One Thousand Little Lights
Final Design

AE3200 Design Synthesis Exercise

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Group 17

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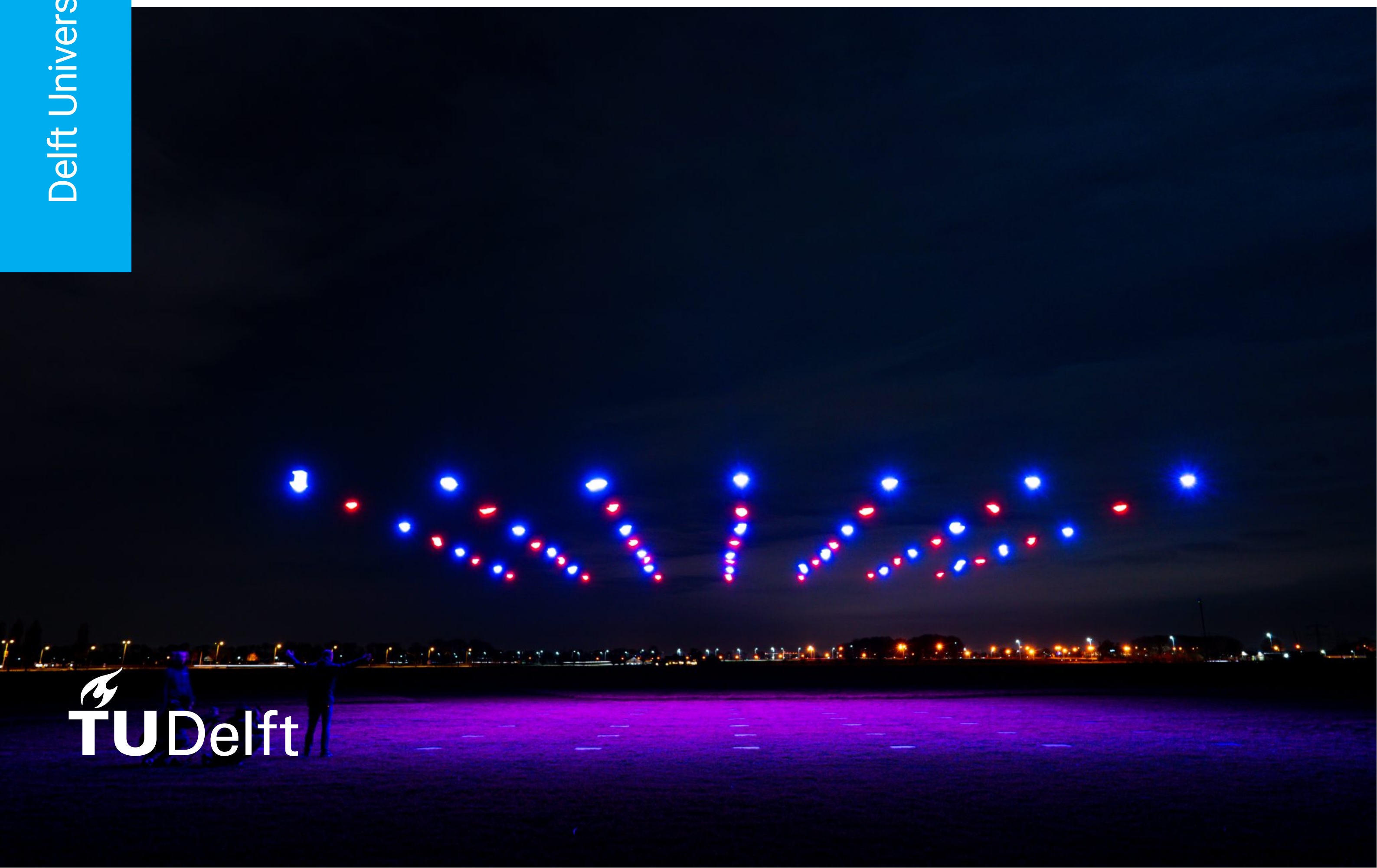


Executive Overview

Contents

Nomenclature

Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AE	Aerodynamics
BFT	Beaufort
BMS	Battery Management System
BOL	Beginning-of-Life
CCE	Communication, Control and Electronics
DOD	Depth of Discharge
DSE	Design Synthesis Exercise
$EEPROM$	Electrically Erasable Programmable Read-Only Memory
EOL	End-of-Life
ESC	Eletronic Speed Controller
FAA	Federal Aviation Administration
FBS	Functional Breakdown Structure
FFD	Functional Flow Diagram
FPV	First-person view
GPS	Global Positioning System
$HDPE$	High-density polyethylene
IMU	Internal Measurement Unit
LED	Light Emitting Diode
$LiPo$	Lithium-ion Polymer
MNS	Mission Need Statement
$NIOSH$	National Institute for Occupational Safety and Health
OP	Operations
PCB	Printed Circuit Board
PET	Polyethylene Terephthalate
PLA	Polylactide
POS	Project Objective Statement
PP	Polypropylene
$PROP$	Propulsion
PS	Polystyrene
PVC	Polyvinyl Chloride
$RAMS$	Reliability, Availability, Maintainability, and Safety
RGB	Red Green Blue
RPM	Rotations per minute
$RTCM$	Radio Technical Commission for Maritime Services
RTK	Real Time Kinematics
SP	Structures
SPI	Serial Peripheral Interface
$SWOT$	Strengths, Weaknesses, Opportunities, and Threats
$TDOA$	Time Difference Of Arrival
TWR	Two Way Ranging
U	Unit test
UWB	Ultra Wide Band
VT	Verification

Symbols

ϵ	Error
η	Efficiency
μ	Dynamics viscosity
ρ	Air density
σ	Stress
τ	Shear stress
θ	Pitch angle
A	Area
C	Scaling factor
c	Distance to centroid
C_d	Drag coefficient
D	Diameter
def	Deflection
E	Energy
E	Young's modulus
e	Error
F	Force
f	frequency
G	Gain
g	Gravitational constant
I	Moment of inertia
I_{max}	Maximum current
k	Correction factor
L	Characteristic length
L_{fs}	Free space loss
M	Moment
m	Mass
n	Number of ...
P	Power
p	Position
P_{cr}	Critical buckling load
R	Transformation matrix
r	Radius
Re	Reynolds number
S	Cross-sectional area
T	Thrust
t	Time
T/W	Thrust over weight
V	Velocity
W	Weight
w	Rotational speed

1

Introduction

2
Project Progress

In this chapter an overview of the project until now will be given. This will be done by first stating the objectives with which we started the project. Then an overview of the chosen concept and the decisions that have already been made will be given. All of this can be found in more detail in the baseline and midterm reports [1] [2].

2.1. Project objective

In the project 'One Thousand Little Lights' a drone will be designed, which is optimised for using in air shows. The entire mission need statement was concluded to be: *To revolutionize the airborne, audio-visual entertainment industry by 2025.* The aim of this project was summarised in the project objective statement: *Design an economically competitive, safe and sustainable drone for indoors and outdoors light shows in 10 weeks, for Anymotion Productions.* Requirements were set up to make sure these goals are reached. These requirements can be found in the beginning of each chapter about each subsystem of the drone. The driver requirements were mainly focused on the flight time of the drone. The killer requirements were focused on the aspect which will make the drone revolutionary. This consists of the modular payload the drone has, including the fact that it is able to carry pyrotechnics. Another important aspect is that the drone is able to perform indoor and outdoor shows, and that the manufacturing and maintenance cost are competitive on the market.

2.2. Concept overview

In this report the entire detailed drone will be designed in subsequent chapters. Before this in the midterm report, a design concept was already chosen and some decisions in the subsystems were already made [2]. An overview of these decisions will be shown in this section.

The concept has a single configuration for indoor and outdoor shows, has a brushless motor and consists of four unconnected and fixed arms. The drone will be made out of polymer thermoplastics. The design is specially shaped for packaging and the landing gear and propellers are removable. The drone has two propellers per arm and two blades per propeller. A Lithium-ion polymer (LiPo) battery is used and the positioning system is split into an indoor and outdoor option. For the indoor shows Ultra-Wideband is used and for the outdoor shows GPS with Real Time Kinematic is utilized. The communication with the ground station is performed via Wi-Fi in case of emergencies, but the show choreography is already fully programmed on the drone beforehand. An extra feature of the drone, next to normal wired charging, is the ability to be able to be conductively charged by the landing pad.

3

System's Functional Analysis

In this chapter, the functional analysis is presented. The functional analysis consists of the functional flow diagram which is presented in Section 3.1, and the functional breakdown structure, presented in Section 3.2.

3.1. Functional Flow Diagram

3.2. Functional Breakdown Structure

4
Market Analysis

Before designing a product, it is important to determine whether there is a market for it and what the product will add to this market. The same holds for a drone for drone shows. In this chapter, the gap on the market for the drone of One Thousand Little Lights will be investigated. The chapter will start with the use cases and possibilities of the drone show industry in Section 4.1. After that, the competitors that are organising drone shows and the size of the market is estimated in Section 4.2. In Section 4.3, the SWOT analysis for the market is shown.

4.1. Drone Show Opportunities

The goal of a drone show is to amaze people, whether this is during a festival, a national holiday or promotion for a company. Many of the drone shows that have been organised were for entertainment purposes, which is in line with the mission need statement to revolutionize this specific industry.

There are several events where drone shows have been applied and they are listed below:

- Brand events
- Campaigns
- Ceremonies
- Concerts
- Festivals
- National holidays
- Sporting events
- Theme park shows

Brand events can be about product launches, company celebrations or other advertisements. Intel has for example organised a drone show in honour of their 50th anniversary [3] and Kia for their new logo reveal [4]. Furthermore, drone shows have been used for the Olympic Games, New Year's Eve and so on. Besides large shows for holiday events, drones can also be used indoors during concerts, sport events or music festivals as an addition to the experience. A very novel application of drone shows has been done by Greenpeace on the 11th of June, 2021. Greenpeace made a film using drone swarms in the form of animals as a campaign during the G7 conference in Cornwall. [5]

4.2. Current Market

The drone show industry has seen enormous innovation and progress in the last six years. Where in 2015 the first world record was set by Intel for having the most UAVs in the air at the same time, which was a 100 drones, Damoda Intelligent Control Technology set a new record with a stunning 3,051 drones in September 2020 [6].

In Table 4.1, a list of companies that execute drone shows is presented. There are not many suppliers that can be found online and information about their revenue is limited. This emphasises the young market of drone shows.

Most of these companies only provide light shows, but Skymagic and CollMot also provide the opportunity to launch so called pyrodrones. These drones have the opportunity to launch a firework fountain. Pyrotechnics are a new addition to drone shows. The car company Kia set a world record by using 303 pyrodrones for the reveal of their new logo in October 2020 [4]. An impression can be seen in Figure 4.1. Firing pyrotechnics from the drone is also a requirement for the drone of One Thousand Little Lights, set by the customer.

Figure 4.1: *Kia set a world record with 303 pyrodrones. [4]*

Some of these companies also provide shows indoors, during concerts or theatre plays. These are Damoda Intelligent Control Technology and Skymagic.

Table 4.1: *Drone show competitors*

Drone show companies	**Country**	**Website**
Anymotion Productions	Netherlands	https://droneshow.nl/
AO technology	Germany, United Arab Emirates	https://www.ao-technology.com/
CollMot	Hungary	https://collmot.com/
Damoda Intelligent Control Technology	China	https://en.dmduav.com/
Drone show events	Netherlands	https://www.droneshowevents.nl/index.html
Geoscan	Finland, Russia	https://geoscan.show/
Intel	United States	https://inteldronelightshows.com/
Skymagic	Singapore, United Kingdom	https://skymagic.show/

4.2.1. Replacement of fireworks shows

In only the last three days of the year fireworks worth over 77 million euro are sold in the Netherlands. However, with the recent prohibition on fireworks in 2020 alternatives need to be sought. An innovative and exciting alternative is the use of drone shows, which have already been used for New Year's Eve in Rotterdam in 2020 [**droneshowrotterdam**].

They are very suitable for replacing fireworks and are less polluting and noisy. With the increase in fireworks regulations and decrease in drone costs the market for drone shows used for entertainment purposes has a large probability to increase, especially when looking at the high number of revenue that is already made each year in this sector.

4.2.2. Advertisement

The advertisement market is worth an estimated 650 billion US dollars in 2021 [**Ad_market_total**], out of which 65 billion come from physical outdoor advertising [**Ad_market_outside**]. Consumer brands finance incredibly expensive advertising events to get as much consumer attention as possible. Drone shows provide excellent opportunity to display companies' advertisements on a scale that is unfeasible to achieve with other methods. It should be noted that a drone show has a very short duration compared to a billboard, which makes it difficult to exactly compare the efficiency of both methods of advertising. Currently drone shows do not occur very often however, so the company can get additional media attention for free which

Table 4.2: *Drone specifications of Sparkl and UVify.*

	Sparkl	UVify IFO
Dimensions without propellers (cm)	40 x 40	27.5 x 27.5
Dimension with propellers (cm)	45 x 45	40 x 40
Height (cm)	15.5	12.5
Weight (g)	1103	635
Weight (incl. battery) (g)	1706	1050
Max. flight time (min)	25	25
Max. airspeed (km/h)	72	60
Max. operational altitude above sea level (m)	1500	500
Max. control range (m)	500	1000
Max. sustained wind (m)	25	15
Vertical hover accuracy (m)	0.1	0.1
Horizontal hover accuracy (m)	0.1	0.1
RGB led (W)	10	27
Light strength (lumen)	550	840
Battery type	Lipo 4S	Lipo 4S
Battery capacity (mAh)	6750	4200
Battery voltage (V)	14.8	14.8

might increase the reach of the ad.

4.3. SWOT Market Analysis

The SWOT analysis of the market is shown in Table 4.3. It can be seen from the table that the strengths and opportunities mainly focus on the possible uses of drone shows, while the weaknesses and threats describe mostly reasons for the product to be not profitable or actually unable to be used (on a frequent basis).

Table 4.3: *SWOT market analysis*

	Helpful	Harmful
	Strengths	**Weaknesses**
Internal	- Custom made drones - More sustainable than firework shows - Low noise emission - Modular payload capability - Ease of maintenance - Autonomous charging	- Operational difficulties - High initial costs - Many safety measures - Damage during transport - Logistical challenges - No reputation
	Opportunities	**Threats**
External	- Multiple use cases - Young market - Replacement of or addition to fireworks shows - Low number of competitors - High demand - Attention of the media	- Future government relations - Future competition - Too expensive for customer

A short explanation might be necessary for some entries in the table:

- **Modular payload capability:** from a meeting with the client, Anymotion Productions, it became clear that the lifetime of a drone is often dictated by its payload. After 2-3 years the quality of the payload, e.g. LED lights, is not state-of-the-art anymore and should be replaced. Without a modular payload capability this means that the entire drone should be replaced instead of just the LED light. If this possibility is achieved, it is an enormous improvement to currently existing drone designs.

- **Ease of maintenance:** it is required by the customer that a one-day training shall be sufficient to replace parts of the drone. This will be taken into account in the subsystem design. The actual maintenance procedure can only be determined in the final design phase.
- **Unique advertisement solutions:** drone shows provide new possibilities for advertisement, as written in Subsection 4.2.2.

4.4. Target Cost

Some examples of operational costs are listed below:

- Charging costs
- Control room costs
- Permits
- Personnel
- Security
- Show animation and choreography design
- Storage
- Testing costs
- Training
- Transport
- etc.

5 Subsystem Design Approach

In this chapter the design approach taken during the detailed design phase will be discussed. The general design approach is discussed in Section 5.1, followed by a recap of the driver and killer requirements in Section 5.2. Thereafter the preliminary budgets and budgeting strategy is presented in Section 5.3. Finally the chapter structure for the subsystem design is discussed in Section 5.5.

5.1. Design Approach

One of the goals of the detailed design phase is to produce a final design with the highest possible level of detail. This is achievable by splitting up the team in smaller departments and designing on a smaller, more detailed, scale. The same team member will be working on the same part for a longer period of time and therefore more expertise can be build up within the time frame of the DSE. Another goal is to produce the most optimal design: a perfect fit within the requirements. Optimisation is a dynamic process. By having the information in a central place the components can adapted to the most up to date information.

Combining these two goals is a systems engineering challenge: optimization will limit the level of detail that can be achieved while maximum level of detail is desired. The team decided proceed the detailed design phase in iterations. From the project planning a set time frame is assigned for subsystem design. During this phase the iterations were performed by all the departments. A method of communication was constructed to have the most efficient iterations. The departments updated their department specific components based on the previous update. Every department constructed a method or tool to rapidly design and select hardware. By designing this tool for dynamic input parameters rapid responses can be delivered in case of a design update. The iterations are structured by deadlines. The initial goal was to to a new iteration every two days. During the detailed design it was observed that the tools and methods are fast enough to produce numbers more often and therefore additional iterations where put in place. Integration will be part of the iterations: by communicating the latest update to the rest of the team the team can adapt to the latest design. By the final iteration an integrated design is delivered. In Table 5.1 the iteration and the deadline dates are shown.

Table 5.1: *Table showing the iteration dates and goals*

Iteration	**1**	**2**	**3**	**4**	**5**	**6 - Final**
Date	4-6-21	8-6-21	9-6-21	10-6-21	11-6-21	11-6-21
Goal	Increasing design confidence	Decreasing weight	Decreasing weight	Decreasing weight	Optimizing for requirements	Optimizing for requirements

The goals of the iteration are shown in the table. The iterations start at at the point of preliminary budgeting. During in the midterm report[2] the design budgets for every concept was presented. The budgeting done for the selected concept is taken as an input parameter of the first iteration.

The first goal is to decrease the uncertainties from the preliminary budgeting during the first iteration. Preliminary budgeting is done using statistics obtained from a paper which have been gathered at the time the paper was written. During the first iteration the departments focused on building more specific tools that are able to make a more detailed and certain estimations on the department specific budgets.

The second goal is to decrease the weight. This was done during iteration 2, 3 and 4. To fit the requirements the drone has to be a light as possible. A lightweight drone will reduce the size and the production costs. Therefore focus is put on finding lighter components that can perform the task.

Finally the goal is to optimize the design for the requirements. The end goal of the design is to meet all requirements. Therefore putting emphasis only on lowering the weight will not be suitable. Some departments have different priorities and therefore choices have to made to create the best fit. An example of a choice that has been made during the final iteration was that the team had to choose between are more lightweight drone or a smaller propeller diameter. The smaller propeller diameter was chosen as this had more benefits.

Every department will be responsible for part of the final design. In Table 5.2 the design activities are summed per department. In the following chapters these design activities will be discussed in detail.

Check by every department: -CCE (done) -

Table 5.2: *Table stating the department design activities*

Department	Design activities
Propulsion and Aerodynamics	Motors, propellers and aerodynamic cover.
Power	Battery, electronic speed controller and battery management system.
Communication, control and electronics	Flight computer, sensors, communication protocols and control simulation
Structures	Frame design
Operations	Landing gear and operational activities

5.2. Driver and Killer requirements

The driver and killer requirements have been reviewed during the detailed design phase. In Table 5.3 the updated driver requirements are shown. These requirements are affecting all subsystems and maintained during the iterations. In the table a short explanation is given regarding the effect on the design. In the following chapters the requirements will be discussed in detail.

Requirements negotiations have taken place during the midterm period. Using the initial budgeting a new requirements proposal was constructed and accepted. The killer requirements where eliminated according to the sizing method. However, some of the driver requirements stated in the table became killer requirements during the iterations. The requirements where not met and changes to the design had to be made. At the final iteration all killer requirements where met and thus eliminated again.

Table 5.3: *Driver requirements*

TAG	Requirement	Reasoning
COST-AP-1	The drones shall cost no more than "1000,- per piece.	Use of expensive materials or concepts is limited
COST-AP-2	The expected cost of replacing parts in 1000 light shows shall be nomore than "650,-.	Use of expensive materials or concepts is limited
SUS-EO-3	At least 80% of drone mass shall be recyclable.	Material selection is limited
OP-AP-3	The drones shall be available in the year 2025	Components have to be selected off-the-shelf hardware and design is limited in technology
OP-AP-2	The drones shall be suitable for mass transport	A small sized drone is preferred
OP-AP-8	The minimum amount of drones in one show shall be 20 for indoor shows, where 'indoors' means venues such as concert halls or stadium	Special equipment is required
POP-SYS-2.2	The drone shall have a minimum thrust to weight ratio of 3	Heavy motors are required
SP-SYS-1.3.1	The megaphone or speaker shall have a power consumption of 20W	High powerconsumption
SP-AP-1.4.1	Future innovations shall have specifications up to a weight of 0.6kg	Heavy components are required to lift the drone
SP-AP-1.4.2	Future innovations shall have specifications up to a 20W power consumption	High powerconsumption
SP-AP 1.4.3	Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm	The payload requires a specially shaped drone
POP-AP-3.2	The drones shall be able to fly for 15 minutes of showtime with a heavy payload.	A large battery is required
POP-AP-3.8	The drones shall be able to fly for 20 minutes of showtime with a lights as a payload.	A large battery is required
AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.	Additional power is required
OP-AP-6	The area off the take-off zone shall be at most 1m2 per drone	Constraining the design space

5.3. Budgeting During the Detailed Design Phase

The primary design budgets cover will be discussed in the list below. Every department had to reproduce these budgets for every iteration in order to optimize the design.

- **Mass:** Mass is the most important design parameter. During the detailed design phase it showed that most of the driver requirements were translated in a mass reduction. Therefore mass reduction was very important to meet the requirements.
- **Power usage:** Power usage is the secondary budget that will have a big influence on the mass. A lower power consumption is always preferred as it lowers the chance of a mass increase. However, power consumption is directly related to parameters such as propeller size and payload functionality. It should be carefully evaluated if the benefits of a lower power consumption out weight the drawbacks.
- **Production costs:** A requirement is set on the maximum production cost. Therefore the cost is closely evaluated every iteration in order to prevent the design from being too expensive. Mass has the biggest influence of cost: A lower mass will have a high impact on the costs related to the power and propulsion departments.
- **Maintenance costs:** A requirement is set on the maximum maintenance costs. During the requirements negotiations these costs were increased to have more room for battery replacements. In case the design performs better than specified in the requirement, the performance should be reduced to the required performance and the maintenance costs should be lowered. The maintenance costs cover the expected replacements and the routine repairs.

Every department has its own set of department specific parameters. These parameters are related to what the department is designing. These parameters will also be updated by every iteration.

Mass will be the most important budget that will be used by all departments. Every iteration will have a newly calculated total mass and therefore the departments are required to work with inputs that can be dynamic. A so called snowballing effect is created when weight is added: a heavier drone will result in bigger propeller blades, heavier motors, bigger batteries and a more reinforced frame. More weight is added to the drone and the design will be heavier each iteration that is performed until it converges to a final value. When weight has to be added the drone will not meet the desired performance as there is always not enough power available to meet the flight time requirement. Therefore it is desired to converge to a lower weight in order to meet all requirements.

During preliminary budgeting a total mass estimation was made. The departments started to design using this initial mass. After the first iteration the design was heavier compared to the preliminary budgeting and therefore the weight had to increase. In order to meet the requirements more weight should be added than necessary by the iteration. Therefore margins are put in place.

Contingency margins are applied over the mass budget. After each iteration a new total weight is produced. Margins are added to the weight to ensure there's is room for uncertainties. The total mass including the added margin is communicated back to the departments and will be used for the next iteration. The margins are shown in Table 5.4. The margins on preliminary budgeting are high: the data contains many uncertainties. It can be seen that the margins decrease over time. The propulsion and aerodynamics and power department have a rapidly decreasing margin. This is due to the fact that these departments will be selecting off the shelf flight hardware in an early stage. The structures department has the highest contingency margins. This originates from the fact that the structures department has to design many different uniquely shaped components which introduced a lot of uncertainties. The control, communication and power department has a constant contingency margin of 10 %. Hardware is selected during the first iteration however unlike the power department a larger uncertainty is present for manufacturing. Finally the operations department did design the landing legs. The department finalized the tool for calculating the weight during the first iterations. Therefore the margins are set low from the second iteration.

Table 5.4: *Table containing contingency margins.*

Margin table	**Preliminary budgeting**	**Iteration 1**	**iteration 2**	**Iteration 3**	**Iteration 4**	**Iteration 5**	**Final margins**
Propulsion & Aerodynamics	30.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%
Power	30.00%	5.00%	5.00%	5.00%	5.00%	5.00%	5.00%
Structure & Payload	30.00%	20.00%	15.00%	15.00%	10.00%	10.00%	10.00%
Controllability, Communications & Electronics	30.00%	10.00%	10.00%	10.00%	10.00%	10.00%	10.00%
Operations	30.00%	10.00%	5.00%	5.00%	5.00%	5.00%	5.00%

It can be argued that a contingency margin of only 5% for the Aerodynamics, propulsion and power department is too low as the team should account for larger uncertainties in case of a design change. However, the goal is to rapidly iterate and optimize the total design. Therefore higher margins will result in an over designed product. It is preferred to do additional iterations over setting high margins as this allows for the most optimal design to be chosen.

The table above only mentions contingency margins for the mass budget. The other budgets are checked during every iteration. The power budget will be heavily dependent on the weight and is difficult to constrain to a set value. Therefore an increase in power was notified to the systems engineer, who can confirm that the increase is within margins. These margins follow from the margins set on the mass and are calculated case specific. The production and maintenance cost budgets are taken from the preliminary budgeting and are decreased by 20% to have margin. In case a department goes over budget, a new budget is set for that department and the budgets for other departments are lowered. This can only be performed in case other departments indicate that they will remain below budget.

The budgets obtained during preliminary are shown in Table 5.5. Contingency margins are not subtracted from these budgets. The budgets with the subtracted contingency margin are given as the starting point of the first iteration for every department. In the table it can be seen that no weight is assigned for the operations department. During preliminary budgeting it was not considered that the operations department will design the landing gear. To compensate for this budget was subtracted from the structures department and added to the operations department during the first iteration.

Table 5.5: *Table containing preliminary budgets*

Department	**Mass [kg]**	**Power [W]**	**Production Costs [€]**	**Maintenance Cost [€/lifetime]**
Propulsion & Aerodynamics	0.43	158.89	230.77	16.30
Power	0.36	0.00	41.85	544.03
Structure & Payload	0.86	20.00	219.69	16.30
Controllability, Communications & Electronics	0.01	10.83	153.85	16.30
Operations	0.00	0.00	76.92	16.30

5.4. Communication During the Detailed Design Phase

Communication was a very important aspect of the detailed design phase. A pitfall would be that the departments will communicate and agree on decisions without informing the rest of the team. However, communicating everything to the full team would be very time consuming. To solve this issue the master systems design sheet was constructed. This sheet will function as a big parameter and budget library which is accessible to every department. By putting all design decisions in this sheet communication was done in a very effective way.

In Table 5.6 a row of the master systems design sheet is shown. In this table a slice of the library tab is shown. The first row contains the iterations and the value obtained preliminary budgeting (statistics). This row is followed by a row stating the department. All parameters are sorted by department in the sheet. Finally the parameter is shown in the third row. It has a unique identifier to aid a quick lookup in the sheet, followed by a parameter name and unit. Every iteration has a different value.

Table 5.6: *An example input for the master systems design sheet.*

ID	**Parameter**	**Unit**	**Statistics**	**1**	**2**	**3**	**4**	**5**	**6 - Final**
1	**Propulsion and Aerodynamics**								
1.16	Power max speed and headwind (heavy configuration)	W	900	536	290	342	272	251	234

The detailed design phase started by making a sheet where every department could fill in their required parameters. The departments where asked to add the required parameters to the master systems design sheet and make a fist estimate in the statistics box in case the parameter was not set during preliminary budgeting. By filling in a statistical value every department had numbers to work with during the first iteration.

Besides the required parameters every department had to fill in the primary budget parameters. By doing this the systems engineer can keep track of the total budgets and act in case a department is over budget. A special dashboard tab is created which is used to construct the total budgets for every iteration. The margins are applied on this tab to calculate the total weight.

All departments where required to fill in numbers for every iteration. By updating the numbers during every iteration the design will adapt to the latest developments in the departments. In case the values did not change the same value had to be entered again for the next iteration. This required the departments to confirm their numbers for every iteration with a minimal effort.

Decisions such as the number of propellers, frame material and propeller diameter can all be put in the library. Every department has access to the numbers and therefore if information on the design is need to continue it can be looked up. While the departments work on an iteration and information has to be retrieved, the departments will use the parameters from the previous iteration. Therefore the used information for every iteration will be static: information used during the iterations will not change. However the detailed design phase will be highly dynamic: every iteration performed the design will converge to a more optimal configuration. One exception is made from the procedure of reading parameters from the previous iterations. The power department is so dependent on the power required by the propulsion department and therefore these two departments work together on producing numbers for an iteration. The battery is sized based on the power required after these parameters are given by the propulsion department.

In the next chapters the design for the subsystems will be discussed. The required parameters obtained during this detailed design phase are obtained from the master systems design sheet. To aid the process of parameters that are exchanged a design N2 chart is made. In this N2 chart the output of every department is shown on the horizontal lines. Inputs for the departments are shown on the vertical line. The design N2 chart can be seen in Table 5.7 . In Chapter 11 a N2 chart will be shown illustrating the interaction between all the designed components. A box on the diagonal stating the total budgets is added. This is done to show the interaction between the departments and the total budgets.

this, n2 chart of final design

Table 5.7: *Exchange of parameters visualized in a design N2 chart.*

Propulsion & Aerodynamics	Power required, motor current	Thrust coefficients	Dimensions, operating temperature, propeller diameter, aerodynamic requirements		Mass, costs, power consumption
Voltage	**Power**	Voltage	Dimensions,		Mass, costs
		CCE	Dimensions,	Landing precision	Mass, costs, power consumption
		Dimensions	**Structures & Payload**		Mass, costs, power consumption
			Dimensions,	**Operations**	Mass, costs
Total mass	Power consumption		Masses		**Total budgets**

5.5. Subsystem Chapter Structure

In this section an overview of the structure in the following chapters will be given. The chapters cover the subsystem design. Every chapter will start with a functional overview. The functional overview will provide an overview of what the subsystem will design during the detailed design to full fill its desired functions. The tasks are linked to the functions described in the functional flow diagram and functional breakdown structure.

The functional overview is followed by a recap of the risk analysis done during the midterm report[2]. The risks and the mitigation responses will be repeated. During the design these mitigation responses will be implemented. Newly discovered risks will be discussed in a separate risk section at the end of the chapter.

A list of requirements is provided in every chapter. The relevant requirements applicable to the subsystem are listed and the requirements will be discussed in the method section. All requirements will be covered in the chapters. The requirements that cannot be answered in the subsystem will be discussed in Chapter 11.

In the method section the design will be discussed. The tools or methods constructed will be shown and results will be presented. The method section is followed by verification and validation. The procedures taken will be verified an validated.

Finally the chapters end by filling in a compliance matrix. The requirements that have been met by the design presented in the subsystems chapter will be shown.

6
Aerodynamics and Propulsion Subsystem Design

Aerodynamics and propulsion is an important aspect of a drone as it affects other subsystems such as the structure and the power. The functions and the identified risks of this subsystem are discussed in Section 6.1. Section 6.2 contains a list of requirements that will drive the design. The methods used for the subsystem design for aerodynamics and propulsion discussed in Section 6.3 and Section 6.4, respectively. The results obtained during the iteration process is presented in Section 6.5. A risk analysis with newly found risks is performed in Section 6.6. Then, the procedure is verified and validated in Section 6.7 and finally a compliance matrix is presented in Section 6.8.

6.1. Functional and Risk Overview of Aerodynamics and Propulsion

The goal of the propulsion subsystem is to make sure enough thrust is provided for the drone to perform the mission. Because the propulsion system is very intertwined with the aerodynamic performance of the propeller, the decision was made that these parts of the system will be analysed and designed together. The system will be active in all the flying phases of the mission, which were presented in Chapter 3. These include the take-off, landing and flying phase for both the practice run as well as the show itself. The main functions of the propulsion system are:

- To provide enough trust to:
  - Reach the maximum speed
  - Be able to perform maneuvers during flight with a thrust over weight ratio of at least 3
  - Perform the mission in windy and rainy conditions
- To perform the mission without causing too much disturbance due to noise
- To perform the mission without influencing other drones during the flight

These functions are translated into requirements which are presented in Section 6.2. The propulsion system can be divided into two parts, which will be designed together as mentioned before. These two parts are:

- The propellers
- The motors

Table 6.1 presents the risks identified in the preliminary design phase regarding the aerodynamics of the drone and the propulsion subsystem. It also shows their likelihood and consequence and the mitigation response that should be implemented in the design. Note that the reasoning behind the scores have been explained in the midterm report [2]. Some of these risks translated into requirements which will be shown in Section 6.2.

Table 6.1: *Risks related to propulsion and aerodynamics*

ID	Risk	Likelihood	Consequence	Mitigation response
2	Unpredictable movement due to wind	High	Moderate	Implement safety margin for maximum horizontal speed
14	One motor malfunctioning	Moderate	Critical	Make sure three motors provide enough thrust for safe landing

6.2. List of Requirements Aerodynamics and Propulsion

Table 6.2 presents the requirements related to the Aerodynamics of the drone and the Propulsion subsystem. On the left column the sub-department they relate to is stated. These requirements will be used as guide to design the subsystems in Section 6.3 and Section 6.4. Note that some of these requirements will be verified at subsystem level in Section 6.7, while the rest will only be verified at a system level in Chapter 16.

Table 6.2: *Requirements related to the propulsion subsystem*

Sub-department	TAG	Requirement
Aerodynamics	AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.
	AD-AP-2	The drones shall be able to fly in rainfall up to 10mm/hour
	AD-NR-4	Noise level shall be less than 80decibels at 1 meter from the drone
	AD-ATC-5	Operations shall continue up to a height of 1000 m
	AD-SYS-5.1	The drone shall be operable in a pressure range between 101325 Pa and 89401 Pa
	AD-SYS-8	The drones shall not affect other drone performance
	AD-SYS-9	The drones shall be able to fly in formation at 2m distance from each other
Propulsion	POP-AP-2	The drones shall be able to achieve a velocity of 20m/s.
	POP-SYS-2.2	The drones shall have a minimum thrust over weight ratio of 3.
	POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from being able to perform an emergency landing.
	AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg
	OP-AP-6	The area off the take-off zone shall be at most 1m2 per drone
	SUS-EO-3	At least 80% of the drone mass shall be recyclable

6.3. Design for Aerodynamics

Aerodynamics is important for any flying object, thus also for a drone. It affects other subsystems such as structures and control, but mainly propulsion as it has considerable influence on the thrust and power required. This section discusses the aerodynamic characteristics, which is focused on the drag coefficient, the propeller spacing, noise generation and the influence of rain.

6.3.1. Aerodynamic Characteristics

It is important for the drone to have an optimal shape in terms of aerodynamic design as it improves its performance. A more aerodynamically shape has a lower drag coefficient which makes it easier to fly at high speeds. This results in less thrust required to meet the maximum velocity required and in turn the power consumption of the propulsion system would decrease as well. It is important to decide on the optimal shape at an early stage because it influences other subsystems as well. For example, the structure of the drone obviously depends on the drone's shape. Besides, the shape is an important factor when it comes to stackability of the drones as well, which affects the operational side. In this section a preliminary analysis will be conducted to see which shape is the most efficient from an aerodynamic point of view. From this a drag coefficient can be obtained, which is used later in the subsystem design of the propulsion system.

First, some shapes that could be used for the design will be analysed. To do this an estimation of the Reynolds number has to be made, because this influences the drag coefficient. The Reynolds number is determined to be in the order of magnitude of 10^5 by using Equation 6.1, in the extreme conditions the drone will experience.

$$Re = \frac{\rho * V * L}{\mu} \tag{6.1}$$

For this Reynolds number, different shapes can be analysed by comparing the drag coefficients. Then it will be decided upon which shapes will be the most optimal for the design. For the core of the drone, a cube and a sphere will be compared. For the arms, the difference between a square rod and a round cylinder will be analysed. The values for the drag coefficients can be found in Table 6.3 [7]. As can be seen it is beneficial to use round shapes from an aerodynamic perspective. For the core of the drone it will thus be beneficial to have a spherical shape. For the arms it will also be preferred to have a circular shape. This will improve the aerodynamic performance of the drone on all sides. Therefore, a spherical shape will be used for the core of the drone and the arms will take the shape of a round cylinder.

Table 6.3: *Drag coefficients for different shapes*

Re $\approx 10^5$	**Drag coefficient**
Cube	1.05
Sphere	0.2
Square rod	2
Round cylinder	0.51

Before going into the subsystem design a first estimation for the drag coefficient of the whole drone was made. This was done by then comparing it to the drag coefficient of an existing model. Experiments done by C. Russell et al. show that the DJI Phantom 3, a quadcopter which is around the same size and shape as we expect our drone to become, has a ratio for drag over dynamic pressure of around 0.3 [8]. Multiplying this by its cross-sectional area, it turns out that the drag coefficient is approximately 1.21. Comparing this with the drag coefficient of a cube, it is clear that they are both in the same order of magnitude. However, the drag coefficient of the DJI seems to be a more reliable approximation for the drag coefficient of our design. That value will thus be used for the propulsion subsystem design.

6.3.2. Propeller Spacing

Due to current technology, drones tend to become smaller and smaller which is a good thing considering accessibility for recreational users as it makes the drones easier to use. In terms of aerodynamic efficiency, however, down scaling of drones turns out to be not beneficial at all as it generally means that the space between the propellers becomes smaller. Besides the aerodynamic effect between propellers on the same drone, there can also occur some influence of one drone on the other. These two phenomena will be discussed briefly.

The influence on aerodynamic efficiency of propeller placed closely together is known to be disadvantageous for its performance. However, it is difficult to quantify the efficiency loss by means of numerical computations. Instead, in order to investigate this, physical experiments would have to be conducted. Unfortunately, experimenting is not possible due to limited resources. Therefore, experiments performed by others will be used to analyse the influence between propellers quantitatively. Research done by D. Shukla et al. shows that there is more interaction between propellers when they are placed close together [9]. Higher wake interaction was observed for propellers that are closer together. Figure 6.1 visualises the effect on interaction between propellers depending on the distance between propellers. Besides propeller spacing, the Reynolds number plays a major role on the wake interaction as well. For a constant propeller spacing, it was observed that the aerodynamic efficiency was affected more at a low Reynolds number. From this it can be concluded that larger propeller spacing and operating at higher Reynolds numbers is beneficial in terms of aerodynamic efficiency. This knowledge can be used when placing the propellers on the arms of the drone. From an aerodynamic point of view, it is desired to place the propellers at the tip of the arms, as far away from each other as possible.

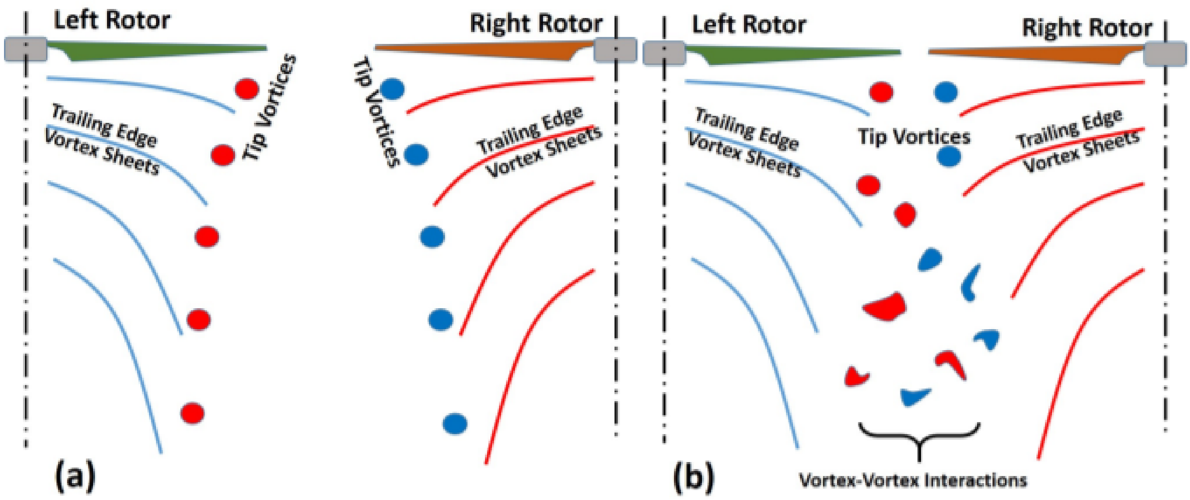


Figure 6.1: *Visual of wake interaction between propellers depending on the spacing. Small spacing in the right figure, larger spacing in the left figure.*

Because the drones have to perform the show in swarms, the aerodynamic influence between drones has been looked at as well. There has not been conducted a lot of research regarding this, specifically not for drones. A look was taken at how this issue is tackled by other rotorcraft such as helicopters. From the AC 90-23G regulations of the FAA it becomes clear that for helicopters other flying vehicles should stay at least three propeller diameters away to not get influenced by the propeller wake [10]. Assuming this regulation also holds for drones it can be considered whether the propellers will influence the other drones at a certain distance and for a certain propeller size. The requirements AD-SYS-8 and AD-SYS-9 concern the distance between drones during the show and influence on performance by other drones. These requirements can be achieved by making sure the distance between drones during the show is at least three times its propeller diameter. Preliminary research in the midterm report has shown that the diameter of the propeller will not exceed 40 cm, so in the most extreme case the distance between drones has to be at least 120 cm [2]. This is well below the required distance of 2 m for formation flight. For smaller propellers the minimum distance between drones will be even smaller. Therefore, these requirements can be considered achieved.

