC even further.

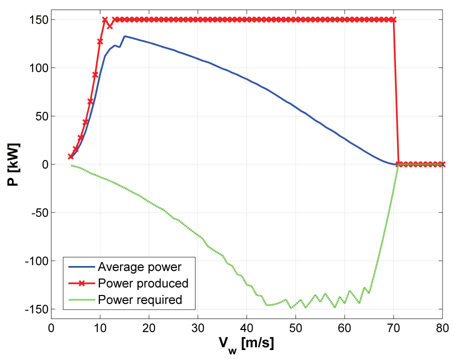


Figure 12.4: Power curve of a $150kW$ system using the same kite and tether

In order to make the total system economically viable many improvements are needed. Assuming a kite life of half a year, a tether life of one years will result in $LPC = 0.0623€/kWh$ for the $150kW$ case.

The above example proves that there is potential in the pumping kite system, especially when considering the relatively low height the system is currently operated in. However much research and development is still needed. Research and development is a very costly business and the need for investors is unavoidable. Although the weight of the tether is not yet taken into account, increasing the operating height of the kite has some promising prospects. Next to this, the system is very environmentally friendly and innovative. Therefore it is certainly part of a solution for a environmentally friendlier future. This is an advantage which can persuade investors and can take the development to the next stage.

13. Conclusions

The various results that were produced in the previous chapters lead the way for several conclusions to be drawn. In this chapter the conclusions on the report and the final design are given which will ultimately determine whether the project objective statement is reached. In order to ascertain the fulfillment of said goal the conclusions chapter is divided into three parts: conclusions on the performance of the design, conclusions on the sustainability of the design, and conclusions on the resources.

Performance

The performance of the automated launch, landing and storage system is considered to be a success. It was shown that the the design can autonomously operate a pumping kite system within the boundaries of the requirements. One of these boundaries involves time; after three months there is a need for human interaction to replace the kite and tether. The replacement and maintenance procedure is taken into account in the design by including doors, ladders and safety line attachment points. The other boundary sets a limit on the wind conditions.

The system can land the kite in a wind speed range of 4 to $25m/s$ and launching can be performed between 5 and $25m/s$. However, this performance fully relies on the capabilities of the control unit. This device is currently in development by the Kite Power Group of TU Delft and is therefore not part of this project but it is vital for its success. The storage functionality is also designed successfully as the kite can be safely and securely stored. By means of folding poles this mechanism ensures there is no entanglement of the bridle system and therefore not compromising the integrity of the kite.

All the aforementioned tasks take place well within the operation time limit set by the client. One full cycle (landing, storage, deployment, and launch) only takes about 17 minutes while the requirement stated a maximum of 226 minutes.

Sustainability

For the system designed in this report conclusions can be made on the different aspects out of the project objective statement. First, conclusions on the sustainable aspect of the subsystem are given. The conclusions on sustainability contain the energy consumption, and the use of materials. This section will elaborate on these parts, starting with the energy consumption, followed by the conclusions on the used materials.

The automated launch, landing and storage system was required to use a maximum of 0.1% of the total energy produced by the system for its own operation energy needs. This requirement was met as the energy consumption is 0.036% of the average energy produced by the kite power system. The vertical boom is the largest energy consumer and uses about 36% of the total energy consumption. This is mainly due to the tilting of the boom and the hoisting process of the kite carrying beam. The second largest energy consumer is the tether folding system in the storage of the kite. This system uses about 33% of the total energy consumption. Furthermore, all actuators used are electrically powered which ensures a relatively high energy efficiency of about 90%. Other solutions were explored but without resulting in a more sustainable solution. The total energy consumed per cycle is calculated to be about $4,000kJ$ which can be compared to having one $50W$ lamp on for a day. Therefore the launch, landing and storage system meats the set goals on sustainability with respect to energy consumption.

Various materials are used in the design of this launch, landing and storage system, however the main material used is steel. Steel has a relatively high weight which increases the energy consumption as the steel structures are to be moved. Furthermore, the production process of steel is highly environmentally unfriendly. As steel is recyclable for 93% without losing its structural properties, it is considered to be a sustainable material for this design. Furthermore, the costs of steel parts are relatively low and therefore suitable for the subsystems of the this launch, landing and storage system. Other materials used are plastic for the cone at the tip of the beam and aluminum for the beam itself. Aluminum is recylable, although the plastic cone is not.

Financial

The cost requirement is not met by the current design. The budget required for building the system – including materials, production, assembly and overhead costs – is estimated to be €53,451. This is 167%

over the budget of €20,000.

As the design stands now it is not commercially viable. To reach a break even after 20 years (the estimated lifetime of the system) the price for $1kWh$ would have to be €0.285 which is unreasonable compared to the common market price of €0.06. However, it should be noted that the main cost driver of the system over 20 years is not the initial investment. The highest cost contribution comes from the replacement of the kite and the tether every three months.

14. Recommendations

The research that has been performed on the automation of the launch, landing, and storage procedure of the kite power system during DSE has resulted in a detailed design. Limitations on time and resources unfortunately do not allow any further research and development by this project group on the topic of automated kite power systems. Nevertheless the thoughts on innovation, improvements and optimization though have been gathered in this chapter. Most of these recommendations follow directly from the conclusions and are handed over to the Kite Power Group of the TU Delft together with the results of the entire design process. Hopefully these suggestions can be of help in future research and development activities.

In section 14.1 all recommendations related to cost, profitability and funding are given. The second section gives suggestions in the area of sustainability. The last section gives the details of a recommendation based on contact with SkySails during this project.

14.1 Cost reduction, profitability and funding

This section discusses all recommendations related to cost reduction, profitability and funding in seven different topics.

14.1.1 Cost estimation

The costs of the materials/parts, production and assembly of the system have at this point been estimated to a total of €53,451. Extensive research and requests for quotes make this number as accurate as possible, yet a moderate level of uncertainty is still present. In section 4.6 cost estimation relationships for assembly have been described. Unfortunately these could not be applied due to time limitations and an overall percentage was assumed. It is recommended to apply these relationships in the possible follow-up of this project to obtain an more accurate estimate of the costs.

14.1.2 Evaluate the necessity of the storage

The storage of the $70m^2$ kite requires quite many mechanisms and that coupled with its size the need for a large storage arises. Both arguments drive up the cost and it is recommended to review the need for a closed storage or futher look into an innovative way of safely storing the kite. Possibly the kite and tether material can be made more durable (see next paragraph) or it could be a cheaper solution to make use partial storage/clamping. This recommendation might be combined with the previously recommended durability review of the kite and tether.

14.1.3 Kite and tether durability

In section 12.4 it is shown that the profit of the current system is very low because the kite and tether need to be replaced every three months. A possible solution to this problem is either to use more weather-resistant materials or to coat the existing fabric with a UV-proof substance.

14.1.4 Upscaling the kite power system

The operating cost of the pumping kite system is proven to be very high. Decreasing the operating cost can be achieved by decreasing the cost of the kite and tether. Another way to increase the profit margin is to increase the revenue, achievable by increasing the power produced by the system

From the power curve in subsection 2.2.2 it becomes apparent that the generator reaches its rated power output of $50kW$ in low wind speeds and is therefore not able to take full advantage of the stronger winds. Increasing the rated power of the generator will account for a large increase in the power produced of the system without the need for any large changes to the landing, launch and storage subsystem. Combining a larger generator with flying the kite at a higher altitude will make a significant change in the levelized production cost (LPC). According to simplified calculations the LPC can be reduced to half the cost by increasing the rated power to $150kW$ and increasing the kites average stroke height from $500m$ to $700m$. However, these simplified calculations only take into account the tether drag and not the effect of the additional tether weight. This can have a significant influence on the produced power if the flying altitude is increased significally. Therefore it is highly recommended to investigate the influence of the tether weight on the power production of the system when the kite is flown at a higher altitude.

The financial analysis clearly shows the costs of the kites and tethers have a determining influence on the profit margins. At this moment the kites are produced in low numbers and are therefore expensive.

Improvements and upscaling of the production process could result in a substantial cost reduction. Another source for cost reduction is the cost of the tether. Currently the retail tether price is very high compared to the cost of the crude Dyneema material. Therefore increasing the production process efficiency of the twining of the tether could be a significant source of cost reduction. It is therefore recommended to investigate any possible improvements to any or both production processes in order to make the pumping kite system commercially feasible.

14.1.5 Offshore implementation and evaluation of the wind speed range

The proposed detailed design is based on an onshore implementation. The wind speed range for launch of this design is $5m/s$ up to $25m/s$. The lower limit of this range however requires a tilt of the tall vertical boom which drives up the cost. It is recommended to review the possibility of an offshore implementation where wind speeds are higher. The elimination of the need for a tilt of the vertical boom will certainly decrease the cost and higher wind speeds can increase the availability of the system. The downside is that the construction of an offshore foundation for the system will be a driver of costs. Thus, it might an interesting exploration topic but one should critically look at the advantages versus disadvantages.

14.1.6 Acquisition of subsidies

The need for renewable energy sources is increasing as Earth's non-renewable energy resources such as oil and gas become scarce. Due to this global need, stimulation of sustainable energy solutions is a hot topic on governmental agendas. As the innovative kite power technology at this point is quite far from competitive energy market prices with at least €0,29 per kWh (based on a break even point after 20 years of operation), it is recommended to start the discussion with authorities as soon as possible. The acquisition of subsidies for research and development, as well as the offering of subsidies to future buyers of this type of energy (comparable to the solar energy stimulation) can shorten the time-to-market and improve acceptance of the community.

