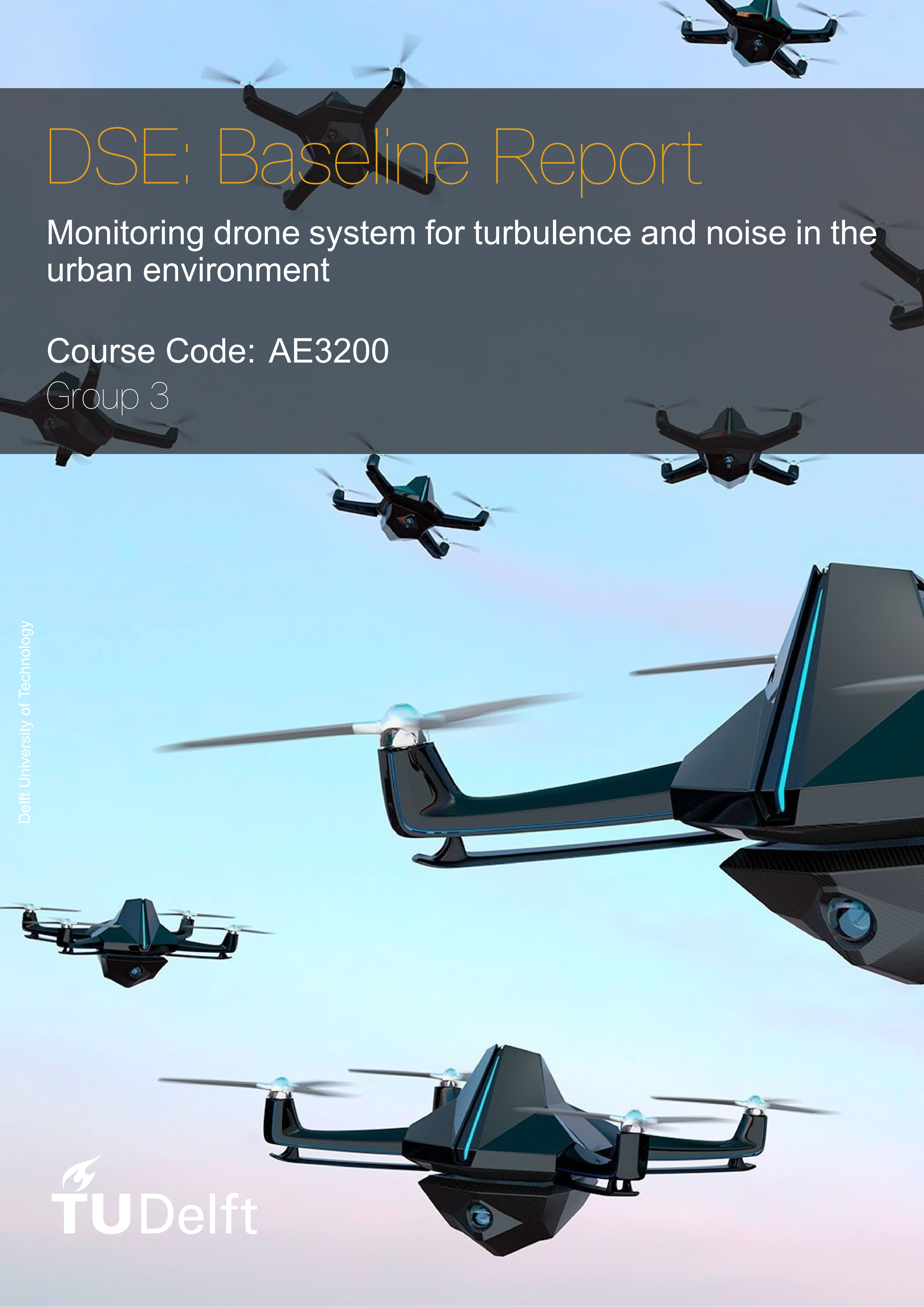
DSE: Baseline Report

Monitoring drone system for turbulence and noise in the urban environment

Course Code: AE3200

Group 3



Delft University of Technology

TU Delft

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by

Group 3

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Place:	Faculty of Aerospace Engineering, Delft
Date:	Friday 30th April, 2021
Version:	1.0
Genre:	Baseline Report

Cover Image: [3]

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Contents

List of Symbols

Abbreviation	Definition
BR	Budget risk
F	Function
FA	Functional analysis
I	Interaction segment
MA	Market analysis
O	Operational segment
P	Payload segment
RU	User requirement
S	Sustainability
SR	Scheduling risk
TR	Technical risk
V	Vehicle segment

1 Executive Overview

This overview is to show the progress so far and to show how the coming weeks are planned and which results are achieved already and which results are expected. The Executive overview is written by group 03 and has had help from respective tutors, coaches and TA's .

Tutors and coaches

The principle Tutors are:

- **Dr D.Ragni**
- **Dr.ir. W.J.Baars**

The coaches are:

- **Dr R.M. Groves**
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The TA is:

- **A. Altena**

The urban environments bear a large responsibility towards the aspects with regards to sustainability. Part of the challenges facing sustainability is the way in which the transportation infrastructure is organized. Our stakeholder's alternative to the convention ground-based vehicle is the advanced air mobility vehicle (AAM). Such vehicle requires rigorous analysis of the characteristics of the possible environments in which the mobility vehicle is meant to operate in. The team was happy to be involved with this project and was dedicated to providing great solution to its stakeholder.

In partnership with its stakeholder, the team was responsible for the design of a system that is able to monitor health hazards and conduct surveys to gauge the hazards in an urban environment for the future use of air mobility vehicles. In particular, the objective of this project was to design a system that is dedicated towards monitoring and surveying noise and turbulence in any urban environment. Turbulence was important as it relates to properties of the airflow such as gusts, vortices and flow turbulence over the lift surfaces. Although a large variety of static sensors exist for these measurements, the point of interest is represented by the need of performing measurements at multiple points above the ground in the same time, points which are inputted by a person or a computer. The data needs to be transmitted in real time to the user or a ground station. Noise maps could be used to ensure that the comfort of residents is not disturbed by excessive noise levels caused by urban air vehicles. Meeting these two conditions, will require a careful analysis of existing systems and out of the box thinking.

This report focused on the determination of the technical requirements, budgets and risk of the design of such system. This system included both a flying element and a ground element. The sections below covers the most important points related to the technical analyses conducted by the team. This baseline report succeeds the project plan, in which the work packages to be performed by the team were identified and scheduled. In the scheduling all task are cut down in smaller task to the point that all tasks could be performed in approximately 4 hours. These are all graphically described in a Work Breakdown Structures (WBS) and Work Flow Diagram (WFD). Subsequently all tasks are assigned to group members, in this way the work is clearly divided and the workload is equal. A Gantt chart was produced to give a quick and clear overview of the planning. Readers curious about the contents of the identified work packages and the content of the WBS, WFD and Gantt chart are referred to the project plan [1].

The **Mission Statement** was defined as follows: A mobile system capable of surveying and mapping the air turbulence and noise in an urban environment.
The **Project Objective Statement** was defined as: To design a system which provides data of turbulence and noise for assessing sustainable cities of the future in a team of 10 engineering students over a span of

10 weeks.
The stakeholder provided the team with initial top level requirements and are listed below:

- **RU-01**:The minimum mission range shall be at least 5 $[km]$.
- **RU-02**:The system shall be operational at an altitude of 0 to 500 $[m]$.
- **RU-03**:The surveying shall be done for half-a-day (>4h), with alternating stops for re-energizing stops.
- **RU-04**:The drones shall have hovering capabilities.
- **RU-05**:The system shall consist of a minimum of three mobile platforms, measuring simultaneously.
- **RU-06**:The system shall be deployable with a maximum wind speed of 8 Beaufort,with and without rain.
- **RU-07**:The drones shall be capable of making a safe landing with 50% of the propulsive system actively working.
- **RU-08**: The acoustic data shall be measured at a single point per drone.
- **RU-09**: The turbulence data shall be measured at a single point per drone.
- **RU-10**:The system shall measure acoustic data in the human hearing range up to 20 $[kHz]$.
- **RU-11**:The measurement of the turbulence shall include all three velocity components at a resolution of 10 $[Hz]$.
- **RU-12**:The drones shall transfer the real-time data to ground at 10 $[Hz]$.
- **RU-13**:The raw acoustic time-series shall be downloadable after each mission.
- **RU-14**:The drones shall comply with standard safety regulations for drones.
- **RU-15**:The system shall be able to be deployed by two certified drone pilots.
- **RU-16**:The drones shall include a collision avoidance system, autopilot and proximity sensors.
- **RU-17**:The drones shall be able to operate as close as 5 $[m]$ from buildings in urban environment.
- **RU-18**:The drones shall comply with European noise and fire-hazard regulations
- **RU-19**:The drones shall comply with aeroacoustic regulations for urban areas
- **RU-20**:The drone's power source shall be at least TBD % recyclable.
- **RU-21**:A sustainable strategy shall be produced and presented for the scenario of mass production, resulting in a carbon dioxide emission of les than TBD kg for 100 drones.
- **RU-22**:The system's lifetime shall be 5 years.
- **RU-23**:After the 5 years lifetime, the power source shall be recycled.
- **RU-24**:The total cost of a stand-alone system with a swarm size of 3 drones shall not exceed 80,000 EUR.
- **RU-25**:The deployment costs, system operational costs and personnel costs shall be included in the budget analysis.
- **RU-26**:In the budget analysis a scenario of a production of 100 drones shall be used.
- **RU-27**: An operational cost estimation shall be performed for the situation of surveillance of three drones for 5 hours.

The focus of the requirements are mainly on measurement performance, safety and reliability, sustainability and costs.

Functional Analysis

In order to obtain an overview of the behaviours of the system throughout its operation life, a functional breakdown and a functional flow diagram was made. The functional flow diagram was branched into the main stages from beginning to the end of life.

The *Main operational life* is further subdivided into functions, to be performed by the system during its operational life. The functional flow diagram is shown in Chapter 3. The breakdown structure was split into the *Operate Drone* and *Operate Ground Station*. The functions were then split into the subsystems. The breakdown structure can be found in Section 3.2.

Market Analysis

Upon researching current market trends and analyzing how companies with similar products to ours operate, it was decided that the most suitable business model is to operate as a service. A client makes contact and requests a data set and a price is negotiated. Then the data is collected processed and made available to the client.

Features to be competitive in the current market were identified: Most companies distance themselves from vehicle design and instead focus on optimising their operations and data processing as this is in higher demand. Most companies manage their data on cloud based platforms as this comes with many advantages internally and as well when it comes to sharing the data with the client. The most in demand applications for drone data collection systems revolve around image data in particular mapping and inspection. Thus making sure the system developed in this project is able to do one of these would be advantageous for market relevance. Finally making and sure the system is easy to transport and can be operated by a single person would be advantageous too.

Regarding cost, if our system is based on one of the most popular commercial drones and the swarm consists of around 3 drones the total cost of the system would be around 40 thousand USD.

Risk management

First, the risks have been divided into budget risks, schedule risks and technical risks. From the subdivided elements the risks were derived, which were then put in a risk map, where they were described in terms of likelihood and consequence. After the risks were derived and risk map was made, the risk mitigation plan was designed. The risk mitigation plan was divided into budget risk mitigation, scheduling risk mitigation and technical risk mitigation.

For the budget risk, the mitigation strategies were to carefully make financial, mass and power budget in order to reduce the risk related to risk of exceeded the budged. Also, a margin can be build into the storage capacity to account for extended mission duration. This would mitigate the risk of collected data exceeding the budget.

For the scheduling risk, on of the mitigation strategies is implementing the quality control to mitigate the risk of maintenance taking longer than expected. In order to mitigate the risk of drone not having enough time to take measurements, the tasks which have to be performed by the drone must be organised and planed in the design. Proper planing of the development of the project in another action which has to be taken in order to mitigate risk. This reduces the risk the product development being rushed.

For mitigating the technical risks the following actions must be performed:

- Code verification must be performed to reduce the risk of software not operating properly.
- Tuning the PID or choosing better gyroscope and accelerometer can reduce the risk of the drone not being stable during the operation.
- A backup GPS can mitigate the risk of loosing GPS signal during operation.
- By implementing a position recognition system, the operator, will know where the final position of the drone is, before the landing phase. This action can reduce the consequence of the drones not returning to the base when they run out of battery.
- Implementing a system which gives an input to the autopilot, or a notification to the operator, when the maximum range is close to being violated can decrease the likelihood of one of the drones going out of range.
- Designing a recovery system based on data from a mounted accelerometer and gyroscope can mitigate the risk the drone loosing control in case of encountering large gusts if wind.
- Mitigating the risk of the drone having a short-circuit can be performed by maintenance.

Requirement Discovery

The set of 27 top-level system requirements or user requirements relate to the following categories: operating performance, measurement performance, safety and reliability, sustainability, and engineering budgets and costs. Using analysis of functional flow, functional breakdown, sustainability, risk and budget more requirements can be derived for the design shown in Chapter 8.

Sustainable Development Strategy

In order to satisfy the sustainability, a sustainable development strategy must be derived. The sustainability development strategy is divided into two parts, the sustainability in the design process and the contribution of the system to sustainability.