6.3.3. Noise

During the drone show, the surrounding environment at the location should have as little nuisance as possible. In addition to that, also for the audience of the performance, it will be a far more enjoyable experience when the noise levels are as low as possible, especially for indoor shows. Therefore, a maximum amount of noise generated by one drone of 80 dB is aimed for, see requirement AD-NR-4.

Previous studies have shown that noise of multicopters is primarily generated by aerodynamic noise from the propellers. The amount of noise is related to RPM, which also affects the thrust efficiency. Experiments performed by D. Han et al. show that the noise of propellers in decibel is more or less linearly related to RPM [11]. The higher the RPM, the higher the noise level. This is caused by the rotational speed at which the propeller blade moves through the air. The faster the movement of the blade, the more friction and turbulence occurs which in turn generates noise [12]. Therefore, it is preferred to have lower rotational speed. This can be obtained by selecting the propulsion system that achieves the highest thrust efficiency as thrust efficiency is negatively related to RPM, i.e. the higher the thrust efficiency, the lower the RPM. When designing for the optimal propulsion system in Chapter 6, thrust efficiency will thus be a determining factor to reduce generation of noise.

In order to quantify the amount of noise of propellers, a previous study will be used as a starting point.

Experiments performed by D. Han et al. show that the noise of propellers in decibel is more or less linearly related to RPM [11]. The propeller used in their experiment has a diameter of 23.9 cm. The noise level is measured for RPM ranging from 2000 to 9000, which increases more or less linearly from 45 to 75 dB depending on the pitch angle. As a consequence, the noise estimation may be slightly less accurate for different pitch angles as a higher pitch angle tends to produce more noise. For these results, a pitch angle of around 20 degrees was used. For the noise estimation of our drone it will be assumed that the pitch angle does not affect the noise level. The results from their experiments can be used to estimate the noise of other propeller types as well. First, RPM can be converted to rotational speed of the tip of the propeller. The tip of a propeller with a diameter of 23.9 cm rotating at 2000 RPM has a rotational velocity of 25 m/s. At 9000 RPM the rotational velocity is 113 m/s. This means the gradient of the linear regression equals 0.341 dB per m/s. It is now possible to plot RPM against noise for different propeller sizes by starting at 2000 RPM and multiplying the velocity with the gradient, see Figure 6.2.

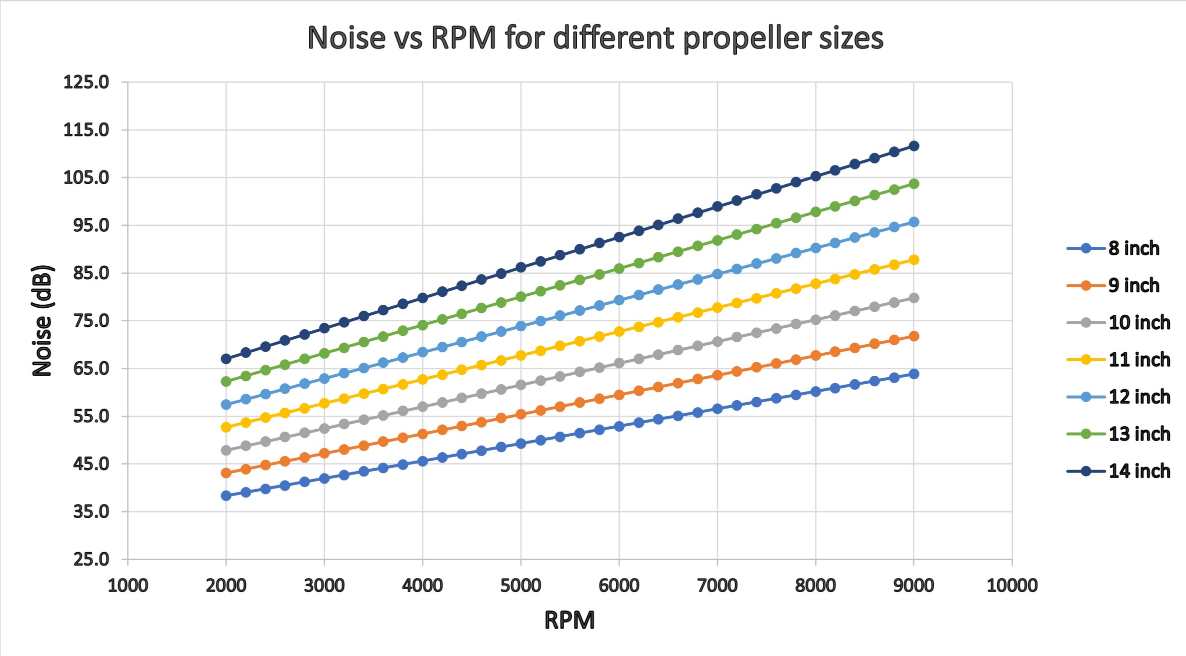


Figure 6.2: *RPM plotted against noise (dB) for different propeller sizes ranging from 8 to 14 inch*

Looking at this figure, it is possible to estimate the amount of noise generated by a propeller of a certain size rotating at a certain RPM. For example, a 14 inch propeller produces approximately 85 dB at 5000 RPM. Requirement AD-NR-4 specifies that the noise level may not exceed 80 dB. Using the figure, the maximum RPM for each propeller size can be determined for which this requirement is met. For example, for a 14 inch propeller the maximum RPM would be approximately 4000 in order to generate 80 dB of noise at most. This can be used later when the propeller size is determined and the RPM is calculated for different thrust settings. If the RPM of the chosen propulsion system stays below the value specified using this plot, then the noise requirement has been met. Note that this is the noise generated by only one propeller. When adding a similar source of noise to the one that is already there, the noise level increases by 3 dB [13]. Thus for four propellers there will be an additional 6 dB of noise compared to the value in the figure.

6.3.4. Rainfall

The drone should be able to perform the show during rainy conditions. Requirement AD-AP-2 states that the drone should be able to fly in rainfall up to 10 mm per hour. To confirm this an estimation was made on how much more thrust the drone should provide in the most extreme conditions. For this first an estimation of the amount of droplets has been made. The requirement of 10 mm/hour can be rewritten as $10*10^6$ mm^3/m^2h. It was assumed that the raindrops have a size of 2mm, which is the average size of raindrops [14]. Together with the assumption that the water drop is a sphere, it becomes clear that a good estimation is around $3*10^5$ raindrops per m^2 per hour. By using the first rough estimation of the full surface area of the drone of 0.05 m^2, there will be around three drops of rain per second on the drone. It will be assumed that these drops hit the drone at the same moment. To compute in how much thrust this will result an estimation was made on how much force one drop of rain will cause. For this the formula for impulse of force is used which can be found in Equation 6.2. It was found that an average rain drops moves at 9 m/s and weighs around 0.000034 kg [15]. Together with the assumption that the stopping time of the rain drop is the time that the drop would move its own dimension of 2mm, a force of around 1.4 N per raindrop is expected to be exerted on the drone. To reach requirement AD-AP-2, in Section 6.4 an extra force of three times 1.4 N, which equals 4.2 N will be added when selecting the propulsion system.

$$F_{average} = m * \frac{\Delta V}{\Delta t} \tag{6.2}$$

When considering the rainfall, a problem that arose was that due to the fast rotational speed of the propellers the rain droplets could cause damage to the propellers. This problem was recognised to be a risk, which will be analysed in Section 6.6.

6.4. Design for Propulsion

The most important parameter for the propulsion system is the required thrust. This is then used to determine the power usage and propeller size which are decisive factors for the power subsystem and the drone structure. During the propulsion design other useful parameters came to light and several assumptions were made in order to complete the process. This will all be discussed in this section along with the method used to design the propulsion system.

6.4.1. Thrust

The two parameters that influence the required thrust of the propulsion system the most are weight and velocity. The requirements related to these parameters are POP-SYS-2.2, POP-SYS-2, AD-AP-1, AD-ATC-5 and AD-SYS-5.1. To meet these requirements the drone has to have a minimum thrust-over-weight ratio (T/W) of 3 and it has to be able to reach a maximum speed of 20 m/s in 6BFT wind conditions. This has to be possible up to a height of 1000 m while enduring the pressure differences.

A wind condition of 6BFT is equivalent to a maximum of 13.8 m/s wind speed [16]. If the drone flies 20 m/s against 6BFT the drone experiences an airflow of 33.8 m/s. Therefore, it can be assumed that the drone can withstand 6BFT wind conditions while moving with 20 m/s if the drone is designed for an absolute maximum speed of 33.8 m/s. This value of 33.8 m/s is used to calculate the minimum thrust required and therefore requirement AD-AP-1 and POP-AP-2 concerning the maximum speed for certain wind conditions will be met. The risk mentioning unpredictable movement due to wind (ID: 2) is hereby mitigated as well as the horizontal velocity of the drone will be high enough to resist wind gusts up to 6BFT.

Forward velocity of a multicopter is highly dependent on the pitch angle. The pitch angle is the angle of the drone with respect to horizontal. Velocity at a certain pitch angle can be calculated using Equation 6.3. The pitch angle can be solved for after substitution of the required velocity. Then the related thrust can be calculated by rewriting Equation 6.4 [17].

$$V(\theta) = \sqrt{\frac{2W\tan\theta}{\rho S\left[C_{D_1}(1-\sin^3\theta)+C_{D_2}(1-\cos^3\theta)\right]}} \tag{6.3}$$

$$\theta = \arccos\frac{W}{n_r T} \tag{6.4}$$

Here, W is the weight of the complete drone, θ is the pitch angle, ρ is the air density, S is the cross-sectional area of the front of the drone, the term inside the square brackets is a computation for the drag coefficient and n_r is the number of propellers. The density can be set to 0.9998 which is the most extreme condition of 40 degrees Celsius at an altitude of 1000 m. By doing so, requirements AD-ATC-5, AD-SYS-5.1 and AD-SYS-6 concerning the operational altitude, pressure and temperature are automatically taken care of. For the cross-sectional area it is assumed that the area of the propellers and the motors is negligible compared to the area of the structure. To account for inaccuracies a margin of around 20% has been added.

Next to the thrust required to reach a velocity of 33.8 m/s, there is also requirement POP-SYS-2.2 to have a T/W of at least 3. Therefore, the thrust that achieves this T/W is computed as well. To make sure the thrust is high enough such that both of these requirements are met, the highest thrust value of these two is used to select the propulsion system. By designing for a thrust-to-weight ratio of at least three, the propulsion system will automatically be able to provide enough thrust for an emergency landing in case one motor fails. Failure of one engine results in 25% less thrust available which means T/W decreases to 2.25. This would be more than enough thrust to perform a safe emergency landing and therefore requirement POP-SYS-4 can be checked off and the risk concerning failure of one motor (ID: 14) is mitigated as well. Besides engine failure, a propeller can break during flight as well. This will be added to the risk analysis in Section 6.6.

6.4.2. Propulsion System Selection

The propulsion system is a combination of the motors and propellers. A database was made containing different motors that all have multiple suitable propellers resulting in unique performance characteristics. While collecting data for the database, the motors having too much thrust (more than 2 kg per motor) and propellers bigger than 40 cm were already filtered out as explained in the midterm report [2]. This means even more data has been considered in the process of creating the database. By only selecting propellers smaller than 40 cm, requirement OP-AP-6 concerning the maximum take-off area of 1 m^2 is taken care of from the propulsion side of things. This requirement will also be analysed in subsequent chapters and it will be confirmed whether this requirement is met for the whole drone in Chapter 16. In the end, the database contained over 60 different motors which resulted in almost 500 combinations to select from. For each option the following parameters were known: propeller size and pitch, maximum thrust together with the RPM, thrust efficiency, input voltage, ampere and power and the mass and cost of both the motor and the propeller [18] [19] [20] [21].

Selection of the most optimal motor and propeller combination was based on the required thrust obtained in Subsection 6.4.1 and on thrust efficiency. First a range of thrust values was determined by adding 5% to the required thrust, which was determined to be an acceptable margin without over-designing too much. From this range the motor and propeller combination having the highest thrust efficiency was chosen for the final design. The reason for selecting the propulsion system based on thrust efficiency instead of other parameters such as propeller size or RPM is that the efficiency of the propulsion system is indirectly driving the battery size of the drone. The more efficient the propulsion system, the lower the power consumption and therefore a smaller battery is required. This turned out to be a very important factor of the design which is why thrust efficiency is deemed more important than other parameters. Of course the size of the propellers is important as well, mainly for transportation. Big propellers bring risks because they are more likely to break, which will be added to the risk analysis is Section 6.6.

6.4.3. Power Consumption

The power consumption of the propulsion system is an important factor for the size of the battery. Therefore, the required power under different circumstances is computed. The varying parameters are velocity and wind speed which can be combined into one parameter; absolute speed. The circumstances considered are as follows:

- Hovering without wind
- Hovering with 6BFT wind
- Flying at maximum speed without wind
- Flying at maximum speed with 6BFT tailwind
- Flying at maximum speed with 6BFT headwind

First, the power input was plotted against thrust for the selected propulsion system and a regression line was drawn through the data points. Then, for all flight circumstances listed before the required thrust was calculated using the method explained in Subsection 6.4.1. Finally, the different power values were obtained by using the required thrust as input. In Figure 6.3 the power is plotted against velocity for the final iteration.

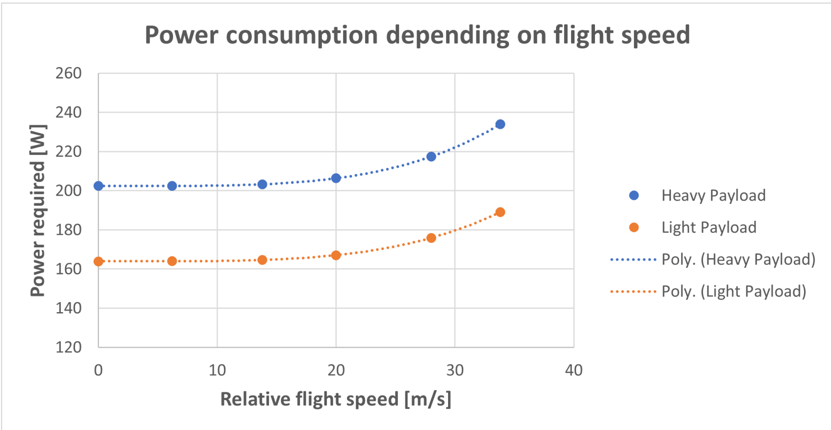


Figure 6.3: *Power consumption of drone with heavy or light payload for different flight speeds*

6.4.4. Recyclability

It is also important to consider the recyclability of the propulsion subsystem, which improves the sustainability of the design. Requirement SUS-EO-3 is focused on this fact. This requirement will also be analysed for the other subsystems and in Chapter 16 there will be checked whether the requirement is reached for the whole drone. The propulsion design is split into the propellers and the motor. The expectation was that the propeller would turn out to be plastic. These propellers are the cheapest while, still having a good performance. They are also very sustainable, because they can be recycled really well. The other option would be that the propellers would turn out to be made of carbon-fibre. These propellers are far more expensive and less good for the recyclability. The recycling of carbon fibre is upcoming. Because carbon fiber is more and more used in the aerospace and automotive industries, also the recycling of carbon fiber is more and more common and efficient. For example Airbus has set the target of recycling 95% of its carbon fiber used in 2025 [22]. So even if the propellers turned out to be carbon fiber the propellers will be fairly recyclable.

The brushless motor is also recyclable, because it basically only consists of metal parts. In the small brushless motor there is not as much expensive material, such as copper and aluminium, as in bigger electric motors. This does not result in very profitable recycling, but because the casing is also made of metal the whole motor can be recycled. This is always better than throwing valuable material away and adds to the sustainability of the entire drone design. Specialised companies in recycling electric motor exist, which also makes the recycling easier for the customer [23].

6.5. Iterations for Propulsion Design

Six iterations were performed to get to the final design of the propulsion system. The most important parameters that changed during the iteration process are presented in Table 6.4 and Table 6.5.

Table 6.4: *Iteration table 1 of the propulsion system design*

Iteration	Drone mass [kg]	Surface area [m^2]	Thrust req [g]	Motor type	Propeller type	Thrust eff. [g/W]
1	2.00	0.025	6000	T-Motor Navigator MN3510 630KV	T-Motor 13x4.4	7.24
2	2.25	0.025	6750	T-Motor Navigator MN3510 360KV	T-Motor 14x4.8	7.22
3	2.25	0.031	6750	T-Motor Navigator MN3510 360KV	T-Motor 14x4.8	7.22
4	2.19	0.020	6570	Cobra CM-4006/36	Gemfan 12x4.5-ABS	6.02
5	2.11	0.018	6330	Cobra CM-4006/36	Gemfan 12x4.5-ABS	6.02
Final	2.11	0.014	6330	Cobra CM-4006/36	Gemfan 12x4.5-ABS	6.02

Table 6.5: *Iteration table 2 of the propulsion system design*

Iteration	Power req Vmax [W]	Noise [dB]	Motor mass [g]	Propeller mass [g]	Motor price [EU]	Propeller price [EU]
1	536	88.4	97	14.2	75	17.39
2	290	79.4	97	19.2	64	25.07
3	342	82.0	97	19.2	64	25.07
4	272	66.7	93	10.0	46	4.36
5	251	66.1	93	10.0	46	4.36
Final	234	65.6	93	10.0	46	4.36

6.6. Risk Analysis Aerodynamics and Propulsion

New risk have been detected during the design phase which are presented in Table 6.6 together with their likelihood and consequences. The risk mitigation response for every risk is stated in Table 6.7. The risks for the propulsion system are mainly concerning damage or complete failure of the propellers. They could break upon collision during flight of while transporting the drones. There is also the possibility of getting damaged during extreme weather conditions by raindrops.

Table 6.6: *Aerodynamics and propulsion related risks that were discovered in the detailed design.*

ID	Risk	LS	Reason for likelihood	CS	Reason for Consequence
34	Propeller breaking during flight	1	Chances of collision are very low	4	If a propeller breaks the drone will not be able to continue its choreography, but there will be enough thrust left for an emergency landing
35	Propeller breaking during transport	4	Because there are a lot of propellers the likelihood is high that one propeller breaks during the transportation phase	2	Propellers can be changed before operating, so it does not endanger the show
36	Damage to propeller due to rain	2	The force of raindrops is very small	3	Damaging during the show will affect the performance. However, the show can still continue and propellers can be changed afterwards

Table 6.7: *Aerodynamics and propulsion related risks that were discovered in the detailed design.*

ID	Risk	Mitigation Response	LS	CS
34	Propeller breaking during flight	It is difficult to lower the likelihood of collisions, but the consequence score can be reduced by designing the propulsion system such that the drone is able to fly with only three propellers operative	1	3
35	Propeller breaking during transport	The likelihood of propellers breaking during transport can be reduced by using safe boxes. The consequence of a propeller breaking will always be replacement.	3	2
36	Damage to propeller due to rain	The likelihood of damage due to rain can be reduced by selecting a strong material. As a consequence a damaged propeller always have to be replaced.	1	3

Risk 34 concerning propellers breaking due to a collision can not be prevented easily. A collision, however, is not very likely to occur anyway, so it will not form a major problem. In order to reduce the consequence of the risk, the drone has to be able to fly with only three motors operating. This is already incorporated in the design as the drone has been for a T/W ratio of at least three, see Subsection 6.4.1.

A propeller breaking during transport is more likely to happen, which is risk 35. When it happens, the consequence will always be to replace the propeller completely. This is not considered a big problem, since the cost to replace a propellers is minimal. In order to reduce the likelihood of it happening the propellers can be protected, for example by wrapping it in foam. This will be further discussed in Chapter 10.

For risk number 36 an estimation can be made to confirm whether the propeller will be damaged when flying through rain. The chosen propeller is made of carbon fibre, which is a really brittle material. This means that if the propeller is getting noticeably damaged, it is very probable that it will break. Therefore the ultimate tensile strength will be used, because carbon fibre will not permanently deform before that. A calculation will be done to see if the propeller will break during the rainfall requirement. For this again a few assumptions have been made. The propeller is modeled as a beam clamped on one end, Then it is assumed that the raindrop falls on the tip of the propeller, because the rotational speed of the propeller is the highest there and the bending moment will be the largest. It is then analysed whether the bending force of three different raindrops, which was determined in Subsection 6.3.4, stays underneath the maximum tensile stress of carbon fibre. The force was determined by adding the speed of the raindrop and the speed of the propeller and then assuming the raindrop is brought to standstill in the time it covers its own diameter as distance. This force is then converted into the moment by multiplying it with the propeller radius. Then the maximum stress could be determined by using Equation 6.5. It turned out that the maximum stress was $4.7*10^8$. The maximum tensile strength of carbon fibre is $3.5*10^9$. This means that as expected the raindrops will not generate enough force to break the carbon fibre. The propeller will thus not get damaged during rainfall and this risk has been mitigated by picking a carbon fiber propeller.

$$\sigma_{max} = \frac{M * c}{I} \tag{6.5}$$

6.7. Verification and Validation Aerodynamics and Propulsion

To confirm all the conclusions made in the previous sections the tools which were made, have been verified and validated. This is done first by verifying the code of the tools, then by verifying the calculations of the tools and in the end by validating the tools.

6.7.1. Code Verification of Tools

Unit tests are applied to verify the tools used during the subsystem design. Three tools were made: one for noise calculations, one for rain calculations and one for calculations related to the propulsion system. Code verification was done on these tools separately by means of unit tests, which can be found in Table 6.8, Table 6.9 and Table 6.10. Each test has been assigned a tag where VT stands for 'Verification', AE for 'Aerodynamics', PROP for 'Propulsion' and U for 'Unit test'.

Table 6.8: *Unit verification tests for noise*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-AE-U.1	V	RPM	Double RPM, expect V to double	RPM = 2000 gives V = 25 m/s, RPM = 4000 gives V = 50 m/s	Yes
VT-AE-U.2	V	Diameter	Double diameter, expect V to double	D = 9 inch gives V = 24 m/s, D = 18 inch gives V = 48 m/s	Yes
VT-AE-U.3	dB	RPM	Set RPM to zero, expect dB to be zero	RPM = 0 gives dB = 0	Yes

Table 6.9: *Unit verification tests for rain*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-AE-U.4	Sigma_{max}	No. of raindrops on propeller	Double the raindrops, expect the stress to also double	$N_{drops} = 1.5 givessigma = 4.7*10^8$, $N_{drops} = 3 givessigma = 9.4*10^8$	Yes
VT-AE-U.5	Sigma_{max}	Propeller width	Double the propeller width, expect the stress to decrease to become 1/4	$w_{prop} = 0.03048 givessigma = 4.7*10^8$, $w_{prop} = 0.06096 givessigma = 1.18*10^8$	Yes
VT-AE-U.6	Sigma_{max}	Propeller thickness	Double the propeller thickness, expect the stress to halve	$t_{prop} = 0.0009144 givessigma = 4.7*10^8$, $t_{prop} = 0.001828 givessigma = 2.35*10^8$	Yes

Table 6.10: *Unit verification tests for the propulsion system*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-PROP-U.1	V	W	Double W, expect V to scale with sqrt(2)	W = 2 kg gives V = 32.91 m/s, W = 4 kg gives V = 46.54 m/s	Yes
VT-PROP-U.2	Theta	W	Increase W to infinity, expect theta to converge to zero	W = 100000 kg gives theta = 1.015E-05 rad, W = 500000 kg gives theta = 2.092E-06 rad	Yes
VT-PROP-U.3	T	W	For a high W, theta approaches zero such that T per propeller is exactly 25% of W	W = 100000 kg gives T = 25000 kg, W = 200000 kg gives T = 50000 kg	Yes
VT-PROP-U.4	T	Theta	T is expected to stay constant when adding 2pi to theta	Theta = 0.1 gives T = 0.53 kg, Theta = 0.1+2pi gives T = 0.53 kg	Yes
VT-PROP-U.5	P	W	Let W approach zero, expect P to converge to zero	W = 1 kg gives P = 119 W, W = 0.001 kg gives P = 0 W	Yes

6.7.2. Calculation Verification of Tools

To verify if the results of the calculations make sense, they were compared to an external tool. The tool that was used for the comparison is a flight evaluation tool based on the paper "Introduction to Multicopter Design and Control" [17]. A drone which has similar requirements is put into this tool and then compared to the results obtained in Section 6.5. Because of all the assumptions made in the tool that was made, the margin for the difference between the external tool is set to be 20%. In Table 6.11 it can be seen that every property falls within that 20% so the calculations can be assumed to be verified.

Table 6.11: *Calculation verification of the tools*

Output to validate	Value	External value	Error	Margin accepted	V?
V [m/s]	33.3	26.9	-19.2%	20%	Yes
Max RPM [-]	7643	6700	-12.3%	20%	Yes
Power required Vmax [W]	234	191.2	-18.3%	20%	Yes

6.7.3. Validation of tools

Method validation can be used to judge the quality of the analytical results. Unfortunately, this is difficult to to do because of the unique characteristics of the design. Besides, physical experiments will not be possible because the drone will not actually be built. Therefore, only a validation procedure will be discussed in case the drone would have been built or will be built in the future. Once the drone is built, the surface area can be measured accurately. Then the drone can be attached to a device that measures the force applied by the propellers. This setup can be placed in a wind tunnel to simulate different wind conditions. While performing this experiment, the current flowing to the motors can be measured at any point in time. Finally, to compute the power required this current can be multiplied by the voltage. The results of this experiment can be compared to the analytical outcomes which completes the validation procedure.

6.8. Compliance Matrix Aerodynamics and Propulsion

Now that all the characteristics of the aerodynamics and propulsion subsystem of the drone are known, it can be checked if these meet the requirements set in the beginning of the chapter. For this a compliance matrix is setup which can be found in Table 6.12. From this table it can be seen that every requirement is met. Requirements OP-AP-6 and SUS-EO-3 will be further analysed in subsequent chapter and in Chapter 16 there will be confirmed whether these requirements are met for the entire drone.

Table 6.12: *Compliance matrix for the aerodynamics and propulsion subsystem*

TAG	Requirement	Compliance
AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.	Yes
AD-AP-2	The drones shall be able to fly in rainfall up to 10mm/hour	Yes
AD-NR-4	Noise level shall be less than 80decibels at 1 meter from the drone	Yes, 65.6 dB
AD-ATC-5	Operations shall continue up to a height of 1000 m	Yes
AD-SYS-5.1	The drone shall be operable in a pressure range between 101325 Pa and 89401 Pa	Yes
AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg	Yes
AD-SYS-8	The drones shall not affect other drone performance	Yes
AD-SYS-9	The drones shall be able to fly in formation at 2m distance from each other	Yes
POP-AP-2	The drones shall be able to achieve a velocity of 20m/s.	Yes, 33.3 m/s
POP-SYS-2.2	The drones shall have a minimum thrust over weight ratio of 3.	Yes, 3
POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from being able to perform an emergency landing.	Yes

7 Power Subsystem

7.1. Functional and Risk Overview of Power

The goal of the power subsystem is to provide the other subsystems of the drone with the energy they require and to meet the flight time requirements at low cost. This requires selecting a economically efficient battery and ESC system with a low mass and great performance. As mentioned in the functional flow diagram and in the functional breakdown structure the main functions of the power subsystems are:

- To provide power to all subsystems of the drone:
  - To the motors via the ESC
  - To the flight computer/controller
  - To the payload
- Have enough power to be able to have a flight time of:
  - 15 min showtime with heavy payload
  - 20 min showtime with light payload

Risks that were identified prior to the detailed design of the power supply are displayed in Table 7.1. Let it be noted that those do not encompass fully the risks of the power supply, as the detailed design phase will reveal new risks. Those will be discussed in Section 7.4.

Table 7.1: *Risks related to power and their mitigation responses*

ID	Risk	Likelihood	Consequence	Mitigation response
13	Power supply draining too quickly	Very low	Critical	Take the risk.
19	Battery Swelling due to abusive use	Moderate	Critical	Design container with clearance in volume to allow for expansion of the battery.
20	Battery Ignition	Low	Catastrophic	Protect the battery from spreading flames to the rest of the drone.
21	Overdischarge of the battery beyond recommended DoD	Very High	Moderate	Set maximum time limit for show / warn operators to be prepared for heavier maintenance costs due to more frequent battery swaps.

The identified risks are accompanied with appropriate risk mitigations. Implementation of those risk mitigations will take place during the design and when operating the drones after they have been completed.

7.2. List of Requirements Power

The requirements that pertain to the power unit are displayed in Table 7.2

1 hour flight time must be updated, or at least mentioned somewhere that we're not aiming for this value anymore after negotiating

Table 7.2: *Requirements related to Powersubsystem*

Sub-department	TAG	Requirement
Power	POP-AP-3.1	The drones shall be able to fly for 15 minutes for preparations and checkups.
	POP-AP-3.2	The drones shall be able to fly for 15 minutes of showtime with a heavy payload.
	POP-AP-3.8	The drones shall be able to fly for 20 minutes of showtime with a lights as a payload.
	POP-SYS-3.7	The energy storage shall be fully charged within 60min.
	AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg
Sustainability	SUS-AP-1	The drones shall be powered by renewable energy sources.
	SUS-EO-6	The components of the energy storage shall not contaminate the environment.
	SUS-EO-3	At least 80% of drone mass shall be recyclable.
Payload	SP-SYS-1.3.1	The megaphone or speaker shall have a power consumption of 20W
	SP-AP-1.4.2	Future innovations shall have specifications up to a 20W power consumption
	SP-EO-2	Drones shall not sink in the water
Operations	OP-AP-2	The drones shall be suitable for mass transport

7.3. Design for Power

Sizing of the power subsystem's components was conducted according to a process involving evaluation of power required during the flight phases of the drone, as well as regression of battery characteristics based on statistical data.

7.3.1. Data Gathering & Analysis

For the calculations of the different battery characteristics, a database of existing batteries on the market was used [24]. After removing erroneous points among the data (some batteries enlisted missed critical information, such as their mass, or their capacity for example), this database was found to consist of 137 li-po batteries. It includes technical information on capacity, weight, cost and other technical performance characteristics. This allowed for the creation of plots of different of these characteristics, such that relations between them could be established through the method of regression. An example of such a plot can be seen in Figure 7.1. Approximating battery characteristics based on its required capacity was then made possible. It was decided to use this method of statistical regression to produce battery properties throughout the first design iterations, as this method proved to be more time efficient than searching for a specific battery for each iteration. Selection of a specific battery model among those in the database was only performed for iterations 5 onward, as the process narrows down on a final design.

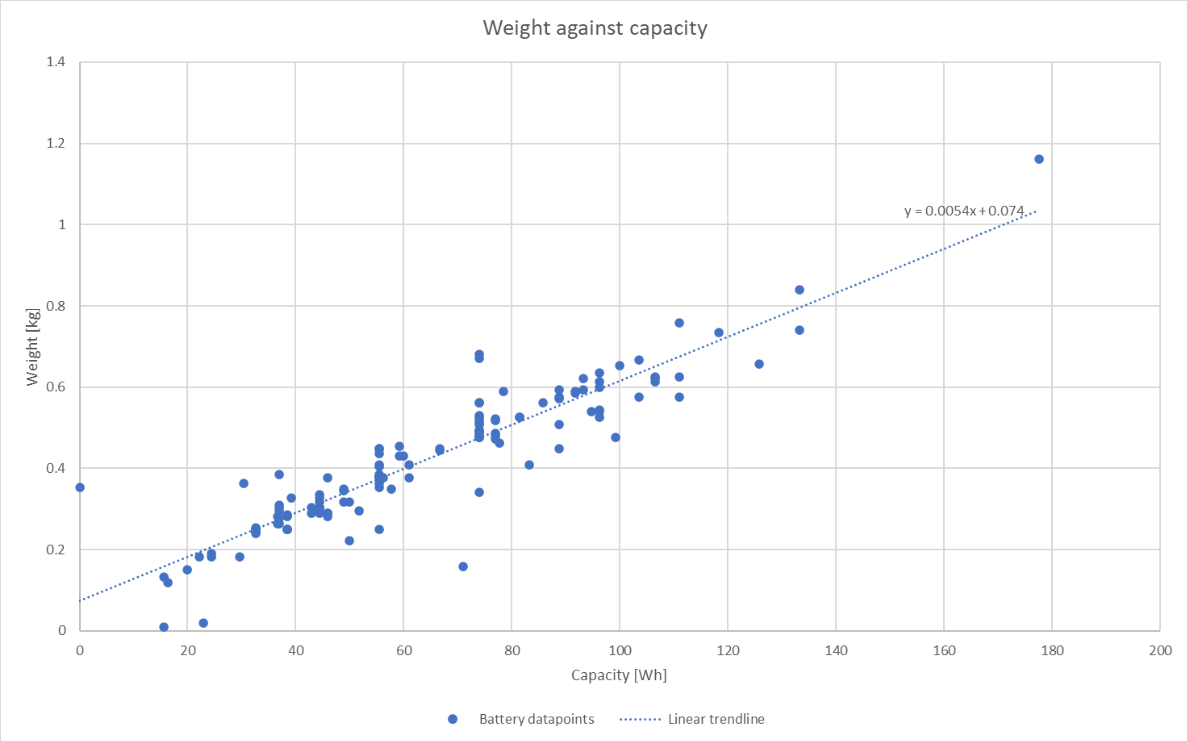


Figure 7.1: *Plot of the battery weight versus capacity. Each point is a singular battery in the database. The whole data set allows for a linear regression.*

7.3.2. Inputs

Obtaining the characteristics of the adequate battery and ESC depends on a number of variables. At the start of each iteration, the latest of these values are used as inputs for the computation of new battery characteristics, and selection of the ESC.

The inputs required are displayed in Table 7.3.

Table 7.3: *The inputs for power calculations.*

Inputs	Symbol	Unit
Power required for flight	P_{flight}	[W]
Power required of flight computer	P_{FC}	[W]
Power required of payload	P_{pl}	[W]
Maximum motor current	$I_{max,m}$	[A]
Battery efficiency	η_{bat}	[-]
Capacity degradation constant	$k_{loss,\%}$	[-]
Depth of Discharge	DoD	[-]
End-of-Life factor	EOL	[-]
Control correction factor	$k_{control}$	[-]
Number of shows in one lifetime	n_{shows}	[-]
Number of flights per show	$\frac{n_{flights}}{show}$	[-]

the input P_{flight} was obtained in the form of a function dependent on the airspeed experienced by the drone ($P_{flight} \rightarrow P_{flight}(V)$). Two of these functions were requested from the propulsion department, one for a drone carrying the heavy payload, the other for the light payload. The battery efficiency is an inherent property of the battery, and can be assumed to be equal to 95%. The depth of discharge, *DoD*, is kept at a value of 80% throughout the design: this ensures that the design will be able to fulfil its mission without draining too much energy from the battery, which may damage it and shorten its lifetime. By adhering to this practice, the mitigation of risk 21 is assured from a design perspective. The capacity degradation constant $k_{loss,\%}$ defines how many percents of the maximum capacity of the battery is lost per cycle. Its value was estimated to be of -0.056% of the Beginning-of-Life capacity per cycle [25]. The end of life factor *EOL* relates to the degradation of the battery over its lifetime. It defines at what percentage of maximum capacity loss the battery is sent to recycle and becomes replaced by a new one. It is set to be equal to 80%, as it is common practice to retire batteries at this state of capacity loss [26]. The control correction factor $k_{control}$ is used as a safety margin to account for small trajectory corrections the drone will perform during flight. It has been assumed to be equal to 5% throughout the whole design phase. Finally, the number of shows and flights per show help determine the amount of battery replacements the drone will have to go through over its lifetime.

7.3.3. Battery Sizing Methodology

The method aims at establishing the total energy required for a given mission. For this, the power required over the time spent in different flight phases must be obtained:

$$E_r = \int P_r dt \tag{7.1}$$

For this, an approximation of the flight phases of a typical mission is created. Those consist of takeoff, travel to initial position for the start of the show, showtime, travel back to the landing pads, and landing. Each flight phase is given an estimated duration (for the travel phases, this estimation is derived from the movement speed of the drone, which is assumed to be equal to its maximum movement speed, 20 m/s, and the distance to travel), and is broken down into a fraction of time spent hovering, and another dedicated to flying at maximum speed. By balancing these two complementary fractions, an estimation of the flight regime of the drone, and the corresponding power required to fly, can be obtained for each flight phase. The power required for each flight phase is built up of the time fractions spent in either flight formation, and the power required for flying in that formation:

$$P_{r,flight} = \%_{hover} \cdot P_{hover} + (1 - \%_{hover}) \cdot P_{move} \tag{7.2}$$

The power required for activating the payload and using the flight computer are added to the power required for flight. This yields the total power required for the given flight phase:

$$P_{r,phase} = P_{r,flight} + P_{computer} + P_{payload} \tag{7.3}$$

From the time spent and power required in each flight phase, the total energy to allocate to each phase can be obtained. Summing all of those energy values yields the total energy the battery shall provide for the mission:

$$E_r = \sum P_{r,phase} \cdot t_{phase} \tag{7.4}$$

This can be calculated for a number of flight situations, depending on wind speeds, average distance between landing pads and show location, or whether the drone is operating a heavy- or a light payload.

In parallel to the computations with regards to power required, a simple model was created, which focuses on the energy available, and the degradation of the battery. First, an estimate of the number of cycles a battery can go through over its lifetime before reaching end of life is performed:

$$n_{cycles} = \frac{EOL - BOL}{k_{loss,\%}} \tag{7.5}$$

Here, the terms *BOL* and *EOL* refer to the beginning- and end-of-life factors, as defined in 7.3.2 (with *BOL* having a similar definition to *EOL*). Let it be noted that, although the theoretical value of *BOL* is 100%, in practice, batteries rarely begin their functional lives at full capacity. This is due to the fact that batteries already experience (small) capacity degradation between their time of production, and time of first use. Another reason for this is the fact that manufacturers tend to overestimate their battery capacities [25]. For this reason, *BOL* is given a value of 95%. This assumption also helps guarantee that, were the final product's energy capacity differ from the value predicted by the model, that value would be higher (and therefore result in a more performant drone) than that of the model.

Then the characteristics of the battery are generated. It can be done either by picking a specific battery from the database, or by the method of regression shown in 7.3.1. From these battery characteristics, the energy capacity is extracted to perform the battery degradation calculations:

$$E_{BOL} = E_{bat} \cdot \frac{\eta_{bat} \cdot DoD \cdot BOL}{(1 + k_{control})} \tag{7.6}$$

$$E_{EOL} = E_{bat} \cdot \frac{\eta_{bat} \cdot DoD \cdot EOL}{(1 + k_{control})} \tag{7.7}$$

Here, E_{BOL} and E_{EOL} refer to the total energy available from the battery at the beginning- and end-of-life, after taking into account battery efficiency, depth of discharge, state of life factors (BOL or EOL) and the controllability safety margin.

These calculations allow for a complete battery degradation prediction model, which takes shape in the form of the following equation:

$$E(t) = k_{loss} \cdot t + E_{BOL} \tag{7.8}$$

$$k_{loss} = \frac{E_{EOL} - E_{BOL}}{n_{cycles}} \tag{7.9}$$

Here, the time variable t is expressed in number of cycles experienced by the battery. The capacity loss coefficient k_{loss} is essentially a translation of $k_{loss,\%}$, which defines the amount of available Wh lost in the battery capacity upon completion of one cycle.

From the generated battery characteristics, an observation of the achievability of possible mission scenarios can be performed. This can be automated in a combined analysis of a large number of scenarios (which vary in wind speeds and show location distance from takeoff area). All of this can then be condensed into the flight envelope of the drone.