14.1.7 Business partners and sponsorships

The onshore implementation of kite power technology has an interesting exposure value for companies if the kite's can be printed with company names and/or logos. As such firms can link themselves with sustainability, generate renewable energy to support their company activities and at the same time advertise their company name. It is recommended to look into the possibility of acquiring a group of reputable business partners that will fund the reserearch and development and will set an example for other companies as early adaptors at the time the product is introduced on the market.

14.2 Sustainability improvement and symbolization

The sustainability of the system could be further improved by using more recycled and/or recyclable materials. Furthermore additional effort can be put in the production of a decommissioning plan.

A second recommendation related to sustainability is exploring the possibility of making the kite power system the true symbol of sustainable energy. As an example, besides the current kite power generation, a wind turbine could be mounted on top of the tall vertical boom and solar panels might cover the roof of storage. Integrating multiple renewable energy solutions into one future-proof design might increase the public interest for the kite power initiative and help during the acquisition of funding.

14.3 Contact with SkySails

The automated launch, landing, and storage system that has been designed has a few similarities with the system that SkySails is using. They are already commercially active on the kite power market and can be a valuable source of information. SkySails has been contacted to challenge some of the project's ideas and has responded enthusiastically about the research project. It is recommended to keep SkySails involved in the research in case the proposed detailed design is developer further by the Kite Power Group of the TU Delft. The contact details are already known by the Kite Power Group.

> *"Please understand that we cannot disclose our cost expectations for the launch and retrieval system at this point. But we can gladly stay in touch and give you technical feedback as your work proceeds, as far as our IP disclosure policies allow. - i. A. Falko Fritz, Projektingenieur, SkySails GmbH*

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A. Functional flow diagrams

In this appendix, the functional flow diagrams showing all low-level functional steps are shown in the order order of landing, storage, deployment and launch.

