Final Report

AmpAir: Regional Mobility Air Taxi

AE3200: Design Synthesis Exercise

Group 5

Delft University of Technology

TU Delft

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by

Group 5

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TU Delft

Executive Overview

The Challenge

Travellers want their trip to be as time-efficient as possible. Flights are often at inconvenient times, passengers waste time at the airport and have to travel to their final destination after flying by another means of transport. Additionally, flight shame is affecting more and more travellers. Therefore, passengers are looking for a time-efficient, sustainable, but affordable transportation alternative.

Another aspect that increases the travel experience is privacy. Going by car allows private travel all the way to your final destination, at any desired time. However, for long distances, they require long travel times. Therefore, there is a need for a novel regional transport service, since there is currently no mode of transportation that is emission-free, fast, flexible, and private. AmpAir will take this chance and introduce an air taxi onto the market. The service has the advantage that it is on demand, faster than travelling by car and gives flexibility in the departure and arrival airports, bringing the passenger closer to their final destination.

There are already air taxi concepts on the market that achieve privacy and time-efficient travel within Europe. However, these services are only affordable for upper-class customers. The main reason for this is that empty leg relocation flights have to be performed when a customer needs to be picked up. These flights are considered 'useless', while consuming resources such as fuel. Additionally, the aircraft needs a pilot, who not only has to be paid, but also limits the useful payload weight. Therefore, a better solution must be created.

The AmpAir Vision

AmpAir provides the step to a greener future by offering an air travel service, unique from any other existing services, connecting Europe with a low-cost, emission-free, private air transport service. By incorporating high levels of automation, customers will be able to fly themselves, at any time, to any location.

AmpAir is aspiring to set up a regional air taxi that has lower cost than current concepts. This will be achieved by removing the need for a licenced pilot by implementing an autonomous autopiloting system. This means empty-legs will be flown autonomously, bringing down the cost of relocation flights. Additionally, an extra passenger can be taken on board, increasing flight revenue.

To ensure the longevity of the aviation sector, any new transportation service should minimise their emissions. This implies implementation of an emission-free propulsion system, as well as creating a 90% recyclable design. This is crucial to limit global warming and create a circular economy. Additionally, consumers are becoming more and more aware of their environmental impact, demanding emission-free travel options. By implementing an electrical propulsion system, AmpAir will engage and encourage people that emission-free travel is possible.

To summarise, AmpAirs' mission is the following: **Provide a sustainable private air transport service that is less expensive and more environmentally friendly than current options.** This will be achieved through a ten-week Design Synthesis Exercise by 10 students of the Delft University of Technology. This research will contribute to future development of cost-effective, emission-free aviation. Both in their operational and logistics concept, as well as proposing a new, more efficient design.

Market

AmpAir expects to attract three different markets within Europe: business travellers, environmentally conscious tourists and flight enthusiasts. The flexibility of the AmpAir taxi service is expected to be competitive with commercial last minute flights, as their cost increases exponentially the closer the booking is made to the departure. Business travellers often book within 48 hours before departure. AmpAir believes it can attract business travellers due to the flexibility and the competitive prices it offers. Assuming a penetration rate of5% of this market, this would amount to approximately 290.000 customers [1] [2] [3]. Furthermore, environmentally

[1]https://maeve.aero/maeve-01 [Accessed on 26.5.2023]

[2]https://www.pwc.com/us/en/industries/consumer-markets/library/corporate-travel-collaboration-essential-for-covid-19-recovery.html [Accessed on 26.5.2023]

[3]https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20190506-1 [Accessed on 26.5.2023]

conscious tourists are willing to pay more to minimize their environmental impact, drawing them to the AmpAir service. This group makes up a large fraction of the expected AmpAir customer base, as over 65% of people in the European Union take at least one touristic trip a year[4]. Assuming a retention of 5% of this market, this would attract additional 840.000 passengers to AmpAir [5],[6], [7],[8],[9]. Finally, AmpAir is an affordable alternative for flight enthusiasts who want to pilot an aircraft themselves. Estimates of the fraction of people in Europe who own a licence, as well as those who show a general interest in piloting, are considered. This includes the users of the Microsoft Flight Simulator game [10]. The additional market of this group is estimated at 50.000 [11], [12][28]. Overall, AmpAir will be able to attract 1.18 million yearly passengers.

Two other markets were analysed, which will be targeted during early project stages, as their certification will be available sooner than manned autonomous flight. Firstly, AmpAir could function as a low-cost flight school, for which the Netherlands would be an ideal location because of its high population density. Secondly, the cargo market can rent the AmpAir aircraft for express deliveries. Because the aircraft is zero-emissions, it would improve the image of both recreational piloting and cargo deliveries by aeroplane.

Certification and Safety

AmpAir envisions the creation of an affordable and eco-friendly transportation service that prioritises minimising total trip time. The necessary technology to accomplish this objective is readily available, as advancements in autopilot systems have reached a stage where autonomous flight, including take-off, cruise, and landing, can be safely executed without human intervention[13]. However, existing certification regulations currently do not permit fully autonomous flight operations. To address these limitations, AmpAir will implement measures that allow for intervention in autopilot operations. Passengers will undergo training to acquire basic piloting skills, assuming the role of a safety pilot. Additionally, a certified remote pilot will have the capability to assume control of the aircraft from the ground. It is anticipated that certification regulations will authorise unmanned remotely piloted aircraft by 2029, with manned flights employing both a safety pilot and remote pilot becoming certified by 2034.

Multiple safety features are implemented in the AmpAir aircraft. Firstly, the passenger can be denied flight if they are deemed incapable of flying. Additionally, the passenger will have emergency buttons that put them into contact with the ground station for assistance. By having a piloting passenger, remote pilot, warning systems and central monitoring systems, the aircraft will maintain and exceed current safety standards. For redundancy within the aircraft, dissimilar avionic systems, backup systems and emergency power capabilities are implemented. The safe life of the autopilot system is designed for lifetime reliability, and the aircraft remains operable even when communication and control links are lost. On top of that, robust security systems are implemented to safeguard against potential malicious intentions. For example, geo-fencing will be implemented to prevent the passenger from deviating from their pre-defined flight path too much. In emergencies, a parachute recovery system enables safe landings and braking. Flight planning is designed to keep the aircraft within gliding distance of a suitable airstrip at all times. All these measures ensure the AmpAir aircraft complies with strict regulations, exceeding industry standards, but is also prepared to achieve full autonomy with anticipated advancements in autopiloting capabilities and regulations.

Growth Concept and Cost

At present, electric aviation is limited by current battery energy densities, while automation of aircraft is limited by certification. To ensure a future-proof design, an analysis was performed based on different battery energy densities and levels of automation. Here, combinations of battery densities (225 Wh/kg, 450 Wh/kg, 675 Wh/kg or 900 Wh/kg) and automation levels (fully-piloted, unmanned remotely piloted cargo aircraft, continuous remotely monitored aircraft with safety pilot, discontinuous remote monitoring with safety pilot and

[4] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Tourism$_{s}tatistics_{-p}articipation_{i}n_{t}ourism$
[5] https://transport.ec.europa.eu/transport-themes/sustainable-transport_en
[6] https://www.iata.org/en/pressroom/2022-releases/2022-11-01-01/#: :text=Bahrain%20%2D%20The%20International%20Air %20Transport,focused%20on%20simplification%20and%20convenience.
[7] https://www.energy.gov/eere/vehicles/articles/fotw-1042-august-13-2018-2017-nearly-60-all-vehicle-trips-were-less-six
[8] https://www.m3consultancy.nl/blog/one-in-three-schiphol-airport-passengers-fly-short-distance-an-exception-in-europe
[9] https://www.phocuswire.com/Majority-travelers-prefer-flexible-booking
[10] https://www.flightsimulator.com/microsoft-flight-simulator-celebrates-10-million-pilots/
[11] https://www.qualityfly.com/airline-pilot-salary/easa-or-faa-licence/
[12] https://explodingtopics.com/blog/number-of-gamers
[13] Source: https://sn.astm.org/features/making-autonomous-flight-reality-ja22.html

fully autonomous). Six different combinations were defined, which are called stages. The AmpAir aircraft was chosen to be optimised for the stage where the available battery density is 450 Wh/kg and passengers will fly the aircraft as a safety pilot, while being remotely monitored. This design has a range of 403 km with a payload of 278 kg, and the payload-range diagram is shown in Figure 1.

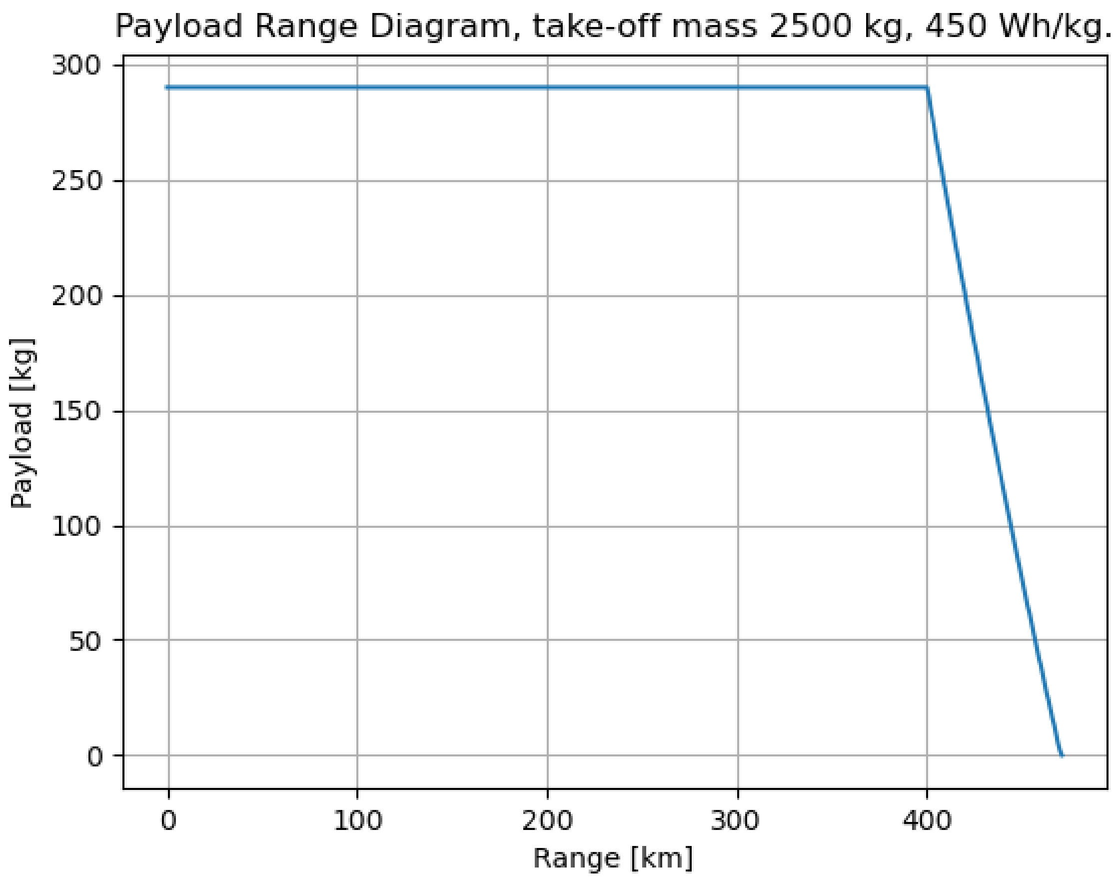


Figure 1: Payload-range diagram

AmpAir is made future-proof by staying adaptable and creating a target road-map for their future business strategy, starting in 2023. This way, the aircraft will perform optimally as advancements in technology and certification are made. If all stages have to be utilised, the ROI of AmpAir will be 135%. However, if the start of operations is postponed to 2030, a ROI of 175% is projected. This shows how the business case runs parallel with the status of development of different subsystems. Current options can fly passengers for around €1.17 per kilometre, whereas in the future, AmpAir will be able to fly their passengers for as little as €0.27, including a sizeable profit margin.

The design stage chosen by AmpAir will require no more than €1.35 million to procure, and as such is competitive on the target market. This will drop to €0.65 million as growth continues to a fleet size of 538 aircraft, with each one expected to fly two flights per day, 365 days per year. Note that this is merely an assumption for the average, based on a maintenance fraction of 0.275. Thus indicating 0.275 hours of maintenance per flight hour.

Operations and Logistics

The aircraft will be optionally-piloted, meaning that it is capable of flying autonomously, but can be piloted as well. Including the passenger in piloting and pre-and post flight checks, which they will be allowed to do after just a single day of training, will create a unique user experience. All of this is made possible by including high levels of automation in the flight systems, while supported by a monitoring ground control station.

Different safety features are implemented in the aircraft. Firstly, deviation from the flight path is prevented by implementing geofencing. On top of that, a game will confirm the reaction speed of the passenger, giving an indication on their capability to fly. Different kinds of safety buttons, namely an emergency button, landing button and help button can be used to contact ground station or initiate an emergency landing. Moreover, ATC communication was automated for take-off and landing clearances, while any other ATC communication will be done by the ground station, unless the piloting passenger is licensed to do this.

After passing a theoretical exam, the customers will learn how to operate the aircraft, which includes the pre- and post-flight checks as well as how to fly it, during a one-day training course. The course is concluded with a simulator run, where the passenger can get familiar with the controls and thrust levers, learn how to taxi, take off, use the highway-in-the-sky and land.

The passengers' pilot responsibilities are tied to their star rating. One star will be obtained after successfully completing the one-day training. Their first flight will be continuously guided and partially piloted by a remote pilot. Afterward, the customer can fly the aircraft themselves under continuous supervision of an observer. Two stars are awarded after 15 hours of piloting. Once a pilot has two stars, they can take customers outside their own party. To upgrade to three stars, another theoretical exam needs to be passed, as well as a physical flight exam, giving the customer responsibility over the ATC and onboard standby instruments. By passing an additional theoretical and practical exam, the passenger will be awarded four stars and is capable of completely controlling the aircraft. This is without the highway-in-the-sky autopiloting system.

The AmpAir air taxi service will operate at both large and small airports in Europe, referred to as hubs and spokes, respectively. Currently, hubs cannot be located more than 400 km apart, because of the aircraft' range. There is potential for future expansion to airports outside of Europe, including remote locations with more challenging landing conditions. At the hubs, preventive maintenance and routine inspections will be conducted. In the event of unexpected damage at spokes, maintenance teams will be relocated for corrective maintenance. Overnight storage of the aircraft will take place at the hubs, as they are equipped with fast-charging facilities, resulting in minimal downtime. Slower charging is available at the spokes, but for future upscaling, it should be discussed with airports how they will accommodate this charging. When the aircraft is plugged in, it will cause a peak in power extraction, straining the grid. A solution could be to install renewable energy facilities at the airport. In the future, when lithium-sulphur batteries are implemented, swappable batteries can replace the need for charging.

After the passenger has booked a flight in the app, they can travel to the desired departure airport. Here, they will complete the pre-flight checklists, while the aircraft itself performs certain system checks. Once all the checks are confirmed by the ground station, the aircraft will receive their clearance for departure. Once the ATC has provided take-off clearance, the aircraft can take off. If an empty leg departs, personnel will be present at the hubs, and contractors at the spokes, to perform the checks. Similarly, personnel or contractors are responsible for storing and charging the aircraft after a flight.

A last component of the operations and logistics is determining the required amount of AmpAir staff. There will be four different functions: operators, instructors, remote pilots and observers. The operators manage the ground station operations and crew. Furthermore, instructors will be responsible for giving trainings, like the one-day training for new pilots and in-depth training for passengers that want to increase their star rating. In addition, the remote pilots have the ability to take over control of the aircraft from the ground station. Lastly, the observers will monitor flights. They are a point of contact for the passengers and can assess if a situation must be forwarded to a remote pilot to be resolved safely. AmpAir will start operations at 10% fleet size, which will grow to the final fleet size within the first five years of operations. This implies that the AmpAir team will grow from 1 to 5 operators, 2 to 14 remote pilots, 10 to 110 observers and 6 to 12 instructors over the course of the first five years.

Sustainable Development Strategy

Creating a Sustainable Development Strategy allows AmpAir to stay accountable and continuously monitor its ecological performance.

Social Sustainability

Social sustainability will be an integral part of AmpAirs' SDS. Here, inclusion and protection of the people involved in the development process or influenced by the operational stage is prioritised. This will be done by protecting the communities involved in mining the rare metals used for lithium-ion batteries (LIBs) and minimising aircraft noise pollution underneath flight paths.

Current mining practices to obtain the raw materials for LIBs violate human rights and are a constant threat to the environment and communities around it. AmpAir will actively avoid batteries that contain cobalt, as its mining is known to increase geopolitical tension in the Congo. Additionally, AmpAir will actively lobby for better environmental surveillance around regions of lithium production, as leakage of lithium brine poses a constant threat to local communities and the surrounding environment. In this way, AmpAir aims to improve the living conditions of the communities involved in mining for battery raw materials.

People living under flight paths experience can experience a negative impact from the increased noise. It has been demonstrated that it negatively impacts children's cognitive development, disturbs sleep patterns, and causes increased annoyance in communities [6]. The propulsion system is the main source of noise. When flying at cruise altitude of 2000 m, the aircraft is expected to emit 34.1 dB noise on the ground, which is barely noticeable by the human ear. When cruising at 1000 ft, the noise on the ground is 51.9 dB[14] requirement of maximum 60 dB. Furthermore, the sound pressure level is expected to be 83 dB inside the cabin. To protect the passengers' hearing, noise-cancelling headphones will be provided which can damp the noise to 53 dB, which is unharmful, even when exposed for a prolonged period of time.

Emission-free Travel

AmpAir will be the world's first emission-free air taxi service. This is achieved by implementing an electrical propulsion system, lowering the aircraft's warming effect by 30% compared to traditional kerosene combustion aircraft. The energy will be stored in lithium-ion batteries. In order to achieve net-zero emissions, the energy sourced to power the operational quarters and charge the batteries will come from renewable energy sources and AmpAir will lobby for battery production practices with lower emissions.

Less Than 10% EOL Waste

Currently, almost all EOL aircraft end up in landfill, because re- or down cycling them is not economically feasible. Reducing waste is integrated in the design process from the start. Material choice, manufacturing methods, assembly strategies are all created to minimise waste. At the EOL, the aircraft will be disassembled, after which functional systems are recuperated and repaired for re-implementation. All non-usable components are indirectly re-used by further disassembling, after which they will be recycled. Future recycling of thermoset composites is looking promising, but before this can be implemented, improvements in its collection and advancements in recycling techniques are necessary. For an electrical aircraft, a large fraction of their EOL weight are the LIBs. Collection and recycling facilities must grow at an even greater pace than the increase of LIB production, as currently, only 5% of global Electrical Vehicle (EV) LIBs are recycled [74]. It is expected that these developments will take place by the time AmpAir becomes operational.

The AmpAir Aircraft

AmpAir believes that a high-wing aircraft with distributed propulsion and a conventional tail is the option that can achieve their goals. Firstly, because of the distributed propulsion, higher lift values are reached, the aircraft reliability is increased, and the noise is decreased. Additionally, choosing a high wing decreases the risk of debris damaging the propellers, radiators and air intakes, allowing AmpAir to operate at airports with unhardened landing strips. Lastly, the conventional tail minimises weight, simplifies maintenance and inspection, and is easier to handle for inexperienced pilots. How the aircraft would look like is shown from various angles in Figure 2 to Figure 5, while an isometric drawing is shown in Figure 6.

One of the key features of the AmpAir aircraft is its distributed propulsion system, which increases the lift coefficient of the wing and increases the effective aspect ratio by reducing tip vortices. The distributed propulsion system consists of two tip propellers, optimised for cruise, and 14 high-lift propellers, which are optimised for take-off and climb. Additionally, the high-lift propellers will be folded during cruise to minimise zero-lift drag. After an optimisation process, the tip propeller diameter was found to be 1.87 m and the high-lift one 0.71 m. The battery system distributes the power to the motors differently for each mission to maximise propulsion efficiency. When combining this with the found diameters, propeller efficiencies of 80%, 65% and 55% for cruise, climb, and take-off were found.

Despite having a relatively low wing surface area of $17.3\,\mathrm{m}^2$, the AmpAir aircraft has good aerodynamic characteristics. Firstly, the NACA65(3)-618 airfoil was chosen because of its favourable lift-to-drag performance. Furthermore, the high-lift propellers increase the lift by approximately 33%. Furthermore, fowler flaps

[14] REQ-STK-USR-02: The vehicle shall not be louder than 60 dB(A) at 1000 ft.

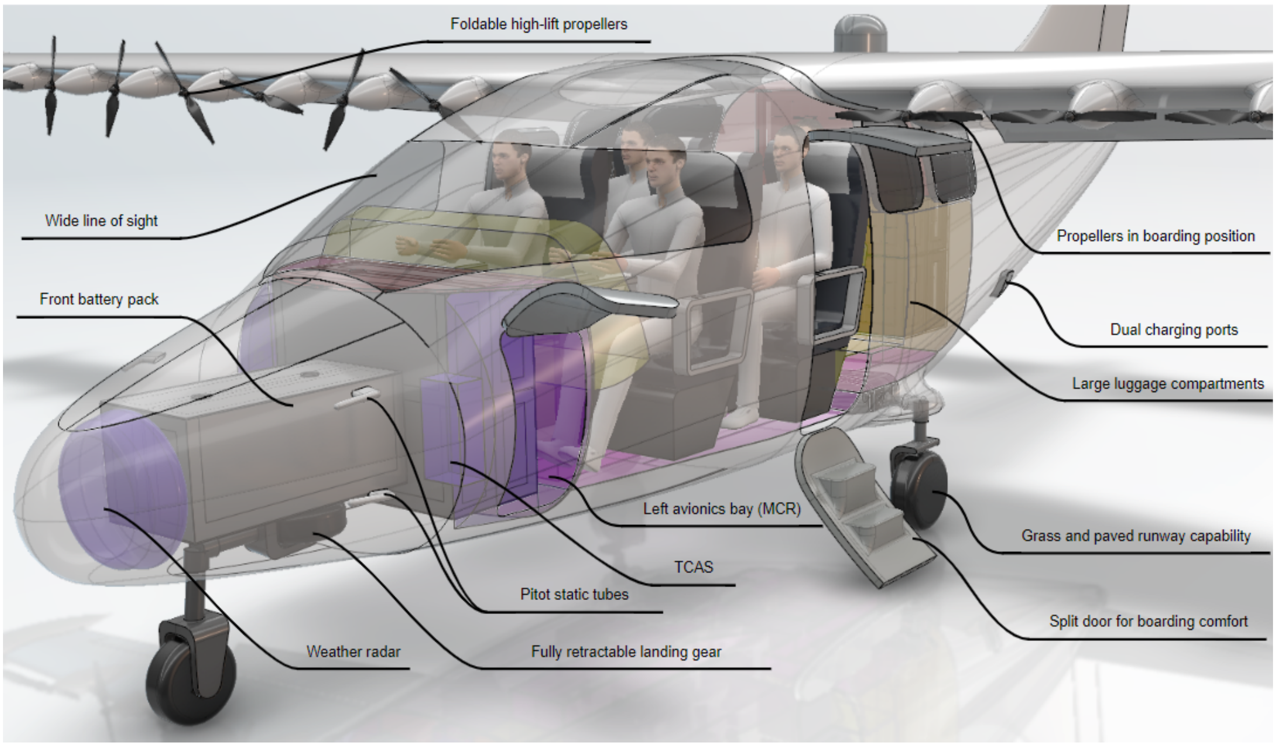


Figure 2: Front view of the final design, containing markup for main design visible design aspects.

are used for passive lift enhancement. This results in a maximum lift coefficient of at least 2.66. From this, a stall speed of 57.3 kts is found, meeting the CS23 constraint of 61 kts.

The electrical system contributes to the safety of the aircraft by being fully redundant. Each subsystem is connected to two controllers, each of which is connected to both batteries. This ensures that even in case of loss of a battery pack, the aircraft can fully function. In case of a total power failure, there is an emergency power unit (EPU) that provides enough energy for the avionics and the electric actuators of the control surfaces and landing gear to perform a controlled emergency landing.

Additionally, there is a motor and battery cooling system to keep them at optimal operating temperature, which will increase safety and longevity of the system. The cabin is cooled and heated using an environmental control system (ECS) to keep the passengers comfortable throughout the flight. Lastly, the aircraft includes a de-icing system, which is important for reliably flying year-round.

The AmpAir aircraft will include multiple crashworthiness principles into its structural and cabin design. A firewall separates the batteries from the cabin and ensures the survivable volume is not crushed by the heavy batteries. Because the compression strength and impact resistance of composites is not known to the same level as is for metals, crash tests will be performed to gain further data and confirm that the structure complies to all requirements.

Risk Mitigation

Certain events during the design and operational phase pose safety risks or could negatively impact the operations of AmpAir. To prevent these events from happening and minimize their impact, a risk assessment is performed, after which these risks are mitigated. This risk assessment consists of four steps: identification, parameter categorisation, indexation, and mitigation. From the identification stage, several risks for the operational and design phase of the aircraft can be defined. Parameter categorisation is then used to define the levels of likelihood and impact of the risks. The combination of identification and categorisation is used to generate a risk map. Mitigation methods are then applied to reduce the likelihood and impact of the individual risks as much as possible. This risk mitigation process is a constant cycle that keeps on going during the entire design and operational phase of the aircraft. There might be unanticipated risks, that lead to a better preparation for risks when taken into account in the risk register.

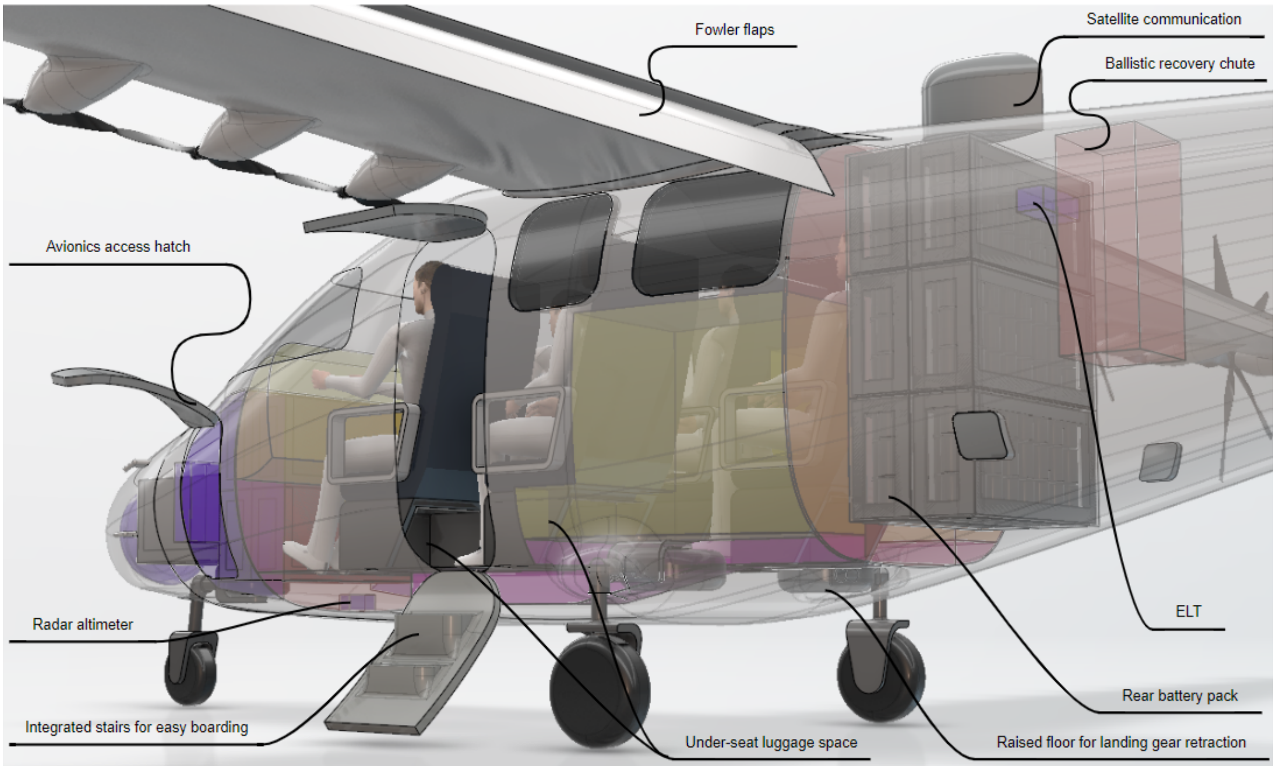


Figure 3: Rearview of the final design, containing markup for main design visible design aspects.

Production

In order to start operations, the aircraft must be produced. The whole production process will implement the strategies from the lean manufacturing ideology, minimising waste while maximising value. This will be done based on a production plan, consisting of five parts, as explained below. During preliminary planning, the workspace must be prepared, relations with suppliers must be set up, and quality control strategies should be created. Afterwards, parts will be manufactured by means of Resin Transfer Method (RTM). This method meets quality requirements and allows for integral part manufacturing, reducing assembly cost. Next, parts and sub-assemblies will be joined into the final product. Lastly, during systems integration, things like the motors, aircraft systems and landing gear are attached.

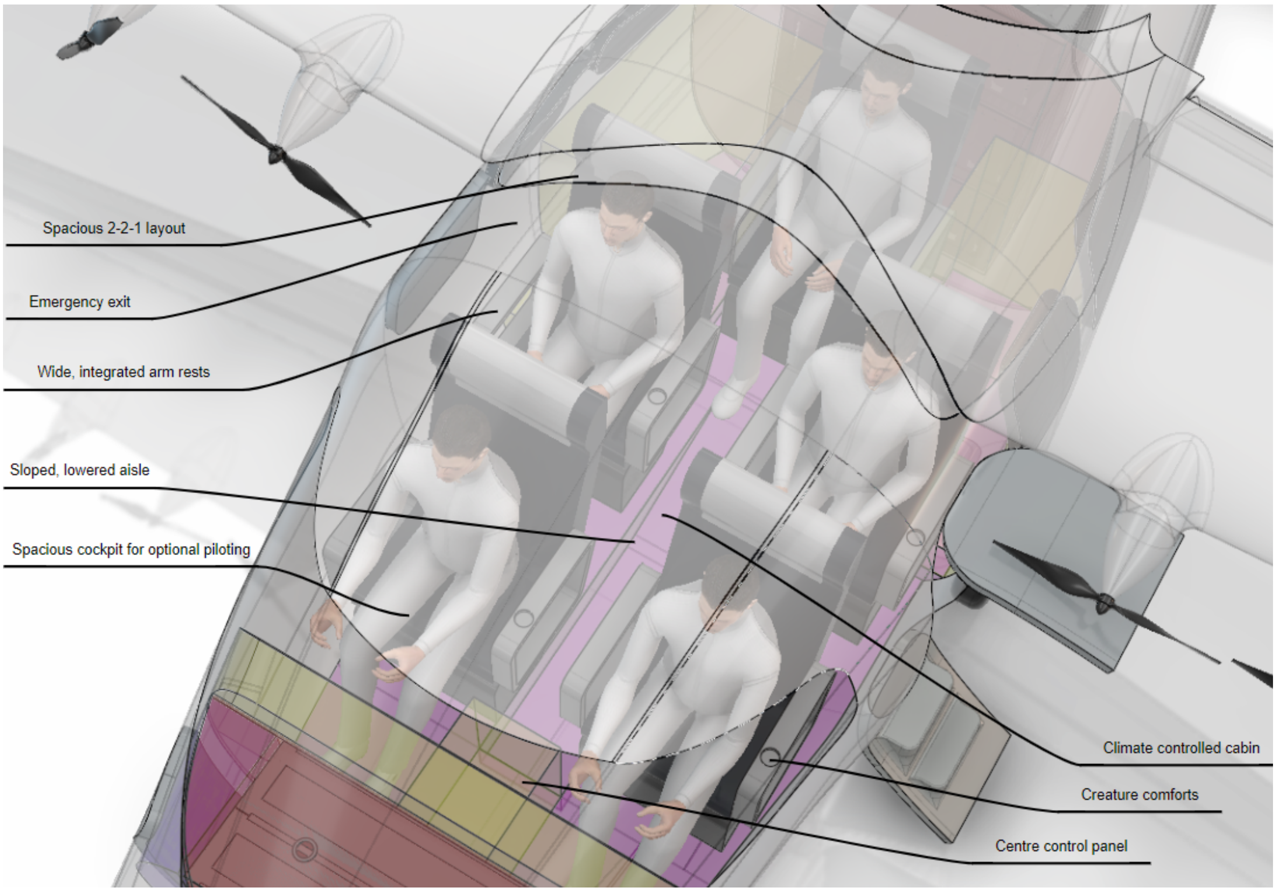


Figure 4: Cabin view of the final design, containing markup for main design visible design aspects.

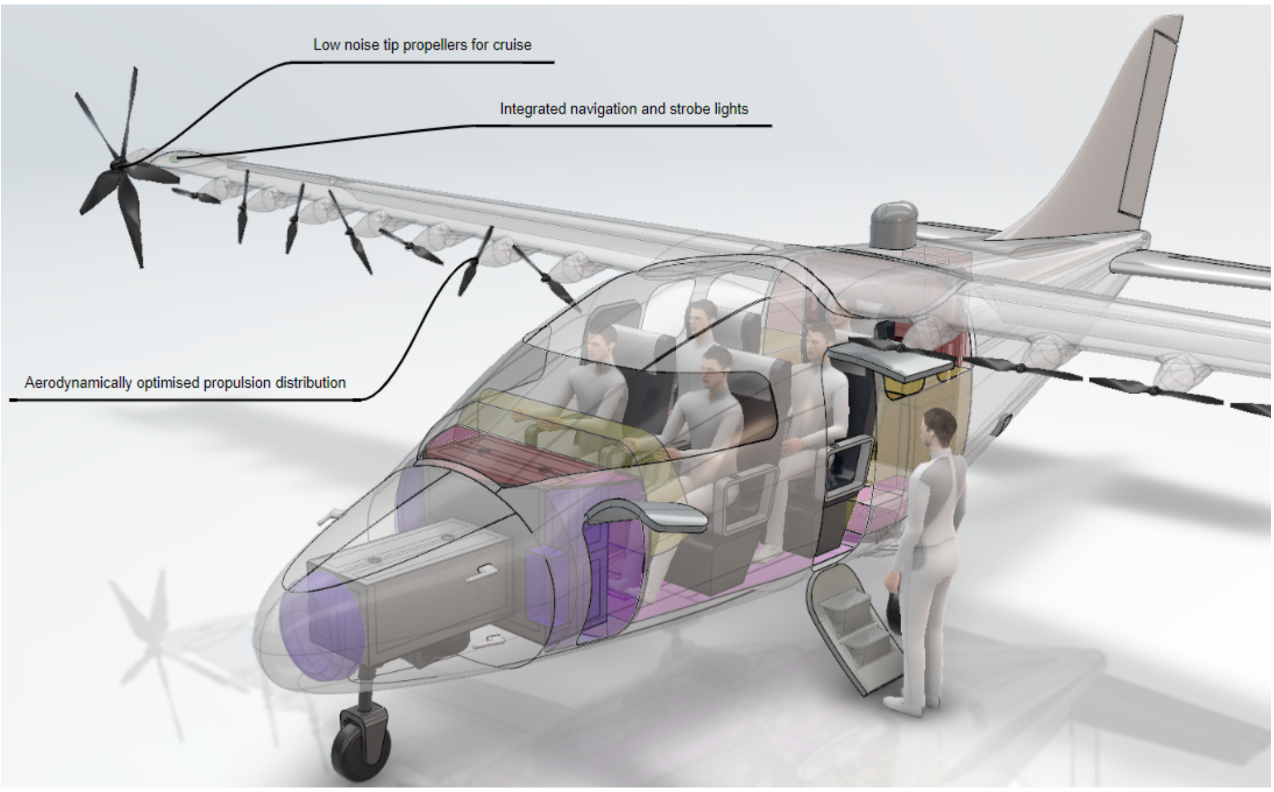


Figure 5: Complete view of the final design, containing markup for main design visible design aspects.

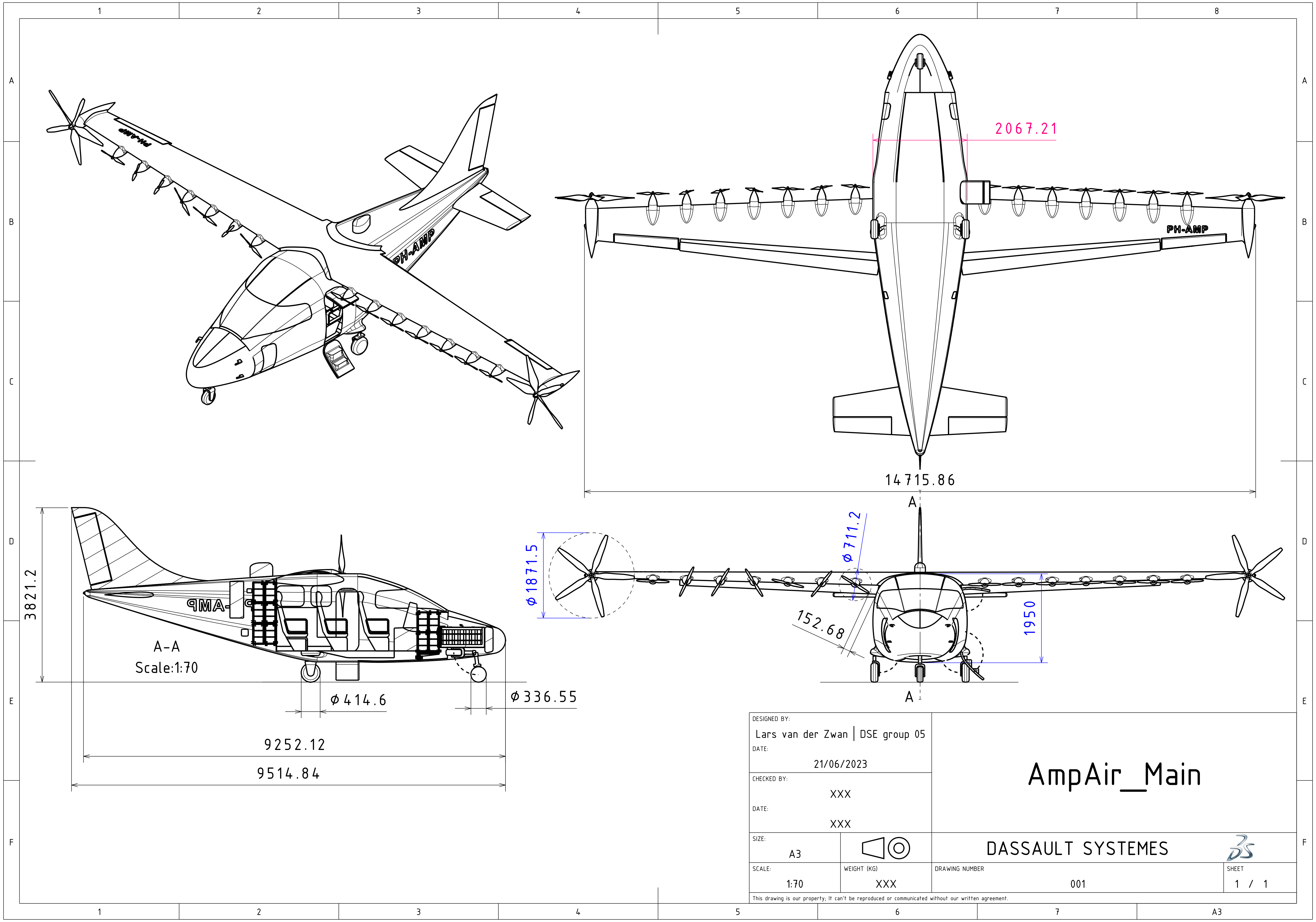


Figure 6: 3-view drawing

Contents

1 Introduction

Over the past decade, there have been significant advancements in the development of air taxi concepts, marking a promising future for private air travel[1,2]. However, these concepts face two key challenges: high costs and significant environmental impact [64, 88]. The AmpAir regional air taxi service takes a proactive approach by operating an emission-free aircraft and offering optional piloting. Stationed in over 40 airports and airfields over Europe, AmpAir offers flexible bookings, competitive prices and lower travel times than commercial, fixed-schedule airlines. Due to its many advantages, AmpAir is capable of attracting a large, diverse market, including business travellers, environmentally conscious tourists and flight enthusiasts. It does so by offering more affordable last-minute travel, being emission-free, and offering a unique piloting experience. This is done by implementing a battery-electric, optionally piloted aircraft, supported by a sound operational and logistics plan. In the previous design stages, the engineering team has, with use of elaborate technical analysis and trade-offs, decided to design a high-wing aircraft with distributed propulsion and a conventional tail [30], which was designed in more detail in the final DSE stage.

This report aims to describe the AmpAir service and the current aircraft design. The operations & logistics plan, as well as the vehicle design, has been developed for the Design Synthesis Exercise by 10 students within 10 weeks. The main goal of the team was *"To provide a sustainable private air transport service that is less expensive and more environmentally friendly than current options"* [5]. Meaning sustainability and efficiency are an integral part of the design philosophy. Furthermore, future developments in technology and regulations have been taken into account when designing, such that the aircraft is made future-proof and will stay relevant in the long-run. This report describes the reasoning behind the design choices and how they help achieve the aforementioned goals.

Firstly, an overview of the project is given in Chapter 2, where the functional flow and the functional breakdown structure are described. Then, the target market is analysed in Chapter 3. Chapter 4 discusses the certification of the aircraft, including the current and future state of regulations regarding optionally piloted aircraft. This is followed by Chapter 5, where the growth concept is described. Here, the timeline of relevant technological advancements and their effect on the AmpAir service are evaluated. The operations and logistics plan is discussed in Chapter 6. This plan also includes the reliability, availability, maintenance, and safety (RAMS) of the concept. Which is followed by Chapter 7, which describes the aircraft design, including the top-level assessment of its performance and the wing design. Furthermore, the C2 link, data handling and communications are discussed in Chapter 9. This is then followed by Chapter 8, where the propulsion and aerodynamic subsystems are explained. Chapter 10 discusses various aspects of sustainability that are taken into account in the design of the AmpAir aircraft. Furthermore, the material selection, crashworthiness, and wing box design are described Chapter 11. This chapter also contains the production plan. A cost analysis is carried out in Chapter 12. Then, the technical risk management is described in Chapter 13, including a risk map and mitigation method. The verification and validation plan can be found in Chapter 14. The final design is summarised together with the recommendations in the conclusion and can be found in Chapter 15.

[1] https://aeroreport.de/en/innovation/air-taxis-a-wide-range-of-concepts-are-on-approach
[2] https://flyaeolus.com/nl/

2
Mission Determination

Before the aircraft can be designed, it must be determined what the team is designing for. By creating a Functional Flow Diagram (FFD) and Functional Breakdown Structure (FBS), it becomes clear what functions have to be fulfilled by the AmpAir service. These diagrams are given in Section 2.1. Afterward, the flight profile for the mission is given in Section 2.2.

2.1. Functional Flow Diagram and Functional Breakdown Structure

The FFD and FBS need to be made in order to determine what functions the product must fulfil throughout its use. The FFD, as shown in Figure 2.1, shows the chronological functions that the system is required to perform throughout its lifecycle. The flow has been split into five main stages: Design (DSN), Production (PRD), Prepare for Flight (PRP), Perform Flight (FL), End-of-Life (EOL). The top level functions of DSN, PRD and EOL are shown in the FFD. The flight preparation and flight phase are elaborated on in the FBS, as shown in Figure 2.2. Here, the functions are broken down one sublevel below those presented in the FFD and are sorted into subgroups.

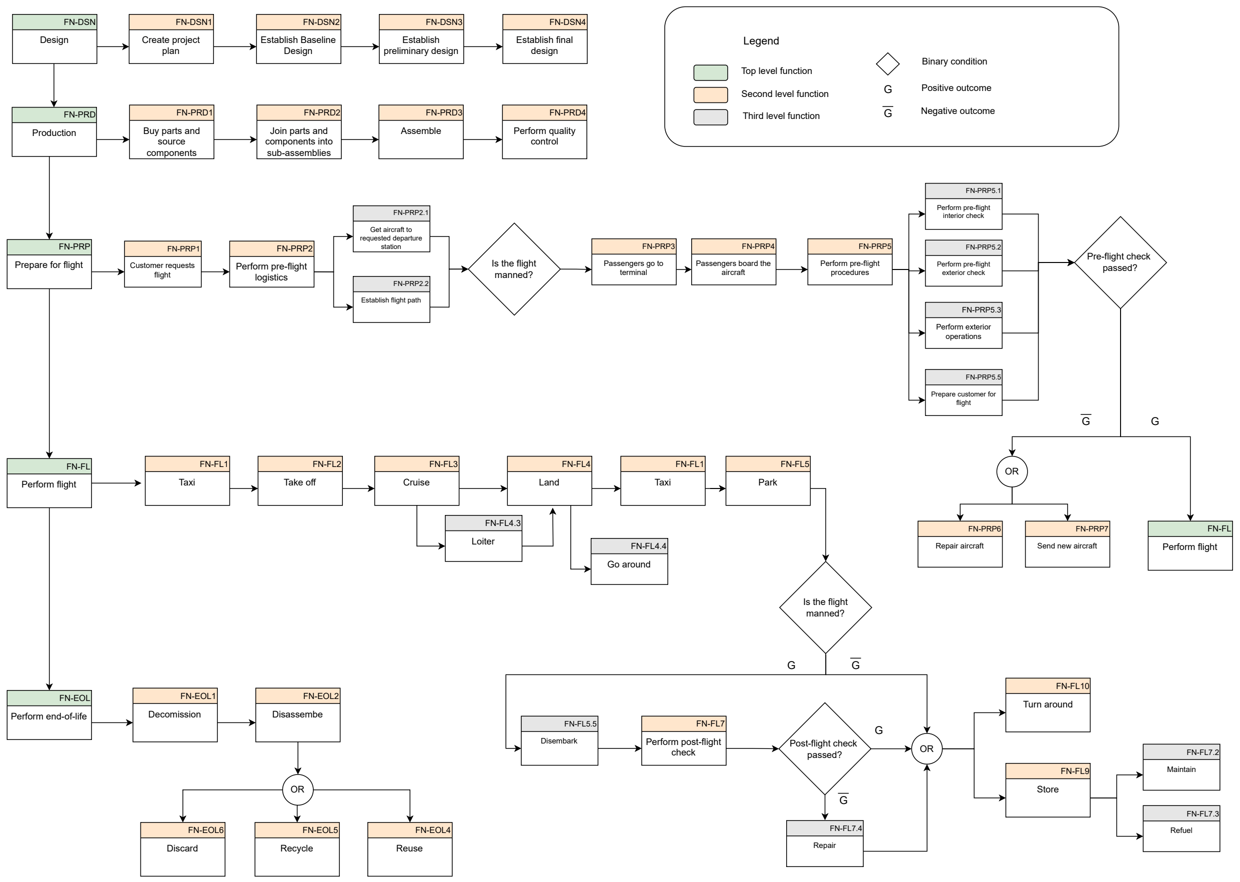


Figure 2.1: Functional Flow Diagram of the AmpAir air taxi service

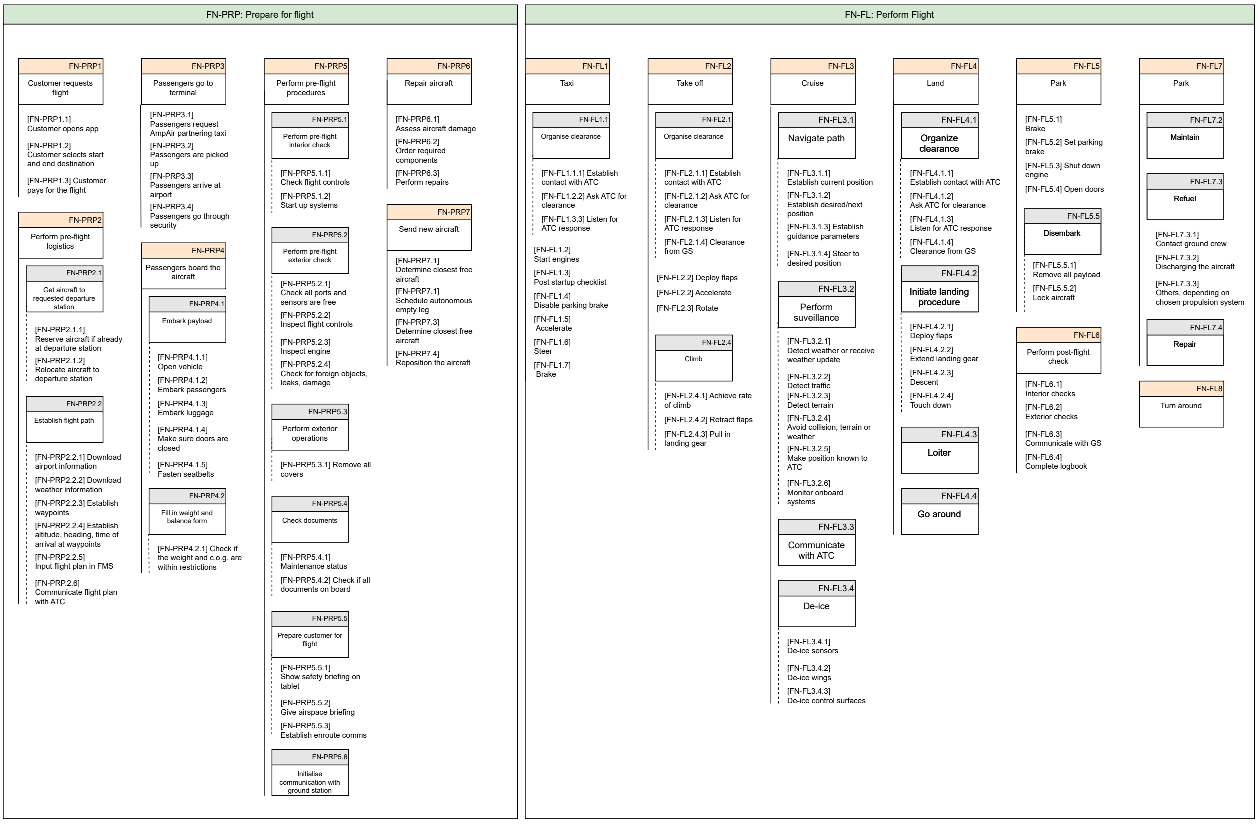


Figure 2.2: Functional Breakdown Structure of the AmpAir air taxi service operational phase

2.2. Flight Profile

Designing the aircraft firstly asks for the description of the flight profile, which provides information that the aircraft needs to adhere to. The AmpAir aircraft flight profile can be seen in Figure 2.3. The main stages of both manned and empty-legged flights are displayed. Each of these flights begins with the system start-up and take-off, which is followed by taxiing. Then, the aircraft climbs until reaching the cruise altitude. The climb is performed at a minimum climb gradient of 8.3%, which is specified in the CS23 regulations [19]. The aircraft then cruises at an altitude of 2000 km. Once it approaches the destination, it begins to descent by gliding. If needed, the aircraft will loiter before landing. The aircraft has available energy for 30 min loiter time for a full-range mission. Full descent is performed, followed by the correct approach, which is dependent on the destination airport and ATC clearance for landing. The final stage of a flight is taxiing to the hangar or to the passenger drop-off area. Each flight phase within the flight profile has an allocated time slot. Take-off is estimated to take within 32 seconds in order to accelerate from stand still to minimum lift speed (identical to stall speed) within 500 meters[1]. Time in the air is considered by the summation of time during cruise, climb and descend. Since distance is limited by both operation and logistics as well as other requirements[2][3], and velocities are known, climb phase is estimated to be within 7.5 minutes, cruise within 80.4 minutes and descend is assumed to be presentable by similar performance to climb. While descent procedures usually take longer than climb procedures, future designs are not constrained by descent time. Additional descent time can be accommodated by adjusting cruise time or, in exceptional cases, incorporating extra loiter time. Loiter time, by regulations[4] is 30 minutes. Lastly, taxi procedures are not as restrictive due to implementations

[1] REQ-STK-USR-11: The aircraft shall be able to take-off and land on 500 m runways.
[2] REQ-STK-USR-10: The minimum range of the aircraft with maximum payload shall be 400 km.
[3] REQ-TP-FPP-01: For low-speed aircraft with all engines operating, during climb a minimum climb gradient of 8.3% shall be possible (CS 23.2120).
[4] REQ-CN-LEG-01: The vehicle shall comply to the CS23 certification standards.