BFT	Wind speeds [m/s]	FLIGHT ENVELOPE: HEAVY PAYLOAD														
7	15	63.6	63.8	64	64.1	64.3	64.5	64.7	64.8	65	65.2	65.3	65.5	65.7	65.9	66
7	14.5	63.5	63.6	63.8	64	64.1	64.3	64.5	64.7	64.8	65	65.2	65.4	65.5	65.7	65.9
7	14	63.3	63.5	63.7	63.8	64	64.2	64.3	64.5	64.7	64.9	65	65.2	65.4	65.5	65.7
6	13.5	63.2	63.3	63.5	63.7	63.9	64	64.2	64.4	64.5	64.7	64.9	65	65.2	65.4	65.6
6	13	63	63.2	63.4	63.6	63.7	63.9	64.1	64.2	64.4	64.6	64.7	64.9	65.1	65.2	65.4
6	12.5	62.9	63.1	63.3	63.4	63.6	63.8	63.9	64.1	64.3	64.4	64.6	64.8	64.9	65.1	65.3
6	12	62.8	63	63.2	63.3	63.5	63.7	63.8	64	64.2	64.3	64.5	64.7	64.8	65	65.2
6	11.5	62.7	62.9	63.1	63.2	63.4	63.5	63.7	63.9	64	64.2	64.4	64.5	64.7	64.9	65
6	11	62.6	62.8	63	63.1	63.3	63.5	63.6	63.8	63.9	64.1	64.3	64.4	64.6	64.8	64.9
5	10.5	62.5	62.7	62.9	63	63.2	63.4	63.5	63.7	63.9	64	64.2	64.3	64.5	64.7	64.8
5	10	62.5	62.6	62.8	63	63.1	63.3	63.4	63.6	63.8	63.9	64.1	64.3	64.4	64.6	64.7
5	9.5	62.4	62.5	62.7	62.9	63	63.2	63.4	63.5	63.7	63.8	64	64.2	64.3	64.5	64.7
5	9	62.3	62.5	62.6	62.8	63	63.1	63.3	63.5	63.6	63.8	63.9	64.1	64.3	64.4	64.6
5	8.5	62.3	62.4	62.6	62.7	62.9	63.1	63.2	63.4	63.5	63.7	63.9	64	64.2	64.3	64.5
5	8	62.2	62.4	62.5	62.7	62.8	63	63.2	63.3	63.5	63.6	63.8	64	64.1	64.3	64.4
4	7.5	62.1	62.3	62.5	62.6	62.8	62.9	63.1	63.3	63.4	63.6	63.7	63.9	64.1	64.2	64.4
4	7	62.1	62.3	62.4	62.6	62.7	62.9	63.1	63.2	63.4	63.5	63.7	63.9	64	64.2	64.3
4	6.5	62.1	62.2	62.4	62.5	62.7	62.9	63	63.2	63.3	63.5	63.6	63.8	64	64.1	64.3
4	6	62	62.2	62.3	62.5	62.7	62.8	63	63.1	63.3	63.4	63.6	63.8	63.9	64.1	64.2
4	5.5	62	62.1	62.3	62.5	62.6	62.8	62.9	63.1	63.2	63.4	63.6	63.7	63.9	64	64.2
3	5	62	62.1	62.3	62.4	62.6	62.7	62.9	63.1	63.2	63.4	63.5	63.7	63.8	64	64.2
3	4.5	61.9	62.1	62.2	62.4	62.6	62.7	62.9	63	63.2	63.3	63.5	63.7	63.8	64	64.1
3	4	61.9	62.1	62.2	62.4	62.5	62.7	62.8	63	63.2	63.3	63.5	63.6	63.8	63.9	64.1
3	3.5	61.9	62	62.2	62.4	62.5	62.7	62.8	63	63.1	63.3	63.4	63.6	63.8	63.9	64.1
2	3	61.9	62	62.2	62.3	62.5	62.6	62.8	63	63.1	63.3	63.4	63.6	63.7	63.9	64.1
2	2.5	61.9	62	62.2	62.3	62.5	62.6	62.8	62.9	63.1	63.3	63.4	63.6	63.7	63.9	64
2	2	61.8	62	62.1	62.3	62.5	62.6	62.8	62.9	63.1	63.2	63.4	63.5	63.7	63.9	64
2	1.5	61.8	62	62.1	62.3	62.4	62.6	62.8	62.9	63.1	63.2	63.4	63.5	63.7	63.8	64
1	1	61.8	62	62.1	62.3	62.4	62.6	62.8	62.9	63.1	63.2	63.4	63.5	63.7	63.8	64
1	0.5	61.8	62	62.1	62.3	62.4	62.6	62.7	62.9	63.1	63.2	63.4	63.5	63.7	63.8	64
0	0	61.8	62	62.1	62.3	62.4	62.6	62.7	62.9	63	63.2	63.4	63.5	63.7	63.8	64
	Distance [m]	0	25	50	75	100	125	150	175	200	225	250	275	300	325	350

BFT	Wind speeds [m/s]															
7	15	66.2	66.4	66.6	66.7	66.9	67.1	67.3	67.4	67.6	67.8	67.9	68.1	68.3	68.5	68.6
7	14.5	66	66.2	66.4	66.6	66.7	66.9	67.1	67.2	67.4	67.6	67.8	67.9	68.1	68.3	68.5
7	14	65.9	66	66.2	66.4	66.6	66.7	66.9	67.1	67.2	67.4	67.6	67.8	67.9	68.1	68.3
6	13.5	65.7	65.9	66.1	66.2	66.4	66.6	66.7	66.9	67.1	67.3	67.4	67.6	67.8	67.9	68.1
6	13	65.6	65.7	65.9	66.1	66.3	66.4	66.6	66.8	66.9	67.1	67.3	67.4	67.6	67.8	67.9
6	12.5	65.4	65.6	65.8	65.9	66.1	66.3	66.5	66.6	66.8	67	67.1	67.3	67.5	67.6	67.8
6	12	65.3	65.5	65.7	65.8	66	66.2	66.3	66.5	66.7	66.8	67	67.2	67.3	67.5	67.7
6	11.5	65.2	65.4	65.5	65.7	65.9	66	66.2	66.4	66.5	66.7	66.9	67	67.2	67.4	67.5
6	11	65.1	65.3	65.4	65.6	65.8	65.9	66.1	66.3	66.4	66.6	66.7	66.9	67.1	67.2	67.4
5	10.5	65	65.2	65.3	65.5	65.7	65.8	66	66.1	66.3	66.5	66.6	66.8	67	67.1	67.3
5	10	64.9	65.1	65.2	65.4	65.6	65.7	65.9	66	66.2	66.4	66.5	66.7	66.9	67	67.2
5	9.5	64.8	65	65.1	65.3	65.5	65.6	65.8	66	66.1	66.3	66.4	66.6	66.8	66.9	67.1
5	9	64.7	64.9	65.1	65.2	65.4	65.6	65.7	65.9	66	66.2	66.4	66.5	66.7	66.8	67
5	8.5	64.7	64.8	65	65.2	65.3	65.5	65.6	65.8	66	66.1	66.3	66.4	66.6	66.8	66.9
5	8	64.6	64.8	64.9	65.1	65.2	65.4	65.6	65.7	65.9	66	66.2	66.4	66.5	66.7	66.8
4	7.5	64.5	64.7	64.9	65	65.2	65.3	65.5	65.7	65.8	66	66.1	66.3	66.5	66.6	66.8
4	7	64.5	64.6	64.8	65	65.1	65.3	65.4	65.6	65.8	65.9	66.1	66.2	66.4	66.6	66.7
4	6.5	64.4	64.6	64.8	64.9	65.1	65.2	65.4	65.5	65.7	65.9	66	66.2	66.3	66.5	66.7
4	6	64.4	64.6	64.7	64.9	65	65.2	65.3	65.5	65.7	65.8	66	66.1	66.3	66.4	66.6
4	5.5	64.4	64.5	64.7	64.8	65	65.1	65.3	65.5	65.6	65.8	65.9	66.1	66.2	66.4	66.6
3	5	64.3	64.5	64.6	64.8	64.9	65.1	65.3	65.4	65.6	65.7	65.9	66	66.2	66.4	66.5
3	4.5	64.3	64.4	64.6	64.8	64.9	65.1	65.2	65.4	65.5	65.7	65.9	66	66.2	66.3	66.5
3	4	64.3	64.4	64.6	64.7	64.9	65	65.2	65.3	65.5	65.7	65.8	66	66.1	66.3	66.4
3	3.5	64.2	64.4	64.5	64.7	64.9	65	65.2	65.3	65.5	65.6	65.8	65.9	66.1	66.3	66.4
2	3	64.2	64.4	64.5	64.7	64.8	65	65.1	65.3	65.5	65.6	65.8	65.9	66.1	66.2	66.4
2	2.5	64.2	64.3	64.5	64.7	64.8	65	65.1	65.3	65.4	65.6	65.7	65.9	66.1	66.2	66.4
2	2	64.2	64.3	64.5	64.6	64.8	65	65.1	65.3	65.4	65.6	65.7	65.9	66	66.2	66.4
2	1.5	64.2	64.3	64.5	64.6	64.8	64.9	65.1	65.2	65.4	65.6	65.7	65.9	66	66.2	66.3
1	1	64.1	64.3	64.5	64.6	64.8	64.9	65.1	65.2	65.4	65.5	65.7	65.9	66	66.2	66.3
1	0.5	64.1	64.3	64.5	64.6	64.8	64.9	65.1	65.2	65.4	65.5	65.7	65.9	66	66.2	66.3
0	0	64.1	64.3	64.4	64.6	64.8	64.9	65.1	65.2	65.4	65.5	65.7	65.8	66	66.2	66.3
	Distance [m]	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725

BFT	Wind speeds [m/s]															
7	15	68.8	69	69.2	69.3	69.5	69.7	69.9	70	70.2	70.4	70.5	70.7	70.9	71.1	71.2
7	14.5	68.6	68.8	69	69.1	69.3	69.5	69.7	69.8	70	70.2	70.3	70.5	70.7	70.9	71
7	14	68.4	68.6	68.8	69	69.1	69.3	69.5	69.6	69.8	70	70.2	70.3	70.5	70.7	70.8
6	13.5	68.3	68.4	68.6	68.8	68.9	69.1	69.3	69.5	69.6	69.8	70	70.1	70.3	70.5	70.6
6	13	68.1	68.3	68.4	68.6	68.8	69	69.1	69.3	69.5	69.6	69.8	70	70.1	70.3	70.5
6	12.5	68	68.1	68.3	68.5	68.6	68.8	69	69.1	69.3	69.5	69.6	69.8	70	70.1	70.3
6	12	67.8	68	68.2	68.3	68.5	68.7	68.8	69	69.2	69.3	69.5	69.7	69.8	70	70.2
6	11.5	67.7	67.9	68	68.2	68.4	68.5	68.7	68.9	69	69.2	69.3	69.5	69.7	69.8	70
6	11	67.6	67.7	67.9	68.1	68.2	68.4	68.6	68.7	68.9	69.1	69.2	69.4	69.5	69.7	69.9
5	10.5	67.5	67.6	67.8	67.9	68.1	68.3	68.4	68.6	68.8	68.9	69.1	69.3	69.4	69.6	69.8
5	10	67.4	67.5	67.7	67.8	68	68.2	68.3	68.5	68.7	68.8	69	69.1	69.3	69.5	69.6
5	9.5	67.3	67.4	67.6	67.7	67.9	68.1	68.2	68.4	68.6	68.7	68.9	69	69.2	69.4	69.5
5	9	67.2	67.3	67.5	67.7	67.8	68	68.1	68.3	68.5	68.6	68.8	68.9	69.1	69.3	69.4
5	8.5	67.1	67.2	67.4	67.6	67.7	67.9	68	68.2	68.4	68.5	68.7	68.9	69	69.2	69.3
5	8	67	67.2	67.3	67.5	67.6	67.8	68	68.1	68.3	68.4	68.6	68.8	68.9	69.1	69.3
4	7.5	66.9	67.1	67.3	67.4	67.6	67.7	67.9	68.1	68.2	68.4	68.5	68.7	68.9	69	69.2
4	7	66.9	67	67.2	67.4	67.5	67.7	67.8	68	68.1	68.3	68.5	68.6	68.8	68.9	69.1
4	6.5	66.8	67	67.1	67.3	67.5	67.6	67.8	67.9	68.1	68.2	68.4	68.6	68.7	68.9	69
4	6	66.8	66.9	67.1	67.2	67.4	67.6	67.7	67.9	68	68.2	68.3	68.5	68.7	68.8	69
4	5.5	66.7	66.9	67	67.2	67.3	67.5	67.7	67.8	68	68.1	68.3	68.4	68.6	68.8	68.9
3	5	66.7	66.8	67	67.1	67.3	67.5	67.6	67.8	67.9	68.1	68.2	68.4	68.6	68.7	68.9
3	4.5	66.6	66.8	66.9	67.1	67.3	67.4	67.6	67.7	67.9	68	68.2	68.4	68.5	68.7	68.8
3	4	66.6	66.8	66.9	67.1	67.2	67.4	67.5	67.7	67.9	68	68.2	68.3	68.5	68.6	68.8
3	3.5	66.6	66.7	66.9	67	67.2	67.4	67.5	67.7	67.8	68	68.1	68.3	68.4	68.6	68.8
2	3	66.5	66.7	66.9	67	67.2	67.3	67.5	67.6	67.8	68	68.1	68.3	68.4	68.6	68.7
2	2.5	66.5	66.7	66.8	67	67.1	67.3	67.5	67.6	67.8	67.9	68.1	68.2	68.4	68.5	68.7
2	2	66.5	66.7	66.8	67	67.1	67.3	67.4	67.6	67.8	67.9	68.1	68.2	68.4	68.5	68.7
2	1.5	66.5	66.6	66.8	67	67.1	67.3	67.4	67.6	67.7	67.9	68	68.2	68.4	68.5	68.7
1	1	66.5	66.6	66.8	66.9	67.1	67.3	67.4	67.6	67.7	67.9	68	68.2	68.3	68.5	68.7
1	0.5	66.5	66.6	66.8	66.9	67.1	67.2	67.4	67.6	67.7	67.9	68	68.2	68.3	68.5	68.6
0	0	66.5	66.6	66.8	66.9	67.1	67.2	67.4	67.6	67.7	67.9	68	68.2	68.3	68.5	68.6
	Distance [m]	750	775	800	825	850	875	900	925	950	975	1000	1025	1050	1075	1100

Figure 7.2: *Flight envelope of the drone. This particular envelope was the result of the 4th iteration, for the case of the drone carrying a heavy payload.*

Figure 7.2 shows an example of the flight envelope. Let it be noted that the term "flight envelope" does not conventionally refer to the graph shown here, at least not within the context of aircraft design. However, it was deemed appropriate to use this terminology for this purpose, as it displays similar information to conventional flight envelopes (a space defined by set conditions, displaying combinations of conditions which result in an achievable mission). For the purposes of the flight envelope created, as can be seen from Figure 7.2, the space is composed of two variables, the wind speed, as well as the distance between the landing pad and the show location. These variables influence the travel time before and after the show, and the power required for flight throughout the whole mission (as heavier winds and poorer weather conditions cause the drone to require more power). From the graph, it seems that moving away from the energy increases the energy required for the mission. This is logical, as flying farther and against heavier winds leads to more energy consumption. The space is divided into three regions, distinguished by the following color code:

- Green: for the specified battery, the mission is achievable for most states of life, even "old" batteries, which have gone through a large number of cycles.
- Yellow: for the specified battery, the mission is achievable, but "old" batteries which have undergone a large number of discharge cycles will not be able to fulfil the mission, or do so with difficulty.
- Red: the mission is questionably achievable. Batteries must be "young"/close to brand new to achieve the mission.

Two additional regions are present, which are not visible in the diagram, but are nonetheless important to mention:

- A "bright green" region, which indicates the scenarios possible for all batteries, at all states of life, even when they have reached their EOL.
- A "bright red" region, which indicates the scenarios which are unachievable, even for a brand new battery that hasn't been through any discharge cycles.

As batteries become older, their total capacity decreases and they become less suited for missions under harsh conditions: their utility becomes more constrained, and their ability to fulfil their mission narrows down to a smaller portion of the graph, focalised around the bottom left area.

One last particular note to mention: in order to delimit the three regions, a definition must be set on what a "young" or an "old" battery means. These terms are simply defined by a number of cycles experienced: those delimitations are set at 100 cycles, and 200 cycles, respectively.

The flight envelope allows for the confirmation of the adequacy of a certain power unit. Throughout all iterations, the choice of a set of battery characteristics (either by regression or by selection of a specific data point) with satisfying capacity performance in the flight envelope lead to a final size of the power unit. Those characteristics are the outputs of the iteration process, and are discussed in Subsection 7.3.6.

7.3.4. Electronic Speed Controller selection

Selection of the ESC was previously conducted according to an available database [2, 27]. However, it was found to be rather outdated, and could not allow for an estimation of the ESC cost, as the prices of each item were not part of the database. This led to the decision of building a custom ESC database, which is more appropriate for the purposes of the project at hand. This was done by documenting adequate characteristics from commercially available ESCs (a total of 41 ESCs were analysed). The main sizing requirement for the choice of the ESC is the maximum current the motors can withstand. A secondary factor to consider during selection of the ESC is the compatibility with the battery: ESCs are given a voltage range, expressed in number of lipo cells at which the ESC can properly operate. This voltage range is not considered during design, but is checked at the end of each iteration, to ensure that the battery and the ESC are compatible with each other. Analysis of the database yielded the conclusion that price was the most important factor to minimise, as ESCs tend to be very lightweight, and it can safely be assumed that their contribution to the total mass of the drone will be very marginal.

Among other potential considerations, the choice of configuration of the ESC is worthy of mentioning: quadcopters are a very popular design configuration for multirotor drones, and as such, a lot of companies offer their ESCs in a "4 in 1" configuration, which covers the control capabilities for 4 separate rotors in one single ESC. 4 in 1 ESCs tend to be cheaper and more compact than singular ESCs, but cost more in terms of maintenance (a broken 4 in 1 ESC must be replaced entirely).

7.3.5. Battery Management System

To ensure the safe operation of the battery during flight and to prevent it from overcharge or overdischarge, as well as provide information about the battery state of life, a Battery Management System (or BMS) must be added to the design. It acts as a safety bridge between the battery and the charging load, and can balance the charge level of each individual cell, to help reduce battery damage.

Initial investigation of the BMS was conducted, the selection of the BMS will mainly depend on the charging and discharging amperage. Those values can be obtained from the mission duration or the charging time, and total battery capacity. BMS chips are also designed with a number of lipo cells in mind. Ensuring that the BMS is compatible with the battery is another important factor to keep in mind during selection.

Acquisition of a final BMS model to implement within the system could not be performed. It is recommended to evaluate possible BMS solutions for the drone in the future, as the design becomes more detailed.

7.3.6. Outputs

As mentioned in Subsection 7.3.3, each iteration terminates with the acquisition of battery characteristics which are suitable for the mission at hand. The obtained characteristics for each iteration are displayed in Table 7.4. Iterations 1 through 4 used statistical regressions from the database, while iterations 5 and 6 were conducted with the selection of a specific battery. It can be observed that the battery characteristics improve over time, with the exception of iteration 4, which results in a heavier, larger, and more expensive battery than iteration 3. This is due to the fact that this iteration saw a significant increase in the power required for flight, due to the reduction of the propeller size. This led to the necessity for more power, more energy, and therefore a larger battery. However, as further iteration progressed, it was made possible to further reduce the size of the battery, as it was possible to obtain singular batteries with better performance characteristics than those normally predicted by regression. This allowed for lighter batteries, with better capacities, which lowered the weight of the drone for the following iteration, and allowed for further reduction of the power required.

Table 7.4: *Battery iteration table*

Iteration	Mass [kg]	Dimensions [mm × mm × mm]	Capacity [Wh]	Voltage [V]	Maintenance cost [Euro]	Production costs [Euro]
Statisitcs	0.36	135 × 42 × 44	145	14.8	544.03	41.85
1	0.86	170.91 × 56.74 × 43.94	144.58	14.8	714.59	119.1
2	0.71	163.42 × 54.25 × 42.02	117.85	14.8	455.74	81.38
3	0.60	157.11 × 52.15 × 40.40	97.14	14.8	378.19	67.53
4	0.65	159.99 × 53.11 × 41.13	106.37	14.8	550.35	73.71
5	0.62	139 × 47 × 48.5	106.56	14.8	434.71	58.22
Final	0.58	152 × 46 × 37	103.6	14.8	446.95	59.86

A few more specifications can be mentioned with regards to the selected battery for the final iteration. The model in question is produced by manufacturer "Zeee". It is a 4-S lipo battery with a charge capacity of 7000 mAh. Although priced at 72.99$ (60.21£) on Amazon [28], it has been assumed that the price of purchase for our purposes would be lower, as buying a large quantity of batteries directly from the manufacturer will reduce expenses. It has been assumed that the retailer entertained a 20% profit margin, which could be cut from purchasing expenses by buying directly from the manufacturer. This assumption stems from typical margins encountered in the industry []. The specifications of the battery indicate a charge rate of maximum 1C, which corresponds to a charging amperage of 7 A, or a charging time of 1 hour for a completely empty battery (with DoD = 100%).Accounting for the fact that normal usage of the batteries will only require to recharge 80% of their capacity, requirement POP-SYS-3.7 (The energy storage shall be fully charged within 60min) is satisfied.

The battery characteristics obtained from the final iteration yielded the flight envelopes shown in Figure 7.3 and Figure 7.4. The first consideration to be made with respect to these diagrams is that the most power hungry case seems to be the light payload. At first it may seem counter intuitive, as the light payload requires less power, and therefore should consume less energy. That is indeed correct, however, the missions for heavy and light payload also differ in showtime duration. While the drone is required to operate a heavy payload for only 15 minutes of showtime, it must be able to conduct a show with a light payload for 20 minutes. This explains where the higher energy consumption in the light payload case comes from.

Another important note to consider is the fact that the "bright green" region has now made its appearance in the flight envelope: this means that some mission cases will always be fulfilled, even with batteries which are at their end-of-life. Furthermore, a heavy portion of the graph is achievable by all batteries which have been submitted to 200 cycles or more. For harsher missions (the yellow region), battery state checks should be preformed prior to the mission to ensure that the state of life of the battery will allow for the mission to be completed. Overall, the flight envelopes displayed show a rather satisfactory result, as the battery selected will be able to provide enough energy for the fulfilment of missions under 6 BFT wind conditions, as well as missions with show location distances of 1000 m (in some cases, the battery may even have enough energy to fulfil missions beyond those requirements, but this consideration is not of relevance to the design, as the drone will be limited in other design aspects, such as the reach of the communication signal for example). The selected battery will comply with the set endurance requirements.

FLIGHT ENVELOPE: HEAVY PAYLOAD

BFT	Wind speeds [m/s] \ Distance [m]	0	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800	825	850	875	900	925	950	975	1000	1025	1050	1075	1100
7	15	59.80	59.96	60.11	60.27	60.42	60.58	60.73	60.89	61.04	61.20	61.35	61.51	61.66	61.82	61.97	62.13	62.28	62.44	62.59	62.75	62.90	63.06	63.22	63.37	63.53	63.68	63.84	63.99	64.15	64.30	64.46	64.61	64.77	64.92	65.08	65.23	65.39	65.54	65.70	65.85	66.01	66.16	66.32	66.47	66.63
7	14.5	59.72	59.87	60.03	60.18	60.34	60.49	60.64	60.80	60.95	61.11	61.26	61.42	61.57	61.73	61.88	62.04	62.19	62.34	62.50	62.65	62.81	62.96	63.12	63.27	63.43	63.58	63.73	63.89	64.04	64.20	64.35	64.51	64.66	64.82	64.97	65.13	65.28	65.43	65.59	65.74	65.90	66.05	66.21	66.36	66.52
7	14	59.64	59.79	59.95	60.10	60.25	60.41	60.56	60.72	60.87	61.02	61.18	61.33	61.49	61.64	61.79	61.95	62.10	62.26	62.41	62.56	62.72	62.87	63.02	63.18	63.33	63.49	63.64	63.79	63.95	64.10	64.26	64.41	64.56	64.72	64.87	65.02	65.18	65.33	65.49	65.64	65.79	65.95	66.10	66.26	66.41
6	13.5	59.57	59.72	59.87	60.03	60.18	60.33	60.49	60.64	60.79	60.95	61.10	61.25	61.41	61.56	61.71	61.87	62.02	62.17	62.32	62.48	62.63	62.78	62.94	63.09	63.24	63.40	63.55	63.70	63.86	64.01	64.16	64.32	64.47	64.62	64.78	64.93	65.08	65.24	65.39	65.54	65.70	65.85	66.00	66.16	66.31
6	13	59.50	59.65	59.80	59.96	60.11	60.26	60.41	60.57	60.72	60.87	61.03	61.18	61.33	61.48	61.64	61.79	61.94	62.09	62.25	62.40	62.55	62.70	62.86	63.01	63.16	63.31	63.47	63.62	63.77	63.93	64.08	64.23	64.38	64.54	64.69	64.84	64.99	65.15	65.30	65.45	65.60	65.76	65.91	66.06	66.21
6	12.5	59.44	59.59	59.74	59.89	60.04	60.20	60.35	60.50	60.65	60.80	60.96	61.11	61.26	61.41	61.56	61.72	61.87	62.02	62.17	62.32	62.48	62.63	62.78	62.93	63.09	63.24	63.39	63.54	63.69	63.85	64.00	64.15	64.30	64.45	64.61	64.76	64.91	65.06	65.21	65.37	65.52	65.67	65.82	65.97	66.13
6	12	59.38	59.53	59.68	59.83	59.98	60.13	60.29	60.44	60.59	60.74	60.89	61.04	61.20	61.35	61.50	61.65	61.80	61.95	62.10	62.26	62.41	62.56	62.71	62.86	63.01	63.16	63.32	63.47	63.62	63.77	63.92	64.07	64.23	64.38	64.53	64.68	64.83	64.98	65.13	65.29	65.44	65.59	65.74	65.89	66.04
6	11.5	59.32	59.47	59.62	59.78	59.93	60.08	60.23	60.38	60.53	60.68	60.83	60.98	61.13	61.29	61.44	61.59	61.74	61.89	62.04	62.19	62.34	62.49	62.64	62.80	62.95	63.10	63.25	63.40	63.55	63.70	63.85	64.00	64.15	64.31	64.46	64.61	64.76	64.91	65.06	65.21	65.36	65.51	65.66	65.82	65.97
6	11	59.27	59.42	59.57	59.72	59.87	60.02	60.18	60.33	60.48	60.63	60.78	60.93	61.08	61.23	61.38	61.53	61.68	61.83	61.98	62.13	62.28	62.43	62.58	62.73	62.88	63.03	63.18	63.34	63.49	63.64	63.79	63.94	64.09	64.24	64.39	64.54	64.69	64.84	64.99	65.14	65.29	65.44	65.59	65.74	65.89
5	10.5	59.23	59.38	59.53	59.68	59.83	59.98	60.13	60.28	60.43	60.58	60.73	60.88	61.03	61.18	61.33	61.48	61.63	61.78	61.93	62.08	62.23	62.38	62.53	62.68	62.83	62.98	63.13	63.28	63.43	63.58	63.73	63.88	64.03	64.18	64.33	64.48	64.63	64.78	64.93	65.08	65.23	65.38	65.53	65.68	65.83
5	10	59.18	59.33	59.48	59.63	59.78	59.93	60.08	60.23	60.38	60.53	60.68	60.83	60.98	61.13	61.28	61.43	61.58	61.73	61.87	62.02	62.17	62.32	62.47	62.62	62.77	62.92	63.07	63.22	63.37	63.52	63.67	63.82	63.97	64.12	64.27	64.42	64.57	64.72	64.87	65.02	65.17	65.32	65.46	65.61	65.76
5	9.5	59.14	59.29	59.44	59.59	59.74	59.89	60.04	60.19	60.34	60.49	60.63	60.78	60.93	61.08	61.23	61.38	61.53	61.68	61.83	61.98	62.13	62.27	62.42	62.57	62.72	62.87	63.02	63.17	63.32	63.47	63.62	63.77	63.92	64.06	64.21	64.36	64.51	64.66	64.81	64.96	65.11	65.26	65.41	65.56	65.71
5	9	59.11	59.25	59.40	59.55	59.70	59.85	60.00	60.15	60.30	60.45	60.59	60.74	60.89	61.04	61.19	61.34	61.49	61.64	61.78	61.93	62.08	62.23	62.38	62.53	62.68	62.83	62.97	63.12	63.27	63.42	63.57	63.72	63.87	64.02	64.16	64.31	64.46	64.61	64.76	64.91	65.06	65.21	65.35	65.50	65.65
5	8.5	59.07	59.22	59.37	59.52	59.67	59.81	59.96	60.11	60.26	60.41	60.56	60.70	60.85	61.00	61.15	61.30	61.45	61.60	61.74	61.89	62.04	62.19	62.34	62.49	62.63	62.78	62.93	63.08	63.23	63.38	63.52	63.67	63.82	63.97	64.12	64.27	64.41	64.56	64.71	64.86	65.01	65.16	65.31	65.45	65.60
5	8	59.04	59.19	59.34	59.49	59.63	59.78	59.93	60.08	60.23	60.37	60.52	60.67	60.82	60.97	61.11	61.26	61.41	61.56	61.71	61.85	62.00	62.15	62.30	62.45	62.60	62.74	62.89	63.04	63.19	63.34	63.48	63.63	63.78	63.93	64.08	64.22	64.37	64.52	64.67	64.82	64.96	65.11	65.26	65.41	65.56
4	7.5	59.01	59.16	59.31	59.46	59.60	59.75	59.90	60.05	60.20	60.34	60.49	60.64	60.79	60.93	61.08	61.23	61.38	61.53	61.67	61.82	61.97	62.12	62.26	62.41	62.56	62.71	62.85	63.00	63.15	63.30	63.45	63.59	63.74	63.89	64.04	64.18	64.33	64.48	64.63	64.77	64.92	65.07	65.22	65.37	65.51
4	7	58.99	59.14	59.28	59.43	59.58	59.73	59.87	60.02	60.17	60.32	60.46	60.61	60.76	60.91	61.05	61.20	61.35	61.49	61.64	61.79	61.94	62.08	62.23	62.38	62.53	62.67	62.82	62.97	63.12	63.26	63.41	63.56	63.71	63.85	64.00	64.15	64.30	64.44	64.59	64.74	64.89	65.03	65.18	65.33	65.47
4	6.5	58.97	59.11	59.26	59.41	59.55	59.70	59.85	60.00	60.14	60.29	60.44	60.58	60.73	60.88	61.03	61.17	61.32	61.47	61.61	61.76	61.91	62.06	62.20	62.35	62.50	62.64	62.79	62.94	63.09	63.23	63.38	63.53	63.67	63.82	63.97	64.12	64.26	64.41	64.56	64.70	64.85	65.00	65.15	65.29	65.44
4	6	58.94	59.09	59.24	59.39	59.53	59.68	59.83	59.97	60.12	60.27	60.41	60.56	60.71	60.85	61.00	61.15	61.29	61.44	61.59	61.74	61.88	62.03	62.18	62.32	62.47	62.62	62.76	62.91	63.06	63.20	63.35	63.50	63.64	63.79	63.94	64.09	64.23	64.38	64.53	64.67	64.82	64.97	65.11	65.26	65.41
4	5.5	58.93	59.07	59.22	59.37	59.51	59.66	59.81	59.95	60.10	60.25	60.39	60.54	60.69	60.83	60.98	61.13	61.27	61.42	61.57	61.71	61.86	62.01	62.15	62.30	62.45	62.59	62.74	62.89	63.03	63.18	63.33	63.47	63.62	63.77	63.91	64.06	64.20	64.35	64.50	64.64	64.79	64.94	65.08	65.23	65.38
3	5	58.91	59.06	59.20	59.35	59.50	59.64	59.79	59.93	60.08	60.23	60.37	60.52	60.67	60.81	60.96	61.11	61.25	61.40	61.55	61.69	61.84	61.98	62.13	62.28	62.42	62.57	62.72	62.86	63.01	63.16	63.30	63.45	63.59	63.74	63.89	64.03	64.18	64.33	64.47	64.62	64.77	64.91	65.06	65.21	65.35
3	4.5	58.89	59.04	59.19	59.33	59.48	59.63	59.77	59.92	60.06	60.21	60.36	60.50	60.65	60.80	60.94	61.09	61.23	61.38	61.53	61.67	61.82	61.97	62.11	62.26	62.40	62.55	62.70	62.84	62.99	63.14	63.28	63.43	63.57	63.72	63.87	64.01	64.16	64.30	64.45	64.60	64.74	64.89	65.04	65.18	65.33
3	4	58.88	59.03	59.17	59.32	59.47	59.61	59.76	59.90	60.05	60.20	60.34	60.49	60.63	60.78	60.93	61.07	61.22	61.36	61.51	61.66	61.80	61.95	62.09	62.24	62.39	62.53	62.68	62.82	62.97	63.12	63.26	63.41	63.56	63.70	63.85	63.99	64.14	64.29	64.43	64.58	64.72	64.87	65.02	65.16	65.31
3	3.5	58.87	59.02	59.16	59.31	59.45	59.60	59.75	59.89	60.04	60.18	60.33	60.48	60.62	60.77	60.91	61.06	61.20	61.35	61.50	61.64	61.79	61.93	62.08	62.23	62.37	62.52	62.66	62.81	62.96	63.10	63.25	63.39	63.54	63.68	63.83	63.98	64.12	64.27	64.41	64.56	64.71	64.85	65.00	65.14	65.29
2	3	58.86	59.01	59.15	59.30	59.44	59.59	59.74	59.88	60.03	60.17	60.32	60.46	60.61	60.76	60.90	61.05	61.19	61.34	61.48	61.63	61.78	61.92	62.07	62.21	62.36	62.50	62.65	62.80	62.94	63.09	63.23	63.38	63.52	63.67	63.82	63.96	64.11	64.25	64.40	64.55	64.69	64.84	64.98	65.13	65.27
2	2.5	58.85	59.00	59.14	59.29	59.43	59.58	59.73	59.87	60.02	60.16	60.31	60.45	60.60	60.75	60.89	61.04	61.18	61.33	61.47	61.62	61.77	61.91	62.06	62.20	62.35	62.49	62.64	62.78	62.93	63.08	63.22	63.37	63.51	63.66	63.80	63.95	64.10	64.24	64.39	64.53	64.68	64.82	64.97	65.12	65.26
2	2	58.85	58.99	59.14	59.28	59.43	59.57	59.72	59.86	60.01	60.16	60.30	60.45	60.59	60.74	60.88	61.03	61.17	61.32	61.47	61.61	61.76	61.90	62.05	62.19	62.34	62.48	62.63	62.78	62.92	63.07	63.21	63.36	63.50	63.65	63.79	63.94	64.09	64.23	64.38	64.52	64.67	64.81	64.96	65.10	65.25
2	1.5	58.84	58.99	59.13	59.28	59.42	59.57	59.71	59.86	60.00	60.15	60.29	60.44	60.59	60.73	60.88	61.02	61.17	61.31	61.46	61.60	61.75	61.89	62.04	62.19	62.33	62.48	62.62	62.77	62.91	63.06	63.20	63.35	63.50	63.64	63.79	63.93	64.08	64.22	64.37	64.51	64.66	64.80	64.95	65.10	65.24
1	1	58.84	58.98	59.13	59.27	59.42	59.56	59.71	59.85	60.00	60.14	60.29	60.44	60.58	60.73	60.87	61.02	61.16	61.31	61.45	61.60	61.74	61.89	62.03	62.18	62.33	62.47	62.62	62.76	62.91	63.05	63.20	63.34	63.49	63.63	63.78	63.93	64.07	64.22	64.36	64.51	64.65	64.80	64.94	65.09	65.23
1	0.5	58.83	58.98	59.12	59.27	59.41	59.56	59.70	59.85	60.00	60.14	60.29	60.43	60.58	60.72	60.87	61.01	61.16	61.30	61.45	61.60	61.74	61.89	62.03	62.18	62.32	62.47	62.61	62.76	62.90	63.05	63.19	63.34	63.49	63.63	63.78	63.92	64.07	64.21	64.36	64.50	64.65	64.79	64.94	65.08	65.23
0	0	58.83	58.98	59.12	59.27	59.41	59.56	59.70	59.85	59.99	60.14	60.28	60.43	60.58	60.72	60.87	61.01	61.16	61.30	61.45	61.59	61.74	61.88	62.03	62.17	62.32	62.47	62.61	62.76	62.90	63.05	63.19	63.34	63.48	63.63	63.77	63.92	64.06	64.21	64.36	64.50	64.65	64.79	64.94	65.08	65.23

Figure 7.3: *Flight envelope of the final iteration: heavy payload case.*

FLIGHT ENVELOPE: LIGHT PAYLOAD

BFT	Wind speeds [m/s] \ Distance [m]	0	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475
7	15	60.74	60.87	60.99	61.12	61.25	61.37	61.50	61.62	61.75	61.88	62.00	62.13	62.25	62.38	62.51	62.63	62.76	62.88	63.01	63.14
7	14.5	60.65	60.78	60.91	61.03	61.16	61.28	61.41	61.53	61.66	61.78	61.91	62.03	62.16	62.28	62.41	62.54	62.66	62.79	62.91	63.04
7	14	60.57	60.70	60.82	60.95	61.07	61.20	61.32	61.45	61.57	61.70	61.82	61.95	62.07	62.20	62.32	62.45	62.57	62.70	62.82	62.94
6	13.5	60.50	60.62	60.74	60.87	60.99	61.12	61.24	61.37	61.49	61.61	61.74	61.86	61.99	62.11	62.24	62.36	62.49	62.61	62.73	62.86
6	13	60.42	60.55	60.67	60.80	60.92	61.04	61.17	61.29	61.41	61.54	61.66	61.79	61.91	62.03	62.16	62.28	62.41	62.53	62.65	62.78
6	12.5	60.36	60.48	60.60	60.73	60.85	60.97	61.10	61.22	61.34	61.47	61.59	61.71	61.84	61.96	62.09	62.21	62.33	62.46	62.58	62.70
6	12	60.29	60.42	60.54	60.66	60.79	60.91	61.03	61.16	61.28	61.40	61.52	61.65	61.77	61.89	62.02	62.14	62.26	62.39	62.51	62.63
6	11.5	60.24	60.36	60.48	60.61	60.73	60.85	60.97	61.10	61.22	61.34	61.46	61.59	61.71	61.83	61.95	62.08	62.20	62.32	62.44	62.57
6	11	60.18	60.31	60.43	60.55	60.67	60.80	60.92	61.04	61.16	61.28	61.41	61.53	61.65	61.77	61.89	62.02	62.14	62.26	62.38	62.51
5	10.5	60.13	60.26	60.38	60.50	60.62	60.74	60.87	60.99	61.11	61.23	61.35	61.47	61.60	61.72	61.84	61.96	62.08	62.21	62.33	62.45
5	10	60.09	60.21	60.33	60.45	60.58	60.70	60.82	60.94	61.06	61.18	61.30	61.43	61.55	61.67	61.79	61.91	62.03	62.15	62.28	62.40
5	9.5	60.05	60.17	60.29	60.41	60.53	60.65	60.77	60.90	61.02	61.14	61.26	61.38	61.50	61.62	61.74	61.86	61.99	62.11	62.23	62.35
5	9	60.01	60.13	60.25	60.37	60.49	60.61	60.73	60.85	60.98	61.10	61.22	61.34	61.46	61.58	61.70	61.82	61.94	62.06	62.18	62.30
5	8.5	59.97	60.09	60.21	60.33	60.46	60.58	60.70	60.82	60.94	61.06	61.18	61.30	61.42	61.54	61.66	61.78	61.90	62.02	62.14	62.26
5	8	59.94	60.06	60.18	60.30	60.42	60.54	60.66	60.78	60.90	61.02	61.14	61.26	61.38	61.50	61.62	61.74	61.86	61.98	62.11	62.23
4	7.5	59.91	60.03	60.15	60.27	60.39	60.51	60.63	60.75	60.87	60.99	61.11	61.23	61.35	61.47	61.59	61.71	61.83	61.95	62.07	62.19
4	7	59.88	60.00	60.12	60.24	60.36	60.48	60.60	60.72	60.84	60.96	61.08	61.20	61.32	61.44	61.56	61.68	61.80	61.92	62.04	62.16
4	6.5	59.86	59.98	60.10	60.22	60.34	60.46	60.58	60.70	60.82	60.94	61.06	61.17	61.29	61.41	61.53	61.65	61.77	61.89	62.01	62.13
4	6	59.84	59.96	60.08	60.20	60.32	60.43	60.55	60.67	60.79	60.91	61.03	61.15	61.27	61.39	61.51	61.63	61.75	61.87	61.99	62.10
4	5.5	59.82	59.94	60.06	60.18	60.29	60.41	60.53	60.65	60.77	60.89	61.01	61.13	61.25	61.37	61.49	61.60	61.72	61.84	61.96	62.08
3	5	59.80	59.92	60.04	60.16	60.28	60.40	60.51	60.63	60.75	60.87	60.99	61.11	61.23	61.35	61.47	61.58	61.70	61.82	61.94	62.06
3	4.5	59.78	59.90	60.02	60.14	60.26	60.38	60.50	60.62	60.74	60.85	60.97	61.09	61.21	61.33	61.45	61.57	61.69	61.80	61.92	62.04
3	4	59.77	59.89	60.01	60.13	60.25	60.36	60.48	60.60	60.72	60.84	60.96	61.08	61.19	61.31	61.43	61.55	61.67	61.79	61.91	62.03
3	3.5	59.76	59.88	60.00	60.11	60.23	60.35	60.47	60.59	60.71	60.83	60.94	61.06	61.18	61.30	61.42	61.54	61.66	61.77	61.89	62.01
2	3	59.75	59.87	59.99	60.10	60.22	60.34	60.46	60.58	60.70	60.81	60.93	61.05	61.17	61.29	61.41	61.52	61.64	61.76	61.88	62.00
2	2.5	59.74	59.86	59.98	60.09	60.21	60.33	60.45	60.57	60.69	60.80	60.92	61.04	61.16	61.28	61.40	61.51	61.63	61.75	61.87	61.99
2	2	59.73	59.85	59.97	60.09	60.21	60.32	60.44	60.56	60.68	60.80	60.91	61.03	61.15	61.27	61.39	61.51	61.62	61.74	61.86	61.98
2	1.5	59.73	59.84	59.96	60.08	60.20	60.32	60.44	60.55	60.67	60.79	60.91	61.03	61.14	61.26	61.38	61.50	61.62	61.74	61.85	61.97
1	1	59.72	59.84	59.96	60.08	60.19	60.31	60.43	60.55	60.67	60.79	60.90	61.02	61.14	61.26	61.38	61.49	61.61	61.73	61.85	61.97
1	0.5	59.72	59.84	59.95	60.07	60.19	60.31	60.43	60.55	60.66	60.78	60.90	61.02	61.14	61.25	61.37	61.49	61.61	61.73	61.85	61.96
0	0	59.72	59.83	59.95	60.07	60.19	60.31	60.43	60.54	60.66	60.78	60.90	61.02	61.13	61.25	61.37	61.49	61.61	61.72	61.84	61.96