A.1 Low-level functional flow diagram of the landing procedure

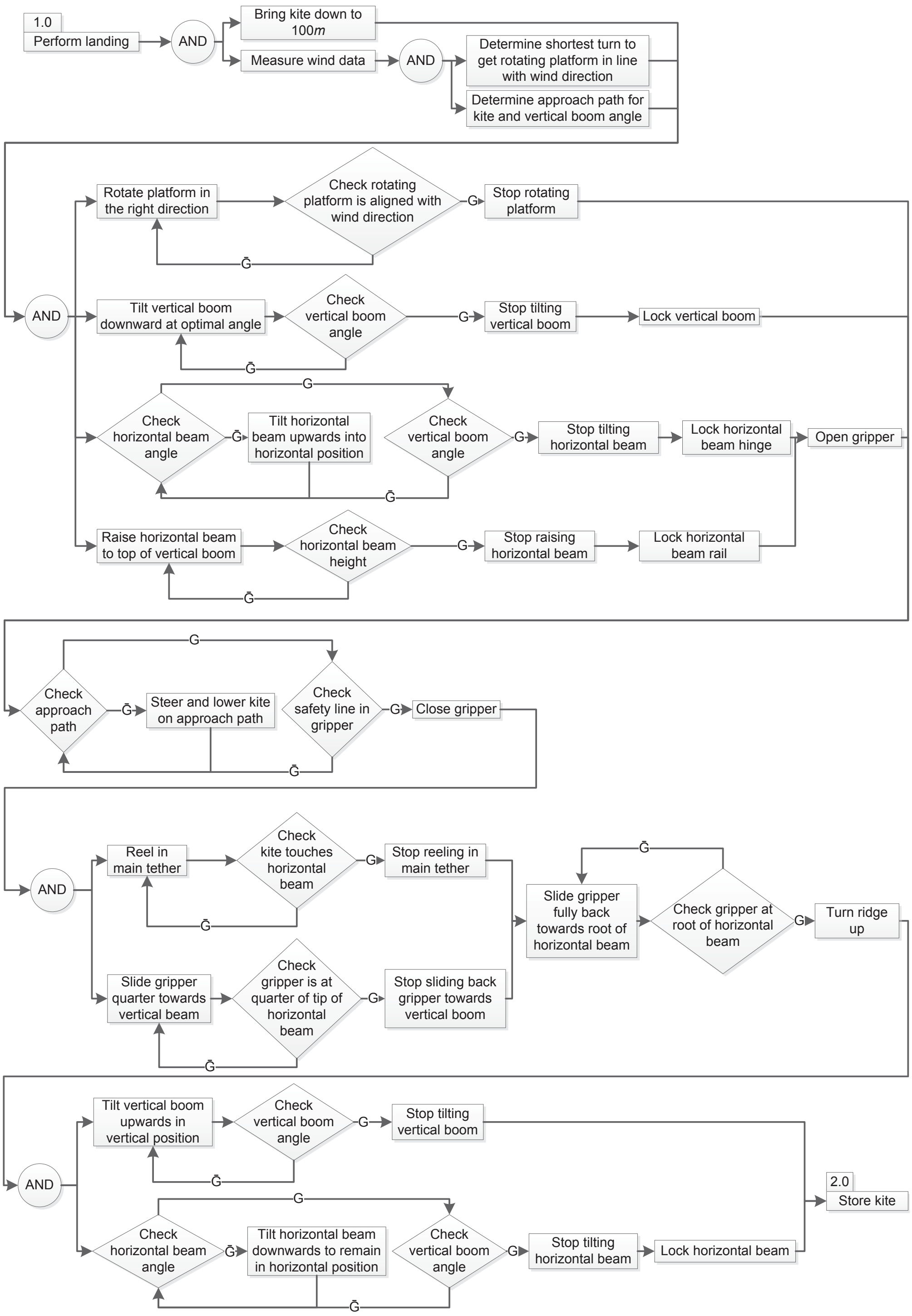

Figure A.1: Low-level functional flow diagram of the landing procedure

A.2 Low-level functional block diagram of the storage procedure

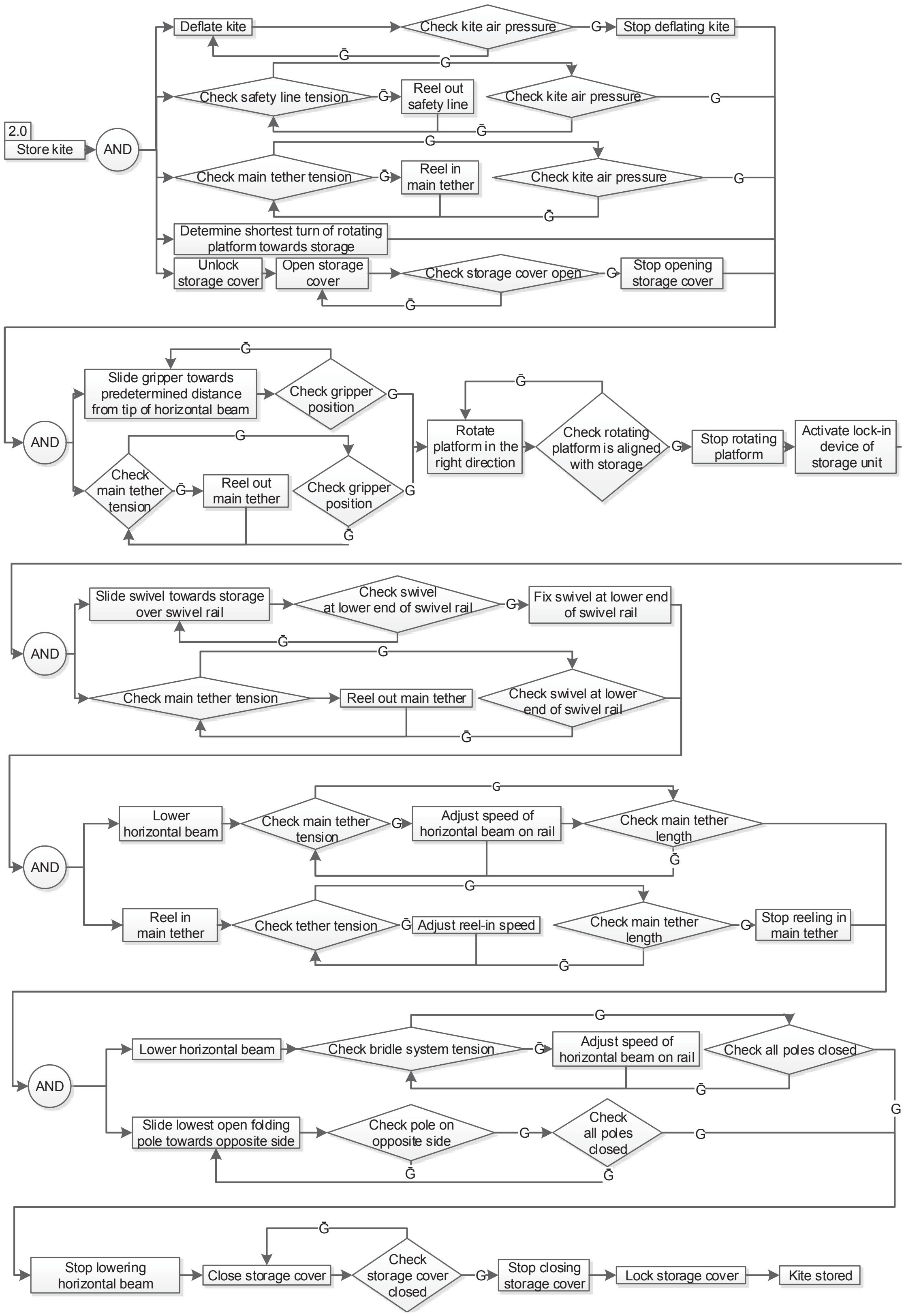

Figure A.2: Low-level functional flow diagram of the storage procedure

A.3 Low-level functional flow diagram of the deployment procedure

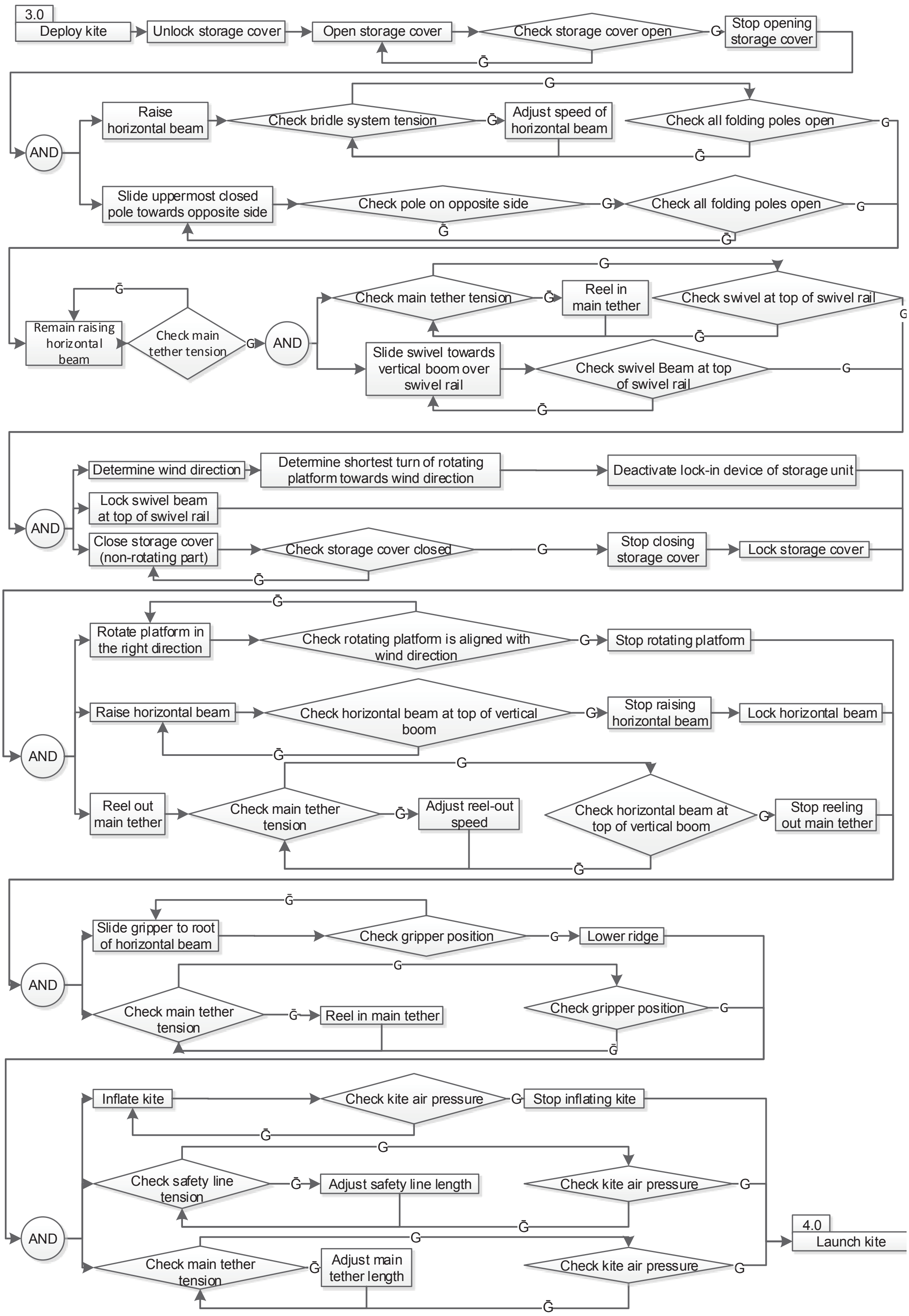

Figure A.3: Low-level functional flow diagram of the deployment procedure

A.4 Low-level functional flow diagram of the launch procedure

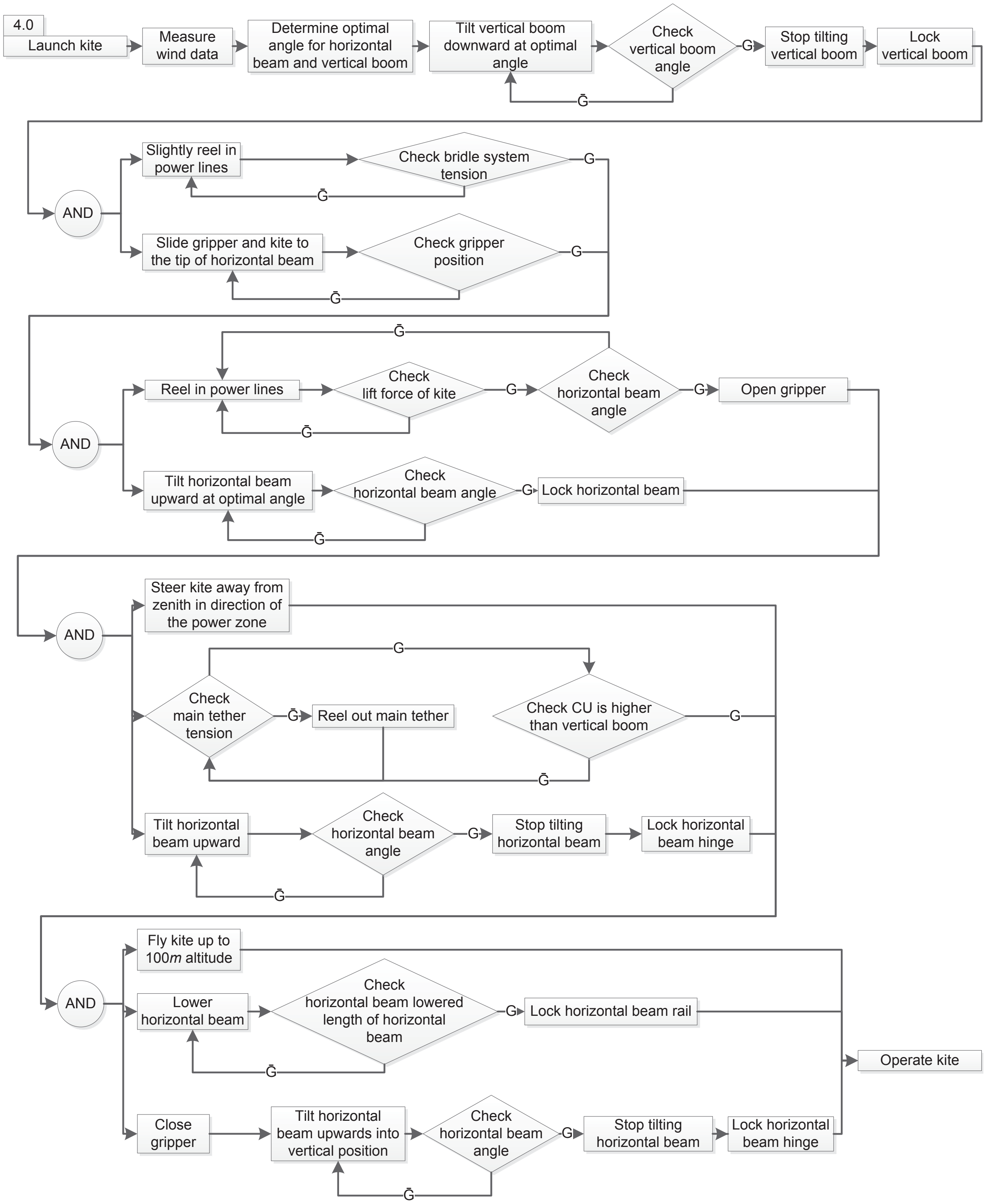

Figure A.4: Low-level functional flow diagram of the launch procedure

A.5 Functional breakdown structure of the complete system

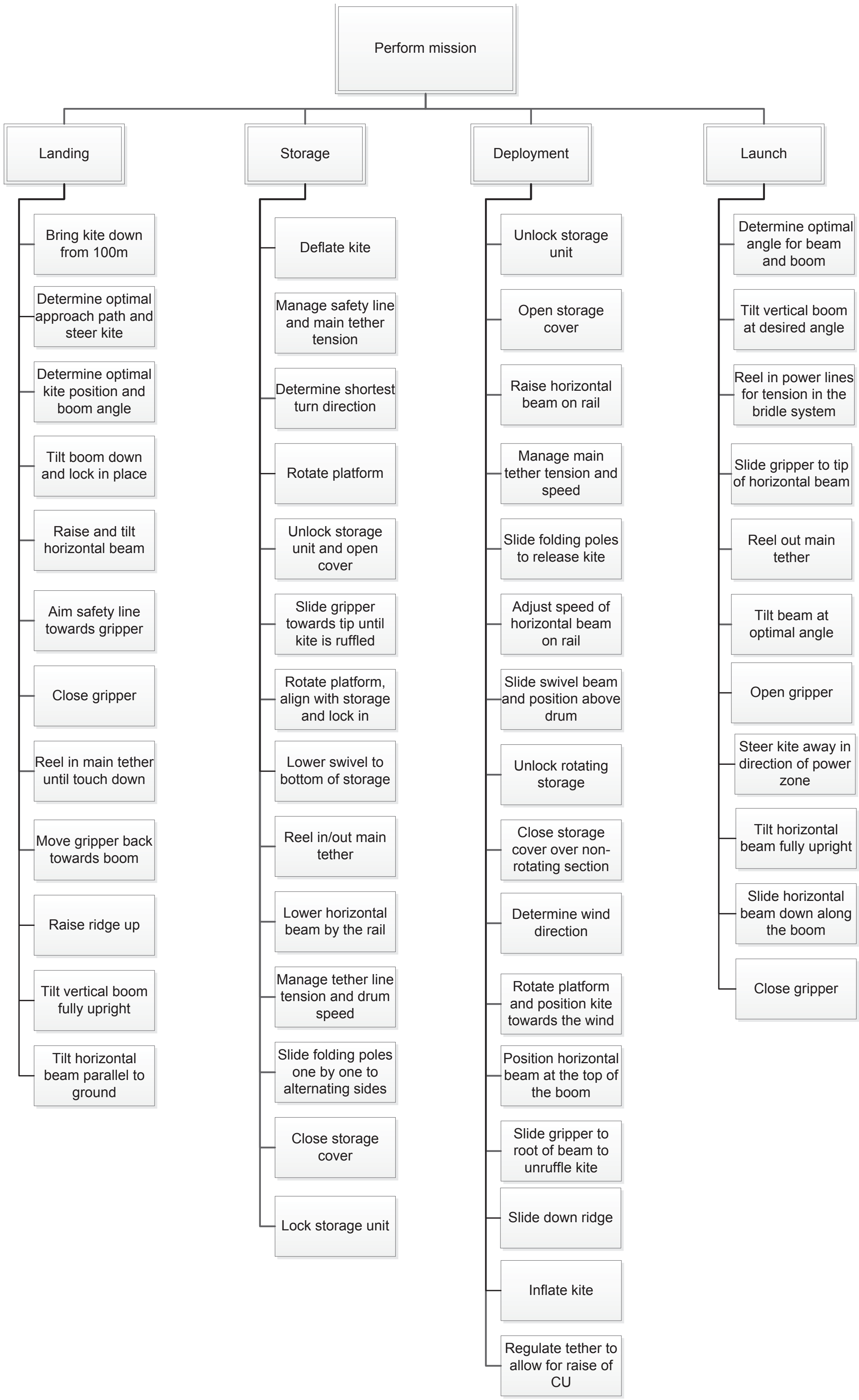

Figure A.5: Functional breakdown structure of the complete system

B. Compliance matrix

B.1 Compliance matrix for the top-level requirements

Table B.1: Compliance matrix for the top-level requirements (1/2)

Code	Requirement	KR	DR	Compliant	Comment	Paragraph
ALLS	The system shall automatically launch, land and store a $70m^2$ inflatable membrane wing if necessary.		X	No	The system does not comply with all elements of the lower-level requirements.	
ALLS-SUS	The system shall be designed in a sustainable way.			No	A sustainable strategy has been followed throughout the design process, but the system does not comply with lower-level requirement ALLS-SUS-1.0	3.3
ALLS-SUS-1.0	The materials used for the production of the system shall be made of recycled or recyclable material.			No	Not all elements (especially critical elements for the mission) are recycled/recyclable.	11.2
ALLS-SUS-2.0	All energy that is used for any subsystem shall be renewable energy.			Yes	The system can fully rely on its own production of renewable kite energy. The PRU relies on the CU for its energy; which is assumed to be self-powered by means of renewable energy.	11.1 + 5.2 + assumption CU01
ALLS-TECH	The system shall satisfy the technical requirements.			No	System does not comply with ALLS-TECH-LNC-1.0 and ALLS-TECH-LND-2.0	
ALLS-TECH-LNC-1.0	The system shall automatically launch the kite if necessary.		X	No	System does not comply with ALLS-TECH-LNC-1.2.	
ALLS-TECH-LND-2.0	The system shall automatically land the kite if necessary.		X	No	System does not comply with ALLS-TECH-LND-2.2.	
ALLS-TECH-STO-3.0	The system shall be able to automatically store/deploy the kite if necessary.		X	Yes	System complies with all lower level requirements.	
ALLS-TECH-RPT-4.0	The kite and the tether shall be replaceable.		X	Yes	A kite replacement procedure has been worked out.	11.6.3
ALLS-TECH-OT-5.0	The kite shall be able to operate automatically for a period of 3 months.		X	Yes	The system is fully automated and only needs human intervention for kite replacement during kite replacement (except for the case of fatal errors during operation)	11.6
ALLS-TECH-DLLS-6.0	The duration of the launch, landing and storage procedure shall not exceed 5% of the total operating time reached in three months.		X	Yes	The automated launch, landing and storage procedures take up only 0.37% of the total operation time (excluding time in storage) in three months.	11.1
ALLS-TECH-EC-7.0	The energy consumption of the subsystems shall not exceed more than 1% of the total energy gained over the operating time of three months.		X	Yes	The automated launch, landing and storage system consumes only 0.036% of the total energy gained in three months.	11.1

Table B.2: Compliance matrix for the top-level requirements (2/2)

Code	Requirement	KR	DR	Fulfill	Comment	Paragraph
ALLS-CON	The system shall remain within the constraints.			No	System does not comply with requirement ALLS-CON-COST.	
