One Thousand Little Lights Final Design

AE3200 Design Synthesis Exercise June 29, 2021

Group 17

Capel, Menno van 4849981 Hollander, Ties 4850939 Bouhali, Walid El 4656369 Janssen, Gijs 4862570 Maarleveld, Ragnhild Féry, Paul 4660625 4660811 4801938 4446232 Gómez Mena, Carmen Wahid, Mustafa Hofman, Lucas 4833287 Yelnyk, Vova 4877659

Cover image: Anymotion productions, droneshow.nl



Executive Overview

The aim of this report is to present the final design phase of the project 'One Thousand Little Lights'.

Project Progress

The mission of 'One Thousand Little Lights' is to revolutionize the airborne, audio-visual entertainment industry by 2025. This will be accomplished by designing an economically competitive, safe and sustainable drone for indoors and outdoors light shows in 10 weeks, for the company Anymotion Productions. The drone has been called "Starling". The concept design developed in earlier design phases consists of a four arm drone, for both indoor and outdoor shows, made out of polymer thermoplastics, with removable propellers and landing gear. An extra feature of the drone is the ability to be conductively charged by the landing pad, next to the wired battery charging.

Market Analysis

The drone show industry is a fairly new market, with relatively few competitors. The goal of drone shows is often to amaze people, which is also why many world records have been set such as 'the largest number of drones simultaneously in the air' or 'the longest animation with UAVs'. Drone shows can be used for many different events, such as brand events or national holidays. A strong aspect of drone shows is that they are better for the environment than fireworks shows. The stricter regulations on fireworks can provide opportunities for the organisation of these shows. Downsides are mainly focused on the difficult logistics and operations. The drone Starling provides additional strengths, such as a modular payload capability and autonomous charging that make the design versatile. This is something new on the market and can be exploited to compete with other suppliers.

Detailed Design Approach

The detailed design phase was performed in iterations. Six iterations have been performed in total which converged to an efficient design, optimized for the set of requirements set by the customer. The design budgets set during preliminary budgeting were used as a starting point of the iterative cycle. Margins were applied to account for uncertainties.

Aerodynamics and Propulsion Design

From an aerodynamic point of view, several different aspects were investigated. Firstly, in order to get a low drag coefficient, the preferred shape of the drone's components is spherical. Secondly, drones should operate at least three propeller diameters apart. Thirdly, the amount of noise depends on the propeller size and its rotational velocity. The final design meets the requirement of generating less then 80 dB noise, as it only generates 65.6 dB noise at maximum velocity. Finally, the down force of 10 mm/h rain was estimated and taken into account for designing the propulsion system. The driving requirements of a thrust-to-weight ratio of 3 and maximum velocity of 20 m/s in 6 BFT wind conditions also were met. The most important parameters for the design were thrust efficiency and propeller size, which were desired to be as low as possible. In the end, Starling carries four Cobra CM-4006/36 motors together with 12-inch propellers.

Power Design

For the power subsystem, the core of the design process rests on the sizing and selection of the right battery to accomplish a full mission. The main challenges to face in this process stem from the necessity to guarantee sufficient endurance even under harsh conditions, such as heavy winds or long travel distances. In addition, the lithium-polymer batteries which are considered for this design tend to degrade as they age; this introduces the implication that their capacity reduces over time. The result of these considerations is a battery that will sustain the endurance requirements. The power subsystem is then completed with the selection of an electronic speed controller, which is chosen in parallel to the battery sizing. Finally, a battery management system must be added to the system, for which an initial investigation was conducted.

Control, Communication and Electronics Design

The control, communication and electronics department designed a controller for the drone and verified it using computer simulations of the drone. The communication and positioning hardware has been selected. All primary electronic components such as GPS,Wi-Fi module, ultra wide bandwidth receiver and radio receiver will be located on printed circuit boards (PCB's). The main components for the flight computer were also selected: an STM32 micro controller, high frequency MEMS IMU, magnetometer, barometer and an additional memory module for logging telemetry. The total cost of the PCB's will be €190, the mass is estimated to be 30 grams and the flight controller will have a power consumption of 3 watt.

0. Executive Overview Group 17 - DSE

Structures Design

The structures department was focused on sizing the arms and the frame of the drone. A casing and motor mounts were designed as well. All frame parts are to be made from polypropylene plastic with an additive flame retardant. The arms are circular hollow tubes with a production length of 0.175 mm, secured 5 mm into the frame. The outer diameter is 1.4cm and the inner diameter is 0.75 cm. With these dimensions the arms can cope with shear, bending, maximum deflection and fatigue loads during their 1000h lifetime. The frame body is 160 mm by 64mm. The total mass of the subsystem is 330 grams total excluding payload and the total cost is estimated to be $261 \in$. Next to sizing the structure itself, an payload mounting system was designed such that lights, megaphones and future payloads can be easily attached and de-attached to the drone.

Operations Design

From an operations perspective, two main features were investigated. First, the landing pad was preliminary designed to support conductive charging of the drones, which will be done through Pogo pins on their landing legs. The landing pad area is estimated to be $0.76 \, \mathrm{m}^2$ and it weighs about 16 kg. However its detailed design is left as a design consideration. Secondly, the landing legs were designed. This led to two removable sets of landing legs of 1.4 cm in diameter: a set 15.8 cm long for stackability and the light payload and a set 23 cm long for the heavy payload. Six drones can be stacked on top of each other with one stack being 1.17 m tall and weighting 12.5 kg.

Subsystem Integration and System Analysis

All subsystems were integrated through the frame of the drone. The electronics are located inside the casing. The battery is incorporated in its own compartment in the middle of the frame and can be easily taken out by pressing down a spring-loaded pin. The compartment allows for battery height expansions of 110%. The landing gear is connected to the arms via spring pins and an O-ring. The propulsion system is attached to the arms via a motor mount and a vibrational analysis was performed on this integration. Lastly, a casing was designed to shield all subsystems and to be able to fly in 10mm/hour rainfall.

For the system analysis, performance of the drone was analyzed. Climb and descent characteristics, wind resistance and typical flight profiles were investigated. Then a RAMS analysis was performed. Also requirements related to system performance were accessed.

In the production plan, a time ordered outline of the manufacturing and integration procedures was presented. The landing legs and arms were produced via polymer extrusion. The propellers, motors, battery, ESC and UWB are bought of the shelf. The flight controller, WiFi, GPS and radio PCBs are custom made to the drone. After molding, the arms, frame and motor mount needed fine machining to finish the part. To make sure each party involved knows how to recycle the part a resin identification code (RIC) was stamped on each.

The production cost of the drone is determined to be €860.72 and the maintenance costs were estimated to be €252.39.

Logistics

In terms of logistics, a time estimation of deployment of drones by the Anymotion Productions' crew was computed for different amounts and types of drones. In addition, the workforce needed to deploy the drones in under 3 hours for the same scenarios was calculated. All logistic and operational actions were summarized in the logistics diagram for the test, practice and show flights. From this diagram, an indicative drone show day schedule was presented and qualitative cost sources in the organization of drone shows were identified. Finally, safety consideration regarding the operation of the drone shows were identified.

Post-DSE activities

After project 'One Thousand Little Lights' is concluded, more detailed research into some sub-components must be performed as well as validation tests. Before the drone can be put on the market some external parts like the ground station and the carrying structure still have to be designed or confirmed as well. These activities have all been placed in chronological order. The expectation is that halfway 2024 the production of the drones can start such that the first shows can be performed by 2025.

Contents

Ex	ecutive Overview	i	9	Structures Subsystem Design	59
1	Introduction	1		 9.1 Functional and Risk Overview of Structures 9.2 List of Requirements Structures 9.3 Design for Structures: Frame 	59 60 60
2	Project Progress 2.1 Project Objective	2 2 2		 9.4 Design for Structures: Modular Payload 9.5 Risk Analysis Structures 9.6 Verification and Validation Structures 9.7 Compliance Matrix Structures 	69 70 71
3	System's Functional Analysis 3.1 Functional Flow Diagram	3 3 3	10	Operations Subsystem 10.1 Functional and Risk Overview of Operations .	77 77
4	Market Analysis 4.1 Drone Show Possibilities of Use	6 6 8 9 11	11	10.2 List of Requirements Operations	78 78 82 88 89 91
5	 Subsystem Design Approach 5.1 Design Approach 5.2 Driver and Killer Requirements 5.3 Budgeting During the Detailed Design Phase 5.4 Communication During the Detailed Design 	12 12 13 14		 11.1 Requirements and Risks Related to Integration 11.2 Subsystems Integration Overview 11.3 Overview of Integrated Final Design System Analysis 	93 98 100
6	Phase	15 16 16 17		 12.1 Requirements Related to System Analysis	100 105 106 107
	 6.3 Design for Aerodynamics 6.4 Design for Propulsion 6.5 Iterations for Propulsion Design 6.6 Aerodynamic analysis 6.7 Risk Analysis Aerodynamics and Propulsion 6.8 Verification and Validation Aerodynamics and Propulsion 6.9 Compliance Matrix Aerodynamics and Propulsion 	17 21 23 24 25 26 27		Production Plan 13.1 Risks in Manufacturing	110 113 113 113 117
7	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 Power 7.6 Compliance Matrix Power	29	15	14.5 Compliance Matrix for Logistics and Safety Requirements	122 124 124 125 127
8	Communication, Control and Electronics Subsystem8.1Functional and Risk Overview of CCE8.2List of CCE Requirements8.3Design for Communications8.4Design for Electronics	40 40 41 41 43		Overall Compliance Matrix & Sensitivity Analysis 16.1 Compliance Matrix	128 128 129
	8.5 Design for Control	47 52		Post-DSE Planning 17.1 Design Recommendations	132
	8.7 Risk Analysis	56 56		Conclusion	136
	8.9 Compliance Matrix	58	A	Specification Sheet	143

Nomenclature

Abbreviations	sion for Maritime Services	FM Fade margin
ABS Acrylonitrile Butadiene	RTK Real Time Kinematics	G Gain
Styrene	SP Structures	g Gravitational constant
AE Aerodynamics	SPI Serial Peripheral Interface	G_{Rx} Receiver antenna gain
BFT Beaufort	SWOT Strengths, Weaknesses, Op-	G_{Tx} Transmitter antenna gain
BMS Battery Management System	portunities, and Threats	I Moment of inertia
BOL Beginning-of-Life	TDOA Time Difference Of Arrival	I_{max} Maximum current
CCE Communication, Control	TWR Two Way Ranging	J_{pr} Moment of inertia of the
and Electronics	U Unit test	propeller and rotor
DOD Depth of Discharge	UAV Unmanned Aerial Vehicle	k Correction factor
DSE Design Synthesis Exercise	UWB Ultra Wide Band	L Characteristic length
EEPROM Electrically Erasable Pro-		l_x X distance from center of
grammable Read-Only Mem-	Symbols	gravity to propellers
ory	ϵ Error	L_{fs} Free space loss
EOL End-of-Life	η Efficiency	M Mass of the requirement
ESC Eletronic Speed Controller	μ Dynamics viscosity	M Moment
FAA Federal Aviation Administra-	- ρ Air density	m Mass
tion	σ Stress	M_n Torque on n^{th} motor
FBS Functional Breakdown Struc-		<i>n</i> Number of
ture	au Torque caused by propellers	P Power
FFD Functional Flow Diagram	θ Pitch angle	p Position
FPV First-person view	$\vec{\Theta}$ State of the system	P_{cr} Critical buckling load
GPS Global Positioning System	\vec{f} Vector of thrust setting of 4	P_{Tx} Transmitter power
IMU Inertial Measurement Unit	motors	R Transformation matrix
LED Light Emitting Diode	\vec{G} Gyroscopic torque caused by	r Radius
<i>LiPo</i> Lithium-ion Polymer	propellers	R_b^E Transformation from b frame
MNS Mission Need Statement	$ \vec{w} $ Rotational velocity of the	to E frame
NIOSH National Institute for Occu-	drone in body frame	R_E^b Transformation from E frame
pational Safety and Health	A Area	to b frame
OP Operations	C Scaling factor	Re Reynolds number
PCB Printed Circuit Board	c Distance to centroid	S Cross-sectional area
POS Project Objective Statement		S_{Rx} Sensitivity of the receiver
<i>PP</i> Polypropylene	c_m Torque on coefficient	T Thrust
PROP Propulsion	c_t Thrust on coefficient	t Time
PS Polystyrene	D Diameter	T/W Thrust over weight
PVC Polyvinyl Chloride	def Deflection	T_n Thrust on n^{th} motor
RAMS Reliability, Availability, Main-	9.	V Velocity
tainability, and Safety	E Young's modulus	W Weight
RGB Red Green Blue	e Error	w Rotational speed
RPM Rotations per minute	F Force	w_n Rotational velocity of n^{th}
RTCM Radio Technical Commis-	- f Frequency	propeller

Introduction

The task to design a drone that is specifically designed to be used in drone shows was given by Anymotion Productions, a company that performs these shows [1]. This assignment, called project 'One Thousand Little Lights', will be taken on by ten aerospace students of the Delft University of Technology. As concluded in the first report of this project, the mission need statement is as follows:

• To revolutionize the airborne, audio-visual entertainment industry by 2025.[2]

The project objective statement was decided upon as well:

• Design an economically competitive, safe and sustainable drone for indoors and outdoors light shows, in 10 weeks, for Anymotion Productions [2].

After the conceptual design phase and the preliminary design phase this report presents the detailed design phase [3] [4]. In the conceptual design phase several analyses were performed on the following aspects: functions, market, sustainability and risk. From these analyses all system requirements were derived. Then a design option tree was created and finally six different design concepts were introduced. In the preliminary design phase different aspects of the drone and the drone show were considered separately to finally choose one of the six design concepts. Besides, smaller trade-offs were made by each department to narrow down the design options. The remaining design options are further investigated and developed in this report. The goal of the detailed design phase is to create the most optimal drone design regarding the customer's needs and finalize the product. The drone will be called "Starling", inspired by the captivating natural aerial displays of these type of flocking birds during the winter months. [5].

The structure of this report is as follows: The progress made so far during the project is presented in Chapter 2. The functions of the system are revised in Chapter 3. A market analysis is conducted in Chapter 4. The general design approach for all subsystems is similar and is discussed in Chapter 5, along with the budget breakdown. The subsequent chapters are dedicated to the separate subsystem designs, starting with aerodynamics and propulsion in Chapter 6, power in Chapter 7, communication, control and electronics in Chapter 8, structures in Chapter 9 and finally the operations subsystem in Chapter 10. The structure in the subsystem chapters is identical and all chapters feature a risk analysis, verification and validation and a compliance matrix. After designing the subsystems separately they were integrated into one product, which is explained in Chapter 11. The final design is analysed in Chapter 12. This contains analyses on performance, RAMS, technical risk and sustainability. Then a production plan is presented in Chapter 13, logistics and safety are covered in Chapter 14, a financial overview is given in Chapter 15 and a system-wide verification and validation is conducted in Chapter 16. Finally, the report ends with the activities that should be performed after the DSE for the drone to become available on the market in Chapter 17 and a conclusion in Chapter 18.

Project Progress

In this chapter an overview of the project until this moment will be given. This will be done by first stating the objectives which we started the project with. Then an overview of the chosen concept and the decisions that have already been made will be presented. All of this can be found in more detail in the conceptual design phase report and preliminary design phase report [3] [4].

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 achieved. They can be found at the beginning of each chapter about the subsystems 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 costs are competitive on the market.

This will eventually result in the design called Starling. The name is inspired by the flocking bird, which performs captivating natural aerial displays during the winter months.

2.2. Concept Overview

In this report Starling will be designed in detail in subsequent chapters. Before this, a design concept was already chosen and some decisions about the subsystems were already made in during the preliminary design phase [4]. An overview of these decisions is 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 optimised for operations and logistics. The landing gear and propellers are removable. The drone has one propeller per arm and two blades per propeller. A Lithium-ion polymer (Li-Po) 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 utilised. 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 battery charging, is the ability to be able to be charged conductively on the landing pad.

System's Functional Analysis

In this chapter, the functional analysis is presented. The goal of the functional analysis is to list all the functions the system shall perform to be able to complete its mission. 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

The functional flow diagram in Figure 3.1 displays the functions of the system in a logical order. If all the system functions can be fulfilled, all the user requirements will be met. Each function has a unique tag and color to define its level in the functional flow diagram. The general flow of the FFD is summarised below. Note that in the FFD, functions may be performed in parallel (AND junctions) or in optional paths (OR junctions).

- Manufacturing the drone is the first step of the entire process. Once the fleet of drones has been built the show preparation can start.
- The show preparation is one of the most time consuming parts of the operation, next to the manufacturing process. It starts by setting up the ground station, unpacking the drones, setting up the perimeter and performing tests.
- Before the flight, a practice run has to be done. The drones can be tested to withstand the environment, detect faulty drones, and check if the drones can follow the choreography.
- Once the practice run has been done successfully, the show can start. The show is one of the shortest activities of the operation, but the whole operations revolves around the success of the show.
- The last phase of the operation is the end of the show. First the drones have to safely fly back to their landing pads. The clean up of the drones, equipment and ground station is the final task of the operation.
- At the end of life of the drone, its components shall be either discarded, recycled, or reused.

3.2. Functional Breakdown Structure

Unlike the functional flow diagram, the functional breakdown structure in Figure 3.2 presents the functions the drone must perform hierarchically in an AND tree. The most important conclusion from the FBS will be listed below:

- The FBS starts with a description of pre-flight operations which consists of the functions that will be performed before the flight, such as assembling the drone, setting up the show perimeter, and performing pre-flight tests.
- Performing maintenance on the drone is an important function to ensure a long lifetime of the drone.
- To ensure proper functioning of the drone components, the power source of the drone must be operational. This will be done by charging the batteries, and ensuring that they can be recharged by wired or wireless charging.
- The payload should be operable. They should be integrated, activated and follow a dynamic payload protocol. For example, the LEDs should flash the correct color at the correct time.
- The communication between drone and ground station is crucial in case anything goed wrong with the drones. The drones shall have an uploaded choreography. In case anything goes wrong, the drones can be controlled manually, or perform an emergency landing.
- Once the show is over, shut down procedures need to be followed, the drones need to be retrieved, and the site should be cleaned up. These steps should be done following regulations and the environment shall not be harmed in the process.

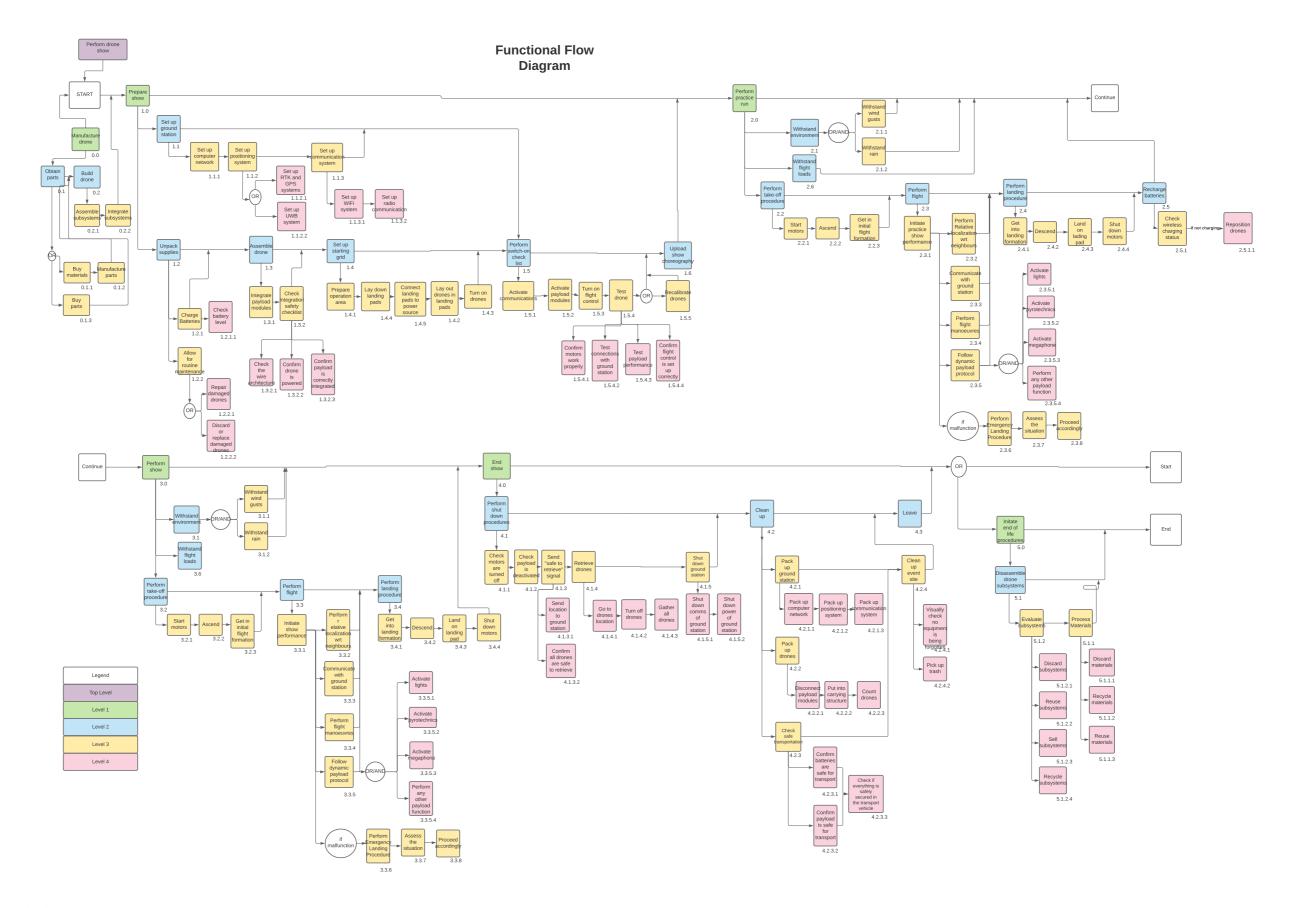
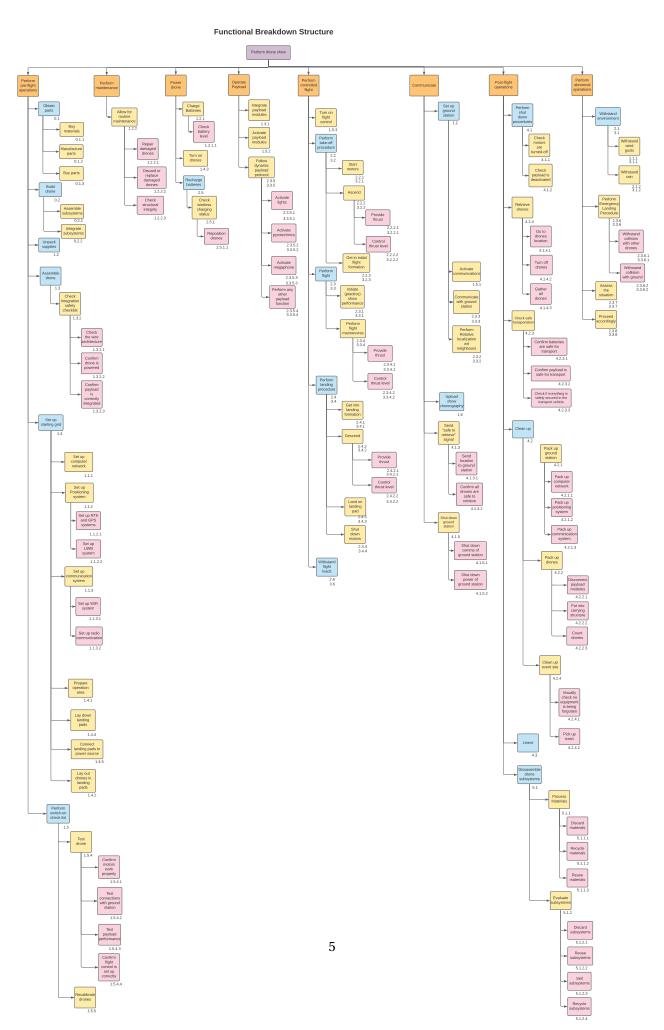


Figure 3.1: Functional Flow Diagram



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 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. Several stakeholders are listed in Section 4.3. In Section 4.4, the Strengths, Weaknesses, Opportunities, Threats (SWOT) analysis for the market is shown and the gap for this project is defined. Finally, in Section 4.5, a target cost for the drone of One Thousand Little Lights is defined.

4.1. Drone Show Possibilities of Use

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 so far 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 can be 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 [6] and Kia for their new logo reveal [7]. Furthermore, drone shows have been used during the opening ceremony of the Olympic Games [8], New Year's Eve [9] 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 [10].

4.2. Current Market

The drone show industry has seen enormous innovation and progress in the last six years. For example, in 2015 the first world record was set by Intel for having the most UAVs in the air at the same time, which was only a 100 drones [11]. In September 2020 Damoda Intelligent Control Technology set a new record with a stunning 3,051 drones [11].

In Table 4.1, a list of nine companies that execute drone shows is presented. There are not many suppliers that can be found online and information about their revenue is limited. These nine companies were found after a research of six hours. This emphasises the young market of drone shows. From the table, it is clear that the number of drones used in a drone show can be far apart for different companies, ranging from 100 to over a 3,000 drones in a constellation. Drone shows using more than a 1,000 drones are less frequent and more often used to break world records. Deducted from the websites of the suppliers, it seemed that between 100 - 500 drones is the most common number of drones. The longest animation performed by UAVs had a duration of 26 minutes and 19 seconds [12]. Most drone shows are shorter than this, e.g. shows from Intel have a duration of 11 minutes [8] and the current shows from Anymotion Productions take around 15 minutes.

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 [7]. 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.

All companies have the possibility to perform shows outside, but some also provide shows indoors, during concerts or theatre plays. These are Damoda Intelligent Control Technology, Dronisos and Skymagic. It is also a requirement for this project to be able to perform indoor drone shows with a minimum of twenty drones with the same drone.

Drone show companies	Country	Max. number of drones	Drone possibilities	Website
Anymotion Productions	Netherlands	100	Outdoor drones	[13]
AO Technology	Germany, United Arab Emirates	1000	Outdoor drones, payload capability	[14]
CollMot Entertainment	Hungary	100	Outdoor drones, aerial image projection, pyrodrones	[15]
Damoda Intelligent Control Technology	China	3000	Outdoor drones, indoor drones	[16]
DroneShow Events	Netherlands	100	Outdoor drones	[17]
Dronisos	France, United States	200	Outdoor drones, indoor drones	[18]
Geoscan	Finland, Russia	2000	Outdoor drones	[19]
Intel	United States	1000	Outdoor drones	[8]
Skymagic	Singapore, United Kingdom	300	Outdoor drones, indoor drones, pyrodrones	[20]

Table 4.1: Drone show competitors



Figure 4.1: Kia set a world record with 303 pyrodrones [7]

4.2.1. Customers and Market Size

The customers of drone show companies will mostly be other companies, governments or municipalities etc. as shows generally start at a price of €25,000 for 50 drones, which is usually too expensive for individuals [13]. This will also be the main type of customers for the drone Starling.

The current market for entertainment drones is estimated to be 8% of the total Unmanned Aerial vehicle (UAV) market of €17,006.46 million in 2020, equal to €1,360.51 million. This is expected to increase to a value around €3,066 million in 2026 [21]. The source did not provide a definition for entertainment, so it will probably also entail drones used for personal entertainment purposes or filming possibilities. Nevertheless, this value gives an estimate of the market size.

4.2.2. Replacement of Fireworks Shows

In the last three days of the year fireworks worth over 77 million euro are sold in the Netherlands [22]. However, with the prohibition on fireworks in 2020 because of COVID-19, alternatives needed to be sought. The prohibition was installed to relieve the burden on employees in health care and the police, as fireworks cause a huge number of accidents every year. Besides, fireworks are polluting and make a lot of noise. During the New Year's Eve of 2019-2020 1300 accidents have been reported in the Netherlands, which costs society around €3.2 million [23]. Although the prohibition is not permanent, the regulations regarding fireworks are getting more and more strict: less types of fireworks are allowed and fireworks free zones are installed in the Netherlands [22], which makes the use of fireworks more difficult. An innovative, exciting and much more sustainable alternative is the use of drone shows, which have already been used for New Year's Eve in Rotterdam in 2020 [9].

The public will not set up drone shows themselves, but they will be organised by dedicated companies. This is different with fireworks, as fireworks can be used both in organised shows as well as for individual purposes. Most of the firework accidents happen when it is used by the public in an unprofessional setting. This makes it difficult to compare the number of accidents involved with drone shows with the number of accidents involved with fireworks, because the drones will be used solely for professionally organised shows. Because of the same reason, it is difficult to compare drone shows with fireworks in terms of safety as well.

Drone shows are very suitable for replacing fireworks shows and are less polluting and noisy. The noise of fireworks is often in the range of 125 - 155 dB at a distance of three meters [24] and the CO2 emissions in the Netherlands due to fireworks amounts to 3.5 million kg yearly [25], not taking into account transport, manufacturing and other operations. For a drone show, the exact noise levels could not be found, but according to Anymotion Productions it does not make a lot of sound and can even be synchronized with music [13]. The CO2 emission of the drones during the show are equal to 0 kg as the drones are powered by renewable energy. This however also does not take into account the manufacturing and transport.

The prices of a drone show, however, are at the moment much higher than those of fireworks shows. The prices for fireworks shows can range from \$2,000 to over \$20,000 [26], whereas the prices for a drone show can range from \$25,000 to over \$300,000 [8],[13]. However, with the increase in fireworks regulations and decrease in drone costs, the market for drone shows used for entertainment purposes has a great probability to increase. Unfortunately, it has not been found what percentage of the 77 million euros spent on fireworks relates specifically to organised fireworks shows and therefore it is hard to determine how much of the fireworks industry can be replaced by drone shows.

4.2.3. Advertisement

The advertisement market is worth an estimated 545 billion euro in 2021 [27], out of which 55 billion come from physical outdoor advertising [28]. Consumer brands finance incredibly expensive advertising events to get as much consumer attention as possible. Drone shows provide excellent opportunity to display companies' advertisements in a way 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 so the company can get additional media attention for free which might increase the reach of the advertisement.

4.3. Stakeholders

The drone displays can be held in a wide variety of locations and will therefore introduce a wide variety of stakeholders. All stakeholders have a different vision and will put their importance in different parts of the design. Therefore these weights will be discussed briefly per stakeholder:

• Anymotion Productions (AP) (or other drone show companies): Anymotion Production has the most interest in the product and will therefore be the primary stakeholder. Most requirements are set by Anymotion

Productions. Anymotion Productions is most interested in creating an all-in-one drone solution which is able to fly indoors and outdoors.

- **Governmental bodies (GB)**: Governmental bodies set regulations to which drones and drone company's have to adhere to. Therefore the main interest is focused on safety. The current regulations only require a certain pilot's license to operate the drones.
- **Spectators (ST):** Spectators will be experiencing the drone display and will therefore be mostly interested in the emerging experience. The requirements to create the drone display experience will be mostly covered by Anymotion Productions requirements. For the spectators, it is also very important that a drone show is safe.
- Environmental organisations (EO): Environmental organisations will have an interest decreasing the product's impact on the climate. Therefore their interest is in a sustainable life cycle, which includes production, operation and recycling.
- Nearby residents and wildlife (NR): Nearby residents will be involved by since the display can be a nuisance to them. Therefore their interest will be in low noise and light levels. Nearby residents will include people and wildlife.
- **Anymotion Productions client (APC):** The client hires Anymotion Productions to organise a drone display. Therefore its interest will be in the spectators experience, budget and operation. These interests will mostly be regarding safety and cost constraints.
- Air traffic control (ATC): Air traffic control will be a sub group of the governmental bodies, but with a special interest in effectively and safely using the airspace.

This section emphasizes the importance of safety of the show, as it is significant for almost all stakeholders.

4.4. Market Gap for One Thousand Little Lights

This section first shows the SWOT analysis, including an explanation. After that, the opportunities specific for the drone of One Thousand Little Lights is discussed. The SWOT analysis of the market is shown in Table 4.2. 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). The green texts are specific for the drone of One Thousand Little Lights and will be explained afterwards.

Helpful Harmful Strengths Weaknesses - Custom made drones - Operational difficulties - More sustainable than firework shows - Logistical challenges - Low noise emission - Many safety measures Internal - Unique advertisement possibilities - Damage during transport - Modular payload capability - High initial costs - Ease of maintenance - No reputation - Stackable drones for mass transport - Autonomous charging **Opportunities Threats** - Applicable for different event purposes - Future government relations w.r.t. drones - Young market - Future competition - Addition to fireworks shows - Too expensive for customer **External** - Low number of competitors - Dependent on low number of shows - Regulations on fireworks getting more strict - High demand - Attention of the media

Table 4.2: SWOT market analysis (green is specific for Starling)

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

• **Unique advertisement possibilities:** drone shows provide new possibilities for advertisement, as written in Subsection 4.2.3.

- **Operational difficulties:** performing choreography with many drones in the air requires detailed planning and organisation, good communication and software in the drone.
- Many safety measures: During a drone show many safety measures are needed, primarily to avoid human errors. Human errors cause the majority of accidents. All safety measures are time-consuming and cost money to comply with.
- Logistical challenges: The organisation of a drone show also brings logistical challenges. One can think about transporting a large number of drones or putting them in a grid and calibrate them while on a tight schedule.
- Attention of the media: As drone shows are not very common, there is often a news article written about the occasion which is beneficial for brand awareness.
- Dependent on low number of shows: A drone show company can host only a very limited number of shows per year. According to their websites, most of them need approximately 2 or 3 months to prepare a show [8], [13], [19]. This means that not many shows per year can be performed and that all profit should come from these shows. If a company does not get an order, it can endanger their annual profit. This could be the reason that Intel and Geoscan also have other forms of income [8] [19].

Next to these, there are also some strengths and weakness coloured green. This is because they are specific for the design for the drone of One Thousand Little Lights. Most of them follow from requirements.

- 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. AO Technology already has drones with the option to carry a payload of 500 grams, but the possibilities have not been specified in further detail [14].
- 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.
- Stackable drones for mass transport: Another requirement on the drones is to be easily stackable. This is useful to make transport processes more efficient. Intel and Geoscan also use this feature together with carrying structures, to make carrying by hand easier and quicker [8], [19].
- Autonomous charging: The last requirement that was given was that the drones should have the possibility of charging autonomously via their landing pad. This can increase the duration of drone shows or make it possible to have multiple drone shows quickly after each other.
- **High initial costs:** Developing the drone, buying a significant amount of them, as well as buying the very expensive wireless charging landing pads involves a lot of costs before any profit can be made. This is thus a risky investment.
- **No reputation:** As the drone that is to be designed will be new on the market, there will be a possibility that companies are hesitant with buying this drone. This could be because the product is very new and does not have a reputation of safety or good choreography yet. This is a weakness that is hard to overcome in the beginning, but should diminish after successful performances have been held.

When looking back at Table 4.1, it can be seen that companies already have many possibilities for drone show performances. They have the capabilities to host large shows, indoor shows, pyrotechnical shows, stack the drones etc. However, all these features have not been combined in one drone yet. Usually different drones are needed for different purposes. This is what the design of One Thousand Little Lights will try to achieve: with the modular payload capability only one drone is needed for all different applications. This makes the use of the drone versatile. Also the possibility of an autonomously charging drone via the landing pad is something that does not exist yet.