During the design process it is important to minimize wastes. This is an important aspect for the design process, when choosing the design option. Selecting the right configuration and elements can minimize the required power and allow to use resources more productively over their life cycle. Choosing a power source is also an important aspect during the design process as it can have a big impact on sustainability. It is also important to choose recyclable materials in order to reduce waste in case of maintenance and at the end of mission.

The are a few ways in which the system can contribute to sustainability. First of all, measuring noise and turbulence can help choosing the most efficient path for the unmanned aerial vehicles (UAV), which will help to minimize the energy consumption.Tracking the airflow and turbulence can also help finding optimal location and orientation for wind turbines in urban environment.

Design Option Tree (DOT)

Table 1.1: Final design concepts for trade-off. Some elements are not considered due to their dependence on further design and will be decided upon in later design phases.

	Option 1	Option 2	Option 3
Drone configuration	Octocopter	Hexacopter	Quadcopter
Drone size	Large	Medium	Small
Drone design procedure	Take existing structure	Take existing platform	Design from scratch
Drone energy source	Electricity	Electricity	Electricity
Propeller material	-	-	-
Propeller pitch	Fixed	Variable	Fixed
Type of battery	Secondary batteries	Secondary batteries	Secondary batteries
Frame material	-	-	-
Motor types	-	-	-
Degree of autonomy	Single layered	Single layered	Single layered
Localisation	GPS	GPS	GPS
Collisions	Stronger material around propellers	Springs	Stronger material around propellers
Measurements	Operator selects the points of measurement for all the swarm	Operator selects the points of measurement for all the swarm	Operator selects the points of measurement for all the swarm
Station-to-drone	Continuous with ground	Continuous with ground	Continuous with ground
Communication method	Radio	Radio	Radio
Obstacle avoidance	Stereo Vision	Radar	Ultrasonic
Ground station	Yes	Yes	Yes
Landing platform	-	-	-
Data processing	Two-step	Two-step	Two-step
Charging configuration	Wired charging	Wireless charging	Wired charging
Type of recharging	Manual - swapping battery	Automatic - recharging	Automatic - swapping battery
Drone control	FPV Goggles	Dedicated Conrol Input on GS	Physical Controller with Integrated Display
Measure noise	One microphone to measure all the frequency ranges	Multiple microphones measuring a specific frequency range	One microphone to measure all the frequency ranges
Measure wind and turbulence	Pitot Tube	Indirect through propeller power	Acoustic Doppler Velocimeter
Measure attitude	IMU	IMU	IMU
Measure altitude	GPS	GPS	Altimeter(ultrasound)
Measure air pollution	CO_2 sensor and Aerosol Sensor	NO_X Sensor and Aerosol Sensor	NO_X Sensor and CO_2 Sensor
Measure temperature	Infrared Sensor	Infrared Sensor	Infrared Sensor
Obstacle avoidance	Ultrasonic	Infrared	Camera

In order to satisfy the requirements a proper design was picked form a broad selection of possible design options generated by the DOT seen in Chapter 9. By going through the requirements and the mission objective some designs were eliminated to narrow to the most feasible design solutions. Using the driving and killer requirements to eliminate unfeasible options from the DOT, 3 feasible options were generated for further development and analysis in table 9.3. There are still a range of feasible options in the DOT not included in the 3 designs chosen but which can still re-appear in further development of the design. The vehicle segment options are narrowed down to the 3 possible configurations shown below. Note that the rest of the aspects of the design option tree that have not been eliminated can change. But the main parts of the three parts remain the same. The other parts will be discussed in the future report.

Contingency Management

It is important to consider the driving costs for the drone systems which is being designed. Therefore, for future stages of the design process it is critical for cost to be monitored and properly distributed between the segments. table 1.2 shows the current estimated cost and contingency.

Table 1.2: Budget allocations is USD

	Vehicle(Per Drone)	Ground Station	Payload(Per Drone)	Extras(Per Drone)
Estimated cost	10000	5500	1500	200
Contingency(%)	100	60	100	100
Maximum Cost	20000	8800	3000	400
	Swarm Size:	**3**	**Total Max Cost:**	**79000 USD**

Conclusion

This report covered a formal briefing of the planning with regards to the technical aspects of the design of a system that should be used to detect noise and turbulence in an urban environment. From all the different performed analysis tools such as the functional analysis and market analysis together with the top-lever requirements a final set of system and subsystem level requirements were defined and from this set the driving and killer requirements were distinguished. All possible design options were found in a structured way by performing a DOT. With the driving and killer requirements choices were made and finally a selected number of design options were chosen and presented.

TABLE HERE
Future reports will provide more detail and expand more into the design and development of all chosen design options. The next step is the initial design where the different options are analysed to obtain the most optimal combination of design options, a proper trade-off will be performed and one final concept will be chosen before the next official briefing, the mid-term review. At the end, a final optimised design will be generated in the detailed design phase. This is to complete the goal to design a drone system for monitoring turbulence and noise in the urban environment which is capable of entering the market and to get one step closer to a more increased use of AAM vehicles and a more sustainable future .

2 Project Objectives

Many vehicle concepts for aerial transportation within cities, such as delivery drones, ambulance drones or personal air mobility vehicles are being developed. The urban environment is characterised by high turbulence induced by buildings and strong heat convection. A lot still has to be learned about these environments before AAM (Advanced aerial mobility) vehicles such as the ones mentioned before can safely operate within it.

Some drone platforms capable of taking wind measurements already exist, however they are not suited for high resolution measurements or capable of simultaneously taking other measurements.

Since the biggest safety hazards associated with extensive operation of AAM vehicles are unpredictable wind gusts and high noise levels as a result of the operation of these vehicles, the system developed in this project will be capable of measuring both of these. This system will be comprised of a collection of drones in a swarm configuration, and it will be able to collect high resolution spatial data for a period of a few hours on a given site, for which the customers shall define a surveying profile. The system will be accompanied by a user friendly ground station to which data can be streamed. An important aspect of this system is that it shall not pollute, be dangerous to people around it while in operation, or annoy people living near the surveying site with its noise.

2.1. Mission Need Statement

A mobile system capable of surveying and mapping the air turbulence and noise in an urban environment.

2.2. Project Objective Statement

To design a system which provides data of turbulence and noise for assessing sustainable cities of the future in a team of 10 engineering students over a span of 10 weeks.

3

Functional Analysis

The mission statement and project objective statement together with the user requirements were found in the project plan [1] and the mission statement and project objective are stated again in Chapter 2. Now before the system requirements can be drafted it must first be analysed what the system shall be able to do. Therefore, a functional analysis will be performed. This chapter will do that in the following way. Section 3.1 will describe the Functional Flow Diagram and Section 3.2 will describe the Functional Breakdown Structure. After this chapter more analyses will be performed which are necessary to get a complete overview of the necessary requirements. All boxes are given identifiers, the identifiers come from the functional flow diagram, and the ones used in the functional breakdown structure use the same identifier for the same functions as for the flow diagram and could therefore appear oddly numbered because it is structured differently.

3.1. Functional Flow Diagram

The functional flow diagram is first branched into the main stages from beginning to end of life. The *Main operational life* is further subdivided into functions, to be performed by the system during its operational life. Numbered functions indicate actions to be taken subsequently, while lettered functions are performed in parallel. The diagram is expanded up to 3 layers of depth in details. To keep the flow chart clearly readable small circular boxes are used containing roman numbering, this is then used to refer to respective boxes. The diagram can be found in figure 3.1 and figure 3.2.