ALLS-CON-REG	The system shall remain within regulations.	X		Yes	The two regulations that have been found are not endangered by the system, it is assumed the system is positioned far enough away from residential areas to prevent shadows. Furthermore compliance of the flight of the kite with the regulations is out-of-scope for this project.	3.2.3 + assumption M12
ALLS-CON-TIME	The system shall be developed within the design period of 10 weeks.		X	Yes	The project has reached the state of a detailed design within a period of 10 weeks. Recommendations for further development have been listed.	12.3
ALLS-CON-COST	The production costs of the system shall remain within €20,000.		X	No	The final costs of production and assembly including overhead come to a total of €53,451.	11.5
ALLS-CON-MNT	The system shall be maintainable.			Yes	The system has been designed with maintenance aspects in mind and additional walking space, stairs, etc. have been included, which ensure the system is maintainable.	11.6 + 11.7.3
ALLS-CON-SFT	The system shall be safe for the community, environment and any involved employees.	X	X	Yes	The safety has been evaluated in RAMS and is considered to fulfill the safety requirements to a sufficient extent.	11.7.4

B.2 Low-level requirements and compliance matrix for the launch procedure

Table B.3: Low-level requirements and compliance matrix for the launch procedure

Code	Requirement	KR	DR	Compliant	Comment	Paragraph
ALLS-TECH-LNC-1.0	The system shall automatically launch the kite if the wind speed is higher than $4m/s$ and below $25m/s$.		X	No	System does not comply with ALLS-TECH-LNC-1.2.	
ALLS-TECH-LNC-1.1	The kite shall be launched in a safe manner.	X	X	Yes	The lower level requirements all comply; safety has also been evaluated in RAMS.	11.7.4
ALLS-TECH-LNC-1.1.1	The orientation of the kite shall be controlled with three degrees of freedom for orientation and three degrees of freedom for position during launch.	X		Yes	This requirement is out-of-scope for this project, but the assumptions will be given back to Kite Power Group as an input for further CU development.	12.3
ALLS-TECH-LNC-1.1.2	The CU may not hit the ground or structure during the launch.			Yes	The vertical boom provides enough clearance from ground and the horizontal beam will tilt upward during launch to avoid interference with the CU.	7.1.1 + 6.1.2
ALLS-TECH-LNC-1.1.3	The structure of the system shall be able to withstand the normal and shear forces, torques and moments that are exerted on it during launch.	X		Yes	Structural dimensions are sufficient to withstand the maximum loading case.	6.2 + 7.2 + 8.2
ALLS-TECH-LNC-1.1.4	The tether tension during launch (F_t) shall not exceed $40kN$.	X	X	Yes	The tether tension is modelled and does not exceed $40kN$.	2.2.2 + Figure 2.9b
ALLS-TECH-LNC-1.1.5	The structure shall not entangle the tether/bridle system or damage the kite during the launch process.	X		Yes	Horizontal beam elements are made blunt to avoid puncture of the kite. The gripper helps to guide the kite and avoid entanglement.	6.1.1 + 6.1.3
ALLS-TECH-LNC-1.2	The kite shall be able to launch within its constraints.		X	No	Both of the lower level requirements do not comply.	
ALLS-TECH-LNC-1.2.1	The kite shall be able to launch within the wind speed range of $4m/s$ to $25m/s$).		X	No	Tilting angle of vertical boom and horizontal beam and the rotating platform can realize a launch from $5m/s$; the structural dimensions accommodate the upper limit.	2.2.2 + 6.1.2 + 7.1.2 + 8.1.1 + 6.2 + 7.2 + 8.2
ALLS-TECH-LNC-1.2.2	The kite power system shall automatically make the decision to launch the kite if the wind speed is within the wind speed range ($4m/s$ to $25m/s$).		X	No	Required wind speed for launch was raised to $5m/s$, but the weather-based decision-making has been automized.	2.2.2