The aim of "One Thousand Little Lights" is therefore to focus the drone design on ease of operation and versatility. It should have the feature to execute choreography with at least 300 drones, as this number is sufficient to make

most of the animations in the air possible, and perform a drone show of at least 15 minutes to be able to have a similar or longer show time than other drone shows. However, in accordance with the Project Objective Statement, the design should also focus on safety and costs as these are both also very important from a market perspective. A safe drone is important for most of the stakeholders as described in Section 4.3 and important to build a good reputation. Cost-effectiveness is also important so the drone has a good value for money.

4.5. Target Cost and Currently Available Drones

TAG

COST-AP-1

COST-AP-2

This section determines a target cost for the drone and looks at specifications of currently used drones.

Anymotion Productions provided the information that the purchase costs of the drone they use is $\[mathebox{\ensuremath{$\in$}}\]$ 1,500. This does not include maintenance, which they estimated to be between $\[mathebox{\ensuremath{$\in$}}\]$ 100 and $\[mathebox{\ensuremath{$\in$}}\]$ 200 for the motor, propellers and electronic speed controller per motor during the lifetime of one drone. With four motors per drone, this leads to a cost per drone between $\[mathebox{\ensuremath{$\in$}}\]$ 2,300. The requirements that were set up in the baseline report [3], which can be revised in Table 4.3, ensue a total cost of $\[mathebox{\ensuremath{$\in$}}\]$ 2,650 per drone, which is less than what Anymotion Productions currently pays for their drones. If these requirements are met, this will also meet part of the project objective statement regarding an 'economically competitive drone'.

Requirement

The drones shall cost no more than €1000,- per piece.

The expected cost of replacing parts in 1000 light shows shall be no more than €650,-.

Table 4.3: Requirements related to the financial overview.

Table 4.4 shows some specifications of two light show drones that were found on the internet. The drone from Sparkl is the same drone that is used by Anymotion Productions. For the design of the drone, it is beneficial if the specifications are similar or better than the drones provided in the table for a similar price to compete in the market. From an operational point of view, it is for example beneficial if the drone is smaller or lighter, as it is then easier to transport and quicker to deploy, but for the flight time it is beneficial if this is a higher number than the flight time of these drones. Throughout the subsystem design, the specifications from Starling will be compared with those of Sparkl and UVify. The comparison will be shown in Chapter 15.

Specifications	Sparkl	UVify IFO	Specifications	Sparkl	UVify IFO
Dimensions without propellers (cm)	40 x 40	27.5 x 27.5	Max. control range (m)	500	1000
Dimension with propellers (cm)	45 x 45	40 x 40	Max. sustained wind speed (kts)	25	15
Height (cm)	15.5	12.5	Vertical hover accuracy (m)	0.1	0.1
Weight (g)	1103	635	Horizontal hover accuracy (m)	0.1	0.1
Weight (incl. battery) (g)	1706	1050	RGB led (W)	10	27
Max. flight time hovering (min)	25	25	Light strength (lumen)	550	840
Max. airspeed (km/h)	72	60	Battery type	Lipo 4S	Lipo 4S
Max. operational altitude above sea level (m)	1500	500	Battery capacity (mAh)	6750	4200
Price (euro)	1500	1680	Battery voltage (V)	14.8	14.8

Table 4.4: Drone specifications of Sparkl [29] and UVify [30].

To conclude the market analysis, the design should focus on versatility, safety, cost and ease of operations, for companies to be willing to buy this drone.

¹Personal communication with drone show expert, 11/06/2021.

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.

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. Another goal is to produce the most optimal design: a perfect fit within the requirements. Optimisation is a dynamic process. By exchanging information between departments the components can be adapted to the most up to date information. This can be done until the results do no longer change significantly.

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. 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 were structured by deadlines. The initial goal was to do a new iteration every two days. During the detailed design it was observed that the tools and methods were fast enough to produce numbers more often and therefore additional iterations where put in place. Integration was 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 the point of preliminary budgeting. During in the preliminary design phase [4] the design budgets for every concept were presented. The budgeting done for the selected concept was taken as an input parameter of the first iteration.

The first goal was to decrease the uncertainties from the preliminary budgeting. Preliminary budgeting was done using statistics obtained from a paper[31]. During the first iteration the departments focused on building more specific tools that were able to make a more detailed and certain estimations on the department specific budgets.

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

Finally the goal was to optimize the design for the requirements. Therefore putting emphasis only on lowering the weight was not 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 the improved mobility required by the operations department outweighs the more efficient larger propellers.

Every department was 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.

Department	Design activities
Propulsion and Aerodynamics	Motors, propellers and aerodynamic shaping.
Power	Battery, electronic speed controller and battery management system.
Communication,	Flight computer, sensors, communication protocols and control
control and electronics	simulation
Structures	Payload and frame design

Landing gear, landing pad and operational activities

Table 5.2: Table stating the department design activities

5.2. Driver and Killer Requirements

Operations

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.

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 no more 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 power consumption
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

Table 5.3: Driver requirements

Requirements negotiations had taken place during the preliminary design stage. Using the initial budgeting a new requirements proposal was constructed and accepted by the costumer. The killer requirements were eliminated according to the results obtained from initial sizing. These requirements where related to the flight time and payload. However, some of the driver requirements stated in the table became killer requirements during the iterations. The requirements were not met and changes to the design had to be made. These requirements were OP-AP-6, POP-AP-3.2 and POP-AP-3.8. At the final iteration all killer requirements where met and thus eliminated again.

5.3. Budgeting During the Detailed Design Phase

The primary design budgets 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.
- **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 costs. Therefore, the cost is closely evaluated every iteration in order to prevent the design from being too expensive. Mass has the biggest influence on 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, which will also be updated by every iteration.

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 by 0.25 kg 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 used for the next iteration.

The power budget will be heavily dependent on the weight and is difficult to constrain. Therefore, an increase in power was notified to the systems engineer, who could confirm that the increase is within margins. These margins follow from the margins set on the mass and are calculated case specific by using the tool produced by the propulsion department. The production and maintenance cost budgets are taken from the preliminary budgeting and are decreased by 20% to have margin for uncertainties.

The budgets obtained during the preliminary phase are shown in Table 5.4. Contingency margins are not subtracted from these budgets. 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 would 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. It can also be seen that the power department has a power value of 0. This is due to the fact that the power department will be providing power and has no power usage by itself.

Table 5.4: Table containing preliminary budgets

Department	Mass [kg]	Power [W]	Production Costs [€]	Maintenance Cost [€/lifetime]	
Propulsion &	0.43	158.89	230.77	16.30	
Aerodynamics	0.43	130.03	230.77	10.50	
Power	0.36	0.00	41.85	544.03	
Structure & Payload	0.86	20.00	219.69	16.30	
Controllability,					
Communications &	0.01	10.83	153.85	16.30	
Electronics					
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 functioned 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.

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 needed 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.

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 understanding 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 5.5. 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.

Table 5.5: 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		Dimensions	Structures & Payload	Dimensions	Mass, costs, power consumption
			Dimensions	Operations	Mass, costs
Total mass	Power consumption		Masses	Masses	Total budgets

Aerodynamics and Propulsion Subsystem Design

Aerodynamics and propulsion is an important aspect as it needs to provide enough thrust to make Starling fly and perform its manoeuvres. It is closely related to other subsystems such as the power required and the load applied on the structure. The functions and the identified risks of this subsystem are discussed in Section 6.1. Section 6.2 contains a list of relevant requirements. 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 6.7. Then, the procedure is verified and validated in Section 6.8 and finally a compliance matrix is presented in Section 6.9.

6.1. Functional and Risk Overview of Aerodynamics and Propulsion

The goal of the aerodynamics and propulsion subsystem is to make sure enough thrust is provided and the drag is minimised, 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 thrust to:
 - Reach the maximum speed
 - Obtain a thrust over weight ratio of at least 3 for the purpose of manoeuvring
 - Perform the mission in windy and rainy conditions
- To perform the mission without generating too much noise, which can create disturbance for the surroundings and the audience.
- To perform the mission without affecting the performance of the other drones when flying in formation.

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, 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 [4]. 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	High	Moderate	Implement safety margin for maximum
	due to wind			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 6.8, while the rest will only be verified at a system level in Chapter 12.

Sub-	TAG	Requirement
department		
	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
Aerodynamics	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
	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.
Propulsion	POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from
Propulsion		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

Table 6.2: Requirements related to the propulsion subsystem

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 aerodynamic 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.

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

Here, Re is the Reynolds number, ρ is the air density, V is the airspeed, L is the characteristic length and μ is the dynamic viscosity. 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 [32]. 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 for the core of the drone and arms in the shape of a round cylinder will be preferred in terms of aerodynamics.

Table 6.3: Drag coefficients for different shapes

Re ≈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. [33] 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. 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, because Starling's shape will be similar to the DJI. It is obvious that Starling will not take the shape of a cube. Therefore, the value of the DJI will 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. [34] shows that there is more interaction between propellers when they are placed close together. 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. If propellers are rotating too close to each other, the tip vortices of one propeller starts to affect the vortices of the other which is called "vortex-vortex interaction". 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, to get as little aerodynamic interference from the structure and the other propellers as possible.

Because the drones have to perform the show in swarms, the aerodynamic influence between drones has been looked

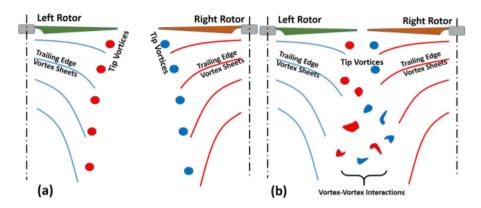


Figure 6.1: Visual of wake interaction between propellers depending on the spacing: (a) large spacing, (b) small spacing.

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 [35]. 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 in Table 6.2 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 [4]. As will be determined further on in the report, the final dimension of the drone width is 63 cm. When flying in a 2 m spaced formation, this means there is 127 cm between the tips of propellers of two drones side by side. This is well above the required distance of 120 cm for in case of 14-inch propellers. For smaller propellers the distance between drones will be even larger. 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 [36]. 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 [37]. 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 Subsection 6.4.2, 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. use a propeller of 23.9 cm in their experiment. The noise level is measured for RPM ranging from 2000 to 9000, which increases 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 through these two points 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.

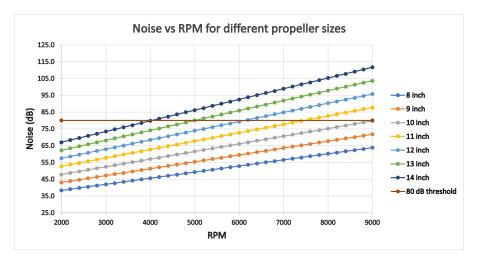


Figure 6.2: RPM plotted against noise (dB) for different propeller sizes ranging from 8 to 14 inch

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 [38]. 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 $10*10^6$ mm³/m²h. It was assumed that the raindrops have a diameter of 2mm, which is the average size of raindrops [39]. Together with the assumption that the water drop is a sphere, it becomes clear that a good estimation is around 3*10⁵ raindrops per m² per hour. By using the first rough estimation of the full surface area of the drone of 0.05 m², 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. In the equation m is the mass of the raindrop, ΔV is the difference in speed and Δt is the time it take the raindrop to stop. It was found that an average rain drops moves at 9 m/s and weighs around 0.000034 kg [40]. 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. This seems on the high end, but this happens because the speed of the end of the propeller is very high. This is thus the absolute maximum when the raindrops are hitting the propeller really hard. When designing for these values it will be able to handle all the forces exerted on the propeller during rain. Therefor, 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.

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

The motors are all delivered in a protective foam around all sides, which will make the motors waterproof. The given weight and dimensions of the protective foam were assumed to be included in the given properties.

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 6.7.

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 [41]. 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 is on the high side when comparing it to the market analysis in Table 4.4, which will probably result in a less agile drone. A detailed look at this will be taken in Chapter 8. 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 (Risk 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 [42].

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

$$\theta = \arccos \frac{W}{n_{\rm r}T} \tag{6.4}$$

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, n_r is the number of propellers and T is the amount of thrust. 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 a huge loss of thrust available which means T/W decreases as well. Flying at full throttle with only three motors operating would be unstable, so basically only two motors can still be used at full performance while the third one is only there to assure stability. Therefore, it can be assumed that the T/W ratio becomes 1.5 in case of one motor failing. This would be 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 (Risk 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 6.7.

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 [4]. 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 m² 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 12. In the end, the database contained over 60 different motors which resulted in almost 500 combinations to select from [43] [44] [45] [46]. 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.

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, which fits into the mass and cost budget, 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 in Section 6.7.

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 for both heavy and light payload. Light payload results in lower drone mass which makes it easier to fly and therefore requires less power.

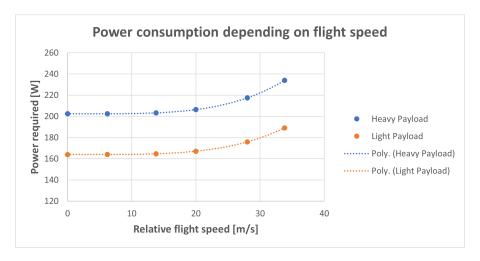


Figure 6.3: Power consumption of drone with heavy or light payload for different flight speeds

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 [47]. 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 smaller brushless motors for drones 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 [48].

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. Note that the noise does include the additional 6 dB as explained in Subsection 6.3.3 to incorporate the fact that a drone has four propellers. Thus one propeller of the final design will generate 59.6 dB of noise and then 6 dB is added to account for a complete drone with four propellers.

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 6.4: Iteration table 1 of the propulsion system design

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. Aerodynamic analysis

For the entire design the value of 1.21 for the drag coefficient has been used. After every subsystem has done the design and the whole drone is done an aerodynamic analysis should be done on the drone, to check whether this estimation was accurate and to see where there still are improvements to be made from an aerodynamic point of view. This analysis is shown in this section.

When the entire drone is designed it was put into Solidworks where it was analysed with the help of the Flow Simulation part of that program. The method used is based on a guide which analyses the drag coefficient of a sphere [49]. The conclusion of this analysis is that the drag coefficient of the entire drone is 1.17. This is a bit lower than the estimation of 1.21 made in Section 6.3, which results in a lower drag force than expected so the drone is a bit overdesigned. However, the difference is very small which means it is assumed that the calculations done are correct. A further recommendation for after One Thousand Little Lights is to consider this difference and see whether this causes a significant deviation.

Also a visualisation of the speed has been made to see whether there are still some improvements to be made from an aerodynamic point of view. This visualisation is shown in Figure 6.4. As can be seen in the figure, the flow is mostly acting aligned with the surface of the drone. Only a problem can be seen at the back of the payload, where the velocity actually goes in opposite direction. A further recommendation is to make the distance between the payload and the frame smaller to prevent this from happening.

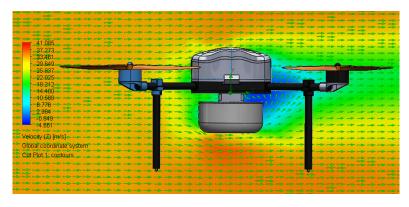


Figure 6.4: Visualisation of the velocity along the drone

6.7. 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.

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 and people involved 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 small	3	Damaging during the show will affect the performance. However, the show can still continue and propellers can be changed afterwards

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

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

Risk 34 concerning propellers breaking due to a collision can not be prevented easily. A collision, however, is not very likely to occur anyway as the choreography of the drones will be pre-programmed, 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 only 4 euros. 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 ABS plastic. This means that if the propeller is getting noticeably damaged, it is very probable that it will permanently deform. Therefore the ultimate yield strength will be used, because ABS plastic 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 2.22 MPa. The maximum yield strength

of ABS plastic is 48 MPa. This means that as expected the raindrops will not generate enough force to break the plastic. The propeller will thus not get damaged during rainfall and this risk has been mitigated by picking a plastic propeller.

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

D = 18 inch gives V = 48 m/s

Yes

RPM = 0 gives dB = 0

6.8. 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.

6.8.1. Code Verification

TAG

VT-AE-U.3

dB

RPM

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'.

Input to vary Output to test **Test Outcome** V3 RPM = 2000 gives V = 25 m/s,VT-AE-U.1 V RPM Double RPM, expect V to double Yes RPM = 4000 gives V = 50 m/sD = 9 inch gives V = 24 m/s, VT-AE-U.2 V Diameter Double diameter, expect V to double Yes

Set RPM to zero, expect noise to be zero dB

Table 6.8: Unit verification tests for noise

Table 6.9: Unit verification tests for rain
--

TAG	Output to test	Input to vary	Test	Outcome	V?
VT-AE-U.4	σ_{max}	No. of raindrops on propeller	Double the raindrops, expect the stress to also double	N_{drops} = 1.5 gives σ = 4.7 * 10 ⁸ , N_{drops} = 3 gives σ = 9.4 * 10 ⁸	Yes
VT-AE-U.5	σ_{max}	Propeller width	Double the propeller width, expect the stress to decrease to become 1/4	$w_{prop} = 0.03048 \text{ gives } \sigma = 4.7 * 10^8,$ $w_{prop} = 0.06096 \text{ gives } \sigma = 1.18 * 10^8$	Yes
VT-AE-U.6	σ_{max}	Propeller thickness	Double the propeller thickness, expect the stress to halve	t_{prop} = 0.0009144 gives σ = 4.7 * 10 ⁸ , t_{prop} = 0.001828 gives σ = 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,	Yes
VI-FROF-U.I	V	VV	Double W, expect V to scale with sqrt(2)	W = 4 kg gives V = 46.54 m/s	168
VT-PROP-U.2	θ	W	Increase W to infinity, expect theta to	$W = 100000 \text{ kg gives } \theta = 1.015E - 05rad,$	Yes
V1-FNOF-0.2	0	VV	converge to zero	$W = 500000 \text{ kg gives } \theta = 2.092E - 06rad$	168
VT-PROP-U.3	Т	W	For a high W, theta approaches zero such	W = 100000 kg gives T = 25000 kg,	Yes
V1-11(01-0.5	1	VV	that T per propeller is exactly 25% of W	W = 200000 kg gives T = 50000 kg	165
VT-PROP-U.4	Т	θ	T is expected to stay constant when	θ = 0.1 gives T = 0.53 kg ,	Yes
V1-PROP-0.4	1	O	adding 2pi to θ	θ = 0.1+2pi gives T = 0.53 kg	ies
VT-PROP-U.5	Р	W	Let W approach zero, expect P to	W = 1 kg gives P = 119 W,	Yes
V11101-0.5	1	**	converge to zero	W = 0.001 kg gives P = 0 W	103

6.8.2. Calculation Verification

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" [42]. 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	V3
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

6.8.3. Validation

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.

6.9. 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 AD-AP-1, AD-AP-2, AD-ATC-5, AD-SYS-6, AD-SYS-9, POP-AP-2, POP-SYS-2.2, OP-AP-6 and SUS-EO-3 are met from the aerodynamics and propulsion point of view and will be further analysed in Chapter 12 and in Chapter 16 it can be seen whether these requirements are met for the entire drone.

Table 6.12: Compliance matrix for the aerodynamics and propulsion subsystem

TAG	Requirement	Verified?
AD-NR-4	Noise level shall be less than 80decibels at 1 meter from the drone	Yes, 65.6 dB
AD-SYS-5.1	The drone shall be operable in a pressure range between 101325 Pa and 89401 Pa	Yes
AD-SYS-8	The drones shall not affect other drone performance	Yes
POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from being able	Yes
	to perform an emergency landing.	

Power Subsystem

The power subsystem is a key component of the drone, as it provides all the electronics on board as well as the motors the energy they require to carry out their function. Sizing of the power subsystem will be covered in this chapter. First, an overview of the susbystem's functions and risks is laid out in Section 7.1. Then, the requirements that will define the design process are contained in Section 7.2. Section 7.3 then describes the design process of sizing the components of the power subsystem, as well as the results obtained from this process. The risks identified during the detailed design phase are shown in Section 7.4. Following, Section 7.5 covers the verification and validation of the methodology employed. Finally, a compliance matrix of the requirements to meet is shown in Section 7.6.

7.1. Functional and Risk Overview of Power

The main goal of the power subsystem is to provide the other subsystems of the drone with the energy they require and to meet the endurance requirements at low cost and mass. This requires selecting an economically efficient and sustainable battery, ESC and a battery management system (BMS) that meets all of their corresponding requirements. As mentioned in the FFD and in the FBS 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.

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

Table 7.1: Risks related to power and their mitigation responses

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. In order to guarantee that the final product functions properly and satisfies the customer, the design process will focus on ensuring that the power source meets those requirements.

7. Power Subsystem Group 17 - DSE

Table 7.2: Requirements related to Powersubsystem

Sub-department	TAG	Requirement
	POP-AP-3.1	The drones shall be able to fly for 15 minutes for preparations and
Power		checkups.
rowei	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.
	SUS-AP-1	The drones shall be powered by renewable energy sources.
Sustainability	ainability SUS-EO-6 The components of the energy storage shall not contaminate	
		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
rayioau	SP-AP-1.4.2	Future innovations shall have specifications up to a 20W power
		consumption
	OP-AP-2	The drones shall be suitable for mass transport.
Operations	CCE-AP-2	The show location shall be at most 1000 m apart from the ground
Operations		station.
	CCE-AP-3	The drones shall be recharged wirelessly through their landing pads.
	CCE-SYS-3.2	The drone shall be able to recharge autonomously on the landing
		pad between preparation and show.

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.

Following the preliminary design phase, it was decided that the type of battery studied are lithium-polymer batteries [4], which present a number of advantages with respect to other power sources. Inherently, they will comply with requirements OP-AP-2, as they are very compact and can be transported easily, provided they are safely contained. They will also allow for possible compliance with SUS-AP-1, as they do not produce any direct emissions. In that sense, ensuring the renewability of the energy source lies in the type of energy used in recharging the batteries. Requirement SUS-EO-6 is also met with this type of power source: during normal use, no waste, pollutants or any form of components exit the interior of the battery. Working temperature ranges of Li-Po batteries are within -20-60 °C, with charging temperatures between 0-45 °C [50]. This allows cover of requirement AD-SYS-6. For the remaining requirements, proper sizing of the battery must be conducted.

7.3.1. Data Gathering & Analysis

For the calculations of the different battery characteristics, a database of existing batteries on the market was used [51]. 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 (which will be referred to in the following sections by E_{bat}), weight (m_{bat}), volume (V_{bat}), cost ($Cost_{bat}$) and other technical performance characteristics. This allowed for the creation of plots of these characteristics, such that relations between them could be established through the method of regression. An example of such a plot is the battery weight versus energy capacity plot, which 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. It was found that linear regression was fitting for determining a relation between mass and capacity (with coefficient of determination $R^2 = 0.844$), volume and capacity (with $R^2 = 0.067$, a rather low value, which is the result of a few heavy outliers rather than a wide spread of the data), and cost and

7. Power Subsystem Group 17 - DSE

capacity (with R^2 = 0.414, which is the result of a wider spread of the data than for the other characteristics, probably caused by the high competitivity between manufacturers in the market). 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.

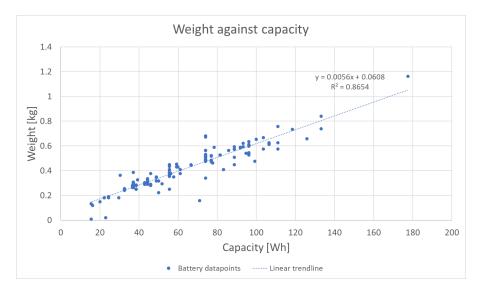


Figure 7.1: Plot of the battery weight versus capacity. Each point is a singular battery in the database. The whole data set allows for a linear regression. Identical data processing was conducted for the battery volume and cost.

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, with the first iteration being based on statistical data. The inputs required are displayed in Table 7.3.

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	$\frac{n_{flights}}{show}$	[-]

Table 7.3: The inputs for power calculations

The input P_{flight} was obtained in the form of a function dependent on the airspeed experienced by the drone $(P_{flight} \rightarrow P_{flight}(V))$. At the start of each iteration, 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% [52]. 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 [53]. The degradation of the battery capacity as a function of life cycle is often approximated as linear until EOL [54]. Further development of the battery decay model in the future is recommended (decay is notably influenced by temperature, a factor which does not take part in the degradation calculations as of now). 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 [55]. 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, E_r , for a given mission. For this, the power required P_r 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:

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

The power required for activating the payload and using the flight computer are added to the power required for flight. For the case of the heavy payload, a value of 20 W was used, to ensure compliance with requirements SP-SYS-1.3.1 and SP-AP-1.4.2. For the light payload, a value of 10 W was originally used, and could be further reduced after a number of iterations to 6 W. This is discussed in Section 9.4. This yields the total power required for the given flight phase:

$$P_{r,phase} = P_{r,flight} + P_{FC} + P_{pl} \tag{7.3}$$

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. Battery decay is here assumed to behave linearly [54]:

over its lifetime before reaching end of life is performed. Battery decay is here assumed to behave linearly [54]:
$$n_{cycles} = \frac{EOL - BOL}{k_{loss}\%} \tag{7.5}$$

Here, the terms *BOL* and *EOL* refer to the beginning- and end-of-life factors, (with *BOL* having a similar definition to *EOL*, which was defined in 7.3.2). 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 [53]. 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:

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

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

$$k_{loss} = \frac{E_{EOL} - E_{BOL}}{n_{cycles}}$$
(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.

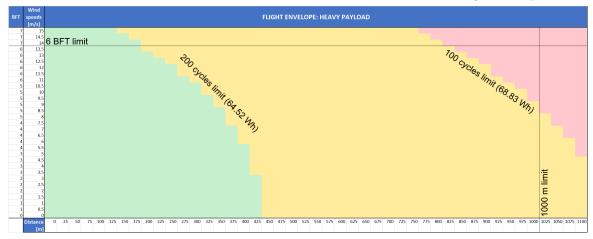


Figure 7.2: Flight envelope of the drone. This particular envelope was the result of the 4th iteration, for the case of the drone carrying a heavy payload.

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. 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 origin 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: the mission is achievable for batteries which have gone through up to 200 cycles. Along with that number of cycles, the total energy available from the battery at that state of life is shown (see Figure 7.2).
- Yellow: the mission is achievable for batteries which have gone through up to 100 cycles. Figure 7.2 also shows the corresponding total energy available for that limit.
- Red: the mission is questionably achievable. Batteries which have gone through more than 100 cycles cannot perform the mission. Battery state of life must be thoroughly assessed before attempting the mission.

Two additional regions are present, which are not visible in the diagram, but are nonetheless important to mention, as they determine the most extreme boundaries of the region of capability of the battery:

- A "bright green" region, which indicates the scenarios possible for all batteries, at all states of life, even when they have reached their EOL (more about this region will be discussed in 7.3.6).
- 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 (if the range and the domain of Figure 7.2 were increased, this
 region would become visible: there is a limit to the maximum theoretical wind speed the drone can handle,
 as well as the longest travel distance it can reach).

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.

The objective of the design process is to obtain a flight envelope that will allow compliance with wind resistance requirement AD-AP-1, and maximum travel distance requirement CCE-AP-2. However, Let it be noted that designing for compliance with both requirements simultaneously, while operating with a battery which is nearing its EOL would result in a severely over-designed product. The design process will therefore aim at complying with the specified requirements independently of each other. This will help reduce the total energy capacity of the battery, lowering its mass, and most importantly its cost.

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 [4, 56]. However, it was found to be rather outdated (as the majority of ESCs enlisted were added before 2010), 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 Li-Po 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 [57, 58]. The BMS also allows for management of multiple charging sources, allowing the drone to be charged through either a landing pad, or via wire. As such, the BMS is a crucial

component, as it helps mitigate risks 13 and 21 [59], as well as provides the functions required for compliance with requirements CCE-AP-3 and CCE-SYS-3.2. The BMS also eases the management and operations of the batteries, as it provides important information related to the battery, such as the state of charge, state of life, voltage temperature, and many others [57, 58].

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 Li-Po 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 remains an action to be completed. It is recommended to evaluate fully detailed 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.

Iteration	Mass [kg]	Dimensions [mm × mm × mm]	Capacity [Wh]	Voltage [V]	Maintenance cost [Euro]	Production costs [Euro]
Statistics	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	595.49	119.1
2	0.71	163.42 × 54.25 × 42.02	117.85	14.8	374.36	81.38
3	0.60	$157.11 \times 52.15 \times 40.40$	97.14	14.8	310.66	67.53
4	0.65	$159.99 \times 53.11 \times 41.13$	106.37	14.8	476.64	73.71
5	0.62	$139 \times 47 \times 48.5$	106.56	14.8	376.49	58.22
Final	0.58	152 × 46 × 37	103.6	14.8	218.09	33.73

Table 7.4: Battery iteration table

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 Li-Po battery with a charge capacity of 7000 mAh. The number of cells (and therefore the voltage) is the same as that of the power sources of the two drones mentioned in Section 4.5. However, Starling being a larger, more power demanding product, the charge capacity of the battery had to be larger than that of its competitors. Although priced at 72.99\$ (£61.30) on Amazon [60], 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 45% profit margin, which could be cut from purchasing expenses by buying directly from the manufacturer, as the retailer profit margins for lithium-polymer batteries can range between 45–60% (the team would like to comment that these acknowledged profit margins seem rather high, as such, more accurate evaluations of those values would be recommended in the future). 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%) [61]. Accounting for the fact that normal usage of the batteries will only require to recharge 80% of their capacity, requirement POP-SYS-3.7 is satisfied. The risks of battery swelling and ignition (risks 19 and 20, as presented in Table 7.1) are however still present. In order to ensure that they be dealt with accordingly, the power department and the structures department cooperated to ensure for a proper mitigation response. For risk 19, the space of occupation of the battery will be given a 10% extra thickness, to allow for expansion (further discussion of this risk in Subsection 9.3.4). For risk 20, delaying the spreading of flames will be conducted by adding a flame retardant to the structure of the drone (more on this in Subsection 9.3.3).

¹This information was obtained from a personal conversation with Dronelaps, info@dronelaps.nl, on the 8th of June 2021.

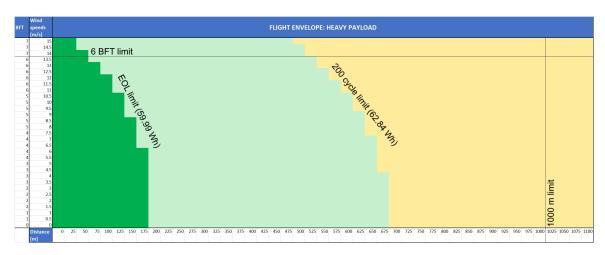


Figure 7.3: Flight envelope of the final iteration: heavy payload case.

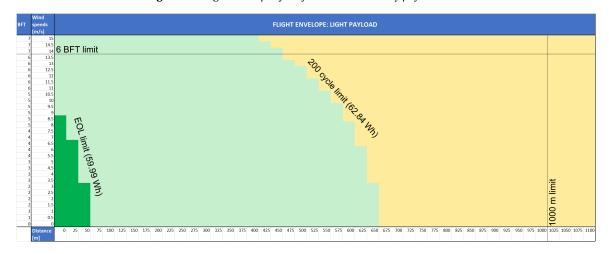


Figure 7.4: Flight envelope of the final iteration: light payload case.

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. This is due to the longer showtime requirement of 20 minutes for the light payload (whereas the heavy payload is only to be carried for 15 minutes of showtime).

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, which corresponds to 267 cycles according to the model. 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 performed prior to the mission to ensure that the state of life of the battery will allow for the mission to be completed. Further explanation regarding this will be mentioned in Section 14.3. The regions displayed may seem rather restrictive initially. However, it must be noted that the vast majority of shows will happen under conditions akin to those found in the lower left corner of the envelope, as the majority of shows will be conducted right above the takeoff area, and high wind speeds occur far less often than low ones (a study conducted in Iowa for example, showed that winds stronger than 3 BFT occur less than 22.07% of the time [62]). Overall, the flight envelopes displayed show a rather satisfactory result, as the battery selected will be able to easily fulfil the typical missions it is expected to perform, even at end-of-life. It will also be capable of providing 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 (POP-AP-3.1, POP-AP-3.2, POP-AP-3.8). From

a power unit standpoint, the drone will also be able to reach distances as far as 1000 m from the ground station (provided the batteries are in sufficiently good condition), which ensures compliance with requirement CCE-AP-2.

For the ESC, the product selected is the "Air50 3-6S 50A 4In1 ESC", manufactured by "Racestar" [63]. It presents all necessary characteristics for an appropriate interface with the battery (3-6S Li-Po compatibility) and the motors (55 A continuous current capability). The choice of a 4in1 ESC was made, because of their advantageous price and their compactness. 4in1 ESC's however present a higher risk than 4 separate ones: a shorted 4in1 ESC requires a full replacement. As such, ESC shortout will be added to the technical risk register. ESCs short out due to sudden interruption of the propellers; although the risk of this happening is fairly low during showtime, the personnel operating the drones during show preparation and dismantling should be careful not to hold or manipulate the drones by the propellers, to minimise the risk which is mentioned in Section 14.4.

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

Table 7.5: ESC iteration table

7.4. Risk Analysis Power

During the detailed design, additional risks have been identified. They can be seen in Table 7.6, along with their risk scores. Following the identification of the risks, mitigation responses were developed, to help reduce the extent of the risks. Those can be seen in Table 7.7.

ID	Risk	LS	Reason for likelihood	CS	Reason for Consequence
32	Battery Mechanical	2	Risk occurrence reasonably low. Me-	5	Mechanical damage like puncture or
	stresses		chanical stresses are not expected		dropping the battery can cause the
			during flight, but operators and show		battery to catch fire or to explode
			personnel may cause accidents		
33	ESC shortout	2	Risk occurence relatively low: drone	4	At least one propeller inoperative. Lost
			shows in open areas (no trees/obstacles		link between motor and and ESC causes
			to hit the props)		a shortout of ESC
52	Battery too old to complete	4	depends on wind speed and distance be-	5	Endurance of battery not high enough to
	mission		tween takeoff and show location. Most		finish the show. Show ends prematurely,
			shows will be conducted under favor-		drones unable to fly back to base.
			able conditions (see Subsection 7.3.6),		
			but unfavorable ones may result in		
			impossibility to complete the show.		

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

Table 7.7: Mitigation responses to the newly identified risks.

ID	Risk	Mitigation Response	LS	CS
32	Battery Mechanical	Carry battery during transport in adapted Li-Po safe bags/cases (lower likelihood:	1	3
	stresses	safer containment. lower consequence: battery damage will not harm or cause		
		damage to environment)		
33	ESC Shortout	Train personnel not to carry the drones by the propellers. (lower probability: less	1	4
		chances of interrupting propeller movement)		
52	Battery too old to complete	Perform battery age checks before the shows. Replace batteries when they are	1	4
	mission	outside of the flight envelope for a given mission.		

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.

7.5.1. 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	$m_{bat} = 0.074020176491188 \text{ kg}, E_{bat} = 0 \text{ Wh}$	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.	$\%_{profit} = 100\%$, $Cost_{bat} = 0 \in \%_{profit} = 0\%$, $Cost_{bat}$ corresponds exactly with value from the database.	Yes
VT-POW- U.5	Flight Enve- lope	P _{flight}	Set <i>P</i> _{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 En- velopes	$P_{flight}, \ P_{payload}, \ t_{showtime}$	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 En- velopes	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 "bright green"	$m_{bat} = 0.074020176491188 \text{ kg } (E_{bat} = 0 \text{ Wh}),$ flight envelopes are completely bright red. $m_{bat} = 100000 \text{ kg } (E_{bat} = 184678213.92 \text{ Wh}),$ 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	$\begin{array}{l} DoD = 0.8, \ E_{BOL} = 71.2373, \ E_{EOL} = 59.9893, \\ DoD = 0.4, \ E_{BOL} = 35.6186, \ E_{EOL} = 29.9946, \\ \eta_{bat} = 0.95, \ E_{BOL} = 71.2373, \ E_{EOL} = 59.9893, \\ \eta_{bat} = 0.475, \ E_{BOL} = 35.6186, \ E_{EOL} = 29.9946 \end{array}$	Yes

7.5.2. 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, because of the easy access to its specifications ([64]), and because it presented a number of features similar to Starling (a payload focused quadcopter, which also uses a lithium-polymer battery as power source). 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 mAhBattery 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 [65]. 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. It might be worthy of interest to verify as well whether the Mavic 2 Pro also actually delivers its specified maximum hover time, and if so, under which conditions exactly. A future recommendation for the verification of the model would be the case study of the battery degradation estimator.