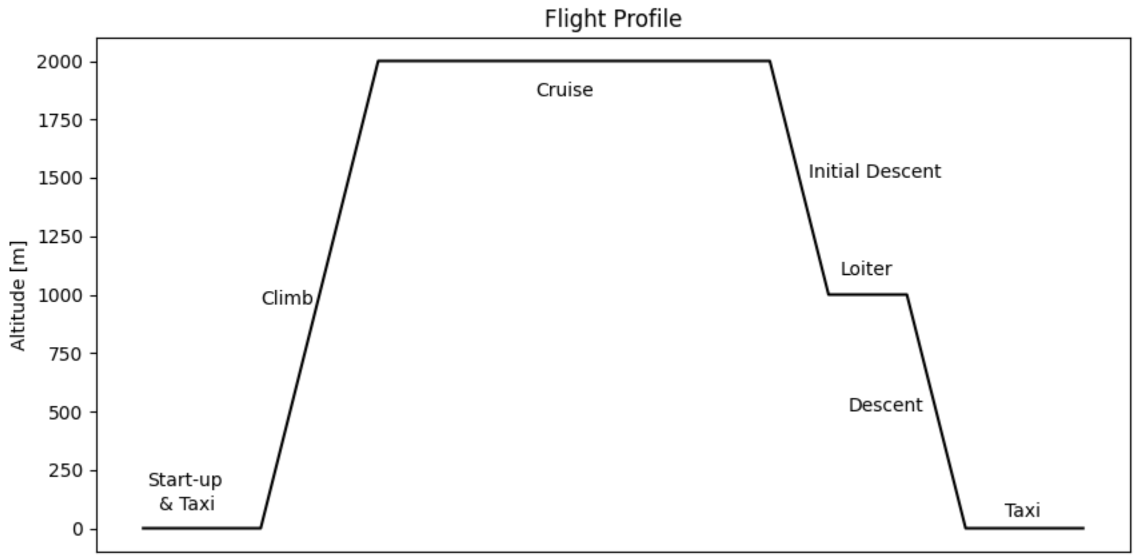


Figure 2.3: AmpAir Aircraft Flight Profile

taken in logistics by flying to less popular airports with less departure and arrival restrictions, thus minimising taxi time. From literature study [52], it is a valid estimation for taxi time to be 20 minutes of power consuming operations (does not include waiting at stand still). This concludes the flight profile for a mission of the AmpAir aircraft. The project was organised by means of a Gantt chart. At the start of each design phase, a detailed planning was set up based on breaking down bigger work packages into smaller units. This way, a list of tasks, that would take around 4 hours each for one person, was created. The top level Gantt planning can be found in Appendix A.

3
Market Analysis

This chapter aims to, both qualitatively and quantitatively, establish the expected and targeted market for the AmpAir service. Firstly, Section 3.1 identifies and quantifies similar concepts already on the market, and presents an outline of where AmpAir stands in comparison to these. Secondly, the target market is discussed in Section 3.2. Lastly, in Section 3.3.2, it is laid out how AmpAir will make use of the cargo market during the first years of operation.

3.1. Analysis of Transportation Substitutes and Competitors

Before the operations and logistics of the novel service can be set up, the target audience must be re-analysed. The price per passenger per kilometre, for the route Frankfurt to Brussels, was calculated for different modes of public transport. This was done for both business and economy flights and train trips. It is also possible to choose a 'green' flight ticket when booking, where the customer can fly more sustainable. This is done partially by offsetting and partially by using SAF (sustainable aviation fuel). The outcomes are showcased in Figure 3.1. The train is always cheaper than economy class commercial flights, and the commercial flights are always cheaper than the business flights. However, for all, ticket prices are higher the closer the booking is made to the departure date [1], [2].

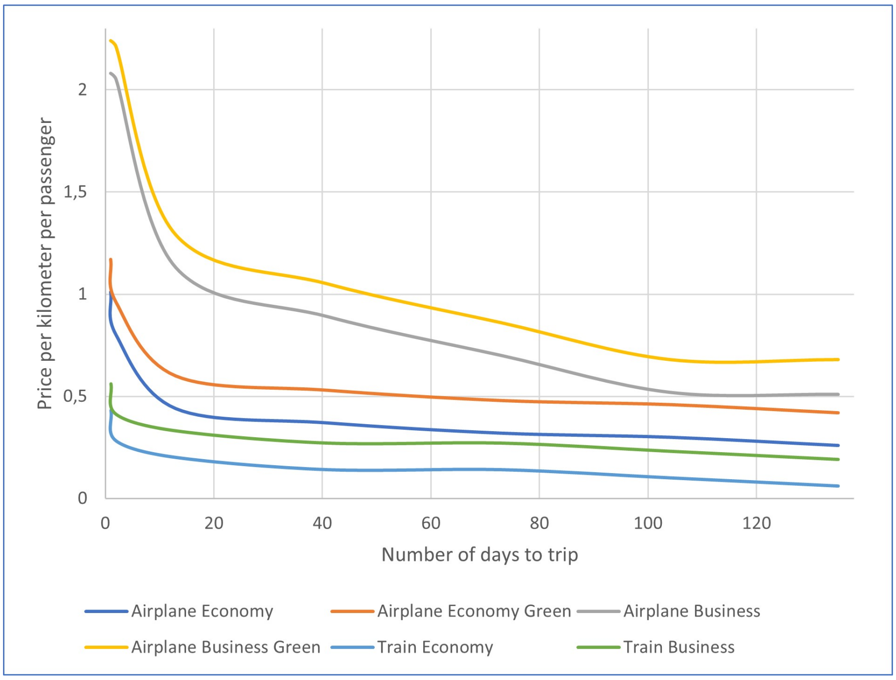


Figure 3.1: Price per passenger per kilometre as a function of the amount of days between booking and the trip

The air taxi will be cheaper than both business and economy flights when booked close to the departure date. The air taxi will always be cheaper than the business flights, and it can also be seen that the greener option is always more expensive than the normal equivalent. It also shows that some customers are willing to pay a higher price for travelling green. Therefore, AmpAir can compete well on the market of luxury flight.

[1] https://www.thetrainline.com [Accessed on 10.5.2023]
[2] https://www.cheaptickets.com [Accessed on 10.5.2023]

Even though the train is cheaper, its travel time is three times longer than with the air taxi. On top of that, the air taxi has the luxury that it is on-demand, private, and it is not needed to be at the airport far in advance. In conclusion, the air taxi is a relatively cheap mode of transportation for last-minute trips and allows the passenger to minimise their total trip time. This is because they can schedule the flight at any time, to any close by airport.

As assessed in earlier stages of the design, it should also be noted that the air taxi is not necessarily a substitute, but rather an addition to current options. Commercial aircraft and trains only reach big airports and dense areas, while the air taxi will be able to fly to small airports. A car could reach these places, but would take much longer. This makes the air taxi the optimal mode of transportation in case areas need to be reached that are not easily accessible by commercial flights and trains. Moreover, the air taxi serves as an intermediate option between a commercial flight and a business jet: it is more private than boarding a commercial flight and does not come with the high costs of buying or renting a business jet.

When looking at possible competitors, it was found that there is a limited amount of firms that have operative air taxis. However, there are many companies that offer private jet charter. Three competitors and their prices have been analysed: FlyAeolus[3], AeroAffaires[4] and Menkor Aviation[5]. None of these companies are emission-free or optionally-piloted. Their prices are shown in Table 3.1. The price offered by AmpAir are estimated to be lower, falling at €1.17 per passenger per kilometer, as explained in Chapter 12.

Table 3.1: Prices from different companies for a flight from Paris to Toulouse, per person

Company	Price pp (€)	Price (€) per km/pass
FlyAeolus	€597	€1.60
AeroAffaires	€2150	€7.26
Menkor Aviation	€1250	€3.35

This information can later be used to compare the price of AmpAir with potential competitors.

3.2. Target Market

AmpAir aims to attract business travellers, tourists and flight enthusiasts, as elaborated on in Section 3.2.1, Section 3.2.2 and Section 3.2.3 respectively. Furthermore, in Section 3.2.4, a quantification of the Total Addressable Market (TAM) is created, of which AmpAir expects to engage approximately 5% [6], along with the estimated penetrated market.

3.2.1. Business travellers

As discussed in the midterm report [30], The market share of business related trips, flown by commercial airlines, presents one of the most promising target audiences for AmpAir. Within Europe, about 200 million passengers fly each year on routes of 400 kilometres or fewer[7]. Out of these trips, approximately 12 to 18 percent are business related[8][9]. This means the market of business related trips counts 24 to 36 million passengers. Business passengers can historically be indexed into three distinct groups; the schedule-driven customers, the corporate cog segment and the informed budgeter segment [54]. Usually, the former two of the three segments tend to fly with business class, whereas the latter tends to fly economy. Overall, for the three segments together, a 50/50 distribution between these two classes can be assumed. From previous cost estimates for the AmpAir aircraft, a cost per passenger per kilometre between €0.8 and €1.5 is deemed reasonable [4]. This would mean an AmpAir taxi flight from Amsterdam to London would cost between €1.200 and €1.600, while a KLM business class ticket costs approximately €700[10]. More than 85% of business parties are up to 3 passengers [11]. This makes AmpAir service competitive on this market, as it can carry a payload

[3]https://flyaeolus.com/ [Accessed on 26.5.2023]
[4]https://aeroaffaires.com/business-aviation-trends-2023/ [Accessed on 26.5.2023]
[5]https://www.menkoraviation.com/en/menkor-aviation-2/ [Accessed on 26.5.2023]
[6]https://gocardless.com/guides/posts/market-penetration#: :text=The%20average%20rate%20of%20market,between%2010%25 %20and%2040%25
[7]https://maeve.aero/maeve-01 [Accessed on 26.5.2023]
[8]https://www.pwc.com/us/en/industries/consumer-markets/library/corporate-travel-collaboration-essential-for-covid-19-recovery.html [Accessed on 26.5.2023]
[9]https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20190506-1 [Accessed on 26.5.2023]
[10]https://www.klm.nl/en/information/legal/copyright [Accessed on 26.5.2023]
[11]https://flyaeolus.com/blog/2017-business-travel-statistics/

of 3 passengers at a distance of 403 km. Commercial business flight travellers, as well as passengers who travel with private flights, are discussed in the following subsubsections.

Commercial Business Flights

Therefore, the focus will be to provide a replacement flight for a business trip with multiple passengers[12]. With similar pricing and trip times as commercial business class flights, additional incentives must be created such that passengers will change their method of travelling. In surveys, 16% of commercial business passengers has stated an improvement in flexibility would improve the travelling experience. Similarly, 35% of passengers has stated so for a decrease in time spent at the airport. Furthermore, 26% of passengers has stated that the availability of direct flights is favourable [53]. AmpAir can satisfy all of these demands. When all previously mentioned factors are considered, and it is assumed that a 10% share of the addressed market can be attained, AmpAir is expected to attract between 462,000 and 693,000 passengers of this market segment every year.

Private Business Flights

The demand of private (business) flight has increased since COVID-19 and is expected to grow by 50% in this decade[13][14]. In 2022, there were around 600,000 private business flights in Europe, while there are only 2,760 business jets. This shows that a business jet owner rents out their aircraft multiple times per year. On average, they only make 10 trips per year[15], leaving 572,400 flights for people that do not own a business jet. These passengers are potential customers for the AmpAir service.[16]. The appeal may lie in the fact that the air taxi offers a similar private service that is cheaper than a business jet[17]. The advantage of AmpAir is that the flight departure and arrival airport is chosen by the customer, bringing them closer to their desired location, reducing the total trip time of the passenger. For passengers travelling for business purposes, this is an important criterion. The lower environmental impact of AmpAir will attract customers or companies that are actively seeking to lower their emissions. The market for private business travel is the biggest in France, Germany, the UK, Italy and Spain, making them the main targeted countries by AmpAir. Some popular airports are Paris, Nice, Geneva, Munich, Berlin, Cologne, London, Edinburgh, Rome, and Mallorca[18]. Therefore, these must be taken into account during route and network determination.

In the midterm report As discussed in the midterm report [30], three other alternative markets have been considered for segmentation: tourists using business class flights, tourists using trains and business trips by trains. Tourists that travel in business class value their privacy and comfort. For a household of 2.2 people on average[19], a business class KLM flight from Amsterdam to London (372 km[20]) would cost them around 1,500 euros in total[4]. In return, they get high levels of comfort: they get a high booking flexibility, food, and drinks are included, they have a comfortable seat, and they can take up to 40 kg of luggage per person. The benefits that AmpAir has for these customers is a great amount of privacy, as well as the convenience of choosing their own departure time, getting picked up close to home and dropped off close to their destination. Additionally, the air taxi provides status, and it is a unique touristic experience, as they can fly the aircraft themselves. No numbers have been found on the size and value of this market segment, although it is believed that it is relatively small. Lastly, the market segment of business and touristic trips by train are considered. Boarding a train takes less time than boarding a commercial aircraft, while providing more comfort than an economy class seat. And, some passengers value a low carbon footprint more than any of the other advantages AmpAir has against other modes of travel. For these customers, AmpAir is the only completely emission-free travel option.

The market segment of commercial business class passengers is economically attractive for AmpAir, because of their large numbers and high budgets. AmpAir makes it possible to provide the customers with privacy and convenience, while being environmentally friendly. Customers of private business flights value comfort, which is more difficult to achieve for a small air taxi. Reaching the segment of train travellers is also more difficult, due to the relatively high price of the AmpAir service. In conclusion, AmpAir will focus on the

[12] https://flyaeolus.com [Accessed on 26.5.2023]
[13] https://www2.deloitte.com/us/en/insights/focus/transportation/business-travel-trends-outlook-2022.html [Accessed on 26.5.2023]
[14] https://www.researchandmarkets.com/reports/5137052/business-jets-market-by-aircraft-type-light [Accessed on 26.5.2023]
[15] https://flyaeolus.com/blog/2017-business-travel-statistics/ [Accessed on 26.5.2023]
[16] https://businesstravelerusa.com/news/flying-private-jets-became-more-popular-in-2022/ [Accessed on 26.3.2025]
[17] https://jetcards.org/comparison [Accessed on 26.5.2023]
[18] https://aeroaffaires.com/ [Accessed on 26.5.2023]
[19] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Household_composition_statistics [Accessed on 26.5.2023]
[20] https://www.airmilescalculator.com/distance/ams-to-lhr/ [Accessed on 26.5.2023]

market segment of commercial business flights. The cumulative estimates for the market size of this segment are presented in Section 3.2.4[30].

3.2.2. Tourists

AmpAir believes it can attract groups of people who want to go on holiday within a 403 km radius. Specifically, it is going to target tourists to which (a combination of) the following statements apply:

- Those travelling in a group. A flight of AmpAir has a set price, making it more profitable for tourists to use AmpAir when they are travelling with a group.
- Those who value the experience of being able to fly the aircraft themselves.
- Those who are conscious of their carbon footprint and value sustainability.
- Those who value privacy during travel.
- Those who do not like waiting at the airport.
- Those who want a short total trip time.

One flight of 403 km with the AmpAir service costs approximately €1600, based on a price of €1.17 per kilometre per passenger. At full capacity of three passengers, this would amount to €471.50 per person. This price is more expensive than most short-range commercial flight tickets in Europe. This means that AmpAir would mainly focus on passengers who can afford to spend more in exchange for an emission-free travel, the unique experience of flying and the privacy that AmpAir provides, as well as the advantage of being able to fly anywhere at any moment.

A study conducted by European Commission has found that 36% of citizens are willing to choose their transport options based on ecological impact[21] and 18% of passengers offset their flight carbon emissions[22]. This shows that travellers are willing to pay for a reduced climate impact. However, the price of a carbon offset is many times lower than what the AmpAir service would be. Therefore, it is expected only middle and upper class passengers that are concerned with the climate will be interested in the service.

65% of Europe's population takes at least one touristic trip per year [23], amounting to 241 million passengers who go on a holiday. On average, roughly 47% of the tourists travel by car, 43% by plane and the rest by train or bus. It can be assumed that a large majority of trips by car, train, or bus are less than 403 km long[24]. Furthermore, approximately one third of flights are short-haul flights[25], meaning 62% of tourists travel at a distance of less than 403 km. Moreover, only 57% of Europe's population belongs to the middle or upper class and seven out of ten tourists value flexibility when booking their mode of transport[26]. Finally, approximately 91% of all travel passengers travel with one or more companions. Combining these fractions results in an estimated total addressable market of between 12.2 million and 22.4 million passengers.

3.2.3. Customers Who Enjoy Flying

Using the AmpAir service is the perfect opportunity for those who want to experience flying an aircraft, but are not capable or willing to invest in a private piloting licence and purchasing or renting an aircraft themselves. A common personal aircraft is the Cessna 182 Skylane, which costs approximately $ 575,000[27]. A cheaper alternative is the Texas Aircraft Colt, which is priced at $ 140,000. This sum of money would allow these clients regular use of the AmpAir aircraft across many years. Moreover, by opting for AmpAir, the customers would not have to concern themselves with maintenance and storage of the aircraft, and have the added benefit that it is more environmentally friendly. Finally, with the AmpAir aircraft, they will be able to fly with one or two companions, making the experience of flying even more attractive.

Approximately 0.2% of people own a piloting licence in the USA [28]. As obtaining a pilot licence in Europe is more costly and takes longer than in the US[28], it is expected that even fewer people have one in Europe. By assuming 0.1% of the European population has a licence, the total addressable market of this segment

[21] https://transport.ec.europa.eu/transport-themes/sustainable-transport_en
[22] https://airlines.iata.org/2022/11/01/convenience-top-priority-passengers#: :text=Passengers%20want%20convenience%20when%20they,easily%20offset%20their%20carbon%20emissions
[23] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Tourism$_{statistics_{-p}articipation_in_tourism}$
[24] https://www.energy.gov/eere/vehicles/articles/fotw-1042-august-13-2018-2017-nearly-60-all-vehicle-trips-were-less-six#: :text=In%20fact%2C%20three%2Dfourths%20of,were%2030%20miles%20or%20less.
[25] https://www.m3consultancy.nl/blog/one-in-three-schiphol-airport-passengers-fly-short-distance-an-exception-in-europe
[26] https://www.phocuswire.com/Majority-travelers-prefer-flexible-booking
[27] https://www.flyingmag.com/guides/what-is-the-best-personal-aircraft/
[28] https://www.qualityfly.com/airline-pilot-salary/easa-or-faa-licence/

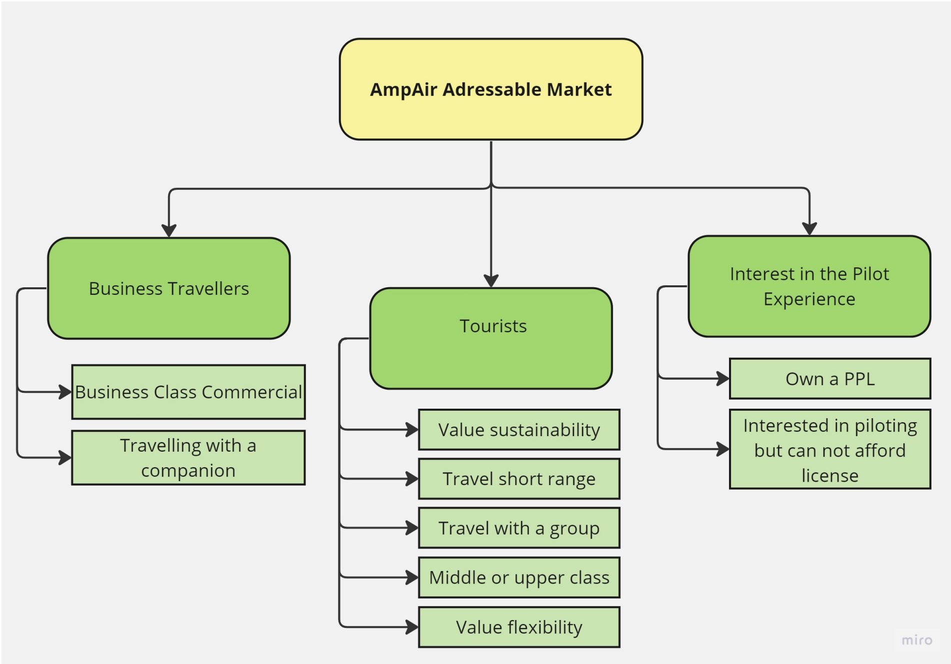


Figure 3.2: AmpAir's Target Market

would be 746,400 potential customers. It can be assumed that those holding a piloting licence are interested in flying. However, there is also a pool of people who may share this passion but cannot afford it. This is illustrated by the fact that there are over 10,000,000 people playing Microsoft Flight Simulator worldwide[29], of which 22% is European[30]. This indicates that there are approximately 2,200,000 flight simulator players on the European continent. By estimating 60% of these players are older than 18 and capable to fly AmpAir, this adds 1,320,000 people to the total addressable market.

3.2.4. Cumulative Estimates

An overview of the target market of AmpAir can be seen in Figure 3.2. The ranges of the size of the addressable market per category are summarized in table 3.2. Here, the potential customer count is found by taking 5% of the total addressable market[31]. This results in the expected market size of AmpAir in the range of $0.82 - 1.54$ million passengers. Taking the average of this range, AmpAir expects $1,180,000$ customers.

Table 3.2: Market total addressable market and potential customer count

	Total Addressable Market [millions]	Potential Customer Count [millions]
Business passengers	4.6 - 7.0	0.23 - 0.35
Tourists	11.2 - 22.4	0.56 - 1.12
Flying enthousiasts	0.6 - 1.3	0.03 - 0.07
Total	**16.4 - 30.7**	**0.82 - 1.54**

3.3. Analysis of the Other Stages

However, in the growth concept of Chapter 5, different stages were designed that might require a different market analysis. A short analysis has been performed in Section 3.3.1 and Section 3.3.2, since stage 0 and stage 1 have different markets than for the later stages. However, once it is decided that one of these stages

[29]https://www.flightsimulator.com/microsoft-flight-simulator-celebrates-10-million-pilots/
[30]https://explodingtopics.com/blog/number-of-gamers
[31]https://gocardless.com/guides/posts/market-penetration#:~:text=The%20average%20rate%20of%20market,between%2010%25%20and%2040%25

will be used, a more in depth market analysis will have to be performed. For the later stages, it is expected that the market size will keep growing. By increasing the amount of passengers and the range, the existing market can be expanded since more people will be attracted.

3.3.1. Flight School

If the operations will be started, it should be assessed how big this market is expected to be. For this, the analysis done in Section 3.2.3 on customers who enjoy flying can be used. Here, it was found that 0.1% of the European population has a licence. Then, this percentage is representative for most larger countries in Europe as well, such as the Switzerland, Germany, Austria, and the Netherlands. Other countries have a lower percentage, such as France and the United Kingdom[32]. To then find out which country would be ideal for the operations, a good metric is the population density. Since the flight school will only be located at one, maybe two places, it is beneficial to have a large addressable market close to the flight school. From the countries mentioned before, the Netherlands has the highest population density, namely $532\,\text{km}^2$[33]. Therefore, the Netherlands has been chosen to base the operations of the flight school. The Netherlands is a smaller country and the different parts are well-connected, meaning that also people that live further away might be attracted. In Chapter 12, it will be analysed what the cost would be for this stage and what fleet size would fit for that. Then, if it is later decided to start with this stage, a more throughout analysis will be performed.

3.3.2. Cargo

As explained in Chapter 5, one of the options for the operations is to transport cargo. 90% of the imports and exports are transported by ocean freight. However, air freight is faster and more reliable. Currently, the largest disadvantages are the cost, emissions, and weight[34]. The AmpAir aircraft is emission-free and has no pilot on board, reducing the cost significantly. The aircraft is ideal for express air freight, since this entails smaller, lighter freight that is transported in medium ranges. Express operators are also called the business class of cargo services, which also fits the general image of the company.

Since the transportation of cargo is very different from the market that an air taxi addresses, AmpAir will partner with freight companies, like DHL, PostNL and Bol.com, that want to use the aircraft to transport their cargo. They would rent an amount of AmpAir aircraft, which can then be used for their freight. A big advantage for those companies is that it is environmentally friendly, adding to their image. Moreover, the aircraft will be remotely piloted, meaning more payload can be carried, and crew cost is reduced, since the pilot can stay in one location. This makes crew rostering easier and saves money that would be spent on overnight stays. For AmpAir, the cargo operations will provide data that can be used for predictive maintenance, as well as prove the safety of the aircraft. This means that, once the air taxi is launched, the company will already have a good image and larger public acceptance. Once the certification for manned remotely piloted aircraft is implemented, the aircraft can start serving as an air taxi. The cargo operations can then be stopped or continue based on its revenue compared to flying passengers.

Germany, the United Kingdom and France are the largest freight transporters, with 31%, 18% and 14% of the European cargo market respectively [90]. Therefore, it will be proposed to partners to develop or use hubs in these countries, as well as Belgium to connect them. The hubs will serve as collecting point of different packages, after which they will be shipped to their destination. For this, an estimate was made on the amount of packages transported. In order for the cargo service to be profitable, the aircraft should fly with almost full cargo capacity.

The aircraft interior can be modified easily to transport cargo. The passenger seats will are removable. In the floor and fuselage structure, connection points will be incorporated. These can then be used to secure the cargo into place. This is necessary to ensure that the cargo does not move during flight, as this could adversely influence the aircraft stability and control characteristics or, in the worst case, make the aircraft unstable.

In the current aircraft layout, a volume of $5.688\,\text{m}^3$ could be used for cargo. However, in practice, this volume can never be filled completely because of empty space when parcels do not line up. Therefore, it was assumed that about 90% of the volume is usable, equating to $5.12\,\text{m}^3$. Assuming a standard density of $167\,\text{kg/m}^3$, the volumetric weight that can be carried is 854.9 kg per flight per aircraft. However, as described

[32] http://www.statemaster.com/graph/trn_act_avi_pil_percap-active-aviation-pilots-per-capita
[33] https://en.wikipedia.org/wiki/Area_and_population_of_European_countries
[34] https://www.freightos.com/?utm_source=google&utm_medium=cpc&utm_term=freightos&utm_campaign=kd-brand-uk-broad-20220713&device=c&gclid=CjwKCAjw-b-kBhB-EiwA4fvKrJJOzhNJG86Tq1yLfO5z4JadKJVIWc1C1ZvPzYeYFs1xoFGCSQqF7RoCA58QAvD_BwE

in Chapter 5, only 278 kg can be transported. When removing three chairs – leaving the possibility to pilot the aircraft – an extra payload of about 60 kg can be taken. Therefore, it would be most practical to take lighter cargo.

4 Certification

In the realm of passenger-carrying aircraft, no certification means no flying. In the case of an aircraft utilising new propulsion methods and remote control capabilities, which have limited historical precedent compared to conventional aviation systems, compliance with certification requirements becomes an even more significant driving factor in the design process.To ensure the success of the AmpAir design, it must be specifically designed with certification in mind. This chapter aims to gather information on the main considerations that need to be taken into account in the further design stages. Section 4.1 outlines some basic certification standards and practices and the applicability to the AmpAir design. In Section 4.2 regulations regarding electrical propulsion are discussed. Certification of autonomous flight is described in Section 4.3. Rules on pilot licensing and the design of a new passenger safety pilot licence is are layed out in Section 4.4. Finally, Section 4.5 discusses regulations on remote piloting.

4.1. Organisation Certification

The certification process for a CS-23 aircraft is a long and complicated process, but compliance with regulatory standards guarantees a baseline of safe operation. There are multiple steps that AmpAir needs to fulfil to register a new aircraft in Europe:

1. AmpAir needs to obtain a design organisation approval according to CS-21 Subpart J, confirming compliance with regulatory requirements for aircraft design and certification. This establishes AmpAir as a design organisation.
2. As a design organisation, AmpAir is permitted to design an aircraft and prove the conformity of the design to certification specification and environmental requirements. If accepted, AmpAir will become the Type Certificate Holder of the AmpAir aircraft Type certificate.
3. AmpAir needs to obtain a production organisation approval to become an official production organisation.
4. As a production organisation, AmpAir is permitted to produce the AmpAir aircraft in series and to issue a statement of conformity to each aircraft that ensures that the manufactured AmpAir aircraft adheres to the issued type certificate.
5. To certify the AmpAir aircraft for traffic, AmpAir needs to obtain a noise certificate and demonstrate ensured liability coverage.
6. If AmpAir aims to maintain the AmpAir itself, they need to obtain a maintenance organisation approval to maintain the aircraft's airworthiness through regular inspections, maintenance procedures, and repairs.
7. AmpAir needs to be prepared to adapt to changing regulations, particularly regarding the increase in automation.

This information is important for planning the scope of operations that AmpAir will provide. If AmpAir intends to handle the design, production, and maintenance of the aircraft, it needs to obtain all three organisational approvals.

4.2. Electric Flight Certification

As summarised in Chapter 1, the AmpAir aircraft will be a battery-powered electric aircraft. Airworthiness regulations were primarily developed for conventional fuel-powered engines, which presents challenges in directly applying them to the AmpAir aircraft. In fact, NASA went through the Part 33 regulations, the regulations for the aircraft power plant, and determined the percentage of regulations that need tailoring or revisions to fit pure battery electrified aircraft. These suggested changes for FAR 33 can be seen in Figure 4.2.

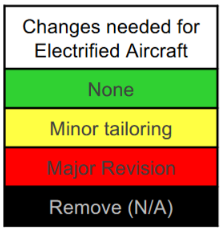


Figure 4.1: Legend explaining the colour code for FAR Updates in E-flight

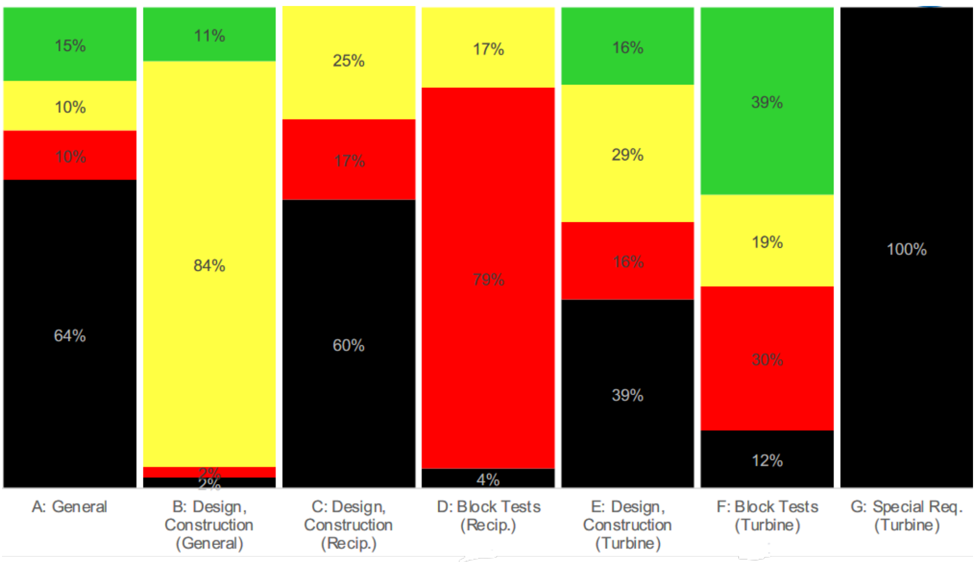


Figure 4.2: Percentage of FAR 33 regulations that require revision for electrified aircraft [13]

The airworthiness differences between the FAA and EASA are minimal and can be seen as representative for the CS-E, the EASA equivalent. The massive need for revision stems from the fact that Part 33 was introduced in 1964 for reciprocating and turbine aircraft engines that utilise aviation fuel as an energy source. Consequently, the current engine regulation specifically address failures related to air and fuel combustion systems operating under conditions involving cyclically loaded high-speed, high-temperature, and highly-stressed components [22]. Electric engines have a distinctive design and operate differently from traditional engines. They incorporate electric motors, controllers, and high-voltage systems, drawing power from electrical storage or generating systems. The technology used in electric engines introduces potential hazards not found in fuel-based engines, including high-voltage transmission lines, electromagnetic fields, and high-speed electrical switches besides the issues associated with the energy storage system, in this case batteries [23].

This, however, does not mean that certifying electric aircraft is impossible. In 2020, EASA certified the Pipistrel Velis Electro, the first fully battery electric aircraft[1]. During this certification process, EASA developed the special condition Electric Propulsion System SC E-19. The content of this special condition describes that the certification of electric propulsion systems can be achieved by demonstrating an equivalent level of safety compared to conventional engines [20]. To design for this equivalent level of safety, key takeaways from the certification process of the Pipistrel Velis Electro, together with information from an expert interview with the

[1] https://www.easa.europa.eu/en/newsroom-and-events/news/easa-certifies-electric-aircraft-first-type-certification-fully-electric [Accessed on 01.6.2023]

E-flight academy on the use of electric aircraft, were collected. As expected, electric flight introduces unique challenges that require careful considerations and clever designs. For instance, certified electrical engines can be purchased instead of designing them in-house. This reduces workload and enables the focus to be on other critical systems, such as the charging and energy storage systems. In these areas, key issues were determined to be battery runaway, energy uncertainty, charging software problems, and cooling failure. More information on this is given in the following list.

1. Battery Runaway: Battery runaway, characterised by uncontrolled temperature increase and energy release, poses a safety risk in any system that employs batteries. To address this issue, robust battery management systems (BMS) and comprehensive thermal management systems should be implemented. The BMS monitors battery parameters, such as temperature, voltage, and current, to prevent overheating and thermal runaway.
2. Battery Energy Uncertainty: The certification process of the Pipistrel Velis Electro revealed that an accurate estimation of remaining battery power to a safe degree was more complicated than anticipated. Cold temperature affected the amount of energy that could be drawn from the batteries. To mitigate battery energy uncertainty, precise battery state-of-charge (SOC) and state-of-health (SOH) estimation algorithms should be employed. These algorithms consider factors like battery degradation, temperature effects, and voltage variations to provide accurate information about available energy and battery health.
3. Charging Software Problems: The issues that cause the most maintenance costs at E-flight are software related charging issues. Reliable and robust charging software not only ensure safe and efficient charging of the batteries but also increase battery life and reduce the chance of thermal runaway. Monitoring charging parameters, such as voltage, current, and temperature, and implementing safeguards against overcharging and overheating are necessary to address potential charging software problems.
4. Cooling Failure: The most critical engine condition that E-flight identifies is the loss of cooling for its engines. Effective cooling systems are critical to maintain optimal operating temperatures in electric flight systems, particularly for batteries and engines. To prevent cooling failure, robust cooling systems and thermal management strategies should be employed. Continuous monitoring of cooling system functionality is necessary to detect and resolve any cooling failures promptly.

4.3. Autonomous Flight Considerations

The goal of AmpAir is to eventually develop an aircraft that is able to autonomously fly its empty legs and, even further in the future, also autonomously transport its passengers. This requires a significant change to the existing regulations, as autonomous flight is currently prohibited by the ICAO [44]. Traditional certification processes for aircraft have relied on a primary/secondary or primary/backup approach, with humans serving as the safety net. However, to achieve the goal of creating an autonomous aircraft, a new certification approach is necessary. The complex nature of autonomous systems, where humans may not be directly involved in the decision-making process, demands a proven and robust framework that ensures safety and reliability. The AmpAir aircraft has the potential to demonstrate this framework and persuade the ICAO to revise its standards and recommended practices.

To enhance safety and enable autonomous flight, it is crucial to consider the automation of aircraft functions, the role of pilots/occupants, and the integration of these systems into the airspace. It needs to be able to fly in all meteorological visual conditions and must show compliance to instrument flight rules (IFR). The requirements for the aircraft and its equipment should align with how it will be flown and the airspace it will operate in, while also meeting certification standards suitable for performing tasks traditionally handled by pilots. Similarly, the requirements for pilots/automation should be determined based on whether they actively fly the aircraft or serve as passengers. This includes developing systems with sufficient integrity to safely replace humans, allowing pilots to become safety pilots or passive participants with minimal responsibility for risk mitigation. By achieving this goal, automation can perform more complex functions than humans alone, as observed in statically unstable fly-by-wire aircraft where automation actively controls the flight. Ultimately, autonomous flight has the potential to deliver an overall safety improvement beyond what humans can achieve, especially when airspace requirements are adapted to accommodate machine-to-machine integration, separation, and operation while ensuring safety.

The first step involves logically reducing or replacing the functions traditionally performed by pilots and controllers. By deconstructing their roles, automation can be designed to handle these functions, focusing on the key aspects. For pilots, three primary functions need to be addressed. The first function is “aviate,” which involves managing the aircraft’s flight path and ensuring proper flying conditions. The second function is “navigate,” which entails managing the flight path within authorised airspace and providing directions for the aircraft’s route. The third function is “communicate,” which involves managing the flight path in relation to other aircraft and complying with air traffic expectations. Similarly, controllers have three main functions to consider. The first is “locate,” which involves determining the aircraft’s position. The second function is “separate,” which focuses on avoiding collisions with other aircraft. The third function is “communicate,” which involves establishing effective communication between air traffic control and the aircraft to manage its course.

The second step is to implement bounded behaviour, which establishes safe limits of authority for the automated system. The architecture of the automation should incorporate expected outcomes and integrate human intentions through bounded behaviour. Additionally, the system should be designed to be fault-tolerant and fail-safe, allowing it to continue functioning even after a failure occurs. Trusted automation necessitates a modular architecture with a top-down hierarchy and clearly defined interfaces. Functions should be partitioned and isolated in both software and hardware, facilitating testing and minimising the impact of failures. Dynamic consistency checks should be implemented to compare derived and measured parameters, enabling real-time monitoring of the system’s behaviour. Lastly, computational agility is crucial for promptly assessing system and situational hazards and responding accordingly.

Once all that is done, to demonstrate that a specific architecture can safely automate critical tasks, several steps need to be taken. Firstly, the mission objectives, including the concept of operation or mission plan, should be identified. These objectives can then be broken down into mission elements. For each mission element, the tasks intended for automation should be specified. Finally, expected behaviour and pass/fail criteria must be established for each automated function within the mission elements. For each fail scenario, a safe reaction scenario needs to be established. These considerations were meticulously incorporated throughout the aircraft design process, with particular emphasis on the design of safety strategies and emergency procedures outlined in Chapter 6. It is important to note that these considerations are not only relevant for full automation, but also play a significant role in the context of optionally piloted aircraft with remote control. As the certification journey for an autonomous aircraft begins, the next pivotal step is to initiate remote control of an aircraft or, when passengers are onboard, to enable remote control with the assistance of a safety pilot. Using the passenger for safety monitoring and piloting tasks reduces the risks involved immensely and helps with proving that an equivalent amount of safety is reached. Similarly, a remote pilot who has the possibility to intervene and control the aircraft in an emergency is crucial to achieving this goal, more information on that is given in Section 4.5.

4.4. Pilot Licensing

The AmpAir aircraft will be flying the empty legs autonomously but remotely piloted, without any human onboard. For passenger flights the autopilot is still used, as it is already present and safe, but a safety pilot is added as a safety net. A safety pilot in the aircraft would aid significantly in overcoming certification issues and ensuring safety of the autonomous air taxi concept. AmpAir aspires to design a revolutionary pilot licence for the highly automated, easy to fly aircraft. This licence will be easy to get, to create a smaller barrier for customers to use the service. Firstly, it is useful to examine what current pilot licences exist. The most basic pilot licence currently approved by European regulations is the Light Aircraft Pilot Licence (LAPL). With this pilot licence the pilot can fly within the EU on single engine-piston aeroplanes, up to 2000 kg, carrying maximum 4 people, only VFR. AmpAir however does not even fall into this category, but for the basic LAPL already about 100 hours of theory and 30 hours of flight instruction are required. Additionally, a medical certificate is required. A private pilot licence (PPL) needs the same theory and 45 hours of flight instruction, but gives more privileges. A night rating can be added for 5 hours of flight training. Commercial privileges and an instrument rating (IR) can also be added to the PPL that allows to fly under instrument flight rules (IFR). This takes 150 hours of theory and 55 hours of flight training.

Under current regulations, a PPL with multi engine rating would allow a person to fly the AmpAir aircraft. To be able to commercially fly the AmpAir air taxi, meaning having a paid pilot, this pilot would need a Commercial Pilot licence (CPL), a more extensive licence. There is currently not a specific licence for electric aircraft. A rating for the AmpAir aircraft will of course be necessary. The existing pilot licences require a lot of theory and flight training hours, and are above all very expensive.

AmpAir believes this can be done differently. The advanced autopilot of AmpAir significantly relieves the workload from the pilot. The aircraft can fly itself, so the pilot barely has to perform any tasks during the flight.

For an aircraft that can fly itself, an extensive training like a PPL is – outside of regulations – practically not necessary, and learning to pilot the aircraft can be done within hours with the help of autonomous systems providing constant guidance. To still comply with regulations, a special AmpAir licence is to be developed and approved that is more suitable for easy to fly aircraft. AmpAir will let passengers that have the AmpAir licence be the Pilot in Command (PIC) during normal operations, meaning autopilot systems working and no emergencies. Additionally, AmpAir will have a remote pilot employed, who can pilot the aircraft from a ground station. This pilot will have a CPL equivalent remote pilot licence and will become the PIC in case of failures of the autopilot system or in case of emergencies. More about the remote pilot is described in Section 4.5. The pilot licence for the passengers will be very simple, and the flight instruction will ideally take only a day. The tasks of the safety pilot are limited, the automatic system will perform most tasks or give the pilot instructions, in case of a problem the remote pilot takes over. Therefore, the flight training can be reduced a lot, even from the 30 hours needed to get a basic LAPL. Additionally, there will have to be some theory. The licence can be expanded if the passenger desires to perform more piloting tasks, as explained in Chapter 6. Passengers that already have a PPL can fly the aircraft after getting a rating for the AmpAir aircraft.

To illustrate how a pilot training that would normally take dozens of flight hours could be brought down to one day, the requirements for the PPL are examined. Currently, to get a Private Pilot licence (PPL), a candidate must be at least 17 years of age, speak English, and receive flight training and a logbook endorsement from an authorized instructor (ATO). Additionally, a Class II Medical Assessment is needed. The pilot has to show certain knowledge, skills, and experience. The following sections will go over the standards recommended practices that ICAO states for PPL licensing [42], and investigate how AmpAir can to comply with these or to deviate from these standards.

4.4.1. Knowledge

A PPL candidate has to show knowledge by passing exams in the following subjects:

- Air Law
- Aircraft General Knowledge
- Flight planning and performance
- Human performance and limitations
- Meteorology
- Navigation
- Operational procedures
- Principles of flight
- Communication (radio telephony)

Most of this material is not useful for the passenger to fulfil their purpose as a safety pilot. Flight planning, navigation, balancing the aircraft, and conforming to the air laws throughout the operation will all be the responsibility of AmpAir's remote pilot station (RPS). Most of the functions will be carried out by the autopilot, and the passenger will only follow up instructions from the autopilot or intervene and give control to the remote pilot (see Chapter 6). Additionally, detailed theory about the aircraft systems, electrics, power plant and principles of flight are not deemed necessary for the safety pilot. For these reasons, the theory that has to be studied for the safety pilot licence is deemed much less than the hundreds of hours that go into getting a PPL or CPL theory. Most knowledge can be discarded because there is the knowledge of the remote pilot to rely on. Basic knowledge about the aircraft and the flight necessary to recognise problems during flight is deemed useful for the passenger. The main knowledge that the passenger will have are procedures.

4.4.2. Skill

ICAO states that a PPL pilot should be able to demonstrate the skills listed in Table 4.1 [42] to be a pilot in command. In the second column, it is described in what way it is assured that a one-star pilot can comply with this (more about the star system is written in Chapter 6). For the basic one-star licence, the pilot will be trained to operate when the autopilot/flight director system is working and how to ask for help from the remote pilot in case it is not or there is another problem. This licence is thus only valid when the autonomous system is working. Procedures in case of C2 link loss, autopilot malfunction, passenger problems or other faults are described in Section 6.11.

Table 4.1: Required skills according to ICAO Annex 1 [42]

Required Skill	How Will AmpAir pilot comply with this requirement?
Recognise and manage threats & Errors	Will be trained to know/recognises in what situations to contact the GS/RPS, who will then manage the threat. Will be trained to follow up instructions from the aircraft and GS in case of failures
Operate the aircraft within its limitations	Is not able to pilot the aircraft outside its flight envelope or geofencing
Complete all manoeuvres with smoothness and accuracy	Will be trained in 1 day to manoeuvre the aircraft
Exercise good judgement and airmanship	Will be trained and assessed on their airmanship. In case the pilot does not show good airmanship the operator will make remote pilot PIC.
Apply aeronautical knowledge	Will complete theory course with essential knowledge and apply it in the 1-day training
Maintain control of the aircraft at all times	The autopilot will remain in control of the aircraft and allows the pilot only to override within a safety zone (geofencing and envelope limits).

4.4.3. Experience

The experience requirements are mostly based on a minimum amount of flight hours rather than demonstrations of specific skills. At a minimum, private pilot candidates qualified for a practical test to achieve the licence will have logged 40 hours of flight time that includes 20 hours of flight training from an authorised instructor as well as 10 hours of solo flight. The solo flight hours should include at least 5 hours of cross-country, and one cross-country flight of one at least 150NM with 2 full stop landings at different airports [42]. These experience requirements will be the main challenge to overcome in certification of the pilot licence. AmpAir aspires to not base the 1-star pilot licence on hours of experience, but on demonstration of the skills needed. For getting higher stars, more experience will be required (Chapter 6.

4.4.4. Flight instruction

To be able to train pilots and give licences, in most cases an Approved Training Organisation (ATO) certificate is needed. This means that the ATO needs to comply with a set of Part-ORA regulations, for example an operations manual, a training manual and a safety management system have to be set up. However, simpler, lighter, and better rules for general aviation flight schools have recently been set up, in the form of the Declared Training Organisation DTO[2]. This will make it easier to become a flight school for general aviation licences lighter than a CPL. The flight instruction for the basic AmpAir licence will include pre-flight operations like the aircraft inspection, flying turns, take-offs, and landings with a flight director (Highway in the Sky), communication procedures with the ground station, and emergency operations, which are outlined in Section 6.11. Expanding the licence will require, amongst others, training in traffic patterns, ATC procedures, navigation, stall recognition and recovery, spiral recognition and recovery, and flying without HITS. More about the training and expanding the licence is described in Chapter 6.

To conclude, for the implementation of such a licence, authorities need to be convinced to change certification. Certification has to allow remote piloting of passenger flights, and fully automated empty leg flights. The new pilot licence also has to be approved by EASA, for this the safety of the licence has to be proven. The safety of the licence is assured through the autonomous system and geofencing, with 3 additional safety nets: the passenger safety pilot, the remote pilot and a parachute. More on the safety of the operations and emergency procedures is described in Section 6.11. Automation will simplify flight, attract more pilots and make piloting more accessible. By implementing the safety pilot certification issues can be overcome. The safety pilot is not just a normal passenger but bears responsibilities and has to pay attention.

[2]https://www.easa.europa.eu/en/domains/general-aviation/ga-talking-points/simpler-and-lighter-rules-for-ga-pilot-training

4.5. Remote Piloting

As mentioned in Section 4.3, remote piloting serves as the initial stepping stone towards autonomous flight, as its regulations are being established and certification is allowed. It holds significant potential in the aviation industry, providing substantial cost reductions for small aircraft operations. Although it represents a small fraction of the potential payload, the absence of a pilot can have a significant impact on smaller passenger aircraft. Recognising this demand, the International Civil Aviation Organisation (ICAO) established the Remotely Piloted Aircraft Systems Panel (RPASP) in 2016 [45].

In 2018, the RPASP proposed an amendment to Annex 1 of the Standards And Recommended Practices (SARP) to incorporate a remote piloting licence, which was implemented in 2022. Furthermore, in 2021, new amendments focusing on communication systems and procedures related to remotely piloted aircraft systems were introduced. These amendments specifically addressed “C2 link procedures” and “C2 link systems” for Annex 10. During the same meeting, the RPASP also defined requirements for remotely piloted aircraft and remote pilot stations (RPS). Additionally, they presented a template for the RPA certificate of airworthiness as part of a new amendment to Annex 8. Moreover, a significant development occurred in 2022 with the inclusion of international RPAS operations in Annex 6. This annex includes all operational requirements, enabling RPAS to conduct international flights within an integrated airspace. Amendments to Annex 6, 8, and 10 are scheduled to be implemented in 2026. The objective behind this timeline is to provide the industry with a span of four years to develop the initial remote pilots and grant authorities sufficient time to incorporate the necessary changes into national regulations. The map depicted in Figure 4.3 outlines the specific regulations that need to be applied based on the intended type of operations. The AmpAir aircraft falls into the purple, high risk international RPAS operations. Thus, the regulations to follow are full certification with CS23 in accordance to Annexes 1, 6 and 8.