BFT	Wind speeds [m/s] \ Distance [m]	500	525	550	575	600	625	650	675	700	725	750	775	800	825	850	875	900	925	950	975	1000	1025	1050	1075	1100
7	15	63.26	63.39	63.51	63.64	63.77	63.89	64.02	64.14	64.27	64.39	64.52	64.65	64.77	64.90	65.02	65.15	65.28	65.40	65.53	65.65	65.78	65.91	66.03	66.16	66.28
7	14.5	63.16	63.29	63.41	63.54	63.66	63.79	63.91	64.04	64.17	64.29	64.42	64.54	64.67	64.79	64.92	65.04	65.17	65.29	65.42	65.54	65.67	65.80	65.92	66.05	66.17
7	14	63.07	63.19	63.32	63.44	63.57	63.69	63.82	63.94	64.07	64.19	64.32	64.44	64.57	64.69	64.82	64.94	65.07	65.19	65.32	65.44	65.57	65.69	65.82	65.94	66.07
6	13.5	62.98	63.11	63.23	63.36	63.48	63.60	63.73	63.85	63.98	64.10	64.23	64.35	64.48	64.60	64.72	64.85	64.97	65.10	65.22	65.35	65.47	65.59	65.72	65.84	65.97
6	13	62.90	63.03	63.15	63.27	63.40	63.52	63.64	63.77	63.89	64.02	64.14	64.26	64.39	64.51	64.64	64.76	64.88	65.01	65.13	65.26	65.38	65.50	65.63	65.75	65.88
6	12.5	62.83	62.95	63.07	63.20	63.32	63.44	63.57	63.69	63.81	63.94	64.06	64.18	64.31	64.43	64.55	64.68	64.80	64.92	65.05	65.17	65.29	65.42	65.54	65.66	65.79
6	12	62.76	62.88	63.00	63.12	63.25	63.37	63.49	63.62	63.74	63.86	63.99	64.11	64.23	64.35	64.48	64.60	64.72	64.85	64.97	65.09	65.22	65.34	65.46	65.58	65.71
6	11.5	62.69	62.81	62.93	63.06	63.18	63.30	63.42	63.55	63.67	63.79	63.92	64.04	64.16	64.28	64.41	64.53	64.65	64.77	64.90	65.02	65.14	65.26	65.39	65.51	65.63
6	11	62.63	62.75	62.87	62.99	63.12	63.24	63.36	63.48	63.61	63.73	63.85	63.97	64.09	64.22	64.34	64.46	64.58	64.71	64.83	64.95	65.07	65.19	65.32	65.44	65.56
5	10.5	62.57	62.69	62.81	62.94	63.06	63.18	63.30	63.42	63.55	63.67	63.79	63.91	64.03	64.15	64.28	64.40	64.52	64.64	64.76	64.89	65.01	65.13	65.25	65.37	65.49
5	10	62.52	62.64	62.76	62.88	63.00	63.13	63.25	63.37	63.49	63.61	63.73	63.85	63.98	64.10	64.22	64.34	64.46	64.58	64.70	64.83	64.95	65.07	65.19	65.31	65.43
5	9.5	62.47	62.59	62.71	62.83	62.95	63.08	63.20	63.32	63.44	63.56	63.68	63.80	63.92	64.04	64.17	64.29	64.41	64.53	64.65	64.77	64.89	65.01	65.13	65.26	65.38
5	9	62.42	62.55	62.67	62.79	62.91	63.03	63.15	63.27	63.39	63.51	63.63	63.75	63.87	64.00	64.12	64.24	64.36	64.48	64.60	64.72	64.84	64.96	65.08	65.20	65.32
5	8.5	62.38	62.50	62.62	62.75	62.87	62.99	63.11	63.23	63.35	63.47	63.59	63.71	63.83	63.95	64.07	64.19	64.31	64.43	64.55	64.67	64.79	64.91	65.04	65.16	65.28
5	8	62.35	62.47	62.59	62.71	62.83	62.95	63.07	63.19	63.31	63.43	63.55	63.67	63.79	63.91	64.03	64.15	64.27	64.39	64.51	64.63	64.75	64.87	64.99	65.11	65.23
4	7.5	62.31	62.43	62.55	62.67	62.79	62.91	63.03	63.15	63.27	63.39	63.51	63.63	63.75	63.87	63.99	64.11	64.23	64.35	64.47	64.59	64.71	64.83	64.95	65.07	65.19
4	7	62.28	62.40	62.52	62.64	62.76	62.88	63.00	63.12	63.24	63.36	63.48	63.60	63.72	63.84	63.96	64.08	64.19	64.31	64.43	64.55	64.67	64.79	64.91	65.03	65.15
4	6.5	62.25	62.37	62.49	62.61	62.73	62.85	62.97	63.09	63.21	63.33	63.45	63.56	63.68	63.80	63.92	64.04	64.16	64.28	64.40	64.52	64.64	64.76	64.88	65.00	65.12
4	6	62.22	62.34	62.46	62.58	62.70	62.82	62.94	63.06	63.18	63.30	63.42	63.54	63.66	63.78	63.89	64.01	64.13	64.25	64.37	64.49	64.61	64.73	64.85	64.97	65.09
4	5.5	62.20	62.32	62.44	62.56	62.68	62.80	62.92	63.03	63.15	63.27	63.39	63.51	63.63	63.75	63.87	63.99	64.11	64.23	64.34	64.46	64.58	64.70	64.82	64.94	65.06
3	5	62.18	62.30	62.42	62.54	62.66	62.77	62.89	63.01	63.13	63.25	63.37	63.49	63.61	63.73	63.84	63.96	64.08	64.20	64.32	64.44	64.56	64.68	64.80	64.92	65.03
3	4.5	62.16	62.28	62.40	62.52	62.64	62.75	62.87	62.99	63.11	63.23	63.35	63.47	63.59	63.70	63.82	63.94	64.06	64.18	64.30	64.42	64.54	64.66	64.77	64.89	65.01
3	4	62.14	62.26	62.38	62.50	62.62	62.74	62.86	62.97	63.09	63.21	63.33	63.45	63.57	63.69	63.81	63.92	64.04	64.16	64.28	64.40	64.52	64.64	64.75	64.87	64.99
3	3.5	62.13	62.25	62.37	62.49	62.60	62.72	62.84	62.96	63.08	63.20	63.31	63.43	63.55	63.67	63.79	63.91	64.03	64.14	64.26	64.38	64.50	64.62	64.74	64.86	64.97
2	3	62.12	62.24	62.35	62.47	62.59	62.71	62.83	62.95	63.06	63.18	63.30	63.42	63.54	63.66	63.78	63.89	64.01	64.13	64.25	64.37	64.49	64.60	64.72	64.84	64.96
2	2.5	62.11	62.22	62.34	62.46	62.58	62.70	62.82	62.93	63.05	63.17	63.29	63.41	63.53	63.64	63.76	63.88	64.00	64.12	64.24	64.35	64.47	64.59	64.71	64.83	64.95
2	2	62.10	62.22	62.33	62.45	62.57	62.69	62.81	62.93	63.04	63.16	63.28	63.40	63.52	63.64	63.75	63.87	63.99	64.11	64.23	64.34	64.46	64.58	64.70	64.82	64.94
2	1.5	62.09	62.21	62.33	62.45	62.56	62.68	62.80	62.92	63.04	63.15	63.27	63.39	63.51	63.63	63.75	63.86	63.98	64.10	64.22	64.34	64.45	64.57	64.69	64.81	64.93
1	1	62.09	62.20	62.32	62.44	62.56	62.68	62.79	62.91	63.03	63.15	63.27	63.39	63.50	63.62	63.74	63.86	63.98	64.09	64.21	64.33	64.45	64.57	64.68	64.80	64.92
1	0.5	62.08	62.20	62.32	62.44	62.55	62.67	62.79	62.91	63.03	63.14	63.26	63.38	63.50	63.62	63.74	63.85	63.97	64.09	64.21	64.33	64.44	64.56	64.68	64.80	64.92
0	0	62.08	62.20	62.32	62.43	62.55	62.67	62.79	62.91	63.02	63.14	63.26	63.38	63.50	63.61	63.73	63.85	63.97	64.09	64.21	64.32	64.44	64.56	64.68	64.80	64.91

Figure 7.4: *Flight envelope of the final iteration: light payload case.*

For the ESC, the product selected is the

Table 7.5: *ESC iteration table*

Iteration	Mass [g]	Dimensions [mm × mm × mm]	Cost [Euro]	Maintenance cost [Euro]
Statistics	25	36 × 36 × 7	46.15	16.30
1	8.5	36 × 36 × 7	14.81	16.30
2	8.5	36 × 36 × 7	14.81	16.30
3	8.5	36 × 36 × 7	14.81	16.30
4	8.5	36 × 36 × 7	14.81	16.30
5	8.5	36 × 36 × 7	14.81	16.30
Final	12.1	30.5 × 30.5 × 7	28.27	16.30

7.4. Risk Analysis Power

Table 7.6: *Power related risks that were discovered in the detailed design.*

ID	Risk	LS	Reason for likelihood	CS	Reason for Consequence
32	Battery Mechanical stresses	2	Risk occurrence reasonably low. Mechanical stresses are not expected during flight, but operators and show personnel may cause accidents	5	Mechanical damage like puncture or dropping the battery can cause the battery to catch fire or to explode

Table 7.7: *Power related risks that were discovered in the detailed design.*

ID	Risk	Mitigation Response	LS	CS
32	Battery mechanical stresses	Carry battery during transport in fire and explosion proof caging (lower likelihood: safer containment. lower consequence: battery damage will not harm or cause damage to environment)	1	3

- Fire/explosion proof container
- Charge in fire/explosion proof casing
- Store in suitable temperature
- Inspection of batteries for any type of damage
- Soldering procedures?
- Special fire extinguisher in case of (chemical) fire
- Don't store batteries at full capacity more then few days

- Don't discharge battery below 20 %
- Enforce maximum flight time duration.

7.5. Verification and Validation Power

The complete methodology described in this chapter was condensed in one tool. The following section will discuss the verification and validation process that was conducted on this tool.

Code Verification
First, it must be said that the power unit sizing tool was built in Microsoft Excel instead of Python. This was done for ease of quick access to multiple team members. The architecture of Microsoft Excel presents some disadvantages with respect to Python. Among them, a reduced flexibility in the freedom of operations, due to a somewhat reduced amount of functions and lack of exhaustive and well documented libraries. However, advantages are present as well: the most important one being the ability to develop the tool faster than in Python, and to implement changes and fixes with instantaneous results.

The tool was thoroughly checked throughout development for errors and inconsistencies such as unexpected orders of magnitudes, divisions by zero, or circular computations. Upon completion of the tool, a series of unit tests was put in place, to verify the correct implementation of the different functions. Those unit tests can be found in Table 7.8. The structure of the information presented is as follows. First a test tag is given for identification purposes (where VT stands for 'Verification', POW for 'Power', U for 'Unit test'). Then the outputs to test and the inputs to change are mentioned, followed by a description of the test and finally its outcome.

Table 7.8: *Unit verification tests of power unit sizing tool.*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-POW-U.1	E_{bat}	m_{bat}	change m_{bat} to the value of the intercept of the regression line (m_{bat} vs E_{bat}), expect E_{bat} to be equal to zero	m_{bat} = 0.074020176491188 kg, E_{bat} = 0 Wh	yes
VT-POW-U.2	V_{bat}	m_{bat}	change m_{bat} to the value of the intercept of the regression line (m_{bat} vs E_{bat}), expect V_{bat} to be equal to the intercept of the regression line (V_{bat} vs E_{bat})	m_{bat} = 0.074020176491188 kg, V_{bat} = 136253.37 mm^3	yes
VT-POW-U.3	$Cost_{bat}$	m_{bat}, $\%_{profit}$	change m_{bat} to the value of the intercept of the regression line (m_{bat} vs E_{bat}), expect $Cost_{bat}$ to be equal to the intercept of the regression line ($Cost_{bat}$ vs E_{bat}) (with an expected retailer profit margin of zero)	m_{bat} = 0.074020176491188 kg, $Cost_{bat}$ = 3.11 €	yes
VT-POW-U.4	$Cost_{bat}$	$\%_{profit}$	set retailer profit margin to 100%, expect battery cost to be equal to zero. Set it to 0%, expect battery price to be the same as the value from the database.	$\%_{profit}$ = 100%, $Cost_{bat}$ = 0 €. $\%_{profit}$ = 0%, $Cost_{bat}$ corresponds exactly with value from the database.	yes
VT-POW-U.5	Flight Envelope	P_{flight}	set P_{flight} to a constant value, independent of airspeed, expect flight envelope results to only vary along the distance axis	P_{flight} = 170, Flight envelope only depends on distance	yes
VT-POW-U.6	Flight Envelopes	P_{flight}, $P_{payload}$, $t_{showtime}$	Set identical input values for both heavy and light payload, expect their flight envelopes to be identical	$P_{flight} = f(V)$, $P_{payload}$ = 20 W, $t_{showtime}$ = 20 min (all values identical for heavy and light payload), flight envelopes are identical	yes
VT-POW-U.7	Flight Envelopes	m_{bat}	set m_{bat} such that battery capacity is zero, expect the flight envelopes to be completely "bright red". set it such that battery capacity is extremely large, expect the flight envelopes to be completely "brigh green"	m_{bat} = 0.074020176491188 kg (E_{bat} = 0 Wh), flight envelopes are completely bright red. m_{bat} = 100000 kg (E_{bat} = 184678213.92 Wh), flight envelopes are completely bright green.	yes
VT-POW-U.8	$P_{r,flight}$	P_{flight}	set P_{flight} equal to zero, expect the flight power required for each phase to be equal to zero	P_{flight} = 0, $P_{r,flight}$ = 0 for all flight phases	yes
VT-POW-U.9	n_{cycles}	$k_{loss,\%}$	double $k_{loss,\%}$, expect n_{cycles} to be halved.	$k_{loss,\%}$ = -0.056%, n_{cycles} = 267.8571429, $k_{loss,\%}$ = -0.112%, n_{cycles} = 133.9285714	yes

VT-POW-U.10	E_{BOL}, E_{EOL}	DoD, η_{bat}	halve the inputs separately, expect E_{BOL} and E_{EOL} to halve	DoD = 0.8, E_{BOL} = 71.2373, E_{EOL} = 59.9893, DoD = 0.4, E_{BOL} = 35.6186, E_{EOL} = 29.9946, η_{bat} = 0.95, E_{BOL} = 71.2373, E_{EOL} = 59.9893, η_{bat} = 0.475, E_{BOL} = 35.6186, E_{EOL} = 29.9946	yes

Calculation Verification

Ensuring that the implementation of the computations within the tool is not sufficient to call the model valid. The obtained model must also be proven to provide realistic and usable values. In order to verify the model, it was decided that an application of the tool on an existing drone would be conducted. No suitable comparison method could be found for evaluating battery degradation or costs. Therefore, this comparison with a commercial product will focus on the endurance calculations. For these purposes, the case of the Mavic 2 Pro from DJI was studied [29]. The following relevant information was retrieved from the product's specification sheet:

- Takeoff weight: 907 grams
- Max hovering time (no wind): 29 minutes
- Battery capacity: 3850 mAh
- Battery Voltage: 15.4 V

Due to the way the tool operates, a number of assumptions needed to be made, to allow for an appropriate estimation of some of the inputs (as there is very little information available regarding some input values, such as flight power for example). The following assumptions will be made:

- the power required is a constant value of 120 W per kg of material in flight, which corresponds to a very efficient system []. This value encompasses power required from the flight computer as well.
- the drone flight profile consists of a singular phase, in which the drone is constantly hovering.
- Depth of discharge is set at 100%. DJI most likely obtained their maximum hovering time of 29 minutes by fully draining the battery.
- η_{bat} remains equal to 95%. It is a typically common value, and stems from dissipation of energy during conversion.
- the battery is assumed to be brand new. the corresponding BOL is taken to be 95%
- there is no payload. All the power drawn from the battery is used for flight. DJI most likely aims for the set of flight conditions which will yield the most optimistic endurance results, to help them advertise their product.
- no control correction factor is applied. The drone performs no manoeuvres, and does not require to counteract on any aerodynamic disturbances: $k_{control} = 0$.

Applying those assumptions to the model, as well as the mass and battery characteristics of the drone to the model yields the following results:

- Total battery capacity: 59.29 Wh
- Battery available energy: 53.51 Wh
- Power required for hovering: 108.84 W
- Total hovering time: 29 min 30 s

The total hovering time computed from the model corresponds well with the 29 minutes of hovering time advertised by DJI. The computation error is:

$$\epsilon = \frac{|29.50 - 29|}{29} = 1.72\% \tag{7.10}$$

Application of the methodology to the case of the DJI drone yields satisfactory results. Ideally, a more deep investigation of the first assumption made in this process (120 W of power required per kg of mass in flight) should be done, as it is not fully certain whether this value is applicable to the presented drone. A future recommendation for the verification of the model would be the case study of the battery degradation estimator.

Validation

Validation of the calculations made in the present chapter would require a fully functional prototype of a drone, such that endurance tests could be performed under different mission scenarios. For these tests, a wind tunnel would be recommended, as the ability to observe the variation of the drone's endurance under different wind speeds would be of significant utility. Additionally, evaluation of the degradation of the battery will require study of the evolution of the capacity over the lifetime of one drone, which is being used in a similar fashion as the expected frequency of usage of the drones to be designed. Repeated charge/discharge would require less time, but will provide inaccurate results, as the battery will not be subjected to the additional degradation caused by time, which contributes heavily to the calendar life of the battery [26].

Implementing those tests will allow for confirmation of the accuracy of the tool. Unfortunately, it is not possible at this stage of the project to acquire or develop a drone prototype, which limits the capability to perform validation. Therefore, focus on the validation of the tool is recommended in the future.

7.6. Compliance Matrix Power

Table 7.9: *Compliance matrix for the power subsystem.*

TAG	Requirement	Compliance
AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.	Yes
		Yes

TEMPERATURE RANGE CHECK : [30]

8

Communication, Control and Electronics Subsystem

In this chapter the communication, control and eletronics subsystem will designed in detail. The midterm report focused on trade-offs on the communication, control and positioning methods that will be used. GPS in combination with RTK was chosen as an outdoor positioning method, while positioning using UWB was selected for indoor situations. Communication will be done over Wi-Fi and radio signals. The show will be uploaded before flight on the drone its memory. In this chapter the communication methods will be further chosen and discussed, hardware will be chosen and a control analysis will be done. This chapter starts by a recap and update of the function and risk overview in Section 8.1. This is followed by a list of relevant requirements presented in Section 8.2. The design for communication will be done in Section 8.3, design for eletronics in Section 8.4 and design for control in Section 8.5. The design is presented in a software diagram shown in Section 8.7. Risk discovered during the detailed design and their mitigation responses are presented in Section 8.8. Verification and validation of the methods and tools used in this chapter are presented in Section 8.9. Finally the compliance matrix is shown in Section 8.10.

8.1. Functional and Risk Overview of CCE

The goal of the communication, control and electronics (CCE) department is to command all subsystems in order to execute the commands received from the ground station. CCE subsystem is the brain of the drone. It's main functions are:

- Control the ESCs
- Control the payload
- Communicate with the ground station
- Provide sensor readings on attitude
- Provide positioning data
- Process the incoming data

CCE subsystem design is divided in following parts:

- Communication
- Electronics
- Control

In the communication part the link budget and different signals received by the drone will be analyzed. The used protocols will be discussed and the communication methods will presented. In the electronics section hardware will be selected and presented. High-level electronic components such as a micro controller and UWB receiver will be selected. Mass, power consumption and costs are calculated. In the control section the controller architecture of the drone is presented. The controller is then applied to the simplified quad copter model.

In Table 8.1 the design risks mentioned in the midterm report[2] related to the CCE department are mentioned. The risks can be mitigated as mentioned in the table by taking measures while designing for the CCE department. Risks discovered during the detailed design of the CCE department will be discussed in the next sections and are grouped in Section 8.8.

Table 8.1: *Risks related to structures and their mitigation responses*

ID	Risk	Likelihood	Consequence	Mitigation response
23	Wi-Fi connection lost during the show	Low	Moderate	Implement a redundant communication system to decrease likelihood. Program an emergency landing mode in case connection is lost.
24	Drone leaves UWB signal range when flying indoors.	Low	Catastrophic	Implement a safety margins between the maximum range and the flight path. Program a manual flight mode.

8.2. List of Requirements Control, Communications and Electronics

The requirements related to the CCE department are presented Table 8.2. Design for CCE will be done in the following sections according to the requirements. In the compliance matrix in Section 8.10 the compliance of the requirements will be assessed.

Table 8.2: *Requirements related to the communications, control and electronics department.*

Sub-department	TAG	Requirement
Electronics	CCE-AP-2.1	There shall be an undisturbed communication to the furthest drone at 1200 m distance.
	CCE-SYS-7	The drone telemetry shall be monitored
	OP-AP-4	The drones shall be operated from a central location
	OP-SYS-10	The energy supply's discharge rate shall be verifiable before every flight
	SR-APC-7	The connection between the ground station and the drone shall be secure.
	SR-SYS-5.2	The operator shall have an emergency stop button
	SR-AP-4:	The connection to the drones shall not be lost during any show, also in urban environments
	CCE-SYS-9	The drones shall be able to be manually controlled.
	SR-ST-4.1	Show shall safely end if connection is lost
	SUS-EO-3	At least 80% of drone mass shall be recyclable.
	OP-AP-3	The drones shall be available in the year 2025
	AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg
	OP-AP-7	The minimum amount of drones in one show shall be 300 for outdoor shows
	OP-AP-8	The minimum amount of drones in one show shall be 20 for indoor shows, where 'indoors' means venues such as concert halls or stadium
Control	SR-AP-5	In case of emergency, the drones shall be able to land safely in less than 90 seconds
	POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from being able to perform an emergency landing.
	SR-AP-3	Malfunctioning of a single drone shall not endanger the entire show
	CCE-SYS-8	Choreography shall be executed.
	CCE-AP-4	The drones shall be able position themselves within 0.5m accuracy

	SP-SYS-1.2.2	The pyrotechnics shall not cause the drone's center of gravity to move outside of the stability and controllabillity margins
	AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.

8.3. Design for Communications

In this section a detailed design for the communication protocols and methods will be discussed. In Subsection 8.3.1 the positioning system and communication protocols are discussed. The required link budget to establish stable communication is presented in Subsection 8.3.2. In Subsection 8.3.3 the command protocols and data transmission methods are discussed.

8.3.1. Protocols

The drones use GPS to navigate outdoors. The positioning accuracy is set to 0.5m by CCE-SYS-9 requrement. This positioning accuracy is not achievable by standard GPS receivers, therefore an RTK receiver is required. Such receiver needs a Radio Technical Commission for Maritime Services (RTCM) data in addition to the phase of the satellite signals. RTCM data is sent from the stationary tower which position is precisely known. Standard RTCM messages include information about the position of the ground station, Ionospheric delay, and properties of the measured carrier wave. RTCM data will be sent to the drones via the radio, because it is faster and less energy consuming than one-to-one messages via WiFi. According to [31] RTCM data for 12 satellites requires data rate of 4800 bits/s.

For indoor navigation UWB modules are used. There are 2 ways to determine drone position: Two way ranging(TWR) and time difference of arrival(TDOA). In TWR technique the drone exchanges messages with each ground beacon one-by-one to determine the distance. This method is more precise, but results in higher power consumption and slower update rate. For TDOA on the other hand, the drone only needs to emit a short pulses at precisely known time stamps. Ground beacons then measure the flight time of the signal and triangulate the drone position. This method is less precise, due to drone and beacon clocks drifting apart, but it saves energy and provides high update rate. A minimum of four UWB tags is needed to provide 3D localization. The range of indoor flight is limited to 290 meters[32] but can be extended when additional tags are added. Expanding the range by adding additional UWB tags will reduce the likelihood of risk 24: the drones flying out of range. The safety margin to prevent drones from reaching the coverage border will be taken into account when programming the choreography.

One of the two communications method between the drones and the ground station is WiFi. By CCE-AP-2.1 the drones can be as far as 1.2 km from the ground station, therefor 2.4 GHz WiFi standard was chosen instead of 5.6 GHz. The lower radio frequencies can propagate further without signal loss.

The second communication system is radio. Most popular radio receiver for UAV applications operate at 2.4 GHz, but this could cause an interference with a WiFi module. There are 2 other legal frequencies in Europe: 433 and 868 MHz. It was decided to use 868 MHz for faster data rate. The modulation type was chosen to be LoRa (Long Range)[33] because of the excellent range performance.

8.3.2. Link budget

The link budget was calculated for WiFi and radio links. According to [34], the link budget equation is :

$$P_{Tx}+G_{Tx}+G_{Rx}-L_{fs}-FM-S_{Rx}>0 \tag{8.1}$$

The terms from left to right are: transmitter power, transmitter antenna gain, receiver antenna gain, Free space loss, fade margin and sensitivity of the receiver. All quantities are in dBm or dB. Free space loss is dependent on the distance d in km and frequency f in MHz of the carrier wave.

$$L_{fs} = 20log(0.621d) + 20log(f) + 36.58 \tag{8.2}$$

Fade margin is the ratio of minimum detectable signal power to the desired signal power. This factor is applied to increase the reliability of the connection. For this analysis it was set to 10 dB,as recommended in [34]. Other parameters in this equation depend on the receiver and transmitter properties. The full link budget will be presented in Section 8.4.

A stable connection is dependent on many variables and is difficult to measure. A procedure can be setup to ensure minimal chances a disturbed signal. First of all, the link budget shall be closed with an additional margin. The bigger the margin is the more excess power there will be, which will result in a higher signal to noise ratio. This is beneficial to a more stable connection. This measure can be implemented by selection appropriate hardware. Secondly, a clear line of sight will decrease the risk of signal loss. If signal is transmitted over longer ranges, objects in the line of sight will greatly impact the received signal. The data rate will drop significantly or the connection will fully break up. This is a newly discovered risk and a solution to signal loss of signal is implemented in Subsection 8.3.3. Finally it is recommended to keep objects such as wireless devices, microwaves, refrigerators and monitors away from the line of sight[35]. Rainfall will influence wireless signals but the effect in not fully know. Further research may provide more insights in the extra link budget required to provide undisturbed communication. While designing it should be acknowledged that an additional margin of unknown magnitude shall be added to the link budget to prevent signal loss. When all these measures are taken into account and the link budget is closed, an undisturbed connection in urban environments can be established and requirement SR-AP-4 will be met.

8.3.3. Commands and Data Transmission

All drones will be operated by a single ground stations on the ground as mentioned by requirement OP-AP-4 and OP-AP-5. This will require the drones to be communicating directly to this point on the ground. Design for such a ground station is out of the scope of the project however, the technological readiness for such a ground station has to be verified.

Commands send over radio signals can be send to all drones at the same time. This can be done by sending an identifier followed by the command. Hereby the response will be instant for every drone. This will be necessary for sending high priority commands such as the start, stop and emergency stop. By implementing this communication method requirement SR-SYS-5.2 is met. All drones can read the commands using the identifier send. The identifier can also be used to provide a more secure signal to limit vulnerability for hackers or signal jammers. Hereby requirement SR-APC-7 is met when communicating over radio signals. Drones can be individually approached using the identifiers. Manual control will be done over radio signals as the link budget for radio signal has a higher margin, which will be shown in Section 8.4. The data rate of radio signals is high enough to fly manually.

Wi-Fi requires a one-to-one connection to sent data. Therefore it is not suitable to send commands to all drones simultaneously trough Wi-Fi, as all drones would have to be approached one after each other. The commands would not be received instantly by every drone. Wi-Fi will be suitable for uploading the choreography on the drones, in-flight flight path adjustments and sending commands to individual drones. Wi-Fi features a high data rate, which is beneficial when uploading large data packets on the drone. Simple Wi-Fi routers used in home situations can host up to 32 devices, while professional routers can up that number to 300 devices. A drawback is that the maximum data rate drops with every additional connected device. When the drones are on the ground, the choreography can be uploaded one by one. If mid air adjustments are required, such as interaction between an actor on stage and the drone it's flight path, the data rate can be limiting when adjusting 300 flight paths at the same instance. However, this will mostly occur at indoor venues where it is required to fly with only 20 drones as stated by requirement OP-AP-8 and therefore the data rate will not be limiting. The drone will be able to send telemetry to the ground station using Wi-Fi. Malfunctioning drones can be detected by monitoring the telemetry and manual control can be taken in case needed. Wi-Fi is suitable to monitor the telemetry and therefore requirement CCE-SYS-7 is met. Measuring the battery its discharge rate is part of the selft diagnosis and the data will be send with the telemetry. Telemetry can be send to the ground station before the drones take-off from the landing pad. Therefore requirement OP-SYS-10 is met. Just like radio, the Wi-Fi connection can be made secure by encrypting the signal. This has to be done before data is sent to the Wi-Fi receiver. The data shall be decypted before it can be read. The impact in processing power will scale with the level of encryption. As the risk for a hacked signal is low, the level of encryption has to be minimal and therefore the reduced processing power is negligible. By implementing this requirement SR-APC-7 is also met for Wi-Fi communication.

As mentioned at the beginning of this section, the drones will be operated from a single location on the ground. Wi-Fi and radio communication allows for such a ground station and connectivity up to 300 devices. Therefore requirement OP-AP-4 is met. The drones will be connected at all times. The communication system will be redundant decrease the risk of loss of signal as mentioned in risk 23. If connection is lost or an unrecognizable signal is received, the drone will automatically go in safety mode. During safety mode the drones will try to fly back to their landing pads while it reestablishes connection. In case a stable connection is reestablished the drone can be put in normal operation mode manually. If the drone is unable to fly back and locate itself due to a failing GPS and UWB receiver, it can ask for manual control. In case manual control is unavailable it will shut down as it lost complete situational awareness. By implementing this feature requirement SR-ST-4.1 is met.

8.4. Design for Electronics

In this section the design of the flight computer and related electronics will be discussed. The electronic hardware components such as sensors and antenna's are chosen and are implemented in a printed circuit board (PCB). Design for electronics is a topic that is not within the field of aerospace engineering and will therefore only be limited to high-level component selection and integration. The required components will be discussed in Subsection 8.4.1, followed by a detailed list of selected components in Subsection 8.4.2. Finally a layout of the components on a PCB and the budget is presented in Subsection 8.4.3.

8.4.1. Component selection

The electrical components required can be divided into different levels. The high-level components contain the parts of the PCB that will process data from the sensors and antenna's and that will run and store the main program ran by the flight computer. Low-level components such as diodes, transistors and capacitors which are used to connect the higher level components are not selected and should be investigated by a more specialized team. Most components necessary for the flight computer are widely available on the market. Therefore a selection based on price and functionality has to be made to pick the best suitable component. The electrical components related to power and propulsion are not mentioned here. These components include motors, ESC's, BMS and battery.

The budgets assigned to the hardware are: manufacturing cost of €153.85, maintenance cost of €16.3, a mass of 10.4 gram and a power usage of 10.8 Watt. The budgets are all without the contingency margin. Hardware was selected for the first iteration and therefore the initial budgets were used as a reference.

In the following list the required components are stated and will be discussed individually.

- **Micro controller:** When choosing the micro controller 3 factors are important: processing power, energy consumption and cost. Most commercially available flight computers for drone racing and hobby use STM32 F4 micro controllers because of the cheap price and availability of open source flight software. Drones for light shows require more computing power, since the drone will use up to 3 different communication types at the same time and the computer still needs to control the motors and read sensors. For these reasons it is desirable to split the computations between 2 processors or have a micro controller with 2 cores, one of which can be used for flight controller and the second one for communications, so that the control process is not halted when external commands are received. Separate CPUs such as Intel core, Qualcomm Snapdragon or Samsung Exynos were not considered due to high price and power consumption. Also micro controllers with 8 or 16 bit architecture such as AVR or PIC were not considered due to low performance. Typical cost of micro controllers suitable for given application ranges from 5 to 20 euro.

- **EEPROM memory:** Internal flight memory is needed to store the telemetry data and reading show commands. According to the customer, the drone show commands take 25 kb of memory. The information could also be stored on the SD card, but this solution is more expensive. Typical price of EEPROM memory does not exceed 5 euros.
- **IMU:** The internal measurement unit (IMU) will be used for measuring the attitude of the drone. The angles cannot be read of directly from the sensor. The gyroscope available on the chip will be used for determining accurate angular rates. The accelerometer on the chip can be used for measuring the gravitational acceleration and its direction. The accurate gyroscope measurement will drift over time have to be corrected using the accelerometer. Using both sensors and an algorithm that integrates and tunes the sensor inputs an accurate attitude determination can be performed using very simple equipment. Costs of a suitable IMU range between 4 and 10 euro.
- **Magnetometer:** A magnetometer is a chip that works as a compass by measuring the earth's magnetic field and will be used to determine the drone it's heading. Magnetometers have a cost range from 4 to 15 euro.
- **Barometer and temperature sensor:** A barometer will be used for accurate altitude determination. Low cost accurate pressure sensors are available that can measure altitude differences up to 10 centimeters of accuracy. The barometer cannot be exposed to direct sunlight as this will damages the sensor. The temperature sensor will be used to calibrate the barometer. Low cost solutions are available ranging from 6 to 15 euro.
- **GPS:** Outdoor positioning will be done using GPS in combination with RTK. The GPS receiver needs to process the GPS data and correct it using the RTK data to make an accurate location prediction. GPS receivers are expensive as advanced hardware is required to reach high accuracy's. An accuracy range of 1 to 2.5 centimeter is achievable within budget. Prices range from 80 to 150 euro.
- **GPS antenna:** An additional antenna is required to receive the GPS signal. The RTK signal will be received over radio signals. The antenna is produced by the same company as the GPS receiver and is selected for the chosen GPS receiver. Therefore the link budget is closed since the antenna receiver combination is designed for this application. A patch antenna will be put on the top of the drone to receive signals. Prices of the antenna range between 15 and 40 euros.
- **Radio:** The radio transceiver will be used for receiving the RTK signal, receiving commands and communication when flying in the manual control mode. Cheap receivers are available on the market and cost ranges from 5 to 10 euro. The components will be selected based on the receiving sensitivity and transmitting power required to close the link budget.
- **Radio antenna:** A radio antenna is required to receive the radio signal. An omni-directional antenna will be used as a reliable connection is required at all times. An omni-directional antenna will have a 360 degree receiving area and will allow the drone to rotate freely. A patch type antenna will be mounted at the bottom of the drone. The antenna gain will be selected based on what is required for the link budget. Only low gain antennas are suitable due to the selected type of antenna. Prices range between 4 and 8 euro.
- **Wi-Fi:** A Wi-Fi module will be implemented to have Wi-Fi connectivity. The Wi-Fi receiver is chosen using a similar method as described for the radio receiver. The link budget for Wi-Fi will more difficult

to meet and therefore extra attention is paid to the receiver sensitivity and transmitting power. The price of a Wi-Fi receiver range between 4 and 20 euro.

- **Wi-Fi antenna:** Similar to the radio antenna is chosen a Wi-Fi antenna is chosen. Prices for a Wi-Fi antenna range between 2 and 15 euro.
- **UWB receiver:** The Ultra Wide Band (UWB) receiver will be used for indoor positioning. It is a new technology which has recently entered the market in commercial products. Therefore the available hardware to choose from is sparse and market prices are hard to find. Prices range from 20 euros for a simple receiving chip up to hundreds of euros for a fully developed solution. The antenna will be included in the chosen solution.

8.4.2. Components

For every component the operating voltage, power consumption, communication protocol, dimensions, temperature range and weight is stated. The values are found by analysing the data sheets for every component. [36–40] In order to limit the use of voltage regulators it is preferred to have all components working at the same voltage. Power consumption is calculated by multiplying the operational current by the voltage. The prices are based on actual market values found when researching the availability of the products. The prices have been adjusted for large purchase numbers. Delivery costs are not included and the availability to deliver in the Netherlands is confirmed. The communication protocol is required to confirm the components can work together and that there are enough pins available on the micro controller. Dimensions are necessary for placing the chips on the PCB. Temperature range and weight are parameters could limit the final design. Masses of the components are rarely shown in data sheets. Some masses have been found and are directly put in the table. The missing masses have been calculated by multiplying the volume (calculated using the dimensions) by the density of Steel. Steel is chosen to overestimate the weight, which will prevent the manufactured PCB to be over budget.

Table 8.3: *Components selected for the PCB design.*

Component	Name	Operating voltage [V]	Power consumption [W]	Price [Euro]	Communication protocol	dimensions XYZ [mm]	Temperature range	Weight [g]
microcontoller	STM32H747	3.3	1.8843	€12.43	6 SPIs, 4 I2C, 4 USARTs	7x7x0.45	-40°C to +85°C	0.218295
EEPROM memory	25CSM04	3.3	0.0099	€2.55	SPI	5x6x0.7	-40°C to +85°C	0.2079
IMU	MPU-6050	3.3	0.00033	€4.00	I2C	4x4x0.9	-40°C to +105°C	0.14256
Magnetometer	HMC5883L	3.3	0.00033	€4.00	I2C	3.0x3.0x0.9	-30°C to +85°C	0.018
Barometer+ temperature	GY-63	3.3	0.00462	€6.15	I2c and SPI	2.45x4.45x1	-40°C to +80°C	0.00099
GPS	NEO-M8P	3.3	0.2211	€80.00	I2C	12.2x16x2.4	-40°C to +85°C	4.637952
GPS antenna	CAM-M8 (active)	3.3	0.2343	€14.88		9.6x14x1.95	-40°C to +85°C	2.594592
Radio	SX1276IMLTRT	3.3	0.396	€4.88		6.1x6.1x1	-40°C to +85°C	0.368379
Radio antenna	ISMP.868.35.6.A.02			€16.17		35x35x6		
Wifi	ATWINC3400A-MU-Y	3.3	0.21087	€6.52	I2C	6x6x1	-40°C to +85°C	2.497
WiFi antenna	SWDP.2458.15.4.A.02			€4.00		15x15x4		
UWB module	DWM1000	3.3	0.0594	€13.10	SPI	6x6x0.8	-40°C to +85°C	0.105

In Table 8.3 the selected components are shown. All components are working at the same operating voltage and the components can be connected to the micro controller. The operating range is meeting the requirement and is limited to -30°C to +80°C. All hardware selected is available. Therefore the electronics meet requirement OP-AP-3.