7.5.3. 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 [55].

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

The power related requirements are displayed in Table 7.9. As can be seen, the drone will be able to comply with all requirements.

TAG	Requirement	Verified?
POP-AP-3.1	The drones shall be able to fly for 15 minutes for preparations and checkups.	Yes, check show
		conditions
POP-AP-3.2	The drones shall be able to fly for 15 minutes of showtime with a heavy	Yes, check show
	payload.	conditions
POP-AP-3.8	The drones shall be able to fly for 20 minutes of showtime with a light as	Yes, check show
	a payload.	conditions
POP-SYS-3.7	The energy storage shall be fully charged within 60min.	Yes
SUS-AP-1	The drones shall be powered by renewable energy sources.	Yes
SUS-EO-6	The components of the energy storage shall not contaminate the	Yes
	environment.	
SP-SYS-1.3.1	The megaphone or speaker shall have a power consumption of 20W	Yes
SP-AP-1.4.2	Future innovations shall have specifications up to a 20W power consumption	Yes
OP-AP-2	The drones shall be suitable for mass transport.	Yes
CCE-AP-2	The show location shall be at most 1000 m apart from the ground station.	Yes, SOL checks
		necessary
CCE-AP-3	The drones shall be recharged wirelessly through their landing pads.	Yes
CCE-SYS-3.2	The drone shall be able to recharge autonomously on the landing pad	Yes
	between preparation and show.	

Table 7.9: *Compliance matrix of the power subsystem's requirements.*

Requirement OP-AP-2 and AD-SYS-6 are met from the standpoint of the power source. However, it must also be complied with on a system level. This requirement will be further discussed in Chapter 12.

Furthermore, it must be remarked that endurance risks POP-AP-3.1, POP-AP-3.2 and POP-AP-3.8 are met, provided that the state of life of the battery is checked before the show, and that it allows for fulfilment of the mission under the show's weather and configuration conditions. To ensure this, battery health checks will be conducted before every show (see Section 14.3). This measure also pertains to the fulfilment of requirement CCE-AP-2. However, the vast majority of shows are expected to occur in conditions in which even a battery at end-of-life could be used.

Communication, Control and Electronics Subsystem

In this chapter the communication, control and electronics (CCE) subsystem will be designed in detail. The preliminary design phase focused on trade-offs on the communication, control and positioning methods that will be used [4]. 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 functions and risks of the subsystem 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, for electronics in Section 8.4 and for control in Section 8.5. This is then presented in a software diagram in Subsection 8.6.2. Risks discovered during the detailed design and their mitigation responses are presented in Section 8.7. Verification and validation of the methods and tools used in this chapter are presented in Section 8.8. Finally the compliance matrix is shown in Section 8.9.

8.1. Functional and Risk Overview of CCE

The goal of the communication, control and electronics department is to control all subsystems in order to execute the commands received from the ground station. The 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 analysed. The used protocols will be discussed and the communication methods will be presented. In the electronics section, hardware will be selected and presented. In the market analysis it is stated that the design requires versatility which can be achieved by indoors and outdoors navigation. To achieve this versatility the required hardware components such as the micro controller and UWB receiver are selected. The 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 identified in the preliminary design phase related to the CCE department are mentioned [4]. They can be mitigated 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 8.7.

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 CCE Requirements

The requirements related to the CCE department are presented in Table 8.2. Design for CCE will be done in the following sections according to the requirements. In the compliance matrix in Section 8.9 the fulfillment of the requirements will be assessed.

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

Sub-department	TAG	Requirement	
	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	
Electronics	SR-AP-4	The connection to the drones shall not be lost during any show, also in urban environments	
Liectionics	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	
	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	
	101-313-4	from being able to perform an emergency landing.	
Control	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 the 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 and 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 requirement. 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 whose 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 radio, because it is faster and less energy consuming than

one-to-one messages via WiFi. According to [66], RTCM data for 12 satellites requires a 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 the 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 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 the 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[67] 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 (Table 8.1). 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 Wi-Fi. By CCE-AP-2.1 the drones can be as far as 1.2 km from the ground station, therefore 2.4 GHz WiFi standard was chosen instead of 5.4 GHz. This frequency was preferred due to tight link budget

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 Wi-Fi module. There are 2 other legal frequencies in Europe: 433 and 868 MHz[68]. It was decided to use 868 MHz for faster data rate. The modulation type was chosen to be LoRa (Long Range)[69] because of the excellent range performance.

8.3.2. Link Budget

The link budget was calculated for Wi-Fi and radio links. According to [70], the link budget equation is Equation 8.1:

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

The terms from left to right are: transmitter power(P_{Tx}), transmitter antenna gain(G_{Tx}), receiver antenna gain(G_{Rx}), Free space loss(L_{fs}), fade margin(FM) and sensitivity of the receiver(S_{Rx}). 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 as shown in Equation 8.2:

$$L_{fs} = 20log(0.621d) + 20log(f) + 36.58$$
(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 [70].. Other parameters in this equation depend on the receiver and transmitter properties. The full link budget will be presented in Section 8.4

To ensure stable signal in all conditions, 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. Communication hardware is. 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[71]. 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 through 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 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. Professional routers can support more than 300 devices. If the number of drones is bigger, multiples routers can be used. 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 self 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 of more than 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 (Table 8.1). 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). Electronic design is not a topic within the field of aerospace engineering and will therefore this analysis will 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 for the drone can be divided into two 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 in the preliminary design phase are [4]: 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.

- **Micro controller:** Microcontroller was preferred over microprocessor for a main computing unit, because of cheaper price and lower power consumption. [72].
- **EEPROM memory:** Internal flight memory is needed to store the telemetry data and reading show commands. According to the Anymotion Production, the drone show commands take 25 kb of memory, so the memory module should have at least this much storage.
- **IMU:** The inertial measurement unit (IMU) will be used for measuring the attitude of the drone. IMU consists of a gyroscope and accelerometer as a two separate modules or 2-in-1 solution.
- **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.
- Barometer and temperature sensor: A barometer will be use as an additional altitude sensor. It will be located under the cap, so the sensor will measure static pressure, and won't be affected by wind gusts or propeller down wash.
- **GPS:** Outdoor positioning will be done using GPS in combination with real time kinematics capability(RTK). RTK is needed to achieve required accuracy of 0.5 meters.
- **GPS antenna:** An additional antenna is required to receive the GPS signal. The antenna will be chose from the same manufacturer as the GPS module so that the link budget is closed since the antenna receiver combination is designed for this application.
- **Radio:** The radio transceiver will be used for receiving the RTK signal, receiving commands and communication when flying in the manual control mode.
- Radio antenna: A radio antenna is required to receive the radio signal. This module will be sellected such that the link budget is closed.
- **Wi-Fi:** A Wi-Fi module will be implemented to have Wi-Fi connectivity. The Wi-Fi receiver. The frequency is chosen to be 2.4 GHz, as it requires much less power to close the link budget.
- Wi-Fi antenna: Similar to the radio antenna is chosen a Wi-Fi antenna is chosen.
- **UWB receiver:** The Ultra Wide Band (UWB) receiver will be used for indoor positioning. An off-the-shelf module with built in radio will be selected for practicality and ease of integration.

8.4.2. Components

For every component the operating voltage, power consumption, communication protocol, dimensions, temperature range and weight is stated in Table 8.3. The values are found by analysing the data sheets for every component [73–77]. 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 num-

bers. Delivery costs are not included as delivery costs will be negligible compared to the part costs 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 table8.3. The missing masses have been calculated by multiplying the volume (calculated using the dimensions) by the density of steel. Steel has been chosen to overestimate the weight, which will prevent the manufactured PCB to be over budget.

Operating Power con-Price Communication dimensions Temperature Component Name Weight [g] sumption [W] XYZ [mm] voltage [V] [Euro] protocol range 6 SPIs, 4 I2C STM32H747 -40°C to +85°C microcontoller 3.3 1.8843 €12.43 7x7x0.45 0.218295 4 USARTs **EEPROM** 25CSM04 3.3 0.0099 SPI -40°C to +85°C 0.2079 €2.55 5x6x0.7 memory 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+ GY-63 I2c and SPI 0.00099 3.3 0.00462 €6.15 2.45x4.45x1 -40°C to +80°C temperature GPS NEO-M8P 3.3 0.2211 €80.00 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 35x35x6 €16.17 ATWINC3400A-MU-Y 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

Table 8.3: Components selected for the PCB design.

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.

WiFi and Radio modules were selected with link budget in mind. Equation 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-directional antenna and therefore adjustments on the antenna its position during the show are not needed [78]. As can be seen in the Table 8.4, 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.

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

Table 8.4: Link budget

The GPS receiver is equipped with RTK and will reach accuracy's up to 2.5 centimeter[77]. 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 until 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[67]. 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. UWB is only used indoors, but this module will be placed on all 300 drones, as the cost of this module is very low.

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 Subsection 8.4.1 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.

Moisture 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[79].

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[80]. 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.

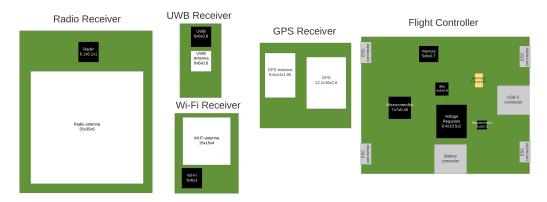


Figure 8.1: Design of the five PCB's that will be included on the drone. The components are drawn to scale.

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 [4]. The mass is over budget by 15 grams and the power consumption is below budget by 7 Watt. The mass over-budget makes virtually no difference in the design, so the CCE subsystem design can be considered successful.

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. Simulation is described in Subsection 8.5.1. Then the control algorithm was developed and tested on the drone model in Subsection 8.5.2. Finally, a simple choreography was simulated and visualized in Subsection 8.5.4. The equations and derivations stated in this sections are deducted from the book 'Introduction to Multicopter Design and Control' [42].

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
- Thrust 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:

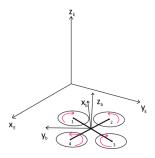


Figure 8.2: Coordinate system used in control simulation

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:

$$R_{E}^{b} = R_{z}R_{y}R_{x} = \begin{bmatrix} c(\psi) & s(\psi) & 0 \\ -s(\psi) & c(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c(\theta) & 0 & -s(\theta) \\ 0 & 1 & 0 \\ s(\theta) & 0 & c(\theta) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c(\phi) & s(\phi) \\ 0 & -s(\phi) & c(\phi) \end{bmatrix}$$
(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} , three 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 in Equation 8.4:

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

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 next. The position derivative is trivial: $\frac{d\vec{p}}{dt} = \vec{v}$. As stated in the assumptions, the thrust and torque of the propellers are modeled as simple quadratic functions:

$$T_n = c_t w_n^2$$
 $M_n = c_m w_n^2$ for $n = 1, 2, 3, 4$ (8.5)

Thrust and angular speed of each propeller is obtained from the thrust setting using Equation 8.5. 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: $w_n = T_n/c_t$.

$$\frac{d\vec{v}}{dt} = \frac{1}{M} \left(F_g + F_a + R_b^E F_{thrust} \right) = \frac{1}{M} \left[\begin{pmatrix} 0 \\ 0 \\ -Mg \end{pmatrix} - \frac{1}{2} \rho \vec{v} || \vec{v} || S C_d + R_b^E \begin{pmatrix} 0 \\ 0 \\ \sum_{n=1}^4 T_n \end{pmatrix} \right]$$
(8.6)

In Equation 8.6, gravity 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 Equation 8.7:

$$\vec{w} = W \frac{d\vec{\theta}}{dt} = \begin{bmatrix} 1 & 0 & -s(\theta) \\ 0 & c(\phi) & c(\theta)s(\psi) \\ 0 & -s(\phi) & c(\theta)c(\phi) \end{bmatrix} \frac{d\vec{\theta}}{dt} \rightarrow \frac{d\vec{\theta}}{dt} = W^{-1}\vec{w}$$
 (8.7)

The derivative of the angular velocity $\frac{d\vec{w}}{dt}$ is calculated using Euler formula for rigid body rotation8.8:

$$I\frac{d\vec{w}}{dt} + \vec{w} \times I\vec{w} = \vec{\tau} \tag{8.8}$$

 τ is external torque caused by the propellers, I is the drone moment of inertia matrix. Since the drone has spinning propellers, the Equation 8.8 is modified to account for gyroscopic torque \vec{G} and becomes Equation 8.9:

$$I\frac{d\vec{w}}{dt} + \vec{G} + \vec{w} \times I\vec{w} = \vec{\tau} \quad \to \quad \frac{d\vec{w}}{dt} = \frac{1}{I} \left(-\vec{w} \times I\vec{w} - \vec{G} + \vec{\tau} \right) \tag{8.9}$$

Gyroscopic torque is equal to:

$$\vec{G} = \sum_{n=1}^{4} w \times J_{pr} \vec{w}_n = J_{pr} \sum_{n=1}^{4} w \times \begin{pmatrix} 0 \\ 0 \\ (-1)^n w_n \end{pmatrix}$$
 (8.10)

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 [81], giving Equation 8.11:

$$\vec{\tau} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} c_m \left(w_1^2 - w_2^2 + w_3^2 - w_4^2 \right) + \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} c_t l_x \left(-w_1^2 - w_2^2 + w_3^2 + w_4^2 \right) + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} c_t l_y \left(w_1^2 - w_2^2 - w_3^2 + w_4^2 \right) \tag{8.11}$$

Equations **??**, 8.6, 8.7 and 8.9 provide the derivative of all state variables. Given an initial condition, discretized Equation 8.4 can be time marched to find the drone trajectory.

8.5.2. Control Algorithm

The control algorithm consists of two main parts: State estimator of the drone and the controller. The first part is performed using Kalman filter [82]. 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 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

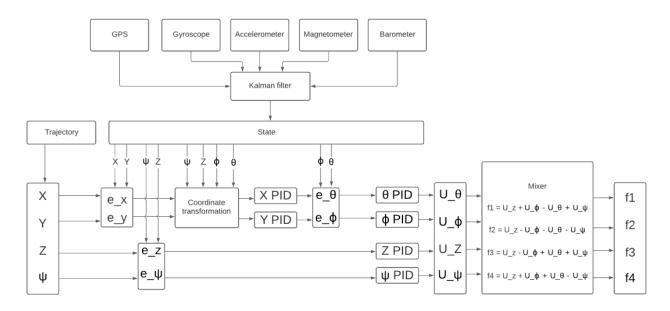


Figure 8.3: Controller architecture

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 are 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 (Equation 8.12):

$$U = K_p e + K_i \int_0^t e dt + K_d \frac{de}{dt}$$
(8.12)

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. Without it, the drone would only be able to achieve small yaw angles.

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 a PD controller was implemented first. The Newton second law in Laplace domain is Equation 8.13:

$$m\ddot{x}(t) = T(t) - mg \rightarrow s^2 mX(s) = T(s) + \frac{mg}{s} = P(s)$$
 (8.13)

Trust and gravitational force were combined in one term in Equation 8.14 to simplify the transfer function:

$$\frac{X(s)}{P(s)} = \frac{1}{s^2 m} \tag{8.14}$$

Then PD controller is implemented to the system as can be seen in Figure 8.4:

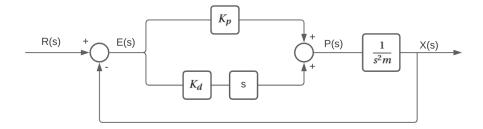


Figure 8.4: Closed loop transfer function

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 in Equation 8.15 from the closed loop transfer function:

$$\frac{X(s)}{R(s)} = \frac{K_p + K_d}{ms^2 + K_d s + K_p} \to s = \frac{-K_d \pm \sqrt{K_d^2 - 4mK_p}}{2m}$$
(8.15)

For the system to be stable, real part of both poles must be negative. This is ensured by two 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 8.15 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.

8.5.4. 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 8.5 shows a drone performing a horizontal helix maneuver in 50 seconds.

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

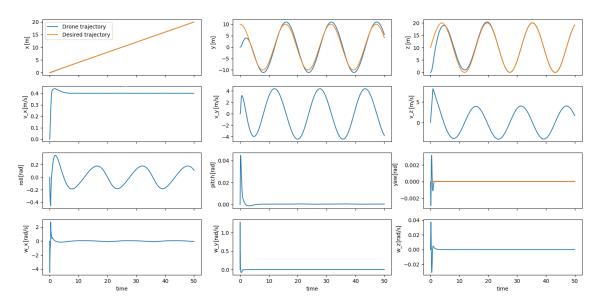


Figure 8.5: Drone states during slow horizontal helix

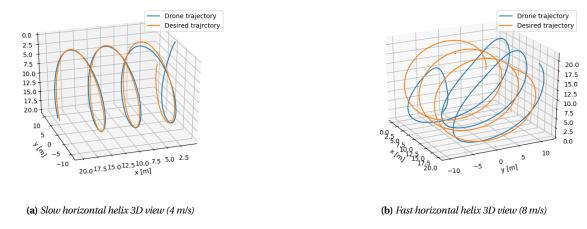


Figure 8.6: Horizontal helixes at different velocities

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 can be found automatically, but this is left for the post-DSE phase.

8.6. Electrical, Software and Communication Flow Diagram

In this section the diagrams related to the power, propulsion and CCE department are shown. These diagrams summarize the work done on the power, propulsion and CCE department and will aid to understand the working principles of the drone. This section starts by the electrical diagram. The electrical diagram will show how all electrical components are physically connected to each other. Components such as motors, ESC and BMS, discussed in the power and propulsion chapter, are also included. The electrical diagram is followed by the software diagram. In the software diagram, the communication between the components selected in Section 8.4 is shown. Some components shown in the software diagram are located on the same PCB. The communication flow diagram is shown. The communication flow diagram will treat the drone as a system and visualizes the CCE related connections to the environment. Some components shown in the software diagram are also shown in the communication flow diagram.

Finally the data handling diagram is shown in Subsection 8.6.4.

8.6.1. Electrical Diagram

Electrical diagram (Figure 8.7) displays all electrical components. Coloured connections represent wires. Black (-) and red (+) wires indicate power supply wires, other colors indicate signals. The main power line connects flight computer, ESCs and payload in parallel, and has a voltage of 14.8V, which corresponds to a nominal battery voltage. The flight computer transforms this voltage to 3.3V to power all electronic components. Next to the data bus, all peripherals are connected to the flight computer via two power wires. As explained in Chapter 7, the battery is connected to the BMS board. Each cell of the battery is connected to BMS separately (4 red wires in Figure 8.7), grounds are combined in one wire. The BMS itself is connected to the charging source, which is a landing pad or any other external charging device. Charging voltage is 16.8V for Li-Po batteries. It can be seen that the payload is connected using the I2C bus and a 3.3 volt power line. Additional power can directly be applied to the payload if needed in case the power usage exceeds 10W. The battery can be charged by connecting the charging wires to a power source. This can be done trough conductive charging or by connecting the battery plug to an external charger.

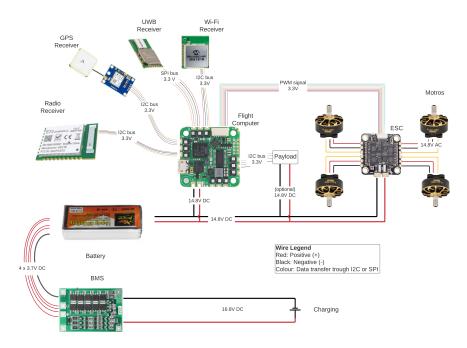


Figure 8.7: Electrical block diagram

8.6.2. Software Diagram

In this section, the software diagram is presented in Figure 8.8. This diagram shows the data transfer between components in the drone. As explained in Subsection 8.4.2, the processor has two cores, the communication is processed by one core, and control is running on the second core. The chosen hardware is shown in boxes connected to the micro controller. A general overview of the computations done in the micro controller is shown in the cores.

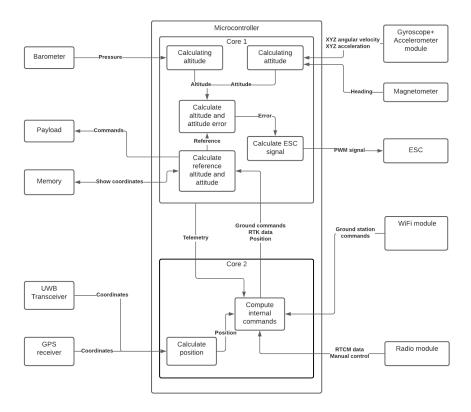


Figure 8.8: Software diagram

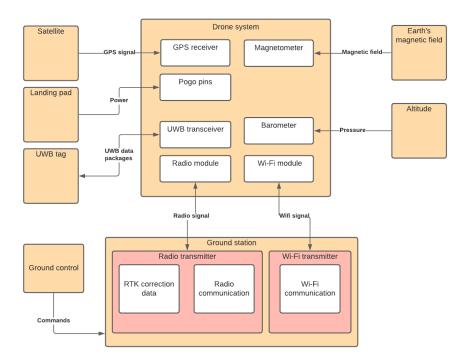


Figure 8.9: Communication flow diagram

8.6.3. Communication Flow Diagram

In Figure 8.9, the communication flow diagram is shown. The boxes are coloured aid readability. The drone is shown as a big system. Components that have a connection to the outside world are shown within the system and are directly connected to the environment. The ground station used for communication and to transmit the RTK connection is shown. The UWB tag will be used for positioning indoors as discussed in Section 8.3 and the drone will be connected to multiple UWB tags. Both Wi-Fi and Radio can be used for communication, however Wi-Fi will not be used to send commands as discussed in Section 8.3.

8.6.4. Data Handling Diagram

The data handling diagram is shown in Figure 8.10. The data handling diagram illustrates how the data is transferred and converted between the sensors and connected systems. Systems are illustrated by grey boxes filled with hardware (orange) and calculations/transformations (white) boxes. External systems such as the ground station are presented in the diagram. The diagram has a strong correlation to the software diagram and the communication flow diagram. The diagram is used to identify the data flow between and within connected systems in a single overview.

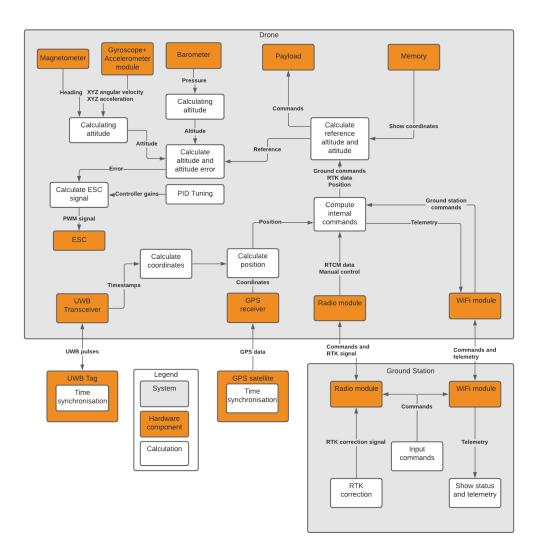


Figure 8.10: Data handling diagram

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

8.7. 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 8.7: *Mitigation responses for CCE related risks discovered in the detailed design.*

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

8.8. Verification and Validation CCE

In this section the verification and validation of the CCE department will be performed. The section will start with verification followed by validation.

8.8.1. CCE 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 8.8.

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[m],100[m],1000[m]) while maintaining 2 rad yaw angle. Figure 8.11 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[83], 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 [84]. The simulation itself is running at 1000 Hz. Similar simulations were performed with different trajectories and simulation frequencies, to make sure that at 1000 Hz the solution has converged.

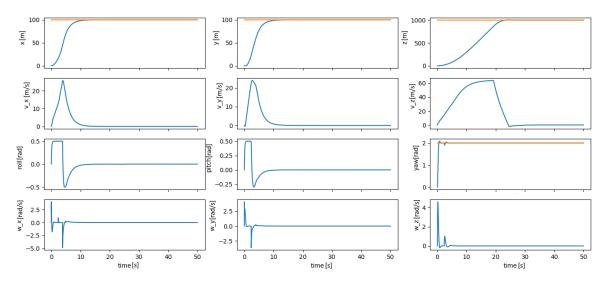


Figure 8.11: System test by flying to coordinates (x,y,z) = (100[m],100[m],1000[m])

TAG Block tested Outcome V? Multiply the transformation VT-CCE-U.1 Identity matrix Yes by the inverse Transformation compute yaw pitch and roll response VT-CCE-U.2 from E to b frame Exact match with program result Yes manually Run the simulation with disabled x,y,z position increases linearly with time, VT-CCE-U.3 Position derivative Yes forces and rotations proportionally to velocity drone accelerates in the negative VT-CCE-U.4 Disable all forces, except gravity Yes z direction at rate of 9.81 m/s² Set the thrust of each motors to drone hovers on the same altitude, slowly VT-CCE-U.5 Yes 1/4 of total weight drifts up or down, depending on the rounding Velocity derivative Set the terminal The drone reaches 100 m/s with VT-CCE-U.6 Yes the given thrust setting velocity is 100 m/s upwards Euler angles Calculate the transformation Results match the VT-CCE-U.7 Yes derivatives matrix by hand for 3 random angles program outcome Spin propellers 1 and 2 faster w_y is negative, decreases VT-CCE-U.8 Yes than 3 and 4 proportionally to the torque Spin propellers 1 and 4 $w_{\rm r}$ is positive, increases VT-CCE-U.9 Yes Derivatives of faster than 2 and 3 proportionally to the torque Spin propellers 1 and 3 angular velocity w_z is positive, increases VT-CCE-U.10 Yes faster than 2 and 4 proportionally to the torque VT-CCE-U.12 Set integral gain of altitude PID to 0 Drone flies at constant offset Yes Set unstable gains as predicted by Drone position diverges VT-CCE-U.13 Yes linearized model from the desired state Plot the output of each PID The output is bounded to the VT-CCE-U.14 module for different altitude specified value. Motor input after Yes PID controllers and angle commands the mixer is bounded to (0-1)

Table 8.8: *Unit tests of the drone simulation*

8.8.2. CCE Validation

VT-CCE-U.17

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 shows tests for electronics, Table 8.10 for communications and Table 8.11 for control:

Set the desired position far away.

Drone pitch and roll angles reach

maximum value of 0.5 rad

Yes

 Table 8.9: Validation of drone electronics

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

Table 8.10: Validation of drone communication and positioning

TAG	Description	Test		
	Confirm that link budget is closed for WiFi	Separate the drone and ground		
VAL-CCE-4	and Radio.	station 1200 meters apart and send		
	and Radio.	commands to the drone		
		Fly the drone at different speeds		
VAL-CCE-5	Confirm the satellite navigation is working	and altitudes while monitoring the		
		GPS signal quality		
VAL-CCE-6	Confirm the satellite indoor	Record positional accuracy with		
VAL-CCE-0	navigation is working	different number of ground beacons		

Table 8.11: Validation of drone simulation and controller

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

8.9. 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. Not all requirements related to control, these requirements will be discussed in the Chapter 12 and will be summarized in the final 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 Chapter 12 and Chapter 11.

 $\textbf{Table 8.12:} \ \textit{Compliance matrix for the CCE subsystem requirements}$

Sub-department	TAG	Requirement	Verified?			
	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				
	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.				
	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	Yes			
	CCE-SYS-9	The drones shall be able to be manually controlled.	Yes			
	SR-ST-4.1	Show shall safely end if connection is lost	Yes			
Control	CCE-SYS-8	Choreography shall be executed.	Yes			
Control	CCE-AP-4	The drones shall be able position themselves within 0.5m accuracy	Yes			

Structures Subsystem Design

The structures subsystem is the interface between all other subsystems and should be designed to integrate 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 is therefore designed by the operations department in Chapter 10. The design of the subsystem is done with manufacturability and integration of other subsystems in mind.

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 [4] and the requirements related to the structures subsystem. These sections serve as an overview of all things to be taken into account when designing the frame and payload integration. Section 9.3 describes the approach to estimate the frame size, mass and cost as well as the iterations performed. Section 9.4 describes the payload integration method.

The last part of this chapter is dedicated to the analysis of the frame design. In Section 9.5 the risks identified during the detailed design are shown. Section 9.6 describes the verification and validation of the tools and subsystem. 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, size 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:

- Allow for routine maintenance
- · Provide structural integrity during flight and landing
- Provide space to integrate all subsystems and the modular payload
- 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, to be presented in Chapter 11
- Production/manufacturing plan, to be presented in Chapter 13

Table 9.1 presents the risks identified in the preliminary design phase regarding the structures subsystem. It also shows their likelihood, consequence and the mitigation response to 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	Very low	Catastrophic	Take the risk, focus on waterproofing during de-	
	can not withstand the rain			sign. 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	Low	Moderate	Recyclability as an important selection criteria fo	
	recycled/reused			materials.	

19	Li-Po battery swells due to	Moderate	Critical	Design Battery container with clearance in volume	
	abusive use			for expansion of battery (lower consequence: swelling	
				will less likely burst into flames).	
29	Structure catches on fire.	Moderate	Catastrophic	Fire resistance is an important consideration in the	
				thermoplastic material choice (lower risk: choosing	
				fireproof material lowers chance of fire).	

9.2. List of Requirements Structures

Table 9.14 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.

Sub-department	TAG	Requirement
	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
Payload	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
	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
Frame	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

 Table 9.2: Requirements related to structures subsystem

9.3. Design for Structures: Frame

The preliminary design phase concluded that the drone frame consists of 4 arms that are fixed to the frame body [4]. 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 protect the motor wires against rain, the cross section is chosen to be hollow to provide a casing for wires coming from the brushless motors. This is to satisfy requirement AD-AP-2.
- 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 from AD-AP-1) with maximum flight speed (20m/s from POP-AP-2), while providing maximum thrust

The forces on the arm during this critical case are presented in Figure 9.1. Here, Ft is the thrust force of the propulsion system, Fp is the weight in Newton of the motors and propellers, WD is the drag force acting on the arm and Ww is the weight of the arm. WD and Ww are distributed loads.

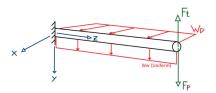


Figure 9.1: Critical load case arm sizing

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, which is for a thrust to weight ratio of 3 from POP-SYS-2.2.

This load case is used for sizing throughout all the iterations. In Section 9.6 3 more load cases are identified and used for sizing to verify that the above stated load case is indeed the critical one.

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-6, 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 for this load case.

- 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 relief.
- 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 verification procedures to ensure it is a valid assumption.
- The absolute value of the shear stress V is equal to $\sqrt{V_x^2 + V_y^2}$.

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 where a moment is positive if it causes a positive stress in the positive quadrant of the x,y axis system [85]. M_x and M_y are the moments about the x-and y axis respectively. y_{max} and x_{max} are the distance from the center of the cross-section to the outer diameter. I_{xx} and I_{yy} are the area moments of inertia around their respectful axis. σ_{max} is the maximum stress. Its equal to the yield stress by SP-SYS-6. Its scaled by the safety factor k_s . d_0 and d_i are the inner and outer diameter respectively. ρ_{air} is the density of the air and ν is the velocity of the drone. c_d represents the drag coefficient of the arm. Lastly, LB is the length of the arm.

$$\sigma_z = \frac{M_x y_{max}}{I_{xx}} + \frac{M_y x_{max}}{I_{yy}} \le \frac{\sigma_{max}}{k_s} \tag{9.1}$$

$$I_{xx} = I_{yy} = \frac{\pi}{64} \left(d0^4 - di^4 \right)$$
 (9.2)
$$y_{max} = x_{max} = \frac{d0}{2}$$
 (9.3)

$$W_D = 0.5 \rho_{air} v^2 d0cd \qquad (9.4)$$

$$M_x = Ft \cdot LB - Fp \cdot LB - \frac{Ww \cdot LB^2}{2} \qquad (9.5)$$

$$Ww = \rho_s \frac{\pi}{4} (d0^2 - di^2)g$$
 (9.6)
$$My = \frac{W_D \cdot LB^2}{2}$$
 (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 and their respective contribution to the deflection, given by the "forget-me-not" functions [MoM]. In these equations E is the E-modulus of the material. The maximum deflection is determined by the propulsion department to be 1 mm. For sizing the arms the maximum deflection is chosen, so either $def l_x$ or $def l_y$, while the total deflection for the critical load case is actually a combination of them.

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

$$(9.8)$$

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

$$defl_{max} = max(defl_x, defl_y) \le \frac{0.001}{k_s}$$
(9.10)

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. It is not initially obvious where the maximum shear stress will be as V_y decreases along the arm and V_x increases along the arm. The position of maximum shear stress can be determined by calculating the shear flow along the arm. It was found 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, with the knowledge from the first iteration, the thickness exceeded 10% of the calculated outer diameter. Thus from the second iteration onwards this assumption was no longer valid. Instead, the maximum shear stress in the rod was calculated by [86]

$$\tau_{max} = \left(2 + \frac{t}{r_o}\right) \frac{V_{max}}{A_c} \tag{9.11}$$

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 the material the arm will be made off.

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 should be considered. However, it can be 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 Python coded tool to perform quick iterations on the design. Six 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 diameters 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 diameters the program calculates 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 inputs of Table 9.3 will be further specified in this section.

Inputs Symbol Unit Density of the air ρ_{air} $[kg/m^3]$ Length of the arm [m]Drag coefficient of the arm Cd[-] Minimum inner diameter of the arm d_{min} Safety factor used in calculations $k_{s}[-]$ Minimum thickness of the arm $t_{min}[m]$ Maximum deflection of the arm $defl_{max}$ [m] $[kg/m^3]$ Density of the material ρ_s Maximum (yield) stress $[N/m^2]$ σ_{max} E-modulus Е $[N/m^2]$

Table 9.3: Inputs for arm sizing calculations

The density of the air ρ_{air} is determined using the International Standard Atmosphere model [87]. 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/m³.

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 it was 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 ends right outside the drone 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. The Reynolds number is a function of the wind speed and outer diameter of the arm. The value for cd is determined using the figure 7 from a paper[88]. 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.

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 [89]. A margin is included to make integration easier. Therefore 14awg wires are chosen to size the inner diameter. From geometry, the minimum inner diameter for inclusion of the 3 cables is then given by Equation 9.12, where r is the radius of the wires and D the the required inner diameter of the arm.

$$D_{min} = 2 \cdot \frac{2r}{\sqrt{3}} + r \tag{9.12}$$

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

- The mitigation strategy for risk 15 is to add a redundancy margin to the structures design
- 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 a cable. The reason for this hole is explained in Chapter 10. 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 clear that the arm requires threading on its ends to avoid misalignment in assembling. 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 [90]. 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 [91]. 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[92].

The maximum deflection is specified such that the thrust vector deviation does not degrade the flight performance. 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 [4]. The characteristics of the plastics is found

using the "ANSYS GRANTA Edupack" tool [93].

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" [94] it is ruled out as an option as well.