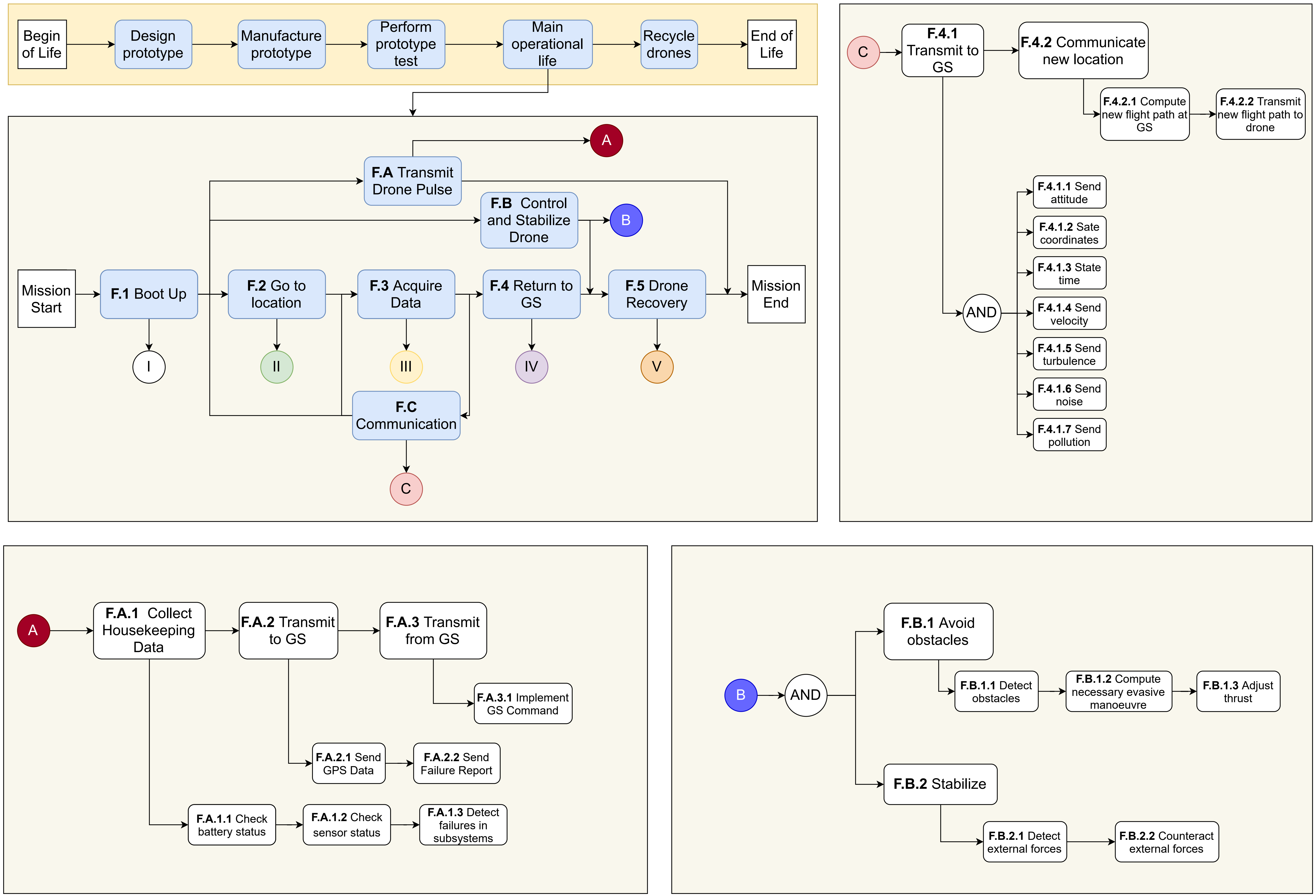

Figure 3.1 Functional flow diagram part 1

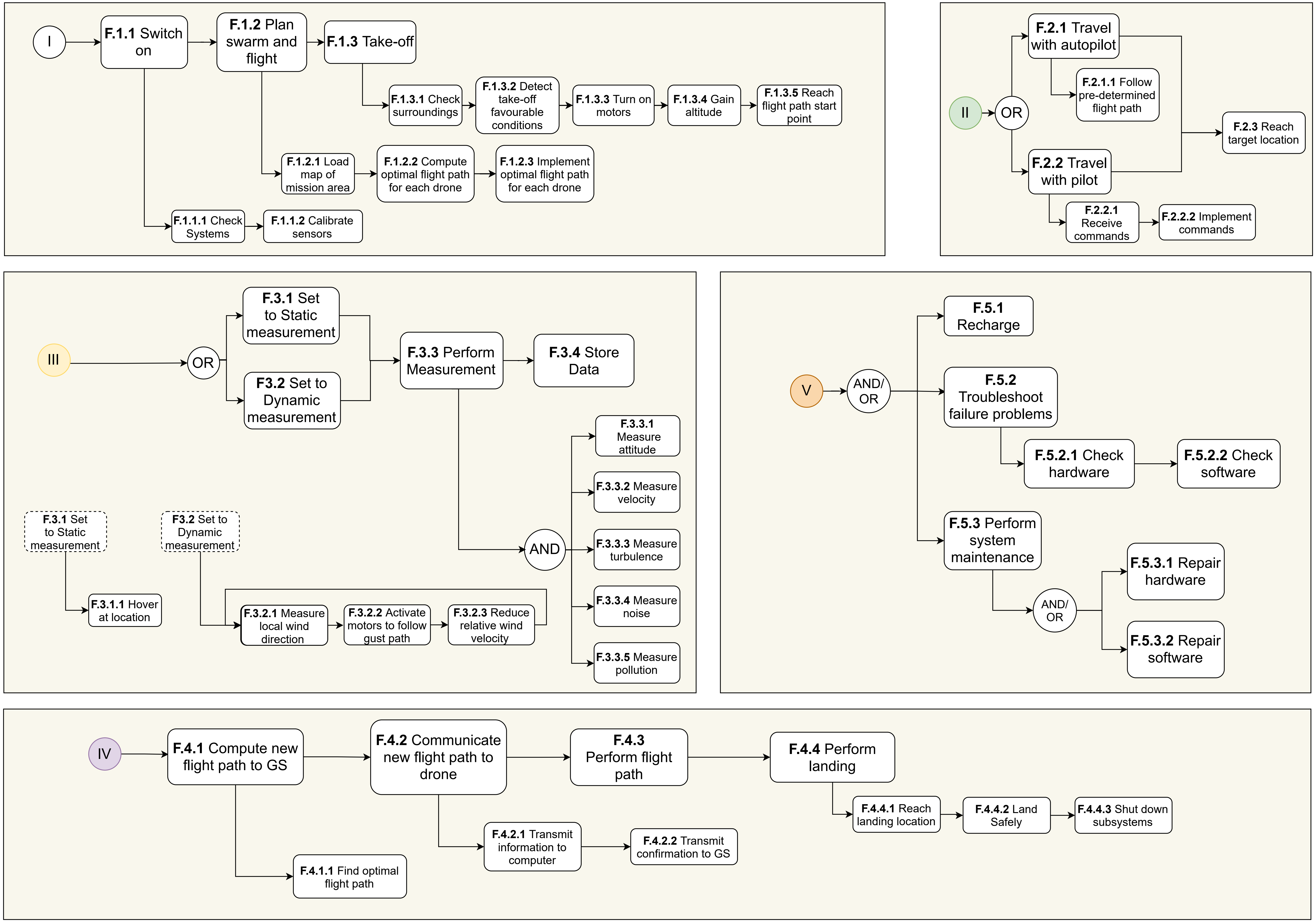

Figure 3.2 Functional flow diagram part 2

3.2. Functional Breakdown Structure

The functional breakdown structure is presented on two pages below in figure 3.3 and figure 3.4. The functional breakdown structure represents the hierarchy of the functions that need to be performed by the system. The system is divided into two main elements, operating drone and operating ground station. The *operate drone* and *operate ground station* elements are then further divided into the main functions. These functions are then sub divided into smaller functions based on the functional flow diagram of the mission, shown in Chapter 3. The figure below shows the functional breakdown. The first aspects of the chart that might be noticeable to the first time reader is that the numbering of the functions is based in the chronological order of the functional flow diagram and thus numbering is out of order. While this diagram is based on phases based on time, the breakdown structure is based on the functions a specific subsystem has to fulfill. The breakdown covers to 1 layer of depth more than the flow-down and this is also based on time. That is the reason why certain functions are put under ”other”: a box of at least one layer higher is already put under another subsystem, but the not all elements of that box are related to that subsystem.

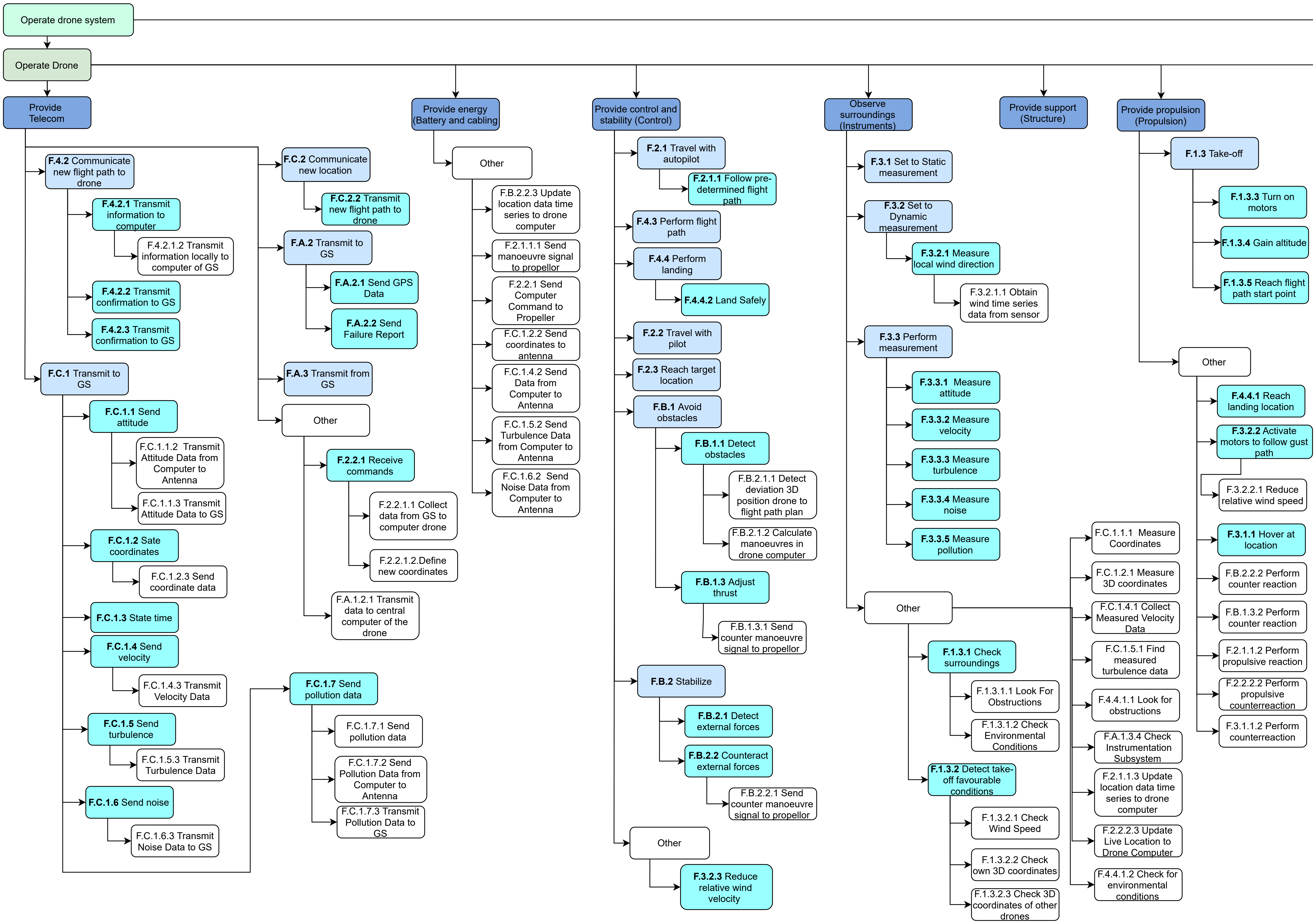

Figure 3.3 Functional breakdown structure part 1

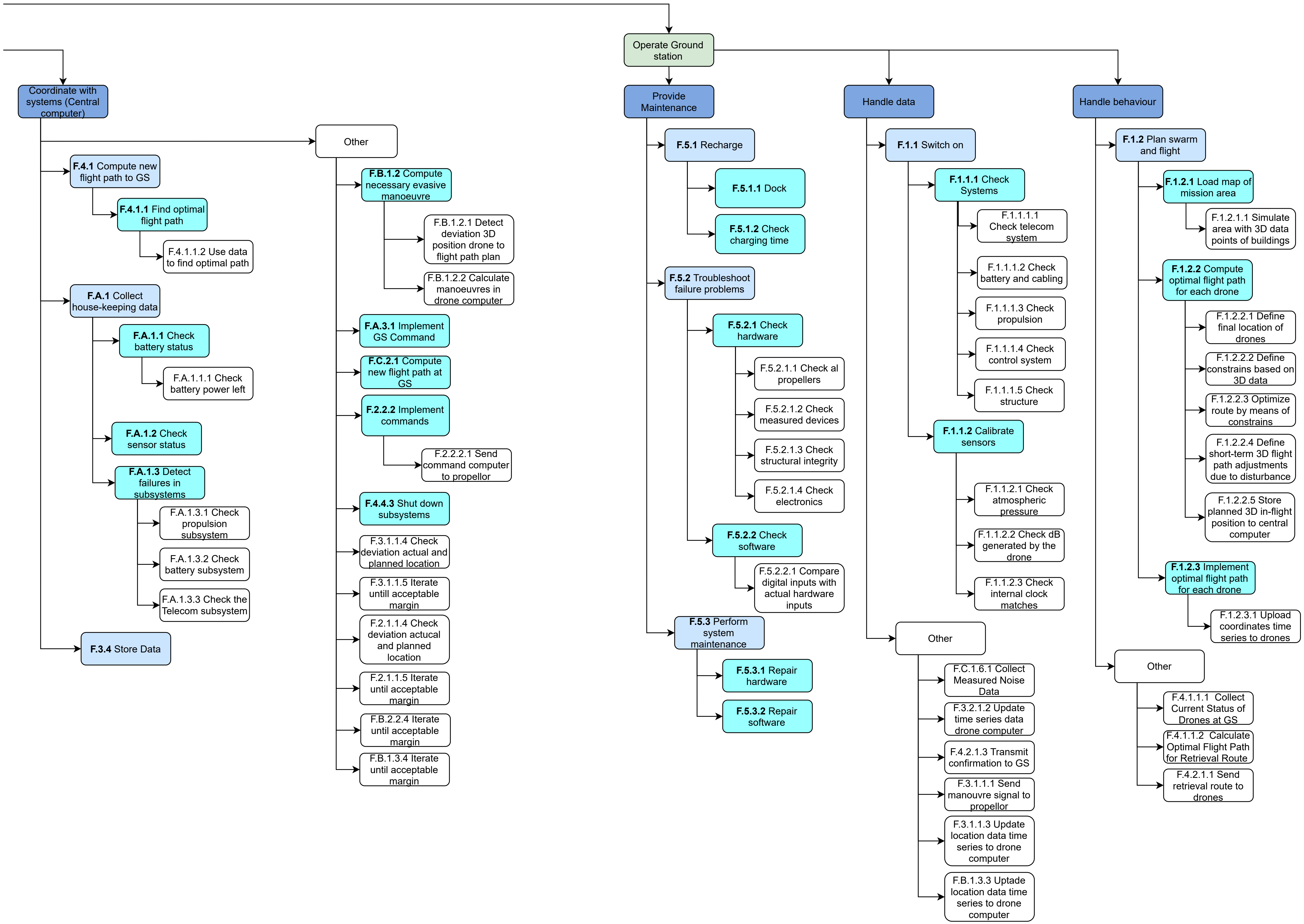

Figure 3.4 Functional breakdown structure part 2

4
Market Analysis

4.1. Market Trends

For many years already the military have been exploiting the use of drones for data collection and autonomous operations. Through improvements in technology and more lenient regulations, the same cost and efficiency benefits that have historically made drones attractive for the military are now available for a broad spectrum of business and government functions. In 2019 the commercial drone market was valued at 1591 million USD, and is projected to reach a value of 8527 million USD by 2027 by Fortune Business Insights[1].

The most common type of data collected by drones is image data. This is reflected by the most in-demand use cases for drone data collection systems, which include mapping, 3d mapping and inspection[2]. For this reason, the most common payload on commercial drones is a high-resolution camera and most software companies that work with drone collected data specialise on processing image data[2].

Analysts predict that drone hardware will be commoditized, and value will derive from services[2]. Since drone hardware is becoming increasingly affordable, manufacturing and the hardware itself will not drive industry growth. Instead, services that operate and manage drones for companies will generate most of the value. For this reason, companies like Parrot SA or Robotics 3D have pivoted from manufacturing UAVs to developing software services for UAVs[2].

4.2. Business Model

Upon observing the trends in the current market, it would make most sense to operate as a service with the data we collect and process for companies as our main product. A typical interaction with a company would play out as follows: The client specifies its data requirements; these requirements are analysed and a price is agreed upon. Next, one of our drone operators visits the specified location and collects the required data. The raw data is uploaded to our cloud platform where it is processed and made available to our client. We also make managing and sharing the data as easy as possible for the client. Some of the most popular companies in this sector such as SiteScan, Kespry, and Aerotas (Click company name to visit website) have very similar business models.

4.3. Desired features to be competitive

The following is a list of the most sought after features and traits of drone data collection systems in the current market. The system developed during this project should comply with as many of these as possible to make it market relevant:

1. **Distance ourselves as much as possible from drone design and manufacture** and instead **focus on efficient operations and data processing**. With giants like DJI leading the way in vehicle design and manufacture, competing with these firms would be a waste of resources. Building on top of the technology that has already been developed by these companies allows for more innovation and more market opportunities.
2. The **raw data collected is processed remotely in a cloud based platform**. This approach is very common in companies as it comes with many advantages. It is cheaper, faster, less vulnerable and readily available 24/7 [3]. In this case, all the ground station has to do with the raw data is relay it to a cloud server where it can be processed. This means that a smaller and less expensive ground station is required making the system easier to transport and reduces risk.
3. A majority of applications in today's market for a system like ours revolve around image data, thus it would be desirable for our system to **be able to incorporate a high resolution camera**.