B.3 Low-level requirements and compliance matrix for the landing procedure

Table B.4: Low-level requirements and compliance matrix for the landing procedure

Code	Requirement	KR	DR	Compliant	Comment	Paragraph
ALLS-TECH-LND-2.0	The system shall automatically land the kite when necessary.		X	No	System does not comply with ALLS-TECH-LND-2.2.	
ALLS-TECH-LND-2.1	The kite shall land in a safe manner.	X	X	Yes	Lower level requirements all comply; safety has also been evaluated in RAMS.	11.7.4
ALLS-TECH-LND-2.1.1	The orientation of the kite shall be controlled with three degrees of freedom for orientation and three degrees of freedom for position during landing.	X		Yes	This requirement is out-of-scope for this project, but the assumptions will be given back to Kite Power Group as an input for further CU development.	12.3
ALLS-TECH-LND-2.1.2	The CU may not hit the ground or system during landing.			Yes	The vertical boom provides enough clearance from ground.	7.1.1
ALLS-TECH-LND-2.1.3	The structure of the system shall be able to withstand the normal and shear forces, torques and moments that are exerted on it during landing.	X		Yes	Structural dimensions are sufficient to withstand the maximum possible, applied forces and moments.	6.2 + 7.2 + 8.2
ALLS-TECH-LND-2.1.4	The tether tension during landing (F_t) shall not exceed $40kN$.	X	X	Yes	The tether tension is modelled and does not exceed $40kN$.	2.2.2 + Figure 2.9b
ALLS-TECH-LND-2.1.5	The kite shall land one hour before lightning is predicted.				The kite will be landed an hour before lightning occurs.	3.2.2
ALLS-TECH-LND-2.1.6	The structure shall not entangle the tether/bridle system or damage the kite during the landing process.	X		Yes	Horizontal beam elements are made blunt to avoid puncture of the kite; the gripper helps guiding the kite and avoid entanglement.	6.1.1 + 6.1.3
ALLS-TECH-LND-2.2	The kite shall land within its constraints.		X	No	System does not fully comply with requirement ALLS-TECH-LND-2.2.2.	
ALLS-TECH-LND-2.2.1	The kite shall be able to land within the wind speed range ($4m/s$ to $25m/s$).		X	Yes	Tilting angle of vertical boom and horizontal beam and the rotating platform accomodate landing at the lower limit, this limit is even shifted towards $3m/s$ for landing. Structural dimensions accommodate the upper limit.	2.2.2 + 6.1.2 + 7.1.2 + 8.1.1 + 6.2 + 7.2 + 8.2
ALLS-TECH-LND-2.2.2	The kite power system shall automatically make the decision to land the kite if the wind speed gets outside of the wind speed range ($4m/s$ to $25m/s$).		X	No	Weather-based decision-making has been automized, but the kite is not always landed within the given range. A weather optimalisation program has been produced to maximize up-time by reducing the lower limit.	3.2.2

B.4 Compliance matrix for the low-level requirements of the storage and deployment procedure

Table B.5: Compliance matrix for the low-level requirements of the storage and deployment procedure

Code	Requirement	KR	DR	Compliant	Comment	Paragraph
ALLS-TECH-STO-3.0	The system shall be able to automatically store/deploy the kite if necessary.		X	Yes	System complies with all lower level requirements.	
ALLS-TECH-STO-3.1	The kite and CU shall not be damaged and tether and bridle system shall not get tangled during storage/deployment.	X		Yes	System complies with all lower level requirements.	
ALLS-TECH-STO-3.1.1	The tensile force on the kite shall not exceed $8.6kN/m$ during storage/deployment.	X		Yes	The maximum tensile force does not increase $2.0kN/m$.	section 5.5
ALLS-TECH-STO-3.1.2	The tether tension shall not exceed $40kN$ during storage/deployment.	X	X	Yes	The tether tension is modelled and does not exceed $40kN$.	2.2.2 + Figure 2.9b
ALLS-TECH-STO-3.1.3	The structure shall not entangle the tether/bridle system or damage the kite during storage/deployment of the kite.	X		Yes	The storage unit contains a system with folding poles that prevent entanglement.	10.1.3
ALLS-TECH-STO-3.1.4	The structure of the system shall be able to withstand the normal and shear forces, torques and moments that are exerted on it during storage/deployment.	X		Yes	Structural dimensions are sufficient to withstand the maximum possible, applied forces and moments.	9.2 + 10.2
ALLS-TECH-STO-3.2	The kite and CU shall be protected when stored.			Yes	System complies with both lower level requirements.	
ALLS-TECH-STO-3.2.1	The kite and CU shall be protected against the weather conditions when stored.			Yes	Storage unit has walls on all sides and a storage cover.	10.1.2 + 10.1.1
ALLS-TECH-STO-3.2.2	The kite and CU shall be protected against theft and vandalism when stored.			Yes	An alarm system is installed into the storage.	10.3
ALLS-TECH-STO-3.3	The kite and CU shall be stored in a storage unit.	X	X	Yes	A storage unit has been designed and system complies with all lower level requirements.	10.1
ALLS-TECH-STO-3.3.1	The rail of the storage and the rotating platform shall align when the storage process inaugurates.	X		Yes	A lock-in device has been designed to ensure the rotating and non-rotating part of the storage are well aligned.	10.1.4
ALLS-TECH-STO-3.3.2	In order to put the kite and CU in the storage unit, the storage unit should be able to open and close.	X		Yes	The storage cover is movable.	10.1.2

C. Kite replacement procedure

In this appendix, the steps that a ground crew would have to perform during the kite replacement procedure are illustrated by means of a flow diagram.

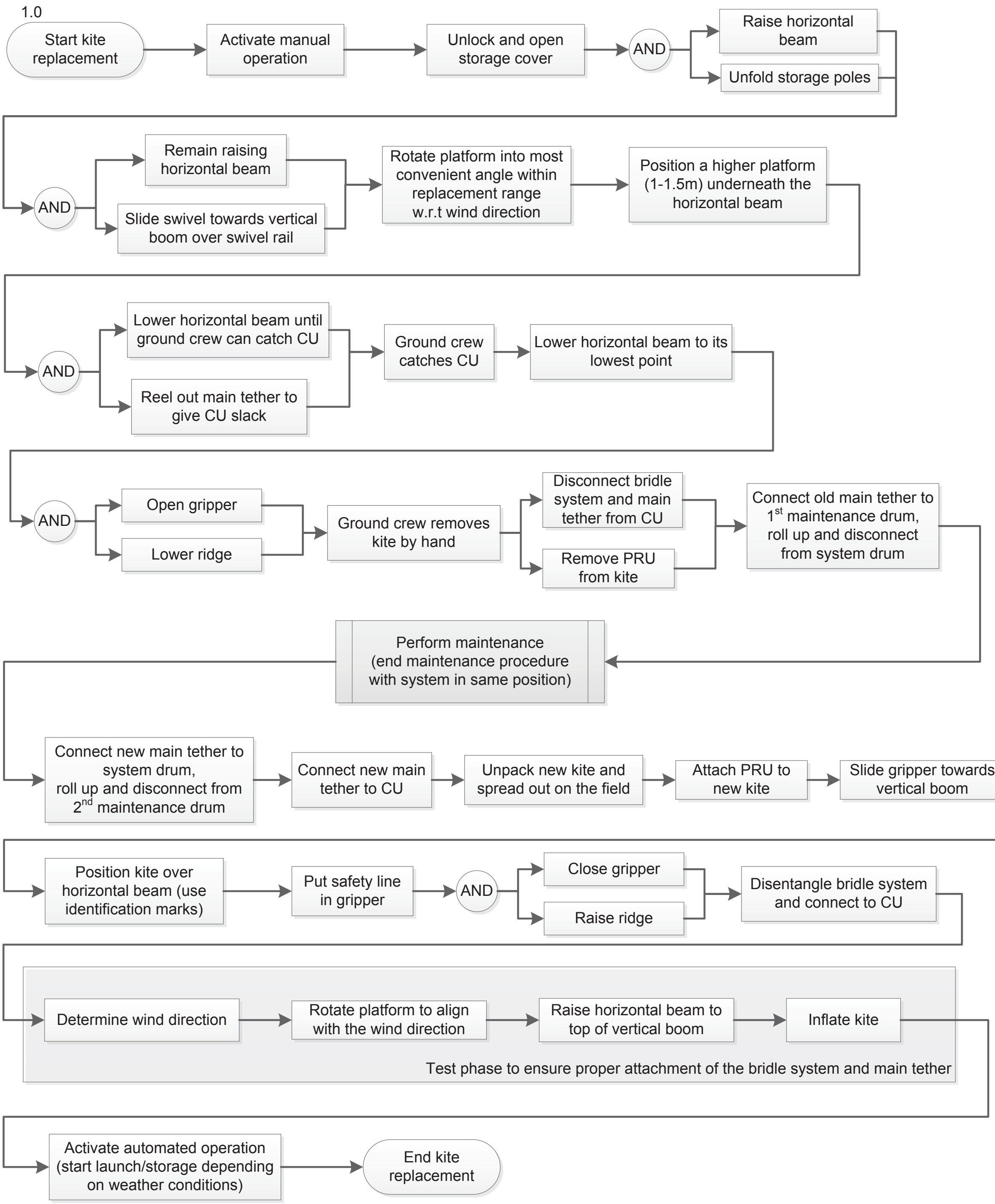

Figure C.1: Kite replacement procedure

D. Hardware diagram

In this appendix, the hardware block diagram shows the interaction between the different mechanisms of the subsystems. The diagram is shown in Figure D.1 and the explanation of the interactions is shown in Table D.1. In Table D.1 also the phase where the interaction occurs is noted.