The remaining material options are presented in Table 9.4. The trade-off is based on the following criteria and weights and follows the approach explained in the midterm phase [4]

- Cost(5/5): Cost is very important as a small difference in material cost will make a big difference in price in mass production. By requirement COST-AP-1 there is a limit on the cost of the drone.
- Mass(4/5): Mass has become a driver requirement(implicitly in POP-SYS-2.2) to be able to meet the budget.
- Risk(5/5): Important to ensure safety, fire resistance is given by risk 29. 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 risk 17 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 to be able to determine how well a material scored on a certain criteria. 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 9.5 and Table 9.6 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 [95]. The heat release rate of PP with ca. 126 μ m-thick coating was reduced by 71.2% using this additive. Furthermore the coating is flexible, anti-ultraviolet and water resistant. The cost of this flame retardant is not yet taken into account in the design.

The material properties of Polypropylene are:

- $\rho_s = 902 \text{ kg/m}^3$
- $\sigma_{max} = 26.25 \cdot 10^6 \text{ N/m}^2 \text{ (Yield stress)}$
- $E = 1.223 \cdot 10^9 \text{ N/m}^2$
- $\sigma_{tensile} = 38 \cdot 10^6 \text{ N/m}^2$

By requirement SP-EO-2 the drone shall not sink into water. The structure of the drone will indeed float [96], but whether the whole integrated system will float is analysed in Subsection 12.2.6

Arm Size Iterations

With the tools in place and the parameters defined iterations are performed. The results of the tool that has the bending and deflection calculations integrated are presented in Table 9.7. Six iterations were performed in total. The first iteration is done for the material Polystyrene (PS). The iterations that follow use Polypropylene (PP) in accordance with the material trade-off. The tool and its output data will be verified in Section 9.6.

Regarding the shear force, the calculated dimensions for the rod were smaller than the dimensions required for bending. To withstand the shear forces, an outer diameter of 1.475cm and thickness of 1.6mm are required. This thickness is less than the minimum wall thickness. 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 deflection.

Table 9.4: 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 pro- duction 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%be- low avg) RF 8.44%	Recyclable: 23.5 (23% below avg), RF 5.5% de- composed 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 9.5: 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 9.6: Technical sensitivity analysis of material trade-off

Criteria	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

Table 9.7: Arm size iterations

Parameter	It 1	It 2	It 3	It 4	It 5	It 6 /final
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

Regarding the fatigue performance, the maximum stress per cycle due to bending is 10.5 MPa. This was calculated using the python programmed arm sizing tool for the first iteration. To simplify the fatigue analysis a critical assumption is made. It is impossible to assume a number of loading cycles per flight. This assumption does not affect the result of the fatigue analysis because 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. The S-N curve of polypropylene is shown in Figure 9.2 [97]. It shows the numbers of cycles to failure under a certain applied stress.

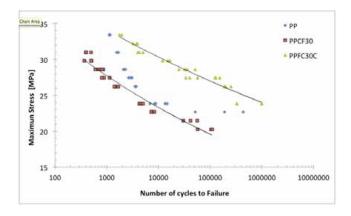


Figure 9.2: S-N curves obtained in the fatigue tests, for pure polypropylene (PP), polypropylene/coir fiber composites without compatibilizer (PPFC30) and with compatibilizer (PPFC30C) (Bettini et al., 2011)

To determine the production cost the "Granta" tool is used[93]. 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. The capital write-off time is the time over which the cost of non-dedicated equipment and the cost of borrowing capital itself is to be recovered. The overhead rate is the time that includes the cost of labor, administration, and general plant costs. Figure 9.3a 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 $4-28 \in$. The average of $12 \in$ is taken as the estimated cost per drone regarding the arms. as can be seen from the graph. If the company would produce more drones, the production costs will decrease significantly. As 300 drones are produced for Anymotion Productions this amount will be used to quantify the cost.

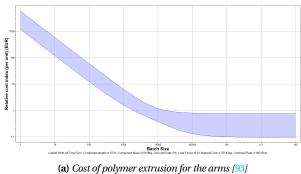
By requirement SR-AP-6 the drone is supposed to fly for at least a 1000 flight hours. With the fatigue analysis of the structure it is confirmed that the drone structure is able to meet this requirement. Therefore there is no expected maintenance cost on the drones structure.

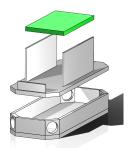
9.3.4. Sizing of the Frame Body

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 9.3b, where the green plate represents the top plate. This is to satisfy requirements SP-SYS-1.5 and SP-SYS-1.6

This frame body design was chosen as it can facilitate the subsystems in a space-efficient way, which is a main driver of the frame design. The arms end in the main box rather than being connected to each other. Therefore the cables that go through the arms are easily accessible without the need of holes in the arm.

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 as described in Chapter 17. A FEM analysis for on the structural integrity of the frame-arm connection will be done in Section 9.6. Lastly, a 2mm margin for the casing was included in the width, as this casing is to fit onto the main box. A more detailed explanation of the drone casing is given in Subsection 9.3.5 and Chapter 11.





(b) Frame body design

Figure 9.3: Adhesive mount system

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. In the first iteration the box is made out of Polystyrene(PS). The mass of the frame is calculated by multiplying the volume with the material density. The iterations that follow use polypropylene(PP), in accordance with the material trade-off.

In the second iteration walls with height according to the outer diameter of the to be incorporated arms are added to the front, the back and the sides of the first bottom plate to create the main box. The same is done to the middle plate, with a wall height of 110% battery thickness to create the battery compartment. This 10% margin was chosen as by risk 19 the battery tends to swell and might get stuck in the frame as a result. The top plate still has the same width and length as the main box. For iterations 3 to 6 the length of this 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 results of the iterations are shown in Table 9.8. The mass calculations will be verified in Section 9.6

The final dimensions were determined after the integration with all subsystems. A few corrections had to be made to the size of the frame of iteration 6 as described in Chapter 11. Because of these alterations the mass of the frame decreased with respect to the model. The model mass is 0.16kg, whereas 0.14kg was measured using the mass properties tool of "SolidWorks". The "SolidWorks" mass is shown in the final column of Table 9.8 as it uses the most recent corrections made to the frame.

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	139x57x5	152x56x5	160X64X5
Size top plate [LxBxH][mm]	170.9x66.7x5	163.4x64.2x5	50x62.1x5	50x63.1x5	50x57x5	50x56x5	83X50X5
D0[mm]	-	19	21	17.5	14	14	14
Height Battery compartment [mm]	-	46.2	44.4	45.2	53.35	40.7	40.7
Mass frame plates [kg]	0.18	0.21	0.16	0.17	0.13	0.14	0.14

Table 9.8: Frame size iterations

To determine the production cost the "Granta" tool is used[93]. The main box parts will be made via injection moulding and will cost €90 to produce as given by this tool. Injection moulding is chosen as the production method as it can be produce the parts relatively quickly and easy. Another option would to weld plates together. However, this increases the production time and introduces the risk of human error in assembly. The top plate can be made out of a plastic sheet for which the price is negligible [98]. This plate cannot be part of the box as an enclosed section can not be separated from the mould.

9.3.5. Sizing of the Frame Casing

To protect the internal components of the drone against rain to satisfy requirement AD-AP-2 and mitigate risk 11 a casing is incorporated in the frame. Important design considerations are that the case is to be removable and can not let water through. The final shape of this casing is determined in the integration phase and elaborated upon in Chapter 11. The mass of the casing is however incorporated in the calculation of the total mass of the structures subsystem from iteration 5 onwards. This case mass was based on the mass of a simple rectangular box casing with body dimensions like the frame dimensions and a 2mm thickness. This box was modelled in "Solidworks" from which a mass of 80 grams was determined. The final casing shape conducted after the integration phase has a mass of 57 grams. The final casing design as presented in Chapter 11 includes hinges to open and close the casing. The mass of these hinges was not taken into account in the iterations, but they are 4 grams each.

9.4. Design for Structures: Modular Payload

The design for modular payload has been performed to meet six requirements mentioned in Table 9.14. Which are the following: SP-AP-1, SP-AP-1.1, SP-SYS-1.1.1, SP-AP-1.2, SP-AP-1.4.1 and SP-AP-1.4.3. 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 a payload mount, shown in Figure 9.4a and a mounting piece on the bottom plate of the drone which is shown in Figure 9.4b.

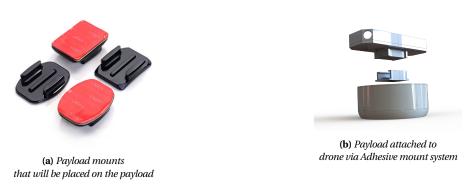


Figure 9.4: Adhesive mount system

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 payload mount. The adhesive mount is a cheap and easily acquirable mount which can be placed on any flat or curved surface. The surface also has 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 payload mount is advertised to be able to hold up to 2kg[99] but there is no specification for the mounting piece since it is specially designed. This system has been chosen for its simplicity, versatility and the availability. 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 $20cm \times 20cm \times 20cm$ 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 14.4 since it cannot be verified from a payload perspective only.

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[100]. The same candle is visible over a distance of 2576 m in a low light condition[101]. 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 m 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 are considered to be outside the scope of this project. To verify SP-AP-1.1 it is needed to place a light source of 30.3 lumen at a distance of 4000m. This light source has to be observed over this distance with the naked eye. SP-SYS-1.1.1 is automatically satisfied and verified if the light source includes an RGB illumination system. The flight time calculations performed using the tool mentioned in Section 7.3 included a light module of 6 watts. This calculation confirmed that this light module with its power consumption will be enough to perform an entire show.



Figure 9.5: *RGB illumination module*[102]

The LED Downlight 6W RGB+CCT 120mm Rond Mi-Light [102], as shown in Figure 9.5a and Figure 9.5b is used as a reference illumination system for 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 I2C bus to the flight computer and held via a custom designed case which is attached to the drone via the adhesive mount system described before. A casing has been designed Figure 9.4b to hold the RGB illumination module. Its shape is designed to spread the light in all direction. Further investigation is required to understand the effect of the material choice on the dissipation of the light from the source.

9.5. Risk Analysis Structures

From the detailed design phase, on top of the preliminary risks presented in Table 9.1, several new risks are identified. The description of the risk, their likelihood, consequence and the proposed mitigation response are presented in Table 9.9 and Table 9.10.

ID Risk Reason for likelihood CS Reason for consequence Arm brakes of at its base No calculations nor analysis performed When 1 arm brakes of the remainon arm-body integration strength ing propellers provide enough thrust for an emergency landing. However emergency landing not guaranteed as additional damage to frame is unforeseen. Furthermore the drone must be discarded afterwards 47 Battery gets stuck 4 The compartment was made to tightly Drone stuck in frame means the frame fit the battery so it cant move around plate must be discarded. No measures in flight. No production margins were should be taken to remove the battery included in the design. for risk of perforation of the battery. It means the top of the main box must be replaced Battery gets out of stock Could be expected as products get out If no alternative can be found the drone of stock, however high chance another is useless, the top of the main box will need to be redesigned around the new option is available battery and replaced 49 PCB gets outdated and Its likely electronics will need an update The trend in technology is that it needs replacement in 5 years as the technology evolves becomes smaller rather than bigger. Therefore the PCBs will still fit the frame quickly Arms Misaligned in body 4 For 300 drones 1200 arms need to be Might be less strong, may alter controls attached to the frame, likely that a few and drone performance arms will be misaligned Arms gets loosened from Generally drones deal with vibrations. When one arm becomes loose there body Vibrations could loosen the arm -body will be enough thrust for an emergency bonding when thread is used landing. However a safe emergency landing is not guaranteed as additional damage to the frame is unforeseen

Table 9.9: Structural risks that were discovered in the detailed design.

Table 9.10: *Mitigation responses for the new structural risks.*

ID	Risk	Mitigation response	LS	CS
46	Arm brakes of at its base	Perform Finite element analysis and tests	3	4
47	Battery gets stuck	Incorporate production margins into the design	2	3
48	Battery gets out of stock	Order in extra batteries	1	4
49	PCB gets outdated and	Take the risk	4	2
	needs replacement			
50	Arms misaligned in body	Add thread to the arms to make assembly easier	1	3
51	Arms gets loosened from	Add epoxy resin or "locktite" solutions to fasten joint	2	3
	body			

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 in this section.

The mass of the frame body was determined by multiplying the volume by the density of the material. No tool was used for this. Calculation verification will be performed to verify the calculation mass.

The cost estimation was done using a verified model [93]. Calculation verification and validation of cost can only be done by asking production companies for a cost estimation of the product. This is to be done in the post-DSE phase.

The assumption that the mass of the motor mount can be excluded was verified after the integration of the subsystems. In Chapter 11 the mass of the designed motor mount is 8 grams. Adding this to the mass of the motors and propellers in the arm sizing tool did not output other required dimensions, so this assumption is verified.

The assumption that the load case for which the arms are sized is the critical one is verified in this section by

performing sizing calculations on 3 more load cases. The arm frame connection is verified on structural integrity using Finite element models.

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 the body is designed and verified in more detail using Finite Element Models and tested on structural integrity using prototypes. This should be done in the post-DSE phase.

9.6.1. 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 9.11 and Table 9.12. With these tests the code was verified.

TAG	Output to	Input to vary	Test	Outcome	V?
	test				
VT-SP-U.1	τ	F_i	Set all input forces to zero, expect	For all $F = 0$, $\tau = 0$	Yes
			shear stress to be zero with no		
			errors		
VT-SP-U.2	(1)-	v	Double velocity, expect distributed	For $V_1 = 10m/s$, $w_D = 1.2141$	Yes
V1-3F-U.2	ω_D	V	drag load to quadruple	For $V2 = 20$ m/s, $w_D = 4.8564$	168
			urag load to quadrupie	For $d_i = 0.01$ and $d_o = 0.02$, $A = 0.00094$	
VT-SP-U.3	Across	t	Increase outer diameter keeping	For $d_i = 0.01$ and $d_o = 0.02$, $A = 0.00054$	Yes
			inner diameter the same, expect	For $u_i = 0.01 a m a u_0 = 0.05, A = 0.0025$	
			area to increase		
VT-SP-U.4	7	V	Double shear force, expect shear	For V = 15.44, τ = 224875	Yes
V1-3F-0.4	τ	V	stress to double	For V = 30.88, τ = 449750	ies
VT-SP-U.5	τ	A	Double cross section area, expect	For A = 0.00016, τ = 224875	Yes
V1-3P-0.3	l l	A	shear stress to halve	For A = 0.00032, τ = 112437	168
VT-SP-U.6	V	ω	Set distributed loads to zero,	Shear flow diagrams are straight lines	Yes
			expect shear force diagram to be		
			constant		

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

9.6.2. Calculation Verification of Tools

Once the code is verified the numerical results of the tool and frame mass calculations need verification. The parameters that can be verified in the tools by the use of an external model are the mass of the arms and the cross sectional properties. The externally verified source used for verifying the mass properties is "SolidWorks". For the cross sectional properties an online inertia calculator [103] is used.

To compare the results an error margin must be set for the relative error between model solution and external solution. This margin results from small explainable differences in the models. For the inertia calculation a margin of 1% is used as both models use the same equation as input. Differences could lie in small machine errors. The same margin is used for the mass calculations. The results are presented in Table 9.13 and they show that the calculations are verified.

TAG V3 Output Input to vary Test Outcome test VT-SP-U.7 d0,di for d0=1.4cm and di=0.75cm,\sigma = \sigma For input d0,di. Expect \sigma Yes to be below \sigmamax/ks = 10.4mpa 14.58mpa VT-SP-U.8 Deflection d0,di For input d0,di. Expect defletion for d0=1.4cm and di=0.75cm,defl = Yes to be below deflmax/ks = 0.55mm 0.5mm VT-SP-U.9 Min thickd0,di For output d0,di. Expect t>tmin for d0=1.4cm and di=0.75cm,t = 3.25mm Yes ness =3.2mm d0,di VT-SP-U.10 Min diameter Expect output di>dmin = 3.5mm output di = 7.5mm Yes VT-SP-U.11 for di=d0=0.014: float division by zero Singularity For Ixx=Iyy, stressfunction has Yes I_{xx}, I_{yy} division by 0, expect error error VT-SP-U.12 do For (d0,di)=(4,2), A=3Pi. For(do,di)=(8,2), Area Double d0, expect area to be 5x Yes bigger A=15pi VT-SP-U.13 Mass Area Double area, expect double mass for (rho,A,lb) = (902,6,0.2) m = 4329.6, for Yes (rho,A,lb) = (902,12,0.2) m = 8659.2

Table 9.12: Verification tests of arm sizing tool based on bending loads

Table 9.13: Calculation verification of Tools

Output to	Value	External	Error	Margin accepted	V?
verify		Value			
Ixx	1.7304e-09	1.7385 x10-9	0.0081	±1%	Yes
Iyy	1.7304e-09	1.7385 x10-9	0.0081	±1%	Yes
Mass arms	0.01732	0.01733	0.00001	±1%	Yes
Mass frame	0.1638	0.16382	0.00002	±1%	Yes

9.6.3. Arm Sizing for 3 Additional Load Cases

To verify that the load case the arms are designed for the critical load case, 3 more load cases are investigated with the dimensions of iteration 6. Note that these load cases now also include the landing gear attached to the arms.

The first load case is similar to the load case presented in Subsection 9.3.2. The difference is that this analysis now includes the forces projected from the arm onto the frame. Subsection 9.3.2 used the maximum thrust setting. However, to reach the maximum flight speed of 20m/s against the 6BFT wind the thrust T_1 is only 5.74N. This was corrected for in this load case. Lastly, the torque induced by the propellers is also taken into account for this load case. This torque is given by Equation 9.13 where ω represents the rpm setting of the propulsion system (252 rad/s for this particular load case) and c_m represents the torque coefficient (4.33·10⁻⁶ for this particular load case).

$$M_{p1} = \omega^2 c_m \tag{9.13}$$

The free body diagram of the first load case is shown in Figure 9.6a. The drag of the propeller is neglected. V represents the direction of flight. D_{A1} represents the distributed drag loading on the arms and D_{LG1} that on the landing leg. W_{A1} is the distributed weight of the arm and W_{M1} is the weight of the propeller and motor. l_A is the length of the arm (0.17m) and l_h is is the position on the arm where the landing gear is attached (0.114m). All reaction forces are displayed at the base of the arm. These reaction forces are used for the Finite Element Analysis of the arm-body integration.

The second load case that is analysed is the static analysis of the landing. The free body diagram of this load case is shown in Figure 9.6b. Here, F is the reaction force of the landing gear with the ground. This force is quantified by dividing the weight of the drone (2.11kg taken from the budget) by 4. As the drone is on the ground, the flight speed and therefore the drag is not taken into account.

It is important to also perform a dynamic analysis of the landing to prove the landing gear can withstand the landing loads. However, the resources for this were insufficient in this project, and this analysis is therefore postponed to

the post-DSE phase.

The third load case is for when the drone is to ascend with maximum acceleration. The free body diagram of this load case is represented by Figure 9.6c. At maximum acceleration the flight speed is 0. Therefore there is no drag in this load case. For maximum acceleration, the thrust setting is maximum. Therefore, T_3 is 16.21N. For this thrust setting, the rpm of the propeller is 800.4 RPM.

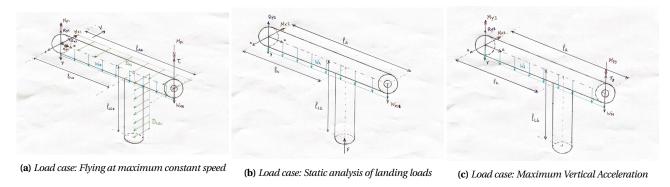


Figure 9.6: Free Body Diagrams Of 3 Additional Load Cases

For these new load cases, a new python programmed tool was set up to calculate the bending stress for a deflection limited to 1mm.

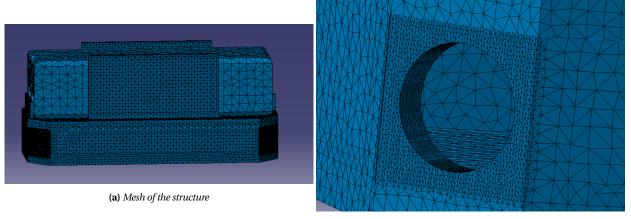
For the first load case, the maximum stress in the arm is calculated to be 5.5MPa. This is much lower than the yield stress including the safety factor (14.6MPa). Therefore it can be concluded that this the current design can withstand this load case. For the second load case, the maximum stress in the arm is 1.6MPa so the structural integrity of the arm is also sufficient for this load case.

For the third load case, the stress in the arm reaches 21.2MPa. This is still below the 26.25MPa maximum yield stress. Therefore, the arm is not expected to fail in the current design, but this is a risky statement as there is no safety factor included. Therefore, in the post DSE phase the arms should be resized accordingly. The inner diameter should increase from 0.75 cm to 1cm and the outer diameter should increase from 1.4cm to 1.6cm. This will result in a maximum stress in the arm of 13.7 Mpa. With this adjustment the total mass of the 4 arms will increase by only 16.4 grams, which is within the budget. Further adjustments to the design are that the arm hole in the frame body should be increased from 1.4cm to 1.6cm and the crater and landing gear holder should be adjusted to fit the arms.

9.6.4. Finite Element Analysis of Frame body

The finite element analysis on the integration of the arms was performed in "Catia". To verify that the program settings are correct, a simple beam was modeled and subjected to a load at one tip and clamped support on the other. The maximum stress given by the program was compared to the analytical solution. The difference in outcome was 10 %, so the solution was considered to be verified. The frame body consists of 3 main parts: 2 parts of the main box and top plate. The case was assumed to carry no load due to low stiffness compared to other parts, so it is not present in the FEA. The battery was modelled, as it is important that the frame does not transfer stress to the battery.

First the model of the frame was discretised with a mesh. The size of the mesh was decreased in areas with high stress gradients or small geometric features. The finite element analysis was performed on a series of increasingly finer meshes, until the maximum stress values converged. The connections of the two frame parts and the battery to the frame were modeled as flexible surface-to-surface connection, which means that that they are firmly connected and can bend together.



(b) Fine mesh near areas of interest

Figure 9.7: Discretization of the model

The analysis was performed with 2 loading cases: Steady flight forward at maximum velocity and maximum acceleration upwards. The static analysis of landing was not modelled in FEM as the calculated reaction forces were lower than the other 2 load cases. The stress in the first loading case can be seen in Figure 9.8a. It is hard to define the support for this loading case, because the forces transferred to the frame are counteracted by the aerodynamic drag on the frame, which is applied over the whole surface of the drone, and is non-uniform. Without the knowledge of the force vector field around the drone body, a few simple supports were tried: rigid clamping of the battery, rigid clamping of the frame sides and support in a form of drone mass inertia. The last one might seem unrealistic, since the drone is not accelerating, but it imitates some aspects of the aerodynamic drag such as acting on all parts of the drone. The inertia condition also resulted in the highest stress in the frame, so it was chosen as a clamping condition for the first loading case. The highest von Misses stress occurs near the arm connection and is 7.97 MPa. With the 10% uncertainty margin in the model the maximum stress is 8.77 MPa, which is lower than the yield stress including the safety factor(14.6MPa). Therefore, under this loading case, the arm frame integration is expected to have the structural integrity to keep the loads. This should however be validated via testing in the post-DSE phase.

For the vertical acceleration loading case, the mass inertia of the drone was used to balance the upward thrust force transferred to the frame by the arms. The results of this calculation can be seen in Figure 9.8b. The maximum stress is calculated to be 24 MPa. This is lower than the yield stress excluding the safety factor(26.25MPa). Therefore the connection is not expected to fail in the current design, but this is a risky statement as their is no safety factor included. Therefore, in the post DSE phase it should be investigated how much further the arm holes should extend into the frame.

In Figure 9.8a and Figure 9.8b it is shown that the von-mises stress is very low (dark blue colored) in the plates that make the center of the drone. Therefore a consideration for the post-DSE phase is to reduce the plate thickness to safe mass.

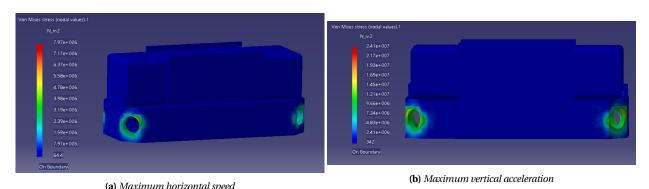


Figure 9.8: FEM analysis of stress in the drone body.

The stress level in both loading cases does not reach the yield stress of PP (26 MPa), however the second loading case comes dangerously close. Also, current model is not detailed enough to include bolts, or other means of attaching two halves of the frame together. Finite element analysis of these features is left for the post-DSE phase.

9.7. Compliance Matrix Structures

Table 9.14 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 9.14 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. These requirements do not appear in the compliance matrix of this department. Note that all risks identified in Table 9.1 were mitigated in the design.

From a market perspective, having the capability of a modular payload is an enormous improvement with respect to other drones. Not only does it open many possibilities for creations of drone shows, it can also potentially make the drones more durable and therefore more sustainable. As mentioned in Chapter 4 the client Anymotion Productions already discards their full drone after 2-3 years when the payload gets outdated.

Furthermore, the structure of the drone is designed such that it will not require maintenance over its 1000 hour lifetime. This is a strength discovered in the market analysis as well.

The power and weight of the megaphone is dependent on the power and propulsion department as well. Therefore it can not yet be verified on a subsystems level.

SP-SYS-4.1 is verified as the arms are sized to keep the maximum stress under the yield stress and the maximum deflection under 1mm.

Sub-department	TAG	Requirement	
	SP-AP-1	The drones shall be able to carry changeable payloads	Yes
Payload	SP-AP-1.1	The light source shall be visible in urban darkness over a distance of 4km	Yes
rayloau	SP-SYS-1.1.1	The drone shall have an RGB Illumination	
	SP-AP-1.3	A megaphone or speaker shall be included in the drones	Yes
	SP-SYS-1.5	Structures shall accommodate power unit	Yes
Frame	SP-SYS -1.6	Structures shall accommodate electronics	Yes
rianie	SP-SYS-4.1	Any structural part of the frame shall not experience plastic deformation under flight conditions	Yes
	SUS-EO-4	The drone shall not break down into small parts	Yes

Table 9.14: Compliance matrix for structures subsystem requirements

Operations Subsystem

The organisation of a drone show faces many operational and logistical challenges. Besides being able to have 300 drones performing choreography safely at the same time, two important challenges are the safe transport of the drones and the conductive charging of the batteries. Operations, however, also involves safety and maintenance. Section 10.1 presents the main functions and risks that the operations department must cover, Section 10.2 presents the design requirements. Then Section 10.3 and Section 10.4 present the methods used to design the required systems as well as the results of the design iterations. Section 10.5 covers the new risks identified and mitigated in the detailed design phase. Finally, Section 10.6 and Section 10.7 present the verification and validation processes of both the tools and the design.

10.1. Functional and Risk Overview of Operations

The goal of the operations department is to optimize 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. As presented in the functional flow diagram and functional breakdown structure in Chapter 3, the main functions to be performed by the operations department are the following:

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

These functions were translated into requirements which are presented in Section 10.2. Note that for this design phase, operations has been divided into five sections:

- · Landing pad design
- · Landing gear design for stacking
- Logistics
- Maintenance
- Safety procedures

The landing pad and stackability will be treated in this chapter while, maintenance will be covered as part of the RAMS characteristics in Section 12.3 and logistics 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 department. It shows their likelihood and consequence score and the mitigation response which should be implemented in the design. Note that the scoring metrics have been explained in Chapter 5. 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 subsystem design phase and are 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 trans-	Very low	Catastrophic	Have some spare back-up drones, avoid damage at
	port			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	Very low	Negligible	Design landing legs with draft angles and tolerances
	stuck			to prevent being stuck.
31	Event site can't power landing	Moderate	Moderate	Transfer risk to customer/ 3rd party company. Give
	pads/ground station			estimation to them of power needed for operation.

10.2. List of Requirements Operations

Table 10.2 presents the requirements related to the operations department. 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 11 or Chapter 12.

Sub-	TAG	Requirement
department		
	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.
Landing pad	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
	101-313-3.7	charged within 60 minutes.
	OP-AP-2	The drones shall be suitable for mass transport.
	OP-AP-2.1	The drones shall safely be stacked on each other.
Stackability	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.

Table 10.2: Requirements related to operations department.

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

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

The autonomous charging is also something that current drone shows do not provide, hence this is a good opportunity for Starling as it can provide versatility in the organisation of a drone show. In the preliminary design phase [4], 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 a functioning conductive charging landing pad is outside the scope of this project, hence it will not be designed in full detail. Starling will be equipped with the possibility to charge conductively, in addition to the usual charging method via a cable battery charger. However the landing pad will not be provided along side this drone's design. These kind of landing pads are already available on the market, but are very expensive. Skycharge sells their outdoor landing pad for $\{6,000\}$ per piece [104]. It is possible that in-house development will be cheaper. It is estimated that a price of $\{4,000\}$ per landing pad could be a possible amount as the $\{2,000\}$ is estimated to be the profit of Skycharge. The value of this investment will be discussed in Chapter 15.

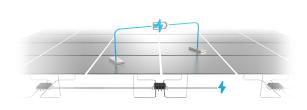
The general technique of conductive charging will be discussed in Subsection 10.3.1 and the method of sizing the pads in Subsection 10.3.2.

10.3.1. Technique of Conductive Charging

In this section, conductive charging of 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 separation between the tiles makes a circuit possible. The charge monitoring system determines which 'side' of the circuit the tile has to be [105]. The pad can be equipped with detection sensors that detect if there is a short circuit caused by water or other objects. As mentioned in Chapter 7 the charging voltage is 14.8V, so it is safe for humans. The concept of conductive charging is already in use for laptop charging as well as drone charging, by the companies Energysquare (Figure 10.1a) and Skycharge (Figure 10.1b).

For designing the tiles, gutters should be implemented in between the different tiles. This is to mitigate risk 27 and fulfill requirement CCE-SYS-3.1 of the landing pad to work during rain. These gutters shall drain the water from the pad. The size of the gutters is however not yet defined.



(a) Power by Contact concept from Energysquare [105]



(b) Autonomously charging pad by Skycharge [104]

Figure 10.1: Applications of conductive charging.

To create the circuit, the 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, due to their high durability and stable electric connection [106]. 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



Figure 10.2: The design of Pogo pins.[106]

pad are not perfectly flat or if vibrations or shocks occur. If insufficient contact occurs, this means that autonomous charging is not possible. Pogo pins mitigate this risk as they are spring-loaded. The risk of insufficient contact is added as Risk 39 to the new risk table for Operations in Section 10.5, including the mitigation by using a Pogo pin. Additionally, using Pogo pins makes it possible to shape the tiles of the landing pad slightly curved so rain will not remain on the landing pad surface but can flow in the direction of the gutters. This makes the draining of rainwater more efficient and makes sure that CCE-SYS-3.1 is fulfilled. However, the steepness of the slope of the tiles has not been determined yet and is left as a recommendation for the detailed design of the landing pad, as stated in Chapter 17.

An example of such a pin can be seen in Figure 10.2a. 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 than the back drill and bias tail and guarantees a smooth slide of the plunger. [106]

The drone has four legs, which are all equipped with a pin. This can ensure even more that charging is possible, if for example, one pin malfunctions. However, how this system would work in detail is recommended to be investigated in a more detail design phase as mentioned in Chapter 17.

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 [106]. The characteristics have been determined by looking at high-current Pogo pins that are available to buy [107]. A Pogo pin with a current of 9A was chosen and this was only modified to be a bit longer to better fit into the landing gear. This is because when the drone lands on the four pins, it should not be compressed until most of the weight is taken by the plastic leg, as the electrical connection must be firm for charging. The pin has a gold layer as that improves conductivity and is good in terms of corrosion [106]. This helps to meet requirement CCE-SYS-3.2.

10.3.2. Sizing of the Landing Pad

In this section, the model to determine the size and mass of the landing pad is discussed, which can be used to estimate how much time, volume and man hours will take to deploy and transport all landing pads. The size of the landing pad is dependent on the largest distance between the legs of the drone, in order for the drone land in any possible orientation. This implies that the closer the legs are to each other, the smaller the landing pad can be. This is desired in terms of logistics, as the pad will then take up less volume and weigh less. The smallest possible distance is thus desired. The model uses the following:

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 Brass with gold layer Material Mass (g)

Table 10.3: Characteristics of chosen Pogo pin.

- The electronics inside the landing pad are not designed hence they are assumed to have a mass of 3 kg. This consists of among others: transformer, fan, cables etc. This is an indicative number based on an existing landing pad [104], but it is still preliminary and should thus be investigated and verified after this DSE.
- A safety factor of 1.25 has been applied to the loads and landing precision in order to account for an increase in mass of the electronics and to avoid that the drone misses the pad during landing. The risk of missing the landing pad has been added as Risk 37 in the risk register in Table 10.9, as well as the mitigation response of increasing the size of the landing pad.
- The surface plate of the landing pad will be made from stainless steel type 304, similar to [104]. This is because it should function outside in bad weather conditions. Type 304 was chosen, because it is the most dominant grade used and easy to shape. The material properties for stainless steel 304 are: $\rho = 8,000 \text{ kg/m}^3$ and E = 193 GPa [108].
- The mass of the landing pad is determined by adding the mass of the electronics, steel surface and plastic structure together.
- The material of the rest of the landing pad case is Polypropylene (PP). Similar to the frame of the drone, this material was chosen, following the same conclusions as in Table 9.4. PP is the most sustainable material on the list. Depending on the final design, it should be re-evaluated whether this is indeed the best material for a conductively charging landing pad.
- Besides the distance between the legs, the size of the landing pad is determined by the positioning accuracy of 20 cm, which was taken from Chapter 8.
- The loads on the pad are limited to the mass itself and the drone during landing, which is assumed to land with a vertical impact of 2g's. This is explained in more detail in Subsection 10.4.1.

From the last bullet point, it was determined that the loads on the entire landing pad itself are really small: namely 177.5 N. When the normal stress per side plate was calculated, the maximum stress was lower than 0.05MPa for both Euler buckling and normal compression and thus the thickness of the side plates is mainly determined by the possibilities of manufacturing and not by the loads. This thickness will be explained in more detail in Subsection 10.4.1.

The size of the tiles is based on the smallest distance between the legs and the size of the landing pad to make sure that in every possible orientation and position, all four landing legs will be positioned on a different tile and an electrical circuit is possible.

Iteration Results: Landing Pad Size

Table 10.4 presents the results of the sizing iteration of the landing pad. Six iterations were performed initially, but the sixth iteration was accidentally performed a bit too soon. The distance between the legs, given by the structures department, changed after this iteration so another iteration was executed only for the landing pad size.

During the iterations, several aspects changed. Between iteration 1 and 2, the material of the sides and bottom of the landing pad changed from ABS to PP as the structures department had determined that this was a better material regarding cost, mass and sustainability. That is also the reason why the thickness of the plastic has changed, as ABS can be produced with a smaller thickness than PP. The thickness of the steel sheet is determined from standard gauges from

Iteration	Drone mass (kg)	Mass of electronics (kg)	Distance between landing legs (m)	Thickness steel surface (mm)	Thickness plastic (mm)	Area landing pad (m²)	Mass landing pad (kg)	# of tiles	Size tile (m²)
1	2.25	5	0.490	1.11125	1.016	0.9801	15.2374	9	0.1082
2	2.25	5	0.364	1.11125	3.200	0.7465	14.3466	16	0.0462
3	2.19	5	0.333	1.11125	2.400	0.6939	13.0884	16	0.0430
4	2.11	5	0.356	1.11125	2.400	0.7329	13.5293	16	0.0454
5	2.11	5	0.364	1.11125	2.400	0.7465	13.6832	16	0.0462
6	2.11	3	0.364	1.786	2.400	0.7465	16.0866	16	0.0462
Final	2.11	3	0.373	1.786	2.400	0.7613	16.3372	25	0.0301

Table 10.4: Preliminary design iterations of landing pad

literature [109] and changed between iteration 5 and 6, as the firstly chosen thickness appeared to be less common.