[1] https://www.inkwoodresearch.com/reports/global-drones-data-services-market
[2] https://www.toptal.com/finance/market-research-analysts/drone-market
[3] https://www.grandviewresearch.com/industry-analysis/drone-data-services-market

4. **Reliability and fast delivery are highly valued**. In the business world time is money, thus if a certain delivery date is promised it must be met, for this reason our process must be streamlined and failure probabilities should be reduced as much as possible. This can be achieved through a higher degree of automation.
5. **Flexibility in sensing capabilities**. The more sensors our system is compatible with the broader its applications will be. These sensors must be easily swapped in/out and ideally are able to be hot-swapped. This can be achieved by using a payload deck.
6. **Most clients require their data to be geo-tagged**. For this reason an accurate localization system is needed. High degrees of accuracy can be achieved using RTK-GPS or a local localization system using beacons.
7. **Safe to operate around people**. Ideally the system should be safe to operate around people so as few precautions as possible have to be taken and no other work is interrupted in the process. This is highly sought after in the business world as usually taking these precautions requires a lot of time consuming paperwork.
8. **Design so as few people as possible are needed to operate the system**. Autonomous flight via predictive or prescriptive analytics would render drone pilots unnecessary, making drones even more economical in commercial operations (Pay less salaries)

4.4. Cost Estimation

Using an already existing commercial drone platform significantly reduces hardware and assembly costs[2]. The main contributions to the cost are the drones, the ground station and all the required payloads. In addition to these, a small extra cost is added to account for other small expenses such as 3D printing a protective shell for the drones or insurances.

The following drones are being considered for the system:

Table 4.1: Commercial drones being considered

Name	Cost USD (Approx)
DJI Matrice 300	10000
DJI matrice 200	6500
Yuneec H520	1999
DJI Mavic Pro Enterprise	1999
Intel Falcon 8+	13000
Airborne Drones ATLAS V	29999

Table 4.2: Consumer drones being considered

Name	Cost USD (Approx)
DJI Mavic Air 2	800
DJI Mavic Pro 2	1400
DJI phantom pro 4	1600
Parrot ANAFI	600
Yuneec Typhoon H	750

The cost of the ground station varies greatly depending on what requirements it is expected to fulfill. Assuming the ground station used by our system is only responsible for monitoring the state of the drones and relaying data to the cloud, the cost is estimated to be around **5500 USD**[4]. The payloads are estimated to cost **1000 USD per drone for commercial drones** and **2000 USD per drone for consumer drones** as commercial

[4] https://www.aeroexpo.online/aeronautic-manufacturer/drone-ground-station-2215.html

drones already come equipped with industry standard sensing capabilities. Finally, the additional costs are estimated to be around **200 USD**. Taking the average cost for each drone class, the following system cost estimations are found:

Swarm Size:	3
Using Hobby:	15190 USD
Using Commercial:	40848.5 USD

5
Risk Management

Identifying and assessing the risks of a future product is one of the most important steps in the systems engineering logic, aiming to ensure the successful completion of the project. It can be recognised that risk is the meeting point between the technical performance, cost of the resources and the scheduled time, all of them being dependent on each others. This chapter will focus on recognising the risks, followed by the risk assessment and finishing with an overview about how the risks are handled and mitigated.

5.1. Identifying Risks

The risks are identified by looking at the requirements generated in Chapter 8 which would lead to the failure of the product and/or the requirements not being met. The development, manufacturing and operation of the product are considered.

5.1.1. Budget Risks

The risks associated with the global parameters which need to be managed during the development, manufacturing and operation of the product to meet technical requirements.

- **BR-1**: Production costs exceed their budget
- **BR-2**: Total mass of the drone exceeds its budget
- **BR-3**: Batteries of the drone hold less than their expected energy budget
- **BR-4**: The drone power consumption exceeds its budget
- **BR-5**: The collected data exceeds its budget
- **BR-6**: The overall production exceeds its carbon-dioxide budget.

5.1.2. Scheduling Risks

The risks associated with time management of activities during the development, manufacturing and operation of the product to meet technical requirements.

- **SR-1**: The drone maintenance takes longer than the expected time
- **SR-2**: The drone re-charge to full capacity takes longer than the expected time
- **SR-3**: The construction and assembly of the drone take more than the expected time
- **SR-4**: The power source degrading faster than the expected time
- **SR-5**: A manufacturing defect is present during construction and/or operation of the drone
- **SR-6**: The drone has insufficient time to take measurements when arriving at specified location
- **SR-7**: The product development is rushed

5.1.3. Technical Performance Risk

The risks associated with technical performance of the product, during the development, manufacturing and operation of the product to meet technical requirements.

- **TR-1**: One of the sensor will fail.
- **TR-2**: One of the engines will fail.
- **TR-3**: The battery system will fail.
- **TR-4**: One of the drones will go out of range.
- **TR-5**: One of the drones will not return to the base when they run out of battery.
- **TR-6**: One of the drones will lose control if large gusts of wind will be encountered.

- **TR-7**: One of the drones hits elements of the external environment.
- **TR-8**: One of the drones will hit another drone from the swarm.
- **TR-9**: One of the drones has a short-circuit.
- **TR-10**: There will be a loss of GPS signal.
- **TR-11**: The drone cannot be stable.
- **TR-12**: The drone will be deployed in a busy airspace.
- **TR-14**: The operator does not check for loose parts before the flight.
- **TR-15**: The operator is not familiar with the drone operation.
- **TR-16**: The software used for the drones has unknown bugs.

5.2. Risks Map

The risk map is a crucial tool in visualising in which proportion, the identified risks will affect the integrity of the project. It is usually comprised of two factors, namely the likelihood that the risk will occur and the severity or the consequence of the risk over the mission. Therefore, the map will be split in three areas, a green one, which is considered that the combination of likelihood and consequence will not pose a danger towards the project, a yellow one, which is considered to pose moderate danger, but for which, no mitigation is urgently needed, and a red one, which deems a strong threat towards the completion of the mission.

Before placing the above-mentioned risks in the map, they need to be categorised based on their likelihood and consequence. These metrics will be given a numbering system as follows: the likelihood will be assessed on a scale from one to five. A likelihood of one - Very low will have a probability of occurrence less than 1%, two - Low will have a probability of occurrence between 1% and 30%, following the same train of thought, a likelihood of five - Very High will have a probability of occurrence of more than 70%. Regarding the consequences, one - negligible, the impact is visible but the whole project can continue as planned, marginal - small reduction in technical performance, up to five - catastrophic event which would result in mission failure. These metrics can be summarized in the table below.

Table 5.1: Likelihood score description

Description:	**Score:**
Very low probability of occurrence	**1**
Low probability of occurrence	**2**
Moderate probability of occurrence	**3**
High probability of occurrence	**4**
Very high probability of occurrence	**5**

Table 5.2: Consequence score description

Description:	**Score:**
Negligible, non operational impact	**1**
Marginal, small reduction in technical performance	**2**
Moderate, small reduction in technical performance, mission success questionable	**3**
Critical, considerable reduction in technical performance, mission success questionable	**4**
Catastrophic, mission failure	**5**

Table 5.3: Budget Risk Map

Likelihood	Negligible	Marginal	Moderate	Critical	Catastrophic
Almost certain					
Likely					
Possible			BR-1,4		
Unlikely		BR-2,5,6	BR-3		
Rare					
	Consequence				

Table 5.4: Schedule Risk Map

Likelihood	Negligible	Marginal	Moderate	Critical	Catastrophic
Almost certain					
Likely					
Possible					
Unlikely	SR-1,4	SR-5,6	SR-7		
Rare		SR-2,3			
	Consequence				

Table 5.5: Technical Performance Risk Map

Likelihood	Negligible	Marginal	Moderate	Critical	Catastrophic
Almost certain					
Likely		TR-16			
Possible					
Unlikely		TR-1	TR-4	TR-11	
Rare		TR-14	TR-2,3,7,8,12,13,15	TR-10	TR-5,6,9
	Consequence				

5.3. Risk Mitigation Plan

Once the risk map is completed, it can be used to visualize the necessary measures to be taken for each risk. Ideally, both the likely hood and the consequences of the risk have to decrease, so the risks have to move to the lower left corner of the risk map.

Some of the mitigation measures can be: choose a different technology, diminish the consequences of failure, incorporating margins of redundancy, and integrate measures to reduce probabilities of failure (such as testing before the start of the mission). Moreover, it can be expected that, in order to mitigate the most dangerous risks, certain design choices will be proposed, which will impose new system and subsystem requirements on the design.

The mitigation measures and associated mitigated risk maps for budget risks is given in Section 5.3.1, for scheduling risks it is given in Section 5.3.2 and for technical risks in Section 5.3.3.

5.3.1. Budget Risk Mitigation

Some of the risks presented in table 5.3 are deemed acceptable risks as their combination of likelihood of occurrence and consequence do not endanger the project. Mitigation strategies for non-acceptable risks and acceptable risks that can be easily mitigated are listed below:

- Mitigation **BR-1**: a careful financial breakdown can be made during the design, minimizing the probability of cost under-estimation to unlikely. In addition, the target production cost can be lowered, creating a margin and thereby reducing the impact to marginal.
- Mitigation **BR-2**: the mass budget is important in designing any aerial vehicle. Thus this must be monitored very carefully. Any exceedance of the mass budget during the design phase must be handled immediately with a design change. This lowers the probability to rare.

- Mitigation **BR-3**: the power budget of the system can be designed with a margin, ensuring sub-optimal energy capacity is still able to fulfil the mission. This mitigation lowers the severity of the impact to marginal.
- Mitigation **BR-4**: the same mitigation strategy can be used for the power consumption, creating a power margin in the design and therefore reducing the impact to negligible. Energy efficient components can be chosen with well-defined power consumption, lowering the probability to unlikely.
- Mitigation **BR-5**: while the sensor data rate should be well defined, a margin can be built into the storage capacity to account for extended mission duration. This lowers the impact to negligible.
- Mitigation **BR-6**: the Sustainability Manager is responsible for enforcing strict carbon budget adherence. No additional mitigation strategy is developed for this.

5.3.2. Scheduling Risk Mitigation

Some of the risks presented in table 5.4 are considered to be acceptable risks as their combination of likelihood of occurrence and consequence do not endanger the project. Non-acceptable risks which can be made safer with mitigation strategies and acceptable risks that can be easily mitigated are given below:

- Mitigation **SR-5**: During development, construction and operation, quality control of the final product needs to be considered and the maintenance aspects when avoiding high consequence event from occurring. Incorporating, this maintenance's of the product into the design through sub-assemblies which are replaceable, the operational risk can further be mitigated reducing the consequence. To check whether a sub-assembly needs replacing during operation and a sub-assembly needs to be rejected due to a defect, quality control need to be implemented sufficiently to ensure safety during the operational lifetime.
- Mitigation **SR-6**: Time management during the operation of the drone needs to be considered through mission plans and profiles. The drone will have limited flight time which needs to be used efficiently with sufficient accuracy and/or repeatably. In addition, to complete a variety of task to complete the overall mission objective. By tracking and organising the tasks which the drone has to accomplish and incorporating the mission plan into the design, this risk likelihood can be reduced.
- Mitigation **SR-7**: Rushed product development, results in a sub-optimal design and can be unavoidable in high work-load phases of the development of the product. To mitigate this risk proper planing of the development of the project can be done a head of time and contingencies can be put in place by using resource and requirements list to track regularly the criteria which the working design meets. If resources are insufficient, a trade-off and prioritisation crucial requirements to complete the mission objective is required. This does not significantly reduce the likelihood but the implementation of such a strategy will reduce the impact.

5.3.3. Technical Performance Risk Mitigation

- Mitigation **TR-16**: The main mitigation actions towards this risk is to find ways to reduce it's likelihood. This can be done by doing better code verification during the design phases.
- Mitigation **TR-4**: The main mitigation actions towards this risk is to find ways to reduce it's likelihood or it's consequence. To reduce the event's likelihood, a system can be implemented which will give an input to the autopilot, or a notification to the operator, when the maximum range is close to being violated. On the other hand, the consequence of this event can be minimized as well, by implementing automatic flight control which will return the drone in the predefined perimeter, when the range is violated.
- Mitigation **TR-11**: The main mitigation actions towards this risk is to find ways to reduce it's consequence and also likelihood. This can be done by better tuning the PID controller used for levelling, choosing a better accelerometer and gyroscope, or minimize the vibrations/noise that can be interpreted by the sensor as noise.
- Mitigation **TR-10**: The main mitigation actions towards this risk is to find ways to reduce its consequence. This can either be done by ensuring a backup GPS receiver/antenna in the payload section, or to design the drone such as, when the GPS signal is lost for more than a certain number of seconds, the drone will hover at the last known position until the connection is re-established.
- Mitigation **TR-5**: The main mitigation actions towards this risk is to find ways to reduce it's consequence. This can be achieved by implementing a position recognition system, namely, the operator, will know where the final position of the drone is, before the landing phase.
- Mitigation **TR-6**: The main mitigation actions towards this risk is to find ways to reduce it's consequence. This can be achieved by designing a recovery system based on data from a mounted accelerometer

and gyroscope.

- Mitigation **TR-9**: The main mitigation actions towards this risk is to find ways to reduce it's consequence. This can be achieved by ensuring that all the maintenance is done correctly, and the operator checks for any wires with no insulation.