1 **INTERNATIONAL** **HIGH RISK (CERTIFIED)** a) Operations: international RPAS b) Regulation: full certification in accordance with Annexes 1, 6 and 8	**2** **INTERNATIONAL** **MEDIUM/LOW RISK (SPECIFIC/OPEN)** a) Operations: • cross-border UAS • high seas UAS b) Regulation: • Annex 6, Part IV not applicable • future SARPs (Annexes 6 and 8)? • future SARPs (Annex 2, new App.)? • certificates scaled to fit
3 **DOMESTIC** **HIGH RISK (CERTIFIED)** a) Operations: domestic certified RPAS b) Regulation: • national regulations • States encouraged to use Annex 6, Part IV	**4** **DOMESTIC** **MEDIUM/LOW RISK (SPECIFIC/OPEN)** a) Operations: domestic UAS b) Regulation: • national regulations • future ICAO guidance? • impact from quadrant 2

Figure 4.3: Applicable regulations

5 Growth Concept

In this chapter, the growth concept of AmpAir will be explained. Seeing as the concept is quite ambitious, the decision is made to analyse the possibilities based on the certification maturity and battery densities available. Based on this, a projected timeline is laid out, ensuring a viable operation at any point in time. Firstly, Section 5.1 will discuss the battery density and the levels of autonomy that are taken into account in the growth concept. After this, Section 5.2 will discuss the 4D matrix that relates the energy density, fleet size and the level of autonomy to the total cost per kilogram per kilometre.

5.1. Battery Density and Level of Autonomy

A three-dimensional matrix is constructed to analyse the available options. This matrix incorporates combinations of battery densities, fleet sizes, and levels of autonomy. Each unique combination is represented by a specific location within the matrix. The cost associated with these concepts is indicated by different colours, providing a visual representation of the cost variations across the matrix and thus adding the fourth dimension.

For the batteries, four milestones in battery density are projected: $225\,\mathrm{W\,h\,kg^{-1}}$, $450\,\mathrm{W\,h\,kg^{-1}}$, $675\,\mathrm{W\,h\,kg^{-1}}$ and $900\,\mathrm{W\,h\,kg^{-1}}$. Nowadays, there is only one certified electric aircraft, namely the Pipistrel Velis Electro. The battery energy density of this aircraft is between 149 and $168\,\mathrm{W\,h\,kg^{-1}}$[1]. However, today's best lithium-ion batteries achieve $250\,\mathrm{W\,h\,kg^{-1}}$, and since the introduction of lithium-ion batteries in 1991, the specific energy and energy density of these batteries have more than tripled at the cell level[62]. It is therefore widely expected that a battery density of $500\,\mathrm{W\,h\,kg^{-1}}$ at the pack level will become available around 2050[62]. Nevertheless, there are also companies claiming to be able to produce $500\,\mathrm{W\,h\,kg^{-1}}$ earlier than that. The company Amprius for example claims to bring their $500\,\mathrm{W\,h\,kg^{-1}}$ to the market in 2025[2] and CATL has already launched a battery with the same energy density[3]. However, this does not mean that they can immediately be used in aircraft.

In addition, due to chemistry limits, solid state batteries, specifically lithium-sulphur, should be considered for the future. The company Lyten[4] and Theion[5] for example are developing such a lithium-sulphur battery. Compared to lithium-ion, lithium-sulphur has, next to the fact that it can provide higher energy densities, the advantages that they are cheaper as they contain no Nickel, Cobalt, Manganese or Graphite, making these batteries more environmentally friendly. They are also inherently safer, since the batteries heat up less, making it more resistant to overcharge and thermal runaway. This also means that no cooling will be required, easing the operations as well as the design[6]. A disadvantage on the other hand would be the limited amount of cycles a battery can go through before being at its end of life, but both companies claim to have solved this and have a good cycle life. They both promise a battery with an energy density of $900\,\mathrm{W\,h\,kg^{-1}}$, available on the market in 2025/2026[7]. However, it has been shown over the years that actually achieving a breakthrough of lithium-sulphur batteries is difficult. An example of this is the company Oxis Energy, that was aiming to produce Li-S battery cells by 2023[8]. However, the company went bankrupt due to a lack of investments[9]. In conclusion, it is very uncertain what battery density will become available when. It is safe to assume that the density will increase in the future, but following from this uncertainty in developments, the necessity of a future-proof design arises.

Based on the certification discussed in Chapter 4, it is expected that regulations will be updated in a stepwise manner with an increasing level of autonomy. Five levels of autonomy are analysed. This is done based

[1] https://www.aviationconsumer.com/aircraftreviews/pipistrel-velis-electro-certified-electric/
[2] https://amprius.com/the-all-new-amprius-500-wh-kg-battery-platform-is-here/
[3] https://www.catl.com/en/news/6015.html
[4] https://lyten.com/products/batteries/
[5] https://www.theion.de/
[6] https://lyten.com/products/batteries/
[7] https://www.electrive.com/2021/09/28/lyten-to-launch-li-s-battery-for-2025-26/
[8] https://www.electrive.com/2019/06/12/oxis-prepares-for-serial-production-of-li-s-batteries/
[9] https://www.electrive.com/2021/05/21/oxis-energy-is-facing-bankruptcy/

on the expectations on when the certification will become available, while keeping in mind that it would then take an additional three years to actually certify the aircraft. The dates when the certifications are expected to become available are shown in Figure 5.1.

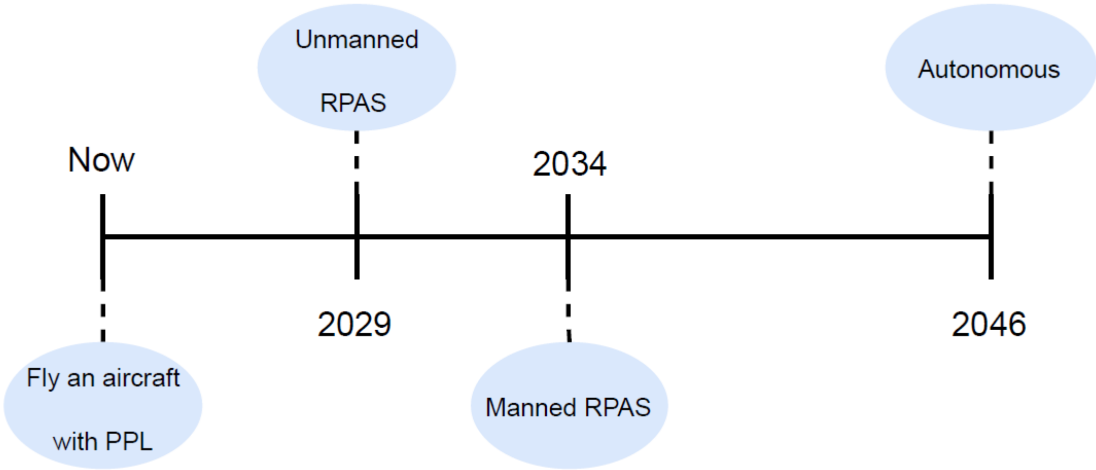


Figure 5.1: Timeline of expectation when different certifications will become available. Years based on [45, 44]

The lowest level of autonomy represents certification that is already available now, meaning that the aircraft will be flown by a PPL pilot. This will then be level zero. For this, it is decided to start the operations with a flight school. The customers could then get a PPL, specifically for the AmpAir aircraft. This is more detailed theory than the theory required for future operations, since there is more knowledge required for a PPL than for the licence that will be described in Chapter 6. The flight school will then provide the licence based on the existing rules for getting a PPL. The advantage of this is that this kind of operations will already help to prove that the aircraft is safe and functions properly. At the same time, this will also help with getting customers. Customers that decide to get their PPL with the AmpAir aircraft will most likely also make use of the AmpAir taxi service once it becomes operational. This already gives an initial group of potential customers.

The first level of autonomy would be to transport cargo with remote pilots. It is expected that this certification will become available by 2026 with a 3 years time to certify that aircraft would enable us to start operations in 2029 [45, 44]. AmpAir will partner with existing express freighters, which will be explained in more detail in Chapter 3.

The second level of autonomy is the point that certification allows manned RPAS who can prove an equivalent amount of safety compared to already existing conventionally manned air taxis. It is expected that the certification for this will become available by 2031 [44, 45]. This second level of autonomy is the concept as described in earlier stages of the design, which will again be explained more elaborately in Chapter 6. Here, the passengers will follow a short course and steer the aircraft using the highway-in-the-sky principle, while being remotely monitored by an observer depending on how often they fly.

A third level of autonomy would involve reducing the number of remote observers. This could be achieved due to two primary reasons. Firstly, during the initial stage, a significant portion of the customer base will consist of beginners who require more remote pilots and observers for assistance. However, as the market matures, there will be a higher proportion of experienced pilots, allowing for a shift in the level of required support. Simultaneously, as the aircraft demonstrates a track record of safe operations over several years, it will foster increased trust in the concept. This increased trust may potentially result in less stringent restrictions from certification authorities, indicating the viability of the concept.

Lastly, the fourth and final level would involve the implementation of a fully autonomous service. Once certified for passenger flights, AmpAir would be able to offer their service to the public. With a fully autonomous aircraft, passengers would not require any special knowledge or training to utilise the service. Nonetheless, they could enjoy a self-piloted flight if desired.

5.2. Matrix and Stages of the Operations

The matrix is shown in Figure 5.2 from two different perspectives. The explanation of the colours is given by the bar in the middle. The cost here is given per kilogram per kilometre, note that this differs from the familiar passenger per kilometre by a factor 100, and is otherwise the same. This is because one of the stages is cargo operations and for this it would not make sense to give the cost per passenger. The colours fade from green to red. The turning point is currently put at €1.00 per passenger per kilometre. It can be seen in the matrix that the influence of the fleet size is relatively small on the matrix. On the other hand, the battery energy density has a major effect on the cost. The level of autonomy also has a large influence, however this influence is smaller than that of the battery.

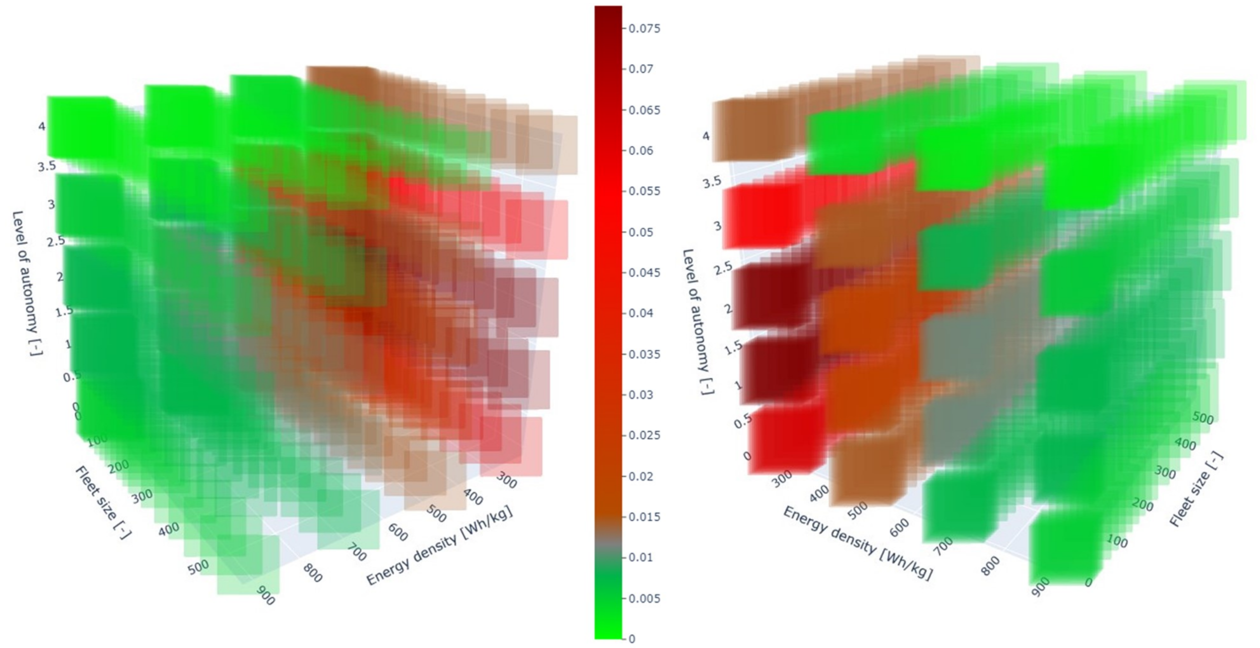


Figure 5.2: 4D matrix showing the cost as a function of energy density, fleet size and level of autonomy.

The purpose of the matrix is to give insight in what the company could do with different combinations of battery density and certification. This has been done because it is quite unpredictable when new batteries will become available, and it is also uncertain what the future certification will look like. This ensures that the company can grow as well as adapt to the available technology. During the design of the aircraft, this will be taken into account such that the same aircraft could fulfil all the different missions. The important thing about the growth concept is that it is designed to make the concept future-proof. This means that for any combination of battery density and level of autonomy, there is a possible design point. Based on the cost following from the matrix as well as the corresponding return on investment, it will be assessed whether the design point makes sense and is feasible. The matrix may also be used in combination with the market analysis to find a fitting fleet size for any point in time, an analysis of which is conducted in Chapter 12. With this knowledge in mind, different stages of the operations were defined. Six design points will be taken at six different stages of the design and will be analysed in more detail. These are described in Section 5.2.1. The chosen design point is then described in Section 5.2.2.

5.2.1. Stages of the Operations

The following list presents the different stages of operations, and a summary of the findings is provided in Table 5.1.

- **Stage 0**: the certification is already available (autonomy level 0), meaning that the aircraft could already fly with this purpose and this battery. So, stage 0 is chosen as the design point that is currently available. This would be with a battery density of $225\,\mathrm{W\,h\,kg^{-1}}$, a range of 178 km and a payload of 164 kg. As described, for this level of autonomy, a flight school will be set up. The range is quite limited, so fly from A to B would also not take you very far. Therefore, flying from A to A as a flight school would be the ideal mission for this stage. The operations themselves will then also be quite easy, since there is only one airport that requires charging facilities, storage, and maintenance.

- **Stage 1**: This stage uses autonomy level 1 and a battery density of $450\,\mathrm{W\,h\,kg^{-1}}$. This means that the certification for unmanned RPAS has become available, and thus the aircraft could be used for cargo. This is to get the operations started, make society gain confidence in the aircraft, and it will also make later certification for autonomy level 2 easier. This combination would lead to a range of 403 km and a payload of 278 kg.
- **Stage 2**: The design point of autonomy level 2 combined with a battery level of $450\,\mathrm{W\,h\,kg^{-1}}$ is chosen. This leads again to a range of 403 km and a payload of 278 kg, corresponding to about three passengers. With this, the maximum capacity of the aircraft is not used yet, however this would get the operations of being an air taxi started. When a better battery becomes available, this would lead to a better range or more payload.
- **Stage 3**: This stage is similar to stage 2, however with less remote pilots and remote monitors required. This would thus be autonomy level 3 combined with a battery energy density of $675\,\mathrm{W\,h\,kg^{-1}}$. With the better battery, the aircraft can still fly 403 km, however now with a payload of 505 kg. This means that five passengers including luggage can be transported over 403 km. By reducing the amount of remote pilots and monitors, the cost can be reduced. This leads to a lower price for the customers, as can be seen in Figure 5.2. At the same time, throughout the years, it is assumed that the amount of charging facilities will increase and that more airports will have charging facilities available. This would ease the operations. AmpAir will also contribute to expanding the charging facilities by assessing popular routes and spokes. At the same time, the hub system will be expanded. Based on the analysis of often requested remote airports, it can be considered to make these into hubs. This means that the charging time will reduce and therefore more flight to and from this airport will be possible. Not only will this help the market expansion, but it will also increase the revenues.
- **Stage 4**: The fourth stage will be with the fourth and final level of autonomy and still a battery density of $675\,\mathrm{W\,h\,kg^{-1}}$. It stems from the assumption that the developments of batteries will be slower than the developments in certification. Therefore, At autonomy level 4, operations are fully autonomous. As said, this will increase the market size since anyone can fly the aircraft.
- **Stage 5**: The last stage is a combination of the battery density of $900\,\mathrm{W\,h\,kg^{-1}}$ and autonomy level 4. With this combination, the aircraft can fly 563 km with 518 kg. This would be for example from Brussels to Lyon. With this increased range, the market size is expected to increase since no stops are required for further flights. This would then also lead to an updated hub and spokes system. Since these batteries are lithium-sulphur, no cooling of the batteries will be required any more, making the design even lighter. Then, the aircraft can fly fully autonomous, however there will still be the option for the passengers to pilot the aircraft themselves.

Table 5.1: Summary of Stages for AmpAir Operations

Stage	Autonomy Level	Battery Density (Wh/kg)	Range/Payload	Usage
0	Level 0	225	178 km / 164 kg	Flight School
1	Level 1	450	403 km / 278 kg	Cargo Operations
2	Level 2	450	403 km / 278 kg	Air Taxi (Up to 3 pax)
3	Level 3	675	403 km / 505 kg	Air Taxi (Up to 5 pax)
4	Level 4	675	403 km / 505 kg	Air Taxi (No Training)
5	Level 3	900	563 km / 518 kg	Extended Range Air Taxi

5.2.2. Chosen Design Point and Future Considerations

However, for the design of the aircraft, it is needed to choose one stage to focus on and design for. It is chosen to do so for stage 2. To ensure that the aircraft is suitable for all stages of the design, the aircraft will be designed with the last stage in mind. The battery locations have a fixed volume and while coming up with the stages it is already taken into account that the batteries can easily be exchanged with newer batteries that suit a further stage. The aircraft will be designed for $900\,\mathrm{W\,h\,kg^{-1}}$ with five passengers, but in such a way that the other stages also make sense with the lower battery energy density. This is already taken into account for the given payloads and ranges.

Nevertheless, it should be noted that the stages described here are just examples. The idea of the growth concept is that the design can work for different combinations of battery densities and available certification. The matrix can then help to find a fitting fleet size based on the cost. Also, when an upgrade to a new stage is possible, it should first be assessed if it is worth it to go to this stage. For example, when it is expected that a better stage will be possible in a few years, it might be decided to wait for better technology or certification to become available. This way, the design is developed to adapt to the future. According to Figure 5.2, some stages are very costly. However, this does not necessarily mean that these should not be taken into account. A more elaborate analysis on these costs will be given in Chapter 12. At the same time, it should be kept in mind that range can be exchanged for payload. The stages are given for a certain combination of payload and range, where increasing the payload has been prioritised over increasing the range. This is because the aircraft will be designed for five passengers. However, for the design point of, 450 W h kg^{-1} a range of 400 km is desired.

When customers choose to fly shorter distances, it allows for a higher payload capacity. This information will be communicated to the customers in advance. With higher energy densities, the aircraft can accommodate the full capacity of five passengers, but the range will be extended when carrying less payload. In Stage 0, the option to remove the extra seats in the back is considered to allow for more payload. Since the flight school operations typically involve only two passengers, and sometimes just one, it is unnecessary to have extra seats in the aircraft that won't be utilised. As battery density increases, the seats can be reinstalled. The cargo mission also does not require the seats, but for the higher autonomy levels, the payload, and range can be easily adjusted. Therefore, even with a maximum payload of 278 kg, the aircraft will still have five seats because customers can choose to fly shorter distances with more passengers. Alternatively, flying at higher altitudes is another possibility. As described in previous design stages, payload can be exchanged for altitude. By carrying less payload, the aircraft can fly at higher altitudes, allowing customers to reach airports located at higher elevations, such as those in the Alps. Additionally, flying at higher altitudes reduces the noise heard at ground level.

6 Operations and Logistics

This chapter will lay out the AmpAir operations and logistics concept. Firstly, a summary of the work done in previous project phases will be given in Section 6.1. Next, the flight planning and its corresponding safety procedures are elaborated on in Section 6.2, which is followed up by an explanation of the implemented communication strategies in Section 6.3. Next, in Section 6.4, the maintenance, storage and recharging plan is presented. Section 6.5 lays out what the one-day pilot training entails and Section 6.6 determines the user experiences and responsibilities. Lastly, future considerations for the operations and logistics concept are defined in Section 6.8.

6.1. Previously Defined Operations and Logistics

During previous phases, a base for the operations and logistics concept was created, in which one aircraft will be operable for 25 years. During the final stage of the DSE, this concept was extended and finalised. A summary of the previous operations and logistics concept is presented here, for more information, the reader encouraged to read the midterm report [30]. This summary will cover the flight scheduling in Section 6.1.1, maintenance and charging in Section 6.1.2 and the piloting strategy in Section 6.1.3.

6.1.1. Flight Scheduling

To optimise the operations, proper flight scheduling is needed, since repositioning and empty leg flights are costly. The AmpAir network is based on a combination of hub and spoke airports. The hubs are based in small airports in Europe, where hangars are available for storage and maintenance. Highly commercial international airports are avoided to minimise cost. They are distributed in a way that each hub has at least one other hub within a 400 km radius. The main routes and fleet coverage can be seen in Figure 6.1, where hubs are located at the centre of each circle.

Figure 6.1: Air fleet coverage for ranges of 400 km, displaying the routes along Europe [30]

The hubs and spokes system extends across most of Europe, centred around Frankfurt-Egelsbach airport. Spokes are smaller stations, where the aircraft can land and take off. Overnight storage of the aircraft happens at the hubs and is optimised using a scheduling algorithm, such that as little empty legs or relocation flights will be required to start the next day. The passenger can book their flights through an app. Here, they can see the location of available aircraft, and can choose to board one that is close-by. They can also request flying from a specific departure station, meaning an aircraft will have to be sent there. An algorithm will identify the optimal aircraft to send, based on the distance and remaining battery life of surrounding aircraft. A pricing algorithm calculates the price of each flight, based on the trip distance and whether it is a shared flight or not. Flying from spokes will be more costly than flying from hubs, since they usually induce empty leg relocation of an aircraft.

Depending on the amount of stars a pilot has, they can choose whether other people can join their flight. If this is the case, other passengers can see this scheduled flight, and book a place in them. This makes it cheaper for both parties, as the flight cost is set for a certain trajectory. This means if more seats are filled, the price per passenger will go down. Lastly, passengers will receive a discount when they join a scheduled empty leg. When a flight is cancelled for any reason, passengers will get a notification that the aircraft cannot fly. They can then either re-book the flight for free at another time, or choose to depart from another airport. The passenger can also choose to cancel the flight and receive a coupon that can be spent on a different flight.

6.1.2. Logistics at the Spokes

AmpAir will have local contractors at the spokes. They will be licensed to performing aircraft maintenance. They will perform minor maintenance tasks, like storing and plugging in the battery chargers. Specific maintenance actions will be done by AmpAir maintenance buses. To reduce the risk of a component braking at a remote non-hub airport, predictive maintenance will be implemented and taken into consideration in the flight scheduling [30]. The hubs will have fast charging facilities available. If necessary, the aircraft can charge with a conventional power outlet. However, the aircraft would need to remain at the station overnight before it can perform the next flight, since this type of charging takes relatively long.

6.1.3. Autonomous Flight and Optional Piloting

The aircraft will be able to fly the empty legs autonomously, and the manned flights will be flown by the passengers themselves. Because of social, ethical, and certification related constraints, a ground station with remote pilots and observers will track and support each flight. Contact can be made with the observers when passengers have questions, and remote pilots can take over control when needed.

The actions of the passengers during the flight depend greatly on their star rating. The more stars, the more piloting actions the passenger is allowed to perform. However, every pilot will be able to steer the aircraft using the highway-in-the-sky principle. This system visually shows the desired flight route as boxes that the aircraft has to fly through. This makes control effortless, even in IFR conditions, and it is supported by research that training people to follow this path is relatively easy [98]. This system makes it possible that passengers can fly the aircraft after a one-day training course. Integrating the game-like highway in the sky interface is likely to increase public appeal, as one will be able to pilot the aircraft themselves, which increases the flight experience. An added benefit is the fact that passengers get less sick because of the visual reference.

The remainder of this chapter further builds upon this concept and explains changes and additions that were made in the final design phase. For further elaboration on the things discussed in this summary, the midterm report can be consulted [30].

6.2. Flight Planning and Safety

The AmpAir service must be made as safe as possible. For this, different risks are analysed and strategies to mitigate or eliminate them are set up.

At the altitude AmpAir is flying, the airspace is not as restricted as it is for higher altitudes. However, the flight path should be created such that minimal communication with ATC is necessary and certain areas are avoided. Therefore, proper flight planning is needed to make sure that the passenger does not have to worry about their route. For each flight, the flight plan is predetermined by the AmpAir ground station. The passenger will fly the aircraft using the highway-in-the-sky principle, which will show the flight path that the aircraft needs to follow. A geo-fenced area will then be implemented to ensure safety. For this, an imaginary box is generated around the route such that the passenger is still free to deviate, to a certain extent, from the predetermined flight path. This will give them the freedom to steer the aircraft within a restricted zone. If the passenger leaves this zone, an alert will go off in the aircraft, telling the piloting passenger to steer back to the allowed zone immediately. If this is not done within ten seconds, the autopilot will take over and fly the aircraft back into the zone automatically. This is not only to ensure passenger safety, but also to ensure safety of people on the ground, in case someone wants to deliberately crash the aircraft.

Similarly, any abuse of the thrust system is avoided. The piloting passenger will get directions on the required position of the thrust levers while using the highway-in-the-sky. There is then again a zone which imposes limits on how much the piloting passenger can vary the thrust. Then, if this position is not adhered to, the pilot will get a warning. If the HITS shows a new thrust, the piloting passenger has ten seconds to change this before a warning will be issued. Similarly, if the piloting passenger changes the thrust to a level that is not within the restricted zone, he will get a warning and if he does not change it within ten seconds, the autopilot will take over the thrust and put the thrust levers back in the correct position. Having many of these messages during the flight is uncomfortable for the passengers. Therefore, it is important that the piloting passenger knows that he has to stay alert when he decides to fly without the autopilot. Passengers can also choose to let the autopilot handle the thrust levers.

Additionally, a detection and collision avoidance system will be implemented. It is expected that in the future, when autonomous flight is more common, smaller aircraft will have to implement these systems. However, currently, not all smaller aircraft have this system, so the AmpAir aircraft will also have a radar/transponder that detects other aircraft. A system shall be developed that can then automatically alter the flight path to avoid collision with aircraft that are too close.

The passenger must be in a suitable state to fly. For example, they cannot be under the influence of alcohol or any other drug that makes them unable to control the aircraft. Additionally, it must be prevented that passengers with the intention of inflicting harm can do so using the AmpAir aircraft. For this, several preventative measures are created. Firstly, any passenger that wants a licence will have to fill in a medical statement, similar to that required for a driving licence. This statement will give insight in the physical and mental health of the passenger and indicate their ability to fly the aircraft. To check the state of the passenger before boarding the aircraft, the piloting passenger will need to play a small game on his phone, measuring any deviations in their reaction time. A decreased reaction time can indicate that the person is under the influence of alcohol, because reaction time decreases the higher the alcohol level is. The game will consist of small white dots appearing on a black background, which the passenger has to click as fast as possible. On the training day, the passenger will have to do this test during different times of the day to create a personal dataset on their reaction time, which can be used as a reference. If the passenger does not pass the test, he will have two more tries. After this, they will be contacted by the ground station to see what is going on. Based on this conversation, the ground station can deny the passenger the right to take off. Moreover, there will also be awareness checks throughout the flight. Every 15 minutes, a button will light up, and the piloting passenger will have to press it to show that he is still paying attention.

Lastly, different kinds of safety buttons will be implemented in the aircraft. The piloting passenger can press a button when they are feeling unwell and unable to pilot the aircraft. If this is the case, the ground station will take over the control of the aircraft, either by flying remotely or by turning on the autopilot and monitoring closely. Then, there is a red emergency button. In case of fire, loss of power or other dangerous situations, the piloting passenger can press this button, notifying a remote pilot who will immediately to take over control and assist the passengers. Next to that, there will be a landing button that, when pressed, sends a message to the ground station with a request to land immediately. If the ground station confirms, the aircraft will land automatically at the nearest airport. For this, the aircraft will continuously locate the nearest airport during flight. At any time, the aircraft should be within 40 km of an airport, based on the glide ratio as calculated in Section 8.10. If an area does not contain feasible airports for landing, this area should be avoided in the flight plan to ensure safe operations. Lastly, there will be a green help button. When the piloting passenger presses this, they will be put into contact with the observers at the ground station. This button is for non-urgent questions or when the passenger is not feeling confident. For example, if they see clouds ahead, they can ask the observers if this is safe. The explanation of these buttons applies to nominal state. For the other cases, more explanation will be provided in Section 6.11.

6.3. Communication

Because the pilots are inexperienced, extra attention must be given to the communication flow. Route scheduling is already arranged in such a way that required ATC communication is minimised and the remaining communication should be simple and understandable for all parties. This will be done by implementing an CPDLC system. Here, the communication with ATC happens via messages instead of speaking. The messages for take off and landing will be automated, meaning the piloting passenger only has to press a button once they are ready to go. Then, the clearance request is confirmed by the ground station, after which a message is sent automatically to the ATC asking for clearance. Similarly, the piloting passenger can press a button when they want to land and again, the clearance request is confirmed by the ground station, after which the message is sent automatically to ATC. When the flight is autonomous, the aircraft system will request clearance automatically, based on the flight plan.

Teaching full ATC communication in a one-day course is not possible. Therefore, as described in Section 6.6.1, the possibility to get an add-on communication package will be offered. For people that do not have either this add-on package or three or more stars, ATC messages directed to the aircraft will be sent to the ground station. Currently, for remotely piloted aircraft, the ATC information will first go to the aircraft and then from the aircraft to the ground station. However, it is expected that in the future it will be possible to send the information directly from the ATC to the remote pilot at the ground station [45].

6.4. Recharging

To make the concept of the AmpAir electric aircraft work, a closer look should be taken at the charging options. One would be to swap the depleted batteries with charged ones, as explained in Section 6.4.1. Another option, which AmpAir will implement, is to charge the non-removable batteries from the grid, as explained in Section 6.4.2.

6.4.1. Swapping batteries

Swappable batteries are a good option as they would allow for fast and optimised operations. This could be achieved by implementing battery swapping stations that can store and charge the batteries at the airports. However, there are a lot of disadvantages. Firstly, the storage of the batteries would take up much more space than a regular charging point would [40]. Additionally, charged batteries will have to be available at every airport AmpAir services, meaning a high initial investment is necessary to obtain this many batteries. On top of that, an accessible, standardised and easy to swap battery mounting system must be designed, requiring a lot of resources. The battery swapping itself is complicated and time-consuming and will require specialised personnel at the location. Lastly, there are many certification related issues, mostly tied to the required cooling systems. Therefore, having swappable batteries is not considered to be a feasible option in the near future [59].

6.4.2. Charging

Charging of large electric batteries is already implemented in the automotive industry. However, aircraft batteries are larger and thus require more time to charge when using a fast charger with the same power [40]. Fast-charging poles can be installed at the hubs during the first years of operation, but would be too costly to install at all the spokes from the start. Installing these fast-charging facilities is advantageous for airports, as this makes them attractive for future electric aircraft fleets, because they have the facilities ready. At the spokes, charging will happen from conventional power outlets. It is expected that in the future the amount of airports with proper charging facilities will increase, which will ease the operations. A disadvantage is that the electricity grid will have to deal with high peak powers. Since the electricity consumption is irregular, this could lead to fluctuations in the supply power quality, voltage instability and increased loss of energy [59, 60]. A solution would be to distribute the energy usage over peak and off-peak times, but this is not optimal from an operations point of view. In order for AmpAir to have net zero-emissions, energy for charging the batteries should come from renewable energy. Airports could start providing their own electricity by installing windmills or solar panels. A disadvantage of this energy supply is it is not continuous because of weather dependency [59]. This problem could be solved by storing the generated energy in batteries at the airport and using these to charge the aircraft. Similarly, the energy from the grid can be saved during off-peak periods such that it can be used during peak periods.

AmpAir will start their operations by using rechargeable batteries. It is expected that by 2026 fast-chargers of 400 kW will be available. At the design point, this would mean that charging the aircraft would take 46 minutes if a 100% efficiency is assumed. When a better charger of 900 kW would become available, this would lead to a charging time of only 20.5 minutes. At the spokes, charging cables will draw power from conventional power outlets.

Once the shift is made to lithium-sulphur batteries that do not require cooling, swappable batteries can be implemented. Battery Swapping Stations will then be placed at the hubs to decrease aircraft downtime. However, it will still be possible to charge the aircraft at the spokes, as they do not have the swapping batteries readily available.

6.5. The One-Day Training

One of AmpAirs' main strengths is the fact that passengers can pilot the aircraft after a one-day training. This section will discuss exactly what this training entails. Before the one-day training can commence, the passenger must pass a theoretical exam specifically about the AmpAir aircraft. The passenger can study from an in house designed study book and practice online exams. By passing, they show knowledge on the AmpAir cockpit layout, operations during flight, pre- and post-flight checks and emergency procedures. The goal of this theoretical exam is to familiarise the passenger with the aircraft, piloting actions and to convince the passenger that this aircraft is safe.

Once the passenger has passed the theoretical exam, they can take the one-day training, in which they will put the theory to practice. A dummy aircraft will be used to practice pre- and post-flight checking procedures, which are based on a user-friendly checklist. The checklists are visual, in the sense that they contain images to clarify the descriptions. This is useful when a piloting passenger is uncertain what a part looks like or how the aircraft should look in normal circumstances. The instructor will walk around the aircraft with the in-training passenger and demonstrate the procedures. They will also highlight how to spot damage or peculiarities in the aircraft. As described in Section 6.2, the passenger will play a game multiple times throughout the day to create a personal dataset on their reaction time. Lastly, the passengers will fly a simulator of the AmpAir aircraft. It will have a screen, showing the Primary Flight Display, a control stick and thrust levers. Here, the passenger can get familiar with the controls and learn how to taxi, take off, use the highway-in-the-sky and land. The customer will be taught how to use the thrust levers, however during cruise the piloting passenger cannot give extreme inputs to the thrust levers, as described in Section 6.2. To keep the cost of this training day low, the passenger will not perform a flight yet on this day. At the same time, such a 'simulator' does not have to be very complicated or expensive. It has been shown, for example, that pilots training in fixed-base simulators have similar performance to pilots training in a moving-base simulator [67].

6.6. User Experience and Responsibilities

This section will discuss the different levels of user experience and their accompanying responsibilities. In Section 6.6.1, the star ratings a passenger can obtain are laid out. Then, in Section 6.6.2, the pre- and post-flight checks are discussed in more detail.

6.6.1. Piloting Levels

Before the first flight can be booked, the passenger must have completed the training, as described in Section 6.5. A star system was created to give passengers the possibility to unlock more responsibilities over time. The star rating is explained in more detail below.

- **0 stars:** When a customer chooses to use AmpAir, they will start with a short theoretical exam, where they will learn about the aircraft layout and basic piloting considerations. Once the passenger has passed their theoretical exam, they can plan their one-day training as described in Section 6.5. Here, they will learn to perform the pre-and post flight checks and fly a simulator, learning how to handle the aircraft. At the end of the day, they are assessed and, if approved, will receive their one-star rating.
- **1 star:** Once the passenger has one star, they are allowed to book the aircraft. For the first flight, a remote pilot will perform the taxi, take-off and landing. During cruise, the remote pilot will guide the passenger through a training circuit, which includes simple manoeuvres and emergency procedures. This allows the passenger to get comfortable and confident with the system. The following flights are not continuously guided by a remote pilot, but an observer. They will act as a help line, answering questions and building the passengers' confidence. Once the passenger has 15 hours of piloting experience, they will upgrade to two stars.
- **2 stars:** Once the passenger has two stars, they will not require continuous contact with a remote observer any more. However, during flight they will always be able to contact them in case of doubt or questions. Additionally, they are allowed to open up spots on their flights for people outside their party to join. The people that join this flight are not required to have a piloting rating.

To obtain the third star, the passenger must have additional theoretical knowledge and training. This will consist of learning how to communicate with ATC and how to use the onboard standby instruments. Again, the passenger will be assessed during a theoretical and practical exam, and if they pass, they will receive three stars.

- **3 stars:** Once a passenger has three stars, they can communicate directly with the ATC and preform more piloting operations themselves. This makes them less dependent on the autopilot.

  For passengers seeking even more responsibility, there is the option to obtain a full piloting licence for the AmpAir aircraft. To upgrade to four stars, the pilot will have to learn more theory, which includes but is not limited to traffic avoidance, traffic patterns and recovering from emergencies. Again, just like for obtaining three stars, theory and practice will be assessed by an instructor.
- **4 stars:** A pilot with four stars will be able to control the whole aircraft by himself. This means the passenger is no longer dependent on any autopiloting features and allowed to fly without the highway-in-the-sky.

The star rating indicates the experience of the pilot and is shown, together with the amount of piloting flight hours, when other passengers want to join a flight. The last three levels are all allowed to take on additional passengers. But higher star ratings mean that a pilot has more experience, increasing the feeling of safety for the joining passengers. This increases user acceptance of people that would be scared off by the low levels of required training, as they can choose to only fly with the more experienced pilots. An ATC communications add-on package is available for two-star pilots. This package only consists of learning how to communicate with ATC, while all other flight operations remain based on the highway-in-the-sky system. This is aimed at the passengers who enjoy having more responsibility, but do not have the time or ambition to upgrade to three stars. It should also be noted that, when the operations start with the stage 0 flight school, as explained in Chapter 5, the pilots that have obtained their PPL for the AmpAir aircraft will immediately be awarded four stars. Once stage 5 is reached, passengers that are not interested in piloting the aircraft themselves have the option to fly in the autonomous aircraft. This will mainly appeal to people who want to relax or work during their flight.

6.6.2. A Flight

Once at least one person of a flying party has followed the one-day course, they can book a flight in the app. Here, they will get information on when to go to the departure airport and where to be exactly at this airport. For flights booked close to the departure time, it should be kept in mind that this is only possible if there is an aircraft close to the passenger already. If the aircraft is too far away, charging would take a long time. Therefore, as mentioned before, there is an optimisation algorithm to make sure that the aircraft are spread out over Europe. Passengers should then be at the airport at least 40 minutes in advance. This gives them enough time to go through security checks, go to the aircraft and do the checks.

Once the passenger gets to the aircraft, they can unlock it by playing the in-app game, as described in Section 6.2. A tablet can be found in the cabin, which will show the pre-flight checklist. Also, there will be a chat option in the app where the passenger can ask any questions he might have concerning the checks. He can also send a picture in case he is not sure about something he is seeing. There will also be a checklist for checking damage and logging this, which allows easy tracing of who is responsible for damage. At the same time, the aircraft will perform system checks by itself using the Central Maintenance Computer, as elaborated on Section 6.10.1. The ground station will then check both the passenger checklist and the feedback from the aircraft itself. If a fault is reported, the ground station must initiate appropriate actions. The technical checks can also be performed remotely by the ground station if needed.

For all components from which a cover needs to be removed, there will also be an integrated light sensor. This way, the ground station can cross-check remotely if the covers are removed. Once the received checklists are approved, the ground station provides clearance for the flight to take off. When a passenger has not flown for a long time, they might have forgotten how to handle the aircraft. For this reason, a recap video will always be available on the tablet before take-off that explains the most important flight controls and operations. This is to boost their confidence and feeling of safety before the flight. This video is mandatory in case the piloting passenger has been inactive for over six months. After two years of inactivity, the piloting passenger will have to renew their licence. Furthermore, the flight cannot take off if the door is opened. Therefore, an automatic door will be implemented that will close the door if the passenger has not done this properly. Once the ATC has then also provided clearance, the flight can start. After arrival at the destination, a post-flight checklist has to be filled in by the passenger before the aircraft can be locked. Again, visual checks are the passengers' responsibility, while the aircraft performs technical system checks. When the aircraft is flying an empty leg, the procedure will be slightly different. Here, the contractors will perform the pre-flight checks before the flight. Afterwards, the aircraft flies autonomously to a hub or to a next passenger. Once the aircraft arrives at the destination, the contractors will perform the post-flight checks [30]. If it did not fly to pick up a passenger, the contractors will store the aircraft, perform maintenance and charge the aircraft. A visual summary of the operations of the customer is shown in Figure 6.2. Here, blue refers to the phase before the flight, yellow is the flight and then red represents the phase after the flight.

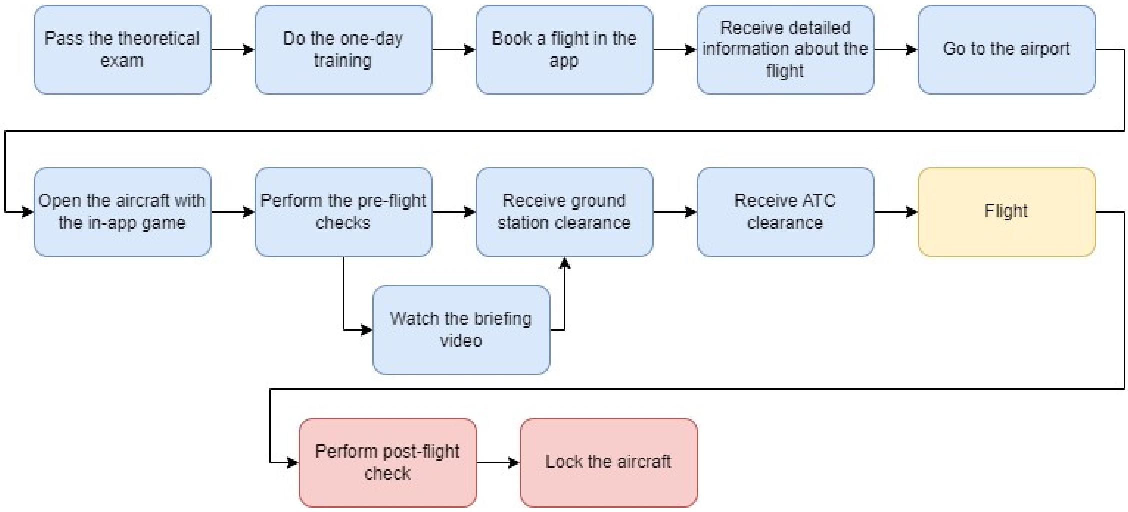


Figure 6.2: Overview of actions of the customers for the flight

Damage and maintenance to an aircraft is inevitable. Therefore, the passenger is not always responsible for any damage that is found on the aircraft. In Appendix B, the AmpAir terms and conditions are laid out. When the customer chooses to start their journey with AmpAir, they will be asked to read this and agree. The terms and conditions were intentionally kept short, to avoid that passengers do not fully read what they could be held accountable for.

6.6.3. Remote piloting and Monitoring

Passengers have the option to pilot the aircraft themselves or act as a safety pilot, as explained in Section 6.6.1. However, there will be support from AmpAir personnel to ensure passenger safety and give them more confidence. The level of support depends on the star rating of a pilot. This section aims to make an estimation of the required AmpAir ground personnel in the first five years of operation.

The AmpAir ground station personnel consists of four different functions. Firstly, the operators are the managers of the ground stations. They make sure that all flights fulfil necessary safety standards, make sure operations are conducted smoothly and have the final say in the decision-making process. The passengers do not have contact with these staff members. Next, the instructors are those that teach the one-day training course, give the training to obtain three or four stars and guide simulator sessions. The passengers will only be in contact with this staff during trainings. The piloting passengers can have contact with the following two functions: the observers and remote pilots. The observers will have two functions: firstly, they can be contacted by the passengers themselves in case of non-urgent questions, concerns or doubts, comparable to a help desk. In this case, they will listen, comfort and guide the passengers through the required steps. Secondly, they will track the data coming from the monitoring software. This will alert them of any anomalies, allowing them to assess the problem at hand. Once the problem is identified, they will guide the passenger through the required steps or forward them to a remote pilot. The observers will always work in pairs, as their attention will be taken away from the other aircraft once a call comes in. On the other hand, remote pilots have full control of the aircraft during the first flight. On top of that, they can seize control of the aircraft in case of an emergency. In conclusion, the main function of the operators is to manage the ground station, the instructors educate the passengers into pilots and the observers communicate with the passengers, while the remote pilots control the aircraft.

In order to determine how much ground personnel is required, the amount of support per star must be determined. One-star pilots will have a remote pilot perform taxiing, take-off and landing during their first flight and during cruise, they will receive a guided tutorial from them. This will further build the confidence of the piloting passenger and allows for immediate intervention in case the passenger undertakes dangerous actions. Thus, each first flight of a piloting passenger, will receive full attention from a remote pilot. After this first flight, the passenger will perform all flight operations, while continuously supervised by an observer, which will increase the passengers' confidence. AmpAir is convinced that after 15 flight hours, most passengers will feel comfortable enough to fly without the continuous guidance of an observer.

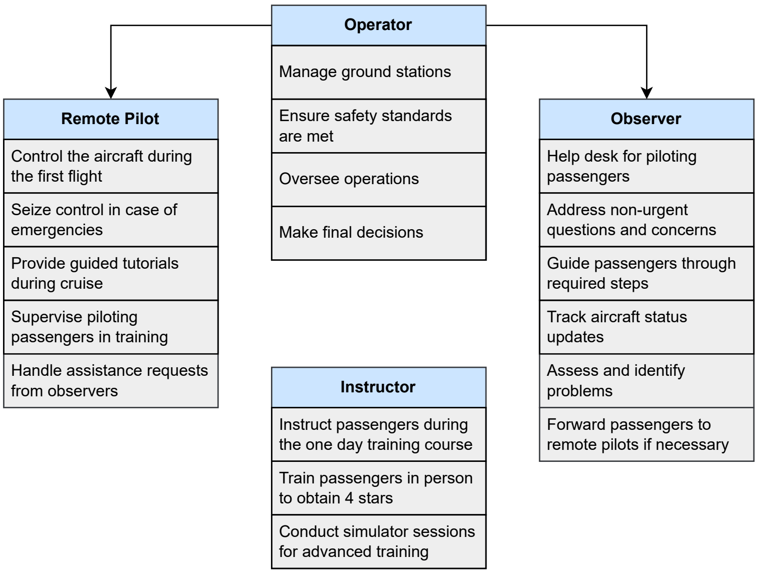


Figure 6.3: Overview of required personnel and their tasks

Once the pilot has two stars, they will not be continuously monitored any more. From now on, the passenger will perform all required manoeuvres themselves, using the advanced autopilot system. Throughout the flight, assistance from the ground station can be initiated in two ways: The passengers themselves can contact the ground station by pressing one of the contact buttons. The observers will listen to the problem and judge the situation. When the problem cannot be solved by the passengers themselves, the observer forwards the conversation to a remote pilot. Next to that, contact with the ground station can be initiated if the monitoring software detects any anomalies. This will be based on data that is collected by the aircraft sensors. A model was created to determine the amount of remote pilots and observers. In this model, the following assumptions were implemented:

- ASM-OPS-01: The initial fleet size is 10% of the final fleet size.
- ASM-OPS-02: The fleet size increases linearly to the final fleet size over a time span of five years.
- ASM-OPS-03: Once an aircraft rolls off the production line, it will fly two times a day, every day.
- ASM-OPS-04: A flight is on average 2 hours, including taxi.
- ASM-OPS-05: The flights are divided equally between vacationers and business parties.
- ASM-OPS-06: Vacationing parties consist of four people and are assumed to take four trips per year (equating to eight flights per year).
- ASM-OPS-07: From a vacationing party, half will pilot the aircraft.
- ASM-OPS-08: Business parties consist of three people and are assumed to take seven trips per year (equating to fourteen flights per year)
- ASM-OPS-09: From a business party, two out of three will pilot the aircraft.
- ASM-OPS-10: Flights are evenly spread across the day, there are no peak times.
- ASM-OPS-11: It is assumed that employees will work a 40-hour work week.
- ASM-OPS-12: The aircraft will operate from 7:00h to 23:00h

Firstly, the operators have a managing function. There will be an operator per 100 aircraft. Passengers with two to four stars will only require assistance from the observer and remote pilot sporadically. This can be in case of questions, poor weather, system malfunctions or emergencies. It was estimated that a remote pilot will have to intervene once every 2000 flights, for a duration of 30 minutes. The amount of flights one observer can handle was based on a comparison with ATC personnel. From there, it was decided that they are able to track 20 flights at a time. Once the passenger passes their exams and obtains 3 or 4 stars, they will become more independent. It is assumed they will be able to solve more problems themselves, meaning one observer can be responsible for 30 and 40 respectively. For the instructors, they will teach a one-day training course to up to 15 passengers at a time. When a passenger wants to go from three to four stars, they will teach additional theory of about 40hrs.

The script determines how many flights of 0, 1,2,3 and 4-star passengers depart each day. From this, the amount of work hours is determined. From this, the required employees over the first five years of operation were found and are shown in Figure 6.4. Here, it can be seen that the amount of instructors remains virtually constant. This is because of the assumption that the amount of new AmpAir users will increase linearly over time. This means that each year there is an equal amount of new pilots that need the one-day training. The amount of instructors necessary to teach the training to upgrade to four stars is negligible compared to the previous number. Over time, the amount of 2 or more star passengers increases faster than the amount of 0 and 1-star pilots. This is reflected in the fact that the amount of observers increases much faster than the amount of remote pilots. By the time AmpAir is fully operational, the company will employ 5 operators, 14 remote pilots, 12 instructors and 110 observers. After this, the amount of employees will remain constant, except an increase in fleet size or aircraft utilisation is implemented.

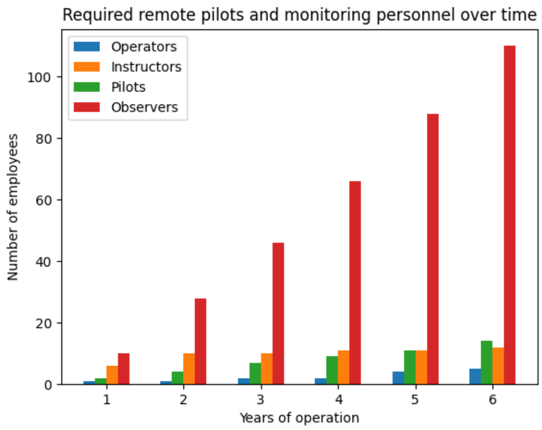


Figure 6.4: A graph showing the required amount of operators, remote pilots, observers, and instructors to sustain the operations of the AmpAir service.

6.7. App Design

In all the previous sections, an app was discussed. In this section, an initial design of the app will be shown and discussed. The design is shown in Figure 6.5.