The size and mass on the landing pad and the number and size of the tiles changed dependent on the given distances by the structures department as it is mainly dependent on the size of the payload. The structures department determined the straight distance between the legs, but the longest distance is between the landing legs that are diagonally opposite to each other. This distance was determined by using the Pythagoras theorem with the other two given distances. In the last iteration the distance was just too small so an extra tile per row and column needed to be added. After seven iterations, this gave the final result for the preliminary mass and size for the landing pad that is visible in the last row of Table 10.4. The deployment of the landing pad will be discussed in Chapter 14.

As the landing pad is not fully designed, it is not possible to determine the amount of power it would require since efficiency is not determined nor how fast the landing pad can charge the battery. Without taking this into account, the charging time can be calculated with Equation 10.1.

$$Time = \frac{Battery Capacity}{Charging Current}$$
 (10.1)

The battery capacity is determined in Chapter 7 and is equal to 7,000mAh or 7Ah. According to Table 10.3, the current can be up to 9A. Assuming a range of 50-100% efficiency, this gives a charging range of 0.78 - 1.56 hours. This means that with a current of 9A, the efficiency of the circuit should be at least 77.8% to satisfy requirement POP-SYS-3.7. The charging time is however also dependent on the amount of current the wire inside the drone's structure can withstand. If the current has to be lower, the charging time will increase. Therefore, depending on the capacity of the wires and the efficiency of the landing pad, requirement POP-SYS-3.7 will be verified for conductive charging or not. This is left as a recommendation for further design as mentioned in Chapter 17.

10.4. Design for Operations: Stackability

According to the sub-requirements of OP-AP-2 presented in Table 10.2, the drones shall be suitable for mass transport, which involves being stackable and stored in rigid containers. In the preliminary design phase [4], 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

Instead of landing on its payload, Starling will carry a landing gear 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 damage to the payload** during landing. The possibility of a protective case around the payload, strong enough to support landing was rejected, since it would hinder the payload modularity and the ability of carrying widely different future payloads. Damage on the payload during landing is identified as Risk 41 (described in Section 10.5) and is mitigated with the use of landing gear.
- 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) which can go up to 600gr. These require different lengths since the heavy payload module is significantly larger than the light payload one¹. As discussed in Chapter 4, the design should aim for ease of operations therefore stackability is a key aspect. Since stackability aims to store drones optimizing the space, this feature will be designed for the short landing gear. The long landing gear will only be used during shows. The implementation of stackability on logistics will be discussed in Chapter 14.

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

Table 10.5: Sets of landing gears and their general characteristics

The exact lengths will depend on the size of the other subsystems of the drone and therefore they will be established only after the iteration process. It is estimated that changing the landing legs of a drone will take less than 5 min, since their attachment method is easily removable.

Landing Gear Model

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

- The landing gear is 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. It is made out of PP, like the frame, in order 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 connector, which
 will allow for conductive charging. This pin is cylindrical and made out of brass with a maximum diameter
 of 9.47mm (Table 10.3), which 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.
- 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 bonded to the PP tube while the landing legs will fit into an attachment piece bonded 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

¹Note that the size of the pyrotechnics is not yet known, however it is desired that the clearance with the landing gear should be as large as possible

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. Therefore, it is assumed that all landing legs take the same load.

The total force on the drone upon landing was assumed to correspond to a vertical impact of 2g's. This was assumed due to a lack of information on the control software, the landing procedures and loads of the drone. It is considered to be an overestimation of the landing which 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 stack them one on top of each other. This means that the landing legs must carry the weight of the drones above. The number of drones that fit in a carrying structure depends on the size and weight of one drone (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 drones fit in a stack, which depends also on their size. Note that only the short landing gear needs to carry the stackability loads as mentioned in Table 10.5, since long landing legs are only use for flight.

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 [92]. Note that this decision was made during the design phase therefore some early iterations assumed a lower possible thickness. Then, the 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 10.2 [85].

$$P_{cr} = C \cdot \frac{\pi^2 \cdot E \cdot I_{xx}}{I^2} \tag{10.2}$$

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 [85].

Note that the number of drones stacked on each other also makes part of this model and can vary between iterations. This is because this number 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.

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.

Buckling Mass of LG set Iter Height Set Drone Outer diame-Thick-Stress LG (cm) stress (MPa) -ation mass ter(cm) ness on leg (kg) (MPa) (kg) tube (mm) 7.800 Short 2.00 0.700 1.0 13.40 1.952 0.024 1 Long 2.00 0.700 1.0 24.40 0.651 2.352 0.044 Short 2.25 1.452 3.2 13.39 0.364 23.797 0.071 2 2.25 3.2 7.174 Long 1.452 24.39 0.121 0.116 2.25 Short 1.292 2.4 15.40 0.435 15.145 0.060 3 2.25 Long 1.292 2.4 26.40 0.174 5.154 0.091 2.19 1.292 2.4 11.90 0.508 25.364 0.050 Short 4 2.19 2.4 Long 1.292 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 2.11 Short 1.404 2.4 15.80 0.531 17.449 0.071 Final Long 2.11 1.404 2.4 23.00 0.1778.234 0.094

Table 10.6: Design iterations of landing gear design

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 $1 \in$ and of the production of the extruded tubes is estimated to be about $1 \in$ per set of landing legs considering a batch size of 1200 tubes (300 drones) using the same method as explained in Subsection 9.3.3 [93].

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 15.8cm long while the long set, 23.0cm 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

An attachment part bonded to the bottom of the arm will be used to attach the removable landing legs to the frame. This part is made out of PP and has a hole which aligns with a small hole on the arm to allow for the charging cables from the charging pin to enter the inside of the arm frame. 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 compress to fit on the attachment part and expand once the pins reach the holes locking the gear into place. The PP body of the leg lies on the attachment part therefore it takes the compressive forces. The integration will be explained in detail in Chapter 11. A representation of the attachment can be seen in Figure 11.2.

The total mass was computed to be 2.94g by a simple model of the part which will be verified in Section 10.6. The spring pin was not chosen in detail and it's left for a more detail design phase in Section 17.2.

Note that a risk raises from this new attachment method, which consists of an unwanted loose 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 Section 10.5. 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.

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 bonded to the top of the arm as shown in Figure 10.3. 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 damaged by excessive compression during stacking. To prevent this, the crater is designed such that 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, this is shown in Figure 10.4. In addition, the scope of the pins is not to fully prevent the lateral movements of the stack, indeed under a high lateral force the pins might get damaged, however it is the role of the carrying structure to prevent the tilting of the stack such that no high lateral loads are applied to the pins.



Figure 10.3: Top view of crater attached to top of drone's arm

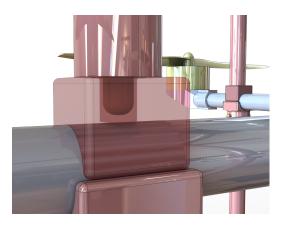


Figure 10.4: View of inside of crater with landing leg of drone above inserted. Note that the leg lies on the crater while the Pogo pin does not touch the bottom.

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

Iter- ation	Outer radius of arm (cm)	Height of notch (mm)	Width and depth of notch (mm)	Mass craters (g)
1	/	1	/	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

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

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, which was estimated using [93].

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 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. This is also beneficial from a market perspective, as described in Chapter 4.

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, so the carrying structure must be raised by hand. Therefore there are two main limitations to the carrying structures: their weight and height. If the stack

of drones is too heavy or the structure is too high, it is difficult for an employee to carry the drones to the deployment location. Repeatedly carrying these structures for a couple hundred meters can cause injuries to the worker. This is a risk, which has also been added as Risk 38 to the risk register in Section 10.5. The following paragraph discusses the mitigation response for this risk.

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 [110]. They set guidelines to employers to limit the physical works that can cause back injuries. For this design, the lifting 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 position. This method is an ISO standard and also recommended by the Dutch government[111]. Since the online tool provided by the "Ministerie van Sociale Zaken en Werkgelegenheid" is in Dutch, the equivalent tool from the Canadian Center for Occupational Health and Safety has been used [112], note that they apply the same internationally recognised method.

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 when holding the load and in between 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 (this is because 150cm is the next option in the NIOSH method, so anything below 125cm rounds to 100cm).
- The vertical distance that the load is displaced from standing on the ground to transport height is of 40cm. This is considered enough height to walk around the field while safely carrying the structure.
- The lifting will be done several times within the same hour for about 5 min each time (for now it is assumed that one worker can place more than one stack of drones per hour, refer to Chapter 14 for a more detailed explanation once the stack has been designed).
- The structure allows for a good grip with two hands, no twist of the upper body is needed and the lifting is done while standing up.

With this method, it was determined that the maximum weight of the stacks must be 12.53kg while 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. Note that what these regulations imply for the landing pad that exceeds the 12.53kg, will be explained in Chapter 14.

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 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 can 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. This will be mentioned in Chapter 14.

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. This structure should allow for a 'secure grip' as mentioned in the assumptions of the load.

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.



Figure 10.5: Render of three Starling drones stack on top of each other via their landing legs

Iteration Results: Carrying Structure Dimensions

The design iterations are shown in Table 10.8.

Iter Drone mass Height drone Drones per stack Height stack (m) Weight stack (kg) Stack area (mxm) -ation (kg) (cm) 2.00 18.76 1.031 11.74 0.96×0.96 2 2.25 18.75 6 0.890 12.02 0.8×0.89 3 2.25 23.70 0.896 10.50 0.73 x 0.8 5 0.836 4 2.19 20.10 6 12.47 0.78×0.85 5 2.11 18.63 6 0.770 12.33 0.735×0.8 2.11 12.53 25.05 6 1.17 0.63×0.72 Final

Table 10.8: Design iterations of carrying structure dimensions

So, as shown in Table 10.8 the carrying structure will hold six drones stacked on each other which will weight 12.53kg and be 1.17m tall. This fulfills requirements OP-AP-2 and OP-AP-2.1 . Figure 10.5 shows a indicative stack of 3 drones. 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.

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 fitting 4 carrying structures in a square configuration would require a box of 1.44x1.26x1.17m, the drones would weight 50kg to which the weight of the box needs to be added. Many different off-the-shelf transportation boxes are available, like for instance in [113], however it is also possible to personalize these boxes, this is left as a further consideration of the design in Chapter 17. Note that one transport box will be too heavy for one worker to move it, these boxes would only need to be unloaded from the truck to an unpacking area and not really be moved by hand long distances, for this reason it is suggested that the boxes are moved by two or more workers and, for instance, that they have wheels for easier transportation.

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 and consequence scores. Table 10.10 shows how these risks were mitigated and provides their new scores.

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

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

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

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

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 [85].

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}	Е	Halve E, expect σ_{buck} to 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	Number 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	Input to	Test	Outcome	V?
	test	vary			
VT-OP-U.8	m_{steel}	l_{pad}	Double the size of the land-	For l_{pad} = 0.856m, m_{steel} = 6.515kg, for l_{pad} =	Yes
		,	ing pad, expect mass of steel	1.712kg, m_{steel} = 26.062kg which is times 4.	
			surface to increase by 4.		
VT-OP-U.9	σ	t_{PP}	Double the thickness of plas-	For t_{PP} = 2.4 mm, σ = 0.0235MPa, for t_{PP} = 4.8	Yes
			tic sides landing pad, expect	mm, σ = 0.0117MPa, which is halved.	
			normal stress per plate to halve.		
VT-OP-	l_{pad}	Landing	Set landing precision to 0, land-	For landing precision = 0m and distance between	Yes
U.10	,	precision	ing pad size should be equal	legs = 0.3561m, l_{pad} = 0.3561m, which is indeed	
			to maximum distance between	equal.	
			legs.		
VT-OP-	# of tiles	Min. d_{legs}	Halve minimum distance by	For $d_{legs} = 0.22$ m, # of tiles = 4 and for $d_{legs} =$	Yes
U.11	next to		two, expect # of tiles next to	0.11m, # of tiles = 8.	
	each other		each other to double.		
VT-OP-S.5	m_{pad}	Max. d_{legs}	Double max. distance between	For $d_{legs} = 0.3561$ m, $m_{pad} = 13.5293$ kg. For	Yes
	,		legs, expect mass of pad to	$d_{legs} = 0.7122$ m, $m_{pad} = 21.8252$ kg, which is an	
			increase with less than double.	increase with factor 1.6132.	

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 [103], 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 Polypropylene parts and not extra components like the pins. For the computation of the moment of inertia a margin of \pm 2% was chosen, since it is a closed formula that depends on a small number of variables, however machine error was expected. For the masses of the parts, a higher margin of \pm 10% was chosen. This is due to the ap-

proximations 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.

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

Table 10.13: Calculation verification of masses and moment of inertia

Validation of Tools

Due to how specific the model is to the design it is not possible to validate it yet 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, 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 Chapter 17.

For the landing pad, this is a much more expensive structure to validate by testing a full-scale prototype. In addition so far this system as only been preliminary designed. The conductive charging could for instance be validated by making a small circuit with the battery and only two tiles and two pins to check the functioning of the system. This can however only be done after the landing pad has been designed in full detail.

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 11 and Chapter 12. In particular, requirement OP-AP-6 states that the take-off zone shall be at most $1m^2$, this is partially fulfilled by the landing bed being $0.7631m^2$, however this is not the entirety of the take-off zone and it will therefore be verified in Table 11.5. Similarly OP-AP-2.3 which requires the total volume of the drone will also be verified in Chapter 11.

Table 10.14: Compliance matrix for operations department requirements

Department	Tag	Tag Requirement		
	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	
Landing pad	CCE-SYS-3.2	The drone shall be able to recharge autonomously on the landing pad	Yes ²	
Landing pad		between preparation and show		
	POP-SYS-3.7	The energy storage should be fully	Yes ³	
	101-313-3.7	charged within 60min.	165	
	OP-AP-2	The drones shall be suitable for mass transport	Yes, stacks of 6	
			drones carried by	
			one worker	
	OP-AP-2.1	The drones shall safely be stacked on each other	Yes, stacks of 6	
Stackability			drones	
	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		Yes, long landing	
		20cm x 20cm	gear set ⁴	

²This is also verified in Chapter 7 from a power subsystem perspective.

³This is dependant on the wires (should take a current of at least 9A) and requires a landing pad efficiency of at least 77.8%

⁴Note that this is only a verification of the height of the payload, however the width and length will be verified in Table 11.5.

Subsystem Integration

Chapter 6 to Chapter 10 presented the overview and results of each subsystem design. This chapter explains how all subsystems integrate with each other. Section 11.1 presents the requirements and risks that are taken into account in the integration process. Section 11.2 explains the integration of each subsystem and Section 11.3 gives an overview of the final design. Note that the process of integration was already started during the subsystem design phase and that the final results presented in the subsystem design chapters are from after integration.

11.1. Requirements and Risks Related to Integration

In Table 11.1 the requirements related to integration are shown. These requirements have not been (fully) answered in the previous chapters and will discussed in this chapter. The compliance matrix for these requirements will be shown at the end of Section 11.3.

Table 11.2 presents the risks with respect to integration that have to be mitigated. These risks were identified during the subsystems design.

TAG Requirement

SP-AP 1.4.3 Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm

OP-AP-6 The area off the take-off zone shall be at most 1m2 per drone

OP-AP-2.2 The volume of the drones shall not exceed 0.5m^3

AD-AP-2 The drone shall be able to fly in rainfall up to 10mm/hour

SR-SYS-8 The drone's electronics and propulsion system shall remain operational under raining conditions of up to 10mm/hr.

SP-SYS-6 The drone body should be tolerable to transportation and in-flight vibrations

Table 11.1: Requirements related to integration

Table 1	11.2:	Risks	related	to	integratio	n
---------	-------	-------	---------	----	------------	---

ID	Risk	LS	Reason for likelihood	CS	Reason for consequence
50	arms misaligned in body	4	For 300 drones 1200 arms need to be attached to the frame, likely that a few	3	Might be less strong, may alter controls and drone performance
			arms will be misaligned.		
51	Arms gets loosend from body	4	Generally drones deal with vibrations. Vibrations could loosen the arm -body bonding when thread is used	3	When 1 arm comes loose their will be enough thrust for an emergency landing. However emergency landing not guar- anteed as additional damage to frame is unforeseen
42	Loosen of attachment of	3	Tolerances can lead to a non tight	2	Misalignment can hinder stackability
	landing gear		attachment		

Table 11.3: Mitigation responses for identified risks.

ID	Risk	Mitigation response	LS	CS
50	Arms misaligned in body	Add thread to the arms to make assembly easier.	1	3
51	Arms gets loosend from body	Add epoxy resin or "Loctite" solutions to fasten joint	2	3
42	Loosen of attachment of	Ensure tight lock by right size pins or an O-ring type seal between the legs and	1	2
	landing gear	attachment piece		

11.2. Subsystems Integration Overview

Starlings frame as presented in Chapter 9 is the basis of the integration. All subsystems are to be facilitated by the frame and protected against the weather by the casing. In this section the integration of each subsystem is presented by department. An overview of the fully integrated drone is shown in the hardware diagram in Figure 11.1. Here, all drone parts have been assigned a number to which is referred in the text.

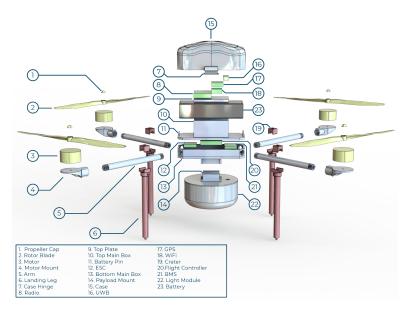


Figure 11.1: An exploded view of the integrated final design

11.2.1. CCE Integration

The CCE subsystem consists of five PCBs that need to be incorporated in the drone. These are the flight controller, GPS, Wi-Fi, Radio and UWB. These parts are represented by numbers 20, 17, 18, 8, 16 respectively. The flight controller is placed in the middle of the frame inside the main box. This is done such that the flight controller experiences as little in-flight disturbances due to for vibrations and manoeuvres as possible during flight. All other PCBs are put on top to have a better signal with respect to the satellite and ground stations, as explained in Chapter 8. In the iterations for the frame design the GPS was initially put inside the main box. During integration the GPS was moved to the top and the frame dimensions were adjusted as explained in Chapter 9.

11.2.2. Power Integration

The power subsystem consists of 3 parts. The battery, the ESC and the BMS. The BMS will be investigated in detail in the post DSE phase, as mentioned in Chapter 7 and described in Chapter 17. It is represented by number 21 and assigned a place in the main box of the frame. The reason for its placement is that all cables from the motors and landing gear, through which the battery is recharged as explained in Chapter 10, end in that box. The ESC, represented by 12 is placed in the main box for that same reason.

The battery is represented by number 23 and is put on top of the main frame box, as explained in Chapter 9. As the drone is designed for light shows, the payload should go on the bottom. Therefore the battery can only be placed on the top part of the drone. As the CCE components need to be all the way on top the battery is placed as shown in Figure 11.1. The advantage of this battery placement is that the center of gravity is approximately in the same plane as the center of thrust. Therefore the force that rotates the drone becomes more efficient, due to a smaller moment of inertia, and control and stability characteristics are improved.

The battery is fixed in its own compartment such that it can not move around. This compartment is made 10% higher than the battery thickness as explained in Chapter 9. This space should however be filled by a compressible material to make sure the battery can not move up and down. This will be further explored in the post DSE-phase as explained in Chapter 17 as the current team was lacking time resources.

The pin indicated with 11 can be pushed down, after which the battery can slide in. The pin is spring loaded, so it will pop up after the battery is positioned and secure it in place. A detailed design of this pin is to be performed in the post-DSE phase as explained in Chapter 17. It is important that this pin is designed such that it has the structural integrity to keep the 580 grams battery in place.

11.2.3. Landing Gear Integration

Two sets of landing gear are designed for the drone as explained in Chapter 10. This means there must be a detachable connection between the landing gear and the frame. For the detachment method the risk of loosend attachment of the landing gear(Risk 42) must be taken into account. Furthermore, each landing leg includes a charging pin which realises wireless charging. A cable has to go up through the leg to be connected to the power system.

The landing gear can be either attached to the arms or to the main body of the frame. Attaching it to the main body however requires external structures. This is because the landing gear needs to mounted away from the main body to include the payload by requirement SP-AP 1.4.3. This attachment option adds mass and makes the drone less aerodynamic, therefore attachment to the arms is first explored.

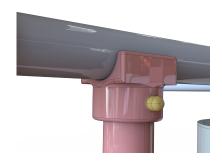
Attaching the landing legs to the arms introduces the risk that the arms brake at collision with the ground. To study the viability of this option a static analysis of the landing was included in 1 of the load cases calculated through in Chapter 9. The structural integrity of the arm was sufficient as the maximum stress in the arms for this loading case was 1.6MPa. It is however very important to also include a dynamic analysis of the impact at landing to verify that the arms can withstand the loads. Unfortunately, due to lack of resources, this analysis has to be postponed to the post-DSE phase as explained in Chapter 17.

The landing legs are placed far enough from the body to make place for the 20x20x20 cm payload with a margin of 1 cm. They will not be placed further outwards to limit the size of the required landing pad that was sized in Chapter 10. This resulted in a distance between the front 2 landing legs of 211mm and a distance of 307mm between the front and aft landing legs. With this distance requirement SP-AP 1.4.3 is satisfied.

Initially, the landing gear was going to be screwed into the arm and this mechanism was used to perform the subsystem design iterations. However, this raised a structural integrity concern with the large size of the hole required on the arm, and the risk of loosening due to vibrations. 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 is to be bonded via a to be determined type of epoxy resin 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, into the frame body, and connected to the BMS. 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. To prevent rotation of the landing gear inside its attachment a spring loaded pin is incorporated. Both sides of this pin are compressed after which the landing gear is put in position. Once the pin and the holes in the attachment align the pin will elongate again and secure the landing gear in place. This mechanism is shown in Figure 11.2 and Figure 11.3.

To mitigate risk 42, a tight O-ring is put into place to tightly seal the space between the leg and the attachment piece. The landing leg touches with the PP attachment. Therefore the compressive forces are not taken up by the spring loaded but but by the attachment piece and the arm.

This attachment mechanism was designed after the subsystem design iterations were concluded. As shown in Chapter 10 the added mass and cost of this new mechanism fitted within the margins. Note that the spring pin was not chosen in detail and it's left for a more detailed design phase in Section 17.2.



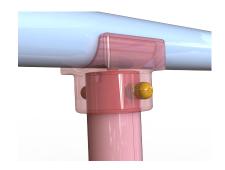


Figure 11.2: Landing gear attachment

Figure 11.3: Landing gear attachment

via the PP part bonded to the arm and spring loaded pin, outside viewvia the PP part bonded to the arm and spring loaded pin, inside view

In the iterations for the the landing gear design the height was determined based on the height of the drone body, including payload. This was done to ensure stackability to meet requirement OP-AP-2. However, during integration miscalculations in the height were spotted for which the length of the landing gear had to be adjusted. These miscalculations originated from not taking into account the height of the electronics, the increased height of the casing due to its shape and the height of the payload mount that was not taken into account. The final length of the landing gear is 23 cm as presented in Chapter 10.

11.2.4. Propulsion System Integration

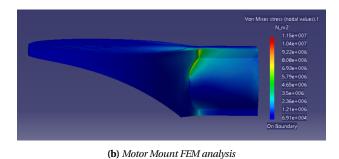
The motors must be mounted onto the arms onto which the propellers are attached. As the arms are circular tubes this cannot be done directly. Instead a mount is needed. In the mass calculations of the structures subsystem an estimation of the mass of the motor mount is made from iteration 4 onwards. For the iterations a simplified model of the mount is used. The mount was modelled in "SolidWorks" as a circular tube that fit onto the arm attached to a circular disk with the diameter of the motor. This gave an initial mass of 10 grams per mount.

After the iterations a more detailed design of the motor mount was made as presented in Figure 11.4a. The mount is made of PP and has a mass of 8.38grams each as given by the modelling tool. The strength of this mount is verified using the Finite Element Analysis of "Catia" as presented in Figure 11.4b. The analysis shows that a maximum stress of 11.5Mpa occurs in the mount when loaded with the maximum thrust force of 16.21 [N]. This is below the maximum yield stress including the safety factor (14.6MPa) as presented in Chapter 9. Therefore it is expected that the motor mount has sufficient structural integrity to withstand the loads. The analysis needs to be validated using testing in the post DSE phase.

The mount is to be permanently screwed onto the end of the arm to avoid misalignment and ease the manufacturing procedure. To ensure the mount does not get loose as a result of vibrations "loctite" [114] or epoxy resin should be used to bond the connection.

The mount will be produced via injection moulding as that is the best production method for the complex shape of the part. With this method, the estimated cost for 4 mounts(so per drone) is $72 \in$ as determined by the "Granta" tool [93] that was also used and explained in Chapter 9.





(a) Motor Mount Design

Figure 11.4: Motor Mount design and analysis

An unbalanced motor introduces axial loads onto the arm. To meet requirement SP-SYS-6 a vibrational analysis is performed on the propeller-motor-arm integration. For this analysis the continuous system is converted into an equivalent discrete system. In this system the arm is modelled as a massless linear spring connector and the mass of the motor, propeller and arm are lumped into a mass component at the top of this beam. The mass of the landing gear is neglected in this analysis. It is assumed that all the deformation is in the connector and that the unbalance in the motor causes harmonically forced undamped vibrations.

The equation of motion in Equation 11.1 follows from the free body- and kinetic diagram, in which X represents the axial displacement and F_0 the amplitude of the forcing load. The deflection as a function of time is given by Equation 11.2 and follows from solving this equation of motion, after noticing that the forcing- and natural frequency, given by Equation 11.4 and Equation 11.5 are not the same and assuming the movement starts from rest. The critical case for the vibrational analysis is the point were the natural- and forcing frequency are closest to each other. This is the case when the forcing frequency of the motors is maximum, or 7643RPM(800.6 rad/s), as given in Equation 11.5. The natural frequency is 5123 rad/s, calculated using Equation 11.4. In this equation A is the area of the cross-section of the arm and m_c consists of the mass of the propeller, motor and arm.

$$\ddot{X} + w_n^2 X = f_0 \cos w_f t$$
 (11.1)
$$X(t) = \frac{f_0}{w_n^2 - w_f^2} \cos w_n t + \frac{f_0}{w_n^2 - w_f^2} \cos w_f t$$
 (11.2)

$$f_0 = \frac{F_0}{m_c}$$
 (11.3) $w_n = \sqrt{\frac{K}{m_c}} = \sqrt{\frac{EA}{LB \cdot m_c}}$ (11.4) $w_f = 7643 \left(\frac{2\pi}{60}\right)$ (11.5)

The stress in the arm caused by the unbalance in the motor is given by Equation 11.6 and is dependent on the maximum deflection. In this equation E is the E-modulus of the polypropylene material the arm is made of. The offset between the center of gravity causing the unbalance of the motor and resulting in this deflection is given by Equation 11.7 and is derived from the radial acceleration. In this equation m_{rotor} includes the mass of the rotating part of the motor and the propeller.

$$\sigma_{arm} = \frac{E \cdot X(t)}{LB}$$

$$O = \frac{\sigma_{arm} A}{m_{rotor} w_f^2}$$

$$(11.7) \qquad \sigma_{arm_{max}} = F_0 \frac{\sigma_{max}}{\sigma_{arm}}$$

$$(11.8)$$

To calculate the offset for which the arm would fail a python programmed tool is set up. This tool implements all

equations above to calculate the offset. No information is available for the mass fraction rotor and stator of the motor. Therefore for the critical case it assumed the whole motor rotates.

In the tool F_0 is given an initial value of 10. This outputs a certain stress σ_{arm} . As their is a linear relation between the forcing load and the response, the maximum stress in the arm is given by Equation 11.8 where σ_{max} is the yield stress of the material polypropylene. The critical offset for which the arm will fail is then computed using this value and is 42.8mm. This offset is very large and is not expected. The maximum deflection for which the arm will fail occurs when F_0 is 0.7. The axial deflection of the arm for this situation is given by Figure 11.5a.

A second aspect of the vibrational analysis is fatigue. The loading cycles of the arm for a 1000h flight hours goes into the millions, as the propeller rotates with 7643RPM. However, as the arm is loaded to only 0.32% of the maximum stress, it is concluded that failure of the arms due to exceeding the loading cycles is not likely to occur. Furthermore, with this additional axial stress the maximum stress in the arm is still well below the yield stress and will therefore not fail either. With this analysis requirement SP-SYS-6 is complied with with respect to the in-flight vibrations. Nothing can be concluded for the transportation vibrations as this depends on the to be determined carrying structure and the road conditions.

To verify the used tool, first the linearity of the response with respect to the forcing load is investigated. For $F_0 = 10$, $X_{t_{max}} = 6.417 \cdot 10^{-6}$ and for $F_0 = 20$, $X_{t_{max}} = 1.253 \cdot 10^{-5}$. Indeed the maximum deflection doubled and the assumption is validated. The next validation step is plot the response and see what happens when the natural frequency is almost equal to the forcing frequency. In this situation "Beats" phenomena is expected, which is indeed the response as visible in Figure 11.5b.

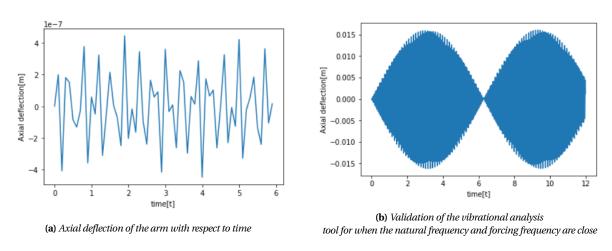


Figure 11.5: Vibrational analysis of arm-motor mount integration

11.2.5. Structures Integration

As introduced in Chapter 9 the frame consists of 4 parts. The main box, which is made up by parts number 10 and 13, the top plate indicated by number 9 and the arms indicated by number 5.

The arms are to be permanently fixed inside the frame [4]. To make sure the arms are not misaligned in the body (Risk 50) thread is used. To ensure the arms will not get loosend from the body (Risk 51) "loctite" [114] is used. The arms are attached under a 45 degree angle with the body. This is done such that required arm length, including the propeller radius and clearance to the body, can be minimised. This will help to meet requirements OP-AP-6, OP-AP-2 and OP-AP-2.2 The arms are made 5mm longer for this attachment mechanism. Whether this 5mm is enough margin to ensure the arms stay attached to the frame should be verified by analysis and testing in the post-DSE phase, as described in Chapter 17.

The final dimensions of the frame body were determined after integration with all subsystems. A few corrections had

to be made. First of all, the 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. The width of the top-plate was adjusted such that it could fit on top of the battery compartment. The aft wall of the battery compartment was made lower to reduce mass, and the front wall was replaced by a loaded pin, to make the battery easily removable. Secondly, in the iterations the length of the main box was the same as the battery length, whereas it should have included the thickness of the battery compartment wall and casing. This was corrected for after integration. The height of the main box was made 4mm taller to be able to screw in the arms. Lastly, the corners of the main box were cut to incorporate the arms. Therefore it no longer had a rectangular shape and the width of the frame had to be adjusted for this to fit the battery. After implementing these corrections every subsystem fits nicely in the frame body as can be seen in Figure 11.1. furthermore the mass of the main frame was still within budget, as margins were put in place as explained in Chapter 5.

The main box part numbers 10 and 13 are joined together by screws. This is done as these parts must be removable to access the flight Controller, ESC and BMS. The top plate can be welded to the battery compartment walls of part number 10 as it can be permanently fixed.

11.2.6. Sizing of the Drone Casing

To ensure the PCBs on top of the frame remain operational under raining conditions (requirement SR-SYS-8) a casing is designed to protect these components. The propulsion system already meets the requirement.

The shape of the casing was determined following the advice of the aerodynamics department to be cylindrical. The basis of the casing is rectangular to exactly fit the main box dimensions. The part is to be produced by injection molding and therefore given a minimum thickness of 2mm [115]. The casing was designed to exactly fit around the drone after integrating all subsystems. This resulted in the casing as shown by number 15 with a final mass of 57 grams. Producing this piece would cost $35 \in [93]$.

To join the casing to the structure a waterproof rubber lining is made around the main body where the casing fits onto. To secure the casing in place a hinge mechanism is designed. This mechanism works as follows: One part of the hinge will be fixed to the case, and the other part of the hinge, which can rotate, will be fixed to the wall of the main box. The rotating hinge will rotate such that it can be clicked onto the part of the hinge on the case. This way the case can be easily removable in case any maintenance is needed or the battery needs to be taken out

The hinges will be made of PP via injection molding. They have a mass of 4 grams each and will cost 52 € to produce two of them for each drone. With this casing requirement SR-SYS-8 is satisfied.

11.3. Overview of Integrated Final Design

After concluding the subsystem design and integration the final design is presented. Note that this final design does not include holes for cables nor their masses. This is to be explored in the post-DSE phase as explained in Chapter 17. An overview of all the parts is shown in Figure 11.1 and their total masses are given in Table 11.4. The final mass is 2065.4 grams, which fits in the budget of 2110 grams. There is still a 44.6 gram margin left for actions proposed for the post-DSE phase. A cost breakdown of the final design is presented in Chapter 15. Appendix A includes a technical specification sheet of Starling.

The size of the full drone is 720.34X623.13X250.51mm. This includes the propellers and the casing. with these dimensions the drone satisfies requirement PO-AP-6 as with these dimensions the area of the drone is only 0.44 m^2 . Furthermore, requirement OP-AP-2.2 is verified as with these dimensions the volume of the drone is only 0.11 m^3 .

AD-AP-2 and SR-SYS-8 are verified with the addition of the casing to the structure and the propulsion system being waterproof as stated in Chapter 6.

Table 11.4: Mass breakdown of final design

Department	Part	Mass[grams]
Propulsion	Propellers	40
	Motors	372
Power	Battery	580
	ESC	12.1
CCE	PCBs	30
Structures	ures Frame Body(incl Payload mount	
	Frame arms	68
	Motor Mounts	32
	Casing(incl hinge)	
	Payload Heavy	600
	Payload light	317
Operations	Operations Long Landing legs and craters	
	Short Landing legs and craters	78
Total	Mass for long landing legs and heavy payload config	2065.4

Table 11.5: Compliance matrix for for the integration

Tag	Requirement	Verified?
SP-AP 1.4.3	Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm	Yes
OP-AP-6	The area off the take-off zone shall be at most 1m2 per drone	Yes
OP-AP-2.2	The volume of the drones shall not exceed 0.5m^3	Yes
AD-AP-2	The drone shall be able to fly in rainfall up to 10mm/hour	Yes
SR-SYS-8	The drone's electronics and propulsion system shall remain operational under raining conditions of up to 10mm/hr.	Yes
SP-SYS-6	The drone body should be tolerable to transportation and in-flight vibrations	Flight yes, Trans- portation de- pends on client

System Analysis

Now that the subsystems are integrated into a drone, the complete design can be analysed. This is done by first presenting the related requirements in Section 12.1. Then a performance analysis is conducted in Section 12.2. RAMS characteristics of the drone are analysed in Section 12.3. Technical risk analysis can be found in Section 12.4. Sustainability will be touched upon in Section 12.5 and finally a sensitivity analysis is done is Section 16.2.

12.1. Requirements Related to System Analysis

In this chapter a full analysis will be performed on the final design. The analysis can be used to answer the requirements that have yet been discussed in previous chapters or have only been analysed at a subsystem level. The relevant requirement are shown in Table 12.1.