Talk about wires and payload connection

Add about memory interaction with the show

WiFi and Radio modules were selected with link budget in mind. Table 8.4 shows all link budget parameters for Wi-Fi and radio. It is assumed that the ground station will have a higher gain due to their static position during the show. The antenna's of the ground station can be directed towards the show its location. 5 dB gain classifies as an omni-direcital[41] antenna and therefore adjustments on the antenna its position during the show are not needed. As can be seen in the table, the required transmission power is smaller than the maximum transmitting power specified in the data sheet of the module. It can be seen that both link budgets are closed by more than 5 decibels margin which will guarantee a stable connection in clear weather. Thereby the Wi-Fi and radio modules are able to transmit and receive undisturbed data over 1200 meters which meets the CCE-AP-2.1 requirement.

Table 8.4: *Link budget*

Link budget dB	Radio	Wifi
Free Space Path Loss	92.72	101.63
Gain of the transmitting antenna	2	5
Gain of the receiving antenna	5	5
Receiver sensitivity	-100	-95
Fade margin	15	15
Required transmitting power	0.72	11.63
Maximum transmitting power of the module	14	17.5

The GPS receiver is equipped with RTK and will reach accuracy's up to 2.5 centimeter[40]. This will result in a high landing precision. Windy conditions and motor control will have an influence on the landing precision. Therefore the landing has to be executed carefully. In case a wind gust appears the landing should be postponed till the drone is in a stable condition. Using this method in windy conditions a landing precision up to 20 centimeters can be achieved. The maximum achievable outdoor landing precision is equal to the accuracy of the positioning chip. This can be achieved by descending slowly before touchdown.

The chosen UWB receiver can reach accuracy's up to 10 centimeters[32]. The precision can always be met as long as the drone is within range of the UWB ground stations. The landing precision can reach down to 10 centimeters.

Using these two receivers the CCE-AP-4 requirement is met from a hardware perspective: the drones can position themselves within 10 centimeters of accuracy. The drone needs to be controlled stably in all weather conditions which will be discussed in Section 8.5 to fully meet the requirement.

8.4.3. Printed Circuit Board Design

All components have to be integrated on a PCB. The assembly and printing of the PCB will be outsourced to specialized companies. This will result in lower production costs, higher quality and large scale manufacturing possibilities.

The components stated in previous subsection will not be put on a single PCB due to possible interference and signal blockage by other drone parts and to prevent overheating. Instead, all components will be mounted on 5 separate boards to lower the total heat generated by a single PCB. The PCB with the GPS module and GPS antenna will be mounted on top of the drone for a maximum GPS range. Boards with radio, WiFi and UWB will be placed under the drone for a better connection with ground station. The PCB with the micro controller, memory, IMU, magnetometer and barometer will be placed inside the drone. This PCB is the flight computer. All boards will be connected to the flight computer with I2C or SPI bus and 2 additional wires for regulated 3.3 V power supply. The flight computer will have an USB-C connector installed.

Sustainability
The decision to separate the electronics is also driven by the environmental considerations. If better modules become available for the drones, there will be no need to replace the entire board. To increase the recyclability of the PCBs, the conductive traces will be gold plated, which does not increase the price significantly, but makes the electronics more attractive for the recycling facilities. This will make the electronics contribute

positively to the SUS-EO-3 requirement.

Moisure risk mitigation
A coating will be applied over the PCB to protect is from moisture. Suitable coatings are available that can operate at temperature ranges between -55°C to +125°C Coatings are very inexpensive and costs will be low when applied at numerous PCB's[42].

Design budgets
The top-level components that have been selected have a total cost of €168.68, a mass of 10.79 grams and a power consumption of 3.02 W. The costs of the PCB have been approximated by using the online tool at JLCPCB[43]. JLCPCB provides PCB building and assembly services and makes a prediction on the costs for high numbers of PCB's. The area of the PCB is estimated by locating the components on the PCB's in a strategic way. This is shown in Figure 8.1.

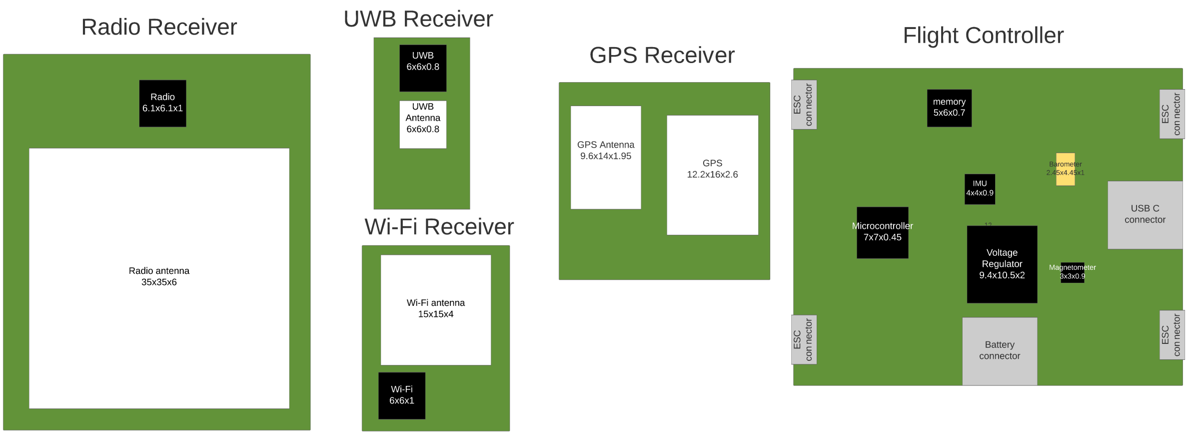


Figure 8.1: *Design of the 5 PCB's that will be included on the drone.*

The cost and mass of of the low-level components is estimated at €5.00 and 2 grams. The PCB manufacturing costs €0.93 and assembly costs €1.13. The selected top-level components will be delivered at JLCPCB and they will assemble all components on the final PCB's. In total 5 PCB's are needed. Therefore the manufacturing and assembly costs of the PCB's are multiplied by 5. The water-proofing coating per drone is estimated to be €1.30. Finally cost and mass for the cabling is added to the budget, which is estimated to cost €5.00 and have a mass of 5 gram based on an estimation on the required wire length multiplied by the wire density. This will all add up to the total budget shown in Table 8.5.

Table 8.5: *Final budgets for the CCE department*

Budget	Value	Unit
Manufacturing cost	191.61	€
Maintenance cost	0.00	€/lifetime
Mass	28.30	g
Power consumption	3.02	W

The hardware has been selected before the first design iteration. Therefore the budgets do not change and are the final budgets. The costs are withing the maximum allowable budget set during the preliminary design. The mass is over budget by 15 grams and the power consumption is below budget by 7 Watt.

8.5. Design for Control

Quadcopter is a naturally unstable system. To perform choreography the drone has to be stable. Since the hardware is not physically available, the drone dynamics was simulated on the computer. Then the control algorithm was developed and tested on the drone model. Finally, a simple choreography was simulated and visualized.

8.5.1. Drone dynamics

Drone is a highly non-linear system with complex aerodynamic and gyroscopic effects. To simplify the simulation some assumptions were made:

- Thrust acts from the center of the propeller strictly downwards in the drone reference frame
- Aerodynamic drag is same in every flight direction
- Propellers can change the rotation speed instantaneously
- Trust and torque of the propellers increase quadratically with rotation speed and don't depend on the speed of the drone.

The model with such assumptions is not detailed enough to determine the maximum performance limits, but it can prove the controller effectiveness in a typical flight regime.

The earth fixed and body coordinate frames are defined as follows:

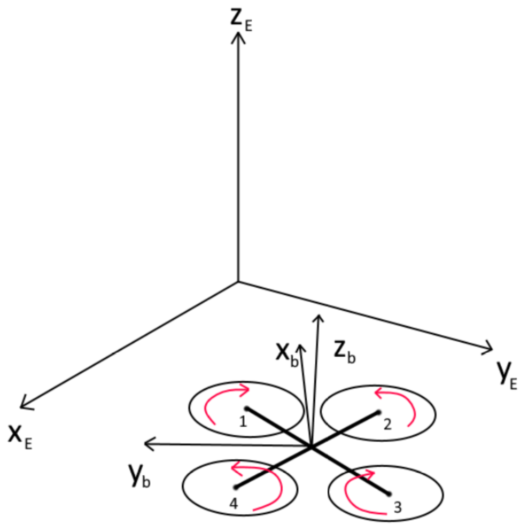


Figure 8.2: *coordinate system*

The transformation from earth fixed(E) to body(b) frame is done using Yaw-Pitch-Roll Euler angles transformation. This transformation is given in equation 8.3

$$R_E^b = R_z R_y R_x = \begin{bmatrix} c(\psi) & s(\psi) & 0 \\ -s(\psi) & c(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\theta) & 0 & -s(\theta) \\ 0 & 1 & 0 \\ s(\theta) & 0 & c(\theta) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c(\phi) & s(\phi) \\ 0 & -s(\phi) & c(\phi) \end{bmatrix} \tag{8.3}$$

Sine and cosine are denoted as s and c. The Transformation from b to E frame is denoted as R_b^E and is equal to $(R_b^E)^{-1}$. The state of the drone is fully described by 4 vectors: position and velocity in the E frame $\vec{p}$, $\vec{V}$, 3 euler angles $\vec{\theta}$ and rotational speed in the body frame $\vec{w}$. A state of the drone is denoted as $\vec{\Theta}$.

The derivative of the system state is a non-linear function, which depends on the system state and inputs. The resulting differential equation is discretized using forward Euler method.

$$\frac{d\vec{\Theta}}{dt} = F(\vec{\Theta}, \vec{f}) \quad \rightarrow \quad \vec{\Theta}_{i+1} = dt * F(\vec{\Theta}_i, \vec{f}_i) + \vec{\Theta}_i \tag{8.4}$$

The inputs to the system $\vec{f}$ is the vector of thrust settings of the motors from 0 to 1. The state vector contains 12 state variables: $\vec{\Theta} = (z, y, z, v_x, v_y, v_z, \phi, \theta, \psi, w_x, w_y, w_z)$ or $\vec{\Theta} = (\vec{p}, \vec{v}, \vec{\theta}, \vec{w})$. Then the derivative of the state is: $\frac{d\vec{\Theta}}{dt} = (\frac{d\vec{p}}{dt}, \frac{d\vec{v}}{dt}, \frac{d\vec{\theta}}{dt}, \frac{d\vec{w}}{dt})$. Each of the component of the state vector derivative is calculated as follows:

$$\frac{d\vec{p}}{dt} = \vec{v} \tag{8.5}$$

As stated in the assumptions, the thrust and torque of the propellers are modeled as simple quadratic functions.

$$T_n = c_t w_n^2 \qquad M_n = c_m w_n^2 \quad \text{for } n = 1,2,3,4 \tag{8.6}$$

Thrust and angular speed of each propeller is obtained from the thrust setting using Equation 8.6.Trust of n'th motor is $T_n = f_n * T_{max}$, where T_{max} is the maximum thrust of the motor. For the rotational speed of n'th motor: $w_n = T_n / c_t$.

$$\frac{d\vec{v}}{dt} = \frac{1}{M}\left(F_g + F_a + R_b^E F_{thrust}\right) = \frac{1}{M}\left[\begin{pmatrix} 0 \\ 0 \\ -Mg \end{pmatrix} - \frac{1}{2}\rho\,\vec{v}\,\|\vec{v}\|\,S C_d + R_b^E \begin{pmatrix} 0 \\ 0 \\ \sum_{n=1}^{4} T_n \end{pmatrix}\right] \tag{8.7}$$

In Equation 8.7 garvity force and aerodynamic resistance are expressed in the E frame. The thrust force is expressed in the b frame, so it is multiplied by the transformation matrix R_b^E. Aerodynamic force acts in the opposite direction to the drone movement. S is the reference aerodynamic area. $f[n]$, $n = 1,2,3,4$ are the thrust settings of each motor.

According to the transformation sequence defined in Equation 8.3 the relation between angular velocity of the drone in b frame and derivative of Euler angles is:

$$\vec{w} = W\frac{d\vec{\theta}}{dt} = \begin{bmatrix} 1 & 0 & -s(\theta) \\ 0 & c(\phi) & c(\theta)s(\psi) \\ 0 & -s(\phi) & c(\theta)c(\phi) \end{bmatrix} \frac{d\vec{\theta}}{dt} \quad \rightarrow \quad \frac{d\vec{\theta}}{dt} = W^{-1}\vec{w} \tag{8.8}$$

The derivative of the angular velocity $\frac{d\vec{w}}{dt}$ is calculated using Euler formula for rigid body rotation8.9:

$$I\frac{d\vec{w}}{dt} + \vec{w} \times I\vec{w} = \vec{\tau} \tag{8.9}$$

τ is external torque caused by the propellers, I is the drone moment of inertia matrix. Since the drone has spinning propellers, the above equation is modified to account for gyroscopic torque $\vec{G}$:

$$I\frac{d\vec{w}}{dt} + \vec{G} + \vec{w} \times I\vec{w} = \vec{\tau} \quad \rightarrow \quad \frac{d\vec{w}}{dt} = \frac{1}{I}\left(-\vec{w} \times I\vec{w} - \vec{G} + \vec{\tau}\right) \tag{8.10}$$

$$\vec{G} = \sum_{n=1}^{4} w \times J_{pr} \vec{w}_n = J_{pr} \sum_{n=1}^{4} w \times \begin{pmatrix} 0 \\ 0 \\ (-1)^n w_n \end{pmatrix} \tag{8.11}$$

Propeller torque around the z axis is simplified by omitting the angular acceleration of the propeller. This simplification reduces the number of state variables and does not degrade the model results much according to[44].

$$\vec{\tau} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} c_m (w_1^2 - w_2^2 + w_3^2 - w_4^2) + \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} c_t l_x (-w_1^2 - w_2^2 + w_3^2 + w_4^2) + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} c_t l_y (w_1^2 - w_2^2 - w_3^2 + w_4^2) \tag{8.12}$$

Equations 8.5,8.7, 8.8, 8.10 provide the derivative of all state variables. Given the initial state of the system, the state is plugged in the

8.5.2. Control algorithm

The control algorithm consists of 2 main parts: State estimator of the drone, and the controller. The first part is performed using Kalman filter [45]. Kalman filter is not modelled in this report, because it requires a measurement model of all on-board sensors. This part of the control algorithm is left for the future development. The focus of this section is primarily on the controller which takes a state estimation from Kalman filter and desired trajectory as an input and outputs a motor thrust setting. The drone controller consists of 6 PID controllers: 4 inner loop controllers to control yaw, pitch roll and altitude and 2 outer loop PID controllers which transform desired x and y position into yaw and pitch angles for the inner controllers. The outputs of the controller are then mixed and send to the ESCs. The controller diagram can be seen in Figure 8.4

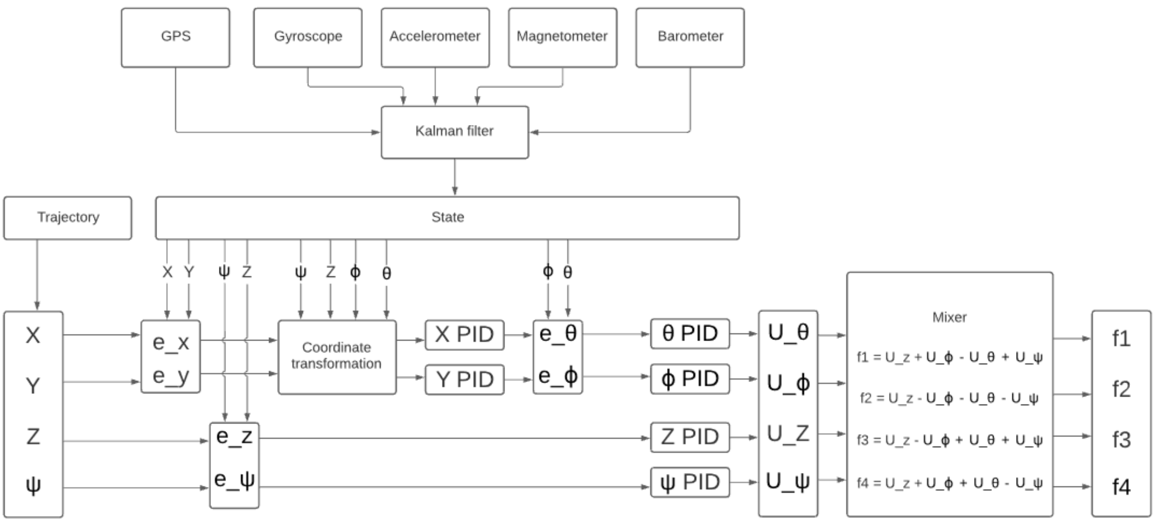


Figure 8.3: *Controller architecture*

First the controller reads desired position from memory. Then the measured position of the drone is subtracted from the desired position. Altitude and yaw errors are passed directly to the inner PID controllers, x and y errors are transformed to the body frame and passed to the outer PID controllers. X and y error a re transformed to pitch and roll commands for the inner PIDs. Finally, the output of inner PIDs is transformed to the motor thrust setting in the mixer.

Each PID controller has the following structure:

$$U = K_p e + K_i \int_0^t e\,dt + K_d \frac{de}{dt} \tag{8.13}$$

where e is the error between the desired and measured state , and p,i and d are gains which are different for every PID controller. To prevent unrealistic control output, every PID block has upper and lower bounds. These bounds are selected such that when control signals are passed through the mixer, the motor signals always stay between 0 and 1. Altitude PID has a range (0-0.7), Yaw pitch and roll PID's have range (-0.1 - 0.1) This way if every PID block outputs maximum value the signal to motors is one. If the drone is rising, but roll, pitch and yaw PID's output -0.1, the motors will receive the thrust setting of 0.4 and the drone will still have enough thrust to climb.

Coordinate transformation block transforms the coordinates of desired location from E to b frame using Equation 8.3. This block is needed to align x and y error with roll and pitch axis.

8.5.3. Gain tuning

Each PID block has 3 gains, so the controller has 18 parameters in total. Blindly trying random combinations would be very time consuming, therefore the gains were tuned in a special order.

Firstly, the inner PIDs were tuned. To do this, the model was linearized about the equilibrium position, and all nonlinear effects such as gyroscopic torque or air resistance were ignored. Below the analysis of Altitude PID is presented. Yaw pitch and roll PIDs were analyzed in the same way. For simplicity Just PD controller was implemented first. The Newton second law in laplace domain is:

$$m\ddot{x}(t) = T(t) - mg \quad \rightarrow \quad s^2 m X(s) = T(s) + \frac{mg}{s} = P(s) \tag{8.14}$$

Trust and gravitational force were combined in one term to simplify the transfer function:

$$\frac{X(s)}{P(s)} = \frac{1}{s^2 m} \tag{8.15}$$

Then PD controller is implemented to the system:

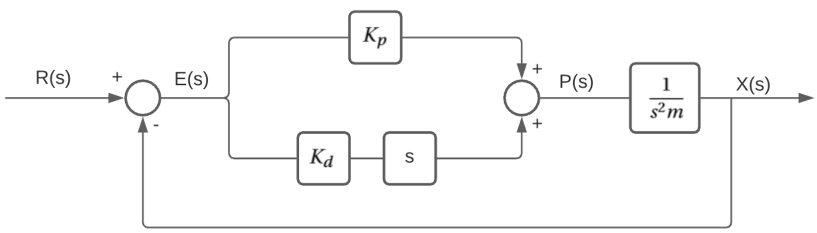


Figure 8.4: *Closed loop transfer function*

R(s) is the reference altitude, E(s) is the error and X(s) is measured altitude. K_d and K_p are derivative and proportional gains. Poles of the system can be found from the closed loop transfer function :

$$\frac{X(s)}{R(s)} = \frac{K_p + K_d}{ms^2 + K_d s + K_p} \quad \rightarrow \quad s = \frac{-K_d \pm \sqrt{K_d^2 - 4mK_p}}{2m} \tag{8.16}$$

For the system to be stable, real part of both poles must be negative. This is ensured by 2 conditions: $K_d > 0$ and $K_p > 0$. To make the system critically damped, derivative and proportional gains should be chosen such that $K_d^2 = 4mK_p$. Unfortunately due to gravity,PD controller causes a constant offset in the altitude, so integration term has to be added. To make matters worse, the neglected air resistance introduces additional damping. As a result, the transfer function in Equation 8.16 only provides a good initial guess of the proportional and derivative gains. Better values are then manually found by trial and error.

Then X and Y(outer) PID controllers were tuned. These controllers also need I gain to cope with constant wind. Outer PID controller are coupled with inner ones, so it is hard to find optimal gains based on the total transfer function, therefore the tuning of outer controllers was also done manually.

8.6. Simulation results

In this section the drone controller was put to the test by commanding the drone to perform different maneuvers, similar to those usually performed in a light show. The choreography is described by parametric curve in 3 dimensions. Figure **??** shows a drone performing a horizontal helix maneuver in 50 seconds.

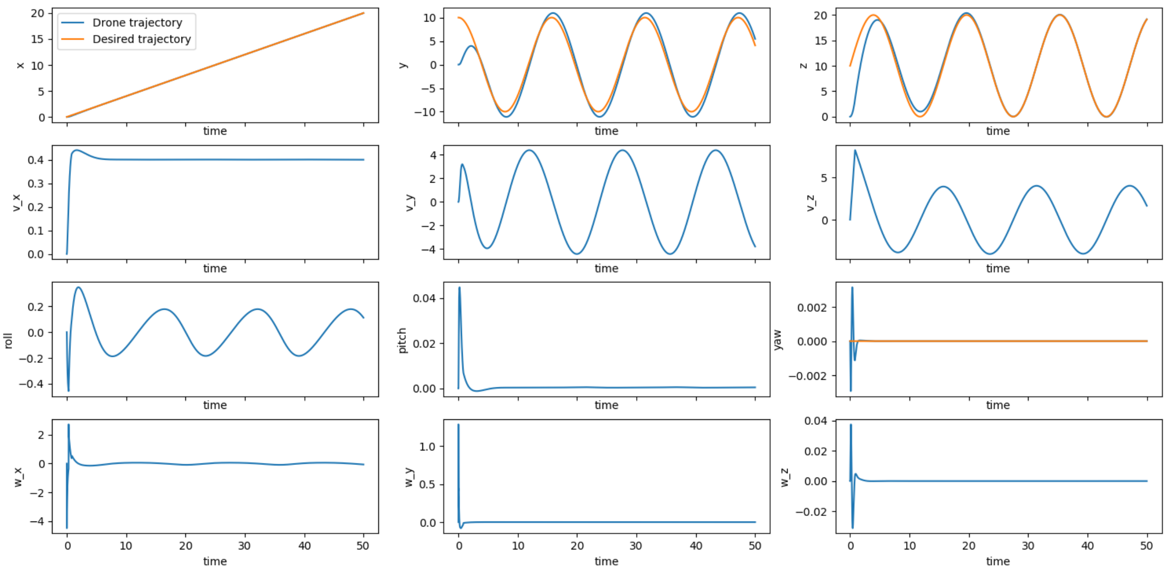


Figure 8.5: *Drone states during slow horizontal helix*

Figure 8.6a shows desired and actual trajectory of the drone. Initially the trajectories are far apart, because the drone starts at different location, but eventually it catches up and follows the pre-determined path quite well. If the drone attempts to perform the same trajectory twice as fast, the performance quality reduces significantly. This effect can be seen in Figure 8.6b.

link this all to requirements and announce that we will discuss them again in system analysis

(a) *Slow horizontal helix 3D view*

(b) *Fast horizontal helix 3D view*

The controller allows the drone to follow predetermined path , therefore requirement CCE-SYS-8 (the drone shall perform choreography) is satisfied.

Drone performance depends on the mass, aerodynamic resistance and moment of inertia, so the behaviour of the drone will be different for different payloads. Optimal controller gains are also different, depending on the choreography. If the

8.7. Software Diagram

Voltage can be read from the battery. Landing position in known from take-off

This diagram, important

8.8. Risk Analysis

New risk have been detected during the design phase. The likelihood and consequences of the mentioned risks are stated in Table 8.6. The risk mitigation response for every risk is stated in Table 8.7.

Table 8.6: *CCE related risks that were discovered in the detailed design.*

ID	Risk	LS	Reason for likelihood	CS	Reason for Consequence
43	Electronics malfunction due to moisture	2	Risk occurrence reasonably low. The cover should protect the drone from rain and water coming into the main body.	4	The flight computer can partially or fully fail during flight
44	Signal being jammed or hijacked	1	Likelihood is really low. Specialized equipment is needed to jam or reproduce the show's signals.	5	The electronics can potentially lose all communication and positional awareness.
45	Line of sight between ground station and drone is lost	2	Low, the flight path is programmed incorrectly or severe weather conditions make the drone drift.	4	The drones do not respond to commands and a potential collision can happen

Table 8.7: *CCE related risks that were discovered in the detailed design.*

ID	Risk	Mitigation Response	LS	CS
43	Electronics malfunction due to moisture	Apply a coating or heat shrink on the sensitive electronic components. Lower the likelihood.	1	4
44	Signal being jammed or hijacked	Encrypt the signal to reduce the likelihood. Measure the frequencies used by other nearby systems to select the optimal channel. Introduce a safety mode on the drone when incorrect signals are received to reduce the chance of total failure.	1	3
45	Line of sight between ground station and drone is lost	Program that the drones will fly back when connection is lost to resolve the line of sight issue. Shut the drone off when recovery is impossible to minimize damage.	2	1

8.9. Verification and Validation CCE

8.9.1. Verification

The code for drone simulation was written in python and is more than 500 lines long. To verify that the equations from Subsection 8.5.1 were implemented correctly in the code a series of unit tests were performed. Unit tests are described in Table **??**.

Table 8.8: *Unit tests of the drone simulation*

TAG	Block tested	Test	Outcome	V?
VT-CCE-U.1	Transformation from E to b frame	Multiply the transformation by the inverse transformation	Outputs identity matrix, as expected	yes
VT-CCE-U.2		set yaw pitch and roll to predetermined values and compute the matrix manually	Exact match with program result	yes
VT-CCE-U.3	Position derivative	Run the simulation with disabled forces and rotations	x,y,z position increases linearly with time, proportionally to velocity	yes
VT-CCE-U.4	Velocity derivative	Disable all forces, except gravity	drone accelerates in the negative z direction at rate of 9.81 m/s^2	yes
VT-CCE-U.5		Set the thrust of each motors to 1/4 of total weight	drone hovers on the same altitude, slowly drifts up or down, depending on the rounding	yes
VT-CCE-U.6		Manually calculate the thrust of the drone, such that terminal velocity is 100 m/s upwards	The drone reaches 100 m/s with the given thrust setting	yes
VT-CCE-U.7	Euler angles derivatives	Calculate the transformation matrix by hand for 3 random angles	Results match the program outcome	yes
VT-CCE-U.8	Derivatives of angular velocity	Spin propellers 1 and 2 faster than 3 and 4	w_y is negative, decreases proportionally to the torque	yes
VT-CCE-U.9		Spin propellers 1 and 4 faster than 2 and 3	w_x is positive, increases proportionally to the torque	yes
VT-CCE-U.10		Spin propellers 1 and 3 faster than 2 and 4	w_z is positive, increases proportionally to the torque	yes
VT-CCE-U.11		Decrese the moment of inertia of the drone	Same torque results in faster rotation	yes
VT-CCE-U.12	Inner PID controllers	Set integral gain of altitude PID to 0	Drone flies at constant offset from desired altitude	yes
VT-CCE-U.13		Set unstable proportional and derivative gains as predicted by linearized model	Drone position diverges from the desired state	yes
VT-CCE-U.14		Plot the output of each PID module for different altitude and angle commands	The output is bounded to the specified value. Motor input after the mixer is bounded to (0-1)	yes
VT-CCE-U.15		Plot the integral term of each PID	The integral term stops rising when saturation is reached	yes
VT-CCE-U.16	Outer PID controllers	Remove the coordinate transformation block	Drone is able to position itself for yaw angle less than 90 degree, for other yaw settings the drone diverges from the desired position	yes
VT-CCE-U.17		Set the desired position far away.	Drone pitch and roll angles reach maximum value of 0.5 rad	yes
VT-CCE-U.18		Introduce constant horizontal wind while maintaining position	Without the i gain, the drone has a constant offset. If i gain is added, the drone is able to hover on the right spot	yes

To check if all parts of the software are properly integrated together, a system test was performed. The drone initial coordinates and angles were set to 0 and then the drone was commanded to fly to coordinates $(x, y, z) = (100, 100, 1000)$ while maintaining 2 rad yaw angle. Figure 8.7 shows how all 12 state variables change during the simulation. Orange line indicate the desired position, blue line represents actual drone state. The simulation is done for a drone in this paper[**ref_drone_param**], but thrust to weight ratio is changed to 3. The controller receives state update 500 times per second, which is a standard update rate for consumer

FPV drones [46]. The simulation itself is running at 1000 Hz.

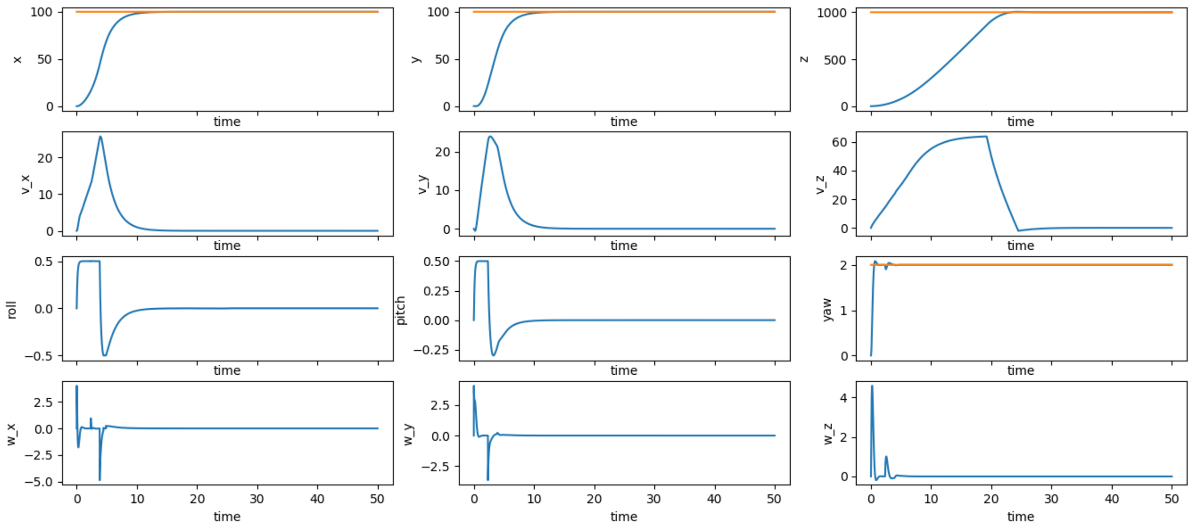


Figure 8.7: *System test*

Similar simulations were performed with different with different trajectories and simulation frequencies, to make sure that at 1000 Hz the solution has converged.

8.9.2. Validation

To validate the tools and design choices experiments must be performed on a pre-production unit. In this section validation tests are proposed. If the drone performs well in these tests, the CCE subsystem design can be considered successful.

Microcontroller and electronic components were selected to be compatible together. Once the circuit board is actually assembled, some tests can be performed to check if the hardware is functional.

Table 8.9: *Validation of drone electronics*

TAG	Description	Test
VAL-CCE-1	Check interference of communication modules	Turn on GPS, WiFi, Radio and UWB at the same time and observe the effect on data rate
VAL-CCE-2	Check power consumption of the electronics	Connect the electronics to the power measurement setup and run the software
VAL-CCE-3	Check the mass of the electronics	Use scales to weight the electronics

For communication and positioning the following tests are proposed:

Table 8.10: *Validation of drone communication and positioning*

TAG	Description	Test
VAL-CCE-4	Confirm that link budget is closed for WiFi and Radio.	Separate the drone and ground station 1200 meters apart and send commands to the drone
VAL-CCE-5	Confirm the satellite navigation is working	Fly the drone at different speeds and altitudes while monitoring the GPS signal quality
VAL-CCE-6	Confirm the satellite indoor navigation is working	Record positional accuracy with different number of ground beacons

To validate control algorithm and simulation program these tests are proposed:

Table 8.11: *Validation of drone simulation and controller*

TAG	Description	Test
VAL-CCE-7	Check if the simulation assumptions are realistic	compare the simulated choreography to the real one performed by the drone.
VAL-CCE-8	Check if the control gains are selected properly	Record the drone responce to the disturbances and compare to the simulation
VAL-CCE-9		Manually change the gains and observe changes in the responce.

8.10. Compliance Matrix

In Table 8.12 the compliance matrix is shown. The requirements have been discussed and verified in previous sections and the outcome is summarized in the table. The requirements related to control are not shown in the table. These requirements will be discussed in the ... section and will be summarized in the final add ref compliance matrix. A few requirements applicable to all departments have been discussed but are not shown in this table. These requirements will also be discussed in . These are requirements OP-AP-7, OP-AP-8, add ref AD-SYS-6, SUS-EO-3 and OP-AP-3.

Table 8.12: *Compliance matrix for the CCE subsystem requirements*

Sub-department	**TAG**	**Requirement**	**Verified?**
Electronics	CCE-AP-2.1	There shall be an undisturbed communication to the furthest drone at 1200 m distance.	Yes
	CCE-SYS-7	The drone telemetry shall be monitored	Yes
	OP-AP-4	The drones shall be operated from a central location	Yes
	OP-SYS-10	The energy supply's discharge rate shall be verifiable before every flight	Yes
	SR-APC-7	The connection between the ground station and the drone shall be secure.	Yes
	SR-SYS-5.2	The operator shall have an emergency stop button	Yes
	SR-AP-4:	The connection to the drones shall not be lost during any show, also in urban environments	Yes
	CCE-SYS-9	The drones shall be able to be manually controlled.	Yes
	AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg	Yes
	SR-ST-4.1	Show shall safely end if connection is lost	Yes
	SUS-EO-3	At least 80% of drone mass shall be recyclable.	Yes

9

Structures subsystem design

The structures subsystem is the interface between all other subsystems and should be designed to facilitate and protect these. This chapter will present the steps taken to design such a structure. The subsystem consists of the frame and the payload integration. The landing gear is closely related to the stackability of the drone and compatibility with the landing pad, and therefore designed by the operations department in Chapter 10.

Section 9.1 and Section 9.2 present an overview of the functions the subsystem must perform, the risks identified in the preliminary design phase [2] and the requirements related to the structures subsystem. This is done first to create an overview of all that should be taken into account in constructing the frame and payload integration. Section 9.3 describes the approach to estimate the frames size and mass and Section 9.4 describes the payload integration method. **??** presents the cost breakdown of the frame and **??** presents the overview of the iteration results by following the explained approach.

The last part of this chapter is dedicated to the analysis of the frame design.In Section 9.5the risks identified during the detailed design are shown. **??** describes the verification and validation of the tools and subsystem and lastly Section 9.7 presents the compliance of the design with the requirements presented at the beginning of the chapter.

9.1. Functional and Risk Overview of Structures

The goal of the structures department is to find the optimal balance between mass, cost and sustainability properties of the frame, while meeting requirements. This ranges from choosing a suitable material, define the cross sectional and drone dimensions and determine the mass and cost.

The main functions to be performed by the structures subsystem are:

- Manufacture drone
- Allow for routine maintenance
- Provide structural integrity during flight conditions and landing
- Provide space to integrate all subsystems and the modular payload
- Provide manoeuvrability and stability(?)
- Protect subsystems from defined weather conditions

For this project, it has been determined that structures can be divided into 3 parts:

- Frame design
- Payload integration design
- Production/manufacturing plan, to be presented in Chapter 13

Table 9.1 presents the risks identified in the preliminary design phase regarding the structures sub-system. It also shows their likelihood and consequence and the mitigation response which should be implemented in the design. Note that more detailed risks regarding the detailed design will be identified once the design is developed. These will be presented in Section 9.5

Table 9.1: *Risks related to structures and their mitigation responses*

ID	Risk	Likelihood	Consequence	Mitigation response
11	The components of the drone can not withstand the rain	Very low	Catastrophic	Take the risk, focus on waterproofing during design. Investigate implementation of waterproofing technologies
15	Frame fails under high loads	Very low	Catastrophic	Add a redundancy margin to structure's design.
17	Not all components can be recycled/reused	Low	Moderate	recyclability as an important selection criteria for materials.
19	Li-Po battery swells due to abusive use	Moderate	Critical	Design Battery container with clearance in volume for expansion of battery (lower consequence: swelling will less likely burst into flames).
29	Structure catches on fire.	Moderate	Catastrophic	Fire resistance as an important consideration during thermoplastic material choice (lower risk: choosing fireproof material lowers chance of fire).

9.2. List of Requirements Structures

Table 9.13 presents the requirements related to the structures subsystem. On the left column the sub-department they mostly relate to is stated. These requirements will be used as a guide to design the frame, together with the required functionalities and risk mitigation strategies. Note that the payload will not be designed In this project. It is up to the customer to attach a payload that meets the requirements. However its size and way of integration should be considered in the subsystem design.

Table 9.2: *Requirements related to structures subsystem*

Sub-department	TAG	Requirement
Payload	SP-AP-1	The drones shall be able to carry changeable payloads
	SP-AP-1.1	The light source shall be visible in urban darkness over a distance of 4km
	SP-SYS -1.1.1	The drone shall have an RGB Illumination
	SP-AP-1.2	The pyrotechnics shall weigh no more than 0.6kg
	SP-ST-1.2.1	The pyrotechnics shall not reach spectators
	SP-AP-1.3	A megaphone or speaker shall be included in the drones
	SP-AP-1.4.1	Future innovations shall have specifications up to a weight of 0.6kg
	SP-AP 1.4.3	Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm
Frame	SP-SYS-1.5	Structures shall accommodate power unit
	SP-SYS - 1.6	Structures shall accomodate electronics 17 errors58 warnings
	SP-EO-2	Drones shall not sink in the water
	SP-SYS-4.1	Any structural part of the frame shall not experience plastic deformation under flight conditions
	SP-SYS-6	The drone body should be tolerable to transportation and in-flight vibrations
	POP-AP-2	The drone shall be able to achieve a velocity of 20m/s
	AD-AP-1	The drone shall be able to fly in 6bft wind
	AD-AP-2	The drone shall be able to fly in rainfall up to 10mm/hour
	AD-SYS-6	The drone shall be operable in a temperature range between 3deg and 40deg
	OP-AP-2.2	The volume of the drones shall not exceed 0.5m^3
	OP-AP-6	The area off the take-off zone shall be at most 1m2 per drone
	SUS-EO-3	At least 80% of drone mass shall be recyclable.
	SUS-EO-4	The drone shall not break down into small parts.
	OP-AP-3	The drones shall be available in the year 2025
	SR-AP-6	Each drone shall have a lifetime of at least a 1000 flight hours
	COST-AP-1	The drones shall cost no more than 1000 € per piece

9.3. Design for Structures: Frame

The preliminary design phase concluded that a drone frame should be designed that consists of 4 arms that are fixed to the frame body [2]. This is done following the approach presented in this section.

9.3.1. Choice of cross section

The arms of the drones carry flight loads introduced by drag forces and thrust forces. The cross section of these arms is chosen to be a closed hollow circle for the following reasons:

- To meet the weather proofness requirement, the cross section is chosen to be hollow to provide a casing for wires coming from the brushless motors.
- The cross-section is circular rather than square as its more inertia efficient. This is beneficial for the volume requirement and is more sustainable as the mass of the frame will be lower, decreasing the power required.
- The cross-section is circular rather than square as this shape is more aerodynamic, resulting in a lower drag coefficient. The drag force is directly scaled by the outer diameter, so the circular tube will result in a more efficient design than a square tube.

This cross-sectional shape is used as a basis for the calculations to come.