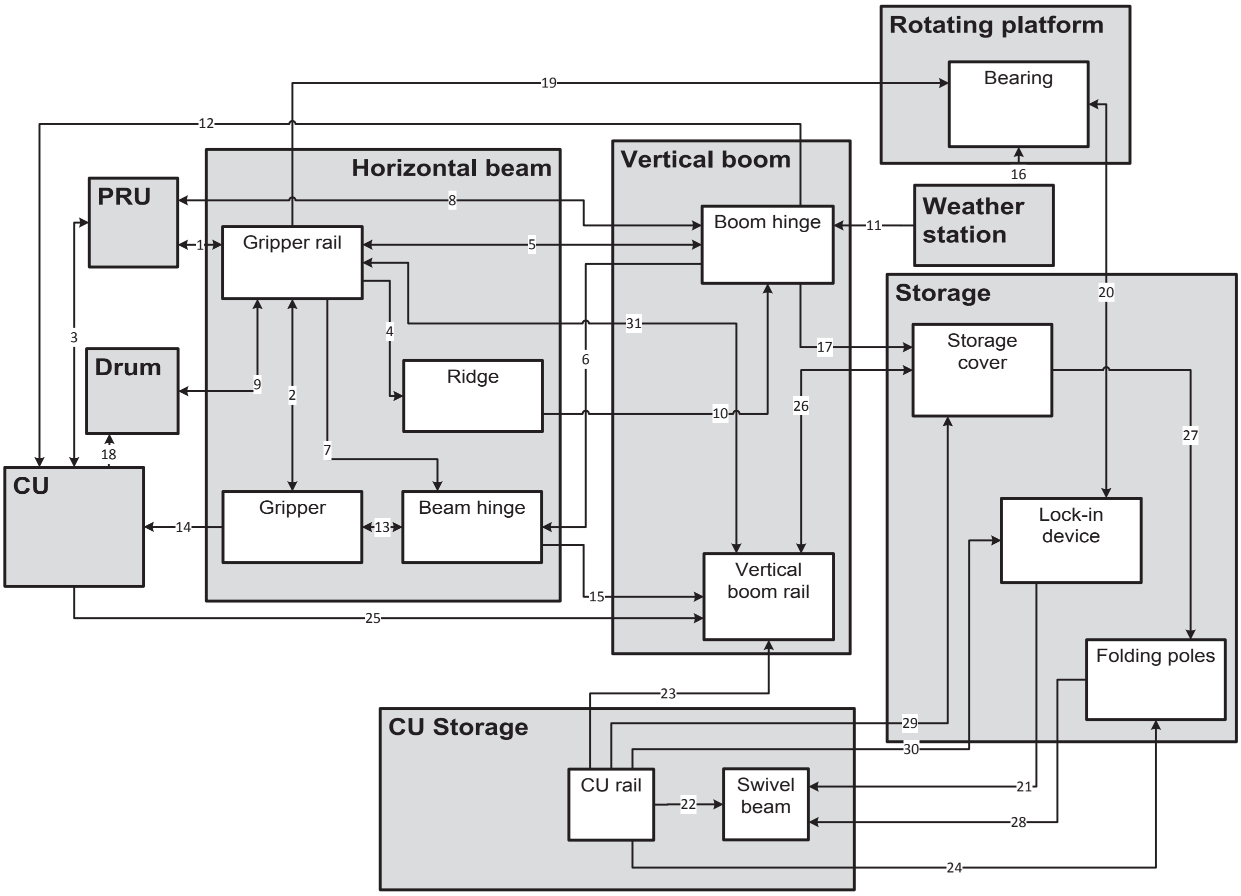

Figure D.1: Hardware block diagram

Table D.1: A description of the interaction between the mechanisms

#	Stage	Description
1	Deploy	When the gripper is at the root of the gripper rail the PRU can inflate the kite.
	Store	When the kite is deflated the gripper rail can start the ruffling.
2	Launch	When the gripper is at the tip of the gripper rail the gripper unlocks.
	Land	When the kite is caught by the gripper and the gripper is locked, the gripper needs to travel towards the root of the horizontal beam.
3	Deploy/ store	The PRU receives all it's power and commands from the CU. The CU transmits all the data from the PRU to the CPU. During the inflation and deflation, the CU should check for both main tether tension and safety line tension.
4	Land	When the gripper is at the root of the gripper rail, the ridge moves up.
	Launch	When the gripper is at the root of the gripper rail, the ridge moves down.
5	Land	When the gripper is at the root of the gripper rail the boom is hinged vertically.
	Launch	When the boom is hinged to the right angle the gripper is moved towards to the tip of the rail.
6	Land/ Launch	When the vertical boom is hinged, the horizontal beam will be kept horizontal.
7	Launch	When the gripper is at the tip of the horizontal beam, the horizontal beam is hinged upwards.
8	Store	When the vertical boom is hinged vertically, the PRU can start to deflate the kite.
	Launch	When the kite is inflated, the vertical boom can start to tilt.
9	Land	When the gripper is at a quarter of the length of the horizontal beam from the tip, the main tether is reeled in by the drum. When the kite touches the horizontal beam, the gripper continues to move towards the root of the gripper rail.
10	Launch	When the ridge is moved down, the vertical boom tilts to vertical.
11	Land/ Launch	Weather and wind speed determines the tilt angle.
12	Launch	When the tilt is finished, the CU powers the kite.
13	Launch	When the beam hinge is fully deflected the gripper is opened.
	After launch	When the beam is hinged parallel to the vertical boom, the gripper is closed.
14	Land	When the gripper is unlocked, the final approach can be made.
	Launch	When the gripper is unlocked, the kite can be flown away.
15	After launch	When the beam is hinged up, the vertical boom rail is moved down to store the horizontal beam during operations.
16	Launch/ Land	The weather station gives wind direction information from which the turn direction is obtained.
17	Store	When the boom is vertical, the storage cover is opened.
18	Store/ deploy	The CU measures the tension and the drum reels in/out to keep this tension within limits.
19	Store	When the gripper is at the ruffle position, the platform is rotated to align with the storage.
20	Store	When the turning platform is aligned, the lock-in device will lock the platform in place.
	Deploy	As soon as the lock-in device unlocks the platform, the platform is rotated.
21	Store	When the platform is locked into place the lowering of the swivel beam is started.
22	Store/ Deploy	When the swivel beam is at the end of the swivel rail, the swivel beam stops and the location of the swivel beam is recalibrated.
23	Store	When the swivel beam is at the end of the of the swivel rail, the lowering of the horizontal beam is started.
24	Store	When the swivel beam is at the end of the of the swivel rail, the folding poles start to fold the bridle system.
25	Store	After the folding is started the CU communicates the tension in the tether to the vertical boom rail to adjust the speed of the horizontal beam to keep the tension constant.
26	Store	When the horizontal beam is at the lowest point of the vertical rail, the storage is closed.
	Deploy	When the storage is open, the horizontal beam can be raised along the vertical rail.
27	Deploy	When the storage cover is opened, the unfolding starts.
28	Deploy	When the unfolding of the kite and bridle system is done, the swivel beam is moved up the swivel rail.
29	Deploy	When the swivel beam is at the highest point of the swivel rail, the cover of the non rotating platform is closed.
30	Deploy	When the swivel beam is at the highest point of the swivel rail, the lock in device is unlocked.
31	Deploy	When the horizontal beam is at the top, the gripper is brought to the root of the gripper rail to unruffle the kite.

E. Electrical block diagram

This appendix shows the elecrical block diagram which gives information on the power required for each subsystem, power conversion and distribution and signal interaction.