5.4. Anticipated effect of mitigation

The goal of the mitigation strategies is to propose actions that will help to minimize either the likelihood and/or the consequence of the proposed risks along the design and operational phases of the product. An updated visual representation of the mitigated risks will be presented to confirm the anticipated effects of them.

The effects of mitigation on budget risks can be seen in table 5.6. Similarly, the new schedule risk values are presented in table 5.7, and the updated technical risk performance risk map is shown at table 5.8.

Table 5.6: Mitigated Budget Risk Map

Likelihood						
	Almost certain					
	Likely					
	Possible					
	Unlikely		BR-1,3,4,5,6			
	Rare		BR-2			
		Negligible	Marginal	Moderate	Critical	Catastrophic
		Consequence				

Table 5.7: Mitigated Schedule Risk Map

Likelihood						
	Almost certain					
	Likely					
	Possible					
	Unlikely	SR-1,4,5	SR-7			
	Rare		SR-2,3,6			
		Negligible	Marginal	Moderate	Critical	Catastrophic
		Consequence				

Table 5.8: Mitigated Technical Performance Risk Map

Likelihood						
	Almost certain					
	Likely					
	Possible					
	Unlikely		TR-1,16			
	Rare		TR-14	TR-2,3,4,5,6,7,8,9,10,11,12,13,15		
		Negligible	Marginal	Moderate	Critical	Catastrophic
		Consequence				

Thus, it can be seen that if all mitigation strategies are correctly followed, all the risks are in the safe zone of the risk map, and the mission has an overall higher chance of success.

6
Sustainable Development Strategy

Sustainability is an important aspect which must be considered during the design process. In this chapter the sustainability development strategy will be discussed. In Section 6.1 the sustainability in the design process is explained. Furthermore, in Section 6.2 the contribution of the system toward sustainability is discussed.

6.1. Sustainability in the Design Process

The focus of the sustainability strategy is to reduce waste. This can be implemented by using the Sustainable Materials Management (SMM), which is a systemic approach to using and reusing materials more productively over their entire life cycles [2]. The main goals of the Sustainable Materials Management are to use materials in the most productive way and reduce toxic chemicals and environmental impacts throughout the material lifecycle.

It is important to consider different design options and payload elements such as electronics, power source, materials, etc. in order to reduce waste. For example, some of the sensors require very low amount of power for operation, and can be powered by an A3 battery. Another possibility is to not use any sensors for measuring turbulence and using drone itself as a sensor. This could be beneficial, because it would not require any additional power for sensors, but it could require a better central computer for data analysis, which could require more power overall.

Another important aspect of the design process is choosing the power source. The possible options are electric batteries and hydrogen. Both sources have low environmental impacts, but in case of the batteries, the rechargeable battery packs should be used to maximize the usage over the life cycle and minimize the toxic wastes.

For the materials it is important to minimize the weight of the drone in order to reduce the thrust need for the hovering, thus reducing the power needed. Also, during the maintenance some elements have to be replaced. Thus, it is important that the elements are made out of materials which can be reused or recycled, for example plastics, metals or woods. Also, it must be taken into account to increase the life cycles of element in order to minimize the need to replacing these elements during maintenance.

6.2. Contribution of the System to Sustainability

There are several ways in which the system can contribute toward sustainability. First of all, the system will measure noise and turbulence in urban environment, which will contribute toward using advanced air mobility vehicles (AAM) in cities. Measuring turbulence can help choosing the most efficient path for the AAMs, which will help minimizing the energy consumption. The AAMs which are perfect for delivery of small packages could possibly replace cars for delivering cargo, which would decrease the emission of carbon dioxide. It is important to keep in mind that the AAMs should be charged using the renewable energy sources such as solar panels or wind energy, otherwise this could lead to a higher emission of carbon dioxide.

Tracking the turbulence and airflow can also help for finding the optimal wind turbine location and orientation in urban environment, which would allow for the most efficient usage. Additionally, by changing the instrumentation inside the payload, the system can be also used to map air pollution in urban environments, which would give very useful information about air quality at important locations.

7
Resource and contingency allocation

It is important to consider what is driving the cost of the drone system that is being designed as understanding where costs are coming from or will come from in future stages is critical for a cost effective design process.

The driving requirement behind this budget allocation is that the total cost of the system hardware and assembly shall not exceed 80,000 euros for a swarm of at least 3 drones. A big decision still has to be made by the group on whether and already existing UAV will be used, an already existing UAV will be modified to meet the requirements or an entirely new UAV is to be designed. This decision will impact how the resources and budget are allocated, however for the moment the budget will be split more generally and depending on the decision that is made a more detailed budget breakdown will be made is future reports. The budget will be split between vehicle, ground station, payload and extras like in the cost estimation subsection of the Market Analysis.

7.1. Vehicle

The vehicle is one of the most important parts of system. What makes the system valuable and interesting is the fact that the platform the sensors are mounted on is able to travel to any point in 3d space, however it can also be a weakness if the platform required to do this is not stable and the data collected is noisy. Naturally then, it is important to assign a large enough budget to make sure that the chosen platform complies with the requirements.

As a reference point, it is assumed that all the requirements set can be met a commercial application grade quadcopter such as the popular DJI Matrice 300 which retails for around 10 000 USD[1]. In a best case scenario only the firmware in the drone needs to be modified before usage, however if this is not enough to fulfill the requirements of the vehicle hardware modifications will be needed which will drive the price up depending on how severe they are. In a worst case scenario a new UAV would have to be designed for which the costs could scale up significantly. To account for all of these scenarios a 100 percent contingency (Double the expected cost) is chosen.

7.2. Ground Station

The cost of a ground station is dependent on the functions it is required to fulfill, however one key feature that is always present regardless is controlling and monitoring the swarm during the data collection process. The ground station is the point of contact the operator has with the swarm thus a good ground station must be selected to ensure smooth operation and a good supervision of the system. An average professional ground control station for a UAV costs about 5000 USD[2]. A contingency of 50 percent is used to account for possible extras that might be required from the ground station such as an RTK GPS antenna for example.

7.3. Payload

The payload consists of the sensors on board and all the other equipment required to support them. This subsystem is important since the quality of the measurements is directly related to what sensors are used and how accurate they are. At the moment it is still very unclear how the measurements are going to be made and how many properties are going to me measured, thus a large contingency is required to accommodate for a large range of possibilities. A contingency of 100 percent (Double the expected cost) is chosen [3].

7.3.1. Extras

The extras account for a variety of small expenses relating to the hardware. An example cost for this section could be 3D printing a shell for the drone or perhaps paying some sort of insurance costs which is quite popular

[1] https://www.dji.com/fr/matrice-300
[2] https://www.aeroexpo.online/aeronautic-manufacturer/drone-ground-station-2215.html
[3] https://us.vwr.com/store/category/anemometers/581131

amongst the larger drones. This section again is unpredictable since a lot of these small costs are not obvious until they are needed thus a large contingency is required. A contingency of 100 percent is chosen.

Table 7.1: Budget allocations is USD

	Vehicle(Per Drone)	**Ground Station**	**Payload(Per Drone)**	**Extras(Per Drone)**
Estimated cost	10000	5500	1500	200
Contingency(%)	100	60	100	100
Maximum Cost	20000	8800	3000	400
	Swarm Size:	**3**	**Total Max Cost:**	**79000 USD**

8
Requirements and Constraints

This chapter will treat the requirement analysis, starting from the user requirements and with the help of the functional analysis, risk analysis and market analysis.

8.1. Requirements Specification

In the Project Plan [1] the user requirements were listed and analysed by the team members. In this phase of the project, it is time to further develop such requirements and derive system specifications. In order to achieve that, the critical design-driving requirements have to be identified and converted into system constraints.

- **RU-01**:The minimum mission range shall be at least 5 $[km]$.
- **RU-02**:The system shall be operational at an altitude of 0 to 500 $[m]$.
- **RU-03**:The surveying shall be done for half-a-day (>4h), with alternating stops for re-energizing stops.
- **RU-04**:The drones shall have hovering capabilities.
- **RU-05**:The system shall consist of a minimum of three mobile platforms, measuring simultaneously.
- **RU-06**:The system shall be deployable with a maximum wind speed of 8 Beaufort,with and without rain.
- **RU-07**:The drones shall be capable of making a safe landing with 50% of the propulsive system actively working.
- **RU-08**: The acoustic data shall be measured at a single point per drone.
- **RU-09**: The turbulence data shall be measured at a single point per drone.
- **RU-10**:The system shall measure acoustic data in the human hearing range up to 20 $[kHz]$.
- **RU-11**:The measurement of the turbulence shall include all three velocity components at a resolution of 10 $[Hz]$.
- **RU-12**:The drones shall transfer the real-time data to ground at 10 $[Hz]$.
- **RU-13**: The raw acoustic time-series shall be downloadable after each mission.
- **RU-14**:The drones shall comply with standard safety regulations for drones.
- **RU-15**:The system shall be able to be deployed by two certified drone pilots.
- **RU-16**:The drones shall include a collision avoidance system, autopilot and proximity sensors.
- **RU-17**:The drones shall be able to operate as close as 5 $[m]$ from buildings in urban environment.
- **RU-18**:The drones shall comply with European noise and fire-hazard regulations
- **RU-19**:The drones shall comply with aeroacoustic regulations for urban areas
- **RU-20**:The drone's power source shall be at least TBD % recyclable.
- **RU-21**:A sustainable strategy shall be produced and presented for the scenario of mass production, resulting in a carbon dioxide emission of less than TBD kg for 100 drones.
- **RU-22**:The system's lifetime shall be 5 years.
- **RU-23**:After the 5 years lifetime, the power source shall be recycled.
- **RU-24**:The total cost of a stand-alone system with a swarm size of 3 drones shall not exceed 80,000 EUR.
- **RU-25**:The deployment costs, system operational costs and personnel costs shall be included in the budget analysis.
- **RU-26**:In the budget analysis a scenario of a production of 100 drones shall be used.
- **RU-27**: An operational cost estimation shall be performed for the situation of surveillance of three drones for 5 hours.

Consider the mission need statement specified in the Project Plan: *A mobile system capable of surveying and mapping the air turbulence and noise in an urban environment*. To accomplish such statement at best, the design phase will need to focus extensively on the methods used to measure turbulence and noise. All requirements regarding instrumentation and aeroacoustics will be design-driving (**RU-08**, **RU-09**, **RU-10**, **RU-11**, **RU-19**). One of the main challenges identified by the group, will be implementing a isolation method, to filter out the noise cause by the drone itself.

A rather significant part of the project is the data collection and processing. This leads to an impact on the design of the swarm organization, as well as on the adopted telecommunication system. **RU-05**, **RU-08** and **RU-12** will most definitely have a large weight in the design phase.

To ensure the operation success, it is strictly necessary to have a stable and controllable drone. The vehicle will need to have both an autopilot and a human-machine interaction option. Great importance will be given to the design of the control system for both options. **RU-04**, **RU-06**, **RU-07**, **RU-15**, **RU-16** and **RU-17** will therefore lead the control system part of the design.

One of the main priorities for the stakeholders is to adopt a green energy source and discard non-recyclable options (**RU-20**, **RU-21**, **RU-23**). Furthermore, given the urban environment as operating space, the rules for aerial vehicles will rigidly constrain the design possibilities (**RU-14** and **RU-18**).

The remaining user requirements are still to be considered as essential, however, they represent margins in the project development, instead of driving elements.

8.2. System and Mission Requirements

In this report a series of preliminary analysis have been done, and one of their use is the derivation of system and mission requirements for the project. Each requirement will have a unique identification code, which will indicate the analysis it is derived from, and the project segment it corresponds to. As an example, R-MA-O-2 would be a risk derived from market analysis, and corresponding to the operations segment.

It is noteworthy to mention, that since the project still is at a preliminary design phase, a lot of the requirement have values which are not determined yet. In this case, a ”TBD” (to be determined) is put in place of a number.