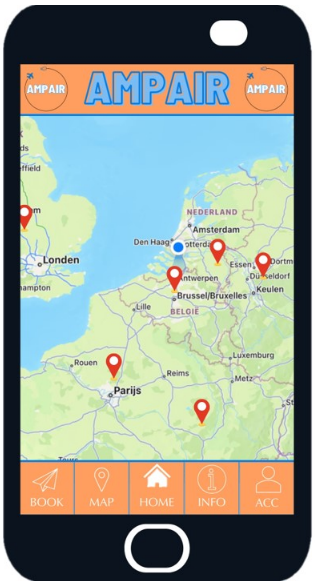


Figure 6.5: Initial design of the AmpAir app

In the lower menu, five buttons are shown: book, map, home, info (information) and acc (account). 'Book' will lead to an interface in the app in which the customer can easily book a flight. 'Map' is then the option shown in the figure. The red pinpoints show locations of aircraft that are currently available. This is for last-minute bookings. The customer can then zoom in or out on the map to get a closer look to airports in the neighbourhood. 'Home' will show the passenger any messages and updates, as well as general information about the service and the app. When the customers go to 'info', they will see up-to-date information about their booking, such as information on where to go at the airport, as well as more practical things closer up to the flight. This includes the pre- and post-flight checklists, as well as the function to open the aircraft with the game. Here, the customer can also contact the ground station for any questions that may come up. Moreover, this menu will give information of the amount of payload that can be taken for the chosen range. Lastly, under 'acc' the customers can see and update information about themselves, such as their name, their amount of stars, flight hours etcetera. The amount of stars and flight hours cannot be changed manually by the customers.

6.8. Future Considerations

This section describes alternatives and future operational practices. At the start of AmpAir operations, the one-day course will be free. This is to avoid any additional barriers that prevent people from using the service and to build up a passenger base. However, once the service becomes well established but is still growing at the same time, a fee will be charged to get the licence. Additionally, the hub and spoke network can be expan ded or adjusted based on the popularity of certain routes. Converting popular spokes into hubs will decrease the cost of flying to or from this destination, as the aircraft will be able to be stored, maintained and fast-charged there, meaning fewer required empty legs.

Additionally, the avionics design that influences operations should be adaptable. Currently, it is only possible to land an aircraft autonomously when there is ILS available, which small airports usually do not have because of its additional cost [80]. This means that a remote pilot has to perform the empty leg landings. However, there is a promising new system in development, called C2LAND. The first tests show it can autonomously land an aircraft without the need of extra infrastructure at the airport [63]. Once the system becomes certified, it will be implemented in the aircraft to ease the operations and reduce the cost.

Lastly, once batteries become more powerful, the aircraft can switch to the next stage, as described in Chapter 5. This means that the hub locations can be revised. The increased range means hubs can be further apart and allows for removal of unpopular ones, which would decrease cost. However, one could also choose to keep the hub spacing close-by, as the aircraft will be able to perform two flights back-to-back without recharging

6.9. Reliability and Availability

Reliability and availability are two key factors in aircraft operations, each with its own significance. Reliability refers to the assurance that a system will consistently function as intended, minimising the occurrence of failures. On the other hand, availability focuses on ensuring that a particular function of an aircraft system can be utilised as frequently as necessary. In terms of importance, availability takes precedence over reliability. This is because, even if a component is deemed unreliable and experiences a failure, as long as there is an alternative component performing the same function, the availability of that function remains assured. On the other hand, if a component is reliable, but unavailable, the function cannot be performed.

One way to guarantee a high availability is by calculating approximates of lost state variables with information available from functioning systems. This is called analytical redundancy. For example, when the GPS receiver of the avionics system loses connection, the aircraft can estimate its position by calculating the flight path based on measurements of true airspeed, geographic heading, and wind speed, which can be projected to the Earth's geography to find the geographic coordinates based on the last known location [17]. However, this strategy will introduce errors that depend on the accuracy of the functioning measurement equipment and due to the nature of using approximations. In general, analytical redundancy provides a valuable method for calculating crucial flight parameters in emergency scenarios. But, it should be emphasised that the accuracy of these estimations does not match that of directly measured data.

Another approach to achieve system redundancy can be done by implementing dissimilar redundancy. This refers to the incorporation of diverse systems or components that perform the same function, but rely on different principles or technologies. By introducing dissimilar redundancy, multiple independent systems can provide redundant measurements or calculations, enhancing the reliability and accuracy of the overall system. Dissimilar redundancy has been implemented by integrating four flight control computers from two different manufacturers, in pairs, utilising unique software to compute the autopilot function. These computers operate in parallel and are supervised by a dedicated module. The supervising module continuously monitors the outputs of each flight control computer to select the most reliable and accurate one for controlling the aircraft. The incorporation of multiple flight control computers with different software introduces diversity into the system, which helps mitigate the risk of single-point or common-mode failures. In the event of a malfunction or erroneous output from one flight control computer, the supervising module can identify and exclude it from the decision-making process, relying instead on the outputs of the remaining functional computers. And lastly, by designing a clever subsystem that always guarantees functioning, reliability can also be ensured. To illustrate this, two subsystems are presented in Appendix C: one for the IRS subsystem and another for the ADS subsystem. For example, as shown in Figure C.2, in the event of an air data system (ADS) failure, there will be another ADS that will take on the job of providing information to the PFD and MFD. Similarly, the IRS subsystem, as depicted in Figure C.1, is designed with the same concept in mind. In the case of an IRS failure, there will be another IRS to continue the job.

6.10. Maintenance

The most important maintenance activities for the aircraft can be divided into scheduled and non-scheduled activities. Scheduled maintenance activities are planned in advance and conducted at routine intervals that vary for each activity. They are presented in Table 6.1, which provides details on the activity type, the specific activities, and the corresponding timing.

Table 6.1: Scheduled Maintenance Activities for the Electric Aircraft

Activity Type	Description	Timing
Inspections and checks	Pre-flight inspection; Post-flight inspection; 100-hour inspection; Annual inspection	Regularly scheduled intervals based on specific inspection requirements
Life-limited component replacement	Tracking component life limits; Timely replacement of life-limited components	Manufacturer-recommended intervals
Battery health management	Monitoring battery health parameters; Performing battery capacity tests and diagnostics; Implementing appropriate charging and discharging protocols; Inspecting for signs of damage or degradation	Manufacturer-recommended intervals
Electric motor maintenance	Inspection and lubrication of motor components; Monitoring performance, temperature, and vibration levels; Motor system diagnostics and troubleshooting	Regularly scheduled intervals or as specified by maintenance manual
Avionics system maintenance	Inspection and testing of avionics systems; Updating firmware and software; Calibration of sensors and instruments	Regularly scheduled intervals or as specified by maintenance manual
Propeller maintenance	Inspection and balancing of propeller; Lubrication of propeller components	Regularly scheduled intervals or as specified by maintenance manual
Airframe inspections	Visual inspection of the airframe for structural integrity; Checking for signs of corrosion or damage	Regularly scheduled intervals or as specified by maintenance manual
Fluid checks and replenishment	Checking and replenishing cooling system fluid, if applicable	Regularly scheduled intervals or as specified by maintenance manual
Landing gear inspection	Inspecting tire condition; Rotating tires for even wear; Landing gear overhaul	Regularly scheduled intervals or as specified by maintenance manual

On the other hand, non-scheduled activities are performed whenever the aircraft requires them. A general representation of these activities is provided in Table 6.2, which shows the activity type and a description, without specifying a predetermined timing, as they cannot be scheduled in advance.

Table 6.2: Non-Scheduled Maintenance Activities for the Electric Aircraft

Activity Type	Description
Corrective Maintenance	Addressing unforeseen issues or malfunctions that occur during operation; Conducting immediate repairs or component replacements to restore functionality; Performing diagnostic tests to identify the root cause of the issue. Verifying and validating the effectiveness of the corrective actions taken
Service Bulletin and Airworthiness Directives	Incorporating Service Bulletin updates; Ensuring compliance with airworthiness directives

The maintenance cost has four major drivers: availability of repair components and equipment, aircraft age, flight hours and dispatch reliability [2]. Composites have yet to reach the same standardisation of maintenance as metal structures. The widespread availability of repair components and equipment is necessary to minimise costly aircraft downtime. On top of that, because of the internal damage modes of composites, inspection practices require expensive equipment and are severely restricted by regulations. However, composite repair patches have been proven to be more efficient than metal ones, on both composite and metal structures, because its fatigue life is much better [2]. When designing these repairs, composite ageing effects must be considered, as moisture can degrade the fatigue properties of the material. Additionally, the older the aircraft, the more the material has deteriorated, meaning the required repairs will become more substantial and costly over time [61]. Lastly, a higher number of flight hours and lower values of dispatch reliability have been linked to higher maintenance costs[61]. This leaves current composite repairs more costly than metal repairs [66]. Another way to cut maintenance costs is by implementing preventive maintenance, as given in Table 6.1. With predictive maintenance, issues are detected before failure occurs, based on an analysis of sensor data. This will minimise aircraft downtime and optimise maintenance operations, as repairs can happen at the time it is needed instead of at scheduled intervals. When the data shows that certain loads or parameters were higher than normally, a part can be checked or replaced before it actually fails. Using this method, the mean time between failures will be estimated more accurately, meaning maintenance can be scheduled less conservatively. This is especially the case for the electrical engines. Currently, there are no specific maintenance regulations yet, and therefore they are required to be checked every 100 flight hours or annually, based on required internal combustion engine maintenance. However, the components of an electrical engine experience lower loads and degrade slower. However, by monitoring the temperature, rotation speed, power and vibrations, predictive maintenance data on electrical aircraft engines is built up and will aid in designing more efficient maintenance regulations and schedules. Predictive maintenance can also be taken into account in the operations. For example, if a non-critical component is expected to fail soon, the aircraft will only fly between hubs where maintenance is available. In conclusion, predictive maintenance will save costs, increase the aircraft availability and reduce unplanned schedule disruptions. The condition of the part is the baseline for protocols instead of preventive inspection intervals for non-safety critical parts. It should be noted that predictive maintenance is an addition to the mandatory maintenance checks, as they can, by current certification, not be skipped.

6.10.1. Central Maintenance Computer

The central maintenance computer, the CMC, collects maintenance data on all the systems in the aircraft. Every computer will have built-in test equipment through which it checks its own functioning. The CMC manages the supervising modules and these system tests and monitors faults and warnings in the systems. In this way, the aircraft can continuously check its own operability. The fault information history is used for maintenance purposes. The CMC also sends flight data to the FDR. The CMC manages the supervising modules, who will shut down a system in case there is an irregularity in the system indicating a loss, and the CMC sends a message to the ground stations. The more time has passed since the start of the operations, the more data will be gathered on maintenance. This means that, over time, the estimates for predictive maintenance will become more precise.

6.11. Safety by Means of Emergency Procedures

AmpAir aims to demonstrate equivalent levels of safety compared to certified aircraft. One aspect of this is having a clear and effective emergency management system, along with a ballistic recovery system that ensures occupant safety during critical situations. These measures collectively ensure the overall safety of the mission. In the following subsections, the safety objectives are explained, along with how safety is ensured in practice. Ensuring the safety of occupants is a primary objective of emergency procedures, driven by both company policies and moral considerations. The manner in which emergency situations are managed and the extent to which they can escalate greatly influence this objective. However, it is crucial to recognize that not all emergencies require an excessively cautious approach. A balanced approach that combines safety with ongoing operations is necessary. AmpAir's strategies to tackle these scenarios are shown in Figure 6.6 to Figure 6.8. The scenarios are labelled with alphanumeric identifiers enclosed in circles, allowing for convenient referencing to other scenarios. The initial condition of each scenario is represented by a rounded green square on the far left. Arrows illustrate the flow of decision-making. Non-rounded grey squares indicate action points involving AmpAir personnel or the aircraft. The yellow rhombus represent pivotal yes or no questions that influence the subsequent flow. The remaining blue rounded squares signify the endpoints of the decision-making process, providing clarity on who will continue the flight and the specific conditions triggering parachute deployment.

6.11.1. Loss of Communication and Control

The most important risk scenario is the loss of the communication and control (C2) data link. As mentioned in Section 9.1, there are numerous reasons why a C2 data link can be lost. Therefore, it is essential to thoroughly examine and ensure proper handling of this scenario. The scenario begins with the aircraft experiencing a loss of the C2 link. It then autonomously determines whether this loss is temporary interference or a persistent problem, as described in Section 9.1.2. If the C2 link remains lost, the aircraft declares a lost link state and initiates a thorough system check by the CMC to identify any additional issues. In essence, if the autopilot (AP) function operates properly, there is no need to escalate the scenario or alarm the passengers about an emergency. It is highly improbable that the autopilot will ever fail during the lifetime of the aircraft, due to the reasons detailed in Section 6.9. However, in the rare event that such a failure occurs, further action will be required.

Once an emergency has been detected, the aircraft must assess whether it can transfer full responsibility to the passenger, who serves as the Pilot in Command (PIC) during normal operations, or if deploying the parachute becomes necessary. Whether full responsibility can be entrusted to the PIC is influenced by various considerations, including the flight conditions, highway-in-the-sky (HITS) system, and the passenger's star rating. In the presence of visual meteorological conditions (VMC), it is less intimidating for a pilot with little experience to assume control. Likewise, with a properly functioning HITS system, even pilots with limited experience can effectively manage the aircraft under VMC. If VMC is not present but the HITS system is operational, a pilot with a 3-star rating is considered capable enough to assume complete control of the aircraft safely. However, if both VMC and the functionality of the HITS system are compromised according to the aircraft's assessment, only a pilot with a 4-star rating is deemed capable to handle the aircraft. If any of these conditions are met, the aircraft will alert the PIC through audio and notifications on the Primary Flight Display (PFD) to assume full command. Once the PIC confirms, they will proceed with the flight as planned. However, if the PIC, despite being considered capable enough, is unable to maintain the aircraft on the intended course, the aircraft will initiate a countdown, allowing time for the re-establishment of the C2 link connection. If the connection is successfully restored, the scenario will progress to scenario B, which involves the loss of the AP but with a functioning C2 data link. However, if the C2 link connection is not re-established within the countdown period, the aircraft will deploy the parachute.

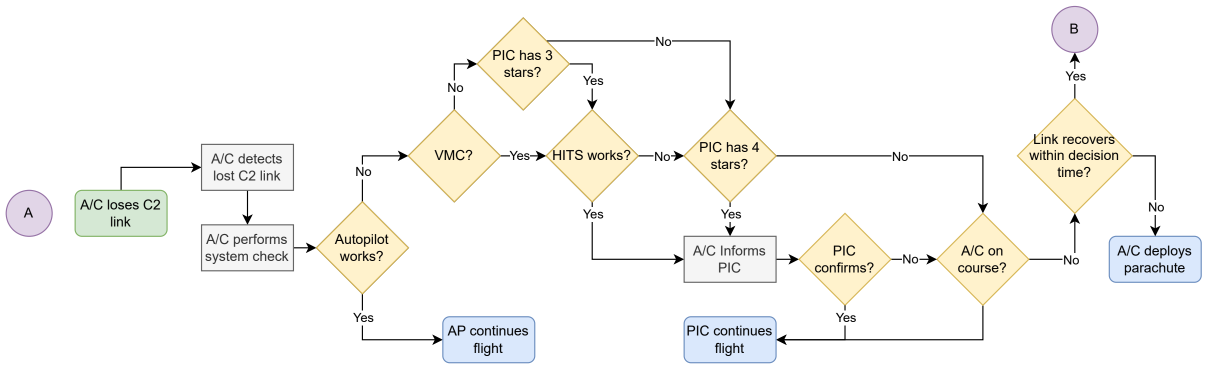


Figure 6.6: Emergency scenario: A/C loses the communication and control data link.

6.11.2. Loss or Malfunction of the Autopilot

The next significant emergency scenario involves the loss or malfunction of the autopilot (AP). Once either the aircraft (A/C) or the PIC detects issues with the AP, they notify the observer at the Remote Pilot Station (RPS) about the problem. The RPS then deactivates the AP function and establishes contact with the PIC if not already in communication. If the PIC is unreachable, the Remote Pilot (RP) assumes the role of PIC and proceeds with the flight. If the PIC responds, they undergo the same assessment process for determining their capability, as described in Figure 6.6. Regardless of the outcome, if the PIC is deemed incapable or unable to maintain the intended course, the RP assumes the role of PIC and continues the flight.

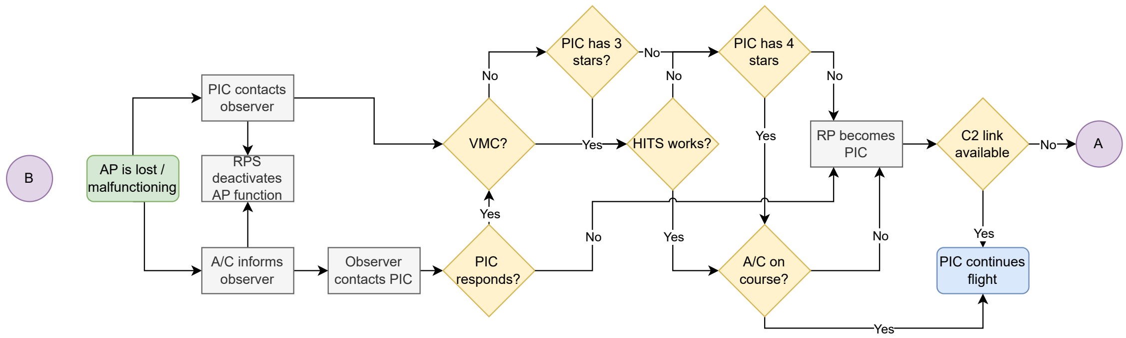


Figure 6.7: Emergency scenario: A/C loses its autopilot function.

6.11.3. Passenger-Related Issues

The following scenarios regard passenger-related issues that may arise during operations. Instances such as passengers exhibiting ill intent or situations where the PIC becomes incapacitated, for various reasons, pose significant safety risks that must be carefully addressed and prepared for.

To address these concerns, the aircraft is equipped with software that continuously generates a geo-fenced area, as mentioned in Section 6.2. This geo-fenced area is utilised by the HITS system and visually displayed on the PFD for the PIC. If the aircraft breaches the geo-fenced boundary, the AP will activate and initiate guided flight back to the designated area. It is anticipated that inexperienced pilots may inadvertently breach the geo-fenced area. This will trigger an audible alarm that requests the pilot to return. If this is not done, the AP will redirect the aircraft automatically.

The same geofencing process is employed when the PIC fails the awareness check, as mentioned in Chapter 6. The PIC serves as a safety pilot and must remain alert at all times. In case the PIC fails to meet expectations, after already having failed the awareness test, an observer will contact them to assess the situation. The observer will then determine whether the PIC is capable and permitted to continue flying. If the observer deems otherwise, the aircraft controls will be locked, and the RP assumes the role of PIC, continuing the flight with the assistance of the AP.

In the event that the C2 link is not available, the aircraft automatically locks the controls. If the AP is functional, it will independently continue the flight. However, if the AP is not available, deploying the parachute becomes the only viable solution. When both the C2 link and the AP fail, the absence of a control algorithm to safeguard against ill intent renders the situation high risk. In such cases, deploying the parachute is a last measure to ensure the safety of the passenger and their environment.

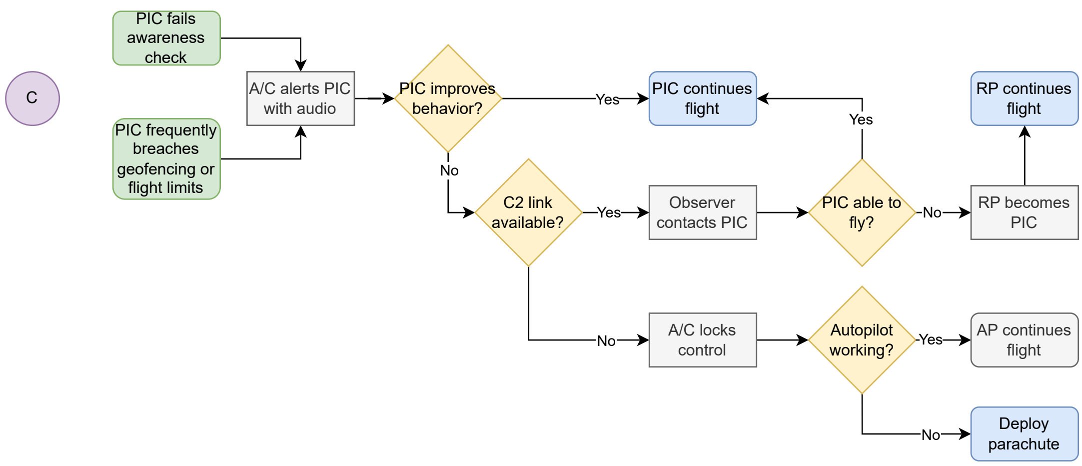


Figure 6.8: Emergency scenario: A/C loses its autopilot function.

6.11.4. Immediate Landing

The following scenario describes a situation in which the aircraft must perform an immediate landing due to passenger-related or medical reasons, or technical issues that pose a threat to passenger safety and require immediate resolution. As mentioned in Section 6.2, the flight plan for the aircraft is designed to ensure the presence of an accessible airport along the flight path. To achieve this, the flight management processor continuously monitors the database for the nearest suitable landing airport. If such an airport is within reach as expected, the autopilot will safely guide the aircraft for landing, unless the passenger pilot possesses the necessary skills, as mentioned in Chapter 6, to land the aircraft themselves. In the event that the aircraft is landing at an excessively high speed due to flap or high lift propulsion system failure, a parachute can be utilised to break the aircraft. If no airport is reachable during a forced gliding flight caused by a complete loss of propulsion, the parachute will be deployed to safely bring the aircraft and its passengers back to the ground.

6.11.5. Parachute Landing

While highly unlikely, certain scenarios, as explained in Figure 6.6, may require drastic measures to ensure the safety of occupants and people on the ground. For this reason, AmpAir aircraft are equipped with a ballistic recovery system or parachute to facilitate a safe landing during cruise in the event of mishaps. Additionally, the parachute is designed to brake the aircraft and prevent a runway overshoot if it lands with excessive velocity. This is made possible through a clever anchor point and parachute hatch design. The opening hatch is securely positioned behind the SATCOM dish and features three harnesses that extend from the hatch to three anchor points on the fuselage. One anchor point is located in the middle front fuselage section to ensure clearance with the high lift propellers, while the other two anchor points are positioned on the left and right sides of the rear opening hatch. Cirrus specifies that the parachute requires a minimum deployment height of 400 feet to ensure the occupants' survival[1]. Furthermore, if the aircraft lands at a speed 10 knots higher than the normal landing speed due to malfunctioning high lift devices or fowler flaps, as suggested in Section 6.11.4, the parachute will automatically deploy to decelerate the aircraft to a safer speed. The precise details of how the AmpAir aircraft can sense the appropriate time for parachute deployment, considering minimal collateral damage, require further in-depth analysis and are beyond the scope of this report.

6.11.6. Hijacking of Remote Pilot Station

While the scenario may appear far-fetched, there exists a tangible risk of malevolent individuals hijacking the remote pilot station, reminiscent of the events that transpired during the tragic 9/11 incident, which shook the very foundations of the aviation industry. In order to mitigate this threat, AmpAir will employ a sophisticated security system akin to those utilised by financial institutions in the present day. In the event of an attack on the RPS, trained personnel will have the capability to activate a panic button, thereby promptly alerting law enforcement authorities and severing the C2 connection linking the ground station to the aircraft. As a result, a seamless handover event will be initiated, transferring control from the compromised remote pilot station to an alternative secure facility.

[1] https://www.cirruspilots.org/Safety/CAPS

7 Aircraft Design

As the concept and operations of the AmpAir air taxi are defined, it is time to show the design of the aircraft that will be able to perform the tasks and operations outlined in Chapter 2 and Chapter 6. Firstly loading diagrams are made to define the wing and power loading in Section 7.1. Next, Class I and Class II weight estimations and iterations are described in Section 7.2. The design of the batteries is shown in Section 7.3. Next, the fuselage and cabin design is illustrated in Section 7.4. Section 7.5 discussing the wing planform and empennage design, followed by a stability analysis in Section 7.7. The landing gear design is shown in Section 7.6. Finally, the aircraft systems are layed out in Section 7.8.

7.1. Loading Diagrams

The wing and power loading diagrams are built in order to size the wing area and find the power required by the AmpAir aircraft. These can be seen on Figure 7.1. The relations used to construct the diagram are based on Roelof Vos' Aerospace Design and Systems Engineering course [95], and they express the power loading as a function of wing loading. These relations will be explained briefly below.

First, the take-off performance can be found using Eq. (7.1). Here, the take-off parameter (TOP) of the aircraft is calculated using empirical relations. For a multi-rotor vehicle with a take-off distance of 500 m, the TOP has a value of $46.021\,\mathrm{kg\,m^{-2}\,s^{-1}}$ [78]. $C_{L_{TO}}$ is the lift coefficient at take-off, which can be found by dividing $C_{L_{max}}$ by 1.21 [78]. With the effects of high-lift propulsion taken into account, the $C_{L_{max}}$ of the AmpAir aircraft is expected to reach a value of 3.5 [7, 95]. Finally, $\frac{\rho}{\rho_0}$ is the ratio of the air density at the cruise altitude of 2000 m to the density at sea level. The required power loading value, as a function $\frac{W}{S}$ of the take-off, is shown as the blue line in Figure 7.1.

$$\left(\frac{W}{P}\right) = \frac{TOP}{\left(\frac{W}{S}\right)} \cdot C_{L_{TO}} \cdot \frac{\rho}{\rho_0} \tag{7.1}$$

Secondly, the constraint from the required climb rate is give by Eq. (7.2). Here, η_p is the propulsion efficiency, ROC is the rate of climb, which follows from the CS23 constraint of a climb gradient of 8.3% [19]. Furthermore, V_{climb} is the climb speed and is assumed to be 1.2 times the stall speed[95]. C_{D_0} is the zero-lift drag coefficient, A_{eff} is the effective aspect ratio, and e is the Oswald efficiency [95]. The power loading as a function of wing loading for the climb rate requirement[1] is shown as the yellow line in Figure 7.1.

$$(\frac{W}{P}) = \frac{\eta_p}{ROC + 0.5 \cdot \rho \cdot V_{climb}^3 \cdot \frac{C_{D,0}}{\frac{W}{S}} + 2 \cdot \frac{1}{\pi A_{eff} e} \cdot \frac{\frac{W}{S}}{\rho \cdot V_{climb}}} \cdot (\frac{\rho}{\rho_0})^{\frac{3}{4}} \tag{7.2}$$

The cruise speed of 150 kts also imposes a constraint on the power loading. This constraint is given by Eq. (7.3). This relation is given by the green line on Figure 7.1.

$$\left(\frac{W}{P}\right) = \eta_p \cdot \left(\frac{\rho}{\rho_0}\right)^{\frac{3}{4}} \cdot \left(\frac{C_{D_0} \cdot \frac{1}{2} \cdot \rho \cdot V^3}{\frac{W}{S}} + \frac{W}{S} \cdot \frac{1}{\pi \cdot A \cdot e \cdot \frac{1}{2} \cdot \rho \cdot V}\right)^{-1} \tag{7.3}$$

The light red vertical line in Figure 7.1 displays the maximum wing loading due to the stall speed requirement. This is given in Eq. (7.4). V_s is the stall speed, which is constrained to be 50 kts at the highest[2]. Furthermore, the $C_{L_{max}}$ is assumed to be 3.5[7]. This results in a wing loading of at most $1418\,\mathrm{N\,m^{-2}}$. Furthermore, the landing distance can be estimated with the statistical relationship given by Eq. (7.5), where V_s

[1] REQ-TP-FPP-01: For low-speed aircraft with all engines operating, during climb a minimum climb gradient of 8.3% shall be possible (CS 23.2120).

[2] REQ-STK-USR-12: The aircraft shall have a maximum stall speed of 50 kts.

is the stall speed in ms^{-1} and s_L is the landing distance in m. At a stall speed of 50 kts, the landing distance is then approximately 391 m, meeting the 500 m constraint[3].

$$\frac{W}{S} = \frac{1}{2} \cdot \rho \cdot V_{stall}^2 \cdot C_{L_{max}} \tag{7.4}$$

$$s_L = 0.5915 \cdot V_s^2 \tag{7.5}$$

The vertical dark red line in Figure 7.1 represents the maximum wing loading for landing. This constraint is given by Eq. (7.6), where V_{land} is the landing speed and equals 1.3 times the stall speed.

$$\frac{W}{S} = \frac{1}{2} \cdot \rho \cdot V_{land}^2 \cdot C_{L_{max,L}} \tag{7.6}$$

Finally, the red curve constraining the power loading originates from the 30-minute reserve flight requirement. The power needed to fly at minimum speed is considered. After flying for 400 km, the aircraft should be able to fly another 30 minutes in case of need. This can be done at minimum speed V_{min}, which is calculated using Eq. (7.7) [92]. Once this speed is calculated, the constraint on the power loading can be found by Eq. (7.8).

$$V_{min} = \sqrt{s \cdot \frac{\frac{W}{S}}{\rho} \cdot \sqrt{\frac{\frac{1}{A_{eff}\pi e]}}{3C_{D0}}}} \tag{7.7}$$

$$(\frac{W}{P}) = \frac{\eta_p}{\frac{1}{2} \cdot V_{min}^3 \cdot \frac{C_{D0}}{\frac{W}{S}} + 2\frac{1}{A_{eff}\pi e}\frac{\frac{W}{S}}{\rho} \cdot V_{min}} \cdot (\frac{\rho}{\rho_0})^{\frac{3}{4}} \tag{7.8}$$

The design space of the AmpAir aircraft is shaded green in Figure 7.1. The design point is indicated by a red dot, and is chosen such that the wing loading would be optimised. It can be seen that the wing loading is limited by the stall speed requirement [4] and has the value of 1418 N m^{-2}. The power loading at this wing loading is limited by the take-off constraint and has a maximum value of 0.09 s m^{-1}.

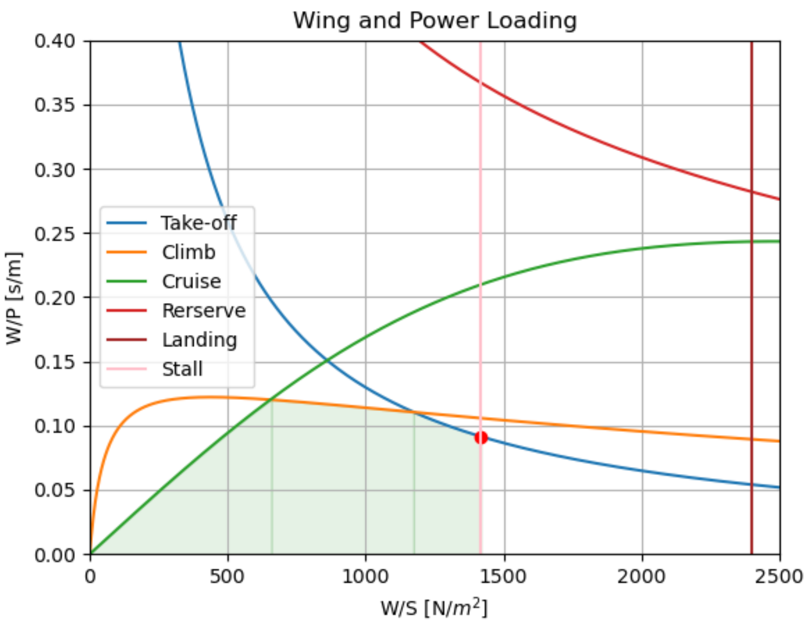


Figure 7.1: Wing and power loading diagram, showing the possible design space in the green area and the design point of the AmpAir aircraft indicated by the red dot

[3] REQ-STK-USR-11: The aircraft shall be able to take-off and land on 500 m runways.
[4] REQ-STK-USR-12: The aircraft shall have a maximum stall speed of 50 kts.

7.2. Weight Estimations

To determine the weight of the aircraft, class I and class II iterations are performed. It should be noted that this process was iterated, meaning that new information from later stages was again used for better estimations. For example, the exact mass of the motors was found in Section 8.6 and this was then used in the formulas. For Class I, a new formula is designed for electric aircraft, since conventional methods are based on fuel aircraft [81]. In general, Eq. (7.9) is used, showing that the take-off mass is the sum of the operational empty weight, the payload mass and the battery mass [97].

$$W_{TO} = W_{OE} + W_{PL} + W_{bat} \tag{7.9}$$

Here, the battery mass is also a function of the take-off weight. It is based on the required power for each phase, which is obtained from the power loading diagram. Rewriting this leads to Eq. (7.10), where the operational empty weight (OEW) already includes the motor mass.

$$W_{TO} = W_{OE} + W_{PL} + \frac{E_{climb} + E_{cruise} + E_{reserve}}{\rho} \cdot 1000 \tag{7.10}$$

This way of calculating the battery mass was described in earlier stages of the design [30].

For class II, the Raymer method is used [78]. However, a few adaptations are made to make the method applicable for electric, fly-by-wire aircraft. The component of the fuel system is removed, since there will be no fuel. Moreover, it is decided to have the furnishing made out of lighter, composite materials, meaning that a correction factor of 85% is applied to compensate for this. This is also done for the other parts of the aircraft, as described by Raymer [78]. However, since fly-by-wire will be used, there are no hydraulics for the flight controls. Nevertheless, this mass is kept, assuming that the mass of the electro motors would be similar to the mass of the hydraulics [78, 97].

Iterations are then performed between class I and class II, for which the final results of the component breakdown are shown in Table 7.1.

Table 7.1: Weight of the different components, following from the class II weight estimations

Aircraft component	Weight [kg]
Wing	230
Horizontal tail	13
Vertical tail	36
Fuselage	444
Main landing gear	137
Nose landing gear	29
Installed engines	311
Flight controls	53

Aircraft component	Weight [kg]
Hydraulics	11
Avionics	77
Electronics	78
Air conditioning and anti-ice	23
Furnishings	98
Operational Empty Weight	1540

By doing these iterations, the maximum take-off weight converges to a value of 2500 kg and the operational empty weight to 1540 kg. This is with a battery mass of 682 kg and a payload mass of 278 kg. For this, it is taken into account that the batteries come in packs and therefore the battery mass is rounded up to the closest possible pack size. For this, the range is then again optimised to a range of 403 km. The final masses are given in Table 7.2.

Table 7.2: Decomposition of the final MTOW

Aircraft component	Weight [kg]
Payload	278
Battery mass	682
Operational Empty Weight	1540
Maximum Take-Off Weight	2500

7.3. Battery Design

Within in this section, the battery placement will be decided on, together with the sizing of the batteries. This will also include an analysis of the battery performance. The battery placement is included in Section 7.3.1, which is followed by the sizing of the batteries in Section 7.3.2, which is iterated over twice in Section 7.3.3 and Section 7.3.4.

7.3.1. Battery Placement

The batteries need to be stored within the aircraft, together with its cooling system. There are different locations possible: under the cabin, in the tail, in the wings or in the nose. These options will be analysed further, while also keeping combinations of these options in mind. First, placing the batteries under the cabin has the advantage that the existing space below the fuselage floor is utilised. Moreover, it contributes to the stability of the aircraft by placing the batteries close to the centre of gravity. The biggest disadvantage of this is that there is a potential danger if the battery catches fire, since the batteries are below the passengers. This would require extra costs for a fireproof structure that separates the battery from the passengers. Another location to put the batteries would be in the tail. This option is safer, as a firewall can be designed between passengers and battery. However, the weight of the battery will shift the centre of gravity backwards, which might impose stability issues.

When the batteries are located in the wing, this could provide bending relief, allowing for a lighter wing design. The biggest advantage is the limited size. The airfoil constrains the battery shape and wing design. Moreover, when swappable batteries are considered for later stages, this would complicate the wing design even further since it should be possible then to open the wing. The batteries are also too heavy for the first stages to be put in the wing. Lastly, it is considered to put the batteries in the nose of the aircraft. Similarly to in the wings, there is limited space in the nose. When the avionics are also put in the nose, this will restrict the space even more. At the same time, due to the proximity to the avionics bay, this requires extra protection of these avionic systems. A large advantage on the other hand is that the batteries are located in front of the aerodynamic centre and shift the centre of gravity forward. This is favourable for stability. For these reasons, it is decided to put batteries both in the nose and in the tail. This way, the batteries are separated from the passengers. Also, the negative stability effects of putting batteries in the tail will be balanced out slightly by having batteries in the nose, at a larger distance from the centre of gravity (i.e. a larger moment arm).

7.3.2. Battery Sizing

Battery sizing has been made for the current design based on preliminary dimension. Electronics and cooling aspects Section 7.8.2 have been taken into account on a qualitative aspect. Current design choices have led to design liquid cooled batteries due to certification restrictions. This decision is taken considering an interview with E-Flight Academy, which gave insight on problems with certification of air cooled batteries and underdevelopment of solid state batteries. The batteries are designed such that each battery pack has a selected number of battery cells. Each battery pack is to be assembled according to design requirements to deliver sufficient power to other subsystems throughout the flight at appropriate voltage. The design of the battery unit packs and the arrangement of such is discussed in the following subsections, based on 2 iterations made. The first iteration was performed before the design of the power subsystem and required power is made. This iteration focused on the optimisation of batteries based on the design choice in Section 5.2.2 and sizing accordingly to volume available within the fuselage of the aircraft to minimise aft shift of the centre of gravity due to batteries.The second iteration was performed due to evaluation of individual cells discharge current. During the first iteration, since volumetric extrapolation is used, the performance of the cells is not estimated, thus left to do at the end for certain power required. Once these values are obtained, the discharge current is well beyond the expected range of discharge current for batteries. A second iteration consisted of reducing the battery volume of the cell back to standard sizing, thus minimising the required discharge current per cell. This second iteration caused a reshape in the unit packs to optimise voltage and current outputs. Both iterations are described within Section 7.3.3 and Section 7.3.4.

The batteries are divided into different groupings to obtain required voltage and current for different phases of the mission (Section 2.2), which would comply with the power required for each mission phase. Each battery system is divided into groups of batteries, which contain an array of unit packs per group. All groups contain the same number of unit packs, which are connected in series to raise the current to the required system current to deliver sufficient power. On the other hand, the groups are connected in parallel to each other to match the voltage of the unit pack to the voltage output of the system. The design of the batteries is then based on a unit pack design, which contains a constant number of unit cells. These cells are limited in voltage and current, thus to maximise efficiency of cabling, the current output is minimised while maintaining a small ratio between voltage and current. The unit packs are then designed by dividing the cells per unit pack in 3 blocks of battery cells. The number of battery cells per block is chosen to be 22, which is originally chosen for sizing reasons for better packing in the fuselage. Thus, the unit pack arrangement of cells is determined to be 22 cells and 3 blocks per unit pack.

The design of battery cells is based on an extrapolation of current battery cells. The first cell is extrapolated based on the battery energy density taken for design of $450\,\mathrm{W\,h\,kg^{-1}}$. As seen in Figure 7.2, the cells sizes have increased over increased energy density. Battery cell 4680[5], displayed in dark blue, has an energy density of $224\,\mathrm{W\,h\,kg^{-1}}$, which is currently reaching the maximum energy density of state-of-the-art batteries. Battery cell 4860 is currently being used in the automotive industry and has gained reputation for reliability, giving an indication on development of battery cells. This lithium-ion cell trend shows that for an increase in energy density, the battery size increases with a ratio of $2.1 \times 10^{-6}\,\mathrm{m^3\,kg\,W^{-1}\,h^{-1}}$. In order to estimate the cell size for a battery energy density of $450\,\mathrm{W\,h\,kg^{-1}}$, a linear extrapolation from the data is taken, which gives a size shown in Figure 7.2 by the red dot. The first battery dimensions are determined to be 75 mm by 130 mm. For the second iteration, a reduction in battery size is needed to reduce the cell discharge current. Thus, an interpolation value is taken based on current state-of-the-art battery technology. The value considered, reduces the current to a maximum of 25 A to match the realistic performance of current cells such as the 4860[6]. Based on the first iteration, the power required can be used as input for sizing of the batteries and by selecting a cell size similar to current cell sizes, the current can be maintained within the realistic region. This results in a size of a cell of 40 mm by 65 mm.

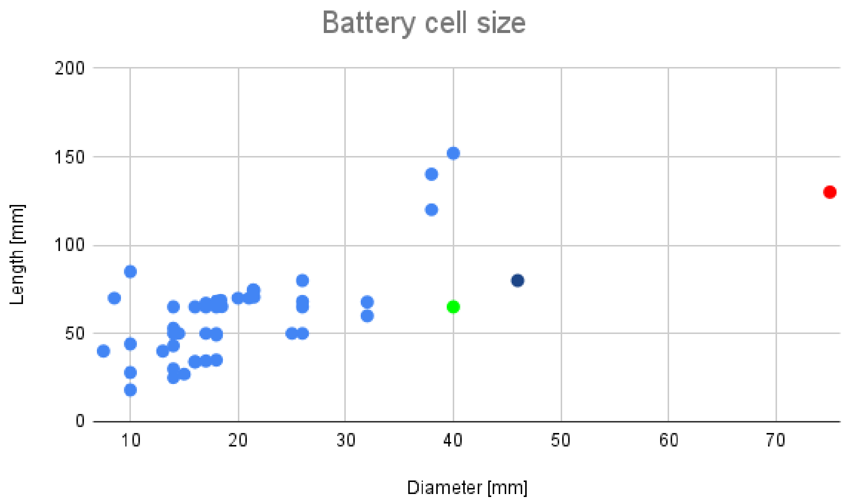


Figure 7.2: Battery cell size for different battery technology

In Figure 7.2 base on data from different rechargeable lithium-ion battery size[7], the red dot represents the cell size of the first iteration. The green dot, the cell size of the second iteration and the dark blue dot represents Tesla's 4860 battery. [8]

7.3.3. First Iteration of Battery Sizing

For the first iteration, the 76×130 mm cell size selected is limited to a voltage output of 3.8 V from the chemistry values of lithium-ion cells[9]. The discharge current is then limited to a maximum of 3C. Firstly, from the battery energy chosen by design combined with the volumetric energy density, the mass required for the batteries in known from which the volume required is known. Thus, from the cell volume and required volume, the number of cells in known. These cells are then divided equally into unit packs in the arrangement described in Section 7.3.2. The arrangement of such packs is then based on the power requirements during the mission. In order to satisfy the power required from the mission as given from the distribution propulsion results (Table 8.6), the unit packs are arranged to deliver power at a limited current while maximising voltage

[5] https://www.notebookcheck.net/Tesla-4680-vs-2170-battery-cell-test-reveals-lower-energy-density-in-the-Texas-made-Model-Y.669162.0.html

[6] https://www.youtube.com/watchv=4XOHetABrag

[8] https://www.xtar.cc/news/List-of-Lithium-ion-Battery-Sizes-and-Uses-158.html

[9] https://www.batteryjunction.com/battery-chemistry-guide4.html

to minimise wire loss. The schematic of battery arrangement is shown in Figure 7.3.

Table 7.3: 75x130 mm cell battery system performance

	Voltage [Volts]	Continuous current [A]	Peak current [A]	Total energy [Wh]
Cell	3.8	47.6	158.1	387.7
Unit pack	83.6	61.5	474.5	25586.1
System	501.6	123.1	949.1	307032.8

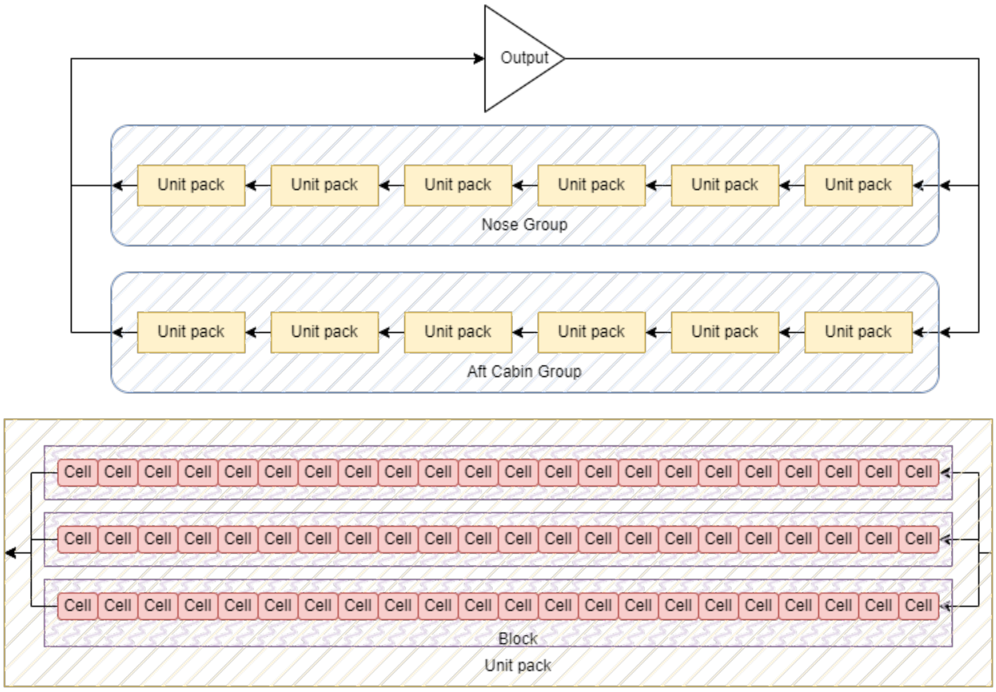


Figure 7.3: Battery schematic for the first iteration

As seen in Table 7.3, the peak currents are very high for each individual cell. This result is considered to be too excessive to be acceptable when compared to current battery cell technology. Furthermore, the battery pack, which is expected to be handled in the case of dealing with swappable batteries, voltages above 50 Volts can be considered life-threatening[10]. Even if the battery system is designed for DC current, the team seams

7.3.4. Second Iteration of Battery Sizing

This subsection contains the results from a secondary iteration made. The reason for this iteration is the high discharge current required as seen in the first iteration. The aim of this second iteration is to make it much more realistic by reducing the discharge current of individual cells.

The battery cells for this iteration have been approximated by decreasing the size of them, which is in contrary of how battery development is currently showing. However, the new size of 40 mm by 65 mm is currently much more realistic to battery sizes of today. Once again, the unit pack is kept with the same number of cells in total. However, the internal structure of the unit pack has doubled the number of blocks as well as halved the number of cells per block. Modification of the total number of cells required due to the decrease in cell volume led to a number of total packs to increase to 84. To maintain the voltage loading of 500 Volts, the packs are arranged in 7 groups connected in parallel, by 12 unit packs per group connected in series. With this, the unit packs only require outputs of 41.8 Volts and current output can be limited to 40.8 A

[10]https://www.pat-testing-training.net/articles/electric-shock.php#: :text=Exposure%20to%20voltages%20less%20than,450V %20a.c.%20are%20especially%20dangerous.

for constant discharge rates and 135.5 A for fast discharge rates. Furthermore, unit cells are no longer loaded with heavy current discharge. Voltage output of the cell remains at 3.8 V and current can vary from 6.7 A to 22.6 A for peak current. This is a significant reduction of current per cell, which makes the battery design process more realistic and closer to current performing battery values.

As an overview, the battery arrangement diagram is given in Figure 7.4 showing the updated arrangement due to changes made in this second iteration.

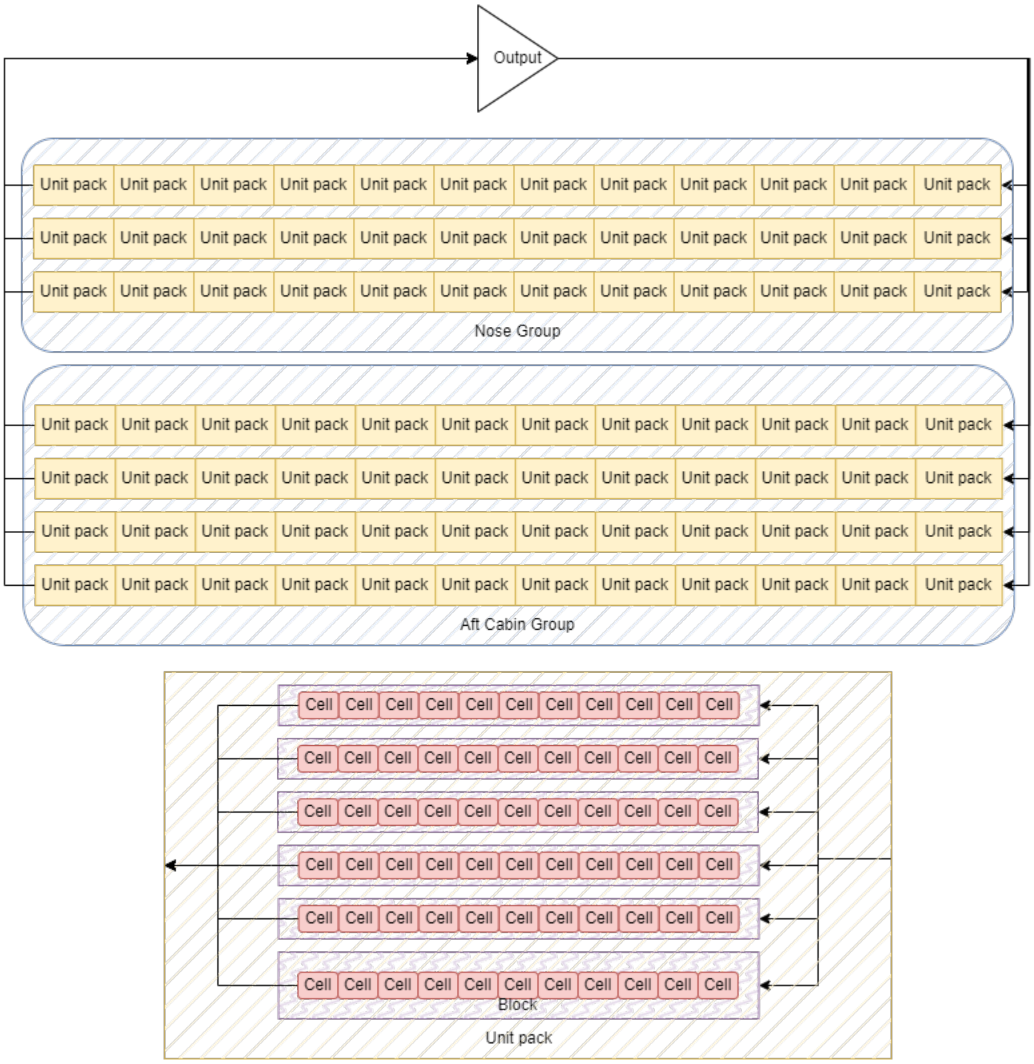


Figure 7.4: Battery schematic for the second iteration

Table 7.4: 40x65 mm cell battery system performance

	Voltage [Volts]	Continuous current [Amps]	Peak current [Amps]	Total energy [Wh]
Cell	3.8	6.8	22.6	55.3
Unit pack	41.8	40.8	135.5	3639.1
System	501.6	285.33	949.1	307032.6

By decreasing the cell's discharge current, the battery life has been significantly increased, as well as the stability of each cell. Current leakage leading to possible thermal runaway is reduced, which increases safety. Further analysis can be made on the design to ensure effects of battery due to increase in temperature and operational limits of the cells.