Requirement type	TAG	Requirement
	AD-SYS-6	The drone shall be operable in a temperature range between
	AD-313-6	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
System analysis	SP-EO-2	Drones shall not sink in the water
	OP-GB-9	The drones shall adhere to drone regulations
	CD AD 1	An unintentional collision with the ground shall happen atmost once every
	SR-AP-1	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
	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
	SUS-EU-7	release of any toxic substances outside of the system.
	SR-AP-5	In case of emergency, the drones shall be able to land safely
	SIN-AF-3	in less than 90 seconds
Control	POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone
Control	POP-313-4	from being able to perform an emergency landing.
	SR-AP-3	Malfunctioning of a single drone shall not endanger the entire show
	CD CVC 1 2 2	The pyrotechnics shall not cause the drone's center of gravity to move
	SP-SYS-1.2.2	outside of the stability and controllabillity margins
	AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.

Table 12.1: Requirements related to the design analysis.

12.2. Performance Analysis

An analysis is conducted on the performance of the final design. The analysis is split up in smaller parts covering specific subjects. In the following subsections these parts will be discussed.

12. System Analysis Group 17 - DSE

12.2.1. Flight Profile

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. The mission can be subdivided into five segments. First the drones take off.Next they fly towards the location where the show takes place and they climb towards the desired altitude. After this it is showtime. Once the show is completed 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.

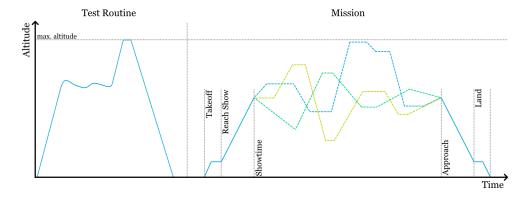
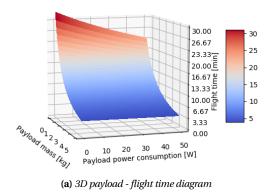
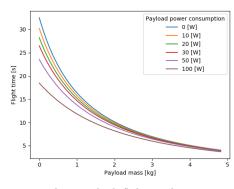


Figure 12.1: Sketch of a typical flight profile

12.2.2. Payload Flight Time Diagram

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.





(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.

12. System Analysis Group 17 - DSE

12.2.3. Wind Resistance

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.

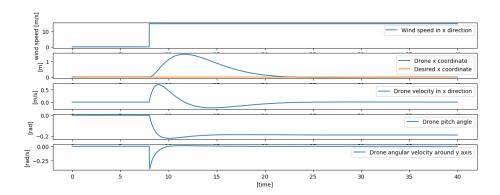


Figure 12.3: Responce to the wind gust

The wind speed exceeds 6 BFt (13.8 m/s) and the drone still stays within 1.5 meters from a specified location. This satisfies AD-AP-1 requirement. 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.

12.2.4. Payload Effect of Controlability

As already discussed in Chapter 8, the payload affects the controlability of the drone. If the drone launches fireworks, the center of gravity might shift, which will introduce additional moment to the drone. Assuming a worst case scenario, 0.6 kg will be shifted by 20 cm. This creates a moment of 0.12 Nm. This results in additional load of 0.18 N per motor, which is 1.2% of maximum thrust. This additional thrust is well within the motor signal bounds dedicated to pitch and roll as described in Chapter 8, therefore requirement SP-SYS-1.2.2 is satisfied .

12.2.5. Operating Temperature

Requirement AD-SYS-6 sets operational limits on the temperature. During subsystem design, all components were selected with temperature requirements in mind, this way all drone subsystems can work in range of -3 to 40 deg. Maximum operating temperature of the battery is only 5 degrees higher than the requirement. Additional heat from electronic components might push the battery above acceptable temperature, so the drone will be operated without the case in hot environments to allow excess heat to escape. Further

12.2.6. Floating on Water

Many drone shows are conducted above rivers in large cities, because the skyscrapers on land interfere with the show. Requirement SP-EO-2 demands the drone to float on water, if case it is forced to land there. Assuming the top cover is not waterproof, the total water displacement is $1.19*10^{-3}m^3$. To float on water, the drone needs additional $0.92*10^{-3}m^3$ of volume. Additional volume will be provided by the payload. To put it in perspective, a sphere with 12 cm in diameter will be sufficient. If the customer wishes to fly above water, a payload has to have sufficient volume. Concept of such payload can be seen in Figure 11.1.

12.2.7. Climb Performance

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 [116]. 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.

12.2.8. Mission Endurance

Typical missions are specified by the flight profile shown in Subsection 12.2.1. For these specific missions, an estimate of the maximum showtime as a function of battery state of life (*SOL*) can be performed, using the method described in Chapter 7. The flight envelopes, such as those shown in Figure 7.3 and Figure 7.4, can be slightly modified, such that they only show what mission scenarios are feasible for a given state of life of the battery (which can be seen as an input value between 0%, which corresponds to the beginning of life, and 100%, which corresponds to the end of life). For a given state of life value, the maximum showtime possible under different scenarios can be studied (for each of them, the standard depth of discharge of 80% is assumed). A compilation of the endurance observations conducted is displayed in Table 12.2. Let it be noted that the time values displayed only pertain to the showtime (the takeoff, travel to and from the show location, as well as landing are not incorporated in these time values).

Table 12.2: Maximum Endurance of specific missions.

Payload Type	SOL	Scenario	Max. Showtime
		takeoff zone 1km away from show, 6BFT wind	16 min 25 s
Heavy	0%	takeoff zone 1km away from show, no wind	16 min 40 s
пеачу	070	show right above takeoff zone, 6BFT wind	18 min 00 s
		show right above takeoff zone, no wind	18 min 15 s
		takeoff zone 1km away from show, 6BFT wind	14 min 55 s
Heavy	50%	takeoff zone 1km away from show, no wind	15 min 15 s
пеачу	30%	show right above takeoff zone, 6BFT wind	16 min 35 s
		show right above takeoff zone, no wind	16 min 45 s
		takeoff zone 1km away from show, 6BFT wind	13 min 30 s
Heavy	100%	takeoff zone 1km away from show, no wind	13 min 45 s
Tieavy	10076	show right above takeoff zone, 6BFT wind	15 min 05 s
		show right above takeoff zone, no wind	15 min 15 s
		takeoff zone 1km away from show, 6BFT wind	21 min 55 s
Light	0%	takeoff zone 1km away from show, no wind	22 min 20 s
Ligit	076	show right above takeoff zone, 6BFT wind	23 min 35 s
		show right above takeoff zone, no wind	23 min 55 s
		takeoff zone 1km away from show, 6BFT wind	20 min 00 s
Light	50%	takeoff zone 1km away from show, no wind	20 min 20 s
Ligit	30%	show right above takeoff zone, 6BFT wind	21 min 40 s
		show right above takeoff zone, no wind	22 min 00 s
		takeoff zone 1km away from show, 6BFT wind	18 min 05 s
Light	100%	takeoff zone 1km away from show, no wind	18 min 25 s
Light	100%	show right above takeoff zone, 6BFT wind	19 min 45 s
		show right above takeoff zone, no wind	20 min 05 s

From the results displayed in Table 12.2, it can be concluded that the 1 km distance from show location parameter influences maximum showtime more than the 6BFT wind condition. Another observation is the fact that a battery at 50% *SOL* will be able to fulfil the 20 min showtime with light payload requirement even under the harshest conditions, and can almost fulfil the 15 min with heavy payload requirement under those same conditions. Another note to make is that the maximum flight time requirements for both heavy and light payload are possible with batteries at their end-of-life, granted that the show does not take place too far from the takeoff zone, and that the weather remains calm. The tool developed in Chapter 7 could potentially be used by the drone show operators, such that they could evaluate while on site the maximum showtime they could deliver based on the state of life of their available batteries, the weather and the layout of the show.

In addition to these possible mission scenarios, a computation of the maximum hovering time was made, as this is a quite common parameter in drone specification sheets, and as such, can help provide a nice comparison between Starling's endurance with its market competitors. For this, it can be assumed that the battery is at its beginning of life (drone companies select the set of conditions that will produce the most optimistic result to help them advertise their product), is kept constantly in hover position, is not being subjected to aerodynamic disturbances by wind, and only carries the light payload, which is not being activated, such that the power available from the battery is only used by the flight computer and the motors to sustain stable flight. From this set of assumptions, the obtained result is a total hovering time of 25 minutes and 35 seconds, which is a rather satisfactory result when compared with the values of 25 minutes advertised by Sparkl and UVify IFO in Section 4.5.

12.2.9. Collision Avoidance

For autonomous swarm UAVs such as Starling, the software part a major weak point when it comes to reliability. The software failure rate is very difficult to calculate, and it is not the part of this project, so only the hardware was analyzed. Electrical motor is the most fail prone part of the drone. According to the [117] mean time between failure (MTBF) for the motors of selected size is about 77000 hours. To comply with requirements SR-AP-1 and SR-AP-2, which demand 1000000 and 100000 hours respectively, an additional software will be used. This software will change the controller behaviour if the motor breaks down during the show. Such advanced control algorithms already exist [118], so it is reasonable to assume that it is possible to implement such controller by 2025. If engine fail is expected to occur $10^6/77000 = 13$ times in million flight hours, the landing of the damaged drone would take a few minutes, so the chance of another engine failure during this time is negligibly low. This safety feature also satisfies POP-SYS-4 requirement. If the drone experiences motor failure, it becomes uncontrollable manually. For this reason, when motor failure is detected, the software slowly lands the drone. Without one motor the drone spins very fast, so the gps and barometer might show the inaccurate altitude, therefore the descent is performed at a safe rate, such that if the drone miscalculates the ground position, it wont break down. This procedure satisfies SR-SYS-5.1.

Failure of electronic components and battery is also possible. If a ESC board or flight computer fails, the drone will crash. Failure of UWB, GPS, WIFi or radio will prevent the drone from continuing the show, but will not lead to a crash. The drone without GPS, can be flown back to base manually, and if the radio fails as well, the flight computer has a barometer, so the drone can still measure it's vertical speed. This way it will descend at a very slow speed, until it gently touches the ground. Failure rates of electronic components are left for the post-DSE phase, as there was no information found on this topic.

If the drone (partially) fails, it can fit nearby drones, causing chain reaction. To prevent this, drones regularly send telemetry data back to the ground station, so in case of emergency, the ground station can command the drones to keep a safe distance from failed units. This way the requirement SR-AP-3 is satisfied. Also it is up for the show organizers to design collision-free trajectories for the show.

12.2.10. Emissions

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.

12.2.11. Regulations

For the last years countries in the EU started to implement drone regulations that differ per country. A need arose to have a set of regulations that can be maintained in every country part of the European Union. By the start of 2021 the first EU regulations were enforced and new drone regulations are currently being implemented. The current regulations state that the drones have to carry a licence plate and shall be operated by pilots who have a licence, which is all the duty of the operator.

The communication system aboard the drone is adhering to the regulations set for Wi-Fi and radio communications as mentioned in Chapter 8. As our drones' hardware adheres to current drone regulations, requirement OP-GB-9 is met. However, special licenses are required to fly our drone and therefore this shall be taken into account when operating the product.

12.3. RAMS Analysis

12.3.1. Reliability

Requirement SR-AP-6 sets a minimum operational flight time to 1000 hours. All subsystems of the drone were designed to meet this requirement. All electronic components have lifetime measured in decades. Motors of the drone are brushless, lifetime of these parts is limited by the bearing wear. According to [119] the lifespan of brushless motors exceed 1000 hours . In addition, manufacturer of motors for Starling claims to use quality bearings to maximize lifespan of the part. LiPo batteries have a relatively short lifespan, so they are changed regularly as described in Chapter 7. Over the lifetime of Starling it is expected that the battery will be replaced 7 or 8 times depending of proper use of the batteries. Structure of Starling is made of non biodegradable , weather resistant material, so it should last for the required time.

12.3.2. 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 Li-Po battery, available in most hobby stores. Similar models with similar performances have similar mass and volumetric properties. Even if the exact model goes out of stock, other models can be used with very little effect on performance. The 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. Therefore, it makes sense 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 [120] [121]. 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.

12.3.3. 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.

To verify OP-AP-1 it is necessary to develop a one day training program and test whether the employee is able to maintain or replace (parts of) the drone. Since at this stage this requirement cannot be verified it will be considered a post DSE activity.

12.3.4. Safety

Several safety recommendations have been preformed in Section 14.4. This relates to the logistics of the batteries, pyrotechnics, propellers or environmental conditions like rain or the ambient temperature.

12.4. Technical Risks Analysis

Throughout the development of the project, each department's investigation of the design led to the identification of new risks, which were appended to the risk register. Each subsystem chapter provides a full overview of the risks pertaining to that particular subsystem, as well as the implementation of response strategies for those risks.

The compilation of all those technical risks can be seen in Figure 12.4, in the form of a risk map. The map divides the risks into three distinct regions:

• Green: The risks are low. Although still inherent to the design of the drone, they do not significantly endanger

the success of the project.

• Yellow: The risks are moderate. Risks in this region must be closely observed throughout the development of the project.

• Red: The risks are high. The mitigation of those risks must aim at removing them from this region, so as to not endanger the progress of the project.



Figure 12.4: All the technical risks of the project, displayed in a risk map.

Figure 12.4 shows a significant number of risks in the yellow and red areas. This is unacceptable, and would drastically endanger the success of the design if no mitigation responses were taken. Therefore, appropriate risk mitigation responses were implemented, in order to bring all the risks within manageable and acceptable boundaries. The result of all those strategies is Figure 12.5, which shows a much more acceptable state of risks.

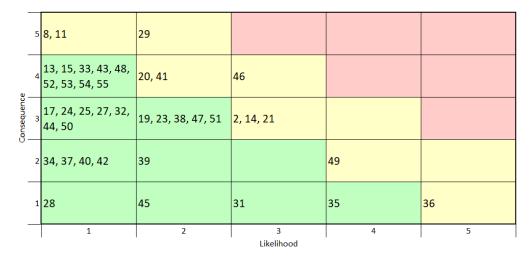


Figure 12.5: Risk map of all technical risks, after mitigation.

12.5. Sustainable Development Strategy

In this section sustainability requirements related to integration are verified. Also the contribution to sustainability is discussed.

Recyclability fraction is set by SUS-EO-3 requirement to at least 80%. 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 [122]. 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:

$$R = \frac{\sum M_{res}}{M_{tot}} = \frac{0.412 + 0.58 \cdot 0.95 + 0.1319}{1.51} = 84.9\%$$
 (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.

Requirements SUS-AP-2 and SUS-NR-6.1 are trivial, since the drone does not use any radioactive parts and it leaves no trash on the ground.

Requirement SUS-EO-7 demands that power supply failure during operation of the drone shall not result in release of any toxic substances outside of the system. Power supply failure Could lead to drone catching fire, of a drone crashing on the ground. The LiPo battery fumes can considered to be toxic, so the requirement is failed in case of fire. In case the power supply does not catch fire, the reqirement is satisfied. The failure modes of the battery are left for the post-dse phase, so this requirement is not verified.

12.5.1. Design Contribution to Sustainability

Starling stays ahead of the competition when it comes to sustainability. Most importantly, the design focuses on reduced emissions for the manufacturing of the drone, and on easy and environmentally friendly recycling. A number of key decisions were made to achieve this. The drone frame was made out of PP, which is a common food packaging plastics. This will greatly boost the recyclability of the product at the end of life. Most of the similar sizer drones use carbon fiber propellers to save weight, Starling uses recyclable ABS propellers. Electronics of the drone is deliberately made more expensive, by coating traces with gold, this way the PCBs have greater value for the recycling companies, and is less likely to end up on the landfill. Electronic components are also placed on separate board, so they can be gradually updated during the lifetime of the drone, without throwing away the whole system at once for every new update. Lastly, every part of the drone has a RIC code printed on it, this way it is esy to direct all parts to the right resyscling facility.

12.6. Compliance Matrix for System Analysis Requirements

In Table 12.3 the compliance matrix regarding the system analysis requirements is shown. The requirements discussed in this chapter are shown and their verification status is shown.

 $\textbf{Table 12.3:} \ Compliance \ matrix for \ the \ requirements \ related \ to \ system \ analysis.$

System analysis requirements	TAG	Requirement	Verified?
	AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg	Post DSE
	SUS-EO-3	At least 80% of drone mass shall be recyclable.	Yes
	OP-AP-3	The drones shall be available in the year 2025	Yes
	SUS-AP-2	There shall be no radioactive parts on board of the drone.	Yes
	SP-EO-2	Drones shall not sink in the water	Yes
	OP-GB-9	The drones shall adhere to drone regulations	Yes
	SR-AP-1	An unintentional collision with the ground shall happen atmost once every 1,000,000 flight hours when flying indoors	Post DSE
Ct	SR-AP-2 An unintentional collision with the ground shall happen atmost once every 100,000 flight hours when flying outdoors		Post DSE
System analysis	SR-SYS-5.1	Emergency landing will occur autonomously.	Yes
	SR-AP-6	Each drone shall have a lifetime of at least 1000 flight hours	Yes
	SUS-NR-6.1	The drone shall not leave any trash on the ground.	Yes
	SUS-EO-7	Power supply failure during operation of the drone shall not result in release of any toxic substances outside of the system.	Post DSE
	OP-AP-1	An employee who has followed a one-day training shall be able to replace parts of a drone	Post DSE
	SR-AP-5	In case of emergency, the drones shall be able to land safely in less than 90 seconds	Yes
	POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from being able to perform an emergency landing.	Yes
	SR-AP-3	Malfunctioning of a single drone shall not endanger the entire show	Depends on client
Control	SP-SYS-1.2.2	The pyrotechnics shall not cause the drone's center of gravity to move outside of the stability and controllability margins	Yes
	AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.	Yes

Production Plan

This chapter gives a detailed overview of the production of Starling. Section 13.1 presents the risks involved in manufacturing that should be mitigated. Section 13.2 gives an overview of how the drone is produced and the steps involved and presents a time ordered outline of the activities required to produce the drone from its parts presented in a flow chart.

13.1. Risks in Manufacturing

Before a manufacturing plan is established risks are identified that should be mitigated in this plan. Table 13.1 presents the risks identified, their likelihood and their consequence. The proposed mitigation response is presented in Table 13.2.

ID	Risk	LS	Reason for likelihood	CS	Reason for consequence
47	Battery gets stuck	4	The compartment was made to tightly fit the battery so it cannot move around in flight. No production margins were included in the design.	3	Battery stuck in frame means the frame plate must be discarded. No measures should be taken to remove the battery for risk of perforation of the battery. It means the top of the main box must be replaced
53	Arm hole misplacement	4	The hole for the landing gear cable is off- set from the middle of the arm. As both sides have different length of threading there is the risk the hole is made to the wrong side of the arms center.	4	Landing gear is possibly asymmetrically placed but more importantly it may be too close to the body to not be able to fit future payloads of 20x20x20cm
54	Misalignment crater	3	The crater is to be placed exactly above the landing gear but no marks are in place to ensure this	4	When the craters are misaligned the drones can not be efficiently stacked upon each other making the operations for the show very difficult
55	Parts not correctly recycled	4	The material type is not specified on any of the parts	4	When the parts are not recycled correctly or even thrown away the 80% recyclable requirement can not be met.

Table 13.1: Risks related to manufacturing

Table 13.2: *Mitigation responses for identified risks.*

ID	Risk	Mitigation response	LS	CS
47	Battery gets stuck	Incorporate production margins into the design	2	3
53	Arm hole misplacement	Include marks on the arms in the production process and perform checks on its position before drilling the hole.	1	4
54	Misalignment crater	Include marks on the arms in the production process and perform checks on its position before permanently fixing the craters	1	4
55	Parts not correctly recycled	Add Resin Identification Code on parts during the production process	1	4

13.2. Overview of Production Steps

The first step in the production of the drone is producing the parts. The rods for the arms and landing gear will be produced via polymer extrusion and cut to size in the process. This method is viable as the parts have uniform cross-sectional properties. Injection moulding can not be used for these parts as the rods are hollow and are therefore not easily removable from the mould. The motor mounts, craters, landing gear attachments, the parts of the frame body, the casing and the hinges for this casing will be made using injection moulding. For all these production

13. Production Plan Group 17 - DSE

processes margins to the dimensions must be incorporated to cope with uncertainties in the manufacturing of the parts (Risk 47). These margins are made concrete in the Post-DSE phase as explained in Chapter 17. To all these PP components a flame retardant will be added as explained in Chapter 9. The propellers, motors, battery, ESC and UWB are bought of the shelf. The flight controller, Wi-Fi, GPS and radio PCB are custom made to the drone by an external party and the BMS is to be explored in the post DSE-phase as explained in Chapter 17.

After the moulding process the parts need to be machined into their final shape. As explained in Chapter 11 the arms are threaded on both sides and a hole is drilled where the landing gear is attached to incorporate the charging cable. The thread on the side of the motor mount is 20mm long and on the side where the arm is attached to frame is 5mm. The inside of the motor mount and the arm holes in the frame body are also threaded. The hole to be drilled for the landing gear cable in the arm is 3mm. To mitigate risk 53 and 54, marks are made on the arms for the placement of the hole and crater. On the the top and bottom of the main box 4 holes on each corner are drilled for screws. The top plate is then welded onto the top main box. A hole is drilled through the landing gear attachment for the spring pin to go through. The last 2 steps are to add a waterproof lining for the casing on the top of the main box and to fill up the battery compartment with a compressible material to be found in the Post-DSE phase. To mitigate risk 55 the Resin Identification code (RIC), as shown in Figure 13.1 is marked on all parts.



Figure 13.1: Resin Identification Code

The next step in the production is to integrate all parts. First, the motor mount is screwed onto the arm. Then, the motor is attached to the motor mount and the cables are guided through the arm and into the main body. The arm is then screwed into the main body. The propellers are attached at the end of integration to not damage them in the process and to not have them in the way. The screw fitting is permanently fixed and secured using "Loctite".

When the arms are in place the Flight controller, ESC and BMS are fixed into the main box and the cables from the motors are soldered onto them. All electrical components are connected to the flight controller and BMS at this stage. Then the box can be closed via the screws and the Radio, GPS, Wi-fi and UWB are secured on the top-plate. Thereafter, the battery can be integrated an the power cable is connected to the BMS. The last step of the integration is securing the casing in place and attaching the hinges to the main box.

Figure 13.2 presents the time ordered flow diagram of all these steps included in production and integration. Checkpoints are added for quality control to ensure parts are produced correctly an no mistakes are made in integration.

13. Production Plan Group 17 - DSE

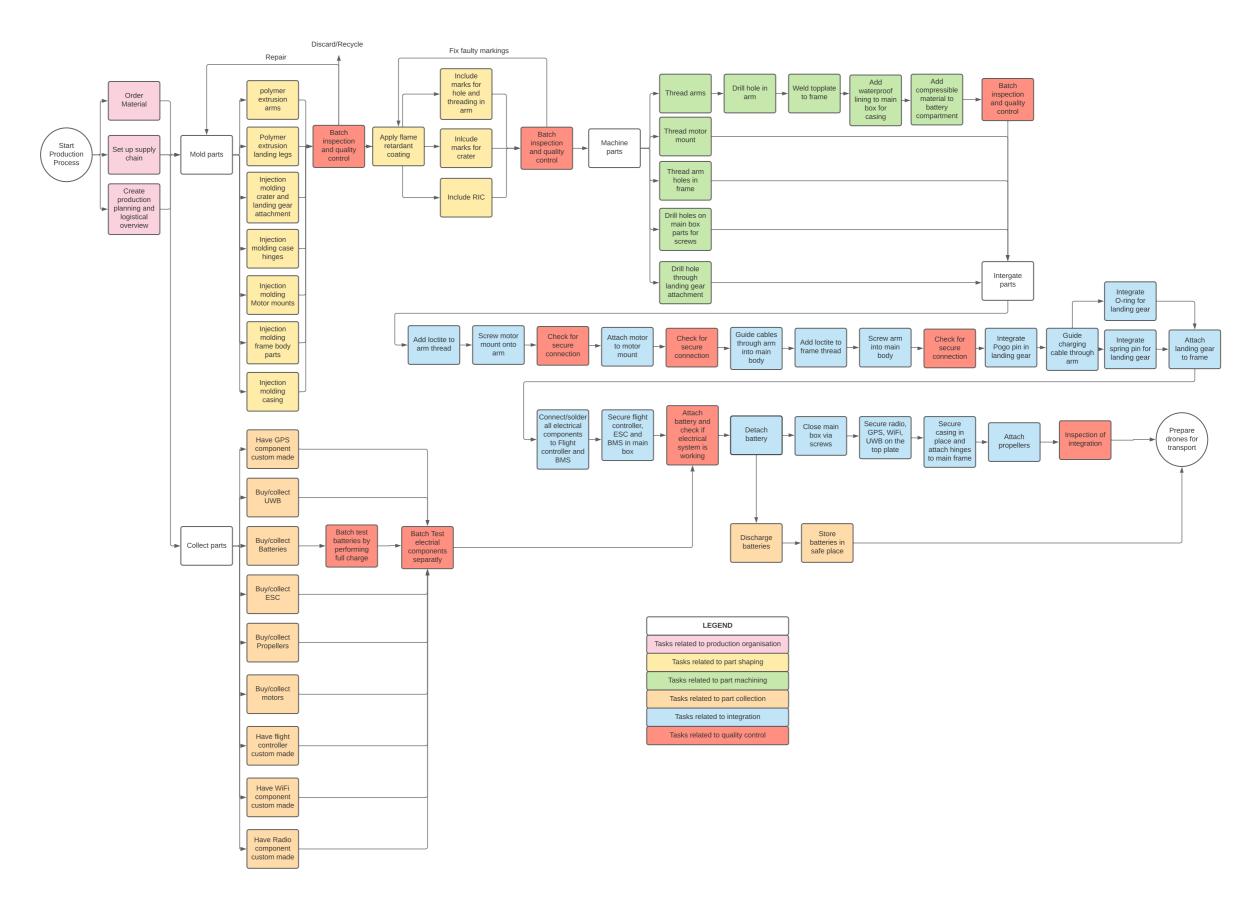


Figure 13.2: Production Plan

Logistics and Safety

This chapter presents the logistics and safety analysis of the drone show. Section 14.1 presents the requirements that influence the logistics and operations of drone shows. Section 14.2 presents a logistics analysis of drone shows focusing on the deployment of drones on their landing pads. Section 14.3 presents an overview of the logistics and operations of drone shows and Section 14.4 presents an overview of the safety measures needed for the different aspects of the operations. Finally, Section 14.5 presents the compliance matrix of the logistics and operations requirements.

14.1. Logistics and Operations Requirements

In the drone show 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 Starling must fulfill.

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

Table 14.1: Requirements related to logistics

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 Time Estimation

As presented in Chapter 10, six drones can be stacked in carrying structures with a total weight of 12.53kg and a height of 1.17m, 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 a common method used in some 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 Section 14.3. The drone deployment time is dependent on many factors, such as the amount and type of drones, 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 take-off area by requirement OP-AP-6 is $1m^2$. Therefore takes 30s for a worker to move to the next landing pad, which includes picking

up the stack, walking 2 meters and placing the stack on the ground.

- 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 optimal, which gives the minimum average walking time for the workers. The workers can walk at a constant speed of 5km/h [123].
- 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, inserting the battery and closing the case
 - Checking payload is correctly connected
 - Powering on the drone ¹
- 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 14.4 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 [124], which can be taken any time or in separate small breaks. In addition, weather conditions are assumed to be favorable, which doesn't require any extra safety measures. Refer to Section 14.4 for some considerations on raining conditions.
- Note that the model assumes that first light payloads are placed and then the pyrotechnic or future payload
 ones. In reality with enough workers some activities can run in parallel making the process more efficient.

Table 14.2 presents the time estimations (in hours) that the crew of Anymotion Productions, which usually consists of 4 workers ², would take in order to deploy different amounts of drones with different percentage of pyrotechnic payload drones.

These quantities go from 100 drones (typical Anymotion Production size ⁴) to 3052 drones, which would beat the current Guinness World Record [11]. In addition, note 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 [7]. Therefore, any drone show with more than 303 pyrotechnic drones or more than 3052 drones in total would beat a Guinness World record, this 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 ⁴. 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. Yellow shows the timings lower than 4 hours are indicated which could potentially be achieved with the four-worker crew with some logistics adjustments.

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 (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 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.

Note that deploying the drones does not require specific capabilities, just an in-house training according to Anymotion

¹This step will depend on the size of the show and time needed for calibration procedures. It might be that to save battery the drones will only be powered up once the entire grid is deployed.

²Personal communication with drone show expert, 11/06/2021.

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	

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
							1	
Legend		1-20 workers			21-75 workers			76+ worke

Productions ⁴, 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. It depends on the financial capabilities of the company how many workers they can hire for the deployment of drones. However note that improving the deployment method, for instance with the help or electric carts to move

Table 14.3 is based on the 3 hour limit which is the higher margin of the current Anymotion Production operations. If the time needed for calibration were to be reduced and more time allocated to the deployment of drones, larger drone shows would be achievable with the same crew.

the drone stacks faster to position, would also reduce the deployment time.

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, 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.

Deployment of Landing Pads

Similar to the drone deployment, an estimation of the time needed to deploy the wireless charging landing pads is made. As presented in Chapter 10, one landing pad has a mass of 16.34kg. According to the NIOSH recommendations, which were explained in Chapter 10, this is too heavy for one person and thus the landing pad has to be carried by two people to its desired location. The carried weight per person is then only 8.17kg. The simulation focuses on the time required to set out all landing pads in a grid. The following assumptions have been made:

- The sizing of the rectangular grid was done in the same way as written above for the drone deployment.
- The landing pads can be transported one by one, in a hand truck ((a handcart with two wheels and handles), a platform truck (a pushing cart with four wheels) or a van.
- For the hand truck, it was assumed that three landing pads can be carried with it. This was determined based on existing hand trucks with a depth of 30cm. [125]
- For the platform truck, it was assumed that eight landing pads can be carried with it per time. This was based on platform trucks that have a usual height of 85cm. [126]
- Lastly, for the van, a Fiat Ducato was taken as an example and it was calculated that a Fiat Ducato (as will later be used in Section 14.3) with the largest cargo space configuration could fit 150 landing pads, if they are stacked vertically and with two rows of landing pads above each other. It was calculated by using the given cargo space by the manufacturer and the volume of the landing pad. [127]
- Deploying the landing pad was estimated to take 1min per pad, since it is bulkier than the drones, including connecting the pad to the power supply by cable. Walking to the next location was estimated to take 1min as well. This is due to the heavy weight and collaboration of two people carrying the landing pad together.
- After a cart is empty, it takes 4 minutes to reload the hand truck and 7 minutes to reload the platform truck.
 These timings include walking back to the cargo truck where the landing pads are stored, placing them on the cart with two people and walking back to the grid.

In Table 14.4, the number of workers are displayed to be able to deploy all landing pads in less than three hours. The reason for this time limit of three hours has already been discussed above for the drone deployment and it is practical if the deployment of the landing pads is of equal length or shorter than the deployment of the drones. The two tasks can be executed at almost the same time in this way, with the deployment of the landing pad starting a bit earlier so the drones can be deployed on the landing pads.

It can be seen, in Table 14.4, that the platform truck needs the lowest number of workers. However, platform trucks are not suitable for every terrain, such as wet fields. A van is less efficient than the hand truck for drone shows under 500 drones, because it requires a driver per van who cannot carry landing pads. A van is also less sustainable than a handheld cart and might not be suitable for every terrain as well. The positive side of a van is that there is less chance of injury of the workers as they have to carry every landing pad for a shorter distance. This is where the hand truck will be useful as it has large rubber tires and can thus be used on a grass field. The amount of workers needed to deploy the pads individually is also shown. It is up to the customer which method of landing pad deployment suits the best in a specific situation.

Table 14.4: Estimation of number of workers needed to deploy different numbers of landing pads with different methods on the optimized grid in less than 3 hours.

		Total number of landing pads							
Types of carts	100	0 150 200 300 500 1000 2000 3052							
Van	5	5	8	10	18	33	64	97	
Platform truck	4	4	6	8	14	28	56	86	
Hand truck	4	6	8	10	18	38	78	124	
Individually	6	10	12	18	32	68	150	248	
		1						I.	
Legend		1-20 workers			21-75 workers			76+ worke	

14.3. Operations and Logistics Diagram

Section 14.2 presented an analysis on the estimated time to deploy the drones for different types of drone shows. However, the logistics of these shows involve many other phases. Figure 14.1 presents the operations and logistics diagram of the drone show, which covers the majority of the actions that are performed during the lifetime of a drone focusing on the general lay-out of performing drone shows. It is based on an outdoor drone show of 300 drones. Note the following:

- The blue background corresponds to logistics stages, which mainly contain transport, packing and security. While the red background corresponds to operations regarding flights. Yellow boxes are performed by external parties, while white boxes by the drone show company themselves.
- All actions show the working-hours and number of people necessary to successfully execute them. These values are rough estimates based on answers from Anymotion Productions³, the analysis in Section 14.2 and other companies studied in the market analysis Chapter 4. Note that for the example of 300 drones, in total on top of the four full time workers, an additional 8 to 18 workers for deploying the landing pads (depending on carrying method, Table 14.4 and 7 to 33 workers to deploy the drones (depending on type of payload, tab:estimationworkers) are needed.
- Note that the unpacking before each show consists of moving relatively heavy transport boxes out of the trucks
 or storage facility, this should be done with more than one worker and ideally with mechanical help like a forklift.
- There are three different flight operations, executed after each other:
 - Test flight: flight at own testing site to test the full choreography or part of it.
 - Practice flight: flight at drone show location usually a day prior to the actual show.
 - Show flight: drone show at location.

The difference between the practice run and the show flight lies on the logistics involved before the flight, since for the show flight some steps are not necessary like the preparation of the ground station which was done for the practice flight the day before. In the practice flight, the pyrotechnic payload or any consumable future payload is not attached, instead a mock payload is used, in order to not waste resources.

- During the show the operations don't stop since the pilots must monitor the drones from the control station and the rest of the crew is monitoring the area for safety.
- In addition, the step "Check battery 'age'" before each flight is key to ensure that the batteries used are the right ones to not waste resources. This mitigates risk 52 for which a 'too old' battery cannot perform the entire show. For instance, newer batteries should be used to run through entire choreography in the show, while older batteries can be used for testing manoeuvres and practicing. This only applies to specific situations such as a show far away from the take-off area or high winds, in most cases relatively old batteries can perform full shows (as explained in Chapter 7).
- The time of some operations is influenced by external parties, such as the manufacturing, maintenance and product disposal. Other operations' time is not possible to determine as they differ every time, such as transport. In addition, there are tasks whose length is independent of the number of drones, these are indicated with a turquoise color.
- Finally, maintenance is shown to be achievable by one worker in one working day, this is due to requirement
 OP-AP-1 which establishes is the maximum training time. Also note that the deployment and packing of the
 drones includes taking off or putting on the foam protection around the propellers, which makes sure they
 are not damage during transport.

 $^{^3}$ Personal communications with drone show expert, 21/05/2021 and 11/06/2021.