8.2.1. Functional flow diagram requirements

There are many requirements to be derived from the functional flow diagram, in Chapter 3, so these will be listed in four different lists, according to their corresponding mission segment (vehicle, interaction, operations, and payload). For the vehicle segment we have:

- **R-FA-V-01:** The system shall be able to operate for a time range of 4 hours
- **R-FA-V-02:** The drones shall detect and avoid unforeseen obstacles within a 5 m radius
- **R-FA-V-03:** The drones shall be able to store GPS data of TBD Mb
- **R-FA-V-04:** The drones shall be able to send GPS data at TBD Mb/s
- **R-FA-V-05:** The drones shall be able to implement commands sent from the ground station
- **R-FA-V-06:** The drones shall be able to store commands of TBD Mb sent from the GS
- **R-FA-V-07:** The drones shall be able to receive from GS with an error rate of at most TBD
- **R-FA-V-08:** The drones shall be able to detect deviation from the flight plan within a resolution of TBD m
- **R-FA-V-09:** The system shall be able to calculate the response required to correct the deviation within a resolution of TBD m
- **R-FA-V-10:** The system shall be able to respond to correct the deviation within a resolution of TBD m
- **R-FA-V-11:** The system shall have an autopilot system
- **R-FA-V-12:** The drones shall be possible to control in terms of pitch, yaw, roll and thrust by two certified pilots
- **R-FA-V-13:** The drones shall be able to hover with a wind speed of 8 Beaufort, with or without rain
- **R-FA-V-14:** The drones shall follow the gust path until the intensity is smaller than TBD m/s, when performing the dynamic measurements
- **R-FA-V-15:** The system shall have hardware to store measurement data of TBD Mb

- **R-FA-V-16:** The drones shall be able to land by themselves, with a resolution within TBD cm from the target landing site.
- **R-FA-V-17:** The drones shall be able to return to the GS and land, with 50% of the propulsive system actively working
- **R-FA-V-18:** The drones shall be able to return to the GS when recharging is required
- **R-FA-V-19:** The drone power system shall be rechargeable
- **R-FA-V-20:** The power system shall be able to recharge to full capacity within TBD hours
- **R-FA-V-21:** The drone propellers shall be detachable, to facilitate inspection
- **R-FA-V-22:** The drone measurement devices shall be detachable, to facilitate inspection
- **R-FA-V-23:** The drone structure shall be detachable, to facilitate inspection
- **R-FA-V-24:** The drone electronics shall be detachable, to facilitate inspection
- **R-FA-V-25:** The system shall be able to store a history of actions taken using TBD Mb storage

The requirements for the interaction segment are:

- **R-FA-I-01:** The system shall constrain the flight path such as the buildings will be avoided within a 5 m radius
- **R-FA-I-02:** The system shall be able to compute the flight paths of every aerial vehicle within TBD seconds
- **R-FA-I-03:** The drones shall transfer the real-time data to the GS at a rate of 10 Hz
- **R-FA-I-04:** The system shall cover a mission range of 5 km
- **R-FA-I-05:** The system shall operate between ground level and 500 m
- **R-FA-I-06:** The system should consist of at least 3 drones and at most 100

The requirements for the operations segment are:

- **R-FA-O-01:** The system shall be checked for nominal operation within <TBD> seconds
- **R-FA-O-02:** The system shall be able to check for failure modes of all sub-systems
- **R-FA-O-03:** The system shall be able to upload the flight plan to each aerial vehicle
- **R-FA-O-04:** The drones shall reach the target altitude within <TBD> minutes from the start-up
- **R-FA-O-05:** The drones shall reach the flight path starting point within TBD minutes from take-off
- **R-FA-O-06:** The system shall be able to detect in real-time the power remaining in the battery of an aerial vehicle with a resolution of <TBD> kWh
- **R-FA-O-07:** The system shall be able to detect in real-time the data transmittance with a resolution of TBD Mb
- **R-FA-O-08:** The system shall be able to detect in real-time, modes of failure within the operation of subsystems
- **R-FA-O-09:** The system shall be able to detect signals with at least <TBD> W transmitted from the GS
- **R-FA-O-10:** The system shall be able to store failure reports of <TBD> Mb
- **R-FA-O-11:** The system shall be able to send failure report of <TBD> Mb
- **R-FA-O-12:** The ground station shall include visual interface of the drone view
- **R-FA-O-13:** The system shall have a lifetime of 5 years
- **R-FA-O-14:** The raw acoustic time-series shall be downloadable after each mission

Lastly, the requirements for the payload segment are:

- **R-FA-P-01:** The system shall calibrate its sensors within <TBD> seconds
- **R-FA-P-02:** The system shall be able to measure the atmospheric pressure with a resolution of TBD Pa
- **R-FA-P-03:** The system shall be able to identify the outside temperature with a resolution of TBD K
- **R-FA-P-04:** The system shall be able to check noise frequencies generated by the system itself with a resolution of TBD Hz
- **R-FA-P-05:** The system shall be able to check the power of the noise frequencies generated by the system itself with a resolution of TBD W

- **R-FA-P-06:** The system shall be able to synchronise its internal clock with the GS with a resolution of TBD seconds
- **R-FA-P-07:** The system shall be equipped with a TBD acceleration measuring sensor
- **R-FA-P-08:** The system shall include an instrument to measure attitude with TBD spatial resolution
- **R-FA-P-09:** The system shall include an instrument to measure all 3 velocity components at a resolution of 10 Hz
- **R-FA-P-10:** The system shall include an instrument to measure turbulence with TBD spatial resolution
- **R-FA-P-11:** The system shall include proximity sensor, to scan the space within a 5 m radius
- **R-FA-P-12:** The system shall include an instrument to measure noise with TBD spatial resolution
- **R-FA-P-13:** The system shall be able to measure the noise of the environment up to 20 kHz.
- **R-FA-P-14:** The system shall be able to isolate the noise coming from the vehicle itself, when taking the measurements

8.2.2. Market analysis requirements

From Chapter 4 the following requirements can be deduced:

- **R-MA-O-1:** Raw data shall be remotely processed in a cloud based platform
- **R-MA-O-2:** The drone shall have a high resolution camera of TBD megapixels
- **R-MA-O-3:** Sensors shall be able to be hot-swapped
- **R-MA-O-4:** The drone shall be able to measure its geolocation
- **R-MA-O-5:** The system shall comfort to regulations and safety standards
- **R-MA-O-6:** The system shall require a maximum of two pilots to operate

8.2.3. Risk management requirements

More requirements can be found in Chapter 5, dedicated to risk management. These requirements are:

- **R-RM-O-1:** The drones shall cost less than TBD euros
- **R-RM-V-2:** The drones shall weigh less than TBD kg
- **R-RM-V-3:** The power system shall hold TBD kWh
- **R-RM-O-4:** Manufacturing shall produce less than TBD CO2
- **R-RM-O-5:** Drone maintenance shall take less than TBD hours
- **R-RM-O-6:** The power system shall charge in less than TBD hours
- **R-RM-V-7:** Battery degradation shall be lower than TBD kWh/year
- **R-RM-O-8:** Construction and assembly shall take less than TBD weeks
- **R-RM-O-9:** The drones shall be able to avoid collisions with unknown objects
- **R-RM-I-10:** The drones shall be able to avoid collisions with other swarm drones
- **R-RM-V-11:** The drones shall be stable
- **R-RM-V-12:** The drones shall be be able to safely return when GS contact is lost
- **R-RM-V-13:** The battery system shall not fail
- **R-RM-O-14:** The operator(s) shall be familiar with the system
- **R-RM-O-15:** The cost of the entire system shall not exceed 80,000 euros

8.2.4. Sustainability requirements

In Chapter 6, the strategy for a sustainable development is described. The requirements that can be derived from it are:

- **R-S-V-1:** Noise levels shall comply with the EU noise regulations
- **R-S-V-2:** Pollution during operation shall be lower than TBD
- **R-S-V-3:** Total carbon dioxide emissions from craddle to grave (start to end of mission) shall not exceed TBD
- **R-S-V-4:** The batteries shall be secondary (rechargeable)

- **R-S-V-5:** The used materials shall be recyclable
- **R-S-V-6:** The drone's power source shall be at least TBD % recyclable.
- **R-S-V-7:** The drone's power source shall be recyclable at the end of life
- **R-S-O-8:** The drones shall comply with aeroacoustic regulations for urban areas

8.2.5. Budget requirements

Chapter 7 focuses on the different budgets of the project, and the requirements that can be taken from this section are:

- **R-BA-V-1:** The vehicle cost shall not exceed 20,000 euros
- **R-BA-V-2:** Weigh less than TBD kg
- **R-BA-V-3:** Power system holds TBD kWh
- **R-BA-P-4:** The payload cost shall not exceed 3,000 euros
- **R-BA-O-5:** The ground station cost shall not exceed 8,800 euros
- **R-BA-O-6:**The cost of the whole system, including 3 drones, shall not exceed 80,000 euros

Note that these requirements are very similar to the first three requirements of the risk management, so they are assigned the same identification code so as to avoid redundancy.

8.3. Requirement Discovery Tree

Once all the requirements have been derived, these can be presented in a requirement discovery tree. In this case, the discovery tree is divided into each type of analysis from which they originate, and then the requirements are catalogued. In case of the function derived requirements, there are many requirements so these are also distributed into each segment of the system: vehicle, interaction, operations, and payload. Besides the requirements derived from the functional flow, the requirements are also derived from Risk, Market, Sustainability and Budget Analysis. Therefore, the requirements identified in these sections can be attributed to the vehicle, but also to the overall mission of the system. The main goal of the Discovery Tree is to provide a helping tool in future phases of the design, especially when multiple design options are being generated and assessed. The tree can be found in figure 8.1 and figure 8.2.