Some final remarks on the structural aspects of the battery, the unit pack is individually contained in a metallic structured coated with an electrical sealant polymer. Their packs have a positive and a negative terminal that are connected to the structure of the aircraft in a fitted order on the aircraft. Since the unit packs are the same sizes, they can be fitted in any of the allocated spots. The allocated battery space in the aircraft are such that the structure is able to be hold in place. This structure is to be tested in the future for operational load factors and vibration analysis. Within the unit pack, the blocks are kept constant to simplify the inside structure of the battery. Unit pack design also allows for liquid or air cooling of the batteries due to the spacing factor between cells that taken into account. However, cooling line implementation is not currently implemented into battery design. This concludes the preliminary design of the batteries.

7.4. Fuselage and Cabin Design

Based on the design choices detailed in Chapter 3 , Chapter 5, as well as previous findings regarding cost [30], it was decided to design a five-passenger cabin. In doing so, first the preliminary sizes of seat boxes were obtained [95] in order to estimate the placement of passengers as well as the overall form factor. For most parameters, business class values were selected in order to ensure a good fit to the target market.

First, a choice was made between a 2-2-1 and 2-3 seat cabin layout as detailed in previous design [30]. Both configurations present some benefits and drawbacks. The 2-2-1 row layout allows for a narrower fuselage, thus reducing wetted area and making the overall fuselage more aerodynamically optimised. However, if implemented in a separated concept, meaning a design with separate doors per row, this layout can decrease passenger travel comfort as one person would have to sit separated from the rest of the group. The 2-3 layout, on the other hand, aims to solve this issue, and as is also used in similar aircraft, such as the Diamond DA62[11] and Cirrus SR22[12]. These tend to resemble a conventional passenger car in terms of layout, with a cramped middle seat in the rear row. However, to suit the objective of a comfortable and spacious cabin, the 2-2-1 layout was selected such that all seats offer sufficient room for a comfortable trip. However, to combat the drawback of the separation of one passenger, as well as to offer the possibility of having only a single door, the layout uses a small dropped aisle through the middle, enabling access to all seats. A split layout is opted for regarding the door, allowing its lower part to function as a step-up into the cabin in order to increase the ease of entering. The top part will separate the passenger from the propellers on entering and disembarking the aircraft. Furthermore, to ensure no passenger ever comes into contact with a propeller, a system shall be in place to make sure the high-lift propellers are in a horizontal position when the aircraft is parked. Opposing the door, on the other side of the fuselage is a smaller rectangular emergency exit, sized according to CS23 regulations, therefore being 48 cm by 51 cm [19]. Moreover, there is also a fire extinguisher included onboard under the right pilot's seat. With this seat as an exception, all seats offer a space underneath for the passenger behind to store any belongings.

This aisle has a width of 0.33 m and the seat width is 0.69 m, including an armrest width of 0.05 m on each side. The seat pitch between the middle and last row is based on an average European passenger dummy with a weight of 80 kg, and is 0.90 m. The seat pitch between the front row and middle row is a bit larger, and the seat pitch for the front row to the cockpit is 1.15 m. A top view of this layout is shown in Figure 7.5, as well as a side view in Figure 7.6. It must be noted that while initial sizing and the layout selection was based on the preliminary seat boxes, this was later replaced by using the ergonomics features that are built into CATIA. For this purpose, a French male passenger weighing 80 kg was put into every seat, after which some iterations were performed to reduce the fuselage wetted area where possible. CATIA automatically scales the length and width of the passengers after the specified weight, and should as such be more accurate than initial seat boxes. Despite this, the seats are kept relatively roomy in order to appeal to the addressable market.

Furthermore, passengers are able to store their luggage on either side of the rearmost passenger, depicted in Figure 7.5 and Figure 7.6 by the yellow boxes. From empirical relations, a luggage volume requirement on 0.59 m^3 [95]. The depicted boxes offer a total luggage volume of 1.066 m^3, thus offering more than enough space, part of which is under the seat of the second row of passengers. Having this bit of luggage below the seat allows keeping the compartments next to the rearmost passengers relatively low such that they can still has good visibility towards the sides. This is important in order to ensure a comfortable and spacious feeling experience. In order to further make sure it's a comfortable experience for the rearmost passenger, some luggage retaining measures shall be in place, such as a simple belt to restrain all belongings. Furthermore, some folding covers or tables may be considered in the future to separate the passenger from the luggage

[11] https://www.diamondaircraft.com/en/private-owners/aircraft/da62/overview/
[12] https://cirrusaircraft.com/aircraft/sr22/

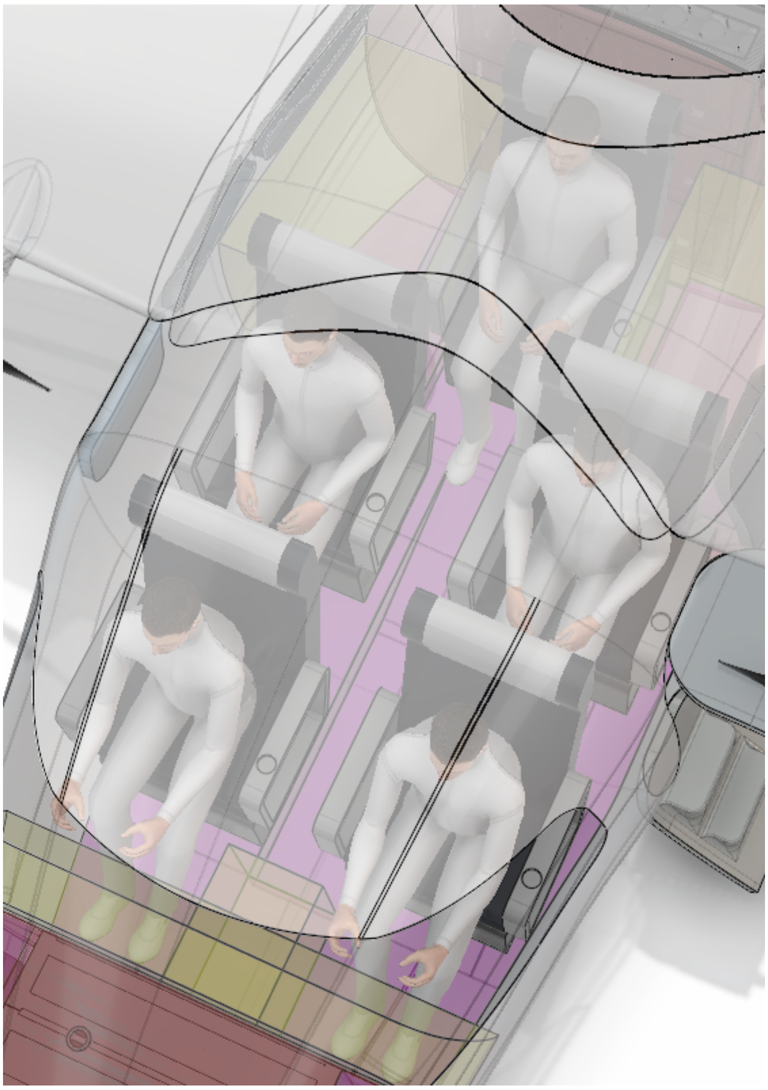


Figure 7.5: A top view of the selected cabin layout.

itself.

In total, twelve battery modules are located in the fuselage. Each battery pack has the same dimensions, a CAD-model of which is shown in Figure 7.7.

For stability reasons, it is preferable to have the batteries in the most forward positioning possible. Using the initial fuselage layout, a side view of which is shown in Figure 7.6, it is decided that six battery modules will fit in the nose. The remaining six are placed behind the last row and cargo compartment. It should be noted that because of a reduction in battery pack size from initial estimates, further iterations may reduce the size of the empennage, as well as the width of the nose. This can both have a positive impact on the zero-lift drag coefficient, to which a strong performance relation has been identified. In order to charge the batteries, two charging ports are included on the lower empennage, one on either side for ease of operation.

The shape of the nose cone is chosen such that it fits around the six battery modules placed in the nose. Furthermore, enough space is maintained for the nose wheel to retract, as well as to house a weather radar and other avionics bays on either side of the battery packs. In order to ensure a small nose cone, the nose wheel rotates by 90 degrees to lay flat in the retracted position, thus taking up space more efficiently. The cockpit window is designed to have sufficient line of sight for the passengers sitting in the cockpit in any direction. This line of sight is chosen to be larger than required, which makes it more pleasant for less-experienced pilots to fly the aircraft. The line of sight, as experienced by the pilots, is shown in Figure 7.6.

The shape of the tail cone is based on literature, and is chosen to have a length of 2.5 times the maximum width of the fuselage [95]. The tail cone includes an aggressive up-sweep angle to account for the minimum

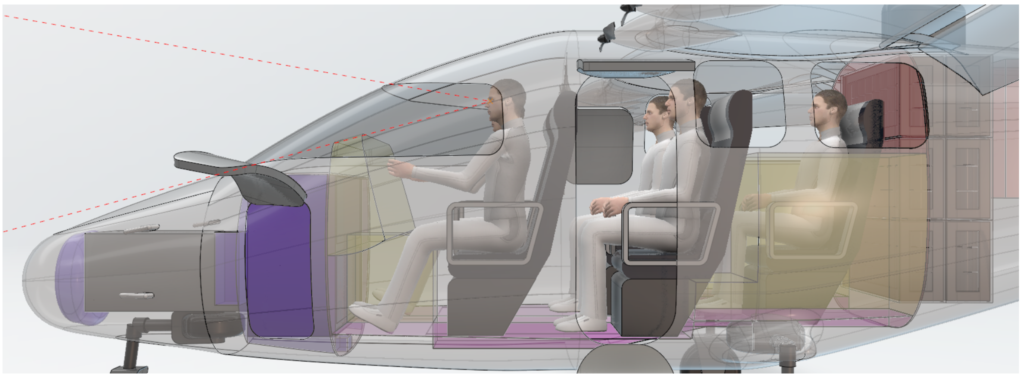


Figure 7.6: A side view of the selected cabin layout, line of sight shown as well, the look-up angle being $10°$ and the over-nose angle $15°$.

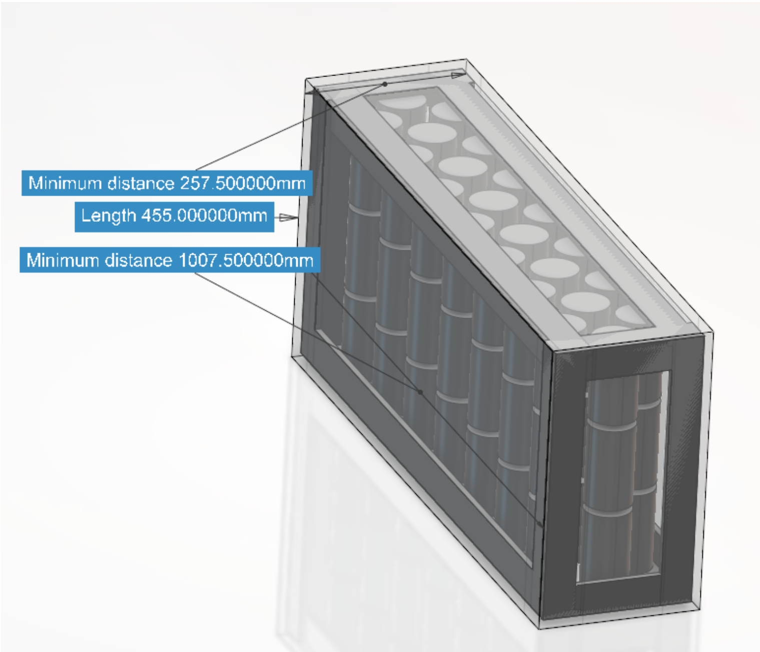


Figure 7.7: Visual representation of one battery pack, including its dimensions, first iteration.

allowable scrape angle of $15°$. This up-sweep will reduce the need for the landing gear to include longer struts, thus saving weight and space in the cabin. Furthermore, the cabin floor under the luggage departments is partially raised by 100 mm. Longer struts would force a similar raise under the rearmost passenger, thus increasing the size of the aircraft altogether. The geometry of the fuselage is presented in Table 7.5, including the length (l_{fus}), width (W_{fus}) and height (H_{fus}).

Table 7.5: Fuselage geometry as measured from the CAD-model.

Parameters	Fuselage
l_{tot}	9.23
$l_{nosecone}$	3.24
$l_{tailcone}$	5.10
W_{fus}	2.07
H_{fus}	1.93

The ballistic parachute, as well as a large portion of the battery packs are stored in the rear of the fuselage. Due to the nature of these systems, some space is left between them, which reduces packaging efficiency but increases safety.

7.5. Wing Planform and Empennage Design

The initial sizing of the wing planform and empennage is done to obtain preliminary estimates used for further design iterations. The wing planform design and empennage design are presented in Section 7.5.1 and Section 7.5.2, respectively. Later, in the stability analysis described in Section 7.7, a more accurate empennage design will be created based on a scissor plot analysis.

7.5.1. Wing Planform Design

In the previous design stage, it was chosen to design a high wing to accommodate the propellers and to create enough clearance from the ground and debris. Additionally, the high wing improves stability, creates better visibility and a reduced ground effect [30]. For structural reasons it was chosen to not put the wing through the fuselage fully on the top either, but to still keep it high. The wing planform design is obtained for the design point with a MTOW of 2500 kg. The geometry and parameters of the wing planform design for the new MTOW are calculated using simple geometry and historical data [78, 91, 96], and presented in Table 7.6[30].

Table 7.6: Wing planform design for the chosen design point

Parameters	Wing Planform AmpAir
$MTOW$ $[kg]$	2500
W/S $[-]$	1418
AR_{geo} $[-]$	12
AR_{eff} $[-]$	17.5
S $[m^2]$	17.3
b $[m]$	14.4
c_r $[m]$	1.71
c_t $[m]$	0.69
MAC $[m]$	1.27
Λ_{LE} $[°]$	2.0
$\Lambda_{c/4}$ $[°]$	0
λ $[-]$	0.4
Γ $[°]$	1
t/c $[-]$	0.18

Due to the high wing loading (W/S), the wing is smaller than that of aircraft which do not use distributed propulsion. The effective aspect ratio (AR_{eff}) is assumed to be 17.5. This value is based on literature for distributed propulsion [87], using a possible rise of over 70%. The wing will have a $0°$ quarter chord sweep angle as the aircraft will be flying at low-speeds, which means there is no need to account for transonic performance [95]. The dihedral is calculated for a high wing configuration, which is chosen for the design [30].

7.5.2. Empennage Design

A conventional tail was chosen in the previous design stage [30]. The design of the empennage is based on preliminary design data and empirical data of comparable aircraft [81]. From this data, an average for the volume coefficients are found to be $\bar{V}_h = 0.086$ and $\bar{V}_v = 0.075$ for the horizontal and vertical stabiliser, respectively. With these coefficients, a volumetric estimate of the most aft centre of gravity position ($X_{CG_{aft}}$) and an initial placement of the empennage, it is possible to size the empennage using simple geometry and formulae from literature [95]. The characteristics of the initial sizing of the empennage are presented in Table 7.8.

A tail volume of 0.086 and 0.04 were taken for the horizontal and vertical stabiliser respectively. A $X_{CG_{aft}}$ of 4.016 was used for the preliminary design. The values for the sweep $\Lambda_{c/4}$, taper ratio λ and AR are chosen to be the average of the usual range for these parameters [95]. As is presented in Table 7.8, the vertical tail volume coefficient is lower than the average of comparable aircraft. This new volume coefficient is assumed to be lower, because $X_{CG_{aft}}$ will most likely move forward significantly. This is because the value for this parameter was initially assumed to be a volumetric estimate, which does not take into account specific subsystem weights. Additionally, the decision to have a smaller vertical stabiliser is justified by the fact that the ability to do yaw control is improved due to using distributed propulsion. Finally, a NACA0012 airfoil is used for both horizontal and vertical stabiliser. This airfoil is used commonly in other aircraft [16]. The initial values used for the stability assessment are presented in Table 7.8, these are not final and are subject to iterations in the stability analysis, making use of scissors plots and a more detailed design data.

7.6. Undercarriage Design

The aircraft needs support of an undercarriage to ensure the landing- and static loads will not damage the aircraft. These loads are carefully transferred into the aircraft's structure by making use of landing gear. The undercarriage also ensures good steerability and braking performance of the aircraft, which are important performance parameters. The undercarriage is designed using CS23 certification [19] and methods covered in aircraft design lectures by Roelof Vos [95].

7.6.1. Gear configuration

In a previous stage of the design, it was decided to install tricycle landing gear with a nose wheel, mostly for ease of operation and stability reasons [30]. In the further determination of the gear configuration, several parameters are considered. Those are the number of wheels, the number of struts for the main landing gear and the possibility of the landing gears being retractable. A retractable system was chosen to reduce the parasite drag of the aircraft. The contribution of parasite drag due to fixed landing gear would reduce the range of the aircraft significantly [31]. The aerodynamic efficiency of the retractable gear therefore outweighs the added weight and complexity that it provides.

Additionally, initial CAD estimates show that there is sufficient space available to store the main landing gear in the fuselage, and the nose wheel in the nose, under the battery packs. Furthermore, according to CS-23 [19], the aircraft must have one nose wheel and two wheels in the main landing gear. The main landing gear must consist of two struts [95].

7.6.2. Tyre Characteristics

The characteristics of a tyre strongly depend on the surfaces it is designed to land on. AmpAir aims to land on hard grass and paved surfaces, this leads to a desired tyre pressure of 310-410 kPa. Furthermore, the static load of the landing gear is an important parameter for the determination of the landing wheel size.

$$P_{static} = \frac{frac_{load} \cdot m}{N_{wheels}} \tag{7.11}$$

Eq. (7.11) gives an equation to calculate the static load of a landing gear wheel. This equation is valid for both nose and main landing gear wheels. The steerability and braking performance of an aeroplane depend on the percentage of the MTOW that is loaded on the nose wheel, which should be at least 8%, to make sure the aeroplane is steerable, and 15% maximum, to make sure the aeroplane can still brake. AmpAir opted for 15% since the steerability of the aircraft is important as the aircraft might land in less spacious areas.

Table 7.7: Landing gear parameters

(a) Landing gear static loads

Variable	Value	Unit
P_{nw}	375	kg
P_{mw}	1062.5	kg

(b) Landing gear wheel dimensions

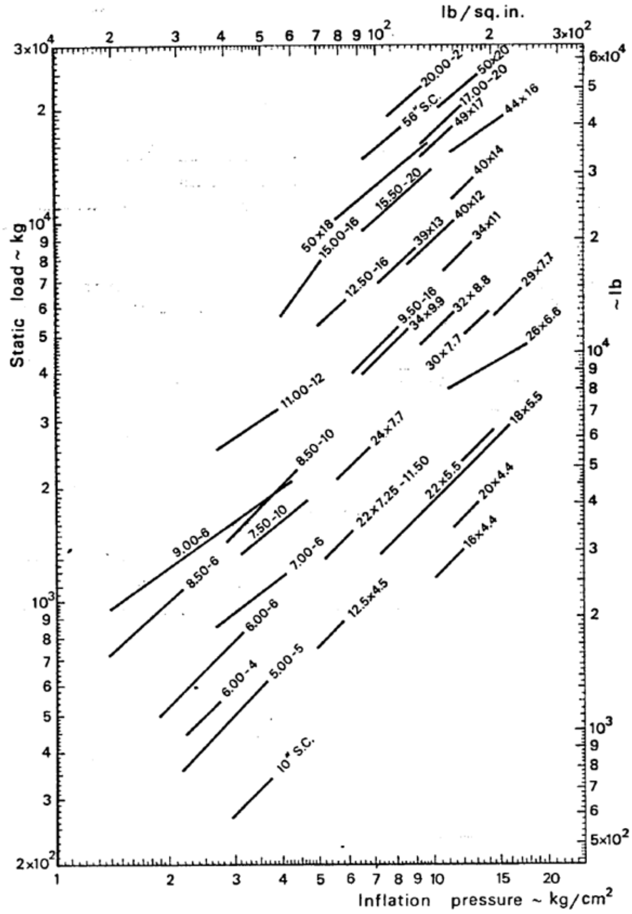
Tyre type	Diameter	Width
Nose	13.25 inch	5 inches
Main	16.323 inch	6 inches

The characteristics that are defined above can be used to size the landing gear wheels with Figure 7.8a. The nose wheel is found to be 5.00-5 and the main wheels 7.00-6. The dimensions of the rubber plus rim were found by selecting a wheel in the Boeing shop [2] . The dimensions of the whole wheel were found to be as shown in Table 7.7b.

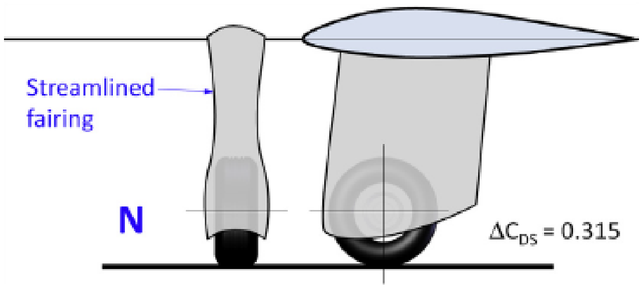
7.6.3. Parasite drag increase fixed landing gear

Fixed landing gear would cause extra drag during the entire flight phase. The selection of the most aerodynamic landing gear fairing, in order to reduce the C_{D0} as much as possible, can be calculated. The addition

[2]https://shop.boeing.com/aviation-supply/p/070-306-0=3T



(a) American wheel sizing graph [95]



(b) Landing gear configuration [32]

Figure 7.8: Wheel sizing

in drag is given by Equation (7.12), where d is the diameter of the tyre, w is the width of the tyre, S_{ref} is the reference area, C_{D_S} is the specific contribution of the gear configuration.

$$\Delta C_{D_{fixed}} = \frac{(d \cdot w)}{S_{ref}} \cdot C_{D_S} \tag{7.12}$$

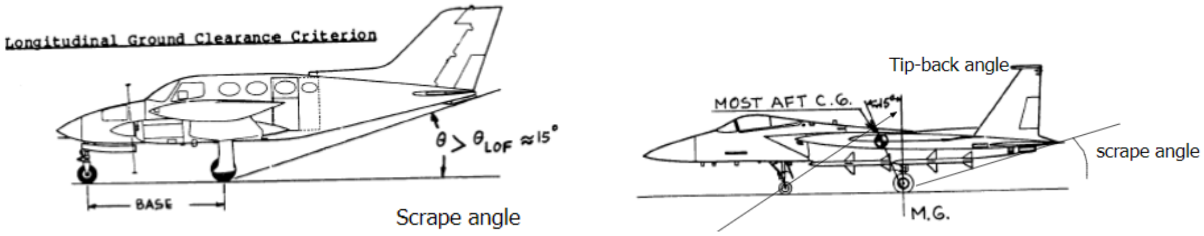
This means when the $\Delta C_{D_{fixed}}$ is to be minimised. When the tire size and S_{ref} are assumed to stay the same, minimising $\Delta C_{D_{fixed}}$ is done by choosing the gear configuration with the smallest C_{D_S}. This is the configuration in Figure 7.8b.

The dimension of the wheels, the gear fairing configuration and the reference area would lead to an ΔC_{D0} of 0.0031. This is a huge increase of the C_{D0}. As discussed in Section 7.6.1, this is a significant increase in parasite drag. Therefore, the choice of using retractable landing gear is justified.

7.6.4. Undercarriage Position

With the undercarriage's number of wheels, struts and wheel dimensions now having been defined the next step is to determine the location of these components. These locations depend on several operating phases. The most important phases and their criterion will be discussed. The first design criterion is the scrape angle of the aircraft tail. This scrape angle is important as the tail of the aircraft should not scrape the runway (tail strike), this could possibly cause significant damage to the aircraft tail. Repairing the damage from tail strikes can also be very expensive[13]. Figure 7.9a gives an indication of the minimum scrape angle, furthermore it indicates how the scrape angle should be measured to ensure it is satisfied.

[13]https://www.boeing.com/commercial/aeromagazine/articles/qtr_1_07/article_02_1.html#:~:text=Tail%20strikes%20can%20cause%20significant%20damage%20to%20the%20pressure%20bulkhead,Tail%20strikes%20are%20expensive%2C%20too

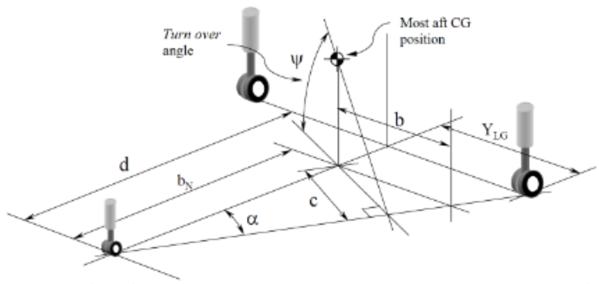


(a) Aircraft scrape angle [95]

(b) Tip-back angle

Secondly, the undercarriage must be positioned in such a way that the aircraft will not tip over (longitudinal stability). This criterion can be ensured by making sure the tip-back angle is $15°$ or larger than the scrape angle. Figure 7.9b gives an indication of how this criterion should be satisfied.

Thirdly, the undercarriage must ensure the aircraft will not tip-over during cornering (lateral stability). This is ensured making use of Figure 7.10.

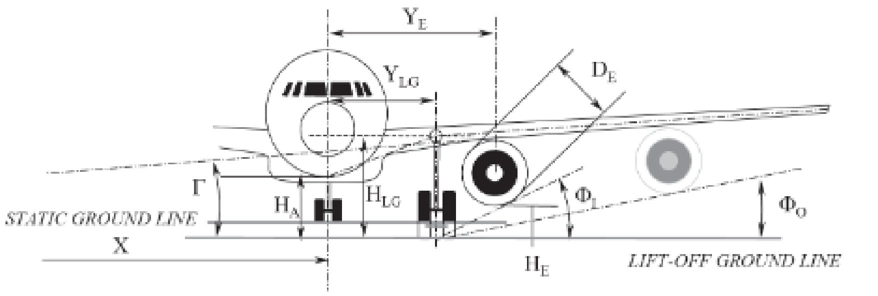


$$\alpha = \arctan\left(\frac{Y_{LG}}{d}\right) \qquad c = b_N \cdot \sin\alpha \qquad \Psi = \arctan\left(\frac{Z_{CG}}{c}\right)$$

$$\psi < 55°$$

Figure 7.10: Lateral stability of undercarriage

Finally, the undercarriage should be positioned in such a way that tipping over 5 degrees laterally to each direction will not result in the propellers hitting the ground. This criterion can be checked by verifying the Φ_1, Φ_0 and Γ values are satisfied.



$$Y_{LG} = (1+\varepsilon)H_{LG} \qquad H_E + D_E = (X + Y_E)\tan\Gamma \qquad H_A = H_{LG} - Y_{LG}\tan\Gamma$$

$$H_{LG} = (X + Y_{LG})\tan\Gamma \qquad H_E = (Y_E - Y_{LG})\tan\Phi_I$$

$$\Phi_I > 8° \qquad \Phi_O > 5° \qquad 3° < \Gamma < 7°$$

Figure 7.11: Propeller clearance undercarriage

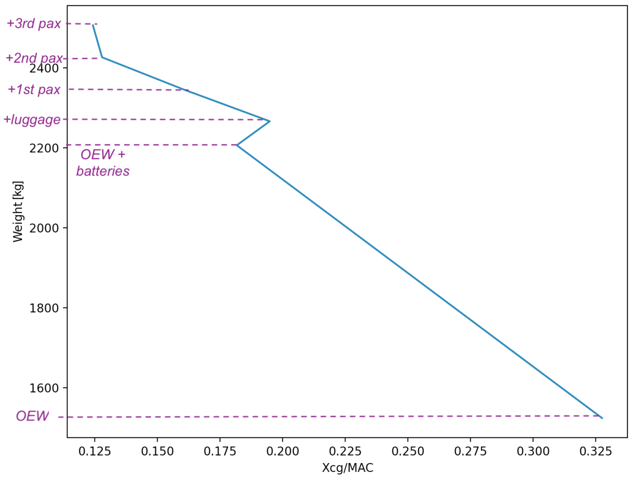
This led to a position for the nose landing gear at 0.62 meters from the nose and a position for the main landing gear of 4.72 meters.

7.7. Stability Analysis

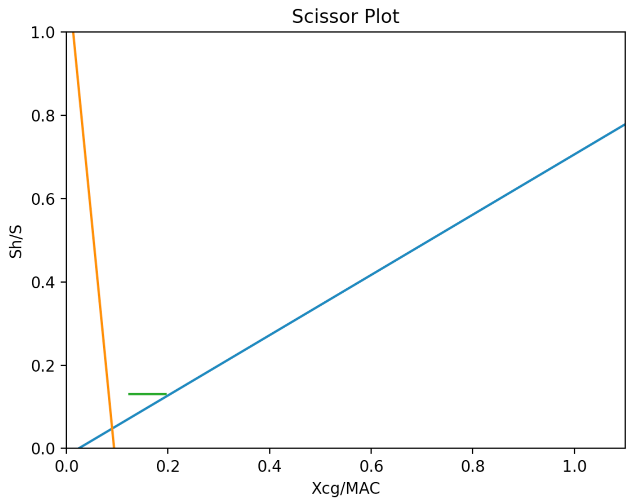
After the preliminary sizing and placement of fuselage, wing, batteries, landing gear and empennage and a more accurate OEW from Class II weight estimation, a stability analysis on the aircraft is performed. Section 7.7.1 and Section 7.7.2 show an analysis of the potato diagrams and scissor plots, respectively.

7.7.1. Center of gravity range

A potato diagram, used to visualise the center of gravity range, is created for different loading conditions of the aircraft. This is done for the case where there are 3 passengers flying with 60 kg of luggage in total. The diagram is shown in Figure 7.12a. As the batteries are not included in the OEW, they are also shown in the diagram. The aircraft will not fly with only the front batteries loaded or only the aft batteries loaded, as this is unnecessary and would create a wide c.g. range, requiring a bigger tail surface. This is the reason why adding the batteries is shown as one line in the diagram, instead of two. In case of battery advancements, where also more payload can be taken, the new batteries can be distributed differently over the front and aft compartments to fit the c.g. range. Therefore, if the battery placement is adapted, the potato diagram should be updated accordingly. Also, when swappable batteries are implemented, it is advised to always load the front batteries first. However, as said, for this a new analysis should be performed. After the batteries, the luggage is added. The loading sequence of the passengers is defined as going from front to back, as one of the passengers will always be the pilot, and the seats in the front are more preferred than the back seat. Officially, from the diagram, an aircraft flying without batteries would give the most aft c.g., however this will never occur. Therefore, the most aft c.g. is achieved when only luggage is loaded. The most forward c.g. is created when all three passengers are seated in the aircraft. This led to a c.g. range of 3.78 meters from the nose to 3.87 meters from the nose. This was compared with the location of the landing gear and it was concluded that, with this c.g. range, the aircraft will not tip over.



(a) Potato diagram showing the shift in c.g as the aircraft is being loaded



(b) Scissor plot showing the stability (blue) and controllability (orange) curves of the aircraft. The c.g. range is also indicated in green.

Figure 7.12: Stability diagrams

7.7.2. Scissor Plots

In Figure 7.12b, the created scissor plot is given, showing the stability curve and controllability curve of the aircraft. These show the tail surface to wing surface ratio in terms of centre of gravity (in terms of MAC). The equation[95] used to plot the stability curve with a 5% margin is:

$$\frac{S_h}{S} = \frac{1}{\frac{C_{L\alpha_h}}{C_{L\alpha_{A-h}}}\left(1-\frac{d\epsilon}{d\alpha}\right)\frac{l_h}{\bar{c}}\left(\frac{V_h}{V}\right)^2}\bar{x}_{cg} - \frac{\bar{x}_{ac}-0.05}{\frac{C_{L\alpha_h}}{C_{L\alpha_{A-h}}}\left(1-\frac{d\epsilon}{d\alpha}\right)\frac{l_h}{\bar{c}}\left(\frac{V_h}{V}\right)^2} \tag{7.13}$$

Where $C_{L\alpha_h}$ is the lift curve gradient of the tail, and $C_{L\alpha_{A-h}}$ is the lift curve gradient of the aircraft without tail, both evaluated using the DATCOM method. $\frac{d\epsilon}{d\alpha}$ is the wing downwash gradient and calculated using the wing aspect ratio. l_h is the distance between wing and horizontal stabiliser aerodynamic centre. The speed ratio $(\frac{V_h}{V})^2$ is 0.85 for a conventional empennage. The aerodynamic centre $\bar{x}_{ac}$ is estimated by adding the wing aerodynamic centre, the destabilising fuselage contributions, and nacelles contributions.

The equation used to plot the controllability curve is:

$$\frac{S_h}{S} = \frac{1}{\frac{C_{L_h}}{C_{L_{A-h}}}\frac{l_h}{\bar{c}}\left(\frac{V_h}{V}\right)^2}\bar{x}_{cg} + \frac{\frac{C_{m_{ac}}}{C_{L_{A-h}}} - \bar{x}_{ac}}{\frac{C_{L_h}}{C_{L_{A-h}}}\frac{l_h}{\bar{c}}\left(\frac{V_h}{V}\right)^2} \tag{7.14}$$

The moment coefficient about the aerodynamic centre $C_{m_{ac}}$ is calculated by adding wing, fuselage, flaps, and nacelles contributions for the low speed case, as this is the most critical case for controllability. As described in Section 8.9.4, the high-lift propellers will create a pitch up moment, whilst the flaps create a pitch down moment. A detailed analysis on the exact contribution of the propellers to $C_{m_{ac}}$ is necessary to acquire a more accurate estimate of the moment coefficient, like CFD and wind tunnel testing.

The c.g range resulting from the loading diagrams is then laid on top of this scissor plot to see what the minimum tail surface area should be to cover the c.g range. As visible from the scissor plot, $\frac{S_H}{S}$ should be 0.13, resulting in a minimum tail area of 2.2476 m^2 as limited by the stability limit. This means the horizontal tail can be decreased from the preliminary sizing estimate. The stability curve is limiting, as can be seen in the plot. Potential optimisation of the tail surface area could be done by increasing the distance between wing and tail.

Table 7.8: Initial and iterated sizing and placement of the empennage

Parameters	Vertical Stabiliser	Horizontal stabiliser initial	Horizontal stabiliser updated
$X_{MAC_{C/4}}$ $[m^2]$	8.356	8.071	8.071
S $[m^2]$	2.44	3.97	2.248
b $[m]$	1.19	3.98	2.998
MAC $[m]$	1.32	1.01	0.76
$\Lambda_{c/4}$ [Deg]	25	6.1	6.1
λ [-]	0.5	0.65	0.65
AR [-]	1.5	4	4
t/c [-]	0.12	0.12	0.12

7.8. Aircraft Systems

In order for the aircraft to fly, different systems have to be implemented and work in harmony. First, the power delivery system is described in Section 7.8.1. Then, the cooling system of both the batteries and the motors is discussed in Section 7.8.2. To move the control surfaces and the landing gear, actuators are needed, of which the layout is presented in Section 7.8.3. The auxiliary power unit (APU) and emergency power unit (EPU) are discussed in Section 7.8.4. Furthermore, The environmental control system (ECS) is shown in Section 7.8.5 and finally, the de-icing system design in Section 7.8.6. The design of these systems is preliminary and will be further refined in the post-DSE phases.

7.8.1. Electrical System

The function of the electric system is to provide power to the right system at the right time. The power delivery system ensures that the energy requirements of each subsystem are satisfied, while the control system ensures that the cue to switch a system on or off is transmitted.

There are two battery blocks, a smaller one in the nose and a larger behind the passengers. The batteries are a high voltage system. The exact value depends on the battery supplier and technology chosen. For this design, an 800 Vdc system is possible[14], while a more conservative value of 500Vdc is used by the NASA X-57 aircraft [12]. It seems reasonable to assume a 500Vdc system, with the potential to improve to 800Vdc in the future. The batteries include modules to monitor their temperature and to control them. They are connected to the controllers, which are the brain of the power delivery system, which is shown in Figure 7.13.

[14] https://arstechnica.com/cars/2021/02/this-crisp-looking-crossover-is-hyundais-next-ev-the-ioniq-5/

There are two controllers and they are fully redundant. Each subsystem is connected to both of the right (R Control) and left controller (L control), so in case of loss of one side of the system, the aircraft can operate as normal, except the range being reduced. The controllers are connected to the front battery (F Batt) and the rear battery (R Batt), and the EPU. In case both of these are lost, the EPU has enough power for the systems necessary to perform an emergency landing. The controllers receive the power from the batteries at the battery voltage, they then convert this to the correct voltage for each subsystem and decide when to deliver it. The wing tip motors require 680Vd, and they have a fully separate, redundant power delivery system [15], while the high-lift motors require 490Vdc [16] on a separate system. The reason for the wing tip motors to have redundancy is that they are more critical for safety than the high lift motors. With only the wing tip propellers operating, normal cruise flight is possible, while the loss of one of the motors would be critical. The loss of a single high lift motor would not be as critical because there are many of them. The system should be such that each individual motor can be shut off in case of failure, such that the problem remains contained within the faulty motor.

The avionics, actuators [17], ECS, de-icing, cabin etc. are assumed to run on 28 Vdc. The actuators are needed for the ailerons, the flaps, the elevators, trim tab, the rudder, the front, and rear landing gear. The size of the wires to each component depends on the required current and potential. This will be further designed in the post-DSE phase.

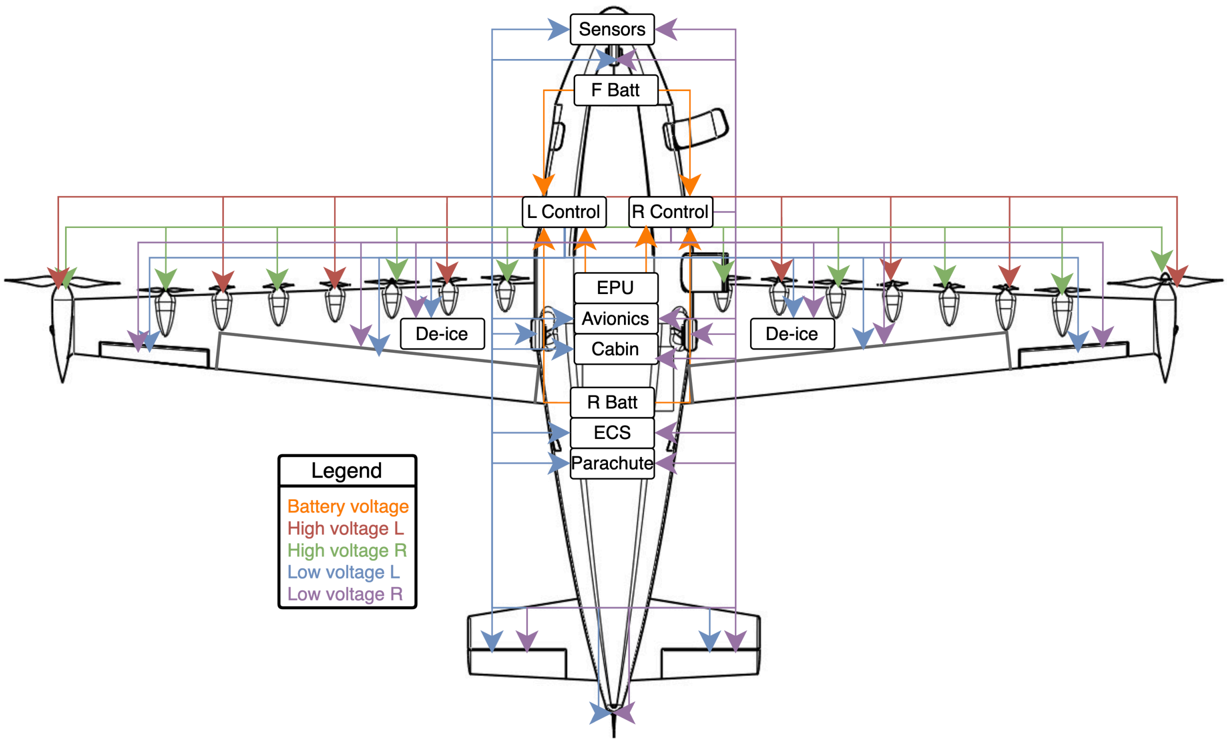


Figure 7.13: Power and control system

7.8.2. Cooling system

Cooling is essential to keep the battery and motors at optimal operating temperature to achieve maximum performance. As discussed in Chapter 8, EMRAX 188 motors are used for the high-lift inboard motors, while the larger outboard motors are the EMRAX 268. There are three cooling options: air cooling (AC), liquid cooling (LC) and combined cooling (CC). The same motor, running at 680 Vdc produces 94 kW of continuous power using AC, 100 kW using LC and 117 kW using CC. The mass is almost identical in each case (21.4 kg, 22.3 kg, 21.9 kg)

Using CC for motor cooling is the best choice. It is lighter than LC, while providing the most power. The

[15] https://emrax.com/e-motors/emrax-268/
[16] https://emrax.com/e-motors/emrax-188/
[17] https://www.moog.com/products/actuators-servoactuators/multi-purpose/linear-actuators.html

fact that it uses both air and liquid cooling offers redundancy – if the liquid cooling fails, there is still the air cooling to keep the temperatures down. According to the specification, the EMRAX 268 needs a flow rate of water/glycol of $6\,\text{L}\,\text{min}^{-1}$, and the pressure drop through the motor is 1 bar [18]. For the EMRAX 188, the flow is $7\,\text{L}\,\text{min}^{-1}$ and the pressure drop is 0.5 bar. The maximum inlet pressure is 2 bar, which means that one circuit could go through one EMRAX 268 motor and two EMRAX 188 motors, while a second circuit could go through the remaining four EMRAX 188 motors. The are two separate, redundant cooling systems in each wing. The size of the pumps and heat exchangers is not known, and depends on the environmental conditions, coolant type and pipe diameter. A more detailed design of the cooling system should be performed in the post-DSE stages of the project.

Battery cooling is important for the safety of the occupants. The X-57 uses passively cooled batteries [13], while the only certified electric aircraft, the Pipistrel Velis uses liquid cooling [19] for certification reasons. However, during development, the batteries were air cooled and performed well [20]. The cooling will heavily depend on the chosen battery type. As this will change over the lifetime of the aircraft, the battery cooling will be determined on a case-by-case basis, depending on the battery supplier. The cooling system needs to be removable as the cooling unit would compromise performance of the aircraft once the switch is made to solid state batteries, that do not require cooling.

7.8.3. Actuators

Traditionally, hydraulic actuators are used to move control surfaces. However, they are maintenance-intensive and are heavy because of their fluid-filled lines. Electric actuators are much simpler, lower-maintenance and are more power efficient than hydraulic systems. Because they only require cables for control, they are also lighter[21]. Low maintenance will make the operations cheaper and run more smoothly. Additionally, they will increase the redundancy of the critical control surfaces and the landing gear.

At this stage of the project, it is unfeasible to go into further detail. To design each actuator, the nominal and critical loads on each component need to be known, as well as its precise dimensions, stroke, force, power, mass, and packaging constraints. This information is often not disclosed, but rather specified in wide ranges of masses and powers [69]. Without knowing the specific forces needed, there is a danger of being highly inaccurate. A standard layout of the actuators, as shown in [22], will likely be applied in the final design, as it reduces complexity and cost.

7.8.4. APU/EPU

The Auxiliary Power Unit is implemented to provide autonomous electrical and mechanical power for functions other than propulsion. An APU is not needed in the AmpAir aircraft, as it can draw power from the main battery packs to supply power to the necessary subsystems. This will decrease the range of the aircraft if it is not plugged into ground power.

The purpose of the Emergency Power Unit (EPU) is to provide power to the avionics and actuators, in case of power loss to the motors. The avionics are needed for navigation, communication, and autopilot functions. The actuators are necessary to move the control surfaces and the landing gear.

The size of the EPU battery depends on the duration it takes to perform an emergency landing. The cruise altitude is just $2000\,\text{m}$ and for L/D ratio of 20 this means a distance travelled of $40\,\text{km}$, which at the cruise speed of 150 knots is just 9 minutes. The speed will decrease as a result of loss of power, so it could be as much as 15 minutes before landing.

The avionics for a two-engine conventional aircraft of medium range have an emergency battery of $37\,\text{A}\,\text{h}$ at $28\,\text{V}$, which translates to about $1\,\text{kW}\,\text{h}$ [9]. This powers items that the AmpAir aircraft will not have, like a water heater or fuel pump. However, the avionics suite of AmpAir is more extensive in terms of remote piloting and robust communication channels. Therefore, the implemented EPU will be the same, meaning that a battery of $1\,\text{kW}\,\text{h}$ at a density of $450\,\text{kW}\,\text{h}\,\text{kg}^{-1}$ will be implemented, having a mass of about $2.2\,\text{kg}$.

The actuators consume significant power, only when they have to move surfaces, meaning the required energy depends on the number and duration of control inputs. Since section 7.8.3 does not provide a power estimate, it is not possible to estimate the size of the EPU. This can only be done after the actuator system is designed.

[18] https://emrax.com/wp-content/uploads/2017/10/user_manual_for_emrax_motors.pdf
[19] https://www.pipistrel-aircraft.com/products/velis-electro/
[20] Personal correspondence, Evert-jan Feld, E-Flight
[21] https://insights.globalspec.com/article/11984/electric-vs-hydraulic-the-differences-are-huge
[22] https://aircraft.tamagawa-seiki.com/applications/business-jet/?q=application17

7.8.5. ECS

For passenger comfort, the cabin environment must be controlled by the Environmental Control System (ECS). Because the aircraft cruise altitude is 2000 m, with a ceiling of 3000 m, there is no need for pressurisation or supplemental oxygen, as the air is breathable at these altitudes.

When the temperatures get too cold, the cabin needs to be heated. One way to do this is full cabin heating, but a more efficient way is to have heated seats. The coils, embedded in the seat, provide a much more efficient way to keep the passengers comfortable than full cabin heating, minimising power consumption. Their mass and power consumption are negligible compared to the rest of the systems.

For cooling, many electrical air conditioning systems are available [23]. The Thermocool system from Kelly Aerospace that had support from NASA [24] will be implemented in the AmpAir aircraft. it has a mass of 47 lbs [25], draws 45 A and uses a brushless DC compressor at 28 V. The mass of the ECS system is thus 21.32 kg and the power required is 1260 W to which a 15% margin is applied, bringing the mass to 25 kg and the power required to 1.5 kW.

7.8.6. De-icing

The aircraft needs to have a de-icing system as it has to operate in all-weather conditions and a safe flight can be guaranteed to the passengers. Many CS23 aircraft do not have de-icing systems that are certified to be flown into known icing conditions [26]. For an aircraft that needs to fly in any weather, the system needs to be certified to fly into known icing conditions.

Traditional methods, where hot air is bled from the engines to the leading edge of the wing, are not possible for electric aircraft. This is because there is no waste heat created by electric propulsion, unlike internal combustion engines. The following paragraphs discuss different de-icing strategies.

First, pneumatic boots that expand and contract to break the ice were considered. This is well suited for an aircraft without leading edge slats. However, several aircraft accidents have occurred with this system[27][28], as the boot only spans a part of the chord. This means ice can build up past the boot. On top of that, the boots alter the shape of the wing, reducing the aerodynamic efficiency. For these reasons, this system was discarded.

Fluid de-icing is another option. Here, anti-freeze liquid is deposited on the wing to prevent ice build-up. The advantage of this system is the low power requirements and mechanical simplicity, and no effect on the aerodynamics. However, the problem is increased maintenance cost due to the mechanical nature of the system, as well as uncertainty on the amount of antifreeze needed [29].

The waste heat from the liquid used to cool the electric motors could be used to de-ice the wings. This would reduce losses massively. The problem with this system is that the coolant from the motors might not have the right temperature to properly de-ice the wings in each phase of the flight. In the future, the batteries will be solid state and thus not require cooling, thus no waste heat. In case of loss of power, the de-icing system would stop working as well, as there is no waste heat from the motors to recover. This is an interesting option, but needs more research to prove that it is a reliable source of heat for de-icing and is left for the post-DSE phase.

Next, an electric heating system could be implemented. This relies on passing current through coils of wire which are attached to the structure of the wing to heat it up. The advantage for a composite structure is that the wire can be embedded in the matrix, having no effect on the aerodynamics. The system is light as it involves just a few meters of wiring and is very simple. The downside is its relatively high power required. [58]. The electric system is simpler, more aerodynamic and lower maintenance than fluid de-icing. Therefore, AmpAir will implement electric heating for de-icing in its wing.

The heated area needs to be determined to estimate the power required. The Boeing 787 Dreamliner uses heating wires attached to the inside of the wing to be heated [30]. The area of the wings is 377 m^2 [31] and the heated are is 20.95 m^2 [58]. Assuming the same ratio for AmpAir, the wing area of 17.29 m^2 will correspond to a heated area of 0.96 m^2. Assuming a power consumption of 3.61 kW m^{-2} [58], the power required is equal to

[23] https://www.aviationconsumer.com/industry-news/aftermarket-air-portables-a-new-option/
[24] https://spinoff.nasa.gov/Spinoff2007/t_5.html
[25] alternator not needed, so the mass is 70 – 23 = 47 pounds
[26] https://www.aopa.org/-/media/Files/AOPA/Home/Pilot%20Resources/ASI/Safety%20Advisors/sa22.pdf
[27] https://www.ntsb.gov/investigations/AccidentReports/Reports/AAR9601.pdf
[28] https://www.avherald.com/h?article=4330efa3&opt=0
[29] https://www.aviation-sphere.com/blog/the-common-types-of-aircraft-de-icing-systems/
[30] https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_07/article_02_4.html
[31] https://www.boeing.com/resources/boeingdotcom/commercial/airports/acaps/787.pdf

3.47 kW. A 15% margin is included to decrease risk, resulting in a required power of 5 kW. The mass depends heavily on the type of material used for the heating – be it Nichrome or Carbon Fibre. The density of one particular de-icing system made of CFRP is 0.263 g mm^{-2} [71]. Using the heated area of 0.96 m^2, the mass of the system will be 2.5 kg. There is a lot of uncertainty about this value, so a 100% margin is included, giving a mass of 5 kg for a first estimate in design.