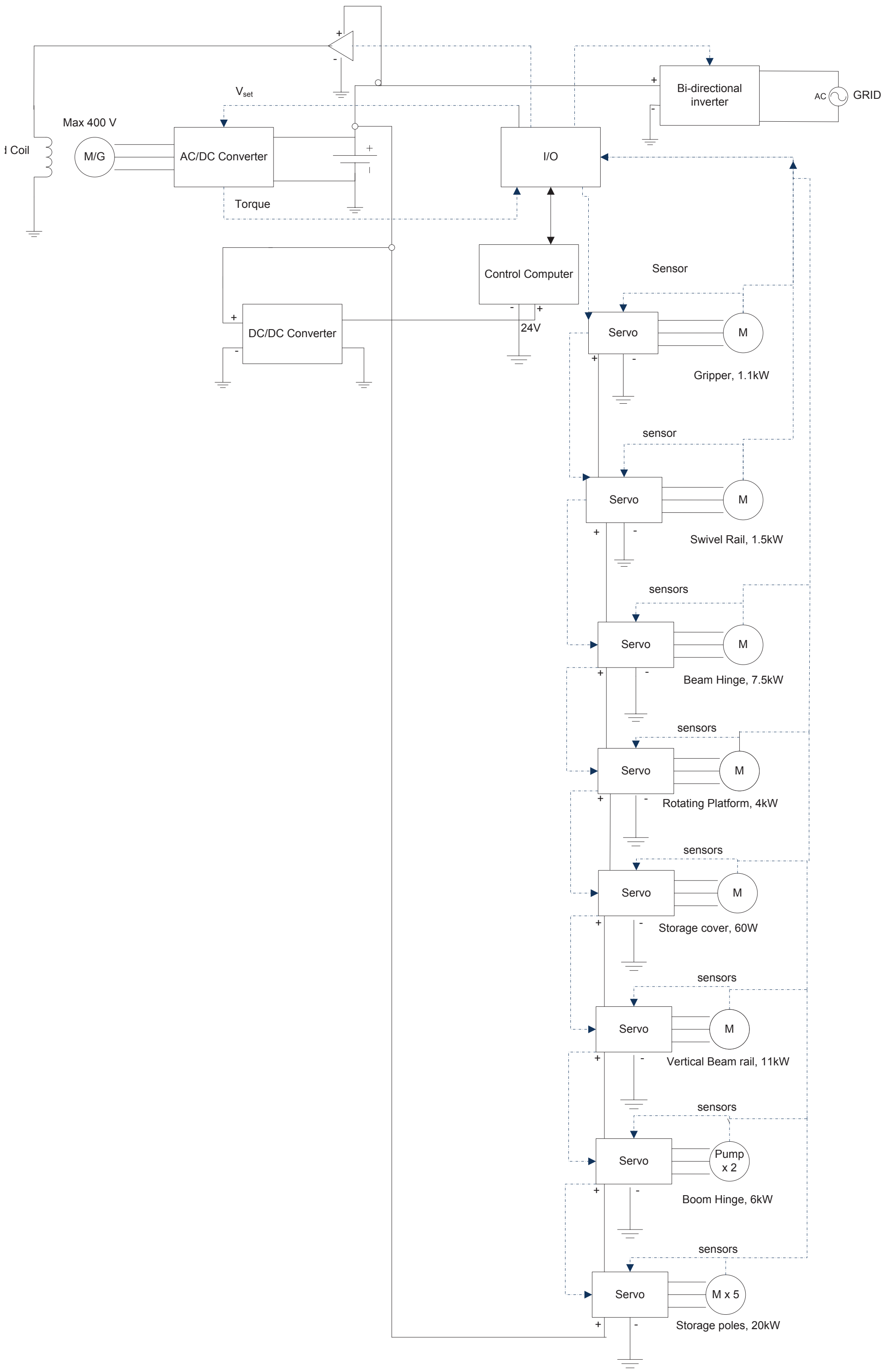

Figure E.1: Electrical block diagram

F. Communication flow and data handling diagram

In this appendix, the communication flow and data handling diagram shows the way data is handled and what the data contains is shown. The sensors which are accompanied by a star are used to calibrate the systems. Most distances are calculated by integrating the angular speed of motors. This method induces large truncation errors when performed over longer times. Therefore the contact switches are used to calibrate the distances again.

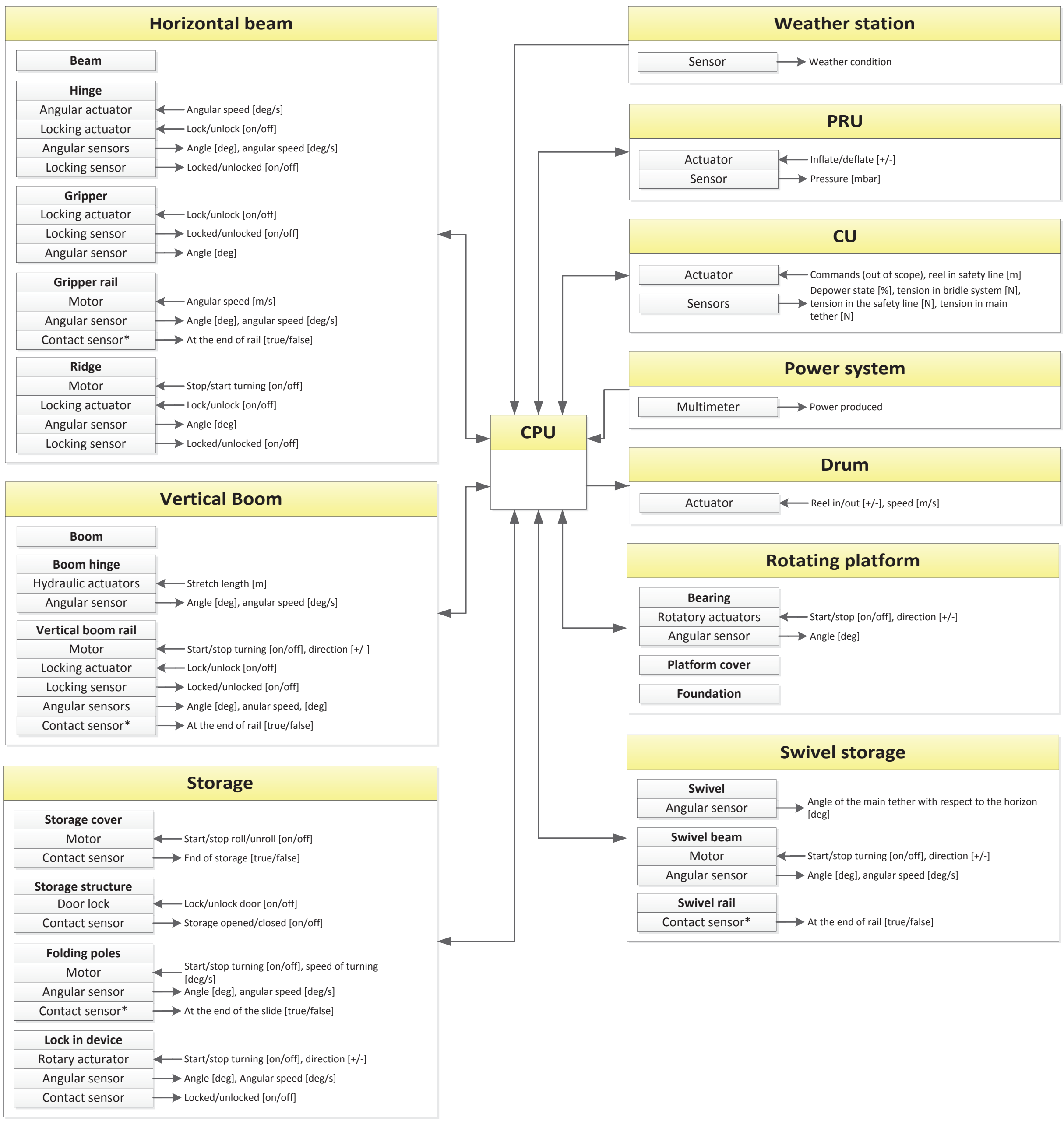

Figure F.1: Communication flow and data handling diagram

G. Software diagram

This appendix shows the software diagram which gives information on the way software should be implemented. The diagram is a 'class diagram' which show the classes to be implemented in for example Java or C++. The diagram is rather large and therefore the left side is visible in Figure G.1 and the right side is visible in Figure G.2. The main 'ALLS' class is shown in both figures for clarity.