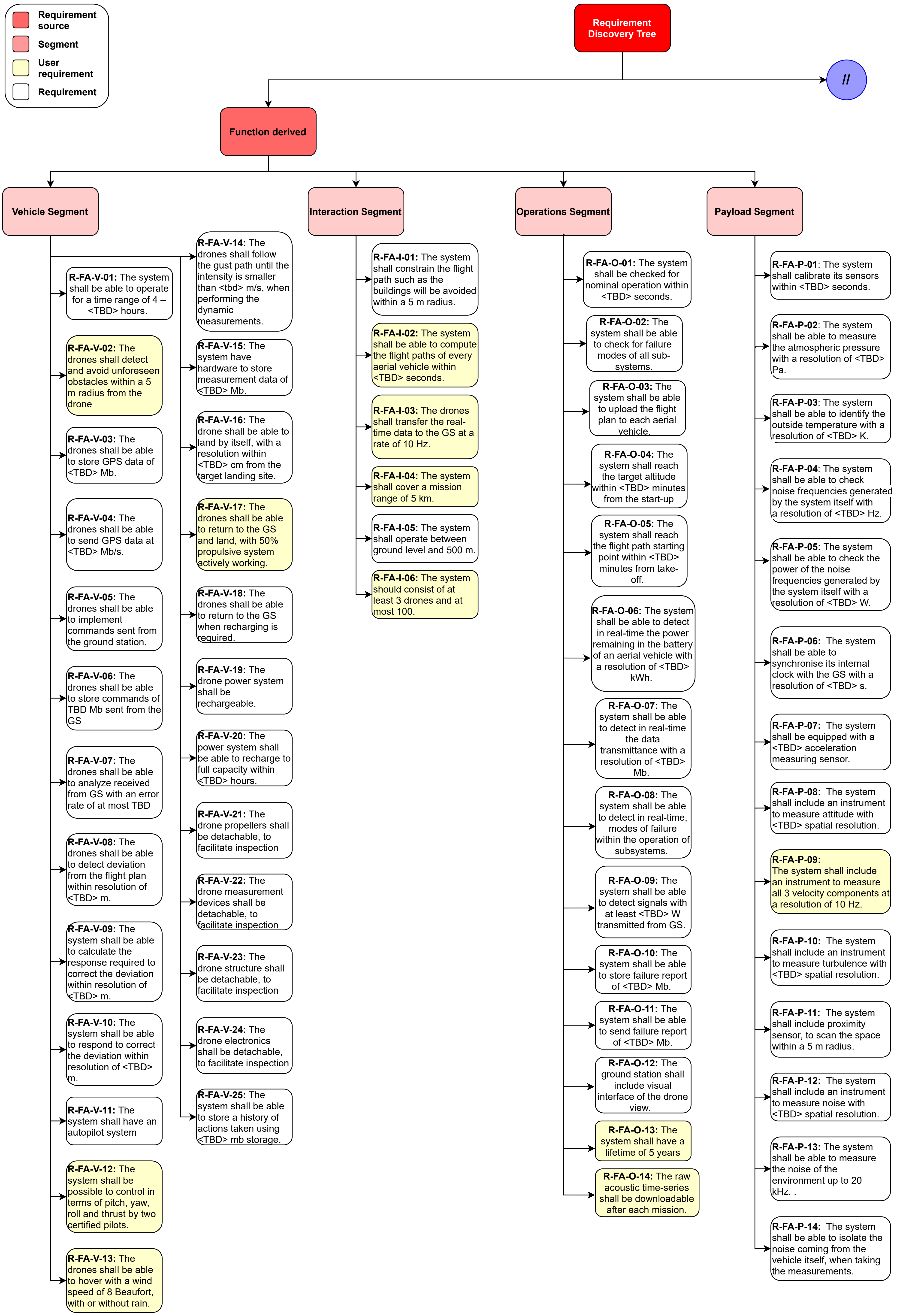

Figure 8.1 Requirements discovery tree part 1

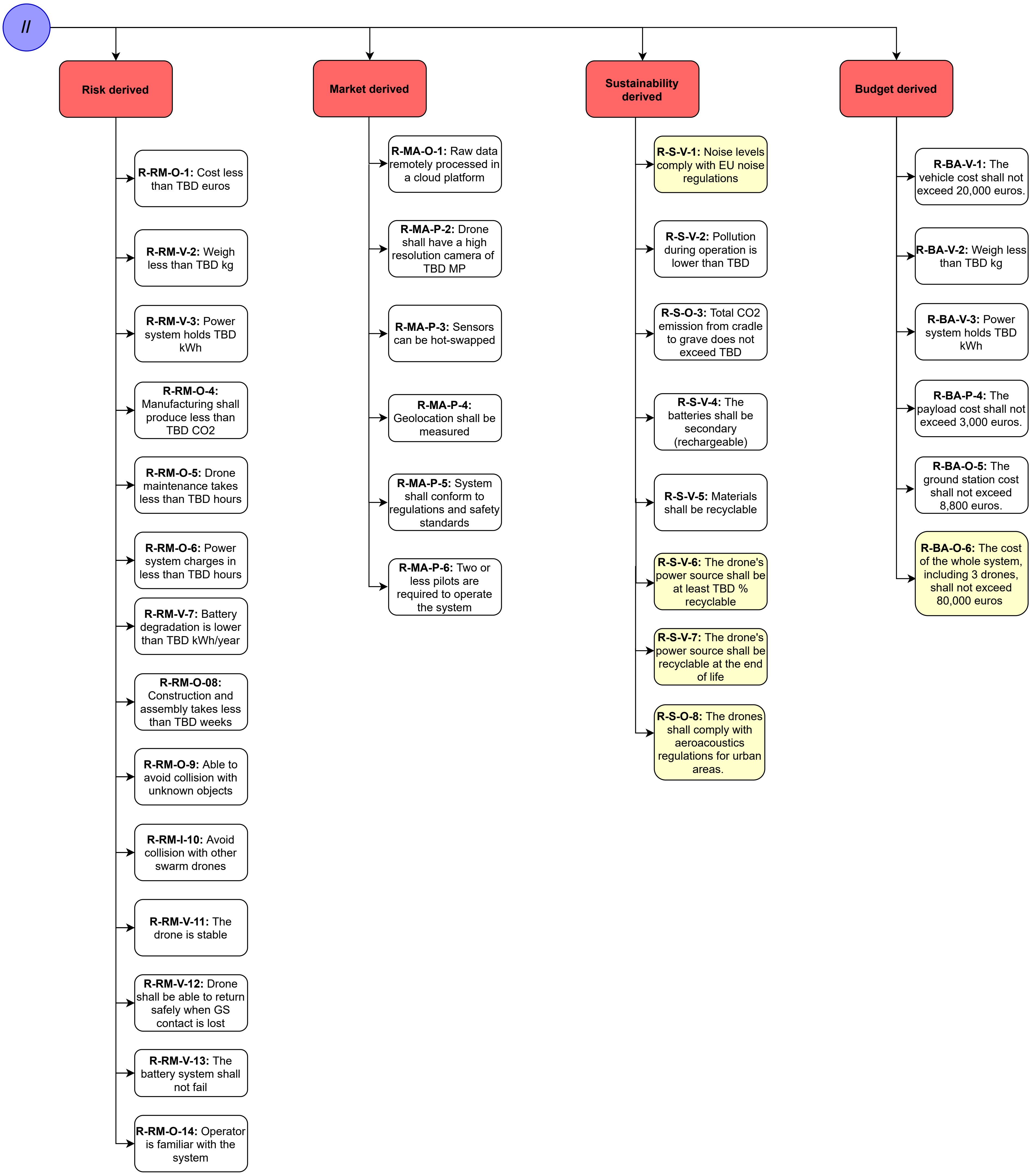

Figure 8.2 Requirements discovery tree part 2

8.4. Killer and driving requirements

It is important to find which of the listed requirements are either killer requirements or driving requirements. Killer requirements are those which drive the system to an unacceptable extent (i.e. it is not feasible), and driving requirements are those which drive the system more than average.

In this phase of the design, some requirements have value constraints which are not yet defined (all the requirements with a TBD), so it is difficult to evaluate these. Therefore, once all these values are more clearly stated, this section should be revised.

8.4.1. Killer requirements

The only killer requirement is the user requirement ***RU-07:**" The drones shall be capable of making a safe landing with 50% of the propulsive system actively working"*, which can be considered to be a killer requirement since losing all of the propulsion system on one side of the drone can cause uncontrolled spin and loss of control of the drone its self due to asymmetric thrust.

In addition, due to the requirement stating "50% of the propulsive system", this problem appears in every drone configuration. The hovering requirement (*RU-04*) only constraints the design even more, as configurations are limited to multi-copter designs seen in Chapter 9.

8.4.2. Driving requirements

The driving requirements of this project are the following:

- ***RU-04:*** *"The drones shall have hovering capabilities"* This requirement rules out the possibility of having small-scale airplanes as drones, and only leaves the possibility of drones which have propellers as a propulsion system.
- ***RU-16:*** *"The drones shall include a collision avoidance system, autopilot and proximity sensors"* This requirement implies the need of complex sensors. Furthermore, a fully capable autopilot system is very complicated and difficult to design and manufacture, so it will take a lot of time out of other possible design tasks.
- ***R-RM-V-12:*** *"The drones shall be be able to safely return when GS contact is lost"* For this requirement, an autopilot is necessary, which as previously mentioned is very time-consuming to produce. Nevertheless, it also has more consequences since the contact with the ground station is lost, and as a result the only way to go back to it requires the drone to record all its previous movements.
- ***R-S-V-5:*** *"The used materials shall be recyclable"* Some parts of the drone can be easily made out of recyclable materials, but some parts such as the propellers will pose a challenge which will definitely impact the overall design.

These requirements shall be carefully taken into account when making crucial design decisions.

9
Design Option Trees

After the functional flows were elaborated, and the requirements were set, the next step in the design process is to evaluate all the viable design options which can help to fulfill the requirements, in the design option trees. The goal of this chapter is to provide a global overview of several design ideas, ordered per segment along with the analysis of the unfeasible options and an evaluation of three to five feasible design combinations which will be traded off in the next phase of the design.

9.1. Design Options Diagram

In order to come up with a design that can fulfil the requirements listed in Chapter 8, several design options were generated for the four identified system segments: vehicle, payload, interaction and operations. These can be found in the design option trees given in figure 8.1 and figure 8.2. Not all design features, such as the battery mount location, are analysed further due to their high dependence on further analysis.

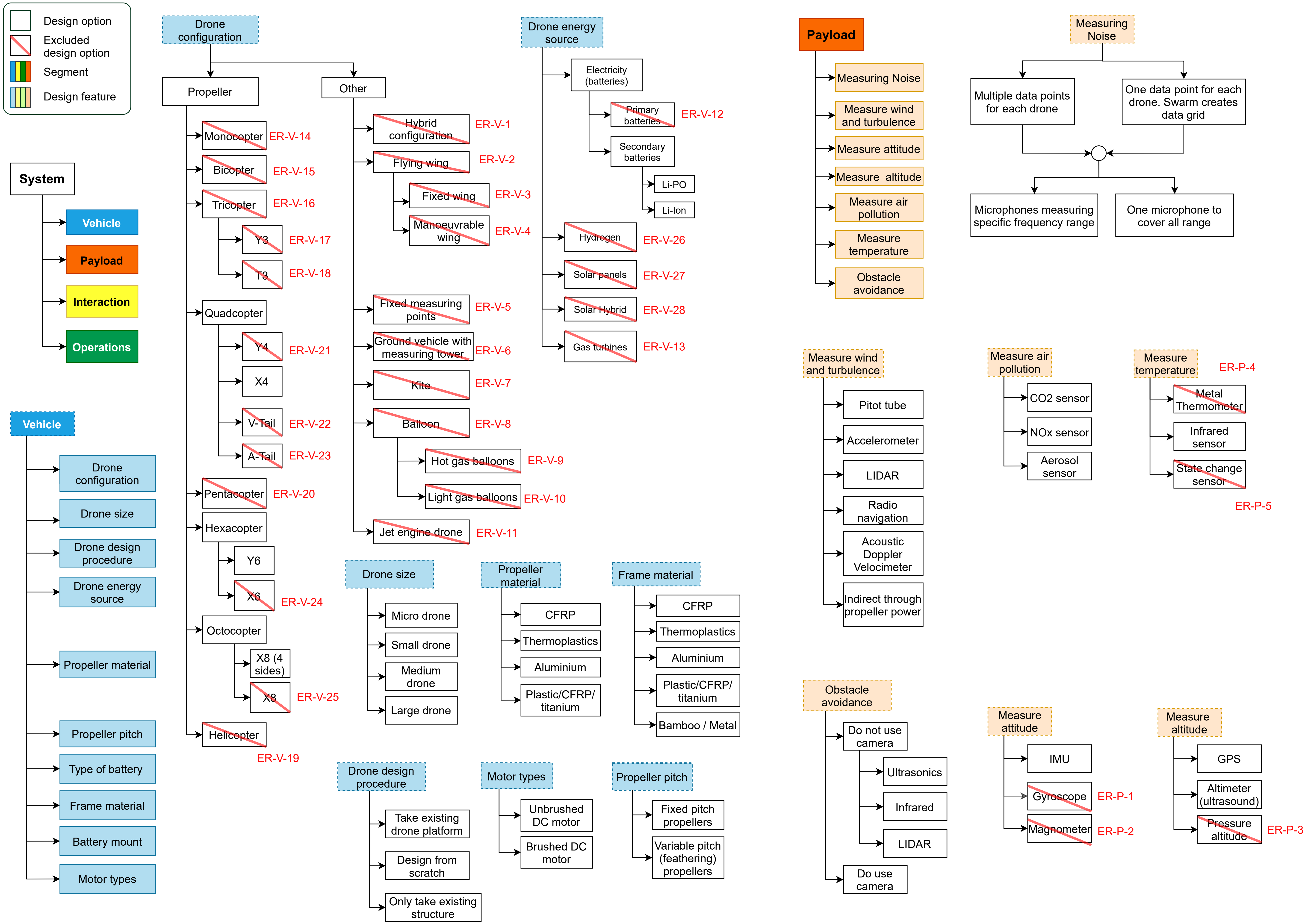

Figure 8.1 Design option trees part 1

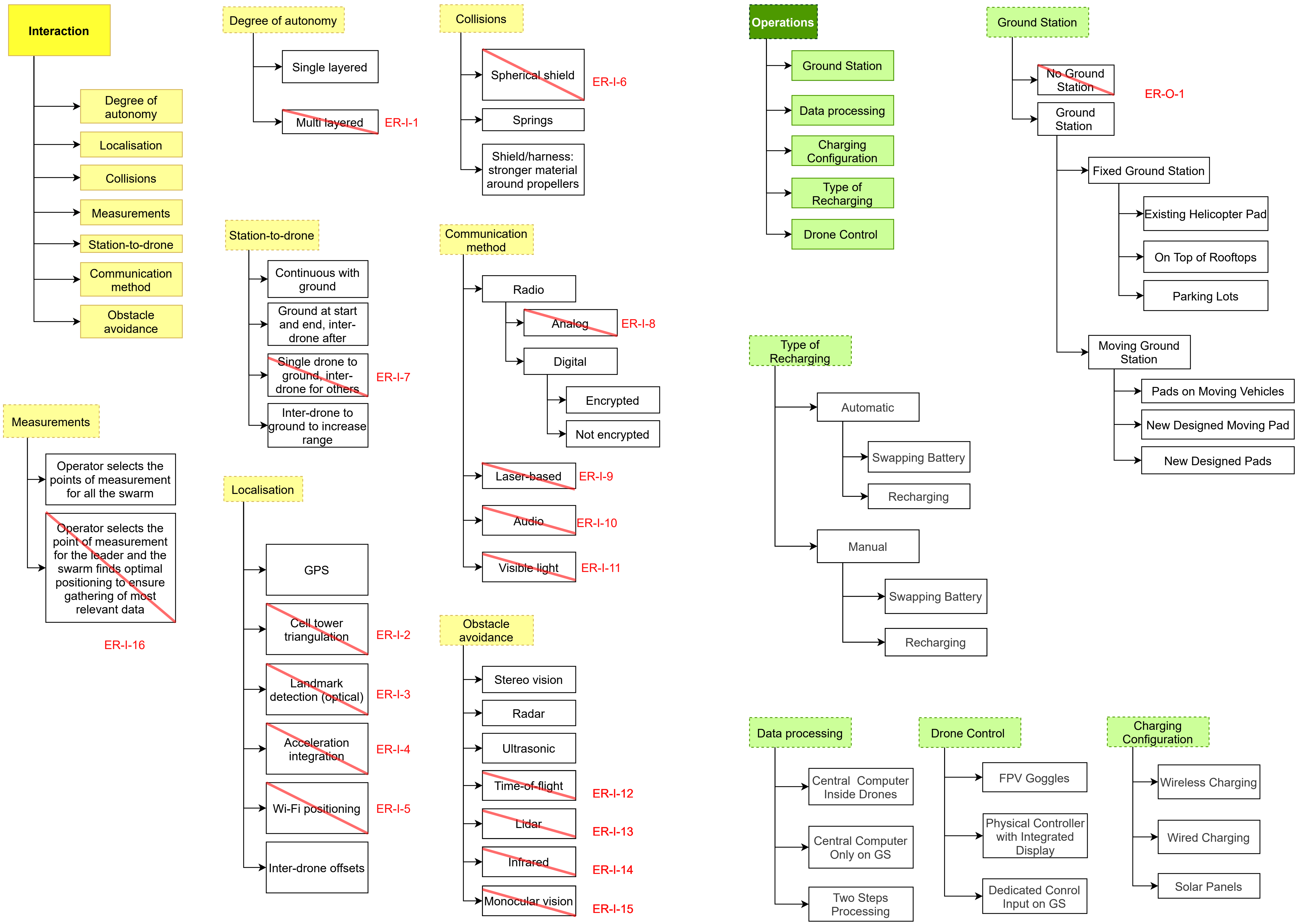

Figure 8.2 Design option trees part 2

9.2. Unfeasible options

A code was given to the unfeasible options marked in red on the diagram. Find below the discarded options for each segment.