8
Propulsion and Aerodynamics

This chapter will discuss the propulsion and aerodynamic characteristics of the AmpAir aircraft. Firstly, a detailed trade-off is made to obtain the most optimal airfoil for the AmpAir aircraft in Section 8.1. After this airfoil selection, some distributed propulsion concepts are discussed, as they form an important foundation for the design concept, this is done in Section 8.2. Following this, the power allocation of the different mission phases is discussed in Section 8.3. Then the chapter focusses on the propeller clearance the aircraft should adhere to in Section 8.4. This is followed by sections on the propeller selection and analysis (Section 8.5), engine selection (Section 8.6), propeller positioning (Section 8.7) and the flow induced by the high-lift propellers (Section 8.8). After which the high-lift performance (Section 8.9), drag estimations (Section 8.10) and climb performance (Section 8.11) conclude the chapter.

8.1. Airfoil Selection

Selecting the airfoil for the aircraft is of high importance as it will give more information on the aerodynamic performance of the entire aircraft, which makes it possible to increase the preciseness of the preliminary design of all subsystems. The airfoil selection will be done using the method presented in General Aviation Aircraft Design [31].

8.1.1. Airfoil Trade-off

Three airfoils will be presented in the trade-off, which are selected based on a thickness-to-chord ratio (t/c) of 0.18, as determined in Section 7.5.1. The airfoils are chosen to have the design lift coefficient, $C_{L_{des}}$, calculated for cruise using Equation (8.1).

$$C_{L_{des}} = 1.1 \cdot \left(\frac{W}{S}\right) \cdot \frac{1}{q} \tag{8.1}$$

Combining the wing loading (W/S) of 1418 N m^{-2} for the design point, determined in section 7.1, the cruise speed of 150 kts and the cruise altitude of 2000 m gives an $C_{L_{des}}$ of 0.53. The selected airfoils for the trade-off are: NACA65(2)-615, NACA65(3)-618 and EPPLER-553[1]. There is one EPPLER airfoil and two NACA 6 series airfoils, of which one has an t/c of 0.15. This airfoil is selected in order to also have an option that includes a lower t/c, which might be more beneficial for the aircraft. Important characteristics of the aircraft will be investigated for a Reynolds number of 1×10^6 and $N_{crit} = 5$. This is not very representative for the flow during cruise, where $Re \approx 5.7 \times 10^6$ for the wing presented in Table 7.6. $N_{crit} = 5$ means a "dirty wind tunnel" is used, making the flow more turbulent than applicable during cruise. This means that the characteristics of the wing in cruise will improve compared to the presented values.

Most characteristics will also be used as criteria, and thus also be given a weight. The first of these characteristics is t/c (weight: 3/5), which directly influences the possible strength of the wing box structure. This criterion is important as the wing is already relatively small due to distributed propulsion. The lift coefficient at zero AOA ($C_{L_{\alpha=0}}$) must lie close to $C_{L_{des}}$ in order to create lift without having to fly with a large AOA at cruise. This is considered a criterion, although it is not as important, as C_d at $C_{L_{des}}$ will give more information about the performance in cruise Therefore, this was given a weight of 1/5. $C_{l_{max}}$ (weight: 4/5) is a crucial characteristic as it will determine the high-lift performance due to the distributed propulsion. A higher airfoil $C_{l_{max}}$ makes it easier to achieve the C_L for landing. The AOA needed for $C_{l_{max}}$ is given a lower importance, namely a weight of 1/5, as it will probably not be achieved in normal operations. The stall characteristics of the airfoil (weight: 3/5) include the way flow separation occurs and if it happens suddenly or gradually at different Reynolds numbers. As already explained before, the AOA's at which stall occur will not be achieved in normal operations, but this criterion is still relatively important for safety if it happens. The minimum drag

[1] http://airfoiltools.com/search/index

coefficient of the airfoil ($C_{d_{min}}$) is considered the most important characteristic with a weight of 5/5, as it will have great influence on the performance of the aircraft. The use of distributed propulsion will increase the drag of the aircraft, making it more important for the other subsystems to have a low drag. The lift coefficient at $C_{d_{min}}$ is considered less important with a weight of only 1/5, as it is already enough for $C_{L_{des}}$ to lie within the drag bucket. The value for $(C_l/C_d)_{max}$ (weight: 2/5) of the airfoil says a lot about the performance of the aircraft, and it is important for glide performance in case of propulsive failure. However, it is more important for the airfoil to have $C_{L_{des}}$ close to C_l at which $(C_l/C_d)_{max}$ is achieved. The criterion for this C_l is thus given a higher importance of 4/5, while the $(C_l/C_d)_{max}$ criterion is considered less crucial. The moment coefficient of the airfoil during cruise ($C_{m_{cruise}}$) is of moderate importance and is therefore given a weight of 3/5. A higher negative $C_{m_{cruise}}$ will make it more difficult to balance the aircraft. The design of the horizontal stabilizer will be affected by this, and the longitudinal eigenmotions of the aircraft will be more sensitive if not counteracted by design. A large width of the drag bucket (weight: 4/5), measured in C_l, ensures the C_d stays close to $C_{d_{min}}$ throughout most of the operations. This is really important for the drag performance of the aircraft. It is also important for $C_{L_{des}}$ to lie within the drag bucket, but this characteristic is not considered as a criterion, as it is true for all three airfoils. It is highly preferable for $C_{l_{ROC_{max}}}$ to also lie in the drag bucket (weight: 3/5). For clearance reasons and to counter noise pollution, it might in some airspaces be required to climb at the maximum rate of climb. The other characteristics that are not considered a criterion as they are considered to overlap with other characteristics. The scoring per airfoil on each criterion is presented in Table 8.1, together with the characteristics for that criterion. The colours represent how well it performs for certain characteristics, as shown in the legend to the right of the table.

Table 8.1: Airfoil selection data

Parameter	Airfoil1	Airfoil2	Airfoil3	Scores		
Name	NACA65(2)-615	NACA65(3)-618	EPPLER553	NACA65(2)-615	NACA65(3)-618	EPPLER553
t/c	0.15	0.18	0.18			
$C_{L_{\alpha=0}}$	0.517	0.506	0.449			
$\alpha_{C_l=0}$	-4.38	-4.40	-4.00			
$C_{l_{max}}$	1.613	1.500	1.461			
$\alpha_{C_{l_{max}}}$	17.5	19.25	17.5			
Stall characteristics	TE-stall LowRe fastdrop	TE-stall LowRe fastdrop	TE-stall Nofastdrop			
$C_{d_{min}}$	0.0066	0.0068	0.0074			
C_l of $C_{d_{min}}$	0.371	0.331	0.0498			
$(C_l/C_d)max$	121.6	128.4	111.4			
Cl of $(C_l/C_d)max$	0.972	1.036	1.145			
Cm_{cruise}	-0.117	-0.116	-0.105			
Drag bucket starts at C_l	0.4	0.3	-0.2			
Drag bucket ends at C_l	0.8	0.9	0.8			
Width drag bucket	0.4	0.6	1.0			
$C_{l_{ROC_{max}}}$ inside drag bucket	No	No	No			
$C_{l_{cruise}}$ inside drag bucket?	Yes	Yes	Yes			
Final Scores				6.9	7.1	5.3

Ideal

Poor

In Table 8.1, the final scoring of each airfoil is given. This final score is based on the weight multiplied by the scoring of each criterion. NACA 65(3)-618 will be selected for the design, however, its score is close to the NACA 65(2)-615 airfoil. The main advantages of the NACA 65(3)-618 airfoil over the NACA 65(2)-615 airfoil are the $(C_l/C_d)_{max}$ and the width of the drag bucket. The t/c is also bigger, which gives the wing box more area for a better bending strength. The NACA 65(3)-618 airfoil is shown in Figure 8.1[2].

8.1.2. Sensitivity Analysis

Performing a sensitivity analysis on the airfoil selection, with 1000 random iterations of 20% increase of the weights, gives the outcome in Table 8.2.

Table 8.2: Sensitivity analysis of the airfoil selection

	Winning percentage
NACA 65(2)-615	20.80%
NACA 65(3)-618	79.10%
EPPLER 553	0.10%

The winning percentages of NACA 65(2)-615 and NACA 65(3)-618 are both significant, where the winning percentage of EPPLER 553 is not significant. The significance of these two airfoils can be explained by the similar aerodynamic characters, where NACA 65(3)-618 overall performs better than NACA 65(2)-615. The

[2]http://airfoiltools.com/search/index

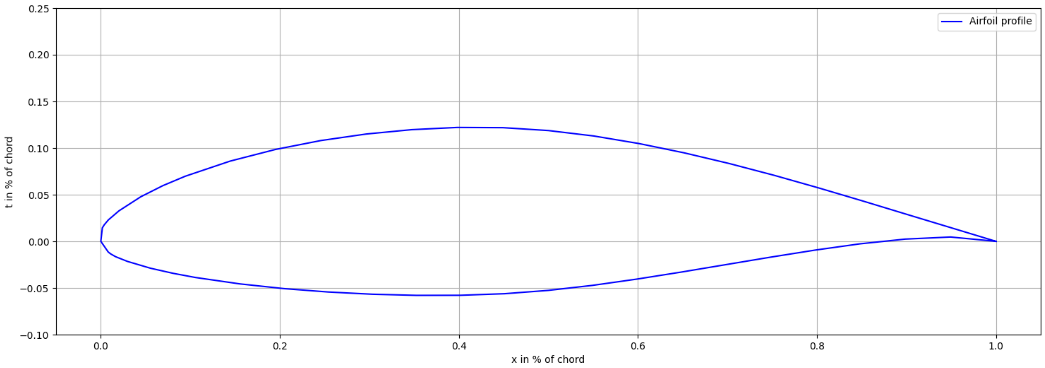


Figure 8.1: 2D-visualisation of the NACA 65(3)-618 airfoil

differences are mostly due to 65(2)-615 scoring a little higher on a few criteria with a high weight (>0.12), but 65(3)-618 generally scoring higher on the other lower weight criteria. There are more low weight criteria than high weight criteria, leading to NACA 65(3)-618 as the best option.

In Table 8.2, it can be seen that the NACA 65(3)-618 is the best trade option in almost 80% of the cases. This is considered a sufficient margin, to have this airfoil as the final selection for the aircraft.

8.1.3. XFLR5 Analysis of the Airfoil

For the analysis of lift performance of the aircraft, analysis first needs to be performed on the selected airfoil (NACA 65(3)-618). This analysis was performed by making use of XFLR5 analysis software. The airfoil was put in the software and analyses were performed for different Reynolds numbers and Mach numbers, at different angles of attack. This data was used as the basis for aerodynamic performance calculations of the distributed propulsion wing configuration. The different Reynolds numbers and Mach numbers for the analysed flight phases are given in Table 8.3. Each of these analyses was performed for angles of attack ranging from -5 to 25 degrees, in steps of 1 degree.

Table 8.3: Reynolds- and Mach numbers flight phases

	Re [-]	M [-]
Stall	2.3×10^6	0.0757
Land	3×10^6	0.0984
Cruise	5.7×10^6	0.23

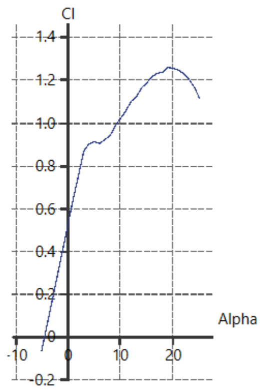


Figure 8.2: Lift-curve from XFLR5

8.1.4. Lift Curve

In order to determine the lift generated by the wing, lift curves were built. Firstly, the clean wing without deployment of HLDs or folding of high-lift propeller was analysed. DATCOM method was utilised to determine the slope of the lift curve $C_{L_{\alpha,clean}}$, as well as the maximum lift coefficient ($C_{L_{max,clean}}$) and the stall angle of attack (α_{stall}). The lift curve slope is found by Equation (8.2) [70], where A is the aspect ratio, $\Lambda_{0.5C}$ is the sweep angle measured at half cord length, η is the airfoil efficiency factor. This factor can be assumed to be approximately, 0.95 Furthermore, β can be calculated by using Equation (8.3) where M_∞ is the free stream

Mach number [70].

$$C_{L_{\alpha,clean}} = \frac{2\pi A}{2 + \sqrt{4 + \left(\frac{A\beta}{\eta}\right)^2 \cdot (1 + \frac{tan^2\Lambda_{0.5C}}{\beta^2})}} \quad (8.2)$$

$$\beta = \sqrt{1 - M_\infty^2} \quad (8.3)$$

For stall speed, this coefficient has the value of $0.089\frac{1}{deg}$. Furthermore, the maximum lift coefficient can be found with Equation (8.4). Here, $\Delta C_{L,max}$ has the value of 0 for Mach numbers lower than 0.2. $C_{L,max}$ and $C_{l,max}$ are the wing and airfoil maximum lift coefficients, respectively. Their ratio is dependent on the leading edge sweep angle. For AmpAir's leading edge sweep angle of 2.05 degrees, this ratio can be approximated to equal 0.9 [70].

$$C_{L,max} = (\frac{C_{L,max}}{C_{l,max}})C_{l,max} + \Delta C_{L,max} \quad (8.4)$$

The airfoil maximum lift coefficient has been found using the XFLR software[3], which can generate the lift curves of airfoils with given Reynold and Mach numbers. In the case that an aircraft starts flying the stall speed, the airfoil is expected to have a maximum lift coefficient of 1.256. Using this value, the $C_{L,max}$ of the clean wing is approximated to be 1.142. Finally, the wing stall angle is found by Equation (8.5). Here α_{0L} is the zero lift angle of attack of the airfoil at the mean aerodynamic chord. With XFLR analysis, this has been found to be -4.5 degrees. Plugging in values from Equation (8.2) and Equation (8.4), the stall angle of attack is found to be 10.3 degrees. From this, the lift curve of the clean wing with no HDLs deployed can be constructed and can be seen on Figure 8.3.

$$\alpha_{stall} = \frac{C_{L,max}}{C_{L_\alpha} + \alpha_{0L} + \Delta\alpha_{C_{L,max}}} \quad (8.5)$$

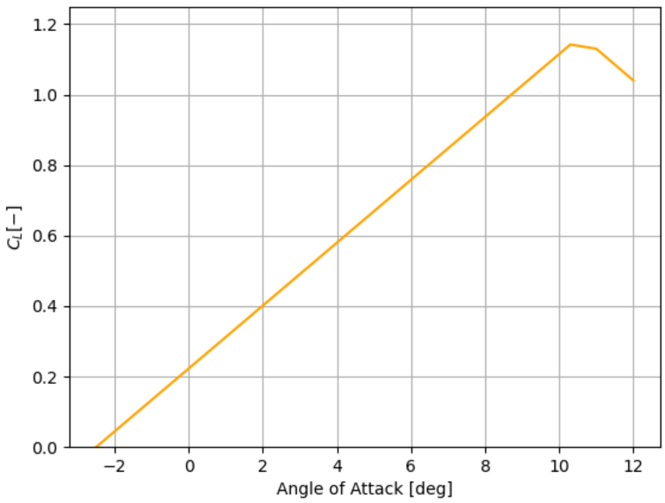


Figure 8.3: Lift curve of the clean wing.

8.2. History of Distributed Propulsion Designs

Distributed propulsion is a state-of-the-art concept, providing many aerodynamic benefits. Multiple concepts have been developed, such as the Aurora XV-24 LightningStrike, the Lilium Jet, as well as many other conceptual concepts currently in testing phases. In particular, an extensive number of technical papers were consulted from the NASA archive[4] on the X-57. This research in electrically powered distributed propulsion has provided the AmpAir team with knowledge and confidence in their own propulsion design. Using these papers, AmpAir has developed their own model to estimate the performance of their propulsion design, without having to model the aerodynamic behaviour with complex computational fluid dynamics (CFD) models.

[3] http://www.xflr5.tech/xflr5.htm
[4] https://www.nasa.gov/aeroresearch/X-57/technical/index.html

8.3. Power Allocation

The propulsion system makes up a large fraction of the mission power budget. The allocated power to the propulsion system is dependent on the stage of the flight mission. From Section 7.1, it was found that take-off is the most power demanding, followed by climb and cruise, meaning these are the critical phases for which the propulsion system must be designed. The power demand for descent, landing, and taxi are significantly smaller compared to other mission phases. However, they are included in the power budget to ensure energy budget is satisfied. Table 8.4 contains the power allocations for each mission phase.

Table 8.4: Power allocations for different mission phases

Mission phase	Time [sec]	Power [W]	Energy [%]
Take-off	40	476058.1	2.15
Climb	449	391940.2	19.90
Cruise	4825	111528.1	61.60
Descend	449	28255.0	1.43
Landing	40	311373.9	1.41
Reserve	1800	63200.0	12.87
Taxi	130	46557.6	0.63

Times for each mission phase are taken directly from the mission flight profile (Section 2.2), with exceptions for take-off for an extra 8 seconds extension for a power margin. Power distributions are directly obtained from results obtained from each mission phase. However, values present in Table 8.4 are modified from values originally assigned for each mission phase from Section 7.1, since propulsion efficiency is introduced based on propeller analysis. Further evaluation of such efficiencies are explained within the Section 8.3.1. Furthermore, reserve power is taken into account by considering minimum power usage. This means that during loiter, the aircraft flies at an adapted speed instead of cruise speed, to maximise endurance time in the air. This speed is approximately 92 knots ($47\,\mathrm{m\,s^{-1}}$).

8.3.1. Distributions of Power and Thrust

The required power is dependent on the mission phase. There are two critical mission scenarios: maximising lift during take-off, climb, and landing and minimising tip vortices during cruise. The function of the high-lift propellers is to maximise lift during take-off, climb, and landing. This means they are optimised for these flight stages and will be maximally loaded during that time. The tip propellers provide the remaining thrust. During cruise, the tip engines minimize drag. This is because they minimise axial flow onto the wings and maximise rotational induced velocity to counteract wing tip vortex effects. These effects are translated into an increased effective aspect ratio, minimising drag during cruise, reducing the power required, as predicted in Figure 7.1.

From this, the following conclusions are drawn: during cruise, the high-lift propellers are not required, thus power is to be redistributed to feed only the tip engines. During take-off, climb and landing, high-lift propeller usage is to be maximised without overloading the propellers outside their efficiency region. An optimisation procedure was created to find the best possible distribution of power such that the efficiency of both tip and high-lift propellers do not compromise each other. Efficiencies and number of propeller selection is described below in Section 8.5. Here, it can be seen that the high-lift efficiencies for take-off are worse than that of climb, as the latter has lower thrust requirements, meaning they are pushed less far from their optimum loading than during take-off.

Table 8.5: Propulsion results per propeller

Mission phase		Thrust [N]	Power [W]	Propeller efficiency [-]
Cruise	High-lift	0.00	0.00	0.00
	Tip	731.50	55764.05	0.819
Climb	High-lift	279.39	11528.45	0.723
	Tip	2217.44	115270.97	0.594
Take-off	High-lift	484.86	22240.99	0.568
	Tip	1771.96	82342.14	0.554

This preliminary design should be verified by analysis of the wing tip vortexes and the tip engine wake interaction. This could be done using a CFD model and simulation. This way, the effective aspect ratio can be verified, which would allow further iteration on the design of the aerodynamic and propulsion subsystems.

8.3.2. Ground Performance

In Section 8.3.1, there is no indication given on the performance during taxi. In this section, a preliminary estimation of the required taxi power is presented.

For this analysis, the taxi speed is assumed to be $35\,\mathrm{km\,h^{-1}}$. To accelerate, the most efficient method is to use the high-lift propellers, as they are optimised for lower speeds. The time to accelerate depends on the thrust setting of the propellers and to compute it, the following assumptions were made: Only inertial acceleration is considered and a rolling friction of 0.02[5], which is on the higher end of friction for roll bearings, is implemented. Based on the preliminary estimate of the taxi aerodynamic drag, the maximum times the aircraft can accelerate from $0\,\mathrm{km\,h^{-1}}$ to $35\,\mathrm{km\,h^{-1}}$ is found to be 5 for taxiing. At maximum thrust, the acceleration is achieved after 2.6 seconds. With this setting, there is less than 5 minutes of power budget for taxiing at $35\,\mathrm{km\,h^{-1}}$. This can be maximised up to 13 minutes if the aircraft is only accelerated twice during taxi. If the thrust setting is reduced to 24% of maximum thrust, the acceleration time is 10.7 seconds, with a remaining almost 18 minutes of power supply for taxiing at $35\,\mathrm{km\,h^{-1}}$. If the aircraft is accelerated only twice, this is increased to 16 minutes. Thus, on average, available taxiing time is estimated to be 14 minutes if excessive accelerations are avoided.

8.4. Propeller Clearance

Propeller clearance must be considered when deciding on the propulsion placement. The regulations of clearance come from **CS 23.925: Propeller clearance**. The following three sub-rules will be used to determine the engine placement.

- **Ground clearance:** For aircraft with a nose wheel, there must be at least 18 cm clearance between each propeller and the ground. This is measured while the landing gear is statically deflected and in the level, take-off, or taxiing attitude, whichever is most critical. In addition, for each aeroplane with conventional landing gear struts using fluid or mechanical means for absorbing landing shocks, there must be positive clearance between the propeller and the ground in the level take-off attitude with the tyre completely deflated and the corresponding landing gear strut bottomed.
- **Water clearance:** There must be a clearance of at least 46 cm between each propeller and the water for emergency water landings, unless compliance with CS23.239 can be shown with lesser clearance.
- **Structural clearance:** There must be:
  1. At least 25 mm radial clearance between the blade tips and the aeroplane structure, plus any additional radial clearance necessary to prevent harmful vibration.
  2. At least 12.7 mm longitudinal clearance between the propeller blades or cuffs and stationary parts of the aeroplane.
  3. Positive clearance between other rotating parts of the propeller or spinner and stationary parts of the aircraft.

8.5. Propeller Selection and Analysis

Propeller analysis is performed for both tip and high-lift propellers. To make a first design, the team has decided to use the propeller database from APC propellers[6] and University of Illinois Urbana-Champaign[7]. However, because of their limited sizes, only the high-lift propeller can be designed from such databases. Because the high-lift propellers will be folded during cruise, the tip propellers must be optimised for cruise, while the high-lift ones are optimised for maximum lift generation. Section 8.5.1 and Section 8.5.2 discuss the design of the tip and high-lift propellers, respectively.

[5] https://koyo.jtekt.co.jp/en/support/bearing-knowledge/8-4000.html#: :text=For%20plain%20bearings%2C%20the%20value, it%20is%200.1%20to%200.2.

[6] https://www.apcprop.com/technical-information/performance-data/

[7] https://m-selig.ae.illinois.edu/props/propDB.html

8.5.1. Tip Propellers

For the first estimate sizing and analysis of the tip propellers, the commonly used Blade Element Momentum Theory is not used. This is because literature showed that it is not valid for distributed propulsion [72]. Instead, blade element theory will be used. By using this method, errors are introduced in overestimation of thrust and efficiency as rotational and axial induced flow are underestimated. It is recommended in the future to look into the Reynolds-Average Navier Stokes (RANS) or external software tool for a more accurate analysis of the propeller design for distributed propulsion.

First, the tip propeller diameter was estimated based on cruise power. From this, the ANCF 125×75 was chosen for the first iteration. Values are taken for optimum conditions, maximising efficiency in order to obtain optimum aspect ratio, as well as optimum thrust and power coefficients. These values then are taken in order to fly during cruise at optimum conditions. Next, the rotational speed is calculated, which allows the thrust and power to be obtained. These values are compared to expected thrust from the equation $Power = Thrust \cdot Velocity$. Further iterations for different advance ratios ($J = \frac{V_\infty}{nd}$) were performed until the thrust values converged to an accuracy of 5%. Once cruise performance is obtained, based on power distributions which are obtained from design of the high-lift propellers (Table 8.4), the advance ratio can be calculated by coupling the power supplied to the power required of the rotor to find the rotational speed and thrust. Values for thrust and power coefficient were found as functions of the advance ratio. Since advance ratios for landing and take-off speed do not match the values for optimum conditions for design propeller, propeller efficiencies are significantly dropped in comparison to cruise conditions.

A function to determine the thrust and power coefficient based on advance ratio was created by extrapolating the ANCF 125×75 propeller data. This means implicitly that it is assumed that the propeller geometry is identical, with a scale-down factor based on diameter decrease. For noise reasons, as will be discussed in Section 10.5, the number of blades is chosen to be 5. It must be stated that, because more blades are introduced, the thrust is overestimated. This is because wake interference between propeller blades is neglected. For future analysis, the RANS method is recommended to compute true performance of such blades. Propeller flow analysis for tip propellers was not conducted due to a lack of CFD resources. However, this could be implemented in the future to analyse the counteracting effect the tip propeller has on wing tip vertices and axial induced flow, contributing to an increased lift coefficient.

8.5.2. High-lift Propellers

For the design of the high-lift propellers, an airfoil selection is made from the same database available by APC. This database contains data specific for small propellers, which are ideal for distributed propulsion concept. Different combinations of amount of engines, propeller diameter and their location along the wing were analysed. Here, the thrust and efficiency of each propeller was calculated for each configuration. It was a multi-stage iteration process which was generated partially autonomously. The procedure consists of finding the number of engines based on the span-wise distribution. A spacing factor was applied to avoid propeller collision in case of thermal expansion or centrifugal strain and to minimise wing tip interactions between propellers. Afterwards, a power allocation is generated which maximises the high-lift propeller thrust, without sacrificing its, or the tip propellers, efficiency. The summary of efficiencies is found in Table 8.5. This procedure is then iterated for a different engine configuration and power distribution. For take-off, the iterations converged to maximising the high-lift propeller diameter. On the other hand, for climb, the results converged to a minimal diameter, which overloads the tip propellers. A compromise was found by setting the high-lift propeller diameter equal to 0.7 m. The propeller chosen for the high-lift propellers will be the PER3 28×20. Results from iterations lead to an effective power distribution between tip and high-lift motors. In Table 8.6, the total number of motors, and the power distribution between them, is shown.

Table 8.6: Power distribution per mission phase

Power distribution [%]	Tip	High-lift
Take-off	34	66
Climb	54	46
Cruise	100	0
Landing*	0	100
Taxi	0	100

There are two remarks to be made about Table 8.6. The first is that the model does not account for any thrust loading by the tip engines. The second is that different mission stages have different optimal configurations. By adjusting the power supply to each engine, the performance can be optimised. The star (*) for landing then refers to an assumption that was made. This is that for optimal efficiency during landing, the high-lift propellers have maximum output. During cruise, the thrust output was designed to be just sufficient to generate the required lift coefficient and during taxi, the high-lift propellers will be used, as they are more efficient at low speeds. Further ground performance is covered in Section 8.3.2. Results of Table 8.6 are due to optimisation of efficiency per mission stage, which lead to overall efficiencies of 82% for cruise, 65% for climb, and 57% for take-off.

8.6. Engine and Propeller Selection

Choosing the proper engine will minimise losses in the power subsystem. At this stage, since there is sufficient insight on the performance and power required by each propeller during each mission stage, electrical motors can be found that match the required performance characteristics. This process was integrated in the power coupling iteration of the power distribution design stage. The team decided that integrating an engine with excess power is detrimental to the aircraft performance. This is because overloading propellers decreases their efficiency, which would not be outweighed by the small increase in thrust. Additionally, because of the distributed propulsion, there are many engines, meaning the excess engine mass must be multiplicated by the amount of propellers. Results of the engine selection are shown in Table 8.7.

Table 8.7: Motor and propeller data

Engine and propeller data	Tip	High-lift
Number of engines	2	14
Engine model	EMRAX 268	EMRAX 188
Engine peak / continuous power [kW]	210 / 117	60 / 37
Propeller diameter / pitch [meter]	1.87 / 0.89	0.71 / 0.51

Before starting to evaluate the electric motors, a quick note on blade tip speed has to be made. The propeller tip Mach number for both tip and high-lift propellers are evaluated during the mission. The maximum propeller tip speeds are 0.62 and 0.60 for high-lift and tip propellers respectively encountered during the mission. Further analysis for maximum blade speeds for each propeller is performed, yielding to 0.69 and 0.92 for high-lift and tip propellers, respectively. This however considers a redistribution of power outside optimal conditions which can only be encountered in failure of either all high-lift propellers or both tip-propellers. Since propeller tips are the elements of the aircraft reaching the highest velocity, blade tip requirement[8] is considered to be satisfied.

The chosen electric motor for the high-lift and tip propellers are the EMRAX 188 and EMRAX 268, respectively. The selection of the engines was based on the continuously required power of the propellers. The EMRAX 188 has a continuous power supply until 37 kW and can reach 60 kW peak power[9]. The EMRAX 268 has a continuous power supply until 117 kW and can reach 210 kW peak power[10]. For both engines, Python functions were made based on the power-RPM-torque diagrams provided by Emrax themselves (`Emrax_188_model.py` and `Emrax_268_model.py`). Furthermore, motor efficiency maps were used to determine the efficiency of the motors during all mission phases. A summary of motor data is presented in Table 8.8.

The engines must be coupled to the rotor, for which a gear must be introduced. For optimal performance, the gear ratio would be 1. However, if the engine rotational speed is coupled directly to the propeller, power coupling becomes highly inefficient. Further iteration would lead to a specific diameter for the power range of the engine selected. However, this method would not satisfy the thrust requirements imposed by the mission, deeming it not applicable. Another option is to design a custom electrical motor for the AmpAir engine, where the rotational output is coupled to the rotational velocity of the propeller. However, due to time constraints[11], designing both electrical motors is impossible.

Because aforementioned strategies cannot be applied, a gearbox will be introduced. These have the disadvantage that they introduce power losses, decreasing the propulsion efficiency. For this, either Dual-Clutch

[8] REQ-TP-AERO-05: In no place on wings or propeller/rotor surfaces shall the airflow exceed velocities over Mach 1.
[9] https://emrax.com/wp-content/uploads/2022/11/EMRAX_188_datasheet_A00.pdf
[10] https://emrax.com/wp-content/uploads/2022/11/EMRAX_268_datasheet_A00.pdf
[11] REQ-STK-DES-01 :The preliminary design shall take no more than 10 weeks for 10 people.

Table 8.8: Motor performance from EMRAX specs

Mission phase	EMRAX 188			EMRAX 268		
	Motor Efficiency [-]	Motor RPM [rev/min]	Gear ratio [Prop/Motor]	Motor Efficiency [-]	Motor RPM [rev/min]	Gear ratio [Prop/Motor]
Take-off	96	4100	1.47	94	3200	0.48
Climb	94	2200	2.04	93	4200	0.52
Cruise	NA	NA	NA	95	2500	0.72

Transmission (DCT) or Continuous Variable Transmission (CVT) can be considered, as the aircraft will need variable gear ratios. Both are highly efficient transmission without requiring loss of power or detached time. However, they will increase the design weight and require high maintenance due to wear. CVT transmissions introduce a fully smooth drive. On the other hand, it has limited torque, meaning it is only applicable for the high-lift engines[12]. DCT is readily proven to be successful in the automotive industry. It is expensive, but applicable for high torque motors. More detailed gearbox design will be covered in future design phases. To conclude the engine and propeller selection, the power and energy consumption of the engines over a single mission is given in Figure 8.4. This figure highlights the most demanding flight stages, as take-off, climb, and landing experience peaks in the required power.

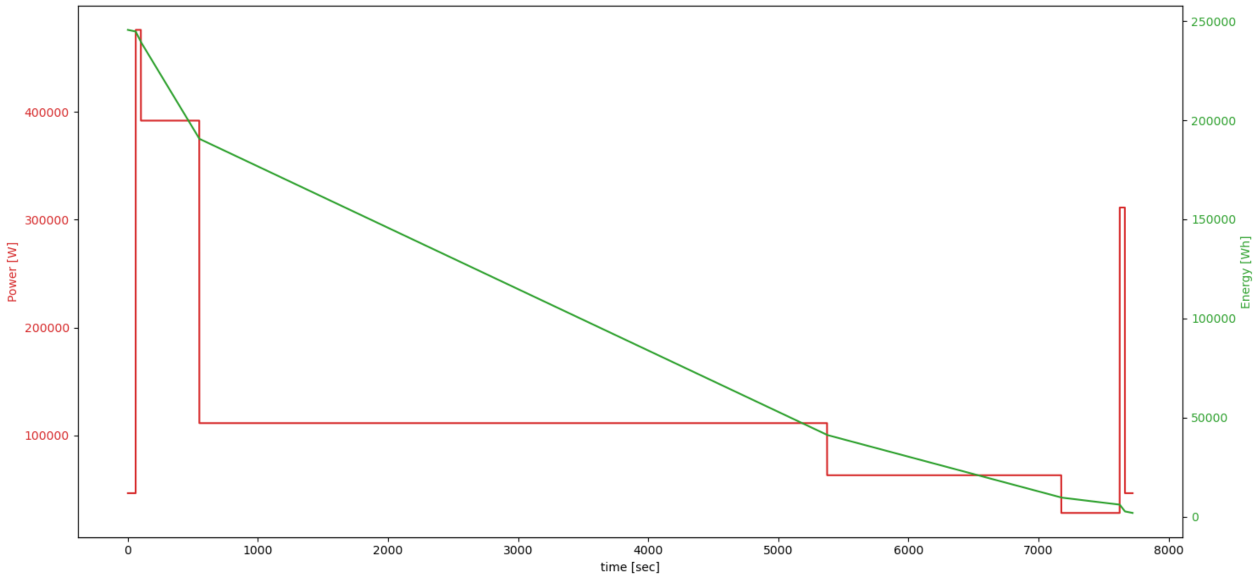


Figure 8.4: Power and energy consumption over a single mission

8.7. Propeller Positioning

The longitudinal and vertical placement of the propellers with respect to the wing has a large influence on the propulsion efficiency and the effectiveness of the high-lift propeller system and possible high-lift devices (HLD's). It is most beneficial to place the high-lift propellers close to the leading edge. This ensures the slipstream is not considerably contracted or slowed down once it reaches the leading edge [72], but increases the flow distortion experienced by the wing. Furthermore, the high-lift propellers will be folded during cruise, meaning a clearance of approximately one propeller radius is needed. The tip propellers are for now placed at an arbitrary longitudinal position between the propeller and the wing's leading edge. This is because tip propellers are not to be folded, thus to maximise tip vortices and minimise propeller shaft, the propellers are placed much closer to the leading edge than the high-lift propellers. This will be decided on in a detailed future analysis.

[12]https://www.spinny.com/blog/index.php/transmission-compared-dct-vs-cvt/#: :text=Among%20all%20the%20types%20of,power%20flow%20to%20the%20wheels.

The rotational axis of the propeller can either be placed above or below the wing chord, both have up- and downsides. It was decided to place the axis of the propellers below the wing chord, as this is preferred when flaps are implemented [72], as shown in Figure 8.5, where an externally blown flap implementation is shown. It will also decrease flow distortion by the wing, lowering stress on the blades. In case maintenance is needed, the propellers will be accessible more easily as they are closer to the ground. During this first design iteration, the wing chord line lies just below the propeller induced airspeed at 70% of the propeller radius. This is the location that experiences the highest increase in airspeed, which is beneficial for creating lift. However, it must be noted that for structural reasons, it is best to place the rotational axis close to the chord line.

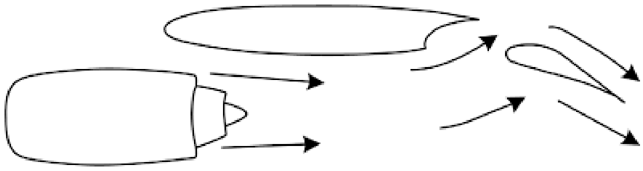


Figure 8.5: Illustration of an externally blown fowler flap [76]

Placing the propellers at a negative angle with respect to the wing chord is shown to increase the achievable lift coefficient of the wing and the propulsive efficiency [94, 29]. The lift coefficient increases for inclination angles of up to $-15°$, beyond these angles, negative effects of stall come into play. Downsides of placing the propeller at an angle are an increase of profile drag of the propellers and a negative lift contribution by the propellers themselves. Therefore, the propellers will be placed at an inclination angle, aligned with the free stream flow [72]. The 14 smaller propellers, used only for flight phases which require high lift (e.g. take-off, climb, and landing)will be aligned with the stall free stream flow. This translates to having the propellers and nacelles inclined at an angle of $-10°$ with respect to the chord line, which does not include the change in angle of attack in case of flaps. This is slightly below the real stall angle of attack in order to prevent that the local angle of attack exceeds above stall. This will be advantageous during stall conditions and increase lift during take-off and landing by having an upward blowing effect [72]. The downside of such a high angle is the increased drag during cruise. This will be minimised by integrating the nacelles into the wing and folding the high-lift propellers during cruise. The two tip propellers will be aligned with the free stream during cruise. For $C_{L_{des}}$, the aircraft will be flying at an AOA of $0.25°$, meaning these propellers will have a downward inclination angle with respect to the chord. However, by choosing their orientation based on cruise, the propulsive efficiency and aerodynamic performance during take-off, climb, and landing will be suboptimal. The drag performance presented in Section 8.10 includes the increased drag due to the orientation of the nacelles. A quantitative analysis of the influence of the orientation on the propulsive efficiency will be done during future design stages.

8.8. Induced Flow by High-lift Propellers

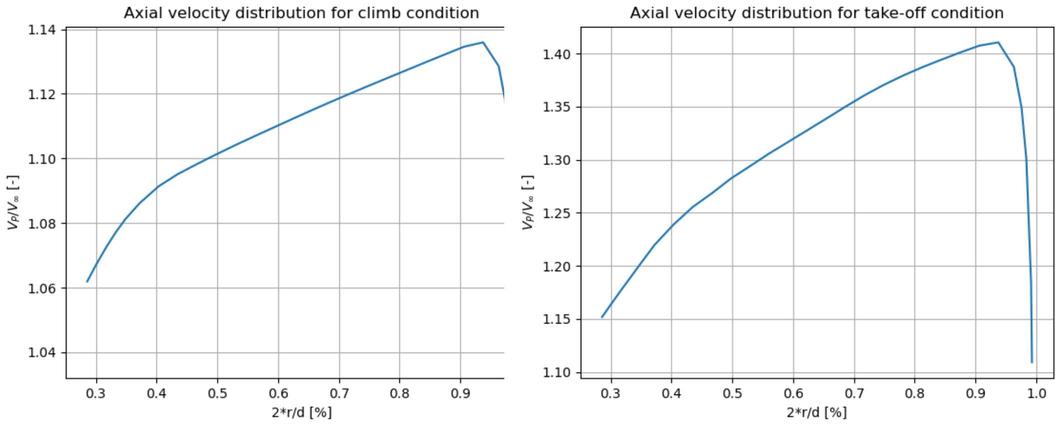
In order to evaluate the effect of distributed propulsion on the aerodynamics of the wing, the propellers must be analysed to evaluate the induced flow at the wake of each rotor. As stated in the beginning of the chapter, the two main aspects to consider are wing tip vortices and axial induced velocity blowing into the wing. Wing tip vortices require high computational aerodynamic models. Examples of such effects are taken for this report from the aircraft X-57 model[18] which shares similarities as described in Section 8.2. For this analysis, only the high-lift propellers are assessed, since they are responsible for the increase in airflow on the wing. Blade element theory is used to calculate the thrust distribution over the blade. The most important equation to consider is the thrust differential, as given in Equation (8.6).

$$T = \int_{y1}^{y2} \frac{m}{2} \cdot \rho \cdot RPS^2 \cdot diameter^2 \cdot (J^2 + \frac{2 \cdot \pi \cdot radius}{diameter}^2) \cdot chord \cdot (C_L \cdot cos(\gamma) - C_D \cdot sin(\gamma))\, dr \tag{8.6}$$

Blade element theory consist of the integral summation of the blade elements along the radius of the blade, where each element is treated like an airfoil. The summation starts at the propeller hub, which is defined by the propeller specs, and ends at the propeller tip. Afterwards, the thrust per blade is multiplied by the number of blades (m), leading to a linear relation between number of blades and thrust. This relation contains errors that stem from wing tip losses and the effect of blade wakes on each other. By choosing two blades for the high-lift propellers, blade wake errors are minimised, increasing the estimated rotor induced flow. However, this does not reduce the error introduced by tip losses. This means that the estimated thrust distribution will be an overestimation. To compensate for this, it is scaled down by comparing it to thrust data for similar conditions. Lastly, the axially induced velocity is computed using Equation (8.7) and Equation (8.8). Solving both equations gives the distribution of induced velocity by the propeller disk per filament area, given by $2\pi dr$.

$$\dot{m} = \rho V_\infty 2\pi r \tag{8.7}$$

$$T = (V_{induced} - V_\infty)\dot{m} \tag{8.8}$$



(a) Propeller induced velocity distribution for climb **(b)** Propeller induced velocity distribution for cruise

Figure 8.6: Propeller induced velocity graphs

Now that the methodology has been described, the results are obtained for take-off and climb mission phases. As seen in Figure 8.6a and Figure 8.6b, the axial induced flow of the propeller increases along the blade. This is to be expected from blade element theory, as the shape of distribution mainly stems from the chosen airfoil and twist distribution. Propeller PER3 28×20 is designed with the intention to maximise operation capabilities, it does not to have an even distribution of axial flow along the blade. An optimal propeller would have a more evenly distribution of thrust and axial induced velocity along the blade. To estimate the average induced velocity, the ratio of axial induced velocity over incoming flow velocity is taken and averaged along the wingspan, taking into account gaps between blades having no axial velocity induced. This results in an average axial induced velocity to incoming flow velocity ratio ($\frac{V_{prop}}{V_\infty}$) of 1.06 in climb and 1.25 in take-off configuration. These values will be used to estimate the increase in lift over the wing due to axially induced velocity.

8.9. High-lift Performance

In this section, the high-lift performance of the aircraft will be analysed. Firstly, this will include an analysis of the effects of distributed propulsion on high-lift performance in Section 8.9.1. This will provide an achievable lift increase due to distributed propulsion. In Section 8.9.2, it will then be discussed if an additional trailing edge HLD is needed.

8.9.1. High-lift Propulsion

To analyse the effects of distributed propulsion on high-lift performance, a model from the literature is used [72]. This model presents 4 scenarios for varying propeller installation angles, of which two are applicable for the propeller orientations introduced in Section 8.7. In stall and take-off ($V_{TO} = V_{stall}$), the small propeller slipstream is aligned with the free stream. For landing, the small propeller slipstream is directed upward (in negative direction). Now, the fractional increase in lift per unit span for an airfoil section can be found using Equation (8.9) and Equation (8.10) for a slipstream aligned with the free stream and a slipstream directed upward, respectively.

$\Delta L'$ is the increased lift per unit span due to distributed propulsion, while L'_0 is the lift per unit span without the presence of a propeller. The induced slipstream velocity is given by V_p, the free stream velocity is given

$$\frac{\Delta L'}{L'_0} = \sqrt{1 + 2\left(\frac{V_p}{V_\infty}\right)\cos\alpha_a + i_p + \left(\frac{V_p}{V_\infty}\right)^2} - 1 \quad (8.9)$$

$$\frac{\Delta L'}{L'_0} = \frac{q_{ep}(\sin\alpha_{ep}/\sin\alpha_a) - q_\infty}{q_\infty} \quad (8.10)$$

by V_∞, α_a is the free stream angle of attack with respect to the zero-lift line and i_p is the incoming angle of the slipstream with respect to the zero-lift line. The effective angle of attack with respect to the zero-lift line is then given by α_{ep}, which is found by summing up the free stream velocity vector and induced slipstream velocity vector. The dynamic pressure of the free stream and effective local velocity behind the propeller are given by q_∞ and q_{ep}, respectively. Now, the effect over the entire wing can be found using Equation (8.11).

$$\frac{\Delta C_L}{C_{L_0}} = \sum_{i=1}^{N}\left(\frac{\Delta L'}{L'_0}\right)_i\left(\frac{S_{blown}}{S}\right)_i \quad (8.11)$$

In Equation (8.11), i is a wing section out of N propeller slipstream sections. S is the total wing area and S_{blown} is the area of the wing that is affected by the slipstream, and is found using the contracted slipstream diameter (D_s), calculated with Equation (8.12).

$$D_s = D\sqrt{\frac{1+a}{1+a\left(1+\frac{x}{\sqrt{x^2+D^2/4}}\right)}} \quad (8.12)$$

The propeller diameter is given by D, a is the induced axial velocity immediately behind the propeller over the free stream velocity, and x is the longitudinal distance behind the propeller. For the most inboard propeller, the diameter contraction is shown in Figure 8.7, with the distance (x) behind the propeller on the x-axis and the contracted slipstream diameter (D_s) on the y-axis. The two red dots show the position of the leading edge and trailing edge.

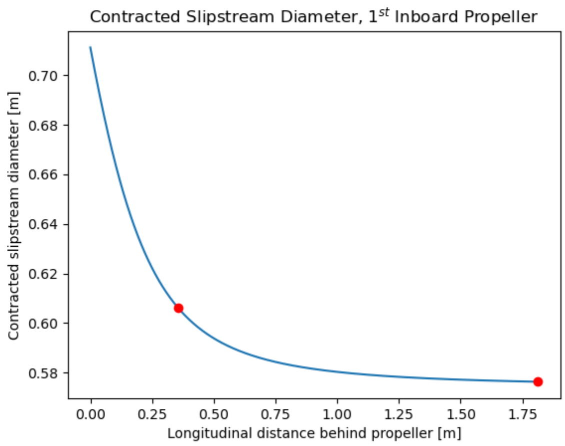


Figure 8.7: Contraction of the slipstream diameter as a function of the distance behind the propeller, where the red dots show the

The model, explained above, makes use of several assumptions [72], which are stated in the list below.

- The propeller slipstream is directed purely in the axial direction and can be calculated as the average value perpendicular to the propeller disk [26, 46].
- The slipstream velocity stays constant behind the propeller.
- The two opposite sides of the propeller cancel out the effects of swirl.
- The twist is zero and the zero-lift line angle stays constant over the span.
- The lift per unit span is the same over the entire wing. Commonly, the lift is higher close to the root chord, making it more beneficial to place high-lift propellers here.
- No part of the wing is at or above stall. For the stall case, the angle of attack is taken just below stall.

- The induced angle of attack over the wing is zero. In practice, propeller swirl and tip vortices will increase the angle of attack.
- The slipstream contraction does not take into account the effects of the nacelle. The slipstream will follow the nacelle contour and decrease the slipstream contraction.
- The wing is completely immersed fully in a wide, incompressible slipstream flow.

In detailed future design, more complex models are to be applied to further analyse the slipstream effects of the high-lift propulsion, and the impact of the made assumptions. Experimental data, obtained from simulation software and wind-tunnel testing, should also be performed for full investigation of the high-lift propulsion. For now, the model is deemed sufficient for a preliminary estimate of the high-lift performance of the aircraft.

The propulsion system data is taken from the design presented in Chapter 8. Applying the wing planform geometry, given in Section 7.5.1, and airfoil data from Table 8.1, a preliminary estimate is made for the fractional increase in wing lift coefficient ($\Delta C_L/C_{L_0}$) during stall and landing. The results are an increase of approximately 33% for stall. The blown area is calculated to be about 60% of the total wing area. This is due to a part of the wing being inside the fuselage, the spacing between the propellers and the slipstream contraction. A semi-emperic relation [70], based on the DATCOM method [25], is used to find the wing lift coefficient without slipstream effects (C_{L_0}). The stall lift coefficient without slipstream effects is found to be 1.14. With the increase of 33% in stall, the lift coefficient in stall becomes 1.52 In order to achieve the required C_L of 3.5 for stall, which was used to determine the wing loading as described in Section 7.1, is thus needed to have a trailing edge HLD, the design of which is covered in Section 8.9.2.

8.9.2. Passive Lift Enhancement

Where high-lift propulsion is considered active lift enhancement, the passive lift enhancement is performed through adding leading edge (LE) and trailing edge (TE) high-lift devices. The installation of a leading edge HLD is not considered, due to structural impracticalities, imposed by the installation of propellers over the entire span. As explained in Section 8.9.1, it is determined that trailing edge HLD is needed to reach the required C_L of 3.5. To achieve the highest increase in lift from the trailing edge HLD, the propellers are placed below the wing to create the effect of an externally blown flap. The propeller slipstream will blow over the flap through the gap between the wing and flap, helping the flow remain attached to the upper surface of the flap [72]. The part of the slipstream that is blown under the flap, can make the flap turn the flow downward more efficiently. An illustration of an externally blown flap was presented in Figure 8.5.

The fowler flap configuration is chosen, as this is one of the configurations that is extended and creates a gap between the wing and flap, which is needed to enable an externally blown flap. Double and triple slotted flaps also create such a gap, but are considered to be too complex for the aircraft. However, the use of a double slotted flap containing a vane is a configuration that needs additional consideration in future detailed design. The complexity of this configuration is lower compared to a double slotted flap containing a tab, and might be very efficient for enabling an externally blown flap. Enabling an externally blown flap could increase the local angle of attack of the flap such that the angle exceeds the stall angle of attack of the flap [72]. This will reduce the effectiveness of the flap and increase drag significantly. A vane could help prevent flow separation, by generating a downstream vortical flow, re-energising the boundary layer [75]. For now, it is assumed that the fowler flap will not encounter local angles of attack exceeding the stall angle of attack of the flap.

The design of the flaps is done using a method from literature, where a maximum deflection angle of $40°$ is assumed. The flap starts directly after the rear spar, which is placed at 75% of the chord. For this deflection angle and flap chord fraction ($c_f/c = 0.25$), the fowler flap enables a chord extension of about 10-13% ($c'/c \approx 1.10 - 1.13$), depending on spanwise location. The resulting addition in lift coefficient ($\Delta C_{l_{max}}$) is about 30% added to c'/c, when fully extended. Now it is possible to determine $\Delta C_{l_{max}}$ for different spans of the fowler flap, the effect of which is shown in Figure 8.8.