9.3.2. Defining the critical load case

The arms should be designed for the critical loading conditions. This condition will demand the most of the structural integrity and is identified to be:

Flying against the maximum wind speed(6bft) with maximum flight speed(20m/s by requirement), while providing maximum thrust

The forces on the arm during this critical case is presented in Present drawing with forces:

As seen in the drawing, the arm experiences bi-axial bending. Bending around the y-axis is created by the drag forces and bending around the x-axis is created by the forces of thrust forces. Furthermore, the weight of the arm and of the motors and propellers create bending relieve around the x-axis. The maximum bending moment around the y-axis is experienced when the drag force is maximum, which occurs when flying at maximum flight speed against the wind speed. The maximum bending moment around the y-axis is experienced when the thrust force is maximum. Indeed, maximum flight speed is achieved at the maximum thrust setting as shown in Chapter 6, so this critical load case is realistic to occur in the shows.

9.3.3. Sizing of the arms

With the cross sectional shape and the critical loading condition defined the arms are sized according to:

- Bending loads: To make sure the frame does not experience plastic deformation by requirement SP-SYS-4.1.
- Deflection: To mitigate vibrations loads by requirement SP-SYS-4.1, and to not have the thrust vector deviate thus far that the flight speed of 20m/s by requirement POP-AP-2 can not be met.
- Shear: To secure the arms can carry the shear forces.
- Fatigue: To be able to fly a 1000 flight hours by requirement SR-AP-6.

To perform calculations on the sizing of the arms several assumptions had to be made:

- The arms can be modelled as cantilever beams, clamped at the frame.
- The cross sectional properties and material properties are constant over the length.
- The thrust vector is exactly aligned above the neutral axis of the arm and the drag force is symmetrically distributed over the length of the arm. This assumption eliminates torsion loads. An unbalanced motor could introduce some torsion, but this assumed to be negligible.
- Assume the tilt angle of the drone while flying at maximum speed is small. For flying forward the thrust vector will be tilted forward, The drag force will then come in at an angle to the arm. As the cross section

is symmetrical and round, the area affected by the drag force will remain the same. It will however cause bi-axial bending in y and x direction. With this assumption the arms will be slightly over designed, as the drag force component in y direction when flying at a tilted angle will cause some bending relieve.
- The mass of the motor mount at the tip of the arm is neglected. The motor with propeller needs to be attached to the arm. As the arm is circular, a motor mount is required. However, the mass of this mount is neglected in sizing the arms. This assumption must be checked in validation procedures to ensure it is a valid assumption.

Sizing for bending loads
To size the arms such that they withstand the bending loads of the critical load case Equation 9.1 to Equation 9.7 are used. These equations follow from a symmetric beam analysis under bi-axial bending using the sign convention that a moment is positive if it causes a positive stress in the positive quadrant of the x,y axis system [47].

$$\sigma_z = \frac{M_x y_{max}}{I_{xx}} + \frac{M_y X_{max}}{I_{yy}} \leq \frac{\sigma_{max}}{K_s} \tag{9.1}$$

$$I_{xx} = I_{yy} = \frac{\pi}{64}\left(d0^4 - di^4\right) \tag{9.2}$$

$$y_{max} = x_{max} = \frac{d0}{2} \tag{9.3}$$

$$Wd = 0.5\rho_{air} v^2 d0cd \tag{9.4}$$

$$M_x = Ft \cdot LB - Fp \cdot LB - \frac{Ww \cdot LB^2}{2} - F_{lg} \cdot L_{lg} \tag{9.5}$$

$$Ww = \rho_s \frac{\pi}{4}(d0^2 - di^2)g \tag{9.6}$$

$$My = \frac{Wd \cdot LB^2}{2} \tag{9.7}$$

Sizing for arm deflection
The deflection of the arm in x direction is given by Equation 9.9 and in y direction by Equation 9.8. The deflection is determined using superposition of the forces on the arm adn their respective contribution to the deflection, given by the "forget-me-not" functions (Mechanics of materials course): For sizing the arms the maximum deflection is chosen, so either $defl_x$ or $defl_y$, while the total deflection for the critical load case is actually a combination of them.

$$defl_y = -\frac{Ft \cdot LB \cdot 3}{3EI_{xx}} + \frac{Fp \cdot LB^3}{/3EI_{xx}} + \frac{Ww \cdot LB^4}{8EI_{xx}} + \frac{F_{lg} \cdot L_{lg}^3}{3EI_{xx}} \tag{9.8}$$

$$defl_x = \frac{Wd \cdot LB^4}{8EI_{xx}} \tag{9.9}$$

Sizing for Shear loads
To verify whether the arms of the drone will fail due to shear, a shear stress analysis is done in python. First, the position of maximum shear stress needs to be determined. This can be done by plotting the shear flow diagrams, which are presented in **??**. In this figure, the internal shear forces in y and x direction, and total magnitude are plotted, respectively. This shows that the total shear force is maximum at the attachment point of the arm to the frame.

Initially it was assumed that the walls of the rod are thin walled. However, this resulted in unreliable results as the minimum thickness was more than 10% of the calculated outer diameter. Thus for the second and last iteration, the rod was not assumed to be thin-walled. Instead, the maximum shear stress in the rod was calculated by

$$\tau_{max} = \left(2 + \frac{t}{r_o}\right)\frac{V_{max}}{A_c} \tag{9.10}$$

Where t is the wall thickness, r_o is the outer radius, V_{max} is the maximum shear force, and A_c is the area of the cross section. The best combination of inner and outer diameter is the one for which the cross sectional area is minimum, but which can still withstand the maximum shear stress of PP of $0.25MPa$. This combination was found to be and resulted in a maximum shear stress of . Note that a safety factor of was applied.

fill diameter combo here

Insert maximum shear stress in rod here

insert SF

Sizing for Fatigue
As per requirement SR-AP-6, the drone should be able to fly 1000 flight hours. During these flight hours the drone is expected to undergo many loading cycles. Therefore fatigue can not be neglected. To simplify the fatigue analysis a critical assumption is made. It is assumed that one flight show represents one loading cycle. Next to this, it was assumed that the maximum load during a cycle is the load case described in Subsection 9.3.2.

The fatigue analysis was performed by comparing the maximum stress in the arm per cycle, determined by the bending and shear analysis of the arm structure, to the number of cycles to failure.

Implementation into sizing tool
The aforementioned approach for arm sizing is implemented into a tool to perform quick iterations on the design. 6 iterations were performed in total. The inputs for the tool are the parameters of the aforementioned equations and a list of possible inner and outer diameter with 5 mm steps in the values. The outputs are the inner and outer diameter of the arm needed to ensure the structural integrity together with its respective mass.

For all combinations of inner and outer diameter the program calculations whether the stress or deflection exceeds the maximum allowed specified value. If this is not the case, the program notes it down as a possible combination. Then, for all the possible combinations of diameters, it gives the combination for the minimum arm mass, which becomes the arm size used in the design.

In this sizing tool, the following inputs will be further specified:

- ρ_{air}, density of the air
- LB, length of the arm
- Cd, Drag coefficient of the arm
- d_{min}, minimum inner diameter of the arm
- k_s, safety factor used in calculations
- t_{min}, minimum thickness of the arm
- Maximum deflection of the arm
- Material properties ρ_s, σ_{max}, E-modulus

The density of the air ρ_{air} is determined using the International Standard Atmosphere model [48]. The highest drag is experienced for the highest air density, which occurs at the lowest operating temperature. This is 3 degrees Celsius by requirement AD-SYS-6 giving an air density of 1.278 kg/m^3.

The length of the arm LB is determined by the size of the propeller and its clearance to the frame body. The propeller is attached to the end of the arm, therefore the half-length of the propeller is the minimum length of the arm. A margin should be included as it is expected that the efficiency of the propeller can decrease due to the aerodynamic interference of the frame body. This effect should be explored in more detail in the post-DSE phase. For now, for the first 3 iterations assumed a propeller clearance of 5 cm, after which it was reduced to 2 cm. For production, the arm should be made longer to be able to fix it inside the frame body, but for the calculations it is assumed the arm is clamped before entering this body.

To determine the drag coefficient, Cd, the arm is seen as a cylinder in a flow field. The drag coefficient is then dependent on the Reynolds number as shown in Figure 9.1. The Reynolds number is a function of the wind speed and outer diameter of the arm. For the first iteration a Cd of 1.2 was used. for the next iterations it was adjusted to 1.0 using the new outer diameter.

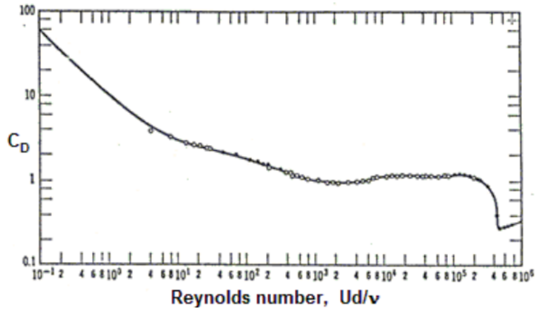


Figure 9.1: *The drag coefficient, Cd, for a circular cylinder as a function of Reynolds number, Ud/v [49]*

A minimum value is assigned to the inner diameter of the arm as its designed to fit the cables coming from the motors. Brush-less motors need 3 cables, and the wire size is usually 18awg [50]. A margin is included to make make integration easier. Therefore 14awg wires are chosen to size the inner diameter. From geometry, the minimum inner diameter for inlcusion of the 3 cables is then given by **??**, where r is the radius of the wires and R the inner radius of the arm.

$$D_{min} = 2 \cdot \frac{2r}{\sqrt{3}} + r \tag{9.11}$$

A safety factor k_s should be implemented in the model for the following reasons:

- The material properties could decrease over the lifetime of the drone because of weather conditions and operating temperatures.
- The conditions used in processing the material can have an effect on the properties of the finished product.
- The determination of the characteristic values of the material includes uncertainties.
- In the process of integration it became clear that the operations department requires a hole in the arm for to fit a cable. This hole will weaken the structure and a local stress concentration could be observed. This needs to be accounted for using the safety factor. The need for this hole is further explained in Chapter 11.
- In the process of integration it became clearit became clear that the arm requires threading on its ends. This will locally reduce the thickness of the arms and thus make it weaker. This should be accounted for in the safety factor. The need for this threading is further explained in Chapter 11.

For the first 3 iterations a safety factor of 3.3 is used in compliance with an existing dji drone frame [51]. For the next iterations the safety factor is more specific to the design. A safety factor of 1.5 is recommended for the predominant performance characteristics of strength and stiffness of plastics [52]. The safety factor is increased to 1.8 to incorporate the small hole for the landing gear.

The minimum thickness of the arm is specified to ensure manufacturability for of the arm. A hollow circular rod is best manufactured using polymer extrusion, as further specified in Chapter 13. For this method, the minimum thickness of the part is 3.2 mm[53].

The maximum deflection is specified to not have the thrust vector deviate thus far that the flight speed can not be met and to mitigate vibrations. the maximum deflection is assumed to be 1mm as requested by the propulsion department.

The last parameters that need further specification are the material properties. For this a suitable material must be chosen which is done in the next section.

Choice of material

The choice of material is between different types of thermoplastic [2]. The characteristics of the plastics is found using the "ANSYS GRANTA Edupack" tool [54] .

The first important factor is the maximum service temperature of the material. It should be well above the operating temperatures expected from the subsystems. The operating temperature from the motors is given by the propulsion department as 44 °C, whereas the battery is given by the power department as 60 °C. This ruled out "PLA" plastic. Another important factor is sustainability. As PVC is seen as the "single most environmentally damaging of all plastics" [55] it is ruled out as an option as well.

The remaining material options are presented in Table 9.3. The trade off is based on the following criteria and weights and follows the approach explained in the midterm phase [2]

- Cost(5/5): Cost is very important as a small difference in material cost will make a big difference in price in mass production
- Mass(4/5): Mass has become a driver requirement to be able to meet the budget.
- Risk(5/5): Important to ensure safety, fire resistance is in the risk register. Note that highly flammable materials do not necessarily need to be ruled out as additive flame retardants could be added to the material.
- Sustainability(5/5): Stated in the project objective statement and important to meet requirement SUS-EO-3.

To score the materials on the cost and sustainability it is assumed that the materials are a good representation of the market, and therefore their average may be used. For each criteria a threshold in scoring is set. Cost uses a threshold of 40% in scoring to account for the range in given cost data and because it is subject to change and unpredictable over time. Sustainability uses a threshold of 22% for production energy and 10% for recycling energy in scoring to account for the range in the given data.

The trade-off also specifies the recycle fraction of the material (RF) which is the fraction of current supply that derives from recycling. This is an important indication of the development of the recycling infrastructure of the material.

The trade-off concludes that the most suitable material for the design is Polypropylene (PP). To show the method is robust a trade-off sensitivity and technical sensitivity are performed as shown in Table 9.4 and **??** respectively. This shows that PET is a strong competitor but PP is still the better option.

Polypropylene is highly flammable. To mitigate risk 29 a highly effective flame retardant is added [56]. The heat release rate of PP with ca. 126 μm-thick coating was reduced by 71.2% using this additive. Furthermore the coating is flexible, anti-ultraviolet and water resistant.

The material properties of Polypropylene are:

- $\rho_s = 902$ kg/m^3
- $\sigma_{max} = 26.25 \cdot 10^6$ N/m^2 (Yield stress)
- E = $1.223 \cdot 10^9$ N/m^2

By requirement SP-EO-2 the drone shall not sink into water. The Structure of the drone will indeed float[**materialfloat**], but whether the whole integrated system will float is analysed in Chapter 11.

Note that the first iteration was based on polystyrene(PS) as it has the lowest mass. After the first iteration the material trade-off was performed and Polypropylene (PP) is used for the following iterations.

Table 9.3: *Material trade-off*

Criteria & Weight	Sub-criteria	PET	HDPE	PP	Polystyrene (PS)	ABS	Nylon
Cost (5/5)	Material cost (eur/kg)	1.06, 41% below avg	1.45, 19% below avg	1.2, 33% below avg	1.5, 16% below avg	1.89, 5.6% above avg	3.66, 104% above avg
Mass (4/5)	Mass frame 1st iteration (kg) vs budget	31% above budget	41% above budget	15% above budget	5.1% above budget	16% above budget	37% above budget
Risk (5/5)	Flammability	Highly flammable	Highly flammable	Highly flammable	Highly flammable	Highly flammable	Slow burning
Sustainability (5/5)	Material production energy (MJ/kg) (50%)	82.4, 10% below avg	80, 13% below avg	69.3, 24% below avg	82.2, 10% below avg	92.2, 0.7% below avg	143.5, 57% above avg
	Material recycling energy (MJ/kg) (50%)	Recyclable: 28.2 (7.8% avg), RF 21%	Recyclable: 26.75 (12.5%below avg) RF 8.44%	Recyclable: 23.5 (23% below avg), RF 5.5% decomposed naturally 20-30 years	Recyclable: 29.25 (4.3% below avg), RF 6%	Recyclable: 32.35 (5.8% above avg), RF 4%	Recyclable: 43.45 (42% above avg), RF <1%
Scores		7.3	6.3	7.6	6.6	6.6	4.8

Table 9.4: *Sensitivity Analysis of the material trade-off*

Cost	Mass	Risk	Sustainability	Winner
5	4	5	5	PP
1	4	5	5	PP
5	1	5	5	PET
5	4	1	5	PP
5	4	5	1	PET
5	5	5	5	PP

Table 9.5: *Technical sensitivity analysis of material trade-off*

Critera	Change	PET	HDPE	PP	PS	ABS	Nylon	Winner
Cost	40% incr	2	2	2	2	1	1	PP
	40% decr	3	3	3	3	3	1	PP
Mass	30% incr	1	1	1	1	1	1	PET
	30% decr	2	2	2	2	2	2	PET
Production energy	22% incr	2	2	2	2	2	1	PET
Production energy	22% decr	3	3	3	3	2	1	PET
Recycling energy	10% incr	3	2	3	2	2	1	PP
Recycling energy	10% decr	3	3	3	3	2	1	PP

Arm size Iterations

With the tools in place and the parameters defined iterations are performed.

Regarding the shear force: The calculated dimensions for the rod were smaller than the dimensions required for bending. Thus it can be concluded that bending is the dominant load case, and the arms will be designed to withstand the applied bending stresses and delfection.

Regarding the fatigue performance: The calculated maximum stress per cycle it can be seen that failure due to fatigue does not occur at the applied stress levels. Therefore it can be assumed that during the drone's life, it will not fail due to fatigue. S-N curve of Figure 9.2 [57].

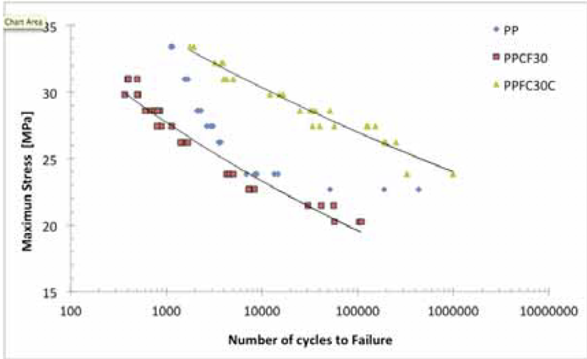


Figure 9.2: *S-N curves obtained in the fatigue tests, for pure polypropylene (PP), polypropylene/coir fiber composites without compatibilizer (PPFC30) and with compatibilizer (PPFC30C) (Bettini et al., 2011)*

The results of the tool that has the bending and deflection calculations integrated are presented in Table 9.6. 6 iterations were performed in total. The tool and its output data will be verified in **??**.

Table 9.6: *Arm size iterations*

Parameter	It 1	It 2	It 3	It 4	It 5	It 6
LB[m]	0.25	0.22	0.23	0.20	0.17	0.17
D0[cm]	2	1.9	2.1	1.75	1.4	1.4
Di[cm]	1.5	1.25	1.45	1.1	0.75	0.75
Mass total [kg]	0.16	0.14	0.17	0.12	0.067	0.067

To determine the production cost the "Granta" tool is used[54]. This tool contains a cost model specific to production processes. The best way to process the rods is by polymer extrusion. Molds can not be used easily as the arms are hollow. The inputs to the cost model are component length, component mass, material cost and load factor. The load factor stated how long the machines are working. It is assumed the machines are on for 8hours a day(working day) so the load factor is 0.33. The capital write-off time and overhead rate are not changed. Figure 9.3 presents the output of the model. The batch size is 1200, as the 300 drones have 4 arms each. The relative cost per unit is shown on the y-axis. This shows the cost per drone for the arms is 4-28 €. The average of 12 € is taken as the estimated cost per drone regarding the arms.

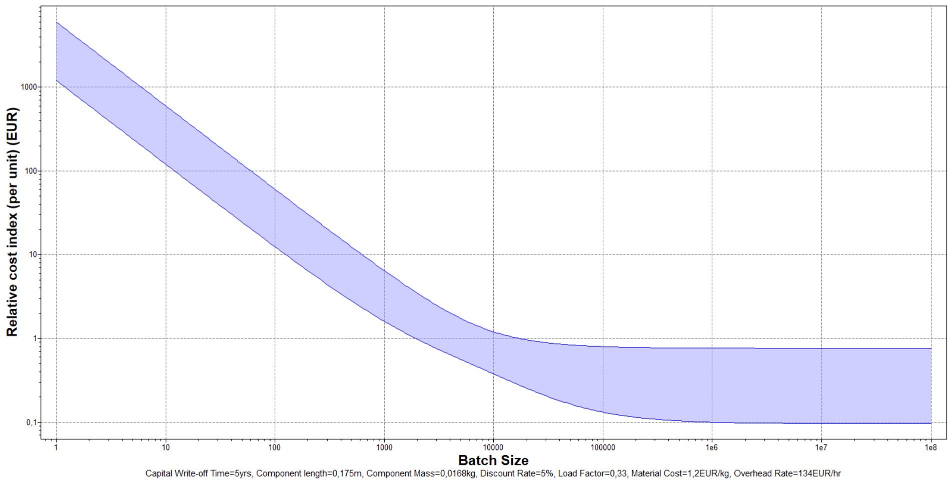


Figure 9.3: *Cost of polymer extrusion for the arms[54]*

By requirement SR-AP-6 the drone is supposed to fly for at least a 1000 flight hours. With the fatigue analysis of the structure it is confirmed that the drone structure is able to meet this requirement. Therefore there is no expected maintenance cost on the drones structure.

9.3.4. Sizing of the frame body

To estimate the mass and cost of the frame body it should be known how the subsystems will integrate into the frame. A detailed explanation of the integration is presented in Chapter 11, but the lay-out used for the iterations is as follows: The frame body will consist of a main box into which the arms are (permanently) attached. On top of this box the battery is placed and on top of the battery is a plate with PCBs, called the top plate. A sketch of the frame body is presented in Figure 9.4 to clarify this explanation.

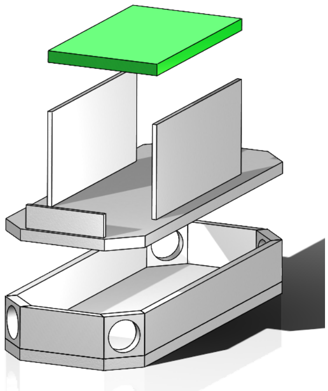


Figure 9.4: *Frame body design*

The size of the main box of the frame is determined by the battery size throughout all iterations. This was done as the battery is the largest subsystem to be integrated. The dimensions of the top plate are determined according to the size of the PCBs. The thickness of the plates was estimated to be 5mm. Whether this thickness is sufficient to hold the loads must be verified through Finite Element Models in the post DSE phase. Lastly, a margin for the casing was included in the dimensions, as this casing is to fit onto the main box.A more detailed explanation of the drone casing is given in Subsection 11.2.8.

For the first iteration it is assumed that the main box and top-plate have the same width and length as the size of the PCBs is yet undetermined at that stage. In this iteration the main box only consists of 2 plates, without the walls that make it into a box. A 5mm margin was added to both sides in the width of the plates to provide space for the casing and for walls to support the top plate. For the second iteration a 22mm high wall was added to the two bottom plates to create the main box. This height is in accordance with the outer diameter of the to be incorporated arms. The top plate still had the width and length as the the main box. For the iteration 3 to 6 the length of the top plate was sized to PCB dimensions, the width was kept the same. The PCBs that go on top are the UWB, radio and WiFi PCB.

The mass of the frame is calculated by multiplying the volume by the density of polypropylene

The final dimensions resulted from the integration with all subsystems. GPS was initially placed inside the main box. However the CCE department made a new request to put the GPS on top. Therefore the top plate had to be made longer. Furthermore, the main box had to be made longer and wider to account for walls that lock the battery into place. This battery compartment was made 10% higher than than the thickness of the battery. This was done as by risk 19 Li-Po Batteries tend to swell. When the battery swells inside the compartment there is the risk that it can not be taken out of the drone anymore which should be avoided. Lastly, the mass decreased with respect to the model as the corners were cut of the main box(see Figure 9.4), making the frame no longer perfectly rectangular.

Table 9.7: *Frame size iterations*

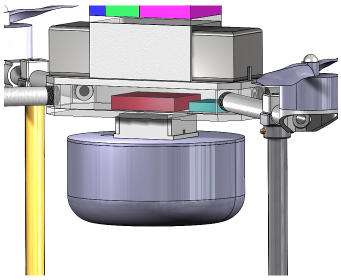
Parameter	It 1	It 2	It 3	It 4	It 5	It 6	Final
Battery size[LxBxH] [mm]	170.9x56.7x43.9	163.4x54.2x42	157.1x52.1x40.4	160x53.1x41.1	139x47x48.5	152x46x37	152x46x37
Size main box plates[LxBxH][mm]	170.9x66.7x5	163.4x64.2x5	157.1x62.1x5	160x63.1x5	139x47x5	152x46x5	160X64X5
Size top plate [LxBxH][mm]	170.9x66.7x5	163.4x64.2x5	50x62.1x5	50x63.1x5	50x47x5	50x46x5	83X50X5
D0[cm]	2	1.9	2.1	1.75	1.4	1.4	1.4
Mass frame plates [kg]	0.11	0.22	0.15	0.14	0.11	0.13	0.14

To determine the production cost the "Granta" tool is used[54]. The main box parts will be made via injection molding and will cost between 5-40 € each. The average is taken of 35 € per drone. The top plate can be made out of a plastic sheet for which the price is negligible [58].

9.4. Design for Structures: Modular Payload

The design for modular payload has been performed to meet several requirements mentioned in Table 9.13. Changeable payload configuration is specified in requirement SP-AP-1. This modular payload requirement is satisfied via an adhesive mount system. This system consists of an adhesive mount, shown in Figure 9.5a and a mounting piece on the bottom plate of the drone which is shown in Figure 9.6b.

(a) *Adhesive mounts that will be placed on the payload*



(b) *Payload attached to drone via Adhesive mount system*

Figure 9.5: *Adhesive mount system*

The mounting piece is part of the structure on the bottom plate of the drone. This piece will be used as point of attachment for the adhesive mount. The adhesive mount is a cheap and easily acquirable mount which can be placed on any flat or curved surface. The surface has also to be smooth. This is intended to be done for the payload. Once placed on the payload, it can be clicked to the mounting piece. This way different kinds of payload can be carried by the drone. The adhesive mount is advertised to be able to hold up to 2kg but there is no specification for the mounting piece since it is specially designed. SP-AP-1 is verified by testing this system with a payload that does not exceed the weight limit of 0.6 kg as specified in SP-AP-1.4.1. If a payload of 0.6kg with a maximum dimension of 20cm x 20cm x 20xm is held during this test then SP-AP-1.2, SP-AP-1.4.1 and SP-AP 1.4.3 are also verified. The condition of a smooth surface so the adhesive mount can stick has to hold for the (future) payload. Verification of SP-ST-1.2.1 will be discussed in Section 14.5 since it cannot be verified from a payload.

Next we have SP-AP-1.1 and SP-SYS-1.1.1. To satisfy these requirements, it is needed to include a light source that is visible over a distance of 4km and includes a RGB illumination system. To determine which brightness is needed (in lumen) for the light source a candle is taken as a reference. A candle has a brightness of 12.57 lumen over a distance of 1 meter[59]. The same candle is visible over a distance of 2576 meter in a low light condition[60]. From the inverse square law, the brightness of the candle decreases with its distance squared. This results in a minimum observable brightness of the human eye by a light source to be $1.894 * 10^-6$ lumen. This brightness has to be observed from a distance of 4000 meter meaning that the light source requires

2.41 times more brightness from the source to acquire the same visibility over this distance. The light source would therefore require a minimum brightness of 30.3 lumen just to be seen over this distance. This method ignores visibility loss due to light pollution from the city and light absorption in the atmosphere which which will be considered to be outside of the scope of this project. To verify SP-AP-1.1 it is needed to fly the drone over a distance of 4000 meter with the light source turned on and then check whether the light can be seen. SP-SYS-1.1.1 is automatically satisfied and verified if the light source includes an RGB illumination system.

(a) *RGB Illumination module*

(b) *RGB illumination module from the side*

Figure 9.6: *RGB illumination module[61]*

The LED Downlight 6W RGB+CCT 120mm Rond Mi-Light [61], as shown in Figure 9.6a and Figure 9.6 is used as the illumination system of the drone. This light source has a brightness of 600 lumen, a power consumption of 6W and it includes a RGB system with 16 million colours. This light source is connected via a cable to the flight computer and held via a custom designed case which is attached to the drone via the adhesive mount system described before. Figure 9.6b shows the specially designed casing for the RGB illumination module.

Next SP-SYS-1.3.1 and SP-AP-1.4.2 are considered. The verified tool described in Section 7.3 is verified for a payload of 20W. Since this tool is verified, it means that both these requirements are also verified The battery will be able to handle payload with a power consumption of 20W.

9.5. Risk Analysis Structures

newly found risks that arised from the structures design and need to be mitigated and how

Table 9.8: *Structural risks that were discovered in the detailed design.*

arms snaps of frame

ID	Risk	LS	Reason for likelihood	CS	Reason for consequence

Table 9.9: *Mitigation responses for the new structural risks.*

ID	Risk	Mitigation response	LS	CS

9.6. Verification and Validation Structures

Two main tools were used in sizing the frame. Both were used to determine the inner and outer diameter of the arms and its mass. The first one was based on coping with shear loads, the second one was based of coping with bending stress and putting a constraint on maximum deflection. These tools are verified through code verification and calculation verification. The mass of the frame body was determined by simple hand calculations and will therefore be verified by calculation verification only.

Due to how specific the models are to the design it is not possible to perform validation on a subsystems level due to the resources available to the design team. For the post-DSE phase it is proposed that the arm and frame body are validated by prototyping. Using prototypes the mass can be weighed and the structure can be validated on strength characteristics via the use of bending tests.

Furthermore, it is important that all part connections, namely the arm-body integration are designed and verified in more detail using Finite Element Models and tested on structural integrity using prototypes. This should also be considered in the post-DSE phase.

Code Verification of Tools

First the tools are visually checked for errors. It is made sure that all units are consistent. Then the moment and shear force diagrams are plotted to verify that the maximum moment indeed occurs at the clamped side, being the side of the arm were it goes into the frame-body. After this was confirmed, code verification tests are performed as presented in Table 9.12 and **??**. With these tests the code was verified.

Table 9.10: *Verification tests of arm sizing tool based on shear loads*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-SP-U.1	τ	F_i	Set all input forces to zero, expect shear stress to be zero with no errors	For all F = 0, $\tau = 0$	Yes
VT-SP-U.2	ω_D	v	Double velocity, expect distributed drag load to quadruple	For $V_1 = 10m/s, w_D = 1.2141$ For V2 = 20m/s, $w_D = 4.8564$	Yes
VT-SP-U.3	A_{cross}	t	Increase outer diameter keeping inner diameter the same, expect area to increase	For $d_i = 0.01 and d_o = 0.02, A = 0.00094$ For $d_i = 0.01 and d_o = 0.03, A = 0.0025$	Yes
VT-SP-U.4	τ	V	Double shear force, expect shear stress to double	For V = 15.44, $\tau = 224875$ For V = 30.88, $\tau = 449750$	Yes
VT-SP-U.5	τ	A	Double cross section area, expect shear stress to halve	For A = 0.00016, $\tau = 224875$ For A = 0.00032, $\tau = 112437$	Yes
VT-SP-U.6	V	ω	Set distributed loads to zero, expect shear force diagram to be constant	Shear flow diagrams are straight lines	Yes

Table 9.11: *Verification tests of arm sizing tool based on bending loads*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-SP-U.7	\sigma	d0,di	For input d0,di. Expect \sigma to be below \sigmamax/ks = 14.58mpa	for d0=1.4cm and di=0.75cm,\sigma = 10.4mpa	yes
VT-SP-U.8	Deflection	d0,di	For input d0,di. Expect defletion to be below deflmax/ks = 0.55mm	for d0=1.4cm and di=0.75cm,defl = 0.5mm	yes
VT-SP-U.9	Min thick-ness	d0,di	For output d0,di. Expect t>tmin = 3.2mm	for d0=1.4cm and di=0.75cm,t = 3.25mm	yes
VT-SP-U.10	Min diameter	d0,di	Expect output di>dmin = 3.5mm	output di = 7.5mm	yes
VT-SP-U.11	Singularity	I_{xx}, I_{yy}	For Ixx=Iyy, stressfunction has division by 0, expect error	for di=d0=0.014: float division by zero error	yes
VT-SP-U.12	Area	do	Double d0, expect area to be 5x bigger	For (d0,di)=(4,2), A=3Pi. For(do,di)=(8,2), A=15pi	yes
VT-SP-U.13	Mass	Area	Double area, expect double mass	for (rho,A,lb) = (902,6,0.2) m = 4329.6, for (rho,A,lb) = (902,12,0.2) m = 8659.2	yes

Calculation Verification of Tools Once the code is verified the numerical results of the calculation need verification. The parameters that can be verified by the use of an external model are the mass of the arms, the mass of the frame and the cross sectional properties.

walls battery com

Table 9.12: *Calculation verification of Tools*

TAG	Output to test	Input to vary	Test	Outcome	V?

9.7. Compliance Matrix Structures

Table 9.13 presents the compliance matrix for the structures related requirements that were used to design the frame and payload mount. The table is similar to Table 9.13 with an additional column on the right stating whether it has been verified or not. Most of the requirements can not be verified on a subsystem level. Instead, they will be verified on a system level in Chapter 11. Note that all risks identified in Table 9.1 were mitigated in the design.

Yes no

Table 9.13: *Compliance matrix for structures subsystem requirements*

Sub-department	TAG	Requirement	Verified?
Payload	SP-AP-1	The drones shall be able to carry changeable payloads	Yes
	SP-AP-1.1	The light source shall be visible in urban darkness over a distance of 4km	
	SP-SYS -1.1.1	The drone shall have an RGB Illumination	
	SP-AP-1.2	The pyrotechnics shall weigh no more than 0.6kg	no, done in Chapter 11
	SP-ST-1.2.1	The pyrotechnics shall not reach spectators	no, done in Chapter 14
	SP-AP-1.3	A megaphone or speaker shall be included in the drones	Yes
	SP-AP-1.4.1	Future innovations shall have specifications up to a weight of 0.6kg	no, done in Chapter 11
	SP-AP 1.4.3	Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm	no, done in Chapter 11
Frame	SP-SYS-1.5	Structures shall accommodate power unit	Yes
	SP-SYS - 1.6	Structures shall accommodate electronics	Yes
	SP-EO-2	Drones shall not sink in the water	no, done in Chapter 11
	SP-SYS-4.1	Any structural part of the frame shall not experience plastic deformation under flight conditions	Yes
	SP-SYS-6	The drone body should be tolerable to transportation and in-flight vibrations	No, done in Chapter 11
	POP-AP-2	The drone shall be able to achieve a velocity of 20m/s	no, done in Chapter 11
	AD-AP-1	The drone shall be able to fly in 6bft wind	no,done in Chapter 11
	AD-AP-2	The drone shall be able to fly in rainfall up to 10mm/hour	
	AD-SYS-6	The drone shall be operable in a temperature range between 3deg and 40deg	no, done in Chapter 11
	OP-AP-2.2	The volume of the drones shall not exceed 0.5m^3	no, done in Chapter 11
	OP-AP-6	The area off the take-off zone shall be at most 1m2 per drone	no, done in Chapter 11
	SUS-EO-3	At least 80% of drone mass shall be recyclable	no, done in Chapter 11
	SUS-EO-4	The drone shall not break down into small parts.	Yes
	OP-AP-3	The drones shall be available in the year 2025	no, done in Chapter 11
	SR-AP-6	Each drone shall have a lifetime of at least a 1000 flight hours	no, done in Chapter 11
	COST-AP-1	The drones shall cost no more than 1000 € per piece	no, done in Chapter 11

10
Operations Subsystem

The organisation of a drone show faces many operational and logistical challenges. Besides being able to have 300 drones or more flying their choreography safely at the same time, two important challenges are the transport of the drones without damage and the charging of the batteries. Operations however also involve safety and maintenance. Section XX ..., Section XX...

10.1. Functional and Risk Overview of Operations

The goal of the operations subsystem is to decrease the time needed to set up a drone show. This ranges from time spent on charging to maintenance or packing. The more efficient a process is, the less the operational costs will be, e.g. salary and transport costs. As covered in the functional flow diagram and functional in Chapter 3, the main functions to be performed by the operations subsystem are the following:

- Enable wireless charging through the landing pad
- Be stackable to be transported in bulk
- Fit in carrying structure
- Ensure maintenance with little training

These functions are translated into requirements which are presented in Section 10.2. For this project, it has been determined that operations can be divided into five sections:

- Landing pad design
- Landing gear design for stacking
- Logistical planning
- Maintenance procedures
- Safety procedures

The landing pad and stackability and logistics will be treated in this chapter while logistics, maintenance and safety procedures will be covered after the subsystems are integrated in Chapter 14.

Table 10.1 presents the risks identified in the preliminary design phase regarding the Operations subsystem. It also show their likelihood and consequence and the mitigation response which should be implemented in the design. Note that the scoring metrics have been explained in XX and the reasoning was presented in XX[midterm]. Some of these risks translated into requirements which will be shown in Section 10.2. Note that more detailed risks regarding the detailed design will be identified and mitigated in the detail subsystem design phase and presented in Table 10.9.

Table 10.1: *Risks related to operations and their mitigation responses*

ID	Risk	Likelihood	Consequence	Mitigation response
8	Drones get damaged during transport	Very low	Catastrophic	Have some spare back-up drones, avoid damage at large scale by proper carrying structures and rigid compartments
25	Corrosion on charging surfaces	Moderate	Moderate	Use rust free metals or apply protection coating on contact surfaces
27	Landing pads flooded	Moderate	Moderate	Design landing pad with water draining system
28	Stacking legs are misaligned or get stuck	Very low	Negligible	Design landing legs with draft angles and tolerances to prevent being stuck.
31	Event site can't power landing pads/ground station	Moderate	Moderate	Transfer risk to customer/ 3rd party company. Give estimation to them of power needed for operation.

10.2. List of Requirements Operations

Table 10.2 presents the requirements related to the operations subsystem. On the left column the sub-department they relate to is stated. These requirements will be used as guide to design the subsystems in Section 10.3 and Section 10.4. Note that some of these requirements will be verified at subsystem level in Section 10.6 while the rest will only be verified at a system level in Chapter 16.

Table 10.2: *Requirements related to operations subsystem.*

Sub-department	**TAG**	**Requirement**
Landing pad	CCE-AP-3	The drones shall be recharged wirelessly through their landing pads.
	CCE-SYS-3.1	The drone shall be able to charge during rain.
	CCE-SYS-3.2	The drone shall be able to recharge autonomously on the landing pad between preparation and show.
	OP-AP-6	The area off the take-off zone shall be at most 1m^2 per drone.
	POP-SYS-3.7	The energy storage shall be fully charged within 60 minutes.
Stackability	OP-AP-2	The drones shall be suitable for mass transport.
	OP-AP-2.1	The drones shall safely be stacked on each other.
	OP-AP-2.2	The volume of the drones shall not exceed 0.5m^3.
	OP-AP-2.3	The drone shall be stored rigidly in a shock-free container.
	SP-AP-1.4.3	Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm.

The following can be noted by comparing Tables 10.1 and 10.2:

- Risk 8 is mitigated by requirements OP-AP-2.3
- Risk 28 is mitigated by requirement OP-AP-2.1
- Risks 25 and 27 are mitigated by CCE-SYS-3.2
- Risk 31 does not have a specific requirement, however it will be assessed during the detail logistics analysis on Chapter 14.

The two main subsystems to be design are the landing pad and the stackability method. These are presented respectively in Section 10.3 and Section 10.4.

10.3. Design for Operations: Landing Pad

As written in requirements CCE-AP-3, CCE-SYS-3.1 and CCE-SYS-3.2 in Table 10.2, the drones shall have the possibility to charge via the landing pad without human interference during both dry weather and rain. Autonomous charging provides several opportunities for drone shows:

- Shows can be performed quickly after each other, without replacing the battery.
- Not replacing the battery in between shows reduces the chance of human errors during assembly and disassembly of the battery.
- Show duration can be longer by using multiple shifts of swarms that alternate flying and charging on their own landing pads.

In the previous phase [2], it was determined that the best method for autonomous charging would be **conductive charging**. This method was especially beneficial due to its lower required positioning precision, which eliminates the use of mechanical arms to place the drone at the correct location after landing. The lack of mechanical arms also makes maintenance and transport easier.

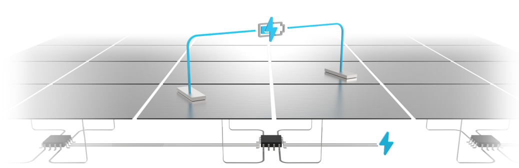
This section will go into the design of the landing pad. Please note that designing an entire autonomously charging landing pad is outside the scope of this project, hence it will not be designed in full detail. The drone will be equipped with the possibility to charge autonomously next to the usual charging method via a separate battery charger, but the landing pad will not be available yet.

The focus lies on the general technique of the method, estimation of size and mass of the landing pad. The general technique will be discussed in Subsection 10.3.1 and the method of sizing in Subsection 10.3.2.

10.3.1. Technique of Conductive Charging

In this section, the method of charging the drone will be briefly discussed. Besides that, the electronic connectors will be discussed.

Conductive charging works by metal-to-metal contact, in this case between the drone and the landing pad. The metal contact will create an electrical circuit through both the landing pad and the drone as well as the drone's battery. Through this circuit, a current can flow and charge the battery. The landing pad consists of several conductive tiles, which are connected to a charge monitoring system. The distinction between the tiles make a circuit possible. The charge monitoring system determines which 'side' of the circuit the tile has to be [62]. The pad can be equipped with detection sensors that detect whether there is water, a person's hand or an electronic device touching the surface. The concept already exists for laptop charging as well as drone charging, by the companies Energysquare and Skycharge respectively. These can be seen in Figure 10.1a and Figure 10.1b.