9.2.1. Vehicle Segment

All the options regarding alternative aerial vehicle configurations such as hybrids, flying wings and balloons were excluded (*ER-V-1*, *2*, *3*, *4*, *8*, *9*, *10*), because of not sufficient hovering capabilities. Fixed measuring points, ground vehicles with measuring tower, and kites were discarded, because incapable to cover user-defined locations in a cost and operational effective manner (*ER-V-5*, *6*, *7*). The jet engine drone is rejected, as it is not considered sustainable and reasonably hazard-proof to operate in the urban environment (*ER-V-11*).

The final options only include drones with propellers, out of which monocopters, bicopters, tricopters and helicopters are discarded (*ER-V-14*, *15*, *16*, *17*, *18*, *19*). Adopting such options would not only represent a challenge in terms of controllability and correct instrumentation functioning, but also *RU-07* would be extremely difficult, if not impossible, to achieve.

Finally, quadcopter A-tail, quadcopter V-tail, pentacopters, hexacopter X6 and octocopter X8 are not considered (*ER-V-21*, *22*, *23*, *24*, *25*), as they do not really introduce any advantage and uniquely increase the dynamic complexity of the control system. The 3 options left are:

- Quadcopter X4: 4 motors placed on a X-shaped frame.
- Hexacopter Y6: 2 motors placed on the 3 branches of a Y-shaped frame, one on the top side and one on the bottom side.
- Octocopter X8: 2 motors placed on the 4 branches of a X-shaped frame, one on the top side and one on the bottom side.

Regarding the energy source, gas turbines (*ER-V-13*) are obviously excluded for being not sustainable. Primary batteries (*ER-V-12*) would result in many problems during the operational life, as substituting could not be automated. Furthermore recyclability would represent an issue. Hydrogen drones are not a mature enough technology and will therefore be ignored (*ER-V-26*), as they would require large time resources for research and design and they do not represent the purpose of the project. Solar panels and solar hybrids (*ER-V-26*, *27*) are excluded as the required panel area to operate for 4 hours (*RU-03*) would most probably be too large, leading to more weight and therefore a challenging snowball effect. Moreover, *RU-06* would not be satisfied, as the system has to operate with rain. The 2 remaining options are: LiPo battery and Li-ion battery. A more complete trade-off will be conducted for the final decision.

Concerning the material choice for both the structure and the blades, none of the options can already be scrapped, as it would require a detailed analysis. Especially for the blades, an elaborate research will be conducted to investigate noise levels.

The drone size will be kept as unspecified, as well as the type of motor, since these two options depend on each other (e.g.: micro drones do not use brush-less motors). A thorough mass estimation is necessary before specifying the mass and size of the vehicle. Another possible option is including variable-pitch blades, which could result in a reasonably significant power save. The thrust could be adjusted by moving the propeller blade, rather than increasing the current flow.

9.2.2. Interaction Segment

The rationales for discarding options in the interaction segment design option trees are given in table 9.1 for clarity. The elimination rationales given mainly originate from challenges of the urban environment. This environment puts limitations on the technologies that can be used due to the materials the environment is constructed from, the layout of the environment and the presence of residents in this environment. For example the line of sight cannot be guaranteed in the urban landscape and the abundant use of glass makes light-based obstacle detection methods unreliable or even impossible. Another influential factor in the elimination process is time feasibility. While some options could lead to more pleasant products for the end-user, the time required to develop them is estimated to be much longer than the typical design phase duration of this project.

Table 9.1: Elimination rationales for Interaction segment

Elimination rationale ID	Rationale
ER-I-1	Multi-layered hierarchy with small swarm size complicates design and could create single point of failure if leader drone fails.
ER-I-2	Suffers from weather disturbance. Method also imprecise due to non-intended use. Imprecision not suited for spatial data mapping goal.
ER-I-3	Large amount of training required and highly dependent on city of deployment. Obtained position also not precise, thus not suited for spatial data mapping goal.
ER-I-4	Heavily dependent on accelerometer accuracy and initial conditions. Additionally requires high amount of post-processing.
ER-I-5	Only gives estimate for general area of position, no precise information. Imprecision not suited for spatial data mapping goal.
ER-I-6	Creates additional turbulence around drone, disrupting turbulence measurements.
ER-I-7	Creates single point of failure if communication drone fails.
ER-I-8	Analog data transmission no longer standard practice. Digital signals have more error correction methods.
ER-I-9	Line-of-sight not guaranteed in urban environment. Additionally, required aiming precision deemed too high for 5km range determined by requirements.
ER-I-10	Highly inefficient method with rapid signal degradation. Additionally, causes discomfort for residents.
ER-I-11	Line-of-sight to ground station or other drones not guaranteed in urban environment. Additionally, disturbing influence for residents.
ER-I-12	Urban environment contains many obstacles constructed from transparent and/or reflective surfaces. Light-based method thus not suited for detecting these.
ER-I-13	Urban environment contains many obstacles constructed from transparent and/or reflective surfaces. Light-based method thus not suited for detecting these.
ER-I-14	Urban environment contains many obstacles constructed from transparent and/or reflective surfaces. Light-based method thus not suited for detecting these.
ER-I-15	Large amount of training (neural net) or precise algorithm (parallax) required. Resulting depth estimate imprecise.
ER-I-16	High degree of drone autonomy required. Construction of such a system deemed unfeasible in given design phase duration.

9.2.3. Operations Segment

Due to the low-level nature of the operations design option trees, no preliminary option elimination is performed except for *ER-O-1* as this is driven by the user requirement *RU-12* stating that a ground receiver and thus station must be present. The design option trees are still provided for completeness and can be used for further analysis in a later design phase.

9.2.4. Payload Segment

The elimination rationales for the payload segment are given in table 9.2.

The sections on the measurement of noise and turbulence did not experience eliminations due to the fact that the options where too involved to make a hard decision on at this moment in time.

Table 9.2: Elimination rationales for Payload segment

Elimination rationale ID	Rationale
ER-P-1	Gyroscope is already contained within the IMU.
ER-P-2	Magnometer is already contained with the IMU.
ER-P-3	Altitude different is not so much higher that there is a significant difference in pressure at different altitudes. Besides, the pressures differs based on weather and this leads to inconsistent measurements.
ER-P-3	Altitude different is not so much higher that there is a significant difference in pressure at different altitudes. Besides, the pressures differs based on weather and this leads to inconsistent measurements.
ER-P-4	Metal thermometer needs time to get the correct measurements and needs a physical pin to gauge. However, the temperature will have to be measures within a certain time interval and pins are harder to incorporate into the drone.
ER-P-5	It is preferred to have a quantitative value of the temperature, not so much knowledge on surpassing a certain threshold.

9.3. Feasible options

In table 9.3 the final chosen concepts are shown. These follow directly out of the design option trees shown in Section 9.1 and their associated elimination procedures in Section 9.2.

Table 9.3: Final design concepts for trade-off. Some elements are not considered due to their dependence on further design and will be decided upon in later design phases.

	Option 1	Option 2	Option 3
Drone configuration	Octocopter	Hexacopter	Quadcopter
Drone size	Large	Medium	Small
Drone design procedure	Take existing structure	Take existing platform	Design from scratch
Drone energy source	Electricity	Electricity	Electricity
Propeller material	-	-	-
Propeller pitch	Fixed	Variable	Fixed
Type of battery	Secondary batteries	Secondary batteries	Secondary batteries
Frame material	-	-	-
Motor types	-	-	-
Degree of autonomy	Single layered	Single layered	Single layered
Localisation	GPS	GPS	GPS
Collisions	Stronger material around propellers	Springs	Stronger material around propellers
Measurements	Operator selects the points of measurement for all the swarm	Operator selects the points of measurement for all the swarm	Operator selects the points of measurement for all the swarm
Station-to-drone	Continuous with ground	Continuous with ground	Continuous with ground
Communication method	Radio	Radio	Radio
Obstacle avoidance	Stereo Vision	Radar	Ultrasonic
Ground station	Yes	Yes	Yes
Landing platform	-	-	-
Data processing	Two-step	Two-step	Two-step
Charging configuration	Wired charging	Wireless charging	Wired charging
Type of recharging	Manual - swapping battery	Automatic - recharging	Automatic - swapping battery
Drone control	FPV Goggles	Dedicated Conrol Input on GS	Physical Controller with Integrated Display
Measure noise	One microphone to measure all the frequency ranges	Multiple microphones measuring a specific frequency range	One microphone to measure all the frequency ranges
Measure wind and turbulence	Pitot Tube	Indirect through propeller power	Acoustic Doppler Velocimeter
Measure attitude	IMU	IMU	IMU
Measure altitude	GPS	GPS	Altimeter(ultrasound)
Measure air pollution	CO_2 sensor and Aerosol Sensor	NO_X Sensor and Aerosol Sensor	NO_X Sensor and CO_2 Sensor
Measure temperature	Infrared Sensor	Infrared Sensor	Infrared Sensor
Obstacle avoidance	Ultrasonic	Infrared	Camera

10
Project Design and Development Logic

After the product design phase, encapsulated by the Design and Synthesis Exercise (DSE), production and deployment of the proposed system will take place. This sequence of events is represented by the project design and development logic. As no aspects of the design are fixed at this point in time, this sequence of events is subject to change in later stages of the design. The preliminary project design and development logic diagram is given in figure 10.1.

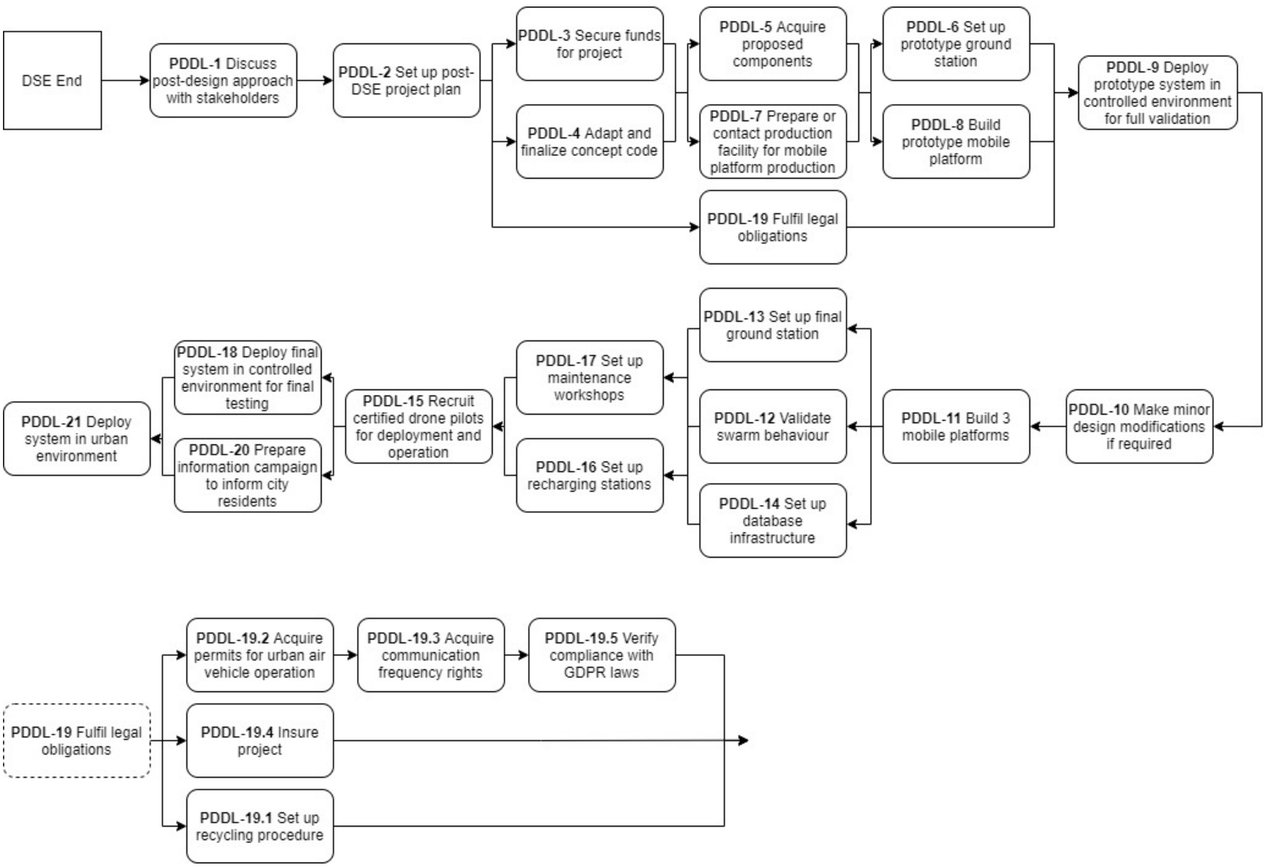

Figure 10.1: Project Development and Design Logic diagram containing all currently identified post-DSE activities and their respective ordering

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