In Figure 8.8, the span is taken from 0 m to 4.81 m, which is the length of the wingspan minus the length of the aileron and the part of the wing inside the fuselage. At the maximum possible span of 4.81 m, an $\Delta C_{L_{max}}$ of approximately 0.87 is found. If this span is chosen, an $C_{L_{max}}$ of 2 can be reached (see for $C_{L_{max}}$ of the wing), without the aid of distributed propulsion. If the same $\Delta C_L/C_{L_0}$ of 0.33, achieved from the high-lift propulsion system, is assumed for the wing as for the trailing edge HLD, the highest possible $C_{L_{max}}$ is 2.66. This means that the aircraft would not be able to reach the stall requirement of 50 kts, for which a C_L of 3.5 is required for the current design. The achievable stall speed with current wing loading and the $C_{L_{max}}$ value of 2.66 can be calculated with Equation (8.13) and is equal to $29.5\,\mathrm{m\,s^{-1}}$, or 57.3 kts. This value complies with the CS23 requirement of 61 kts [19]. In order to achieve a lower stall speed and meet the 50 kts requirement at this lift

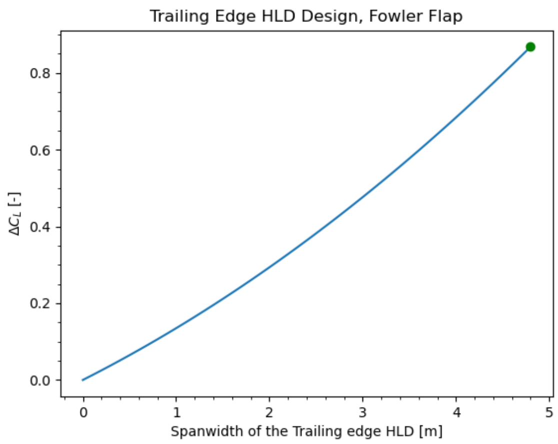


Figure 8.8: Effect of the span of the fowler flap on the increase in maximum lift coefficient, where the maximum deflection is $40°$ and the flap chord fraction ($c_f/c = 0.25$)

coefficient, a higher wing loading will be required. Furthermore, with the stall speed of 57.3 kts, The landing distance is approximated to be 514 m using Equation (7.5), failing to meet the requirement of 500 m[13]. The stall speed, and thus also the landing distance required, can be improved by reiterating on the wing sizing and designing for a larger wing area.

$$V_{stall} = \sqrt{\frac{W}{\frac{1}{2}\rho C_{L_{max}}}} \tag{8.13}$$

The consequences of this result are discussed in Section 8.9.4. For the preliminary design, the trailing edge HLD is chosen to be the 4.80 m in order to approach the stall requirement as close as possible (shown by the green dot in Figure 8.8. The assumption, that $\Delta C_L/C_{L_0}$ due to high-lift propulsion is the same for the wing and the trailing edge HLD, is very rough and is most likely inaccurate. There are several effects that make the effect of high-lift propulsion less for flaps. First, the area of the flap that is blown is smaller for the flaps, as the slipstream is contracted more at the location of the flaps, which is not taken into account. All the assumptions made in Section 8.9.1, used to calculate $\Delta C_L/C_{L_0}$, still apply for the flaps. Especially, the assumption that the induced slipstream velocity stays constant is less valid, as the slipstream has travelled a longer distance. It is also assumed that no part of the wing is above stall, which as already discussed before, is more likely in use of an externally blown flap. However, enabling an externally blown flap will increase the efficiency of the flaps. The effects of this have not been investigated, but experimental data on double slotted flaps in literature shows increases in C_L of over 50%, and some data even showing increases of over 200% [55]. This would imply that the trailing edge HLD is over-designed, however the trailing edge HLD is now kept at the same maximum possible span of 4.81 m.

8.9.3. Updated Lift Curve

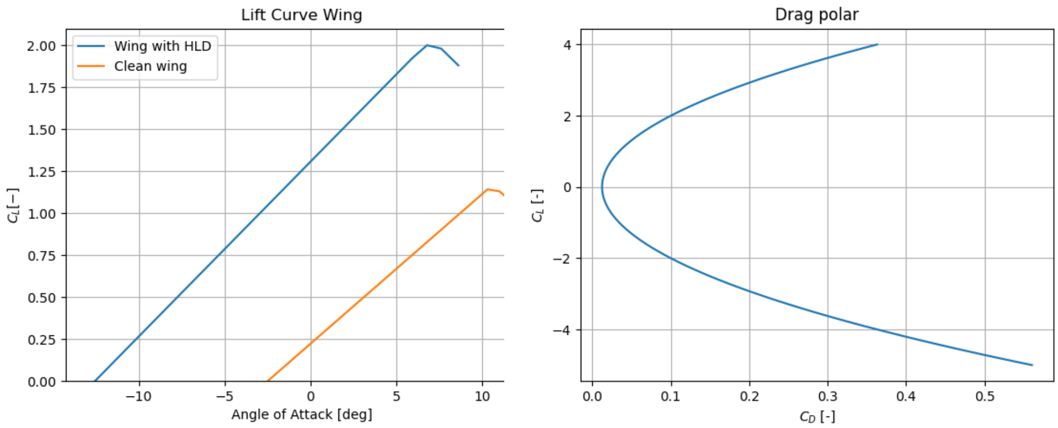
The lift curve from Section 8.1.4 can be revisited to find the difference made by the addition of fowler flaps. When HLDs are deployed, the difference in zero lift angle of attack and the new maximum lift coefficient must be accounted for. The change in the former can be seen on Equation (8.14), where $\frac{S_{wf}}{S}$ is the ratio of the effective wing area to the total wing area and Λ_{hinge_line} is the sweep angle at the hinge line. $\delta\alpha_{0L}$ can be approximated to be -10 degrees for trailing edge HLDs [70]. Furthermore, the maximum lift coefficient increases by 0.87, as discussed in Section 8.9.2. Lastly, the lift slope must be considered, which is altered whenever extended flaps are used. This effect can be expressed with Equation (8.15), where S' is the increased wing surface by the extended fowler flaps [70].

$$\Delta\alpha_{0L} = (\Delta\alpha_{0L})_{airfoil}\frac{S_{wf}}{S}cos\Lambda_{hinge_{line}} \tag{8.14}$$

$$C_{L\alpha,flapped} = \frac{S'}{S}C_{L\alpha-clean} \tag{8.15}$$

[13]REQ-STK-USR-11: The aircraft shall be able to take-off and land on 500 m runways.

Combining Equation (8.14) and Equation (8.15) results in a renewed lift curve for when the flaps are deployed. This can be seen alongside with the lift curve of the clean wing on Figure 8.9a.



(a) The lift curve after deployment of fowler flaps.

(b) Drag polar

Figure 8.9: Lift and drag curves

In Figure 8.9a it can be seen that the angle of attack decreases due to the use of fowler flaps. This requires a change in orientation of the high-lift propellers. To have the high-lift propellers aligned with the free stream flow, the negative orientation will be $6.8°$, where a negative angle of $10°$ was chosen in Section 8.7. The new orientation angle assures that local angles of attack do not exceed the stall angle of attack. The calculated increase in lift of 33%, mentioned in Section 8.9.1, is not changed as the slipstream is still aligned with the free stream flow.

8.9.4. Aerodynamic Performance Discussion

The use of high-lift propulsion and a trailing edge HLD as lift enhancement methods has attained the aircraft a preliminary $C_{L_{max}}$ of 2.66 in stall. The methods use several assumptions and the estimate is still very rough, as is discussed throughout the analysis. Regardless, the stall requirement is not met for an $C_{L_{max}}$ of 2.66. This increases the stall speed from the required 50 kts to 57.3 kts.

Future analysis must also be done on the effects that distributed propulsion has on the drag of the wing. Drag might especially increase in case the flaps are deployed. Analysis must also be done on the longitudinal stability of the aircraft, when lift enhancement is performed. The distributed propulsion will create a larger suction peak at the leading edge of the aircraft, creating a higher pitch-up moment. When the flaps are deployed, the moment will become more negative. It is suggested to deploy flaps first, before gradually turning on the high-lift propellers. Deploying the flaps after turning on the high-lift propellers will cause a sudden pitch down moment, as well as a large increase in speed when the flaps are still in clean configuration.

8.10. Drag Estimations

The performance of the aircraft in terms of lift and drag can be described by a drag polar. This polar plots the drag coefficient (C_D) as a function of the lift coefficient (C_L). The drag consist of two main components, the parasite- or zero-lift drag, and the lift induced drag. These drag components are related to the lift coefficient by formula Equation (8.18). Figure 8.9b gives the drag polar of the AmpAir aircraft.

As discussed in Section 8.9.4, there are several factors that could possibly further increase the parasite and lift-induced drag of the design. Such an increase in the drag coefficient could lead to not satisfying the requirements of the aircraft. Therefore, these increases could lead to the need for more design-iterations to satisfy these requirements. The drag polar can be used to find the $(L/D)_{max}$ of the aircraft. The $(L/D)_{max}$ at no engine operative is the most important value, since this value is valid in case of engine failure. The AmpAir aircraft has an $(L/D)_{max}$ of 19.74 during no engine operative, this value will be used further in the report.

8.11. Climb Performance

The power required by the AmpAir aircraft can be expressed with Equation (8.16), where D is the drag and V is the cruise speed. The drag can be calculated with Equation (8.17), with ρ being the air density and S being the wing surface area.

$$P_r = D \cdot V \quad (8.16)$$

$$D = \frac{1}{2} \cdot C_D \cdot \rho \cdot S \cdot V^2 \quad (8.17)$$

The drag coefficient C_D can be expressed as a function of the lift coefficient C_L, as shown in Equation (8.18). Here, A is the aspect ratio and e the Oswald efficiency. The lift coefficient in cruise can be expressed as a function of the total empty weight. This relation is shown in Equation (8.19).

$$C_D = C_{D_0} + \frac{C_L^2}{\pi A e} \quad (8.18)$$

$$C_L = \frac{2W}{V^2 \rho S} \quad (8.19)$$

Combining Equation (8.17), Equation (8.18) and Equation (8.19), Equation (8.16) can be rewritten as a function of speed. This is shown in Equation (8.20). This relationship is plotted alongside the available power in Figure 8.10. The total available power is 792 kW, as described in Chapter 8.From the plot, it can be obtained that the speed which requires the least power is $47\,\mathrm{m\,s^{-1}}$. Thus, this is the speed at which the maximum rate of climb can be achieved. This point is indicated by the green dashed line in the figure. The maximum rate of climb (RoC) can be found with Equation (8.21) and is equal to $30.55\,\mathrm{m\,s^{-1}}$, or 1833 meters per minute.

$$P_r = \frac{1}{2} \cdot \left(C_{D_0} + \frac{\left(\frac{2W}{V^2 \rho S}\right)^2}{\pi A e} \right) \cdot \rho S \cdot V^3 \quad (8.20)$$

$$RoC = \frac{(P_a - P_{\text{req}})_{\text{max}}}{W} \quad (8.21)$$

Table 8.9: Climb performance parameters with corresponding velocities, with two tip propellers operating

	Value	Corresponding velocity
Maximum climb angle	29.4 [°]	61.7 [m/s]
Maximum rate of climb	30.5 [m/s]	47.0 [m/s]

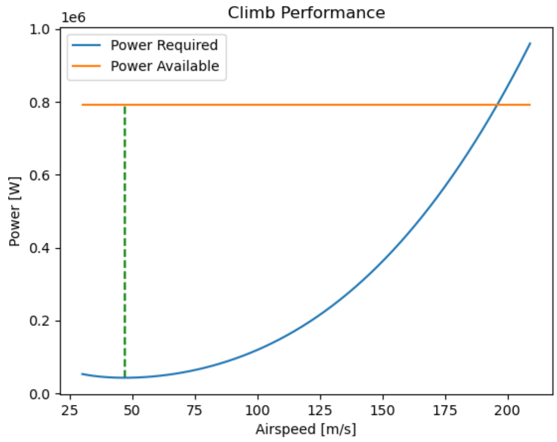


Figure 8.10: Climb Performance

Furthermore, The maximum climb angle of an aircraft is achieved whenever the $\frac{C_L}{C_D}$ is maximised [95]. The $C_{L,opt}$ at which this occurs can be calculated with Equation (8.22), where k is equal to $\frac{1}{\pi A_{effe}}$. The corresponding velocity can be found with Equation (8.23). V_{opt} is then found to be $61.7\,\mathrm{m\,s^{-1}}$.

$$C_{L,\text{opt}} = \sqrt{\frac{C_{D0}}{k}} \quad (8.22)$$

$$V_{\text{opt}} = \sqrt{\frac{W}{S} \frac{2}{\rho} \frac{1}{C_{L_{\text{opt}}}}} \quad (8.23)$$

The maximum climb angle γ of the aircraft can then be found with Equation (8.24) and is equal to $29.4°$.

The climb parameters with the two tip propellers operating are summarized in Table 8.9.

$$V_{opt} \cdot sin\gamma = \frac{P_a - P_r}{W} \tag{8.24}$$

At a pressure altitude of 1524 m, the climb performance is analysed in the event of one engine failure to comply with climb[14]. With only one propeller operational, available power is halved, and the higher altitude reduces air density. The analysis reveals a maximum climb angle of $13°$ and a maximum rate of climb of $14.39\,\mathrm{m\,s^{-1}}$. These values occur at velocities of $61.9\,\mathrm{m\,s^{-1}}$ and $47\,\mathrm{m\,s^{-1}}$, respectively. The climb gradient achievable under one-engine failure while cruising at this altitude is 38%, meeting the climb requirement[15].

[14]REQ-TP-FPP-07: For low-speed aircraft, the vehicle shall have a climb gradient of 1.5% at a pressure altitude of 1524m in cruise in case of critical loss of thrust (CS 23.2120).

[15]REQ-TP-FPP-07: For low-speed aircraft, the vehicle shall have a climb gradient of 1.5% at a pressure altitude of 1524m in cruise in case of critical loss of thrust (CS 23.2120).

9
Data and Power Diagrams

This chapter aims to present information on the data handling systems and the required hardware. The chapter does this by firstly discussing the C2 link system of the aircraft in Section 9.1. After this, Section 9.2 will discuss the satellite communication of the aircraft. Then the data handling and hardware block diagram will be discussed in Section 9.3. The communication flow diagram is discussed in the section following that (Section 9.4), and finally, the power budget is discussed in Section 9.5.

9.1. C2 Link

The C2 Link is a vital data link that connects the remotely piloted aircraft (RPA) and the remote pilot station (RPS), enabling effective flight management. It is a unique component of RPAS (Remotely Piloted Aircraft Systems). The data rates are not anticipated to be high due to the specific nature of the transmitted information. The link primarily handles voice data and commands that require only a few thousand bits. Furthermore, the aircraft communicates status information to the ground station, providing periodic updates, indicating that the system is functioning properly. In the event of any system issues, the aircraft sends an update specifying the problems encountered, never exceeding a data transmission rate of 50kbit/s. This lower data rate has the advantage that it allows for easier achievement of higher performance C2 Links.

There are several operational considerations to keep in mind. Line-of-sight (LOS) links tend to suffer from significant signal fades, especially when the RPA is in proximity to the ground. Additionally, beyond radio line-of-sight (BRLOS) links, which rely on satellite connections, can be susceptible to signal fading caused by adverse weather conditions. Moreover, signal path obstruction caused by the RPA's airframe can also lead to signal fading issues. Different strategies will be employed. Firstly, multiple antennas could be used on both the RPA and the ground, improving signal reception and transmission. Frequency diversity could be implemented to enhance signal robustness. Furthermore, employing multiple C2 Links and selecting the most optimal one in terms of signal quality and reliability can help overcome signal fading limitations.

9.1.1. C2 Link Architecture

In the design of the link architecture for aircraft control and communication, it is crucial to ensure that no changes are required in air traffic control (ATC) procedures or infrastructure. Additionally, it is important to distinguish between radio line of sight(RLOS) and beyond radio line of sight (BRLOS) communication. For effective control and communication, a direct line of sight between the aircraft and the radio station is necessary. However, this line of sight is limited in range due to factors such as the curvature of the Earth, buildings, mountains, or other obstacles that can obstruct the direct connection. A simplified figure that illustrates the availability of RLOS is given in Figure 9.1.

During take-off and landing, the very high frequency (VHF) connection is the preferred option, as it offers higher reliability. However, once the aircraft enters the cruise phase, BRLOS communication in the L band is necessary. In fact, it is recommended to utilise both BRLOS and VHF connections simultaneously to improve accuracy during critical mission phases. The C2 link architecture facilitates communication between RPA and the RPS through a radio station, collocated with the RPS, during RLOS operations. This architecture enables direct communication between the RPA and RPS with minimal additional signal delay. While RLOS is commonly used for take-off and landing, BRLOS operations come into play during the en route phase when direct communication is not possible due to the large distance between the RPA and RPS. In BRLOS scenarios, where the curvature of the earth hinders direct communication, the C2 Link can be established through the use of a SATCOM relay and a satellite dish close to the RPS. Signal delay is significantly longer than for RLOS and needs to be accounted for. For future considerations, a non-relay communication between RPA pilots and ATC can be constructed. By using VHF radio-to-VHF radio communication, direct communication between ATC and remote pilots is established without the need for additional relay through the aircraft. This

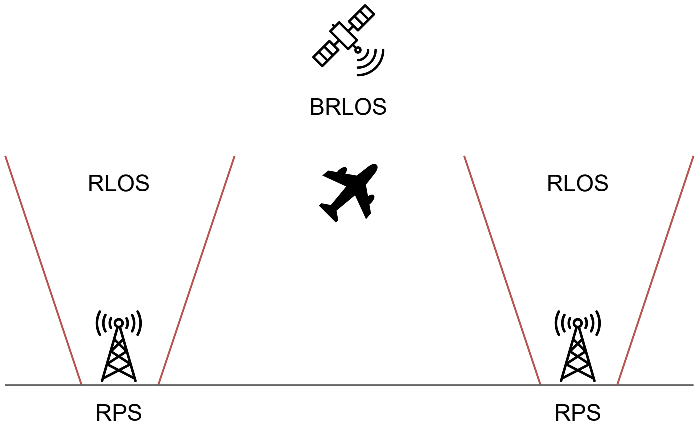


Figure 9.1: Illustration of the availability of RLOS and BRLOS during flight operations

architecture would integrate well with existing ATC infrastructure and procedures, utilising standard VHF ATC equipment available in the RPS. The outlined communication and control flow is illustrated in Figure 9.2. More details on communication as a whole is given in Figure 9.5.

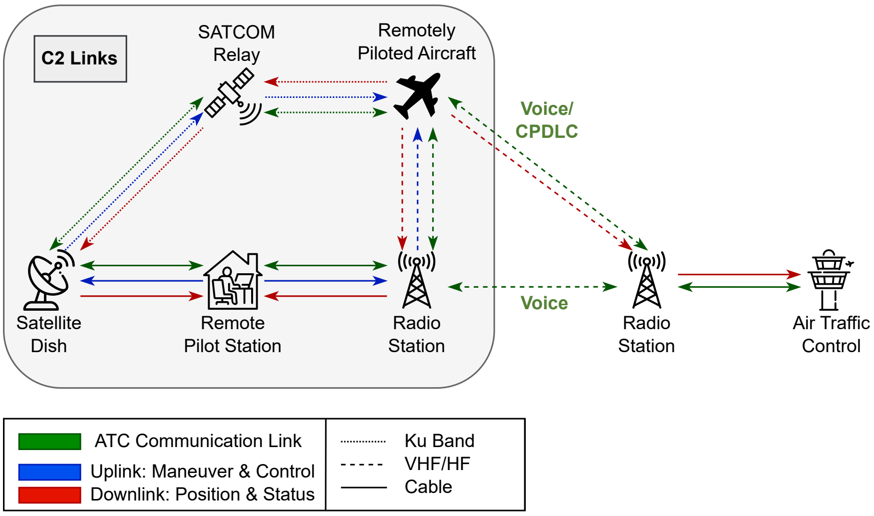


Figure 9.2: Control and communication architecture and the use of C2 links

Another consideration was to employ 4G or 5G cellular internet connections to increase dissimilar redundancy with the available C2 data links. This technology is already employed for drone operations[1]. Indeed, ZTE has built a chain of base stations in China explicitly and purely for upward transmission. They enable normal cellular service and internet connection on flights between Beijing and Shanghai[2]. However, this is not a feasible solution as cell towers usually do not point upwards. As determined in Section 2.2 the AmpAir aircraft will in nominal state cruise at about2000 m (6500 ft), an altitude above the upward range of almost all cellular towers and building a chain of cell tower stations as in China purely to point upwards may be something that happens in the future for general aviation flight, but it is unfeasible for AmpAir itself. But as the airspace and infrastructure in Europe advances, it might become possible to employ this strategy.

Additionally, the Starlink data link system is considered to support the C2 link. It offers extensive coverage in Europe[3] and boasts significantly lower latency compared to geostationary communication satellites, with a range of 20 to 40ms as opposed to approximately 600ms[4]. In 2022, Starlink announced its aviation services,

[1]https://www.kpn.com/zakelijk/internet-of-things/drones.htm
[2]https://www.thefastmode.com/technology-solutions/1341-air-china-pilots-in-flight-internet-services-using-zte-ground-air-solutions
[3]https://www.starlink.com/map
[4]https://www.starlink.com/technology

set to provide Starlink services to airlines starting from 2024. Several airlines, such as Air Baltic and Hawaiian Airlines, have agreed to test the service[5]. Promised data rates of up to 350 Mbit/s are offered, and if the service performs as intended, it has the potential to greatly enhance the C2 link for AmpAir may make it possible to remove the SATCOM system in the future.

9.1.2. Lost Link Procedures

While the C2 Link is expected to be available throughout the entire flight, there may be rare instances of degradation, failure, or unavailability. In such cases, it is crucial for RPAs to have onboard automation that ensures predictable aircraft operation, particularly within the context of air traffic management. If a loss of C2 Link occurs, the RPA will automatically notify air traffic control using a dedicated code through the Mode S XPDR. The lost C2 data link emergency procedures are analysed in Section 6.11 and figure 6.6. They describe how these situations are handled to ensure passenger safety. The potential reasons for a loss of C2 Link connection are outlined below:

1. Limited size of coverage area
2. Ionospheric/atmospheric/rain attenuation
3. Equipment or ground infrastructure failure
4. Unintentional interference
5. Malicious interference and malicious spoofing/link takeover

The management of C2 links is crucial for ensuring the reliability and safety of RPA operations. The different states and decision-making processes associated with the loss of C2 link in RPAs are explained below. This information aims to provide insights into maintaining operations and safety during such scenarios.

- **Nominal State:** In the nominal state, the C2 link is fully available, representing standard operational conditions. This enables the remote pilot to actively manage, and the observer to monitor the flight.
- **Decision State:** When the C2 link is lost, the RPA enters a decision state where it does not immediately declare a lost C2 link. Instead, it takes a certain amount of time before officially declaring the C2 link loss. This decision time allows for potential temporary disruptions or brief communication outages to be resolved, ensuring that the C2 link is genuinely lost before declaring it as such.
- **Lost Link State:** In the scenario, the remote pilot loses the ability to intervene in the management of the flight due to an unavailable C2 link. However, the aircraft is following a pre-programmed flight plan set up by the ground station using ICAO procedures. This ensures the aircraft's safe operation as it adheres to a predetermined route and parameters designed to comply with aviation regulations and ensure safety. The case where the pre-programmed flight plan is not working is discussed in Section 6.11.

Decision Time: The decision time regarding the declaration of a lost C2 link must be balanced, taking into account potential consequences. A very short decision time may result in frequent and unnecessary lost C2 declarations, causing disruption and potentially scaring the passenger. Conversely, an excessively long decision time may lead to unsafe conditions. Determining the appropriate decision time depends strongly on the RPA's phase of operation and the level of risk associated with the operating region. This analysis is yet to be done and beyond the scope of this report.
Pre-Programmed Flight Plan: According to ICAO procedures, an RPA must demonstrate the ability to follow a pre-programmed flight plan in the event of a lost C2 link. However, the exact details of these flight plans is yet to be established by ICAO. Currently, three general approaches are being considered:

1. Continuing the Flight Plan: One option is to allow the RPA to continue following the pre-programmed flight plan autonomously. This approach ensures operational continuity while minimising disruptions caused by the lost C2 link.
2. Climbing to Regain C2 Link: Another approach involves instructing the RPA to climb to a position where the C2 link can be re-established. This strategy aims to restore active control and communication as quickly as possible.
3. Hovering: In certain circumstances, instructing the RPA to hover in place until the C2 link is re-established is an appropriate course of action. This ensures stability and prevents unintended flight deviations during the lost C2 link state.

[5]https://www.aerotime.aero/articles/the-airlines-switching-to-elon-musks-starlink

Because of the absence of a harmonised course of action, as recommended by the ICAO, it is essential for RPAs to possess adaptability to perform all the aforementioned actions. By being equipped with the capability to execute various responses during a lost C2 link state, the RPAs ensure compliance with future regulations and swiftly adapt to changing operational requirements.

9.1.3. Security

The security of C2 links of remotely piloted aircraft is a source of significant concern, as internationally harmonised security requirements are not yet in place. A threat to the aircraft operations are malicious interference or spoofing. Therefore, it is crucial to develop a security system that is adaptable and can meet future security requirements effectively. Key aspects of C2 link security include authentication, integrity, confidentiality, and end-to-end encryption. Authentication ensures that only qualified individuals have access to equipment, while integrity maintains data accuracy during transmission. Confidentiality protects sensitive information, limiting access to authorised entities. End-to-end encryption secures data from unauthorised access during operation. The implementation of these security measures for C2 links in remotely piloted aircraft will be addressed in future design stages.

9.2. SATCOM Analysis

The SATCOM antenna must be sized based on the available link budget and the required data rates for the C2 data link, as mentioned in Section 9.1. It is planned to use the Ku-band frequency range for transmission, as is common for commercial aircraft [6]. The expected data rate is not expected to exceed 50 kbit/s, and this is the data rate for which the SATCOM antenna needs to be sized. The scenario that is considered here looks at the transmission from the geostationary satellite to the AmpAir aircraft.

9.2.1. Link Budget

The calculation process and parameters are derived from and adhere to the guidelines for link budget analysis outlined in the reference [95]. The provided values are approximations from the same document:

- Output Power Pt: 5 W
- Transmitter Gain Gt: for a parabolic antenna it can be calculated by

$$Gt = 6 * A/\lambda^2 \tag{9.1}$$

If we assume a diameter of 15 cm and the carrier frequency is assumed to be 14 GHz, yielding a wavelength λ of 0.0214 m, this becomes:

- Gt: 24.7 dBi

Now the effective isotropic radiating power EIRP is given by:

$$EIRP = Pt \cdot L \cdot Gt \tag{9.2}$$

With assuming a cable loss L of 0 this yields an EIRP of

- EIRP: 61.7 dBm

Next step is to determine the power received by the receiver through the Friis Transmission equation

$$Pr = \frac{EIRP \cdot Gr \cdot \lambda^2}{(4 \cdot \pi \cdot d)^2} \cdot \eta_r \tag{9.3}$$

By assuming that the communication satellite has a diameter of 1.8 m Eq. (9.1) yields an Gr of 46.27 dBi. The distance to a geostationary satellite d is about $35\,786$ km. And an average receiver antenna has an efficiency of η_r = 0.5[7] All this together gives:

- Pr : 7 x 10^{-14} W

[6] https://www.satmodo.com/blog/2019/11/25/ku-band-and-its-use-in-satellite-communications/
[7] https://www.mouser.com/pdfDocs/radiatedefficiencyatruemeasureofantennaperformance.pdf

Important now is to check the signal-to-noise ratio as:

$$Eb/No = \frac{Pr}{k \cdot T \cdot DR} \tag{9.4}$$

where k is the Boltzmann constant $1.38 \times 10^{-23}\,\mathrm{J\,K^{-1}}$ and T the noise temperature, in this case assumed to be $135\,\mathrm{K}$. DR is the required data rate of 50 kbit/s. All these values together yield a signal-to-noise ratio of:

- Eb/No = 758

The analysis suggests that the aircraft SATCOM transceiver requires an antenna with an estimated diameter of approximately 15 cm to achieve the desired link budget and maintain reliable communication. This would result in a very good signal-to-noise ratio. This value was then used to size the SATCOM antenna on top of the fuselage. However, it is important to note that in this specific case, only free space loss was considered, and no noise effects due to rain or fade were accounted for. Rain fade, in particular, is a concern for frequencies above 11 GHz[8] as in this case. Therefore, having a high signal-to-noise ratio does not guarantee reception under all circumstances. A more comprehensive analysis, considering all atmospheric effects, is beyond the scope of this report. A similar analysis was conducted for transmissions from the aircraft to the satellite, yielding similar results.

9.3. Data Handling and Hardware Block Diagram

In order for the AmpAir aircraft to function, data from different systems must be collected, transported and processed. It has been decided that AmpAir will use ARINC 429 to connect avionics equipment with one another and allow the exchange of data. The different hardware and the data flow between them is visualised in Figure 9.3. The following subsections give a brief explanation about the different systems.

9.3.1. Modular Avionics Unit

The modular avionics unit (MAU) serves as the data processing and handling hub. Within the MAU, processors perform the flight management tasks, flight director and thrust director functions, and communication management functions. The MAU also includes modules for data acquisition, earth ground and proximity warning, graphics modules for flight screens, the highway in the sky-graphics module (HITS-GM), the central maintenance computer (CMC), the environmental control system (ECS), all relevant databases for the flight management, passenger control modules and a communication and control module for processing ground station inputs. All these processors are connected through the network interface controller (NIC) which distributes information from one processor to the other within the MAU. The MAU collects and distributes data through its data acquisition units (DAU) from and to other systems in the aircraft. Internal sensors monitor cabin conditions to ensure passenger comfort, with the ECS dynamically adjusting heating and ventilation systems to maintain desired conditions.

9.3.2. Navigation and Surveillance

The navigation system utilises smart probes, true air temperature (TAT) sensors, air data computers (ADC), attitude and heading reference systems (AHRS), inertial reference systems (IRS), traffic alert and collision avoidance system II (TCAS II), radar altimeters, GPS, localizer antennas, glide slope antennas, and a Mode S antenna. These components work together to provide precise aircraft positioning, landing capabilities, air data measurements, attitude and heading information, collision avoidance capabilities, altitude control, navigation guidance, and communication with air traffic control systems. Additionally, the AmpAir aircraft incorporates a weather radar positioned at the nose to provide valuable weather information for improved flight planning and safety. Information on surveillance is given in Section 9.4.

9.3.3. Indicating and Recording

The MAU processes all information and displays it trough its displaying it through its avionics graphic modules (AGM) on the electronic flight instrument system. This comprises the primary flight display (PFD), providing the "highway in the sky" system for passengers, and the multi functional display (MFD), presenting various status information relevant to the passengers. The flight data acquisition unit (FDAU) receives data from the CMC, recording data in the flight data recorder (FDR) and the cockpit voice recorder (CVR) captures

[8] https://www.everythingrf.com/community/what-is-rain-fade

the flight deck's audio environment for incident investigation. More information on communications will be given in Section 9.4. The indicating systems in the cockpit interface (PFD and MFD), will be covered by a waterproof screen. The rest of the interfaces and buttons are also waterproof, to prevent spilling of beverages causing any avionics failure. Consuming beverages is also prohibited during take-off, landing and turbulence.

9.3.4. Flight Control System

The flight control computer (FCC) interfaces with the flight data concentrator (FDC) and the actuator control and monitoring unit (ACMU). The FCC assumes autopilot and yaw damper functions, receiving inputs from the FDC, which collects data from the Flight Director (FD) or direct control inputs. The FCC sends commands to the ACMU to manage control surfaces and high-lift devices such as rudders, ailerons, elevators, and flaps. Position sensors provide feedback to the FDC, and the maintenance and avionics interface computer (MAIC) ensures accurate deflection measurements. The MAIC collects status information about the FCC, FDC, and ACMU, as well as Flight Control Law and surface positions, and sends it to the MAU for further processing and display.

9.3.5. Propulsion System

The thrust director (TD) handles the auto thrust function, issuing commands to the full authority digital engine control (FADEC) to regulate thrust. In addition, the ECS is connected to the battery management unit (BMU), propulsion management unit (PMU), and cooling control. These units provide relevant status information to the ECS, which then distributes the information over the NIC to the CMC and AGM. The CMC records the data and the AGM displays it on the MFD.

9.3.6. Passenger Interface

The passenger has access to the speaker and headset, control stick and emergency and communication buttons. Also these will be waterproof. More information on the Ballistic Recovery System is given in Section 6.11.5.

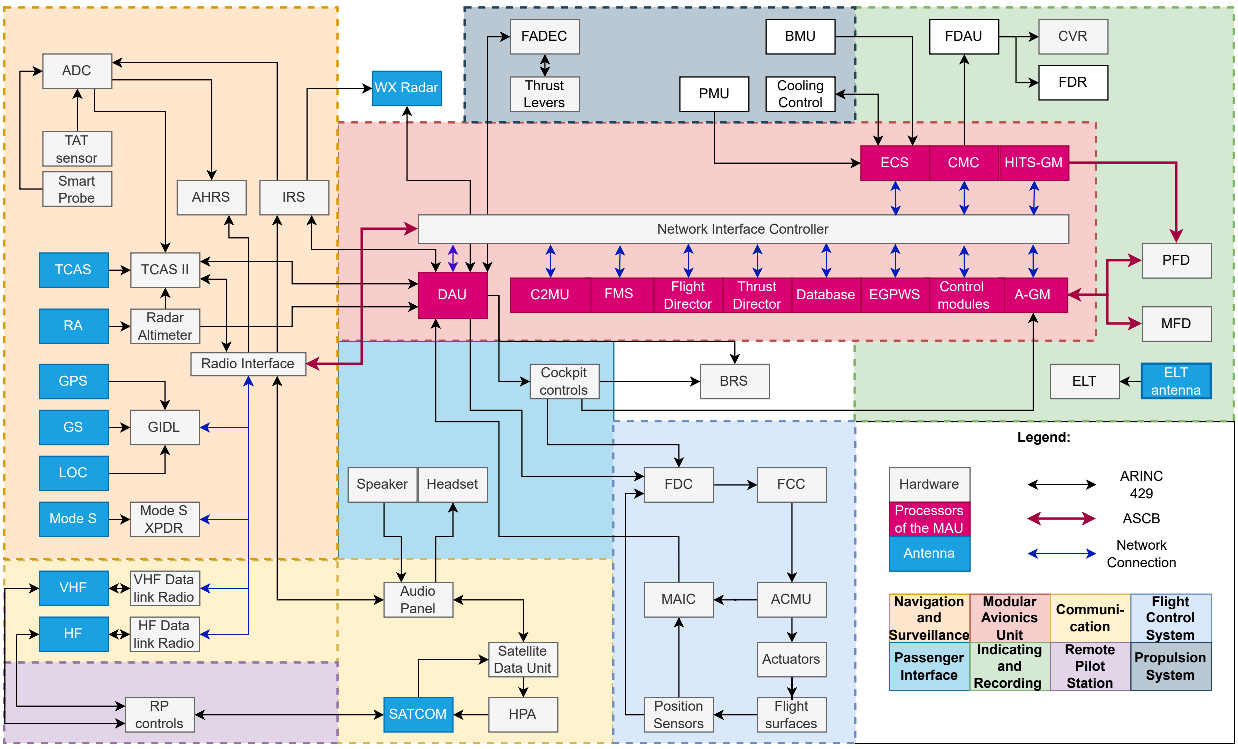


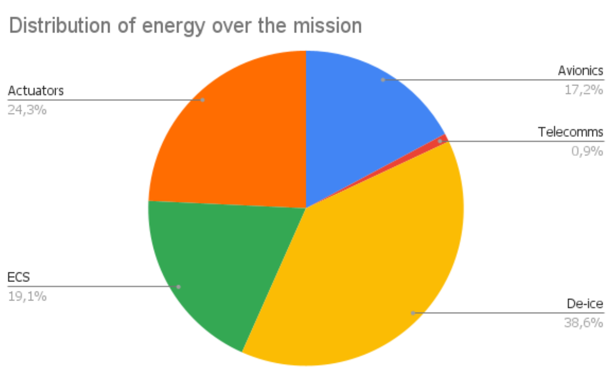
Figure 9.3: Data Handling and Hardware: The Modular Avionics Unit (MAU) as the Central Hub

9.4. Communication Flow Diagram

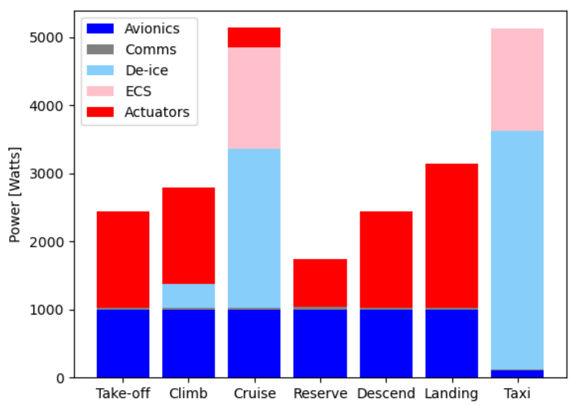
The flow of communications and surveillance is complex, so a separate flow diagram, Figure 9.5, was created to visualise it. The key components include CPDLC communication between the aircraft and ATC, the ADS-B surveillance system, and communication channels such as VHF, HF, and SATCOM. TCAS II is used to identify cooperative aircraft and provide audio and visual warnings for passengers to ensure their safety. The Mode S XPDR is used to receive and send surveillance information to ATC, especially regarding non-cooperative aircraft. However, identifying non-cooperative aircraft independently, without relying solely on information provided by ATC, is beyond the scope of this report. Passengers can contact the observer through the help button, as specified in Chapter 6, and communicate using the speaker, receiving feedback via the headset. ATC communication can be initiated through the ATC button if the conditions mentioned in Chapter 6 apply; otherwise, clearance can be requested by pressing the clearance button. All communication is managed through the audio panel and either the satellite data unit or the VHF/HF data link radios. The communications and control module within the MAU ensures that the aircraft is always connected through the best available communication options. The specific details regarding handover events between VHF/HF and SATCOM and between radio towers are beyond the scope of this report. This is a preliminary design optimised for stage 2 of the growth model presented in Chapter 5.

9.5. Power Budget

The power budget and allocation determines how much energy a subsystem will receive and how it is connected. The power budget for the AmpAir aircraft will be dominated by the engines, as 95% of the energy consumption is due to the propulsion. However, it will also consider the estimated power for avionics, telecommunications, de-icing system, Environment Control System (ECS), and actuator power supply. All other systems' contribution to the power budget are considered negligible. In Table 8.4, the power consumption for each mission was determined. During the creation of the power budget, the following assumptions were made based on Section 7.8 and Section 6.3: The avionics power is constant and equal to 1kW for the entire duration of the mission. The telecommunications and data transmission will require 50 W of power throughout the mission. A de-icing system, implemented in the aerodynamic surfaces of the wing, consumes 3.6 kW during critical sections of the mission based on Section 7.8.6. Environment Control System (ECS) provides the power for in-cabin systems and climate control, consuming 1.5 kW over the duration of the entire mission. During loitering, it is assumed that the ECS is deactivated to save power for more critical purposes. Lastly, the energy usage of the actuators has been calculated by assuming the work done by the actuator is equal to 11 kJ. This is based on a rotating actuator that deflects $50°$, using a torque up to 5 kNm. A conservative overestimate is that this action is to be done 1000 times per mission. This over-design is implemented to account for possible losses and multiple actuators operating during the mission in future AmpAir designs. From this, the remaining 5% of energy, that is not used on the propulsion subsystem, is divided among other subsystems as shown in Figure 9.4a.



(a) Distribution of the remaining 5% of energy



(b) Distribution of additional power to other subsystems

Figure 9.4: Power and energy diagrams

Another constraint on subsystem energy usage is the power required during different mission stages. As seen in Table 8.4, take-off is the demanding in terms of power, followed by climb and landing. It is therefore beneficial for the battery life to disconnect all non-essential power consuming subsystems from the power source during take-off and minimise their usage during climb and landing. This can only be done for non-critical subsystems which are not required to have continuous power, like the de-icing or ECS systems. Subsystems like actuators, certain avionics, and telecommunications must have a continuous power supply throughout the mission and cannot be disconnected from the battery, also not during the critical mission phases.

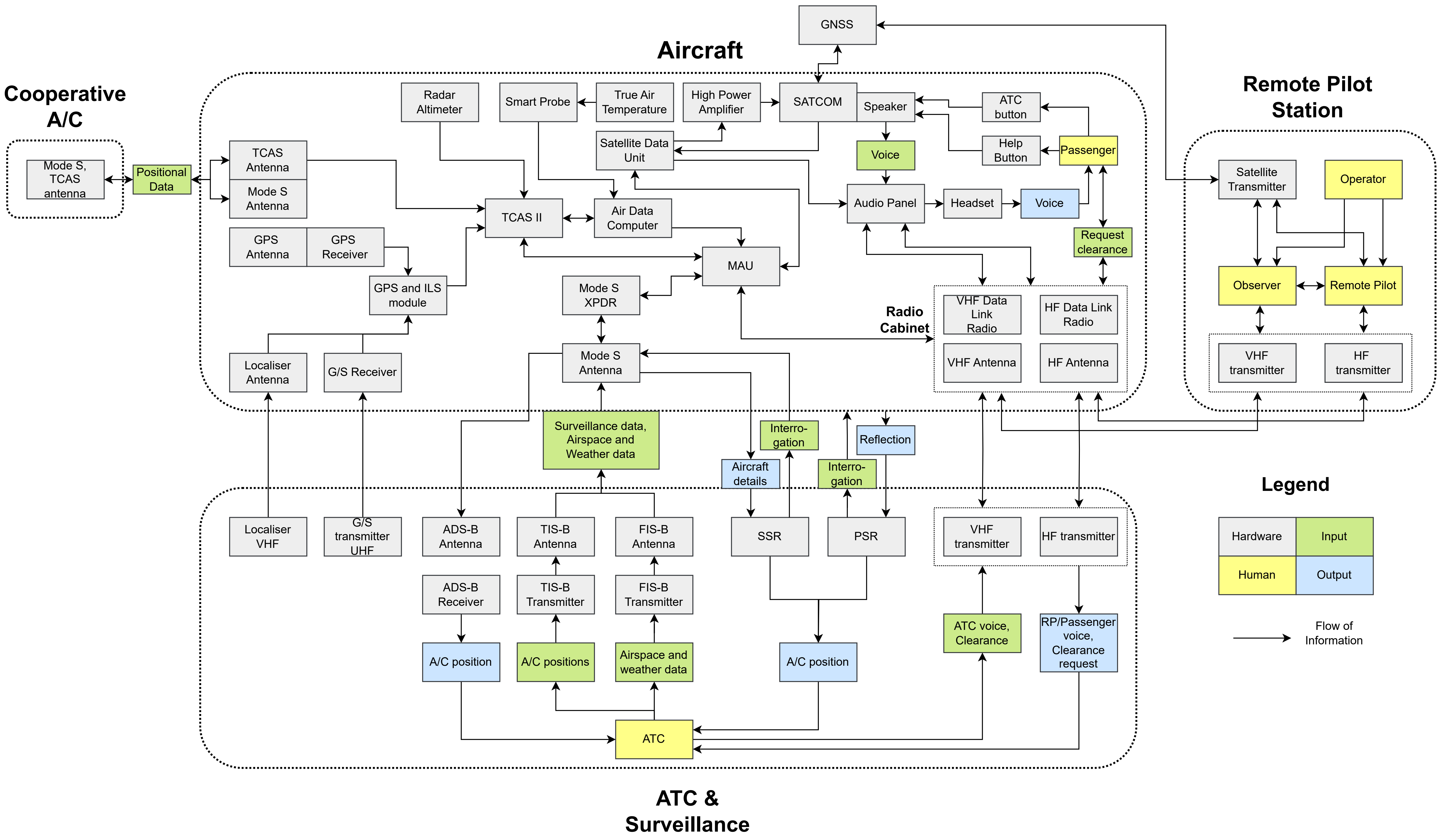


Figure 9.5: Communications and surveillance flow diagram

From Figure 9.4b, it can be seen that there will always be power provided to the avionics since they must be maintained for a constant performance. At taxi, power for avionics is reduced to minimize consumption, as most avionics are placed on standby (Section 9.3). Communications, as determined in Section 9.2.1, the power assigned for data transferring is 10 watts. However, to comply with analysis from link budget conclusions taken from the midterm report as well as from Section 9.2.1, the power allocated for data transferring is 25 W constantly with an exception during reserve, where the power is incremented to 37.5 W to expand the radius of coverage for emergency scenarios. De-icing within this power budget is highly restrictive. The true power usage will be maximum when environment temperatures during the mission are lower. For this scenario, maximum power for de-icing is implemented during taxi and standby while on group, to remove ice from the wings. To safe power, the de-icing system is off during take-off, descend and landing, on reduced power during climb and on two thirds of maximum power for de-ice for cruise. For reserve/loiter, de-icing is not considered critical. ECS is only switched on during taxiing and cruise to safe power, since sections of during the mission are most important to improve user experience and comfort. lastly, actuators are operational during the entire mission on the air. Power is only reduced for cruise as actuator power is averaged out during cruise time, which does not require manoeuvres continuously. The same applies for reserve but with a larger margin. Landing on the other hand is increased by 50% for redundancy for possible corrections for gust loads and unexpected manoeuvres. The overall increase in power during each mission phase can be summarised in Table 9.1: Since this increase in power has lead to an increase in energy required, the battery

Table 9.1: Power increase over mission power from Table 8.4

	Take-off	Climb	Cruise	Reserve	Descend	Landing	Taxi
Power increase [%]	0.51	0.71	4.61	8.63	1.01	2.76	11,01

efficiency previously considered of 80% is no longer valid. Currently, a battery efficiency of 82% has been assumed, which implies that the depth of discharge has been increased, thus a reduction in battery cycle life, or a worsened end of life performance of the battery, which leads to a lowered range or lowered payload. In a realistic scenario, the battery life during operation is to be monitored to know the true range of the battery.

10 Sustainable Development Strategy

One of AmpAirs' goals is to create a regional air taxi service, sustainably. The Sustainable Development Strategy (SDS) consists of different aspects: Firstly, the AmpAir aircraft will be emission-free during flight, as explained in Section 10.1. On top of that, Section 10.5 proves that noise pollution is minimised by implementing distributed propulsion. Next to that, the way in which AmpAir sources their resources will be done in a socially sustainable way, as laid out in Section 10.2. Finally, Section 10.3 and Section 10.4 explain how the manufacturing and End-of-Life (EOL) practices are designed in such a way to reduce waste to less than 10% of the aircraft weight.

10.1. Emissions

The operational phase makes up over 75% of the total climate impact of an aircraft life cycle. This is because of greenhouse gases, but also other warming effects like contrail and NOx production [51]. First and foremost, the AmpAir aircraft will be emission-free because of its electric propulsion system. When considering direct aircraft emissions, battery powered electric propulsion cause the lowest atmospheric warming effect from all propulsion options [4, 15, 56, 82]. However, fully electrified aircraft still have lifetime CO2 emissions that stem from battery production and battery charging [84], which can be up to 20% higher than jet variants [84]. This highlights the importance of non-CO2 related warming effects. Electric aircraft have a 30% lower warming effect than equivalent kerosene combustion aircraft because of the absence of NOx or contrail creation [36, 56, 57].

Another source of CO2 emissions in the life-cycle of electric aircraft happens during the LIB manufacturing process. During manufacturing, 350 MJ-650 MJ per kWh is required and 150 kg–200 kg of CO2 per kWh is emitted. Additionally, battery-grade materials must first be produced, emitting about 60 kg–70 kg of CO2 per kWh. Up to half of these emissions stem from the cathode and anode production. By recuperating the nickel and cobalt from EOL LIBs, energy of cathode production can be reduced by up to 51%. The step of shaping and assembling the battery-grade materials emits another 70 kg–110 kg CO2 per kWh. In conclusion, up to 380 kg of CO2 per kWh is emitted during production of LIBs [21]. An electric aircraft fleet of all global aircraft, operating between 400 and 600 nautical miles, would require up to 1.7% of the global energy consumption [84]. Therefore, the energy required to charge the batteries must come from renewable energy to avoid indirect GHG emissions, making it an integral part of the SDS.

10.2. Social Sustainability

The AmpAir aircraft will store its energy in LIB, of which the production is already under strain because of an uncertain supply chain threatened by geopolitical conflict in mining regions. Examples of this are cobalt, which is mined in the Congo, lithium, which is predominantly sourced in Australia and Chile, and graphite, which mainly comes from China [10]. To secure the longevity of the AmpAir battery-electric aircraft, the social sustainability of battery production must be included in the SDS.

Current battery design depends on raw materials that are mined and processed in ways that are detrimental to local ecosystems and communities. Lithium, an essential component in LIB, negatively impacts local freshwater systems by depleting groundwater reserves, decreasing vegetation and exterminating wildlife in mining regions. Next to that, local agriculture is constantly threatened by the risk of lithium brine leaking, causing potential food scarcity. These effects are already present under the current LIB production scale. Implementing LIB batteries in electric aircraft will only increase this pressure, as lithium demand is predicted to double by 2035 [11]. The communities in mining regions often receive minimal amounts of revenue from the resources that are extracted by international companies from their land, and are often left with highly polluted plots of land after resource depletion. Human rights are often violated, and geopolitical conflict threatens the people in regions of cobalt production in the Congo [11].

It is of utmost importance that a surveillance system is introduced to protect these communities and ecosystems from further harm. Furthermore, AmpAir will partner with suppliers that provide traceable production lines, have batteries without cobalt and are investing in better mining practices. The additional cost of these batteries is quickly outweighed by the moral obligation to stop corruption and pollution in this industry.

10.3. Manufacturing

Creating an aircraft that is sustainable all throughout its life cycle begins with minimising emissions and waste during production [37]. Firstly, all components must be designed optimally to use as little material as possible while creating minimal waste. Next to that, AmpAir will partner with companies that use sustainable energy sources, which significantly lowers the Global Warming Potential during production [68]. Today, the bought-over-used ratio of pre-woven pre-preg composite fabric is stuck at 1.5, even with proper nesting [1]. Additionally, the carbon fibres originate from fossil fuels. Manufacturing methods should be optimized to reduce waste in all aspects. For this, the lean manufacturing ideology will be applied [24, 86], as further explained in Chapter 11. Manufacturing methods need to limit their energy usage. The manufacturing and assembly line should be arranged such that transportation of people and products is minimised and smart climate control methods shall be applied to maintain pleasant working conditions while using as little energy as possible. Between 5%-40% of batteries are discarded immediately after manufacturing. This is due to the fact that small flaws can significantly affect the quality of the electrochemical performance, caused by high interdependencies [11]. Improving battery design to reduce the amount of interdependencies will further reduce waste.

10.4. Sustainability in the End-of-Life Strategy

The last component of the SDS is complying to EOL requirement[1]: 90% of the EOL aircraft will not go to waste. This means that virtually all aircraft components must be recycled, down cycled or repurposed. Reducing the EOL waste is essential to limit the use of finite resources and help manage the large volumes of waste that, otherwise, would have to be disposed somewhere [73]. AmpAir will implement two recycling ideologies: direct and indirect re-use, as discussed in Section 10.4.1. Next, material consideration that will increase the EOL product recyclability are discussed in Section 10.4.2. Lastly, in Section 10.4.3, the EOL battery strategy is presented.