(a) *Power by Contact concept from Energysquare [62]*

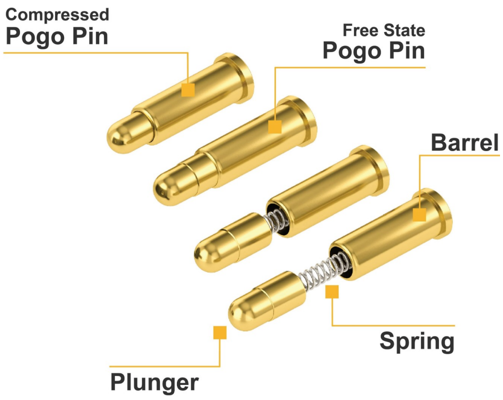
(b) *Autonomously charging pad by Skycharge [63]*

Figure 10.1: *Applications of conductive charging.*

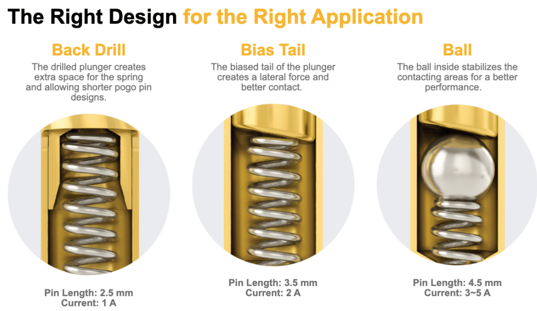
This metal contact should be implemented into the drone's structure. It was decided that this will be incorporated in the landing gear by using Pogo pins. Pogo pins are very frequently used connectors in electronic devices. They are frequently used for their high durability and stable electric connection. This last characteristic is especially useful for the application of autonomous charging, as the connection must be reliable and also work if the drone's legs or landing pad are not perfectly flat or if vibrations or shocks occur.

A Pogo pin consists usually of three parts: a plunger, a barrel and a spring. An example can be seen in Figure 10.2a. Pogo pins are spring-loaded and can thus provide a stable connection. They are widely available in all shapes and sizes and there are high-current pins available as well, which is useful for the application of charging a battery which can decrease the charging time. Three different designs are shown in Figure 10.2b. The ball design is the best option for a high current (>3 A) application. This is because the ball design has more contact points inside the pin and guarantees a smooth slide of the plunger. [64]

The drone has four legs, which are all equipped with a pin. This could make it possible to make two charging circuits and decrease charging time more. However, whether this is feasible is recommended to



(a) *Structure of a Pogo pin.*



(b) *Different designs of Pogo pins.*

Figure 10.2: *The design of Pogo pins.[64]*

be investigated in the future.

The characteristics of the selected Pogo pin are stated in Table 10.3. The pin is not available on the market in these exact sizes, but since over 1000 pins are needed it is possible to make custom-sized pins.

Table 10.3: *Characteristics of chosen Pogo pin.*

Pogo pin characteristics	
Height (mm)	31.5
Working height (mm)	27.0
Compressed height (mm)	25.5
Current (A)	9
Diameter of plunger (mm)	5.0
Diameter of spring (mm)	2.76
Diameter of barrel (mm)	7.24
Diameter of reinforcement (mm)	9.47
Material	Brass with gold layer
Mass (g)	5.31

10.3.2. Sizing of the Landing Pad

In this section, the model to determine the size and mass of the landing pad are discussed. Knowing the size and mass is useful from a logistical point of view, to make an estimate of how much time, volume and man hours it will take to deploy and transport all landing pads.

The model developed to estimate the size and mass of the landing pad, assumes the following:

- The electronics inside the landing pad is not developed and is therefore assumed to have a mass of 3 kg, which consists of among others, transformer, fan, cables etc.
-
- A safety factor of 1.25 has been applied to the loads and landing precision to account for an increase in mass of the electronics and to have some room for the landing legs.

stainless steel surface plate with tiles size Size dependent on accuracy of landing ABS or PP as the rest of the material: change the thickness in the tool

As the landing pad is not fully designed, it is not possible to determine the amount of power it would require

Table 10.4: *Design iterations of landing pad*

Iteration	Drone mass (kg)	Mass of electronics (kg)	Distance between craters (m)	Thickness steel surface (mm)	Thickness plastic (mm)	Area landing pad (m^2)	Mass landing pad (kg)	# of tiles	Size tile (m^2)
1	2.25	5	0.490	1.11125	1.016	0.9801	15.237	9	0.1082
2	2.25	5	0.364	1.11125	3.200	0.7465	14.347	9	0.0824
3	2.19	5	0.333	1.11125	2.400	0.6939	13.088	9	0.0765
4	2.11	5	0.356	1.11125	2.400	0.7329	13.529	9	0.0809
5	2.11	5	0.364	1.11125	2.400	0.7465	13.683	9	0.0824
Final	2.11	3	0.364	1.786	2.400	0.7465	16.087	9	0.0824

as efficiency is not determined or how fast it can charge the battery. This is also left as a recommendation for further design.

10.4. Design for Operations: Stackability

According to the requirement OP-AP-2 presented in Table 10.2, the drones shall be stackable, which involves being suitable for mass transport and to be stored in rigid containers. In the preliminary design phase [2], it was decided that the drones would be stackable by means of placing their landing gear on notches of the drone below. In addition, the stacks of drones should be transported in carrying structures which should conveniently fit into transport containers. This section will cover the landing gear design in Subsection 10.4.1 and the carrying structures in Subsection 10.4.2.

10.4.1. Landing Gear Design

Not all drones carry a landing gear, however for this design it was decided to do so for the following reasons:

1. To allow for **stackability** by fitting the landing legs on notches on the drone below.
2. To allow for **conductive recharging of batteries** through the landing pads (as explained in Section 10.3), this will require a charging device on the landing legs.
3. To allow for **autonomous take-off and landing**, which combined with the autonomous recharging will allow for multiple flights of a large group of drones with no human intervention between flights.
4. To **prevent the damage of the payload** during landing. The possibility of a protective case around the payload, strong enough to also support landing was rejected, since it would hinder the payload modularity and the ability of carrying widely different payloads, that might not allow for such case.
5. For **safety**, in particular when carrying pyrotechnic payloads, landing on landing legs reduces the risk for the drone itself, the landing pad and the environment.

It was decided that each drone will have two types of interchangeable landing legs as presented in Table 10.5. The main reason for this decision is the two main types of payload that the drone must accommodate: a light payload (lights or megaphone) and a heavy payload (pyrotechnics or any future payload). These require different lengths since the heavy payload module is significantly larger than the light payload one. Overall, the landing gear turned out to be cheap and light allowing for two sets per drone to fit within budgets.

Since it is expected that the light payloads will be used more often than the heavy ones, stackability, which aims to store drones optimizing the space, will be designed for the short landing gear. The long landing gear will only be used during shows.

The exact lengths depend on the size of the other subsystems of the drone and therefore they will be established only after the iteration process.

Landing gear model
The model developed to size the landing gear, assumes the following:

Table 10.5: *Sets of landing gears and their general characteristics*

Landing gear set	Payload	Transport	Conductive charging?
Short	Light or megaphone	Yes, it accommodates light payload while stacking	Yes
Long	Pyrotechnics or future payloads	No, for transport replace by short landing gear and remove heavy payload	Yes

- The landing gear is modeled as a vertical hollow circular beam loaded in pure compression. The cross section is circular to allow for the cylindrical pin at the foot of the leg and hollow to save weight and accommodate the charging cable.
- The main material of the beam is PP, which has a E = 1.223 GPa, a density of 902 kg/m^3, an ultimate tensile strength of 38 MPa and a yield strength of 26.25 MPa. This is the same material as the frame, this choice was made to reduce the amount of materials used, which contributes to recyclability.
- There will be four independent legs. They will be located on the arms of the drone to allow for large payload (requirement SP-AP-1.4.3) but placed as closed to the body to minimize the size of the landing pad as explained in Subsection 10.3.2.
- As explained in Subsection 10.3.2, the foot of the landing leg will be formed by a "Pogo pin" type of connector, which will allow for conductive charging with the landing pad. This pin is cylindrical and made out of brass with a diameter of 6mm. Its outer diameter corresponds to the inner diameter of the tube plus a tolerance. The effect of the springs of the pins on the loads has been neglected due to the limited size of the spring with respect to the system.
- The PP tube is designed to carry the full loads on the landing legs, while it is ensured that the brass pins can survive the loads but are not tailored to them since they are off-the-shelf items. Stackability has been design for such that the PP tube carries the loads and not the pin.
- A safety factor of 1.5 has been applied to the loads to account for possible uneven loading of the legs and effects of simplifications in the model.
- The Pogo pin will be glued to the PP tube while the landing legs will fit into an attachment piece glued to the frame and hold by spring pins. The integration will be explained more in detail in Chapter 11.

In order to size the landing legs two main sizing situations were taking into account: the loads due to landing and due to stackability.

Sizing for Landing Loads
First, the landing gear should be able to ensure a safe landing during nominal landing conditions. The control software should make sure that the landing is controlled, to both not damage the drone or the landing pad. It is then assumed that all landing legs take the same load.

In absence of detailed control software information or trajectories, the total force on the drone upon landing was assumed to correspond to a vertical impact of 2g's. This would also account for possible unequal distributions of load between legs due to the payload distribution or crosswinds during landing. Note that both the short and long sets of landing gears should be able to resist the landing loads.

Sizing for Stackability Loads
When loaded into the carrying structure, the landing gear of the drones is used to place them one on top of each other. This means that the landing legs must carry the weight of the drones above. The amount of drones that fit in a carrying structure depends on their size and weight (as will be explained in Subsection 10.4.2).

Therefore the stackability loads vary each iteration depending on the mass of the drones and how many fit in a stack. Note that only the short landing gear needs to carry the stackability loads as mentioned in Table 10.5.

Inputs and Outputs of Model

The main input for the sizing of the landing gears is the total mass of the drone, as this is needed to compute the force on each of the four legs for both landing and stackability. Another input is the height of the landing gear, which depends mostly on the height of the payload and of the body of the drone (which includes the frame, electronics and battery).

The landing gear will be located as close as possible to the body while allowing for the heavy payload to be carried. This is in order to minimise the landing pad area needed. Final location is therefore set by the structures department and it does not affect the loads on the landing gear model since it assumes pure compression forces.

Once the landing loads are computed, the PP tube is sized based on a set inner diameter defined by the Pogo pin determined in Subsection 10.3.2 and a variable outer diameter. Polymer extrusion was chosen as main production method due to its low required production energy. Therefore this method set a minimum PP tube thickness of 2.4mm [53]. Note that this decision was made during the design phase therefore some early iterations assumed a lower possible thickness. Then outer diameter is set such that the normal stress on the leg does not surpass three key structural stresses: the ultimate tensile stress, the yield stress and the Euler buckling critical stress (σ), computed with by $\sigma = P_{cr}/A$ and with Equation 10.1 [47]:

$$P_{cr} = C \cdot \frac{\pi^2 \cdot E \cdot I_{xx}}{L^2} \tag{10.1}$$

where P_{cr} is the buckling critical load, A is the cross-sectional area, E is the E-modulus, L the length and I_{xx} is the cross-section moment of inertia. Finally, C is a scaling factor based on the clamping modes of the column. The landing leg has been modeled as a beam with one end fixed and one pinned which corresponds to a $C = 0.6992$ [47].

Note that the amount of drones stack on each other also makes part of this model and can vary between iterations. This is because this amount depends on the size and mass of the drone to meet weight and size requirements for transport. The carrying structure iteration will be explained in Subsection 10.4.2.

The cost of the pins was added to the cost of the extrusion of the PP tubes which was computed using the batch size and length of legs similarly to Chapter 9.

Iteration Results: Landing Gear Design

Table 10.6 presents the results of the design iteration of the landing gear. Six full iterations were computed for both the long and short landing gears.

Table 10.6: *Design iterations of landing gear design*

Iter -ation	Set	Drone mass (kg)	Outer diameter(cm)	Thickness tube (mm)	Height LG (cm)	Stress on leg (MPa)	Buckling stress (MPa)	Mass of LG set (kg)
1	Short	2.00	0.700	1.0	13.40	1.952	7.800	0.024
	Long	2.00	0.700	1.0	24.40	0.651	2.352	0.044
2	Short	2.25	1.452	3.2	13.39	0.364	23.797	0.071
	Long	2.25	1.452	3.2	24.39	0.121	7.174	0.116
3	Short	2.25	1.292	2.4	15.40	0.435	15.145	0.060
	Long	2.25	1.292	2.4	26.40	0.174	5.154	0.091
4	Short	2.19	1.292	2.4	11.90	0.508	25.364	0.050
	Long	2.19	1.292	2.4	26.10	0.169	5.273	0.091
	Short	2.11	1.404	2.4	10.94	0.531	36.395	0.056

5	Long	2.11	1.404	2.4	25.94	0.177	6.473	0.103
Final	Short	2.11	1.404	2.4	15.80	0.531	17.449	0.071
	Long	2.11	1.404	2.4	23.00	0.177	8.234	0.094

It was determined that for all iterations the stackability loads significantly exceeded the landing loads and that the buckling stress was the limiting factor. However, the minimum thickness due to manufacturability was actually setting the thickness of the tube in all iterations, for both the long and short landing legs. In addition note that the cost of production is not reported in Table 10.6, this is because through the iterations it does not vary much: the cost of each charging pin is about 1€ and of the production of the extruded tubes is about 14€ per set of landing legs considering a batch size of 1200 tubes (300 drones).

Also note the significant increase in length of the sort landing leg set in the last iteration, this is due to some miscalculations on the height of electronics and payload that were only spotted during integration.

Therefore, from Table 10.6 it can be seen how both sets will be extruded PP tubes of 1.4cm in diameter and 2.4mm of thickness. The short set will be 12.4cm long while the long set, 25.6cm long. Both sets with pins will have a cost of around 18€, making the total cost of both sets for one drone about 36€. Each drone will be sold with the two sets of landing gears.

Attachment of Landing Gear to Frame

Initially, the landing gear was going to be screwed into the arm, however this raised a structural integrity concern with the large size of the hole required on the arm. For this reason, an extra part to facilitate the attachment was designed. This part is made out of PP as the rest of the frame, and it glues to the lower part of the arm. It has a hole which aligns with a small hole of 3mm in diameter on the arm to allow for the charging cables from the charging pin to enter the inside of the arm frame. On the other side. On the bottom side, it contains a hollow cylinder, 1cm long and 3mm thick, with two lateral holes to which the landing gear fits tightly. The landing gear will contain two spring loaded pins perpendicular to the axis of the tube which compresses to fit on the attachment part and expands once the pins reach the holes locking the gear into place. This attachment is removable by pressing the pins into the tube and sliding it out. The pin still allows for the cable to fit around it. The body of the tube lies on the part meaning that it takes the compressive forces. The integration will be explained in detail in Chapter 11.

This part was design later in the design phase to tackle the concern of failure of the original thread attachment, therefore no iterations were made. Note that, thanks to the margins in the iterations, adding the small mass and cost of this part does not put the subsystem out of budget. The total mass was computed to be 2.94gr for the PP and XXgr for the spring-loaded pin, which is located on the inside of the landing leg. The cost is XX€. The mass of the PP part was computed by a simple model of the part which will be verified in Section 10.6.

Note that a risk raises from this new attachment method, which consists on an unwanted loosen attachment that can cause the landing leg to wiggle under vibrations causing misalignment or the stacks to be unstable. This corresponds to risk 42 on Table 10.9. The mitigation response would be to ensure that the lock is tight by means of small tolerances or with an O-ring type of seal between the leg and the attachment piece. add picture

Design of Notch on Drone's Arm

In order to fit the landing gear foot on the drone below for stackability, the arm of the drone much contain a notch. For structural integrity reasons it was decided that the structure should not be weakened further by making a hole. Instead, a piece would fit to the top of the arm and contain a notch where the pin of the landing gear can fit into. This piece has been named 'crater'.

The crater is made of PP, like the frame and the landing gear, and is glued to the top of the arm as shown in XX. The main dimensions that influence the crater are the outer radius of the frame's arm and the dimensions of the pin to size the notch. Four craters are needed per drone, located on the vertical axis of the landing gears. Note that one of the risks identified (Risk 40 in Table 10.9) is that the charging pins get damage by excessive compression during stacking. To prevent this the crater is design such the pin only prevents lateral movements but does not carry any vertical loads (it does not touch the bottom of the notch), which are carried by the PP body of the landing gear in contact with the crater.

add render

Table 10.7 presents the design iterations of the crater. Note that the craters were not introduced until the second iteration.

maybe take cost out

Table 10.7: *Iterations of crater design (mass and price are of 4 craters)*

Iter-ation	Outer radius of arm (cm)	Height of notch (mm)	Width and depth of notch (mm)	Mass craters (g)
1	/	/	/	/
2	1.00	5	3	9.943
3	0.95	5	3	8.284
4	1.05	5	4	6.872
5	0.88	7	5.5	7.267
Final	0.70	7	6	7.297

Therefore as can be seen in the last row of Table 10.7 the final craters will have a mass of 1.1gr each (4.439gr per drone) and a production cost of about 4€ per drone.

10.4.2. Carrying Structure Design

The aim of stacking the drones on each other and and moving them around in carrying structures is to of facilitate their storage as well as the their deployment at large scale. Time and money are key: the fastest the drones can be deployed and the least amount of work needed, the better the design and logistics.

The carrying structure should facilitate the deployment of the drones by allowing one worker to place a group of drones at their landing pads without having to come back to the ground station to pick up the drones one by one. Due to the uncertainty of the outdoors terrain, wheels might not always work, therefore the carrying structure must be raised by hand. Therefore there are two main limitations to the carrying structures: their weight and height.

Maximum Weight and Height of Carrying Structure

Regulations from the European Union are in place to prevent workers from getting injured when carrying loads by hand frequently [65]. They set guidelines to employers to limit the physical works that can cause back injuries. The maximum load recommended to be carried depends on how and where the load can be hold as well as the physical characteristics of the worker. For this design, the lifting equation method from NIOSH (US National Institute for Occupational Safety and Health) will be used to estimate the maximum load of the carrying structure based on its size and holding method. In particular, the online calculator provided by the Canadian Center for Occupational Health and Safety has been used [66].

The NIOSH method assumes a starting maximum load of 23 kg which, under ideal conditions, is safe for 75% of females and 90% of males. Then it applies reducing factors based on the position of the hands on the load, the type of displacement and frequency of displacement. The following assumptions were made to estimate the effort to deploy the drones outdoors:

- The horizontal distance between the hands of the worker and his/her feet is about 40cm, this is due to the large size of the drones.
- The vertical location of the hold with respect to the ground is of about 100cm. This also places a limitation to the maximum height of the stacks, which has been set to be 125cm.

- The vertical displacement of the loads while transporting them is of 40cm. This is considered enough height to walk around the field while safely carrying the structure.
- The lifting will be done repeatedly within the same hour for about 5 min.
- The structure allows for a good grip with two hands, no twist of the upper body is needed and the movement is done while standing up.

With this method, it was determined that the maximum weight of the stacks must be 12,53kg and their height cannot be larger than 1,25m, of which the secure grip should be at around 1m from the ground. The carrying structure will be optimized for the maximum possible drones in a stack while respecting these limitations.

Carrying Structure Model
The drones will be stacked on each other by fitting the feet of landing legs in the arms of the drone below. Therefore the The stack of drones will be put in a carrying structure formed by a bottom plate, a top plate and vertical rods that prevent the column from tilting and safeguard the drones during transport. The rods may contain handles to allow for easy grip by either one person or several people at the same time.

Due to the size of the propellers and location of landing gear, the landing gear does not allow for the free rotation of propellers when stack. To avoid damage a foam protection on the propellers or around the landing leg is recommended.

Note that it is not the scope of this design project to design in detail this carrying structure. Therefore it has been assumed that the structure will weight 10% of the weight of the drones and add 5% of height to the height of the stack.

The main inputs for the design of the carrying structures are the total mass of the drone, the height of the landing gear and the dimensions of the drone including the propellers.

Iteration Results: Carrying Structure Dimensions
The design iterations are shown in Table 10.8.

Update last iteration

Table 10.8: *Design iterations of carrying structure dimensions*

Iter -ation	Drone mass (kg)	Height drone (cm)	Drones per stack	Height stack (m)	Weight stack (kg)	Stack area (mxm)
1	2.00	18.76	7	1.031	11.74	0,96 x 0,96
2	2.25	18.75	6	0.890	12.02	0,8 x 0,89
3	2.25	23.70	5	0.896	10.50	0,73 x 0,8
4	2.19	20.10	6	0.836	12.47	0,78 x 0,85
5	2.11	18.63	6	0.770	12.33	0,735 x 0,8
Final	2.11	24.28	6	0.855	12.46	0,65 x 0,75

So, as shown in Table 10.8 the carrying structure will hold six drones stacked on each other which will weight 12.46kg and be 0.869m tall. A trend that can be observed in the iterations is the decrease in area of the stack, which shows how the drone has become smaller which simplifies the logistical operations. Note that the limiting factor in the size of the carrying structures turned out to be the weight rather than the height, this means that they are smaller than their maximum height which can simplify their operations.

Finally, with the long landing legs the final volume of the drone is $0.0599m^3$, which complies with requirement OP-AP-2.2 to be less than $0.5m^3$.

The carrying structures then can be put into big transport boxes which will provide a rigid-case protection for transport which fulfills requirement OP-AP-2.3. For instance in the box XX, 6 carrying configuration fit in a X x X configuration.

10.5. Risk Analysis of Operations

During the detailed design, on top of the preliminary risks presented in Table 10.1, several new risks were identified and mitigated. Table 10.9 presents an overview of these risks, their likelihood, consequence and Table 10.10 shows how they were mitigated and their scores.

Table 10.9: *Operational risks that were discovered in the detailed design.*

ID	Risk	LS	Reason for likelihood	CS	Reason for consequence
37	Drone misses landing pad during landing.	2	Risk occurrence reasonably low, drone can land with wind.	2	It can still land on the field, but autonomously charging is not possible.
38	Worker gets injuries due to heavy loads.	4	Stacks of drones are quite heavy and tall, which need to be carried for several hundred meters.	4	Less employees and possibility of more costs for the company .
39	Insufficient contact between charging pins and landing pad.	3	Manufacturing processes might not make the landing pad or drone flat enough.	2	Autonomously charging is not possible.
40	Charging pin damaged due to stacking.	3	Stacking loads are much higher than landing loads, which might cause the pin to damage.	3	Autonomously charging is not possible anymore.
41	Payload gets damaged during landing.	3	Drone is relatively heavy and lands with a higher G-force than 1.	5	Can lead to explosion if payload consists of pyrotechnics that did not fire during flight.
42	Loosen attachment of landing gear	3	Tolerances can lead to a non tight attachment	2	Misalignment can hinder stackability

Table 10.10: *Mitigation responses for the new operational risks.*

ID	Risk	Mitigation response	LS	CS
37	Drone misses landing pad during landing.	The landing legs should prevent damage to the payload and allow landing on the field. Size of landing pad should be determined with a safety factor to account for less landing precision.	1	2
38	Worker gets injuries due to heavy loads.	Determine maximum weight and height of drone stacks and comply with government regulations to ensure safe load handling.	2	3
39	Insufficient contact between charging pins and landing pad.	Use spring loaded pins and have multiple points points of contact.	2	2
40	Charging pin damaged due to stacking.	The polypropylene landing gear body should carry the stackability loads instead of the pin.	1	3
41	Payload gets damaged during landing.	Design landing legs that take up all the loads instead of the pyrotechnics.	2	4
42	Loosen attachment of landing gear	Ensure tight lock by right size pins or an O-ring type seal between the legs and attachment piece	1	2

10.6. Verification and Validation Operations

Two major tools were used in the sizing of the subsystems related to operations: one for the landing legs and one for the landing pad. The verification and validation of these tools is presented in this section.

Code Verification of Tools

First, the tools were checked for spelling mistakes and consistency of units and orders of magnitude. Then, unit tests were performed, after which they were scaled to module and system tests. These are presented in Table 10.11 and Table 10.12, where the columns state the output tested, the input varied, the test performed and the numerical outcome that supports the verification. Each test has been assigned a tag where VT stands for 'Verification', OP for 'Operations', U for 'Unit test' and S for 'System test'.

In addition to the numerical tests note that in the landing gear tool, the Euler buckling method assumes that the material stays within its elastic limits. Indeed, this has been verified by noting that the stress on the leg is always lower than the critical buckling stress that is lower than the yield stress. Meaning that no inelastic buckling needs to be considered [47].

Table 10.11: *Verification tests of landing gear and attachment part sizing tool*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-OP-U.1	σ	m_{drone}	Double m_{drone}, expect stress to double	For m = 2kg, σ = 0.46MPa, for m = 4kg,σ = 0.92MPa	yes
VT-OP-U.2	A_{tube}	t	Double t, expect A_{tube} to increase	For t = 2.4mm, A_{tube} = 7,9E-5m2. For t = 4.8mm, A_{tube}= 1,9E-4 m2	yes
VT-OP-U.3	σ_{buck}	E	Halve E, expect to σ_{buck} halve	E = 1.22GPa gives σ_{buck} = 29.15MPa, E = 0.61GPa gives σ_{buck} = 14.57MPa	yes
VT-OP-U.4	σ_{buck}	L	Double L, expect σ_{buck} to become 1/4	For L = 0.111m, σ_{buck} = 29.15MPa. For L= 0.222m, σ_{buck} = 7.28MPa	yes
VT-OP-U.5	m_{stack}	m_{drone}	For set $drones$, double the m_{drone}, expect m_{stack} to about double	For 6 drones, m= 2kg, m_{stack} = 10.76kg, for m=4kg, m_{stack} = 22,76kg	yes
VT-OP-U.6	A_{drone}	w_{drone}	Double the w_{drone}, expect A_{drone} to double	For w_{drone}= 0.73m, A_{drone}= 0.584m2. For their w_{drone} = 1.46m , A_{drone}= 1.168m2 which is double	yes
VT-OP-U.7	σ	A_{tube}	Double A_{tube}, expect σ /2	For A_{tube}= 79.3 mm2, σ = 0.5 MPa, for A_{tube}= 158.6 mm2, σ =0.25MPa which is halved	yes
VT-OP-S.1	σ	drones	Double drone, expect stress to double	For 3 drones, σ = 0.254 MPa. For 6 drones, σ = 0.507 MPa	yes
VT-OP-S.2	Failure of leg	F_{leg}	Increase load on leg by 100 and expect leg to fail under buckling	For F*100, σ = 50.8MPa which is above critical $\sigma_{buckling}$ = 25.6MPa, so it would fail	yes
VT-OP-S.3	h_{stack}	Number drones	Double number of drones, expect h_{stack} to about double	For 4 drones, h = 0.56m, for 8 drones h = 1.12m	yes
VT-OP-S.4	m_{attach}	r_{LG}	Increase the r_{LG}, expect m_{attach} to increase	For r = 7mm, m = 2.94gr, for r = 14mm, m = 4.13gr	yes

Table 10.12: *Verification tests for landing pad sizing tool*

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-OP-U.8	m_{steel}	l_{pad}	Double the size of the landing pad, expect mass of steel surface to increase by 4.	For l_{pad} = 0.856m, m_{steel} = 6.515kg, for l_{pad} = 1.712kg, m_{steel} = 26.062kg which is times 4.	yes
VT-OP-U.9	σ	t_{PP}	Double the thickness of plastic sides landing pad, expect normal stress per plate to halve.	For t_{PP} = 2.4 mm, σ = 0.0235MPa, for t_{PP} = 4.8 mm, σ = 0.0117MPa, which is halved.	yes
VT-OP-U.10	l_{pad}	Landing precision	Set landing precision to 0, landing pad size should be equal to maximum distance between legs.	For landing precision = 0m and distance between legs = 0.3561m, l_{pad} = 0.3561m, which is indeed equal.	yes
VT-OP-S.5	m_{pad}	d_{legs}	Double distance between legs, expect mass of pad to increase with less than double.	For d_{legs} = 0.3561m, m_{pad} = 13.5293kg. For d_{legs} = 0.7122m, m_{pad} = 21.8252kg, which is an increase with factor 1.6132.	yes

Calculation Verification of Tools

Once the implementation of the model was verified, the numerical results also need to be verified. This means that the outcome was compared to an external verified source. In order to do so, a margin must be set for the relative error between the model solution and the external solution. If the model's outcome lies within this margin, then the results are considered to be verified.

Note that not all outcomes of the models can be verified due to the really specific scenario. Therefore, the calculation verification has been focused on cross-sectional properties of the landing leg and masses of the leg and the craters. In particular, an external online calculator was used to verify the moment of inertia of the leg [67], and CATIA was used to model the landing gear and craters and compute their mass based on the given density. Note that this only applies to the masses of the PP parts and not extra components like the pins. For the computation of the moment of inertia a margin of ± 2% was chosen, since it is a closed formula that depends on a small number of variables, however machine error is expected. For the masses of the parts, a higher margin of ± 10% was chosen. This is due to the approximations of the model for certain geometries, for instance the trimming of the edges or small holes that the model neglects.

The calculation verification process is presented on Table 10.13, where it can be seen that the tool was verified.

Table 10.13: *Calculation verification of masses and moment of inertia*

Output to verify	Value	External value	Error	Margin accepted	V?
I_{xx}	1.150E-09	1.154E-09	0.07	±2%	Yes
$m_{Short-tube}$	0.0125	0.0130	3.83%	±10%	Yes
$m_{Long-tube}$	0.0182	0.0180	-1.11%	±10%	Yes
m_{crater}	0.00182	0.0020	8.78%	±10%	Yes
m_{attach}	0.00295	0.0030	1.79%	±10%	Yes

Validation of Tools

write paragraph

Due to how specific the model is to the design it is not possible to validate it with resources available to the design team. Since the landing gear is a relatively cheap part, it is suggested that validation is done by means of testing a prototype, which for example can be 3D printed, and tested under different loads in compression to validate the model output.

In addition, it is important to validate the attachment method of the landing leg to the arm through the spring loaded pins as well as the resistance of the joint between the pogo pin and the leg. These are also recommendations for a more detailed design phase mentioned in **??**.

10.7. Compliance Matrix Operations

Finally, Table 10.14 presents the compliance matrix for the operations related requirements that were used to design the landing gear, landing pad and stackability. The table is similar to Table 10.2 with an additional column on the right stating whether it has been verified or not. The reasoning behind this has been presented thought the method in Section 10.3 and Section 10.4. Note that there are some system requirements that will be presented and verified in Chapter 16.

Table 10.14: *Compliance matrix for operations subsystem requirements*

Department	Tag	Requirement	Verified?
Landing pad	CCE-AP-3	The drones shall be recharged wirelessly through their landing pads	Yes, charging pins
	CCE-SYS-3.1	The drone shall be able to charge during rain	Yes
	CCE-SYS-3.2	The drone shall be able to recharge autonomously on the landing pad between preparation and show	Yes
	OP-AP-6	The area of the take-off zone shall be at most $1m^2$ per drone	Yes, landing pad is XXm2
	POP-SYS-3.7	The energy storage should be fully charged within 60min.	Not possible[1]
Stackability	OP-AP-2	The drones shall be suitable for mass transport	Yes, stacks of 5 drones carried by one worker
	OP-AP-2.1	The drones shall safely be stacked on each other	Yes, stacks of 5 drones
	OP-AP-2.2	The volume of the drones shall not exceed 0.5m^3	Yes, it is $0.0599m^3$
	OP-AP-2.3	The drone shall be stored rigidly in a shock-free container	Yes
	SP-AP 1.4.3	Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm	Yes, long landing gear set

[1]Fully charging the battery within 60 minutes could not be verified for wireless charging as the landing pad specifications have not been defined. Charging by cable within 60 minutes has been verified in Chapter 7.

11
Subsystem Integration

chapter intro

11.1. Requirements related to integration

Table 11.1

TAG	Requirement
OP-AP-6	The area off the take-off zone shall be at most 1m2 per drone
OP-AP-2	The drones shall be suitable for mass transport
SP-EO-2	Drones shall not sink in the water
OP-AP-2.2	The volume of the drones shall not exceed 0.5m^3
SUS-EO-4	The drone shall not break down into small parts.
OP-GB-9	The drones shall adhere to drone regulations
SR-AP-1	An unintentional collision with the ground shall happen atmost once every 1,000,000 flight hours when flying indoors
SR-AP-2	An unintentional collision with the ground shall happen atmost once every 100,000 flight hours when flying outdoors
SR-SYS-5.1	Emergency landing will occur autonomously.
SR-AP-6	Each drone shall have a lifetime of at least 1000 flight hours
SR-SYS-8	The drone's electronics and propulsion system shall remain operational under raining conditions of up to 10mm/hr.
SUS-NR-6.1	The drone shall not leave any trash on the ground.
SUS-EO-7	Power supply failure during operation of the drone shall not result in release of any toxic substances outside of the system.

11.2. Subsystems Integration Overview

11.2.1. structures

11.2.2. Design of the motor mounts

The motors and propellers should be mounted to the arms. As the arms are circular tubes this cannot be done directly. Instead a mount is needed. From iteration 4 on wards an estimation of the mass of the motor mount is made to be included in the mass of the structure. For the iterations a simplified model of the moount is used. In Chapter 11 a more detailed design of the mount is presented

iteration 4 10grams The arm should integrate mass design cost designed frame battery integration system. resized frame plate accordingly.

integrated cce, redesigned size topplate accordingly. arms are rods. frame plate made longer to account for casing

show catia drone show catia of plate-arm and subsystems integration

The arm rod will be manufactured via polymer extrusions.

Buis extruded Motor stukje molding met schroefdraad Gat met schroefdraad voor landing legs Bott9mplate en blokjes als 1 geheel molded. Schroefdraad in blokjes boren Topplate schroefjes

11.2.3. Motors and Propellers

propeller mount

11.2.4. Battery Integration

11.2.5. CCE Integration

GPS moved to top, first it was inside the main box

11.2.6. Landing Gear Integration

show it can be mounted to arms. include landing loads analysis. include weigh of arms in critical load case explain arms provid space for wire. explain mistake in height and reiteration.

landing gear position: as close to body as possible, far away becasue of the paylaod.

11.2.7. Payload Integration

seen that it was a bit to short after putting it in solidworks. height of pcb's, casing and payload mount where not taken into account. fixed by making legs longer

11.2.8. Sizing of the drone casing

the drone casing is to fit

11.3. Overview of Integrated Final Design

11.4. Verification and Validation of Subsystem

12
System Analysis

chapter intro

12.1. Requirements related to system analysis

Table 12.1: *Requirements related to the design analysis.*

Requirement type	TAG	Requirement
System analysis	AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg
	SUS-EO-3	At least 80% of drone mass shall be recyclable.
	OP-AP-3	The drones shall be available in the year 2025
	SUS-AP-2	There shall be no radioactive parts on board of the drone.
	OP-AP-1	An employee who has followed a one-day training shall be able to replace parts of a drone
Control	SR-AP-5	In case of emergency, the drones shall be able to land safely in less than 90 seconds
	POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from being able to perform an emergency landing.
	SR-AP-3	Malfunctioning of a single drone shall not endanger the entire show
	CCE-SYS-8	Choreography shall be executed.
	CCE-AP-4	The drones shall be able position themselves within 0.5m accuracy
	SP-SYS-1.2.2	The pyrotechnics shall not cause the drone's center of gravity to move outside of the stability and controllabillity margins
	AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.

12.2. Drone Characteristics Overview

Diagrams in drone characteristics overview

refer to specs table in appendix B

12.3. Performance Analysis

An analysis is conducted on the performance of the final design. Specific analyses addressed are a mission flight profile, payload-flight time diagrams, climb performance, positioning accuracy, disturbance resistance, coverage, mission duration and emissions.

The trajectory of the mission flight profile consists of two main phases: the test routine and the actual mission. During the test routine the drones will do a quick test flight in which performance and safety is verified. After the test routine the batteries will be charged and then the actual mission takes place. Both the test routine and the mission can be subdivided into five segments. First the drones take off, then they fly towards the location where the show takes place and they climb towards the desired altitude, then it is showtime, after the show the drones have to fly back to the landing area after which they actually land on the ground. The mission flight profile is presented in Figure 12.1. The choreography is different for each show, which is why the showtime segment in the figure has multiple trajectories in different colours as examples.

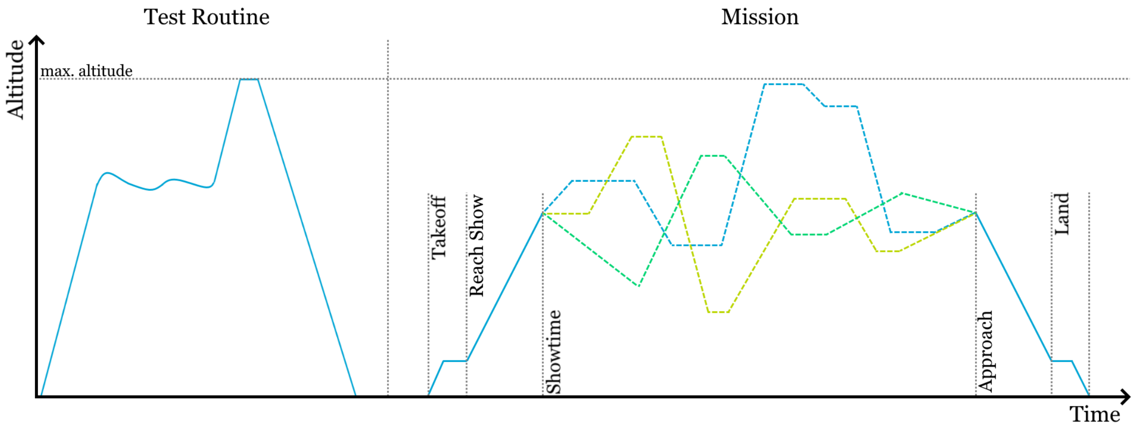
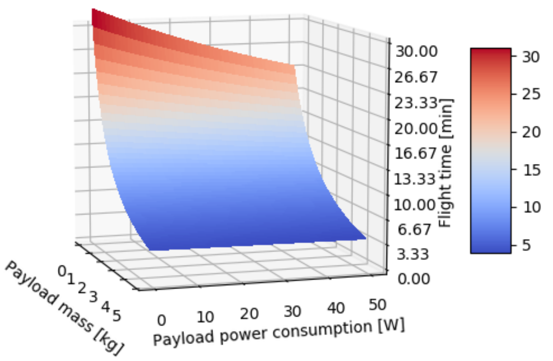
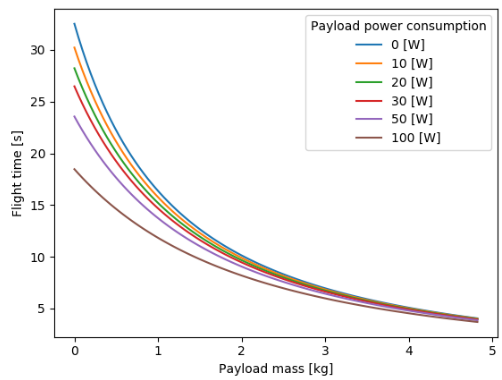


Figure 12.1: *Sketch of a typical flight profile*

One of the main innovation of our drones is the ability to change payload. The flight time depends on the payload mass and power consumption. To show the relation between achievable flight time, mass and power Figure 12.2b and Figure 12.2a were created. In the drone industry is common to specify the maximum flight time in hover mode with no wind, so the graphs below assume no wind and fresh batteries with depth of discharge of 80% . The range of the drone is limited by the communication link, rather than endurance. The communication system allows for a range up to 1200 m, as described in Subsection 8.3.2.



(a) *3D payload - flight time diagram*



(b) *2D payload - flight time diagram*

When the drone carries 0.6 kg payload, it has thrust to weight ration of 3, so the absolute maximum payload mass is 4.8 kg. While in theory the drone can lift such payload, it would leave no additional thrust for acceleration. This issue has to taken into account when planning a drone show.

Another important feature of swarm vehicles is wind resistance. Strong winds can disturb the trajectories of the drones and cause unintended collisions. In Figure 12.3 a strong wind gust is applied to the drone.