14. Logistics and Safety Group 17 - DSE

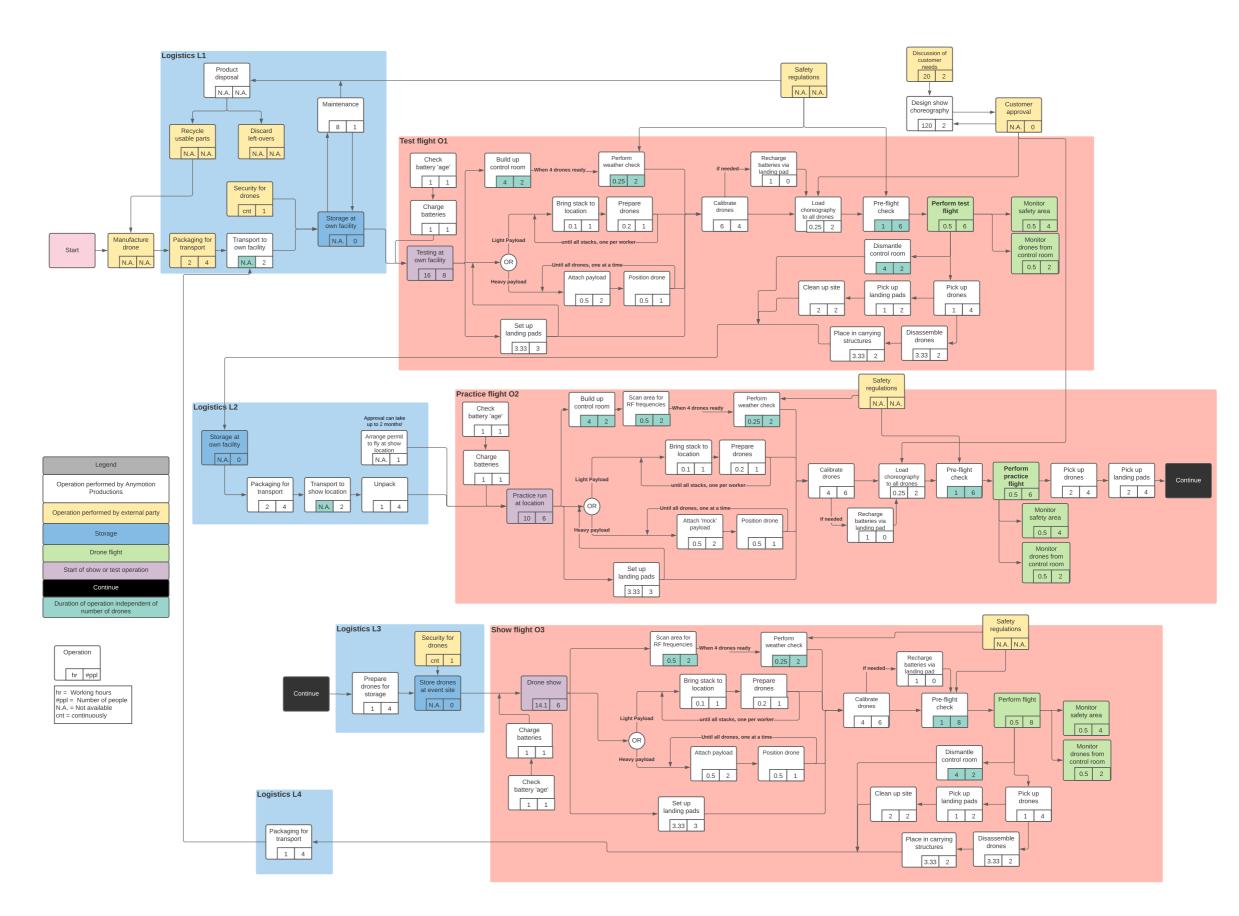


Figure 14.1: Operations and Logistics Diagram

Typical Drone Show Day Schedule

Based on Figure 14.1 and the time estimations of Section 14.2, a possible day schedule for a drone show can be presented. Table 14.5 shows the schedule is for an outdoor show of 300 drones carrying light payload and a crew of 7 workers available for the deployment of the drones. Table 14.6 shows a similar drone show of 300 drones of which 25% carry pyrotechnic loads deployed by 11 workers. Both shows start at 9pm.

Table 14.5: *Indicative drone* show schedule of outdoor show of 300 drones with light payloads

Table 14.6: *Indicative schedule of outdoor show with 300 drones of which 25% carry pyrotechnic loads*

Time	Action	Time	Action
09:00	Arrive at location	09:00	Arrive at location
09:00-09:30	Unpack drones from storage facility	09:00-9:30	Unpack drones from storage facility
09:00-10:00	Charge batteries	09:00-10:00	Charge batteries
10:00-11:00	Perform battery checks	10:00-11:00	Perform battery checks
10:30-13:30	Landing pad deployment	10:30-13:30	Landing pad deployment
11:00-14:00	Drone deployment	11:00-12:30	Light payload drone deployment
11:15-11:45	Weather check	12:30-14:00	Pyrotechnic drones deployment
14:00-20:00	Calibration and load choreography ⁴	14:00-20:00	Calibration + load choreography ⁴
20:00-21:00	Pre-flight checks	20:00-21:00	Pre-flight checks
21:00-21:30	Perform show	21:00-21:30	Perform show
21:30-00:00	Recover drones, pack up ground station	21:30-00:00	Recover drones, pack up ground station
22:00-00:30	Recover landing pads	22:00-00:30	Recover landing pads
00:30-01:00	Finalise packing and leave site	00:30-1:00	Finalise packing and leave site

Note that the major difference between Table 14.5 and Table 14.6 it's the deployment of drones. For Table 14.5 the 3 hours are fully dedicated to the deployment of light-payload drones, which is done in stacks of 6. For Table 14.6, about 1.5hrs is dedicated to the 225 light payload drones, while the other 1.5hours is dedicated to the deployment of the 75 pyrotechnic drones, which take longer to prepare and are deployed individually.

It can be seen how some actions overlap such as the deployment of landing pads and drones and the weather check, this is possible as long as each landing pad are deployed slightly before each drone. The landing pad deployment was mentioned in Section 14.2 and it is assumed to take about the same time as the drone deployment, however it must start before the start of the drone deployment and end before the end of the drone deployment. In addition, the 'weather check' is a manoeuvre in which four drones are used to check the weather of the event site and decide weather the drone show can continue, so it is performed as soon as four drones are ready.

Note that the ground station doesn't need to be deployed since that was done the day before for the practice show. Other logistics actions such as breakfast, lunch and dinner of the crew are not considered. Note that this is just indicative since schedules depend on a lot of variables, the main five questions that influence the schedule are: Workforce available, time of start of drone show, number of drones and types of payloads, location characteristics and time needed for calibration procedures and pre-flight checks.

The time needed for calibration is based on the time needed by Anymotion Productions ⁴. However, this value might vary depending on the capabilities of the drone show company and the software of the drones, which can alter the schedule significantly.

Logistics Costs

It is not the aim of this project to go into detail on the costs of organizing a drone show, since these depend on a lot of factors such as personnel, facilities or country. However, an indicative overview of some of the main costs of an outdoor drone show of 300 drones at close enough distance to travel by land and with a full-time crew of four people (two pilots, one operations manager and one technical manager). This is presented here:

• <u>Transportation:</u> This refers to the trucks for drones and the vans for the crew and landing pads. Landing pads are transported in vans since they potentially can be used in any terrain to also deploy them, if this is not the

⁴Personal communication with drone show expert,11/06/2021.

case they can be transported in trucks as well. 300 drones are transported in 13 boxes with 4 stacks per box, which can potentially be stuck on top of each other. An common truck has a volume of $50m^3$ [128] and one box has a volume of $2.12m^3$. Assuming 30% of the space is not utilize, 9 trucks are needed, which can have an average renting price of $100 \text{€}/\text{day}^5$ [128]. For the crew, a total of 21 people need to be moved, this corresponds to 3 vans of 9 seats each, for instance the Fiat Ducato van has a rent of about 40 €/day [127], which makes the passenger transport costs 240 € for the two-day show. Finally, the same type of van in a cargo configuration has a cargo volume of $17m^3$ and can carry a weight of 2800 kg. One van could carry about 150 landing pads (assuming 30% of the space is lost) which weight about 2400 kg. Therefore, two vans would be needed for the 300 landing pads giving a cost of 160 €.

- Workforce: As suggested in Section 14.2 large drone shows require a large crew to deploy the drones and landing pads in less than 3 hours, which could be made up of part-time workers that only help in the most-demanded operations. 7 workers are needed to deploy 300 drones and 10 workers are needed for the 300 landing pads (assuming small carts are used). At a salary of 10.93€/hour (minimum salary in The Netherlands for over 21-years-old part-time workers, [129]) and working for 6 hours a day (3 in the morning for deployment and 3 in the evening for recovery), it gives 1,112.82€ of part-time crew salary.
- Accommodation and food: Usually shows span over two days (one practice day and one show day) so the crew must stay over night in hotels or other types of accommodation. Their expenses during this stay, such as food, should also be covered. According to [130], in The Netherlands the average cost of hotel accommodation for one person is 71€/night and 36€/day of food. Therefore, for both the part-time (17 workers) and full-time (4 workers) crew the cost of the 2-day stay is 2,247€.
- <u>Security</u>: Needed during the show to make sure no one walks into the safety area and after the show, when the expensive equipment stays overnight at the show site. According to [131], the cost of one security guard is about 20.96€/hour. Considering, for instance, that two security guards are continuously present for the entire 2 day event (48 hours), this leads to a 2,012€ security cost.

Table 14.7 summarizes and adds the indicative costs of the drone show:

	Туре	Cost
	Trucks	1,800 €
Transportation	Passenger vans	240€
	Landing pad vans	160€
Accommodation and food	Part-time crew	1,819€
Accommodation and lood	Full-time crew	428€
Salaries	Workforce part-time	1,112.82€
Salaries	Security	2,012.16€
	TOTAL	7,571.98€

Table 14.7: Indicative costs of two-day outdoor drone show of 300 drones and landing pads.

As can be seen in Table 14.7, the total cost for drone shows would be around 7600€ this does not include however the following:

- <u>Salary of full-time workers and equipment</u>: two pilots, one operations manager and one technical manager. This is not dependant on how many shows are performed or the length of the show.
- <u>Training of part-time crew</u>: which has been assumed to travel to the location along with the full-time crew, which is not always the case.
- <u>Truck/van drivers and fuel</u>: if some of the crew drives the trucks or vans then maybe two passenger vans are needed instead of three, however they would need special licenses to drive the trucks. In addition, the cost of fuel is not included in Table 14.7 since it depends on the location of the show.
- Event site: The renting of a large enough field and access to their facilities such as electricity. In particular the powering of the landing pads if conductive charging is used can be a key logistical challenge as mentioned in Risk 31. The drone show company must ensure that this electricity is available or provided by a third party.

⁵Usually trucks have renting prices per month, this average price has been computed by dividing the monthly price times 31 and adding a margin of 25%

• <u>Permits:</u> Depending on the country and type of show different permits might be necessary to be allow to fly a swarm of drones.

The prices of drone shows can go from about 25,000€ (for about 100 drones [132]) to 250,000€ (for 500 drones [8]). This would leave a margin of between $17,400 \in \text{and } 242,000 \in \text{for the costs not mentioned in Table } 14.7 \text{ and profit for the drone show company.}$

14.4. Safety Recommendations

There are many safety considerations involved in the organisation of a drone show. This section presents some of the main ones. In addition Table 14.8 presents the requirements that bring safety considerations with them:

Table 14.8: 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

Indoor shows imply a smaller field as well as closer public to the drones. If the performance is within certain limits of the audience or potentially above them, the use of safety cages around the drone's propellers should be studied. This is a further recommendation presented in Chapter 17. Also the effects of different types of pyrotechnics on possibly closed environments should be taken into account.

Ground Station

The ground station is a key element of the show. It must maintain communication with the drones at all times and allow the pilots to manually control them in emergencies (as explained in Chapter 8). It should also contain an emergency stop bottom which will initiate a landing procedure of the swarm according to requirement SR-SYS-5.2. In order to always fulfill these functions, the ground station should be independent of the power grid (so it should run for instance on batteries or have an emergency power generator), in case the grid goes down, the drones can still be controlled. If communications are lost, the drones will autonomously perform an emergency landing on their landing pads (requirement SR-ST-4.1 in Chapter 8).

Heavy Loads and Safety Area

When carrying the drones stacks and possibly the landing pads some safety measures must be taken. Workers should wear safety shoes and not carry, on their own, above the maximum recommended weight in order to avoid possible injuries. This was explained in detail in Subsection 10.4.2 and refers to risk 38 in Table 10.9. Loads above the recommended maximum load for that carrying posture, which can be estimated with [112], must be carried by more than one worker.

It is essential that a safety area around the location of the show is established and that no one is allowed 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 must be used. The workers inside the safety area should wear a safety helmet. In addition, the drones are 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 drone show 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, placed again in the carrying structures and brought to the landing pads.

Li-Po Battery

There are specific safety regulations regarding the handling and transport of li-po batteries that the drone show company should adhere to. In terms of handling, the batteries should be held by their body and not by their charging cables, which could damage soldered joints for instance. Note that holding drone by the body can only be done when the drone is turned off to avoid being injured by the propellers. Next to this, if the propellers suddenly stop while the drone is turned on then it can cause a shortout to the ESC. Handling the body while the drone is turned off mitigates risk 33. Before usage, as part of the safety checks, it should be checked that the batteries are not swollen or present visual damage, if they do then they should be discarded or repaired at a later stage. To mitigate risk 32, the batteries should be charged and transported in a fireproof location, such as a dedicated box or a li-po safe bag. For instance, the Zeee li-po Safe Bag can, for transportation, safely carry up to 25 li-po batteries[133].

Finally, the batteries should not be stored at high temperatures, this can be concerning for instance if they are stored or transported for a long period of time inside a truck or van in a hot climate. Charging should happen between 5C and 45C [134]. They should ideally be stored at room temperature (between 5C and 21C) and they should not reach more than 77C to avoid risks of catching fire [135]. This should be taken into account to ensure proper refrigeration during storage mostly in hot climates [136].

Note that these safety considerations should also be taken into account in case of charging multiple batteries together, which can have logistical advantages but more safety concerns. In addition, safety considerations of conductive charging through the landing pads as well as the safe handling of the charging pins when the battery is connected should also be looked into in detail once the system is developed further.

Pyrotechnic Payload Drones

In case pyrotechnic payloads are being used, they need to be safely loaded into the drone. This must be done one drone at a time and the drone cannot be placed back 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. Note that this is a general situation and that it works also in case of rain or wind since the safety tent is protected, in some other situations it could be possible to prepare the pyrotechnics directly at the landing pads. The pyrotechnic drones should be placed only after all other drones are ready on their pads to limit the amount of time the pyrotechnic loads stay on the grid. Depending on the amount and types 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 during landing (this is risk 41 in Table 10.9).

Pyrotechnic loads must be handled by certified personnel and pyrotechnic equipment must be labeled accordingly 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. Note that requirement SR-SYS-5.1, which ensures spectators are not hit by pyrotechnics, cannot be fulfilled yet with with the information available for the pyrotechnic payload module. A more detailed design will be needed to comply with this requirement which might add more safety measures to this section. For instance, if the range of pyrotechnics is less than the distance to the ground or public then this requirement can be fulfilled. This is left as a further consideration in Chapter 17.

14.5. Compliance Matrix for Logistics and Safety Requirements

Table 14.9 presents the compliance matrix for the requirements that can be verified from a logistics perspective, therefore if they are feasible logistically, not necessarily technically. Note that not all requirements of Table 14.1 and Table 14.8 are verified here, since those tables presented the relevant requirements for developing the method, however some of them have been verified already in other sections and are summarized in Chapter 16.

Table 14.9: Compliance matrix of logistics and safety

Tag	Requirement	Verified?
OP-AP-5	The drones shall be controlled by a ground station.	Yes
OP-AP-7	The minimum amount of drones in one show shall be 300 for outdoor shows.	Yes
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.	Yes
SP-ST-1.2.1	The pyrotechnics shall not reach spectators.	Post DSE 6
SR-SYS-5.2	The operator shall have an emergency stop button.	Yes

⁶This is left for a more detailed design phase since the pyrotechnic module for the Starling drone has not been designed yet. Pyrotechnic payloads such as in the KIA show [7] could fit the requirement, but a formal verification and validation has not yet been completed and is left as a further design recommendation.

Financial Overview and Market Comparison

To have a successful product for a company, it should be profitable. This means the price of a drone cannot be too low, as it will not be enough to cover all the costs, nor too high, as then not enough companies are interested in buying the product. This chapter starts with a recap of the financial requirements in Section 15.1. In Section 15.2, the production and maintenance costs of the designed drone are shown. Then, in Section 15.3, the return on investment is discussed. For the return on investment, it is assumed that project "One Thousand Little Lights" is a company that sells show drones to other companies, but does not organise the drone show themselves. After that, Starling will be compared with two other drones on the market in Section 15.4. Finally, the compliance matrix for finance is shown in Section 15.5.

15.1. Financial Requirements

Two requirements were set with regards to cost, which are shown in Table 15.1. The requirement COST-AP-1 determines the selling price and it is therefore very important to know if the product will be profitable with a selling price of €1,000. Requirement COST-AP-2 is more important for the customer as maintenance is a cost for them. If the design does not meet this requirement, it might be harder to find buyers due to higher maintenance costs of the drones.

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 no more than €650,

15.2. Production and Maintenance Costs

This section discusses the production and maintenance cost of the designed drone. In Table 15.2, the production costs are listed and in Table 15.3, the maintenance costs are presented. The costs written in these tables are discussed in the corresponding subsystem design chapters, except for the maintenance costs of the landing legs: it is assumed that during the life time of the drone one set of landing legs needs to be replaced, which is half of the legs of the drone. This value is a rough estimate and can be accurate and validated after performing tests on the drone. The structures department does not have any costs related to maintenance as the frame is designed to have a lifetime of a 1,000 flight hours.

Table 15.2 also contains a margin of 5% for the total production costs. This is taken into account because small things such as the machining of the frame to make a hole for electric wiring have not been taken into account. The exact cost of these small activities should be determined for a future design. Besides that, the heavy payload has not been determined in this project and is thus also not included in the production cost. The heavy payload has not been determined as the drone has the freedom to use many different payloads that satisfy the volume and mass requirements.

The results from the tables make it possible to compare Starling with the drone that is currently used by Anymotion Productions. This comparison is made in Table 15.4. The client mentioned that their current drones need replacement approximately every 2-3 years, due to the payload that is not state-of-the-art after this time and should be replaced. As the payload is fixed to the drone, this means that the entire drone has to be replaced¹. They also noted that they want to upscale their business to 200 drones very soon, which is why this number has been selected to make the comparison. From the table it can be seen that during the life time of a drone, Starling is 647.61 cheaper due to the lower purchase price. If Anymotion would choose to buy this drone when their current drones need to be replaced,

¹Personal communication with drone show expert, 11/06/2021.

they can save around €129,522.00. Because of the modular payload capability, these drones also do not have to be replaced every 2-3 years if the light payload should be changed which could increase the number of savings even more. Revenues from shows and other costs than purchase or maintenance for Anymotion Productions are not determined in this table as these will not change much if Anymotion Productions buys another drone than their current one and thus does not largely influence the money they can save. From this section, it can be concluded that it could be a profitable investment to buy the Starling drones, when replacement of the current drones is necessary.

Table 15.2: Production cost of one drone.

Department	Part	Production Cost	
Propulsion	Propellers	€ 17.42	
Propulsion	Motors	€ 181.00	
	Battery	€ 33.73	
Power	BMS	€ 50.00	
	ESC	€ 28.27	
CCE	PCBs	€ 190.31	
	Frame body (incl.	€ 90.00	
	payload mount)	C 30.00	
	Frame arms	€ 12.00	
Structures	Motor mounts	€ 72.00	
	Casing (incl. hinges)	€ 87.00	
	Payload light	€ 18.00	
	Payload heavy	€ N.A.	
	Long landing legs	€ 18.00	
Operations	Short landing legs	€ 18.00	
	Craters	€ 4.00	
Subtotal		€819.73	
Margin of 5%		€40.99	
Total		€860.72	

Table 15.3: *Maintenance cost of one drone.*

Department	Part	Maintenance Cost	
	Battery	€218.09	
Power	BMS	€-	
	ESC	€16.30	
	Long landing legs	€18.00	
Operations	Short landing legs	610.00	
	Craters	€ -	
Total		€252.39	

Table 15.4: Preliminary cost comparison between current drone of Anymotion and Starling²

Drone currently used by Anymotion Pro	Starling		
Current purchase price	€ 1,500.00	Purchase price	€ 1,000.00
Current minimum maintenance costs	€ 400.00	Maintenance costs	€ 252.39
Total	€ 1,900.00	Total	€ 1,252.39

Money saved per drone	€ 647.61
Money saved by buying 200 Starling drones	€ 129,522.00
upon replacement of the current drones	€ 129,322.00

15.3. Return on Investment

This section describes the return on investment and determines the number of drones that needs to be sold to reach break-even. A tool was made to determine preliminary development costs, the break-even point, return on investment and payback period.

Table 15.5 shows several costs involved in the design process after DSE. First, it was determined by the team that an additional 20 weeks were needed to finalise and test the drone design: 10 weeks for more detailed design and 10 weeks for prototypes and testing. This was based on the progress made during the past 10 weeks of the DSE. To continue with these 20 weeks of drone development, a similarly sized team of ten engineers was taken and an office size to work in was selected corresponding to this group size. Via the website Skepp [137], it was determined that 65 m^2 was needed. On average, office areas in the Netherlands cost $€132.00 \text{ per m}^2$ [138]. The average salary of an engineer was estimated on €4,000 per month [139].

The costs in Table 15.5 concern the production costs that were already discussed, but also transport costs and development costs. The transport costs are based on postal deliveries of packages the size and mass of the drone. The development costs are taken from literature, where some costs such as mold tooling were already taken into account in the production cost and were therefore left out from the development costs. This resulted in a short list

of costs as shown in the table under constant costs. Together with the rent of an office and labour costs the constant costs were determined to be €241,200.00.

Return on Investment =
$$\frac{\text{Revenue of Investment} - \text{Cost of Investment}}{\text{Cost of Investment}} \cdot 100\%$$
 (15.1)

Table 15.5: Preliminary cost estimation for future design: constant costs and variable costs.

Variable costs	
Production costs	€ 819.73
Margin production costs	€ 40.99
Transport costs per drone	€ 15.00
Total variable costs	€ 875.72
Constant costs	
Development costs	
- Industrial design	€ 6,800.00
- Prototyping	€ 3,000.00
- Certifications and testing	€ 21,000.00
- Packaging design	€ 1,700.00
Rent	€ 8,700.00
Labour	€ 200,000.00
Total constant costs	€ 241,200.00

Table 15.6: Estimated market share and feasibility of Starling.

Estimated number of shows per year	300	
Estimated number of drones in	40,000	
show industry around 2025	40,000	
Estimated replacement	25%	
rate per year	2370	
Estimated market share of Starling	3-10%	
Min. number of drones	300	
sold per year	300	
Max. number of drones	1000	
sold per year	1000	
Break-even point	1941 drones	
Max. payback period	6.5 years	
Min. payback period	2.0 years	

After that, in Table 15.6, the estimated market share, break-even point and payback period of Starling was determined. It was estimated that in 2025 there will be approximately 300 drone shows worldwide on a yearly basis with around 40,000 drones operating at different companies [21]. Determined from the life time of drones currently used in drone shows³, it was estimated that drones need to be replaced once every four years. This gave a replacement rate of 25%. It was estimated that the market share of Starling could be between 3-10%. This is based on the number of competitors that have been identified in Chapter 4, which was 9. Therefore, it is estimated that the highest market share that can be obtained in the coming years is 10%, but the worst case scenario is assumed to 3%, however this is a preliminary number that should be verified.

The break-even point was then calculated by dividing the total constant costs by the selling price and variable costs subtracted from each other, which is equal to 1941 drones. This resulted in a minimum payback period of 2.0 years and a maximum of 6.5 years, which is relatively feasible.

15.3.1. Landing Pad Investment

This subsection investigates the profitability of the investment in wireless charging landing pads. As was discussed in Chapter 10, if the landing pad is developed in-house a possible price could be $\[mathebox{\ensuremath{$}}\]$ 4000. If 300 pads are needed for 300 drones, the investment is $\[mathebox{\ensuremath{$}}\]$, 200,000. However, having a wireless charging landing pad will probably not increase the price of a drone show by a lot as it can only increase the duration of the show or have the ability to have two shows quickly after each other. In most of the cases that were determined in Section 4.1, a show only has to be performed once. The only case where a landing pad might be profitable is for theme park shows as these shows are often performed twice a day for a longer period of time. In that case it is possible to save manpower by keeping the drones and pads on the starting grid and perform shows with a couple of hours in between. Per show, it can save the cost of the workforce for the part-time workers which was calculated to be $\[mathebox{\ensuremath{$}}\]$ 112.82 for a show with 300

³Personal communication with drone show expert, 29/04/2021

drones in Chapter 14. If there are two shows performed per day where you only have to deploy the drones and landing pads once instead of twice (assuming they have to be stored overnight), the investment of &1.2 million will be profitable after 2157 shows. This is an incredibly large amount, which indicates that the wireless charging landing pad is unfortunately not profitable for most of the cases if its price remains as high as &4000.

15.4. Market Comparison

An investigation of the market opportunities for drone shows has been done in Section 4.4. This was done in Table 4.4 by looking at the specifications of other drones in this area of industry, namely Sparkl and UVify IFO. The specifications that are the most interesting for the customer have been taken from that table and can be found in Table 15.7. Starling has been added to this table to make a comparison.

It can be seen that Starling's weight is in between the other two drones, the flight time is similar and the battery and payload properties are similar as well. Furthermore, Starling is quite a bit faster, it can withstand high wind speeds and its control range is very large. To top it off, the drone will be available for only €1000 which is 33% and 40% cheaper than Sparkle and UVify IFO, respectively. The only property of Starling which may be less salable is its size, but this depends on how important this is in the eyes of the customer. Thus, to summarise the promising features of Starling: it is fast and lightweight, it can operate in heavy weather conditions, it has a large control range and it is very cheap.

Specifications	Sparkle	UVify IFO	Starling
Dimensions with propellers (cm)	45x45	40x40	63x72
Height (cm)	15.5	12.5	25
Weight (g)	1103	635	890
Weight (incl. battery) (g)	1706	1050	1470
Max. flight time hovering (min)	25	25	25
Max. airspeed (km/h)	72	60	122
Max. sustained wind speed (kts)	25	15	27
Max. control range (m)	500	1000	1200
RGB led (W)	10	27	6
Light strength (lumen)	550	840	600
Battery type	Lipo 4S	Lipo 4S	Lipo 4S
Battery capacity (mAh)	6750	4200	7000
Price (euro)	1500	1680	1000

Table 15.7: Market comparison: Sparkle vs UFify IFO vs Starling

15.5. Compliance Matrix for Financial Requirements

Table 15.8 presents the compliance matrix for the financial requirements: these are related to the production and maintenance costs of the drone. Both of the requirements are verified, as described in Table 15.2 with a production cost of €860.72 and in Table 15.3 with a maintenance cost of €252.39.

Table 15.8: Compliance matrix of the financial requirements.

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

Overall Compliance Matrix & Sensitivity Analysis

To have a clear overview of all the requirements, it was decided to collect the compliance matrices in one big compliance matrix of all subsystems and departments. The compilation of all matrices is displayed in Table 16.1, which contains a description of each requirement, their tag, whether they are verified, and which section of the report have discussed them. The requirements are either marked with a 'yes', 'Depends on client' or 'Post DSE'. In this chapter the overall compliance matrix is presented in Section 16.1, and the sensitivity analysis is presented in Section 16.2.

16.1. Compliance Matrix

In this section the compliance matrix is presented. It can be noted how the verification of seven requirements had to be postponed to the post-DSE phase, while three requirements depend on the client that is to use the drone.

Table 16.1: Complete Requirements table

Tag	Requirement	Status	Sections
AD-AP-1	The drones shall be able to fly in 6BFT wind conditions.	Yes	6.4 6.9 9.3
AD-AP-2	The drones shall be able to fly in rainfall up to 10mm/hour	Yes	6.3 6.9 11.3
AD-ATC-5	Operations shall continue up to a height of 1000 m	Yes	6.4 6.9
AD-NR-4	Noise level shall be less than 80decibels at 1 meter from the drone	Yes	6.3 6.9
AD-SYS-5.1	The drone shall be operable in a pressure range between 101325 Pa and 89401 Pa	Yes	6.4 6.9
AD-SYS-6	The drone shall be operable in a temperature range between 3 deg and 40 deg	Post DSE	6.4 6.9 7.6 8.9
			9.3 12.2.5
AD-SYS-8	The drones shall not affect other drone performance	Yes	6.3 6.9
AD-SYS-9	The drones shall be able to fly in formation at 2m distance from each other	Yes	6.3 6.9
CCE-AP-2	The show location shall be at most 1000m apart from the ground station	Yes	14.1 7.3 7.6
CCE-AP-2.1	There shall be an undisturbed communication to the furthest drone at 1200 m distance.	Yes	8.3 8.4 8.9
CCE-AP-3	The drones shall be recharged wirelessly through their landing pads	Yes	10.7 7.3 7.6
CCE-AP-4	The drones shall be able position themselves within 0.5m accuracy	Yes	8.4 8.9
CCE-SYS-3.1	The drone shall be able to charge during rain	Yes	10.7
CCE-SYS-3.2	The drone shall be able to recharge autonomously on the landing pad between preparation and show.	Yes	10.7 7.6
CCE-SYS-7	The drone telemetry shall be monitored	Yes	8.3 8.9
CCE-SYS-8	Choreography shall be executed.	Yes	8.5 8.9
CCE-SYS-9	The drones shall be able to be manually controlled.	Yes	8.3 8.9
COST-AP-1	The drones shall cost no more than 1000,- per piece.	Yes	9.3 15
COST-AP-2	The expected cost of replacing parts in 1000 light shows shall be no more than 650,	Yes	15
OP-AP-1	An employee who has followed a one-day training shall be able to replace parts of a drone	Post DSE	12.3.3
OP-AP-2	The drones shall be suitable for mass transport	Yes	10.4 10.7 7.6
OP-AP-2.1	The drones shall safely be stacked on each other	Yes	10.4 10.7
OP-AP-2.2	The volume of the drones shall not exceed 0.5m ³	Yes	11.3
OP-AP-2.3	The drone shall be stored rigidly in a shock-free container	Yes	10.4 10.7
OP-AP-3	The drones shall be available in the year 2025	Yes	12.3 8.9
OP-AP-4	The drones shall be operated from a central location	Yes	8.3 8.9
OP-AP-5	The drones shall be controlled by a ground station	Yes	14.1 14.4
OP-AP-6	The area off the take-off zone shall be at most 1 m2 per drone	Yes	6.4 6.9 11.3
OP-AP-7	The minimum amount of drones in one show shall be 300 for outdoor shows	Yes	14.1 14.2 8.3
OP-AP-8	The minimum amount of drones in one show shall be 20 for indoor shows, where 'indoors' means	Yes	14.1 14.4 8.3
	venues such as concert halls or stadium		
OP-GB-9	The drones shall adhere to drone regulations	Depends	12.2.11
		on client	
OP-SYS-10	The energy supply's discharge rate shall be verifiable before every flight	Yes	8.3 8.9
POP-AP-2	The drones shall be able to achieve a velocity of 20m/s.	Yes	6.4 6.9 9.3
POP-AP-3.1	The drones shall be able to fly for 15 minutes for preparations and checkups.	Yes	7.6
POP-AP-3.2	The drones shall be able to fly for 15 minutes of showtime with a heavy payload.	Yes	7.6
POP-AP-3.8	The drones shall be able to fly for 20 minutes of showtime with a lights as a payload.	Yes	7.6
POP-SYS-2.2	The drones shall have a minimum thrust over weight ratio of 3.	Yes	6.4 6.9
POP-SYS-3.7	The energy storage shall be fully charged within 60min.	Post DSE	7.3 7.6

Table 16.1: Complete Requirements table

Tag	Requirement	Status	Sections
POP-SYS-4	Partial failure of the propulsion unit shall not prevent the drone from being able to perform an emergency landing.		6.4 6.9
SP-AP-1	The drones shall be able to carry changeable payloads	Yes	9.4
SP-AP-1.1	The light source shall be visible in urban darkness over a distance of 4km	Yes	9.4
SP-AP-1.2	The pyrotechnics shall weigh no more than 0.6kg	Yes	9.7
SP-AP-1.3	A megaphone or speaker shall be included in the drones	Yes	9.7
SP-AP-1.4.1	Future innovations shall have specifications up to a weight of 0.6kg	Yes	9.7
SP-AP-1.4.2	Future innovations shall have specifications up to a 20W power consumption	Yes	7.6
SP-AP-1.4.3	Future innovations shall have specifications up to dimensions of 20cm x 20cm x 20cm	Yes	10.4 11.3
SP-EO-2	Drones shall not sink in the water	Depends	12.2.6
		on client	
SP-ST-1.2.1	The pyrotechnics shall not reach spectators	Post DSE	14.4 9.7
SP-SYS-1.3.1	The megaphone or speaker shall have a power consumption of 20W	Yes	7.3 7.6
SP-SYS-1.1.1	The drone shall have an RGB Illumination	Yes	9.7
SP-SYS-1.2.2	The pyrotechnics shall not cause the drone's center of gravity to move outside of the stability and controllability margins	Yes	12.2.4
SP-SYS-1.5	Structures shall accommodate power unit	Yes	9.7 11.3
SP-SYS-1.6	Structures shall accommodate electronics	Yes	9.3 11.3
SP-SYS-4.1	Any structural part of the frame shall not experience plastic deformation under flight conditions	Yes	9.3
SP-SYS-6	The drone body should be tolerable to transportation and in-flight vibrations	Post DSE	9.7 11.3
SR-AP-1	An unintentional collision with the ground shall happen at most once every 1,000,000 flight hours when flying indoors	Post DSE	12.2.9
SR-AP-2	An unintentional collision with the ground shall happen atmost once every 100,000 flight hours when flying outdoors	Post DSE	12.2.9
SR-AP-3	Malfunctioning of a single drone shall not endanger the entire show	Depends on client	12.2.9
SR-AP-4	The connection to the drones shall not be lost during any show, also in urban environments	Yes	8.3.2
SR-AP-5	In case of emergency, the drones shall be able to land safely in less than 90 seconds	Yes	12.2
SR-AP-6	Each drone shall have a lifetime of at least 1000 flight hours	Yes	12.3 9.3
SR-APC-7	The connection between the ground station and the drone shall be secure.	Yes	8.3 8.9
SR-ST-4.1	Show shall safely end if connection is lost	Yes	14.4 8.3 8.9
SR-SYS-5.1	Emergency landing will occur autonomously.	Yes	12.2.9
SR-SYS-5.2	The operator shall have an emergency stop button	Yes	14.4 8.3 8.9
SR-SYS-8	The drone's electronics and propulsion system shall remain operational under raining conditions of up to 10mm/hr.	Yes	11.3
SUS-AP-1	The drones shall be powered by renewable energy sources.	Yes	7.6
SUS-AP-2	There shall be no radioactive parts on board of the drone.	Yes	12.3
SUS-EO-3	At least 80% of drone mass shall be recyclable.	Yes	12.3 9.3 6.4 6.9 8.4 8.9 9.7
SUS-EO-4	The drone shall not break down into small parts.	Yes	9.7
SUS-EO-6	The components of the energy storage shall not contaminate the environment.	Yes	7.3 7.6
SUS-EO-7	Power supply failure during operation of the drone shall not result in release of any toxic substances outside of the system.	Post DSE	12.3
SUS-NR-6.1	The drone shall not leave any trash on the ground.	Yes	12.3
			_

16.2. Sensitivity Analysis of Final Design

The sensitivity analysis is done to observe how feasible the final design is. It is crucial to know how changes in parameters affect the performance of the drone, and whether the drone will still meet the requirements when certain changes are made. The sensitivity analysis will be done by changing one parameter at a time, and calculating the changes to other relevant parameters. For all parameters, a deviation of 10% was assumed to evaluate the changes. Note that 10% is a relative large deviation, however this is done to apply an extra safety margin.