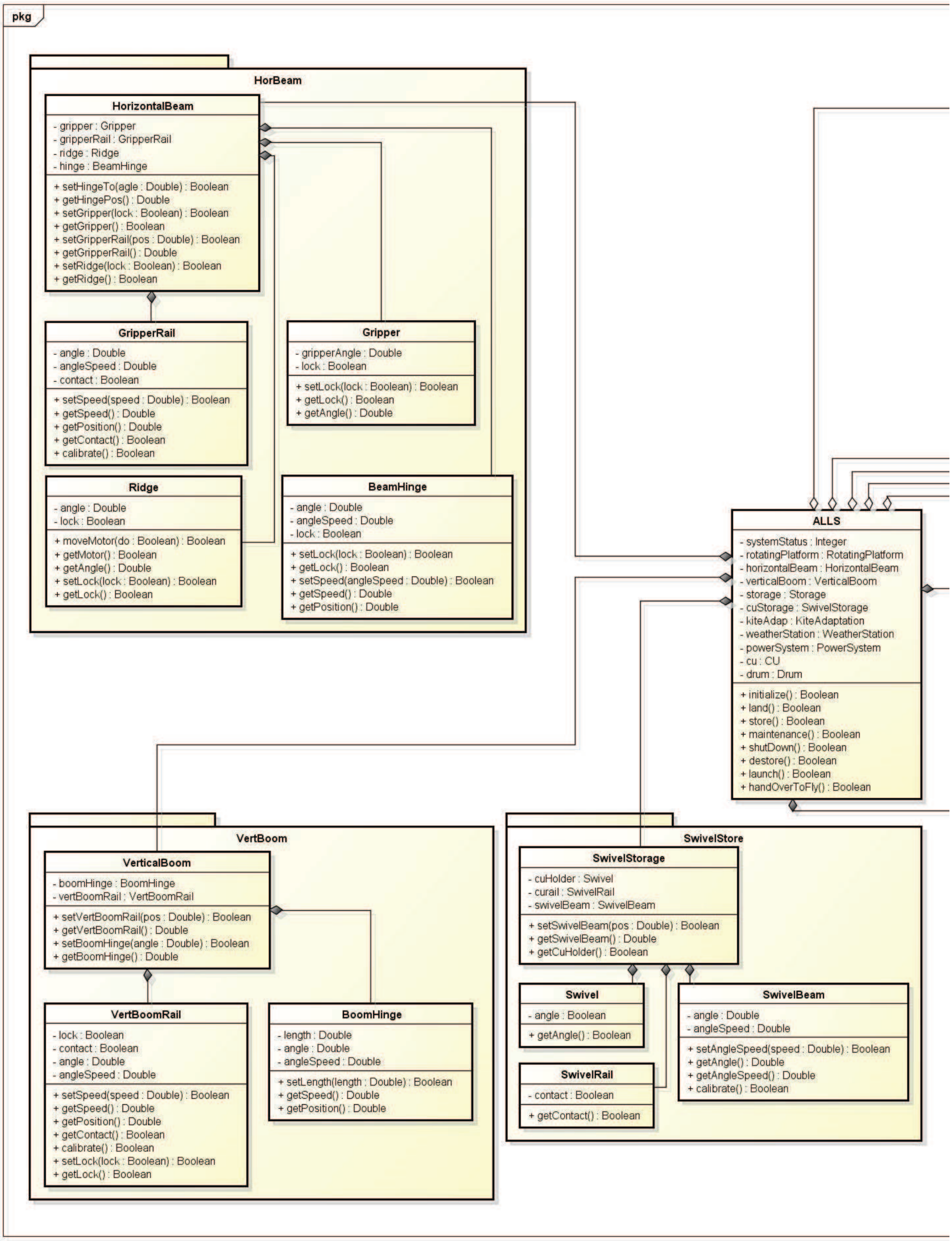

Figure G.1: Software (class) diagram (left part)

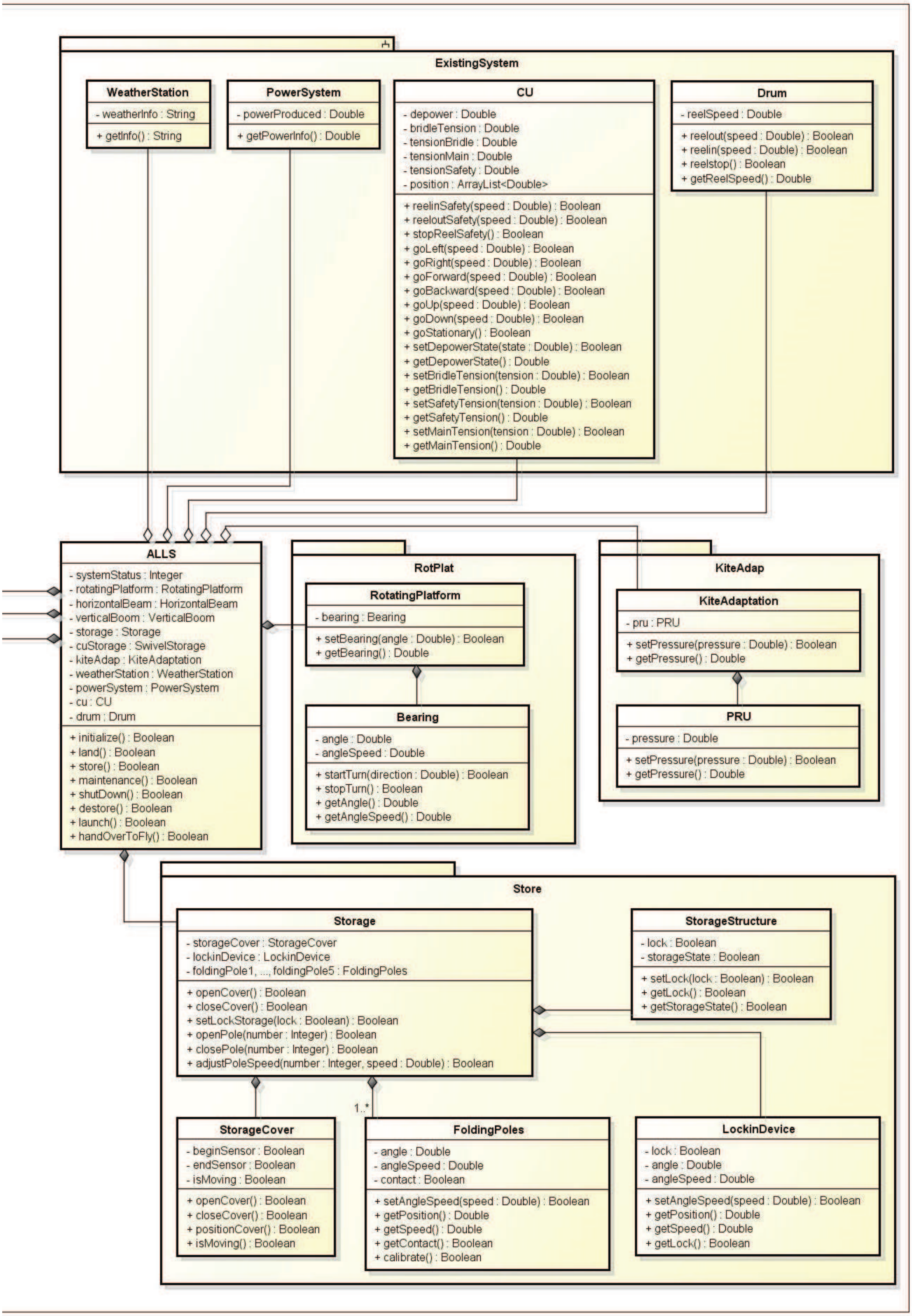

Figure G.2: Software (class) diagram (right part)

H. Post-DSE project planning

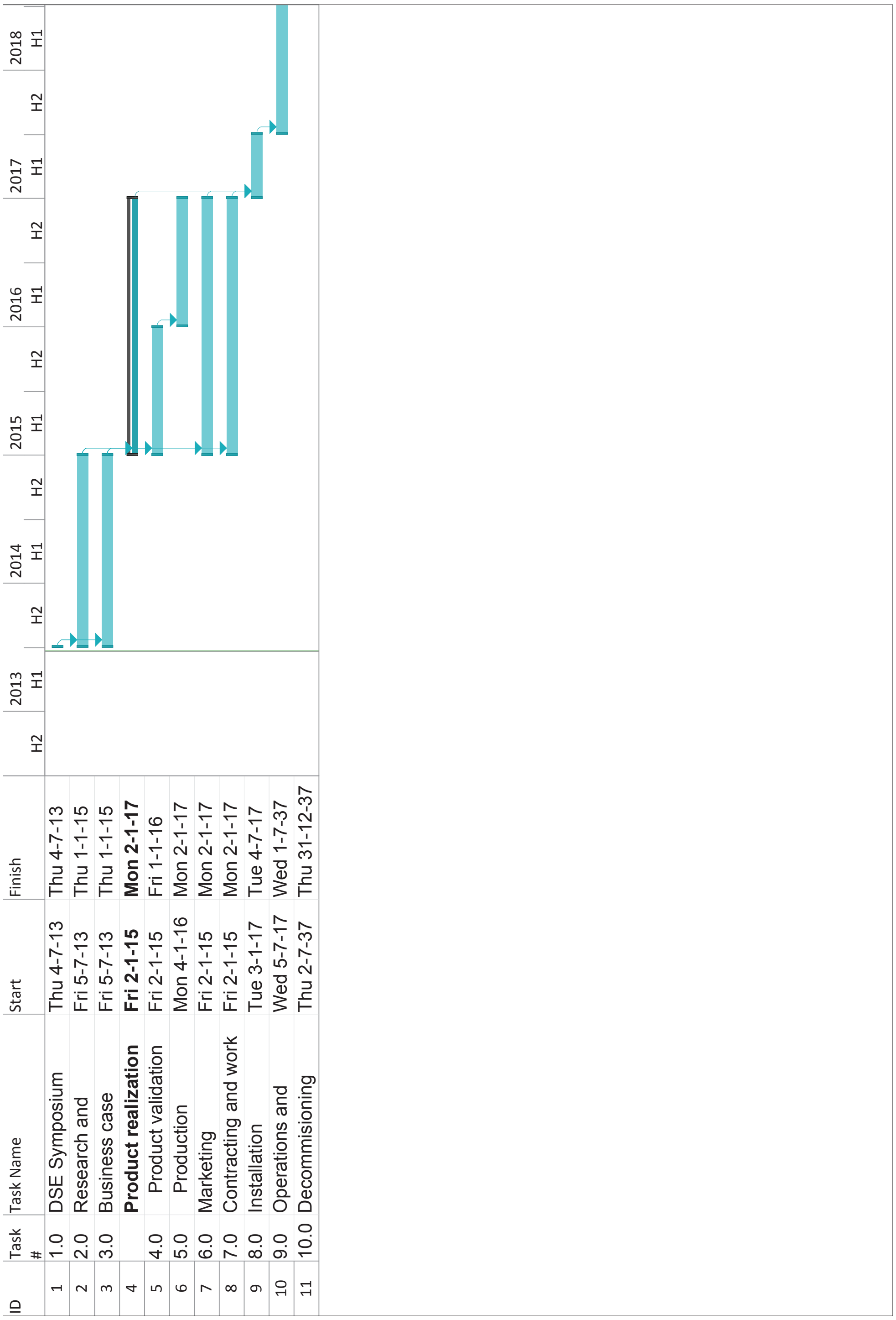

Figure H.1: Post-DSE project planning of the launch, landing and storage system running from the Symposium up until the decommissioning of the system 20 years after production