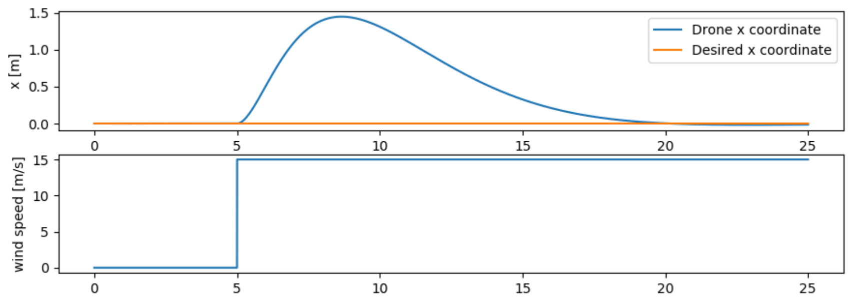


Figure 12.3: *Responce to the wind gust*

The wind speed exceeds 6 BFt (13.8 m/s) and the drone still stays within 1.5 meters from a specified location. This proves the ability to fly in formations 2 meters apart from other drones. This result is achieved with manually tuned gains, better PID gains will allow for less wind disturbance.

Climb performance of the drone and the ability to land quickly are useful to investigate. According to requirement SR-AP-5, the drone has to be able to land safely within 90 seconds at all times. In order to check this requirement it was calculated how long it takes for the drone to reach the ground in free fall from 1000 m altitude. This was done by computing the net force on the drone while taking into account gravity, drag, and weight [68]. Drag depends on the drag coefficient, air density, velocity and surface area. The drag coefficient and surface area were taken already computed during the subsystem design. Air density was assumed a constant at sea level. Velocity depends on time and acceleration and was updated every 0.1 seconds. It turns out the drone can reach the ground in 31.8 seconds while free falling. During the fall the drone will reach a terminal velocity of 34.1 m/s. The time it takes to decelerate from the terminal velocity was computed as well by taking into account thrust at full throttle, which is 64.8 N. It takes approximately 1.5 seconds to slow down to a full stop. Using the same approach but adjusting it to acceleration instead of deceleration, the time it takes to reach 1000 m altitude starting on the ground was computed as well. It turns out the drone can get to that altitude in only 21.8 seconds, which results in an unexpected rate of climb of 45.9 m/s. This is much higher than the maximum horizontal velocity of 33.8 m/s for which the drone is designed. This might be due to the fact that during ascending the thrust vector is aligned with flight path of the drone, while during horizontal flight the thrust vector has both a horizontal and a vertical component.

The preliminary design phase led to the conclusion that the drone will be powered by li-po batteries. Lithium-polymer batteries are very common in the multirotor drone industry. Among their attractive performance characteristics, they have the benefit of not producing any emissions during flight. As such, the operation of the drone itself will not result in any emissions of pollutants or harmful substances.

12.4. RAMS analysis

12.4.1. Availability

The majority of the parts in the drone are off-the-shelf components, which makes it very easy to replace or upgrade parts. For example the battery is a common 4 cell LiPo battery, available in most hobby stores. Even if the exact model goes out of stock, similar models can be used with very little effect on performance. Same is true for plastic propellers. Electrical motors, on the other hand, are quite different from manufacturer to manufacturer, so it is crucial to buy enough spare parts with the initial batch. As for the frame, injection molding is cheap for large batches, but quite expensive otherwise. It makes sense, therefore, to produce spare frames with the initial batch as well.

Concerning electronic components, drones do not use any advanced processors that are not available due to world wide chip shortages in 2021. All components are available in sufficient quantities from big electronic suppliers such as Mouser or DigiKey. UWB board is sold as a ready module, but other PCBs are custom made in China. It is much cheaper to order PCB printing and assembly for large batches, so spare electronics should be included in the initial batch.

The software for the flight computer is not readily available, because the flight computer is custom made and has non-standard peripherals such as UWB module and RTK GPS module. The flight computer is based on the top end STM 32 H7 microcontroller, which is not common yet in the drone industry, but the SP Racing H7 Extreme drone has the same microcontroller and supports open source autopilots such as Betaflight [69] [70]. So the flight software for the drone needs to be modified, but not written from zero.

All of-the-shelf components and manufacturing techniques are readily available and proven, so requirement OP-AP-3 is satisfied.

12.4.2. Maintainability

Maintainability is an important subject as it is desired to reduce costs related to repair and maintenance. The biggest influence on easy maintenance is the accessibility of all components. The easier components can be accessed, the less time consuming reparations will be. Besides, some components are made interchangeable instead of fixed, such that the drone can be repaired and it does not have to be thrown away completely. For example, as described in Chapter 9 the arms are fixed, but landing legs are changeable. This allows a possibility of replacing broken landing legs with 3D printed ones made in-house. The toughness of 3d printed parts is lower, but ultimate strength is very similar if the layer orientation is selected properly.

Propellers are known to be one of the most vulnerable component of the drone. They can break or get damaged easily due to small accidents, for example during transport or while stacking drones on top of each other. These little accidents are unavoidable. Fortunately, propellers can be replaced easily by new ones as they are accessible from the outside without interference with other components. Besides, propellers are quite cheap so replacing those should not form problems.

The battery is one of the most critical components of the drone, so it is important to maintain it carefully. This can be done by use of a battery management system (BMS). This device keeps track of the battery's state of health. This way, the battery can be replaced at the right moment. Besides, the BMS protects the battery from over-current, over- and under-voltage. Therefore, the battery can be properly charged inside the drone.

The software updates can be done via WiFi, so drones don't need to be connected by cables to the computer. The communication and positioning modules are connected to the flight computer by wires with connectors, so if the user wishes to replace some or all of these modules, it is easy to do. Payload is connected to the flight computer via I2C cable with detachable connectors, so the payload can be easily swapped as well. It is important to note that I2C protocol may require additional electronics on the payload side to convert I2C signals to PWM signals for the lights or any other signal type for future payload.

12.4.3. Reliability and safety

12.5. Technical Risks Analysis

12.6. Sustainable development strategy

In this section sustainability requirements related to integration are verified.

12.6.1. SUS-EO-3 At least 80% of drone mass shall be recyclable.

Because the payload design is not a part of this project, only the drone without the payload is analyzed. In principle, all materials can be recycled, but the cost of recycling can be higher than the profit. This is true for fiberglass in circuit boards.Recyclability of Lithium batteries heavily depends on the process. By EU directive 2006/66/EC Lithium batteries should be recycled at least 50% by mass, however processes with 95% efficiency exist [71]. Frame and propellers are made from common plastics and are 100% recyclable. Electric motors are made of valuable metals, so they are also fully recyclable. Total mass of the drone is slightly higher than the total mass of all subsystems to account for manufacturing deviations, wires and coatings. Those are assumed to be non-recyclable. To calculate the recyclability fraction the following equation is used:

$$R = \frac{\sum M_{res}}{M_{tot}} = \frac{0.412 + 0.58 * 0.95 + 0.1319}{1.51} = 84.9\% \tag{12.1}$$

Where M_{res} are masses of all recyclable parts and M_{tot} is the total mass of the drone, excluding the payload. in Equation 12.1 the calculation was done for the case of 95 % battery recyclability. If the battery is recycled with least efficient legal process (50%) then total recyclability is 67.6%. Similar analysis can be performed for the total waste during the lifetime of the drone. Batteries are replaced most often, so they degrade or improve the recyclability fraction the most. For the 95% process R = 92.2 % , for 50% efficient process R = 54.7%.

From the analysis above it can be seen that in the worst case scenario the design does not meet the requirement. In 2006/66/EC document recyclability bar for other types of batteries is set much higher, namely 65% for led-acid and 75% for nickel-cadmium. These batteries are not energy dense enough for UAVs.Also, reducing the battery size would fail the flight time requirement, so there is no alternative design choice to minimize battery impact on recyclability.

Recyclability requirement states that the drone should be recyclable, and because it is possible to have recyclability fraction of 84.9%, the requirement is satisfied. However, it is up for the customer to direct the components to the right recycling facility.

12.6.2. SUS-AP-2 There shall be no radioactive parts on board of the drone

This requirement is verified, as no components of the drone are radioactive.

12.7. Sensitivity Analysis of Final Design

13 Production Plan

thread, glue arms and motor mount screw into blocks attached to frame plates. end of arm has screw on propeller mount lAnding has to be removble material to fill up battery expansion cavity.

dsign margins for production

risk of landing gear thread wearing out risk of misalignment of the crater

14
Logistics and Safety

This chapter presents the logistics and safety analysis of the droneshow. Section 14.1 presents the requirements that influence the logistics and operations of droneshows.**??** presents a logistics analysis of droneshows focusing on the deployment of drones on their landing pads. covers..., **??** ... and Section 14.5 presents an overview of the safety measures needed for different aspects of the operations.

14.1. Logistics and Operations Requirements

In the droneshow market it is key that a design is easy to operate which simplifies the logistics of the shows. Table 14.1 presents the requirements related to logistics that the design must fulfill.

Table 14.1: *Requirements related to logistics*

TAG	Requirement
OP-AP-1	An employee who has followed a one-day training should be able to replace parts of a drone.
OP-AP-4	The drones shall be operated from a central location.
OP-AP-5	The drones shall be controlled by a ground station.
OP-AP-6	The area off the take-off zone shall be at most 1m^2 per drone.
OP-AP-7	The minimum amount of drones in one show shall be 300 for outdoor shows.
OP-AP-8	The minimum amount of drones in one show shall be 20 for indoor shows, where 'indoors' means venues such as concert halls or stadiums.
CCE-AP-2	The show location shall be at most 1000m apart from the ground station

Requirements OP-AP-4 and OP-AP-5, from a logistics perspective, state that a ground station must be deployed on location and close to the grid of drones. From here, the drones are controlled, therefore it includes equipment such as computers and antennas, and it's where the pilots will work from. The maximum distance between the ground station and the drones is 1000m (requirement CCE-AP-2), so that poses a logistical limit to the location of the ground station with respect to the drone grid.

14.2. Deployment of Drones Estimation

As presented in Chapter 10, six drones drone can be stacked in carrying structures with a total weight of 12.46kg and a height of 85.5cm, which can be safely carried by one worker by hand. This hand-carrying method will be assumed to simulate the logistics of a drone show, since it can be used in any terrain and it is the method most widely used in the current drone show companies as mentioned in Chapter 4. However, note that more efficient carrying methods such as carts with wheels or vehicles could be used.

Outdoor Show Deployment

The simulation focuses on the time required to deploy the drones on a field. Other actions such as the calibration of drones or deployment of ground station can be found in the logistics diagram in **??**. The deployment time is dependant on many factors, such as the amount and type of drones, the number of drones per stack, the amount of workers that can deploy the drones simultaneously and the distance between the drones in the field. The following assumptions have been made to give an estimation of the time needed to deploy the drones on a grid:

- Drones are placed in a rectangular grid with a spacing of 2m. Since their maximum takeoff area by requirement OP-AP-6 is $1m^2$. It takes 30s to walk between landing pads.
- The stacks of drones transported to the event are initially located at the ground station, which is at one of the corners of the rectangular grid. On average, for each stack, the worker will walk to the middle of the field and come back.
- The size (rows x columns) of the grid is assumed to be the optimum one, which gives the minimum average walking time for the workers. The workers can walk at a constant speed of 5km/h [72].
- Deploying the light payload (lights or megaphone) drones takes 3min at the landing pad. This consists of:
  - Taking the drone out of the carrying structure
  - Opening the case, sliding in the battery and closing the case
  - Checking payload is correctly connected
  - Powering on the drone
- Drones with heavy payload (pyrotechnics or future payload) need to be prepared at the ground station and walked one by one to their location. The preparation is assumed to take 10min per drone. These drones are placed last on the grid. Note that in Section 14.5 it is recommended that pyrotechnic drones are located in a safe area of the grid, so this estimation assumes that these drones are placed on the grid as far as possible from the ground station.
- For each 5 hours of work, each worker gets a break of 30min [73]. In addition, weather conditions are assumed to be favorable, which doesn't require any extra safety measures. Refer to Section 14.5 for some considerations on raining conditions.

However the model assumes 1st light payload drones them pyrotechnic but in reality workers can work in parallel making the process more efficient.

- Extra calibration steps of drones is not considered due to lack on information on the software or safety checks, so estimations are indicative.

Table 14.2 presents the time estimations (in hours) that the crew of Anymotion Productions, which usually consists of 4 workers[1], would take in order to deploy different amounts of drones with different percentage of pyrotechnic payload drones.

These quantities go from 100 drones (usual Anymotion Production size [1]) to 3052 drones, which would beat the current Guinness World Record [6]. In addition, 300 drones is the minimum number of drones in an outdoors show by requirement OP-AP-7 and 303 pyrotechnic drones is the current Guinness World Record for a fully pyrotechnic drone show [4]. Therefore any drones show with more than 303 pyrotechnic drones or more than 3052 drones in total would beat record, this is indicated Any record-breaking drone amount is indicated in blue.

Currently Anymotion Productions takes about 2 hours to deploy 100 drones with 4 people. Then they need about 6 hours to perform calibration tests before starting the show [1]. Therefore it's important that the deployment of the drones on their landing pads gets done as quickly as possible. In Table 14.2, green indicates the deployment times below 3 hours. Note that with the carrying structures Anymotion Productions could deploy the drones in 1.7 hours, quicker than their current method. In yellow, the timings lower than 4 hours are indicated which could potentially be archived with the four-worker crew if the working day starts earlier.

On Table 14.2, below the time estimates, the optimal grid size is shown as well as the maximum distance between the drones and the ground station which has been computed with a 20% safety margin due to the assumptions of the model. It can be noted how this ground distance is well below the 1000m requirement for communication (CCE-AP-2), so, at least on the ground, the requirement can be met.

However, it is clear from Table 14.2 that even with the carrying structures most types of shows are not

[1] Personal communication with N. Cornelissen (Creative Manager at Anymotion Productions), 21/05/2021.

Table 14.2: *Estimated time (in hours) of deployment of drones on grid for a crew of 4 workers for different amount and types of drones showing the optimized grid size and maximum distance from ground station*

	Total number of drones							
Pyrotechnique drones	**100**	**150**	**200**	**300**	**500**	**1000**	**2000**	**3052.00**
0%	1.71	2.53	3.45	5.11	8.68	17.6	36.17	56.29
25%	2.56	3.87	5.15	7.98	13.88	30.64	72.9	129.7
50%	3.41	5.16	6.96	10.74	19.07	43.77	109.75	203.12
75%	4.26	6.5	8.77	13.6	24.27	56.81	146.59	276.53
100%	5.02	7.69	10.47	16.36	29.46	69.84	183.33	349.84

Grid with 2m spacing	10x10	10x15	20x10	20x15	20x25	32x32	50x40	56x55
Max distance to ground station	33.936	43.272	53.664	60	76.8	129.24	153.6	187.56

Legend		Less 3hrs			Less 4hr			Record

logistically possible with a working crew of 4 people. Therefore, Table 14.3 shows how many workers would be needed to keep the deployment time of the drones under 3 hours. Green indicates less than 20 workers, yellow between 21 and 75 and red more than 76.

Table 14.3:
Estimation of number of workers needed to deploy different amounts and types of drones on the optimized grid in less than 3hours

	Total number of drones							
Pyrotechnique drones	**100**	**150**	**200**	**300**	**500**	**1000**	**2000**	**3052.00**
0%	4	4	5	7	12	23	47	75
25%	4	6	7	11	18	40	89	175
50%	5	7	9	14	25	58	148	270
75%	6	9	12	18	32	75	200	363
100%	7	10	14	22	39	93	250	470

Legend		0-20 workers			21-75 workers			76+ workers

Note that deploying the drones does not require specific capabilities, just an in-house training according to Anymotion Productions [1], therefore it is possible to reinforce the main crew with an additional crew of part-time workers only during the most demanding parts of the event such as the deployment of drones and their recovery from the landing pads.

Table 14.3 is based on the 3hr limit which is the higher margin of current Anymotion Production operations. If the time for calibration were to be reduced and more time allocated to the deployment of drones. Then

Indoor Show Deployment

While the main logistics of deploying and preparing the drones remains the same, indoors drone shows have additional aspects to consider:

- Amount of drones is lower, by requirement OP-AP-8, these shall be at least 20 drones, while the maximum number depends on the size of the venue.
- As an indication, 20 light-payload drones could be deployed by Anymotion Production's crew (four workers) in about 25min and 20 pyro-drones in about 1 hour and 15min. So an indoor show would be doable with their current crew.
- Safety becomes a major factor, drones need to keep enough distance with the public, which can limit their amount and manoeuvres. Possibly safety cages can be added to mitigate the risk of injuring the public (risk XX in XX), this is proposed as a consideration for more detailed phases of the design in Chapter 17.

- Weather has less influence since the site will be more protected from winds and likely covered. This allows for easy deployment of drones and operation of electric components.

14.3. Operations and Logistics Diagram

Section 14.2 presented an analysis on the estimated time to deploy the drones for different types of drones show. However, the logistics of these shows involve many other phases. **??** presents the operations and logistics diagram of the drone show. Note the following:

- Maintenanis is done by one worker in one day (req. XX)
- Steps such as manufacturing, recycling parts or ... are shown for completeness of the operations however no amount of people or working hours are assigned.

14.4. Logistics Costs

Cost of transportation boxes Cost of renting trucks Cost of part-time workers Cost of security over night

14.5. Safety Regulations

There are many safety considerations involved in the organization of a drone show. This section presents some of the main ones. In addition Table 14.4 presents the requirements that bring safety considerations with the.

Table 14.4: *Requirements that influence safety*

TAG	**Requirement**
SR-SYS-5.2	The operator shall have an emergency stop button
SP-ST-1.2.1	The pyrotechnics shall not reach spectators

Indoor show

Enough distance with public, safety cage around propellers is recommendation

Ground Station

Contains emergency stop bottom, two pilots are located, licensed (AM license), stand-alone power supply (not grid) in cse the grid goes down the communications with the drones is not lost, in any case if drones loose comms they should perform emergency landing and end show as explained in **??**.

Heavy loads

The following safety measures must be taken when carrying the drone stacks. Workers should wear safety shoes when handling heavy loads like the transportation boxes of the carrying structure. Relatively heavy loads must be carried by more than one worker to avoid injuries.

Safety Area

It is essential that a safety area around the location of the show is established and that no one is aloud to enter for their own safety in the unlikely case a drone suffers a malfunction. To ensure that no one enters the safety area, clear signs must be put in place and the public must be warned. In case of really crowded events the aid of security guards or local authorities could be used. In addition the drones shall be able to receive and execute the command of terminating the show at any moment in case this safety area is compromised.

Raining Conditions

In the case that the droneshow is performed outdoors under raining conditions, further safety measures must be taken. Opening the waterproof drone casing should be avoided, this means that operations that require the opening of the case, such as battery insertion or electronics checks, must be performed under a tent or inside a building. Therefore, the drones should be taken out of the stacks, prepared for flight, place again on the carrying structures and brought to the landing pads where significant operation is needed.

Li-Po Battery

There are specific safety regulations regarding the handling and transport of Li-Po batteries....

Pyrotechnic Payload Drones

In case of pyrotechnic payloads, they need to be loaded into the drone. This must be done one drone at a time and the drone cannot be placed on the carrying structure once loaded. Therefore, pyrotechnic drones will be prepared under a safety tent by trained personnel and walked individually to their landing pads once loaded. They should be placed only after all other drones are calibrated and ready to take off to limit the amount of time the pyrotechnic loads stay on the grid. Depending on the amount of pyrotechnics, these drones shall also be located on landing pads away from the main grid of drones and the public or workers, to avoid possible damage if they were to explode or catch fire either before take-off or on landing (this is risk 41 on Table 10.9).

Pyrotechnic loads must be handle by certified personnel and pyrotechnic equipment must be labeled according and transported in a safe manner according to local regulations.

Extra safety measures such as fire extinguishers shall be placed near the landing pads of these drones and, if applicable, emergency services such as the fire department must be made aware of the exact location of these drones. This might also apply for the use of 'future payloads', if they involve any danger to the workers, public or objects around them.

15 Financial Overview

15.1. Requirements

Table 15.1: *Requirements related to the financial overview.*

TAG	Requirement
COST-AP-1	The drones shall cost no more than "1000,- per piece.
COST-AP-2	The expected cost of replacing parts in 1000 light shows shall be nomore than "650,-.

16

System Verification and Validation

17
Post-DSE Activities

After the project 'One Thousand Little Lights' there is still a lot to be done before the drone will be made available on the market. This chapter will discuss which design recommendations followed from the design process in Section 17.1. Also the activities which need to be taken until the drone is ready to be produced are presented in Section 17.2.

17.1. Design recommendations

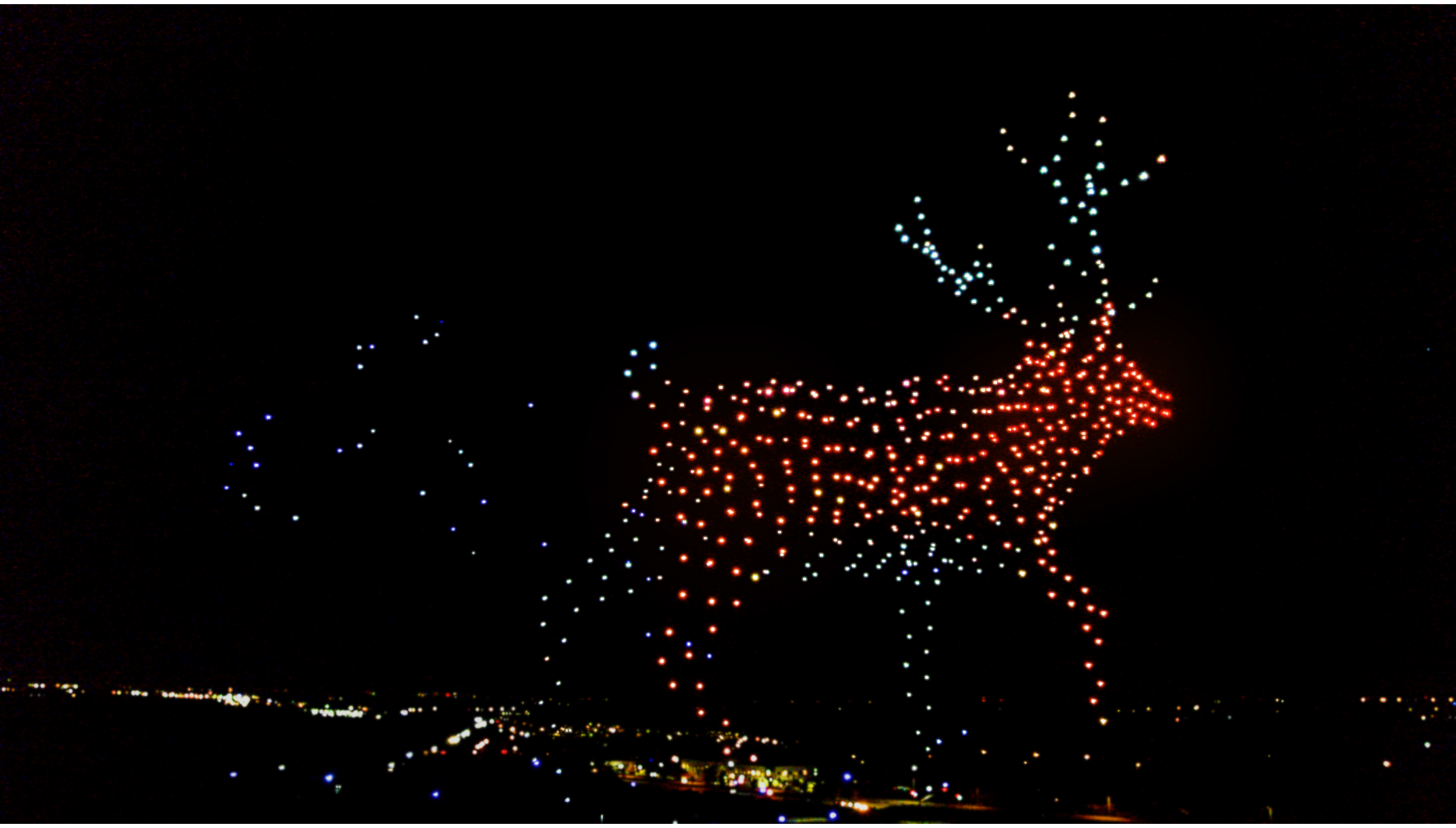
In this section the recommendations which followed from the design process, for the design activities after the project 'One Thousand Little Lights' are presented. The first recommendations which is mentioned in every subsystem chapter is the fact that the calculations still need to be validated, with a prototype model. This is especially important for

17.2. Post-DSE activities

18
Conclusion

19

Spec sheet



19.1. First Section

All human things are subject to decay. And when fate summons, Monarchs must obey.

Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language. Hello, here is some text without a meaning. This text should show what a printed text will look like at this place. If you read this text, you will get no information. Really? Is there no information? Is there a difference between this text and some nonsense like "Huardest gefburn"? Kjift – not at all! A blind text like this gives you information about the selected font, how the letters are written and an impression of the look. This text should contain all letters of the alphabet and it should be written in of the original language. There is no need for special content, but the length of words should match the language.

Bibliography

[1] DSE-Group 17. *One Thousand Little Lights: Baseline Report*. Apr. 2021.

[2] DSE-Group 17. *One Thousand Little Lights: Midterm Report*. May 2021.

[3] *50 Years of Record Breaking Innovation | Drone Light Show | Intel*. 2018. URL: https://www.youtube.com/watch?v=xwQ31-vSgfs&ab_channel=Intel.

[4] *Most unmanned aerial vehicle (UAV) launching fireworks simultaneously*. 2020. URL: https://www.guinnessworldrecords.com/world-records/551056-most-unmanned-aerial-vehicle-uav-launching-fireworks-simultaneously.

[5] Phil Richards. *Swarm of 300 drones descends on Cornwall demanding G7 world leaders 'ACT NOW' to protect the planet*. 2021. URL: https://www.greenpeace.org.uk/news/drones-demand-g7-leaders-act-now/.

[6] *3,051 drones create spectacular record-breaking light show in China*. 2020. URL: https://www.guinnessworldrecords.com/news/commercial/2020/10/3051-drones-create-spectacular-record-breaking-light-show-in-china.

[7] El-Sayed Aziz et al. "AC 2008-613: ONLINE WIND TUNNEL LABORATORY". In: (June 2008), pp. 16–17.

[8] Carl Russell et al. "Wind Tunnel and Hover Performance Test Results for Multicopter UAS Vehicles". In: (May 2016), pp. 16–17.

[9] Narayanan Komerath Dhwanil Shukla. "Multirotor Drone Aerodynamic Interaction Investigation". In: (Nov. 2018), p. 13.

[10] FAA. "Advisory Circular 90-23F". In: (Oct. 2014), p. 14.

[11] S. Lee D. Han D.Y. Gwak. "Noise prediction of multi-rotor UAV by RPM fluctuation correction method". In: (Jan. 2020), p. 15.

[12] *Causes of aircraft noise*. 2021. URL: https://corporate.aucklandairport.co.nz/sustainability/managing-aircraft-noise/understanding-aircraft-noise/causes-of-aircraft-noise.

[13] *Noise level calculations*. URL: https://www.hoevelakenbereikbaar.nl/www2/MilieuZaken/Geluid_lawaai/Noise%5C%20level%5C%20calculations.pdf.

[14] *Raindrop*. 2012. URL: https://glossary.ametsoc.org/wiki/Raindrop.

[15] *Quadcopter Dynamics and Simulation*. 2001. URL: https://www.uu.edu/dept/physics/scienceguys/2001Mar.cfm.

[16] *De complete windschaal van Beaufort*. 2021. URL: https://www.weerstationuithuizermeeden.nl/Schaal-van-Beaufort.htm.

[17] Quan Quan. "Introduction to Multicopter Design and Control". In: (Dec. 2016), p. 393.

[18] *Robotshop.nl*. May 2021. URL: https://www.robotshop.com/nl/nl/uav-drone-motors.html.

[19] *Innov8tive designs*. May 2021. URL: https://innov8tivedesigns.com/products/brushlessmotors/cobramultirotormotors.html.

[20] *T-motor*. May 2021. URL: https://store-en.tmotor.com/category.php?id=2.

[21] *MCM Racing*. May 2021. URL: https://www.mcmracing.com/nl/974-moteur-brushless-drone.

[22] Lydia Heida. "Boom time for carbon fiber recycling". In: (Sept. 2016).

[23] Eco-Cycle. *A-Z Recycling Guide – Electric Motors*. URL: http://www.ecocycle.org/a-zguide/electric-motors.

[24] *Lipo Battery Database*. URL: https://www.notion.so/b57745bb5d2a4fb8a3612e88a4a87738?v=ae41b4f22dba4d33ae574d7a173e0f3a.

[25] *BU-808: How to Prolong Lithium-based Batteries*. URL: https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries.

[26] *Battery Life (and Death)*. URL: https://www.mpoweruk.com/life.htm.

[27] URL: http://www.drivecalc.de/.

[28] *Zeee 14.8V 100C 7000mAh 4S RC Lipo Battery Deans Connector with Metal Plates for RC Car RC Truck RC Tank Racing Hobby*. URL: https://www.amazon.com/dp/B07YP7MT6V/ref=as_li_ss_tl?ie=UTF8&linkCode=ll1&tag=httpwwwbook05-20.

[29] *Mavic 2 - Product Information - DJI*. URL: https://www.dji.com/nl/mavic-2/info#specs.

[30] Pascal Simon. *6 Important Parameters for the Design-In of Lithium Polymer Batteries*. Sept. 2019. URL: https://www.jauch.com/blog/en/6-important-parameters-for-the-design-in-of-lithium-polymer-batteries/.

[31] *Communication Options for Network RTK*. 2005. URL: http://www.wasoft.de/e/iagwg451/wegener/communication.html.

[32] DECAWAVE. *DWM1000 Module*. URL: https://www.decawave.com/product/dwm1000-module/.

[33] *LoRa*. 2005. URL: https://en.wikipedia.org/wiki/LoRa.

[34] *Link Budget Calculations and Choosing the Correct Antenna*. 2015. URL: https://docs.aerohive.com/330000/docs/guides/Aerohive_LinkBudgetCalculations.pdf.

[35] ActiveReach. *Causes of wifi interference*. URL: https://activereach.net/support/knowledge-base/connectivity-networking/wifi-interference/.

[36] *Mouser Electronics*. 2021. URL: https://eu.mouser.com/.

[37] *Digi-Key SWDP.2458.15.4.A.02*. 2021. URL: https://www.digikey.nl/product-detail/en/taoglas-limited/SWDP.2458.15.4.A.02/931-1594-1-ND/9972891?utm_adgroup=RF%5C%20Antennas&utm_source=google&utm_medium=cpc&utm_campaign=Shopping_Product_RF%5C%2FIF%5C%20and%5C%20RFID&utm_term=&productid=9972891&gclid=Cj0KCQjwh_eFBhDZARIsALHjIKcmhDS3quc9ZAvPfj3jCntDPVRigLsnHSlYj1syhdSY15YjuyN22P8aAv6MEALw_wcB.

[38] *TaoGlass*. 2021. URL: https://www.taoglas.com/.

[39] *Tinytronics*. 2021. URL: https://www.tinytronics.nl/shop/nl.

[40] *U-blox CAM-M8 series*. 2021. URL: https://www.u-blox.com/en/product/cam-m8-series.

[41] W. A. Kissick et al. *Antenna System Guide NIJ Guide 202–00*. 2001. URL: https://nij.ojp.gov/library/publications/antenna-system-guide-nij-guide-202-00.

[42] *RS-online Electrolube transparent 15 ml Can Conformal Coating for PCBs*. 2021. URL: https://nl.rs-online.com/.

[43] *JLC PCB*. 2021. URL: https://jlcpcb.com/.

[44] *Quadcopter Dynamics and Simulation*. 2012. URL: https://andrew.gibiansky.com/blog/physics/quadcopter-dynamics/.

[45] Tony Lacey. *Tutorial:The Kalman Filter*. URL: http://web.mit.edu/kirtley/kirtley/binlustuff/literature/control/Kalman%5C%20filter.pdf.

[46] QuadmeUp. *PID looptime: why it is not only about frequency*. URL: https://quadmeup.com/pid-looptime-why-it-is-not-only-about-frequency/.

[47] T.H.G. Megson. *Aircraft Structures for Engineering Students Sixth Edition*. ISBN 978-0-08-100914-7. Elsevier, 2017.

[48] Engineering Toolbox. *Air Density calculator based on ISA*. 2020. URL: https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html.

[49] Brennan caltech. *Drag on a sphere and cylinder*. 2020. URL: /http://brennen.caltech.edu/fluidbook/externalflows/drag/dragonasphere.pdf.

[50] GetFPV. *FPV Drone Wire Sizes and Cable Management*. 2020. URL: https://www.getfpv.com/learn/fpv-essentials/fpv-drone-wire/.

[51] Jerrin Bright et al. "Optimization of quadcopter frame using generative design andcomparison with DJI F450 drone frame". In: *IOP Conference Series: Materials Science and Engineering* (2021).

[52] Wesley Mascarenhas, Carlos Ahrens, and Andre Ogliari. "Design criteria and safety factors for plastic components design". In: *Materials Design - MATER DESIGN* 25 (May 2004), pp. 257–261. DOI: 10.1016/j.matdes.2003.10.003.

[53] *By Design: Polypropylene part design, Part 1*. 2002. URL: https://www.plasticstoday.com/materials/design-polypropylene-part-design-part-1.

[54] *ANSYS(CES) Granta EduPack*. 2021. URL: https://www.ansys.com/products/materials/granta-edupack.

[55] *Ten reasons to avoid PVC Plastic*. 2004. URL: https://www.greenpeace.org/usa/wp-content/uploads/legacy/Global/usa/report/2007/8/ten-reasons-to-avoid-pvc-plast.html.

[56] Xuesong Li et al. "Highly efficient flame retardant, flexible, and strong adhesive intumescent coating on polypropylene using hyperbranched polyamide". In: *Chemical Engineering Journal* 324 (2017), pp. 237–250. ISSN: 1385-8947. DOI: https://doi.org/10.1016/j.cej.2017.05.037. URL: https://www.sciencedirect.com/science/article/pii/S1385894717307787.

[57] Baltus Cornelius Bonse Alessandra de Almeida Lucas José Donato Ambrósio and Sílvia Helena Prado Bettini. "Natural Fiber Polymer Composites Technology Applied to the Recovery and Protection of Tropical Forests Allied to the Recycling of Industrial and Urban Residues". In: *Advances in Composite Materials - Analysis of Natural and Man-Made Materials* (2011), p. 178.

[58] *Clear pp sheets shop*. 2021. URL: https://benl.rs-online.com/web/p/plastic-sheets/2012785/.

[59] A.P. Mentzer. *3 Million Candle Power Spot Light Vs. 600 Lumens Spotlight*. 2020. URL: https://sciencing.com/3-vs-600-lumens-spotlight-8713715.html.

[60] Kevin Krisciunas and Don Carona. *At What Distance Can the Human Eye Detect a Candle Flame?* 2015. arXiv: 1507.06270 [astro-ph.IM].

[61] BESLED. *Mi-Light - LED Downlight - Smart LED - 6W - RGB+CCT - Aanpasbare Kleur - Dimbaar - Inbouw Rond - Mat Wit - Aluminium - Ø120mm*. URL: https://www.besled.nl/mi-light-led-downlight-smart-led-6w-rgb-cct-aanpasbare-kleur-dimbaar-inbouw-rond-mat-wit-aluminium-o120mm?utm_source=google_shopping_de&utm_medium=cpc&utm_term=29416-BSE403091&gclid=Cj0KCQjw5auGBhDEARIsAFyNm9EucI2Th3GX2OmB9yUm6fSaAUpZnQ6Gaj5nOuVUavPtACtzRoUbL5UaAkAvEALw_wcB.

[62] energysquare. *Power by Contact Technology©*. 2019. URL: https://energysquare.co/technology/.

[63] Skycharge. *Skycharge*. 2021. URL: https://skycharge.de/.

[64] C.C.P. Contact Probes. *How Does a Pogo Pin Work?* 2021. URL: https://www.ccpcontactprobes.com/application/how-does-pogo-pin-work.

[65] *Directive 90/269/EEC - manual handling of loads*. URL: https://osha.europa.eu/en/legislation/directives/6.

[66] *Calculating Recommended Weight Limit (RWL)*. 2021. URL: https://www.ccohs.ca/oshanswers/ergonomics/niosh/calculating_rwl.html.

[67] Calc Resource. *Moment of Inertia of a Circular Tube Calculator*. 2020. URL: https://www.calcresource.com/moment-of-inertia-ctube.html.

[68] Nancy Hall. *Terminal Velocity*. 2021. URL: https://www.grc.nasa.gov/www/k-12/airplane/termv.html.

[69] *SP Racing H7 extreme*. 2021. URL: https://shop.seriouslypro.com/.

[70] *Betaflight*. 2021. URL: https://betaflight.com/.

[71] CSIRO. *Lithium-ion battery recycling*. 2020. URL: https://www.csiro.au/en/research/technology-space/energy/Energy-storage/Battery-recycling.

[72] *Preferred walking speed*. 2021. URL: https://en.wikipedia.org/wiki/Preferred_walking_speed.

[73] *What are the legal rules for breaks during my work?* 2021. URL: https://www.rijksoverheid.nl/onderwerpen/werktijden/vraag-en-antwoord/wettelijke-regels-pauzes-tijdens-werk.

A

Appendix A

In the following table the task distribution of the final design phase is shown. The letters indicate the following:

R - responsible , C - contributed , P - proofread.

		Lucas	Menno	Mustafa	Gijs	Vova	Ties	Walid	Carmen	Paul	Ragnhild
	Executive Overview										
1	**Introduction**										
2	**Project Progress**										
2.1	Project objective										
2.2	Concept overview										
3	**System's Functional Analysis**										
3.1	Functional Flow Diagram										
3.2	Functional breakdown structure										
4	**Market analysis**										
4.1	Drone Show Opportunities										
4.2	Current Market										
4.3	SWOT Market Analysis										
4.4	Target Cost										
5	**System Design Approach**										
5.1	Design Approach										
5.2	Driver and Killer requirements										
5.3	Budgetting during the Detailed Design Phase										
5.4	Communication During the Detailed Design Phase										
5.5	Subsystem Chapter Structure										
6	**Aerodynamics and propulsion Subsystem Design**										
6.1	Functional and Risk Overview of Aerodynamics and Propulsion										
6.2	List of Requirements Aerodynamics and Propulsion										
6.3	Design for Aerodynamics										
6.4	Design for Propulsion										
6.5	Iterations for Propulsion Design										
6.6	Risk Analysis Aerodynamics and Propulsion										
6.7	Verification and Validation Aerodynamics and Propulsion										
6.8	Compliance Matrix Aerodynamics and Propulsion										
6	**Power Subsystem**										
7.1	Functional and Risk Overview of Power										
7.2	List of Requirements Power										
7.3	Design for Power										
7.4	Risk Analysis Power										
7.5	Verification and Validation Aerodynamics and Propulsion										
7.6	Compliance Matrix Aerodynamics and Propulsion										
6	**Communication,Control and Electronics Subsystem**										
8.1	Functional and Risk Overview of CCE										
8.2	List of Requirements Power										
8.3	Design for Communication										
8.4	Design for Electronics										
8.5	Design for Control										
8.6	Simulation results										
8.7	Software Diagram										
8.8	Risk Analysis										
8.9	Verification and Validation CCE										
8.10	Compliance Matrix CCE										
9	**Structures subsystem design**										
9.1	Functional and Risk Overview of Structures										
9.2	List of Requirements Structures										
9.3	Design for Structures: Frame										
9.4	Design for Structures : Modular Payload										
9.5	Determination of Production and Maintenance cost										
9.6	Risk Analysis Structures										
9.7	Verification and Validation Structures										
9.8	Compliance Matrix Structures										
10	**Operations Subsystem**										
10.1	Functional and Risk Overview of Operations										
10.2	List of Requirements Operations										
10.3	Design for Operations: Landing Pad										
10.4	Design for Operations: Stackability										
10.5	Risk Analysis Operations										
10.6	Verification and Validation AOperations										
10.7	Compliance Matrix Operations										
11	**Subsystem Integration**										
11.1	Requirements related to integration										
11.2	Subsystems Integration Overview										
11.3	Overview of Integrated Final Design										
10.4	Verification and Validation of Subsystem										
12	**System Analysis**										
12.1	Drone Characteristics Overview										
12.2	Performance Analysis										
12.3	RAMS analysis										
12.4	Technical Risks Analysis										
12.5	Sustainable development strategy										
12.6	Sensitivity Analysis of Final design										
13	**Production Plan**										
13.1	XXXXX										
13.2	XXXXX										
13.3	XXXXX										
14	**Logistics**										
14.1	Logistics and Operations Requirements										
14.2	Deployment of Drones estimation										
14.3	Operations and Logistics Diagram										
14.4	Logistics Costs										
14.5	Safety Regulations										

B

Appendix B

Make fancy specs page