16.2.1. Change in Frame Mass

Manufacturing imperfections may occur. The weight of the frame may increase or decrease as a result. This will have either a negative or positive impact on the flight time. In this case, frame weight will have a direct impact on the power required for the motors, which impacts the flight time. For simplicity's sake, only the hovering time will be considered. The hovering time is based on hovering with a light payload and no payload power consumption. A larger frame mass will increase the total mass. In this case, a change of 10% of frame mass was considered. The nominal frame mass

is 330g. In Table 16.2, it can be seen how changes in the frame mass affect the power required, and total hover time.

It can be seen that a 10% increase in frame mass results in an increase of 1W for the motor's power required and a decrease in hover time of 2.3%, or approximately half a minute. This can be considered as acceptable. In the ideal case, for a 10% decrease in frame mass, the motor power required decreases by 1W and the hovering time is 2.5% longer. However, it should be noted that if the frame is lighter this may go at the cost of structural integrity. In short, it can be said that a 10% change in frame mass does is not very sensitive to the performance of the drone.

16.2.2. Changes in Battery Capacity and Power Required

The battery capacity may not be exactly as is stated in the battery specifications. In case the battery capacity is increased or decreased, and all other parameters stay the same, the flight time will change. Logically, increasing the battery capacity while having the same battery mass, will increase the hovering time, and vice versa. Similarly, for power, it may be that the power required for some components is more, or less than stated in the specifications. This will also have an effect on hovering time. If the power required decreases, the flight time will be longer, and vice versa. The result of this analysis is presented in Table 16.3.

The battery capacity is directly proportional to the hovering time. A 10% increase or decrease in battery capacity results in a 14% increase, or 10% decrease in hovering time, respectively. The power required is inversely proportional to the hovering time. In this case, if the power required is increased or decreased by 10%, the hovering time decreases by 9%, or increases by 11%, respectively. From this can be concluded that changes in battery or power required have a significant impact on the flight performance.

16.2.3. Changes in Thrust

The motors may have some inaccuracy in the RPM and maximum thrust it can provide. Changes in thrust will have an effect on the maximum velocity and acceleration of the drone. The thrust to weight ratio will increase linearly with the increase in thrust, assuming that the weight of the drone remains constant. The result of the thrust sensitivity analysis is presented in Table 16.4.

In case the maximum thrust is increased and all other parameters are constant, this is positive since the maximum velocity is higher. However, if the maximum thrust is less than advertised, requirement POP-AP-2 may not be met. If the maximum thrust is 10% less than is specified, the maximum velocity will decrease by approximately 5%. This is not a relative large change, however if the drone's maximum velocity is 32.07 m/s, the drone will not be able to fly 20m/s in 6BFT wind conditions, thus requirement POP-AP-2 is not met. The maximum velocity would be 18.3 m/s in this case, which is acceptable considering the fact that 6BFT wind conditions are very unlikely.

A more detailed sensitivity analysis may be done during the post-DSE activities. In a continuation of the sensitivity analysis, the change in show time could be included instead of the hovering time.

Table 16.2: Frame mass sensitivity analysis

	Frame mass [g]	Power required per motor [W]	Hovering time [s]
Nominal	330	41	1535
10% mass increase	363	42	1500
10% mass decrease	297	40	1573

Table 16.3: Power sensitivity analysis

	Battery capacity [Wh]	Power required [W]	Hovering time [s]
Nominal	103.6	167	1535
10% capacity increase	113.96	103.6	1749
10% capacity decrease	93.24	103.6	1383
10% power required increase	167	183.7	1396
10% power required decrease	167	150.3	1707

Table 16.4: Propulsion sensitivity analysis

	Maximum thrust [N]	T/W	Maximum velocity [m/s]
Nominal	22.96	3	33.8
10% thrust increase	25.26	3.3	35.45
10% thrust decrease	20.66	2.7	32.07

Post-DSE Planning

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 performed 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. First, the recommendations that still need to be considered because of time constraints should be researched before the design can be confirmed. These can be divided in the different departments. All the recommendations can be found in Table 17.1.

Table 17.1: Design recommendations

Department	Recommendation	
Aerodynamics & Propulsion	Consider more motor and propellers combinations	
Actodynamics & Fropulsion	Further optimise aerodynamic shape	
Power	Size and select Battery Management System	
Fower	Investigate DJI drone hovering power required for more accurate verification	
	Research how rain affects link budget	
	Develop the Kalman filter for the controller	
CCE	Optimize the simulation code	
	Implement automatic PID tuning	
	Implement advanced controller for when one engine is broken	
	Design cable architecture and analyse effect of cable holes	
	Investigate compability cables from payload with cables in the drone	
	Perform research into different types of thread and bonding/resin types	
	More detailed research into propeller-frame clearance	
Structures	Design pyrotechnics module to verify safety of audience	
	Investigate whether the screws used are strong enough	
	Consider using a propeller casing for indoor flying	
	Consider filling up the battery compartment with compressible material	
	Research whether drone can be made from the recycled PP	
	Perform dynamic analysis for landing loads	
	Include margins in the design for production	
	Perform FEA on the body to reduce the plate thickness	
	Consider safety cage around propeller for indoor shows	
Operations	Consider ways of charging an entire stack of drones at the same time	
	Develop conductive charging landing pad and charging mechanism in more detail	
	Design carrying structure and transport boxes in detail	

After these recommendations are all researched and decisions have been made the design can be confirmed. After the first prototype it is important that all the calculations done in the design process are validated as well. After the drone is fully tested, some other external part have to be designed or chosen before setting up the entire manufacturing process. This consists of the ground station, the UWB tags, the carrying structure, the landing pad and the software for the flight computer. This last one can be self-written or bought from existing companies.

17. Post-DSE Planning Group 17 - DSE

17.2. Post-DSE Activities

In this section the activities which have to be performed after the project One Thousand Little Lights are presented. All the activities in Figure 17.1 are presented in the order in which they will be performed. After that the project Gantt chart is shown in Figure 17.2. It is a loop in the sense that after the drone is made available on the market, new versions should be developed to keep up with the competition.

In the project Gantt chart the planning with dates can be seen. According to this planning the entire production of the drones can be setup in the end of 2023. This means that after this the drones can be produced in 2024 and the first shows can be performed in the year 2025. Some parts have been given longer than it is expected to take, but if anywhere during the process it turns out that it does not meet the requirements some parts has to be repeated. Therefore, this is taken into account in the time schedule.

The cost breakdown structure is shown in Figure 17.3. Most of the costs have been explained in Chapter 15. These costs are then split into smaller parts. For testing the budget is divided between the different tests. These percentages can be found in Table 17.2. The performance, strength and flight behaviour tests are considered to be the most important, so focus lies on those. Communication is also an important test, but it will probably be a bit cheaper. The tightness and aerodynamic test will be performed in a very basic matter, because for example doing a test in a wind tunnel is going to be too expensive and it is expected that when using for example flow-visualization paint it will result in an acceptable test. The difference between the cost for the manufacturing for the first drone comes from the fact that the entire production chain is not yet setup resulting in higher cost and also it may have to be repeated when it turns out the requirements are not met. This is taken into account in every cost in the diagram.

Table 17.2: The cost divided between the different tests

Type test	Percentage	Cost
Performance	25.00%	3930
Strength	25.00%	3930
Tightness	5.00%	786
Aerodynamic	5.00%	786
Flight behaviour	25.00%	3930
Communication	15.00%	2358
Total		15720

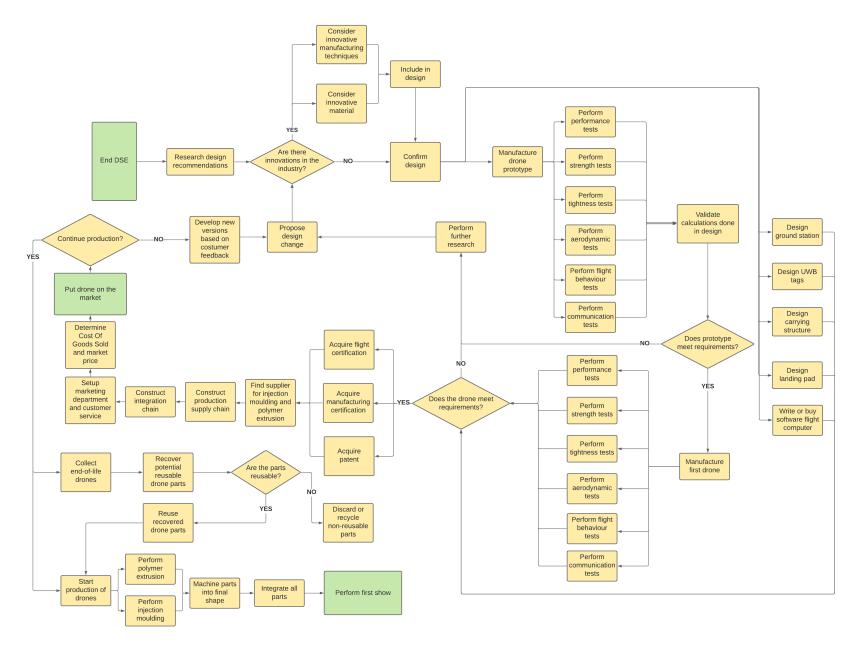


Figure 17.1: Project design and development logic diagram

134

Figure 17.2: Project Gantt Chart

17. Post-DSE Planning Group 17 - DSE

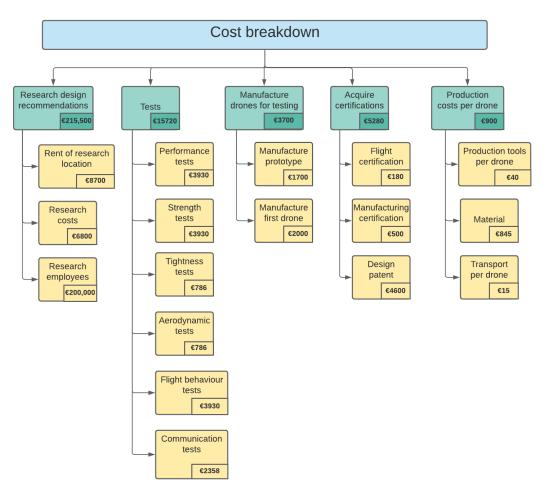


Figure 17.3: Cost breakdown structure

Conclusion

The goal of this report is to present the detailed design phase of the project One Thousand Little Lights. This was done by further designing the concept which was picked in the midterm report [4]. This was done by designing every sub-component of the drone and then checking if it meets the requirements set in the baseline report [3]. In the end, all these components were integrated after which the entire drone could be analysed and again checked whether it meets all the requirements. This resulted in the final design called Starling.

Starling has met all the requirements on subsystem level, expect POP-SYS-3.7, which states that the drone should be fully charged within 60 minutes. This is confirmed for charging by wire, but can not yet be verified for the wireless charging. On the system level Starling meets all requirements. Starling is a drone with four, unconnected and fixed arms. On every arm there is a brushless motor with a propeller with 2 blades. It has a li-po battery which gives the drone the ability a flight time of up to 20 minutes. When the drone is equipped with the heaviest payload it can carry, which can be up to 600 grams and 20 W, it can fly for up to 15 minutes. This payload can be interchanged to any payload up to a size of 20x20x20 cm, including payloads like lasers, megaphones and pyrotechnics. Starling has a lifetime of at least 1000 flight hours. It uses GPS with real time kinematics as positioning system for the outdoor shows and for the indoor shows it uses ultra-wideband. Communication with Starling happens through Wi-Fi, when manual control is needed. Normally, the choreography of the show will be fully pre-programmed on the drones before the shows.

The frame is made of polypropylene, which allows the drone to be over 80% recyclable, together with the fact that the propellers and landing gear can be removed. There is a short and a long landing gear available, which can be interchanged depending on the required payload. This also improves the stackability, which has a positive effect on the way Starling can be transported. Starling can be stacked with 6 drones on top of each other, which can be carried by one employee. This employee can also learn to maintain the drones with only one day of training. All the subsystems are integrated through the frame of the drone. The flight controller, BMS and ESC are placed inside the main body, while the radio, UWB, Wi-Fi and GPS receivers are placed on the top side to improve signal reception. The battery is stored in its own compartment and can be easily taken out by pressing down a spring-loaded pin. The drone has the feature that it can charge itself with conductive charging on the landing pad, next to the normal wired battery charging. A render of Starling can be found in Figure 18.1. The planning is that Starling is available on the market mid-2024, so the first shows can be performed in 2025.



Figure 18.1: Render of Starling

18. Conclusion Group 17 - DSE

Some recommendations can also been made. For every department it can be seen that some more detailed research in a part of the design needs to be done. These recommendations can be found in Table 18.1. After these recommendations a prototype of the drone can be made and tested. This can also be used to validate all the calculations done in the design process. After that the actual drone can be made, for which all the requirements can be checked. If this reaches all those requirements then some other external parts have to be designed or chosen to comply with Starling. This consists of the ground station, UWB tags, carrying structure, landing pad and the software for the flight computer. After this the supply chain can be setup, the market price determined and finally put out onto the market.

Table 18.1: Design recommendations

Department	Recommendation	
Aerodynamics & Propulsion	Consider more motor and propellers combinations	
Aerodynamics & Propulsion	Further optimise aerodynamic shape	
Power	Size and select Battery Management System	
Fower	Investigate DJI drone hovering power required for more accurate verification	
	Research how rain affects link budget	
	Develop the Kalman filter for the controller	
CCE	Optimize the simulation code	
	Implement automatic PID tuning	
	Implement advanced controller for when one engine is broken	
	Design cable architecture and analyse effect of cable holes	
	Investigate compability cables from payload with cables in the drone	
	Perform research into different types of thread and bonding/resin types	
	More detailed research into propeller-frame clearance	
Structures	Design pyrotechnics module to verify safety of audience	
	Investigate whether the screws used are strong enough	
	Consider using a propeller casing for indoor flying	
	Consider filling up the battery compartment with compressible material	
	Research whether drone can be made from the recycled PP	
	Perform dynamic analysis for landing loads Include margins in the design for production	
	Perform FEA on the body to reduce the plate thickness	
	Consider safety cage around propeller for indoor shows	
Operations	Consider ways of charging an entire stack of drones at the same time	
	Develop conductive charging landing pad and charging mechanism in more detail	
	Design carrying structure and transport boxes in detail	

Bibliography

- [1] J. Maas. Project guide Design Synthesis Exercise: 'One Thousand Little Lights'. Apr. 2021.
- [2] Group 17. 'One Thousand Little Lights' Project Plan. Apr. 2021.
- [3] DSE Group 17. One Thousand Little Lights: Baseline Report. Apr. 2021.
- [4] DSE Group 17. One Thousand Little Lights: Midterm Report. May 2021.
- starlingsintheuk. Starling Murmuration Frequently Asked Questions. 2021. URL: https://www.starlingsintheuk.co.uk/faq-section.html.
- [6] 50 Years of Record Breaking Innovation | Drone Light Show | Intel. 2018. URL: https://www.youtube.com/watch?v=x wQ31-vSgfs&ab_channel=Intel.
- [7] 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.
- [8] Intel Drone Light Shows. Illuminate Your Story. 2021. URL: https://inteldronelightshows.com/.
- [9] S. van der Gaag. 3-2-1...samen tellen we af! Luid het nieuwe jaar in met spectaculaire droneshow op AD.nl. 2020. URL: https://www.ad.nl/rotterdam/3-2-1-samen-tellen-we-af-luid-het-nieuwe-jaar-in-met-spectaculaire-droneshow-op-ad-nl~abba599bc/.
- [10] 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/.
- [11] 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.
- [12] Echo Zhan. 600 drones create dazzling Van Gogh animation across night sky. 2021. URL: https://www.guinnessworldrecords.com/news/commercial/2021/2/600-drones-create-dazzling-van-gogh-animation-across-night-sky-645910.
- [13] Anymotion Productions. Drone Light Shows. 2021. URL: https://droneshow.nl/.
- [14] AO Technology. AO Lighting Technology. 2021. URL: https://www.ao-technology.com/.
- [15] CollMot Entertainment. Drone Light Shows. 2021. URL: https://collmot.com/.
- [16] Damoda Intelligent Control Technology. Shenzhen Damoda Intelligent Control Technology. 2021. URL: https://en.dmduav.com/.
- [17] DroneShow Events. DroneShow Events. 2021. URL: https://www.droneshowevents.nl/index.html.
- [18] Dronisos Entertainment. Drone Light Shows. 2021. URL: https://www.dronisos.com/.
- [19] Geoscan Group. Drone Light Shows. 2021. URL: https://geoscan.show/.
- [20] Skymagic. Drone Light Shows. 2021. URL: https://skymagic.show/.
- [21] NajmIbraheem KasimIbraheem Aws Abdulsalam. "DRONES MARKET GROWTH, TRENDS, COVID-19 IMPACT, AND FORECASTS (2021 2026)". In: *Engineering Science and Technology, an International Journal* (2020).
- [22] Trouw. Nog nooit werd zoveel vuurwerk verkocht: omzet 77 miljoen euro. 2019. URL: https://www.trouw.nl/nieuws.
- [23] Huib Valkenburg and Susanne Nijman. Ongevallen met vuurwerk, Jaarwisseling 2019-2020. Jan. 2020.
- [24] Sandy Smith. How Big of a Health Risk Are Public Fireworks Displays? 2015. URL: https://www.ehstoday.com.
- [25] Tim Kraaijvanger. Hoe vervuilend is vuurwerk voor het milieu? 2018. URL: https://www.scientias.nl.
- [26] Premier Pyrotechnics Inc. Six Levels of Service. 2017. URL: http://premierpyro.com.
- [27] statista. statista. 2021. URL: https://www.statista.com/topics/990/global-advertising-market/.
- [28] businesswire. Worldwide Billboard and Outdoor Advertising Industry to 2030 Identify Growth Segments for Investment. 2021. URL: https://www.businesswire.com/.
- [29] Sparkl Drones. Sparkl one. 2019. URL: https://files.ugcs.com/s/baX2DWgxR2SXYgN.
- [30] UVify. Swarm Light Show Drone: IFO. 2019. URL: https://files.ugcs.com/s/LDHRgQJTqREF7A4.
- [31] Mauro Gatti. "Complete Preliminary Design Methodology for Electric Multirotor". In: Journal of Aerospace Engineering 30.5 (2017), p. 04017046. DOI: 10.1061/(ASCE) AS.1943-5525.0000752. eprint: https://ascelibrary.org/doi/pdf/10.1061/\%28ASCE\%29AS.1943-5525.0000752. URL: https://ascelibrary.org/doi/abs/10.1061/%5C%28ASCE%5C%29AS.1943-5525.0000752.
- [32] El-Sayed Aziz et al. "AC 2008-613: ONLINE WIND TUNNEL LABORATORY". In: (June 2008), pp. 16–17.
- [33] Carl Russell et al. "Wind Tunnel and Hover Performance Test Results for Multicopter UAS Vehicles". In: (May 2016), pp. 16–17.
- [34] Narayanan Komerath Dhwanil Shukla. "Multirotor Drone Aerodynamic Interaction Investigation". In: (Nov. 2018), p. 13.
- [35] FAA. "Advisory Circular 90-23F". In: (Oct. 2014), p. 14.

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

- [37] Causes of aircraft noise. 2021. URL: https://corporate.aucklandairport.co.nz/sustainability/managing-aircraft-noise/understanding-aircraft-noise/causes-of-aircraft-noise.
- [38] Noise level calculations. URL: https://www.hoevelakenbereikbaar.nl/www2/MilieuZaken/Geluid_lawaai/Noise%5C%20level%5C%20calculations.pdf.
- [39] Raindrop. 2012. URL: https://glossary.ametsoc.org/wiki/Raindrop.
- [40] Quadcopter Dynamics and Simulation. 2001. URL: https://www.uu.edu/dept/physics/scienceguys/2001Mar.cfm.
- [41] De complete windschaal van Beaufort. 2021. URL: https://www.weerstationuithuizermeeden.nl/Schaal-van-Beaufort.htm.
- [42] Quan Quan. "Introduction to Multicopter Design and Control". In: (Dec. 2016), p. 393.
- [43] Robotshop.nl. May 2021. URL: https://www.robotshop.com/nl/nl/uav-drone-motors.html.
- [44] Innov8tive designs. May 2021. URL: https://innov8tivedesigns.com/products/brushlessmotors/cobramultirotormotors.html.
- [45] T-motor. May 2021. URL: https://store-en.tmotor.com/category.php?id=2.
- [46] MCM Racing. May 2021. URL: https://www.mcmracing.com/nl/974-moteur-brushless-drone.
- [47] Lydia Heida. "Boom time for carbon fiber recycling". In: (Sept. 2016).
- [48] Eco-Cycle. A-Z Recycling Guide Electric Motors. URL: http://www.ecocycle.org/a-zguide/electric-motors.
- [49] Finding Drag Coefficient using Solidworks Flow Simulation. URL: https://webpages.uidaho.edu/mindworks/Adv %5C%20Solidworks/CFD/Drag%5C%20coefficient%5C%20of%5C%20sphere%5C%20-%5C%20Final.pdf.
- [50] Pascal Simon. 6 Important Parameters for the Design-In of Lithium Polymer Batteries. Sept. 2019. URL: https://www.jauch.com/blog/en/.
- [51] Lipo Battery Database. URL: https://www.notion.so/b57745bb5d2a4fb8a3612e88a4a87738?v=ae41b4f22dba4d33ae574d7a173e0f3a.
- [52] Z. M. Salameh and B. G. Kim. "Advanced lithium polymer batteries". In: 2009 IEEE Power Energy Society General Meeting (2009). DOI: 10.1109/pes.2009.5275404.
- [53] BU-808: How to Prolong Lithium-based Batteries. URL: https://batteryuniversity.com.
- [54] R. Spotnitz. "Simulation of capacity fade in lithium-ion batteries". In: Journal of Power Sources 113.1 (2003), pp. 72-80. ISSN: 0378-7753. DOI: https://doi.org/10.1016/S0378-7753(02)00490-1. URL: https://www.sciencedirect.com/science/article/pii/S0378775302004901.
- [55] Battery Life (and Death). URL: https://www.mpoweruk.com/life.htm.
- [56] URL: http://www.drivecalc.de/.
- [57] Battery management system. June 2021. URL: https://en.wikipedia.org/wiki/Battery_management_system.
- [58] Infineon Technologies AG. Battery Management System (BMS). URL: https://www.infineon.com/cms/en/applications/solutions/battery-management-system/.
- [59] Battery Management Systems (BMS): Battery Packs for UAV UGV Systems. URL: https://www.unmannedsystemstech nology.com/category/supplier-directory/propulsion-power/battery-management-systems-battery-packs/.
- [60] 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.
- [61] What Is A Battery C Rating How Do I Calculate C Rate. Mar. 2021. URL: https://www.power-sonic.com/blog/what-is-a-battery-c-rating/.
- [62] Saeed Arabi and Behrouz Shafei. "Multi-stressor fatigue assessment of steel sign-support structures: A case study in Iowa". In: *Engineering Structures* 200 (2019), p. 109721. DOI: 10.1016/j.engstruct.2019.109721.
- [63] 30.5*30.5mm Racerstar Air50 3-6S 50A 4In1 ESC Built-in Current Sensor BLheli_SD Shot600Compatibled with Air F7Lite. URL: https://www.banggood.com/.
- [64] Mavic 2 Product Information DJI. URL: https://www.dji.com/nl/mavic-2/info#specs.
- [65] Bogna Szyk. Drone Flight Time Calculator. June 2018. URL: https://www.omnicalculator.com/other/drone-flight-time.
- [66] Communication Options for Network RTK. 2005. URL: http://www.wasoft.de/e/iagwg451/wegener/communication.html.
- [67] DECAWAVE. DWM1000 Module. URL: https://www.decawave.com/product/dwm1000-module/.
- [68] Electronic Communications Committee (ECC). THE EUROPEAN TABLE OF FREQUENCYALLOCATIONS AND APPLICATIONS IN THEFREQUENCY RANGE 8.3 kHz to 3000 GHz (ECA TABL. 2020. URL: https://docdb.cept.org/download/2051.

- [69] LoRa. 2005. URL: https://en.wikipedia.org/wiki/LoRa.
- [70] Link Budget Calculations and Choosing the Correct Antenna. 2015. URL: https://docs.aerohive.com/330000/docs/guides/Aerohive_LinkBudgetCalculations.pdf.
- [71] ActiveReach. Causes of wifi interference. URL: https://activereach.net/support/knowledge-base/connectivity-networking/wifi-interference/.
- [72] Guru 99. microcontroller_vs_microprocessor. 2021. URL: https://www.guru99.com/difference-between-microprocessor-and-microcontroller.html.
- [73] Mouser Electronics. 2021. URL: https://eu.mouser.com/.
- [74] Digi-Key SWDP.2458.15.4.A.02. 2021. URL: https://www.digikey.nl/.
- [75] TaoGlass. 2021. URL: https://www.taoglas.com/.
- [76] Tinytronics. 2021. URL: https://www.tinytronics.nl/shop/nl.
- [77] U-blox CAM-M8 series. 2021. URL: https://www.u-blox.com/en/product/cam-m8-series.
- [78] 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.
- [79] RS-online Electrolube transparent 15 ml Can Conformal Coating for PCBs. 2021. URL: https://nl.rs-online.com/.
- [80] JLC PCB. 2021. URL: https://jlcpcb.com/.
- [81] Quadcopter Dynamics and Simulation. 2012. URL: https://andrew.gibiansky.com/blog/physics/quadcopter-dynamics/.
- [82] Tony Lacey. *Tutorial:The Kalman Filter*. URL: http://web.mit.edu/kirtley/kirtley/binlustuff/literature/control/Kalman%5C%20filter.pdf.
- [83] Davi Castro Igor Prado, Mateus de Freitas Virgilio Pereira, and Davi Antônio dos Santos. *Asymptotically stable control for a nonlinear-based multirotor aerial vehicle model.* URL: https://www.researchgate.net/publication/3104688 43_Asymptotically_stable_control_for_a_nonlinear-based_multirotor_aerial_vehicle_model.
- [84] QuadmeUp. PID looptime: why it is not only about frequency. URL: https://quadmeup.com/pid-looptime-why-it-is-not-only-about-frequency/.
- [85] T.H.G. Megson. Aircraft Structures for Engineering Students Sixth Edition. ISBN 978-0-08-100914-7. Elsevier, 2017.
- [86] P.C.J. Hoogenboom and R. Spaan. "Shear Stiffness and Maximum Shear Stress of Tubular Members". In: *Department of Civil Engineering and Geosciences, Delft University of Technology* (2005).
- [87] Engineering Toolbox. Air Density calculator based on ISA. 2020. URL: https://www.engineeringtoolbox.com/air-density-specific-weight-d_600.html.
- [88] Brennan caltech. *Drag on a sphere and cylinder*. 2020. URL: /http://brennen.caltech.edu/fluidbook/externalflows/drag/dragonasphere.pdf.
- [89] GetFPV. FPV Drone Wire Sizes and Cable Management. 2020. URL: https://www.getfpv.com/learn/fpv-essentials/fpv-drone-wire/.
- [90] Jerrin Bright et al. "Optimization of quadcopter frame using generative design and comparison with DJI F450 drone frame". In: *IOP Conference Series: Materials Science and Engineering* (2021).
- [91] 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.
- [92] By Design: Polypropylene part design, Part 1. 2002. URL: https://www.plasticstoday.com/materials/design-polypropylene-part-design-part-1.
- [93] ANSYS(CES) Granta EduPack. 2021. URL: https://www.ansys.com/products/materials/granta-edupack.
- [94] 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.
- [95] 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.
- [96] BRADY. Why does polypropylene float and repel water? 2021. URL: http://www.brady.eu/en-eu/related-information/sorbents-and-spill/spc-faq/faq-5.
- [97] 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.
- [98] Clear pp sheets shop. 2021. URL: https://benl.rs-online.com/web/p/plastic-sheets/2012785/.
- [99] FASYUAN. POKIENE 36 stuks Helm Zelfklevende Pads Sticker 18 Gebogen en 18 Platte Mounts voor Go pro Hero 1/2/3/, Suptig Sport Camera. URL: https://www.amazon.nl/POKIENE-stuks-Helm-Zelfklevende-Sticker/.

[100] 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.

- [101] Kevin Krisciunas and Don Carona. At What Distance Can the Human Eye Detect a Candle Flame? 2015. arXiv: 1507.062 70 [astro-ph.IM].
- [102] BESLED. Mi-Light LED Downlight Smart LED 6W RGB+CCT Aanpasbare Kleur Dimbaar Inbouw Rond Mat Wit Aluminium Ø120mm. URL: https://www.besled.nl/.
- [103] Calc Resource. Moment of Inertia of a Circular Tube Calculator. 2020. URL: https://www.calcresource.com/moment-of-inertia-ctube.html.
- [104] Skycharge. Skycharge. 2021. URL: https://skycharge.de/.
- [105] energysquare. Power by Contact Technology©. 2019. URL: https://energysquare.co/technology/.
- [106] C.C.P. Contact Probes. How Does a Pogo Pin Work? 2021. URL: https://www.ccpcontactprobes.com/application/how-does-pogo-pin-work.
- [107] 0868 SPRING-LOADED PIN WITH SOLDER CUP TERMINATION. 2021. URL: https://www.mill-max.com/products/pin/0868.
- [108] Grade 304 Stainless Steel: Properties, Fabrication and Applications. May 2021. URL: https://www.azom.com/article.aspx?ArticleID=2867.
- [109] Standard gauge for sheet and plate iron and steel. 1993. URL: https://www.law.cornell.edu/uscode/text/15/20 6.
- [110] Directive 90/269/EEC manual handling of loads. URL: https://osha.europa.eu/en/legislation/directives/6.
- [111] Ministerie van Sociale Zaken en Werkgelegenheid. What is the NIOSH method? 2021. URL: https://www.arboportaal.nl/onderwerpen/tillen-en-dragen/vraag-en-antwoord/wat-is-de-niosh-methode.
- [112] Calculating Recommended Weight Limit (RWL). 2021. URL: https://www.ccohs.ca/oshanswers/ergonomics/niosh/calculating_rwl.html.
- [113] Ameripack. Extreme environments require extreme cases. 2021. URL: http://www.ameripack.com/cases/AP5545-2 323/.
- [114] Henkel Adhesives. Adhesive technologies. 2021. URL: https://www.henkel-adhesives.com/nl/nl/producten/industri%5C%C3%5C%ABle-afdichtingsmiddelen/schroefdraadafdichting.html.
- [115] stratasysdirect. injection-molding-design-mistakes. 2021. URL: https://www.stratasysdirect.com/.
- [116] Nancy Hall. Terminal Velocity. 2021. URL: https://www.grc.nasa.gov/www/k-12/airplane/termv.html.
- [117] M.Sc. Kambushev K.M. ANALYSIS OF THE RELIABILITY OF DC BRUSHLESS ELECTRIC MOTORS WITH POWER UP TO 200WUSED IN MAVs. 2019. URL: https://stumejournals.com/journals/mtm/2019/6/257.full.pdf.
- [118] By Ben Coxworth. *Algorithm lets quadcopters keep flying on three or less propellers*. 2013. URL: https://newatlas.com/quadcopter-failure-algorithm/30031/.
- [119] Angelica Perzan. *Brushed vs Brushless motors*. 2019. URL: https://drive.tech/en/stream-content/brushed-vs-brushless-dc-motors.
- [120] SP Racing H7 extreme. 2021. URL: https://shop.seriouslypro.com/.
- [121] Betaflight. 2021. URL: https://betaflight.com/.
- [122] CSIRO. Lithium-ion battery recycling. 2020. URL: https://www.csiro.au/en/research/technology-space/energy/Energy-storage/Battery-recycling.
- [123] Preferred walking speed. 2021. URL: https://en.wikipedia.org/wiki/Preferred_walking_speed.
- [124] 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.
- [125] Allekabels.nl. Steekwagen tot 200 kg. 2021. URL: https://www.allekabels.nl.
- [126] Kruizinga. Magazijnwagen. 2021. URL: https://www.kruizinga.nl/magazijnwagen/magazijnwagens.
- [127] Truckland. Fiat Ducato. 2021. URL: https://www.truckland.nl/rent/bestelwagens/fiat-ducato.
- [128] Truckland. Truckland. 2021. URL: https://www.truckland.nl/rent/bakwagen.
- [129] Rijksoverheid. Minimum wage amounts 2021. 2021. URL: https://www.rijksoverheid.nl/onderwerpen/minimumloon/bedragen-minimumloon-2021.
- [130] Budgetyourtrip. How much does it cost to travel to The Netherlands? 2021. URL: https://www.budgetyourtrip.com/netherlands.
- [131] Bizbash. Pricing guide: Security. 2006. URL: https://www.bizbash.com.
- [132] Anymotion Productions. Frequent Asked Questions. 2021. URL: https://droneshow.nl/en/most-frequently-asked-questions/.
- [133] Zeee Lipo Safe Bag Vuurvaste, explosiebestendige tas, grote lipo-accu-opbergdoos, veiligheidstas voor het opladen en bewaren. URL: https://www.amazon.nl.

[134] Benzo Energy. The safe temperature for lithium-ion battery. 2019. URL: http://www.benzoenergy.com/blog/post/the-safe-temperature-for-lithium-ion-battery.html.

- [135] Large. Storing LiPo Batteries in Cold Weather- Storage methods. 2020. URL: https://www.large.net/news/8ju43nb.html.
- [136] LiPo Batteries and Safety for Beginners. 2018. URL: https://www.cnydrones.org/lipo-batteries-and-safety-for-beginners/.
- [137] Joost Lansink. Zoveel vierkante meter kantoorruimte heb je nodig per persoon. 2019. URL: https://skepp.nl/nl/blog/kantoorruimtetips/zoveel-vierkante-meter-kantoorruimte-heb-je-nodig-per-persoon.
- [138] Carlos Obdam. Wat is de gemiddelde huurprijs kantoorruimte per m2? 2019. URL: https://www.flexas.nl/blog/huurprijzen-kantoorruimte-waar-kun-je-op-rekenen.
- [139] Salaris Electrical Engineer. 2019. URL: https://www.nationaleberoepengids.nl/electrical-engineer.
- [140] Ektor Tsolodimos. ROI berekenen (calculator). 2021. URL: https://epsilonstudios.nl/blog/roi-berekenen-calculator#formule.

STARLING One Thousand Little Lights



Specification Sheet

Swarm Light Show Drone



Technical Specifications

Dimensions (W x L x H)	63 x 72 x 25 cm
Weight w/o battery	0.89 kg
Weight with battery	1.47 kg
Max payload weight	0.6 kg
Wind resistance	6 BFT
Max speed	33.8 m/s
Max altitude	1000 m
Max flight time light payload	25 minutes
Max charge time	1 hour
Control range	1200 m
Cost per unit	€846
Recyclability	Up to 85 %

Technical Specifications

Telemetry link	2.4 GHz WiFi
RTK correction link	860 MHz LoRa
RTK support	Yes
Hover accuracy indoors	10 cm
Hover accuracy outdoors	2.5 cm
RGB LED	6 W, 600 lumen
Battery type	Lithium-Polymer
Battery voltage	14.8 V
Battery capacity	103.6 Wh
Stack capacity	6 drones
Stack height	117 cm
Stack weight	12.5 kg