10.4.1. Direct and Indirect Re-use

At the end-of-life, there will be systems or parts that are still functional. These can be recuperated from the aircraft during disassembly. After retrieval, the component will go through quality control, to ensure its performance is as expected. After passing these checks, the component can be directly re-used in a new aircraft. In order for this to work, the new aircraft should be designed such that the reused component fits. In case the components fail the quality control checks, they can be repurposed to serve different functions, like art, as done by the Belgian company Aero Circular [2]. There will also be components which cannot be reused in a different aircraft or fail quality control after manufacturing. These products will be indirectly reused. Several examples of how this will be done are given below.

- **Cooling lines** These lines are mainly made out of thermoplastics. These are easy to recycle, so they will be sent to companies that are specialised in this.
- **Cables** Electrical cabling consist of two materials that can be recycled, thermoplastics and copper. They are easily separated, and after that, they will be shipped to specialised recycling companies.
- **Engines** The engines will be disassembled, and their metal components will be sent to a recycling facility.
- **Structural components** The structure of the aircraft is fully made out of thermoset composites. Their recycling is further discussed in Section 10.4.2
- **Propellers** The propellers will be sent to specialised recycling facilities.

[1] REQ-STK-OPE-04: At the end of the service life, 90% of the aircraft should be reused or recycled.
[2] http://aerocircular.green/ [Accessed on 26.5.2023]

10.4.2. Material Choice For Reducing EOL Waste

Because the aircraft primary and secondary structures will be made of composite materials, a recycling strategy must be set up in order to achieve EOL[3]. Currently, carbon fibre composites are often combusted to generate energy, or they go to landfill. This is because material separation technology is not mature yet, while waste disposal is cheap [73]. Recycling technologies are currently very energy intensive and, in case of chemical separation technologies, they create hazardous material, which could contaminate the environment. A major hurdle of composite recycling is that currently, there are no facilities or infrastructure to collect, sort and separate the material [100]. There are two approaches for recycling composite materials. One can separate the fibres from the matrix or down cycle the material [1]. The quality and material properties of the extracted fibres greatly depend on the type of composite and method of extraction. Research of Boeing on the 777 and 787 has shown that fibres can be recovered from the matrix while having the same properties as the virgin fibre, meaning they could be reused in high-end applications [100]. However, most methods require the large component to be cut into smaller sections, meaning there are no methods to extract a continuous fibre again. A major limitation of this is the reduced length of the fibres, leading to lower strength and stiffness. The second strategy is a solvent-assisted process that transforms the thermoset into a new class of materials called vitrimer polymers[4]. This new type of plastics can be reformed by thermally activating chemical reactions in the vitrimer[5], which allows the material to be reformed into a new component. It is expected that recycling facilities will scale up and improve in the near future, and AmpAir is choosing materials based on developments in the industry. If recuperating the fibres from the matrix is not possible, the material can be down cycled. Here, a chemical is used to break the links within the thermoset. Afterward, the material is ground into a powder[6]. This material can then be used in lower-end applications, like fillers. Recyclate powders have been used in composite components to provide better noise insulation [73].

10.4.3. Battery EOL

Within the foreseeable future, in order to support the increased battery production that comes with the electrification of aircraft, better collection and recycling facilities must be developed. Recycling of LIBs is not common practice. This is proven by the fact that only 5% of LIBs were recycled in 2019, far below what must be recycled to sustain the predicted LIB production rates [74]. Having LIBs end up in landfill must be avoided for two reasons: Firstly, they contain toxic and flammable materials that are a safety hazard to both people and the environment. Secondly, they contain exhaustible materials that are threatened to run out if mining trends continue as is. To enable successful large-scale recycling of LIBs, collection infrastructure must improve. Current collection capacity is less than 50% [99], because of their class 9 hazardous material classification, making their transportation to recycling facilities highly regulated, potentially hazardous and costly. Establishing local recycling facilities can reduce transportation cost and by implementing tracking IDs for every aircraft battery, as done by China since 2018 [10], monitoring the full life-cycle becomes possible.

Aircraft batteries that are considered to be at their EOL still contain 80% of their original capacity [10, 77]. This means a significant amount of energy can still be stored and extracted from the battery. Remanufacturing will restore them to their original performance, but requires rigorous quality checks before re-implementation. Therefore, AmpAir will focus on re-purposing these batteries for other applications, like in the automotive industry or for grid storage. Once the battery has degraded below this level, it must be recycled. Recycling technology is still immature, but there is growing research on the topic [50]. Due to the complex chemical composition of a battery, the recycling is a multistep process [10]. Current battery recycling is focused on rare metal recovery, such as cobalt, nickel and copper, to regain as much economic value as possible. Afterward, the remaining material is often disposed of as waste in landfills [74]. Current recycling technologies have high energy consumption and low yield, but recovers economic value by reintroducing rare metals back into the production chain, reducing the strain on supply chains of exhaustible materials [50].

The way in which batteries are developed is currently solemnly focused on increasing energy density. This is achieved by using exhaustible cathode/anode materials, which pose ethical concerns as described in Section 10.2. There are multiple reasons to change the battery design. In order for LIB recycling to become feasible on a large scale, efficient, modular separation processes must be set up that are adaptable to different battery compositions. Recycling facilities must be equipped with the necessary tools to handle these different

[3] REQ-STK-OPE-04: At the end of the service life, 90% of the aircraft should be reused or recycled.
[4] https://en.wikipedia.org/wiki/Vitrimers
[5] https://www.recyclingtoday.com/news/case-western-researchers-develop-technology-recycle-plastic-scrap/#˜text=Thermoset%20is%20another%20type%20of,have%20a%20cross%2Dlink%20structure.
[6] https://news.mit.edu/2020/tough-thermoset-plastics-recyclable-0722

architectures [10, 99]. Flexibility and robustness in recycling methods are essential to accommodate changes in battery composition driven by factors like efficiency improvement and cost reduction. In the future, battery design will evolve to use materials that have an infinite supply. Additionally, it is expected that battery recycling technology will have developed to be able to process all EOL batteries. And the economic, ecological and longevity must be assessed, proving the overall benefit of recycling batteries [10]. AmpAir will lobby for better recycling guidelines and incentive programs, protecting communities and benefiting governments in achieving emission goals [11].

10.5. Propulsion Noise

The primary source of noise within an aircraft resides in its propulsion subsystem. High noise levels have been found to have adverse effects on communities. Namely, they can negatively influence children's cognitive abilities, as well as disturb sleep patterns and cause higher levels of irritability and annoyance [6]. Due to these reasons, noise requirement[7] stipulates that the aircraft's emitted noise is limited to 60 dB at a distance of 1000 ft [30]. As stated in the midterm report, Electrical engines have a potential noise reduction of 50% during take-off, compared to traditional internal combustion engines [84]. However, because the battery weight remains constant during flight, their landing noise can be up to 15% louder, due to the relation between aircraft noise and weight. Reducing the aircraft noise can allow extended operational hours and additional flight routes due to the fact that noise constraints will no longer night operations and populated villages any more[30].

As described in the midterm report, the propeller noise can be described by two key factors: the tone and the sound pressure level (SPL). The tone refers to the frequency of the noise, influencing its pleasantness to the human ear, while the SPL indicates the intensity. Among the various tones, one of great significance is the blade passage frequency, which corresponds to the frequency at which the propeller blades traverse through the air. This particular tonal frequency, denoted as f_1, can be determined using the following equation (Eq. (10.1)), where n_p represents the rotational speed in rotations per minute, and B signifies the number of blades [85]. It is generally preferable to have lower frequencies, as they are perceived as less bothersome [30].

$$f_1 = B \cdot \frac{n_p}{60} \tag{10.1}$$

Moreover, the sound pressure level produced by the propeller in a piston engine aircraft can be approximated using an empirical correlation, which is denoted by equation Eq. (10.2). In this equation, $SPL_{1,max}$ signifies the sound pressure level at a distance of one meter from the source, measured in the direction of maximum intensity [dB][30]. P_{br} represents the engine power [kW], D corresponds to the propeller diameter [m], M_t indicates the rotational tip Mach number, and N_p denotes the number of propellers on the aircraft. The rotational tip Mach number, M_t, can be calculated using equation Eq. (10.3), where c denotes the speed of sound [m/s] [85].

$$SPL_{1,max} = 83.4 + 15.3 \cdot log(P_{br}) - 20 \cdot log(D) + 38.5 \cdot M_t - 3(B-2) + 10 \cdot log(N_p) \tag{10.2}$$

$$M_t = \frac{\pi D}{c} \frac{n_p}{60} \tag{10.3}$$

As AmpAir is fully battery-electric, it is expected that the engine noise is lower than that of conventional aircraft. As mentioned in the midterm report, research conducted by Hallez et al. (2018) examined the acoustic performance of the Extra 330 and the Magnus Fusion 2-seater aircraft. Both were equipped with either a combustion engine or an electric motor [33]. The findings revealed that the noise during fly-overs was reduced by 14 dB when using electric propulsion. Consequently, a correction of -14 dB will be incorporated into equation Eq. (10.3) for the initial calculations [30]. Additionally, it is important to consider the effect of sound attenuation. This phenomenon plays a crucial role in predicting the impact of noise on the ground by accounting for the variations in the sound pressure level as it travels through the atmosphere. The final sound pressure level, denoted as SPL, can be calculated using equation Eq. (10.4), where r represents the distance from the noise source in meters, and α represents the sound attenuation coefficient for a particular frequency through the atmosphere in decibels per meter[30].

[7] REQ-STK-USR-02: The vehicle shall not be louder than 60 dB(A) at 1000 ft.

$$SPL = SPL_{1,max} - 20 \cdot log(r) - \alpha r \quad (10.4)$$

The value of α depends on the tonal frequency, temperature, and relative humidity [85]. A lower relative humidity results in a higher α. Generally, the sound attenuation coefficient ranges from 10^{-4}dB/m to 10^{-3}dB/m. Consequently, at 1000 ft altitude, the effect of atmospheric sound attenuation is approximately limited to 0.2 dB to 2.5 dB [85].

With the parameters of the propellers and their rotational speeds known and described in Section 8.5, the definitive calculation can be done on the estimated noise sound pressure level at $1000ft$, as well as the cruise altitude of 2000 m. An altitude of 1000 ft is evaluated in order to confirm noise[8]. Cruise conditions are considered, as this will be the bulk of the flight. The results of the analysis can be found in Table 10.1.

The frequencies of the noise and its sound pressure level at 1 m and on ground were calculated for the case where only the tip propellers are used. It can be seen that both when cruising at 1000 ft or 2000 m, the frequencies are on the lower side of the human hearable spectrum, which are preferred over higher frequencies in terms of pleasantness [85]. Furthermore, the SPL at 1000 ft is 51.9 dB, satisfying noise[9]. It also has to be noted that the noise heard on the ground when AmpAir is flying at its cruise altitude of 2000 m has an SPL of 34.4 dB, which is barely perceptible to humans[10].

Moreover, the noise SPL at 1 m distance is expected to be no higher than 103 dB during cruise. Assuming a fuselage sound attenuation of 20 dB [47], the noise inside the cabin can be limited to 83 dB, meeting maximum noise[11], that states 85 dB. Furthermore, by using noise-cancelling headphones, the experienced noise SPL will be reduced by 30 dB[12]. This means the noise in the cabin, using damping devices, is expected to be 53 dB, meeting cabin noise requirement[13] that states a maximum of 65 dB.

Table 10.1: Characteristics of noise emitted when cruising at 1000 ft or 2000 m.

Cruise Altitude	Frequency [Hz]	SPL at 1 m [dB]	SPL on ground [dB]
1000 ft	114	102	51.9
2000 m	150	103	34.4

For further analysis, the noise emitted during the climb phase is evaluated. In this phase, all propellers are deployed, and the tip propellers are operating at higher power than during cruise. The results found can be found in Table 10.2.

Table 10.2: Characteristics of noise emitted during climb.

	Frequency [Hz]	SPL at 1 m [dB]	SPL on ground [dB]
High-Lift Propellers	149	126.8	76.7
Tip Propellers	182	114.0	63.9

Once again, the frequencies generated by the propellers are in the lower range, which is preferred. Due to the difference in the rotational speed of the propellers, the frequencies of the noise generated by the tip and high-lift propellers are different. This means the two noise sources are incoherent, and their added sound pressure level L_{tot} can found by using Equation (10.5) [34]. Here, L_{HL} and L_{tip} are the sound pressure levels of the high-lift and tip propellers expressed in dB, respectively. Using the values from Table 10.2, the total sound pressure level is found to be 77.2 dB. While this value does not comply with the 60 dB requirement[14], this noise level is comparable to that of a passenger car at a distance of 7.6 m. It is not harmful or annoying to the human ear unless exposed for a prolonged amount of time[15].

$$L_{tot} = 10 \cdot log_{10}(10^{\frac{L_{HL}}{10}} + 10^{\frac{L_{tip}}{10}}) \quad (10.5)$$

While the noise emitted by the AmpAir aircraft during climb is not harmful to communities, AmpAir strives to become progressively more socially sustainable in the future. In the future, high-lift propellers with increased

[8]REQ-STK-USR-02: The vehicle shall not be louder than 60 dB(A) at 1000 ft.
[9]REQ-STK-USR-02: The vehicle shall not be louder than 60 dB(A) at 1000 ft.
[10]https://www.chem.purdue.edu/chemsafety/Training/PPETrain/dblevels.htm
[11]REQ-STK-USR-03: The cabin noise shall at no point be higher than 85 dB(A).
[12]https://hearlife.org/how-does-active-noise-cancelling-work/#:~:text=Using%20active%20noise%20cancellation%2C%20headphones,we%20are%20exposed%20to%20everyday.
[13]REQ-STK-USR-01: The cabin noise shall be no higher than 60 dB(A) during cruise including damping devices.
[14]REQ-STK-USR-02: The vehicle shall not be louder than 60 dB(A) at 1000 ft.
[15]https://www.chem.purdue.edu/chemsafety/Training/PPETrain/dblevels.htm

amount of blades will be considered, as this can result in a decreased diameter or rotational speed, resulting in decreased SPL [85]. However, before this is implemented, it is crucial that an accurate method is available to determine the effects of increasing the number of blades on the blade wake errors.

11
Materials, Structures, and Manufacturing

This chapter will discuss the design of the structure, choice of materials and production of the aircraft. First, materials properties and considerations are given in Section 11.1. Next, loading diagrams, crashworthiness, and the wing box design are discussed in Section 11.2. Finally, the manufacturing and production process of the aircraft is shown in Section 11.3.

11.1. Materials

When choosing materials, multiple factors are of importance like their material properties, environmental impact, durability, and cost [89]. Within aerospace structures, there are two main material groups: composites and metals. In this section, the performance of these materials will be assessed and compared.

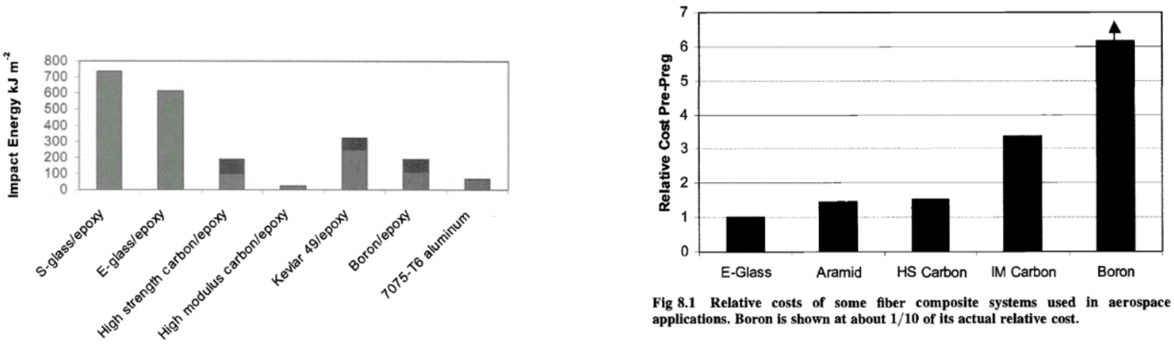
11.1.1. Material Properties

When designing a lightweight structure that must endure high loads, good material selection is essential. The mechanical properties of different composite materials and metals are summarized in Table 11.1. In this table, the following material properties are presented: density [ρ], tensile yield stress [σ_1^{ty}], compression yield stress [σ_2^{cy}], tensile ultimate stress [σ_1^{tu}], compression ultimate stress [σ_2^{cu}], shear ultimate stress [τ_u], Young's modulus [E], shear modulus [G] and Poisson's ratio [ν_{12}]. From this table, it becomes clear that composites have higher tensile ultimate stresses. This is because of their anisotropic nature, allowing their strength to be optimised through fibre orientation. Only titanium can compete, but its specific gravity is more than double that of all composites, making it less attractive. On the other hand, composite compression performance is far worse than that of metals. Boron can resist the highest compressive stresses because of its large fibre diameter. However, this is still only 15% of the ultimate compressive stress aluminium can resist. Aramid composites have bad compression resistance, but due to their non-linear compression behaviour, they are good at absorbing energy in case of impact, which can be used in crash resistance as elaborated on in Section 11.2.2. Glass fibres have a relatively high specific gravity and their mechanical properties, like young's moduli and strengths, are far worse than other composites. Glass fibre will therefore not be used for weight-critical load-bearing applications in the aircraft primary structures. In case of carbon fibres, the choice of fibre greatly influences the mechanical properties. However, in general, they are known for their high specific stiffness and strength and are widely applied in aircraft high-performance primary structures.

Table 11.1: Summary of the material properties of different composites and common aerospace metals [39] [3].

Property	Units	E-glass fibre	S-glass fibre	Boron	Aramid K49	HT carbon fibre	HM carbon fibre	UHM	Al 2024	Ti-6Al-4V	Stainless steel
ρ	$\frac{Mg}{m^3}$	2.1	2.0	2.0	1.38	1.58	1.64	1.7	2.79	4.4	7.89
σ_1^{ty}	-	-	-	-	-	-	-	-	414	924	207
σ_2^{cy}	-	-	-	-	-	-	-	-	414	924	207
σ_1^{tu}	MPa	1020	1620	1520	1240	1240	760	620	469	1102	517
σ_2^{cu}	MPa	40	40	70	30	41	28	21	469	1102	517
τ_u	MPa	70	80	90	60	80	70	60	290	640	-
E	GPa	45	55	210	76	145	220	290	73.1	120	193
G	GPa	5.5	7.6	4.8	2.1	4.8	4.8	4.8	27	44	75
ν_{12}	-	0.28	0.28	0.25	0.34	0.25	0.25	0.25	0.35	0.36	0.27

11.1.2. Other Material Considerations

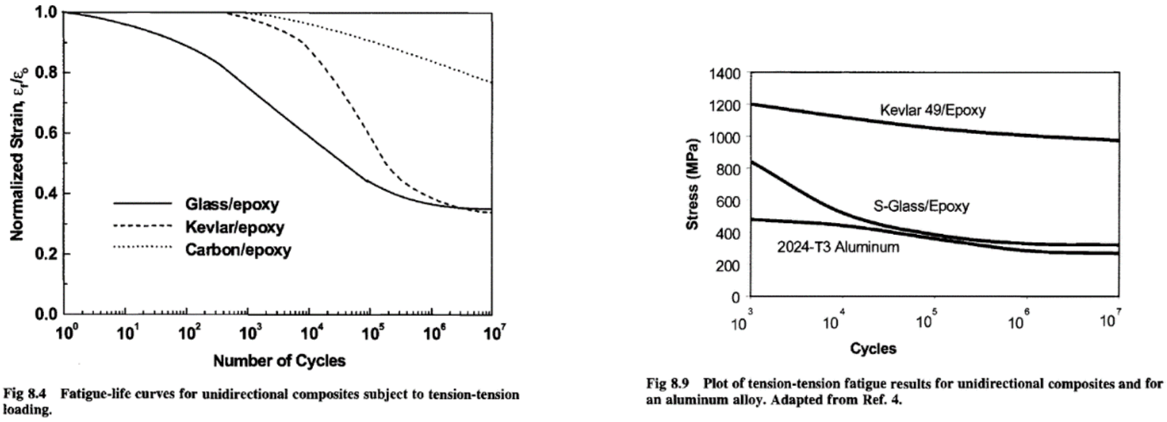


(a) (b)

Figure 11.1: Mass estimate and power loading diagrams.

Composites are more expensive than metals but vary amongst each other depending on the fibre. Glass fibres, Aramid and Carbon composites are all significantly cheaper than boron/ epoxy composites, which can be up to 12 times as expensive as carbon/epoxy prepreg composites as shown in Figure 11.1b.

Furthermore, composites have superior corrosion and fatigue resistance to metals. As can be seen in Figure 11.2a and Figure 11.2b, glass fibre composites perform worst and carbon fibres best in terms of fatigue life. Opposite to metals, which show surface cracks, composites have internal failure modes like fibre breakage or delamination, which cannot be found by visible inspections. Inspecting for damage is therefore more difficult than for metallic structures, which show surface cracks in the presence of fatigue [35].



(a) (b)

Figure 11.2: Mass estimate and power loading diagrams.

Moreover, composites have varying performance when it comes to impact resistance. All composites except for high modulus carbon/epoxy composites can absorb more energy than aircraft-grade aluminium, as shown in Figure 11.1a. Glass fibre/epoxy composites are up to 35 times more impact-resistant than high-modulus carbon/epoxy, and 11 times more resistant than aerospace-grade aluminium. This composite material can be implemented in areas of the aircraft that are prone to unexpected collisions with debris or bird strikes, like at the leading edge of the wings or at the nose.

A disadvantage of composites is their sensitivity to environmental conditions like temperature, moisture and UV exposure. High temperature and humidity can cause cracks and delamination, which in turn can reduce stiffness and strength of the material. UV radiation can break bonds in the epoxy resin, which must be considered for aircraft with high flight hours [3]. Furthermore, some fibres, such as aramid, absorb moisture, causing their properties to degrade.

Finally, all materials within the cabin must be fire-resistant[1]. This is defined as a material that will maintain its integrity for at least 5 minutes when exposed to a 1100 °C flame [83]. All primary composite structures will be treated with a fire-resistant coating to protect the aircraft structural integrity. Additionally, all items that are implemented for increased cabin comfort, like seat covers or a carpet, will undergo fire-resistance testing. For these, their flammability is more important than maintaining their function of comfort and aesthetics in case of a fire. Therefore, they will be tested on their flammability properties.

In conclusion, composites allow for lighter structures than metals, without sacrificing performance. Carbon/epoxy composites shall be used for weight-critical load-bearing primary structures, such as spars and stringers. This is because of their high strength and stiffness properties, as well as good fatigue behaviour. Composites will be used for the fuselage structure because of their high strength-to-weight ratio. And for the aircraft leading edge, nose and lower belly, aramid composites are used because of their high energy absorption and impact resistance. Glass fibres will not be considered further because of their low mechanical properties, even though they are low cost.

11.2. Structures

Creating a lightweight structure will result in the snowball effect, where a lower weight leads to less required lift, meaning smaller wings are necessary, which results in lower weight and the cycle repeats. Aircraft weight can be brought down significantly by making smart material selections and performing force analysis on structural components to optimize their geometry. By switching to composite wing structures, for example, the wing can be up to 40% lighter than an equivalent metallic one, which can in turn result in a fuel saving of up to 8% [48].

11.2.1. Gust and Manoeuvre Loads

The gust and manoeuvre loading diagram, constructed based on CS23 regulations [19]. The maximum load occurs at the lowest mass and the highest altitude. This is when operating empty, at 2000 kg and at the maximum altitude of 3000 m. The diagram is shown in Figure 11.3. The flight velocity is shown on the x-axis, while the load factor is shown on the y-axis. It can be determined from the graph that the maximum positive load is equal to 3.65 and the maximum negative load to -1.46.

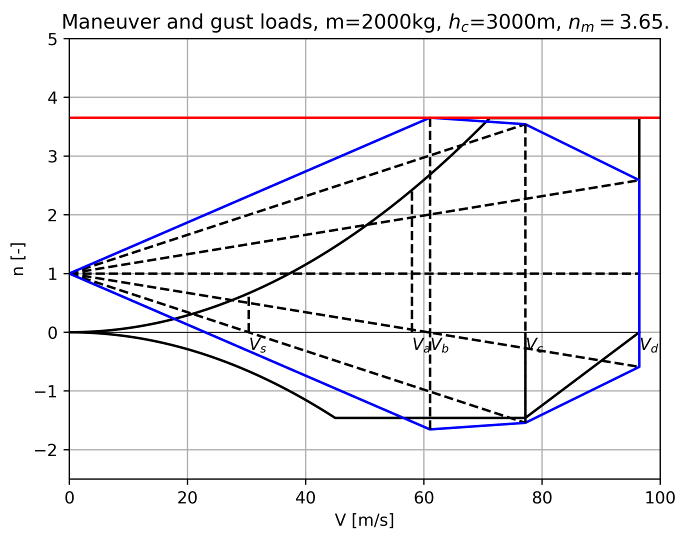


Figure 11.3: Power and control system

11.2.2. Crashworthiness

Crashworthiness of a vehicle defines its ability to protect involved people and cargo in case of an accident and minimize the chance of injury of the passengers [41]. AmpAir will implement certain features in the

[1] REQ-TP-MAT-02: All materials used in the cabin structure shall be fire-resistant.

structural design to protect the safety of the passengers. This includes protecting the batteries and ensuring the cabin compartment stays intact.

The crashworthiness of the batteries will be tested by means of drop tests from 50 ft height [2]. In case an additional enclosure of the batteries is required, fibre-reinforced polymer sandwich structures shall be used due to their high strength-to-weight ratio [27].

Furthermore, the cabin shall be designed in such a way that it does not collapse after a crash. The survivable volume shall be maintained for all load factors up to the minimum crush strength, as given in Table 11.2. This is done by creating multiple, parallel load paths such that local impact damage does not result in complete loss of structural integrity. This can be done by implementing multiple structural members instead of a single larger one. To validate the structure crashworthiness, drop tests will be performed. This way, experimental data will be collected, and a FEM analysis can be performed to evaluate the safety of the passengers at different angles of the possible crash [79]. All objects of mass inside the cabin and cockpit of the AmpAir aircraft can be considered an injury hazard[3] For this reason, seats, and restraint systems will be designed such that all internal cabin components remain fixed in case of a survivable crash.

Table 11.2: Recommended structural load factors for maintaining survivable volume in case of aircraft crash [41].

Load direction	**Minimum crush strength [g]**	**Preferred crush strength [g]**
Upward	3	4.5
forward	9	26
sideward	1.5	4.5
downward	6	16.5

Another method to ensure crashworthiness is early dissipation of kinetic energy. The absolute velocity change experienced by the passengers is of less importance than the time over which it occurs [41]. By controlling what structures collapse, energy can be dissipated smartly, decreasing crash impact on the passengers. The following strategies can be implemented in the aircraft structure for energy absorption after initial contact, helping to reduce deceleration magnitudes to tolerable levels:

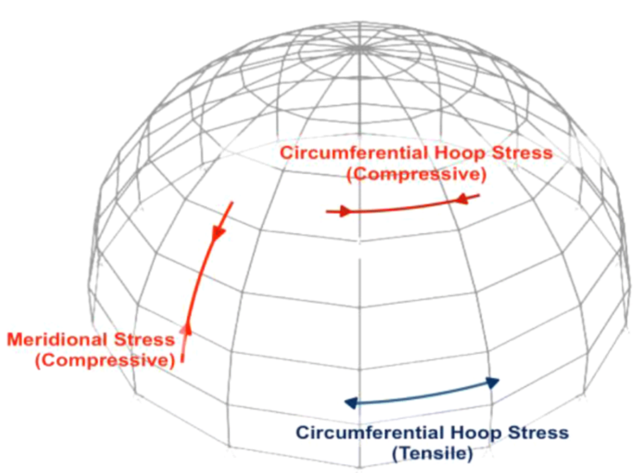
- **Energy-Absorbing Landing Gear:** The plastic deformation of the landing gear and the friction with the ground will dissipate energy.
- **Structural Deformation:** Energy may be absorbed by intentionally implementing weak points in the structure that will crush first, protecting other structural parts. This ensures that the energy is not solely absorbed by the primary structures which support large mass items, as their failure would have catastrophic consequences.
- **Breakaway of High-Mass Items:** By intentionally implementing weak points in the attachment of high mass components, they will be the first to break off during collision. This instantaneous mass change will reduce the kinetic and potential energy that must be absorbed by the remaining structure.

A part of the batteries is positioned behind the passenger cabin. In case of a crash, their large mass combined with sudden deceleration of the aircraft would have the capability to crush the cabin, if not constrained properly. Therefore, a structural barrier will be incorporated that separates the passenger cabin from the batteries. This doubles as fire protection by separating the cabin from the batteries.

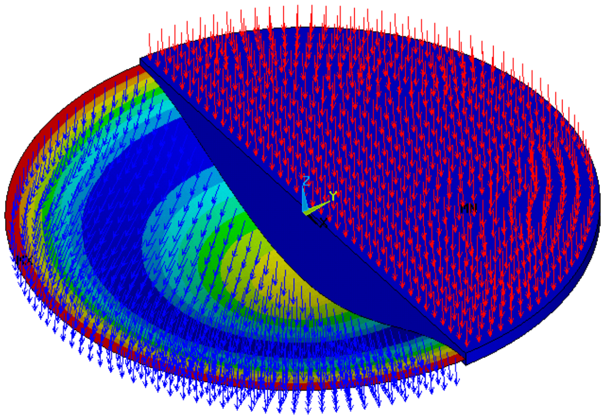
Ideally, the back of the passenger cabin should be a parabolically shaped dome, behind which the batteries are mounted. Their forward momentum would be carried and redistributed by the dome shape into the fuselage structure, as shown Figure 11.4a. However, due to space constraints, creating this conical shape is not possible. Instead, a flat, reinforced panel will separate the passenger cabin from the batteries, which will be connected to the rest of the fuselage structure, as shown in Figure 11.4b

A preliminary calculation, where this separation is modelled as a flat circular plate clamped all around, showed that a 7 mm thick aluminium panel can resist the forces generated when experiencing a 9g longitudinal deceleration, as obtained from Table 11.2. However, this assumes there will be no deformation in the centre of the panel, where the highest loads occur. In reality, it is highly likely that the panel will bulge towards the passenger cabin, creating stress concentrations and improper load paths, resulting in failure of the structure. To prevent this, stiffeners will be applied, as shown in Figure 11.5. The specific energy absorption (SEA)

[2]https://aerospaceamerica.aiaa.org/faa-advances-testing-for-airworthiness-of-electric-aircraft-battery/
[3]https://sassofia.com/blog/aircraft-certification-crashworthiness-and-survivability-considerations-easa-faa/



(a) Load redistribution of forces when a load is applied to the top of a dome



(b) Deflection of a flat plate under a uniform, distributed load. The highest stresses occur at the clamped edges

Figure 11.4: Structural barrier options

(amount of energy absorbed per unit weight) of the material is of even higher importance than its strength when considering crashworthiness, as the crushing of the structure must happen without rupture of the materials. Therefore, they must have sufficient ductility to resist the fast conversion of energy. Because the SEA of composites has not been sufficiently proven, sub-structure testing must be performed to confirm the expected structural behaviour. Incorporating sandwich structures can help increase the achieved energy absorption. This can be implemented for lateral impact resistance, as these are predicted to exhibit lower load factors [41].

11.2.3. Wing Box Design

In this subsection, the design of the wing box will be discussed.

Internal Force and Moment Diagrams

In order to make a wing box, the applied loads must first be analysed and translated into the internal forces and moments in the structure. The wing weight and the lift were considered as distributed forces, while the engine weights are modelled as point forces. The free body diagram (FBD) is shown in Figure 11.6. From this, the internal shear force was plotted in Figure 11.7a, where 0 refers to the wing root. By integrating this function and assuming no point moments were applied, the internal moment along the wing span was found and plotted in Figure 11.7b. These both behave as expected: the internal forces and moments decrease to zero towards the wing tip, and the engines cause a jump in the internal shear force.

Wing Box Design

The wing box design is showcased in Figure 11.8. It weighs 193 kg and, as mentioned in Section 11.1, The material for the wing box is a carbon composite sandwich structure. This means that the wing box can be produced integrally, eliminating the need for riveting and bolting. Because composites are used, the thickness of the panels can be varied spanwise as well.

A model was created that could compute the internal stresses of a given structure. This is based on an idealised version of the structure, where a complex geometry is simplified into booms, connected by panels of a theoretical zero thickness. In the model, the following assumptions were integrated, simplifying the computations:

- **ASM-STRUC-01:** Thin walled assumptions are used in the computation of the moment of inertia and shear.
- **ASM-STRUC-02:** It is assumed that the torsional load along the wing linearly decreases from T_max at the wing root to 0 at the wing tip.

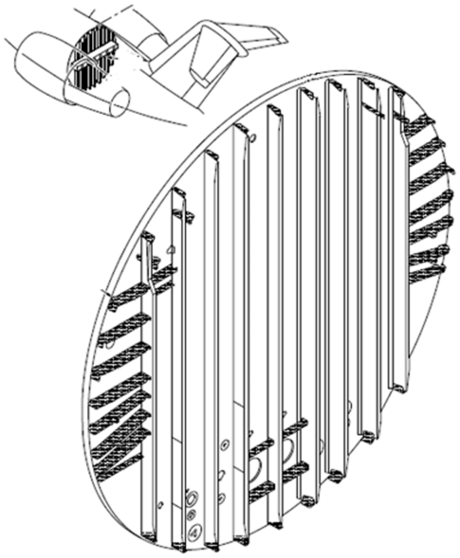


Figure 11.5: Example of a structural optimisation of a flat bulkhead panel.

- **ASM-STRUC-03:** It is assumed that the wing box shape is symmetrical with respect to the horizontal plane, causing $I_x y = 0$, meaning the shear centre coincides with the centroid of the cross-section of the wing box.
- **ASM-STRUC-04:** It is assumed that the ultimate compressive stress of composite sandwich structures is 50% of its ultimate tensile stress [93].
- **ASM-STRUC-05:** The loading due to drag is neglected, making $V_x = 0$.
- **ASM-STRUC-06:** The lift, wing weight and propeller weights are assumed to be applied in the shear centre, making $q_{s,0} = 0$.
- **ASM-STRUC-07:** Because composites are used, the thickness of the wing box, spars, and stringers can be variable along the wing.
- **ASM-STRUC-08:** There is no bending moment around the y-axis ($M_y = 0$) or the z-axis ($M_z = 0$)
- **ASM-STRUC-09:** Only the spar webs experience shear stress due to the internal shear force. All skin panels experience the shear stress due to torsion.

The wing box is designed to resist the following loads: vertical shear forces caused by the lift, the wing weight and the propulsion weights, the bending moment that results from this shear loading and a torsional load. The shear force is primarily carried by the spar webs, while compression and tension caused by the bending is carried by the spar caps, stringers, and skins. Lastly, torsion is carried by the closed section of the wing box. The front and back spars are located at 25 and 75% of the wing chord, respectively. This leaves space for anti-ice systems and slats in the front, and flaps, HLDs, control surfaces and navigational lighting in the back. The height of the wing box is restrained by the airfoil shape and is a function of the chord length. The front spar has a height of 0.165c, the back spar 0.085c. The wing box is split into one meter sections. For the analysis, it is assumed this whole section experiences the maximum loading of that section. Because the wing is tapered, the section skin thicknesses and amount of stringers are based on the shortest chord length of that section.

The wing box design is generated using an idealised structure. Here, the stringers, skins, and spars are reduced into theoretical booms that carry all tensile and compression forces, while the theoretical panels of zero thickness carry all shear forces. The area of the booms is determined by Eq. (11.2.3). From this idealisation, the moment of inertia can be computed, using Eq. (11.2.3), after which the boom stresses and panel shear forces can be computed with Eq. (11.2.3), Eq. (11.2.3) and Eq. (11.2.3). From the shear flow, the shear stresses can be found by going back to the original geometry, where $\tau = \frac{q}{t}$. One must note that due to this idealisation, the bending stiffness is underestimated, while the maximum normal stresses will be overestimated, as the skin contribution to carrying the bending stresses is neglected. Additionally, the maximum shear flow will be underestimated. However, it is believed that for the first iteration of the wing box design, this method is sufficient.

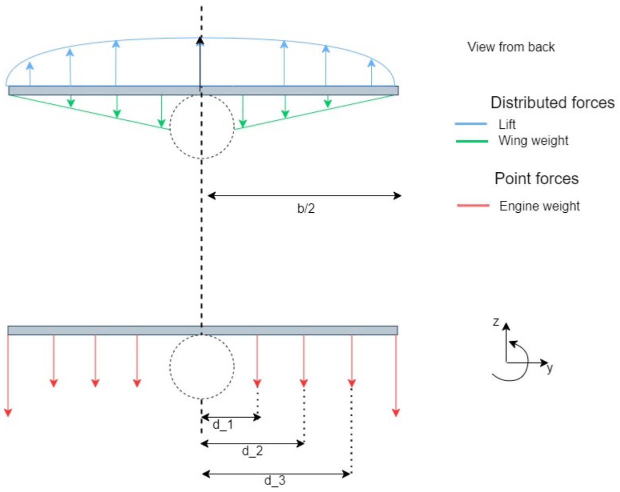
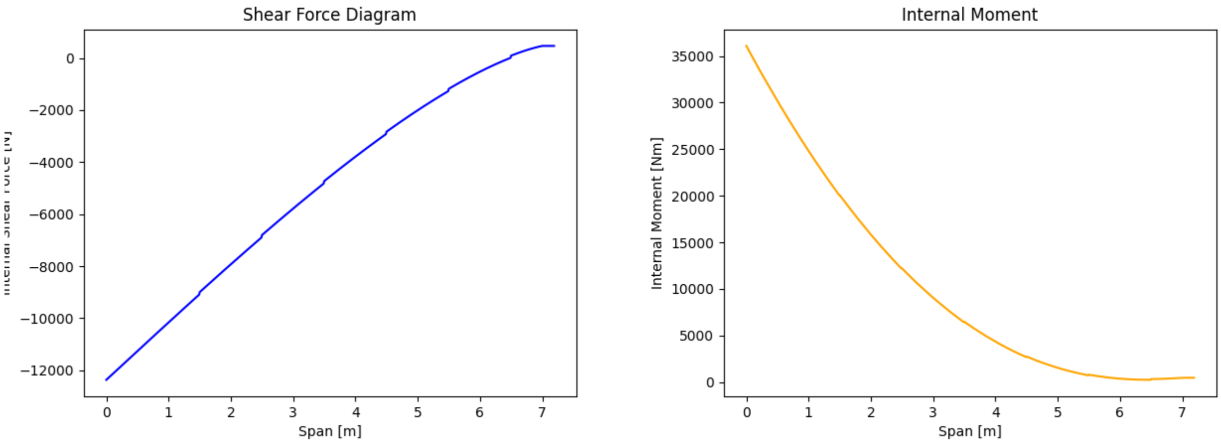


Figure 11.6: FBD of the loads on a wing. The drawing is looking from the back to the front of the aircraft (to keep the coordinate system standard.



(a) Diagram of the internal shear force in the right wing

(b) Diagram of the internal moments in the right wing.

Figure 11.7: Shear and moment diagrams

$$B_1 = \frac{t_{skin} b}{6}(2 + \frac{\sigma_2}{\sigma_1}) \qquad B_2 = \frac{t_{skin} b}{6}(2 + \frac{\sigma_1}{\sigma_2}) \qquad I_{xx,idealised} = \sum_{i=1}^{n} y_i^2 B_i$$

$$\sigma = -\frac{M_y \cdot y}{I_{xx}} \qquad q_2 - q_1 = -\frac{\delta \sigma_z}{\delta z} B_r \qquad q_2 - q_1 = -\frac{V_y}{I_x x} \cdot \sum_{r=1}^{n} B_r y$$

$$q_T = \frac{T}{2 \cdot Am} \tag{11.1}$$

Buckling For a wing box, critical buckling stress often occurs before the yield stress of the material is reached. Therefore, the web buckling due to shear and the instability of the reinforced skin panel were analysed using Eq. (11.2) and, Eq. (11.3) respectively. It was found that L- and Z-stringers have low critical buckling stresses due to instability of the protruding stringer face [102]. Therefore, the hat stringer, as shown in, Figure 11.9 was chosen to be most suitable for the wing box.

$$\tau_{cr} = \frac{\pi^2 \cdot k_s \cdot E}{12 \cdot (1 - \nu^2} \cdot (\frac{t}{b})^2 \tag{11.2}$$

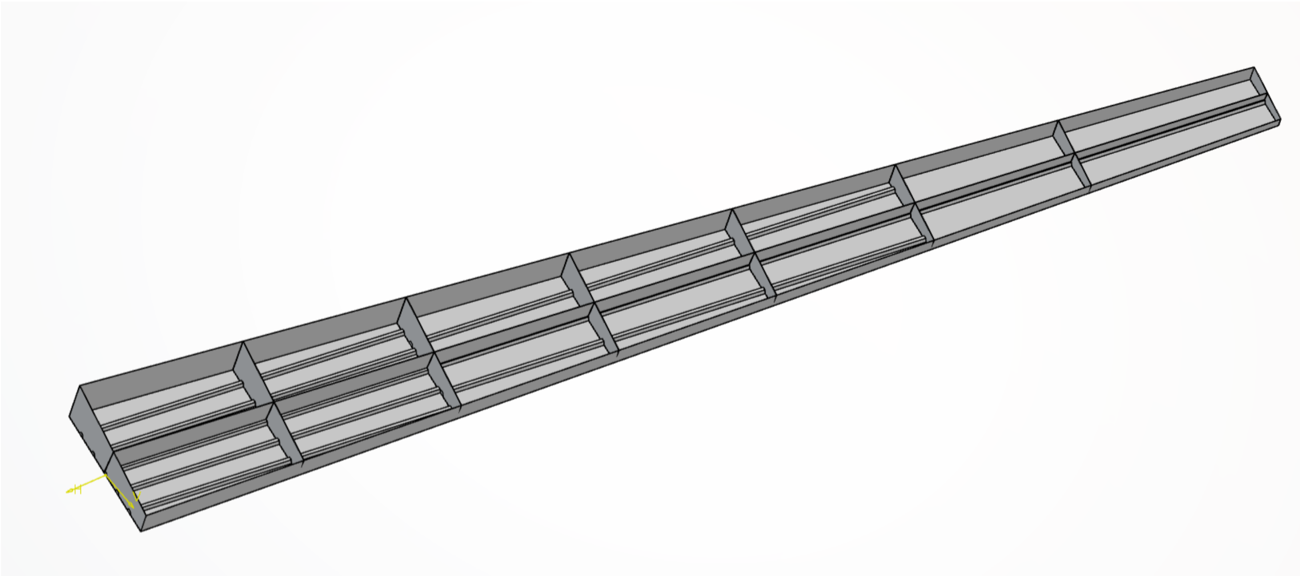


Figure 11.8: Full view of the wing box of one side

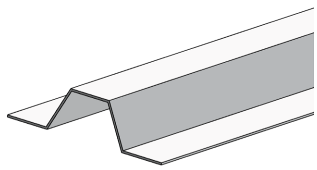


Figure 11.9: Close-up of the chosen stringer geometry, a hat stringer.

$$\sigma_{cr} = \frac{\pi^2 \cdot E}{(L_e/r)^2} \tag{11.3}$$

In the above equations, k_s is the column effective length factor, which depends on the clamping conditions, E is the material Young's modulus, ν is the material Poisson's ratio and is set equal to 0.25, t is the panel thickness and b is the length of the panel in the direction of the applied compressive force. L_e/r is the slenderness ratio of the column. In case of stringers, the rib spacing determines this ratio. The larger the L_e/r, the further apart the ribs are, reducing the critical Euler buckling stress. To check the skin between stiffeners, K is set equal to 4, as it is simply supported on all sides. For an L shaped stringer, K would be set to 0.43, as it has one free and three simply supported sides. From this, it becomes clear that the longer the L-stringer protrusion, the lower the critical stress becomes. Therefore, a further analysis was done on other kinds of stringers that have higher critical buckling stresses.

After considering all these modes of failure, a wing box was generated that could resist all forces without exceeding any of the critical or yield stresses and is shown in Figure 11.8. In the future, further optimisation of the wing box should be performed by creating an iterative script that can independently compute the optimal wing box geometry and rib spacing which can resist all loads while being as light as possible. Additionally, the analysis should be extended to analyse the complete geometry, instead of an idealised structure. On top of that, all aerodynamic forces and thrust vectors should be implemented in the model. Furthermore, the ribs should be further analysed, as cutouts, required for cabling, could influence their structural performance. Lastly, the stringer layout on the top and bottom panel could be individually analysed, as it is likely that fewer stringers are required on the bottom panel. However, because of the distributed propulsion, it might be that the most critical load case occurs during landing, right after touchdown, when the wing will bend downwards due to the outboard engine weights. This would cause compression in the bottom panel, meaning it might need more stringer reinforcement to avoid buckling after all. Once all these extra factors are considered, the applied contingencies in the design can be reduced, e.g. by reducing the applied safety factor.

11.3. Manufacturing Plan

The manufacturing plan will, firstly, include a preliminary planning of the production in Section 11.3.1. Then, it will include the manufacturing ideology (Section 11.3.2), the manufacturing methods (Section 11.3.3), the acquisition and storage of raw materials and external components (Section 11.3.4) and finally the post-manufacturing processes(Section 11.3.5).

11.3.1. Preliminary Planning

Several preparatory tasks are performed before the start of the production phase. These mainly consists of preparing the workspace, establishing relations with material and component suppliers and defining quality parameters. A preliminary list of actions is given below and can be extended or altered during the startup of production.

- Make a list of outsourced materials and their required characteristics.
- Perform quality control on outsourced materials and components.
- Create a manufacturing and assembly plan.
- Set up a quality control plan with clearly defined quality standards.
- Clean and organise manufacturing and assembly facilities.
- Order required equipment.
- Set-up and maintain partnerships and relations with material and equipment suppliers.
- Create a fire safety plan for the battery modules.

An integral part of manufacturing is checking the quality of the structure. First, quality standards are determined and procedures to check if they are met are set up. All throughout the manufacturing and assembly phase, quality control checks will be performed. Only when all the previously defined quality-aspects are met, the product goes into the final phase of production, which is systems integration.

11.3.2. Manufacturing Ideology

AmpAir aims to minimise all types of waste during the manufacturing process by implementing the lean manufacturing ideology. Here, any activity that does not add value for the stakeholders, but uses resources, must be eliminated. This will contribute to AmpAir's sustainable development strategy by minimising waste, while maximising profit. There are eight types of waste that can be distinguished for this method: Firstly, over-production and "Work In Progress" are considered waste because of their additional required storage of parts or materials. Additionally, transportation and motion are considered waste, as the movement of respectively components and personnel is a waste of time. Next, waiting time and underutilising of people creates waste because of suboptimal productivity. Additionally, processing waste occurs when unnecessary processing steps are performed. Lastly, rework is considered waste, as the extra work, caused by a faulty first product, could have been avoided. Different lean manufacturing methods will be implemented by AmpAir during manufacturing, production and assembly. Cellular manufacturing with load levelling will be combined, while applying the 5S strategy within the cells. This will result in short travel distances to the assembly location. The assembly will be performed in the middle of the flow cell. Since the AmpAir aircraft is a fully composite aircraft, the cells/workstations will concern composite part manufacturing processes. The lay-out of the manufacturing area will be further discussed in Section 11.5.

- **5S (Sort, Simplify, Scrub, Standardise, Sustain:** All the items of the workplace have to be sorted, separating the useful from the useless items and removing the latter. Each item should have a designated storage spot. The workplace is cleaned on a regular basis and the machinery is cleaned every day. The improved methods and changes are documented, and agreements are made to comply to the new storage and cleaning rules.
- **Load levelling:** All stages shall require equal amounts of work, as to avoid bottlenecks.
- **Cellular manufacturing:** When a customer wants high variety products that can be made using more or less the same equipment, cellular manufacturing can be applied. There is no separate production line per component. Rather, there is a product line consisting of multiple cells, each containing multiple

work stations (5-15) and people (3-12). This way, similar products can be made in the same assembly line. Within the cells, the workers will use appropriate equipment. When the subprocess of the cell is finished, the component moves to the next cell, until the product is finished as a whole.

11.3.3. Manufacturing Methods

Choosing the right manufacturing method can improve aircraft performance, along with reducing cost. The AmpAir aircraft will be fully composite, which allows for promising manufacturing methods. Integral production of larger structures can save weight, because there is no need for heavy fasteners, bolts, or rivets. It also reduces cost, as 50% of airframe cost results from assembly [35]. A disadvantage of integral manufacturing is that these components are often very large, meaning a damaged component could require a full replacement, as composite repair methods are still under development and have to comply to stringent regulations. Additionally, because of the large component size, large manufacturing facilities are required.

The production method selected by AmpAir is resin transfer moulding (RTM). This is based on the several arguments. Firstly, it allows for rapid manufacturing of large, complex, high-performance structures. On top of that, the process happens under relatively low pressures, thus requiring low press forces, reducing the tooling cost. Furthermore, it improves design flexibility, as reinforcements can be placed in the desired place and orientation, allowing for design optimisation. Lastly, many parts can be combined into one, decreasing assembly costs.

11.3.4. Raw Material and External Component acquisition

Aircraft manufacturing can only start if the raw materials are available. The material AmpAir selected is CFHT, which is readily available on the market[4]. There are several types of resin available for this type of fibre that fulfil the desired material characteristics.

Apart from the in-house composite components produced by AmpAir, some parts will be outsourced to other companies. These parts are, among other things, the electric engines, radar system and cooling components. The acquisition and supply of these externally sourced components are critical for the manufacturing and assembly process. Therefore, close relations will be set up between AmpAir and these companies, to safeguard the supply of these critical components.

The raw materials must be stored until they are processed. This means that there needs to be space allocated for storage. They should adhere to optimal storage conditions, like humidity, temperature or light exposure, as set by the supplier. The area allocated for this storage is discussed further in Section 11.5.

11.3.5. Post-manufacturing Processes

After the individual composite parts of the aircraft are produced, post-manufacturing processes need to be executed. Some parts will be joined, as will be discussed in Section 11.4.1. The parts that are not joined into subassemblies immediately go into post-processing. The subassemblies will be ready for post-manufacturing processes once their joining is finished. The post-manufacturing processes are the following:

- **Trimming of the parts or subassemblies.** By trimming the edges, the component is finished into its final dimensions and is safer to handle.
- **Coating of the parts/subassemblies:** Composites require a coating to protect them against weather effects, chemicals or to enhance their surface properties.
- **Surface finishing processes:** This ensures the smoothness of the parts/subassemblies, also positively influencing the aerodynamic performance of the aircraft.
- **Spray-painting and decals:** AmpAir wants to change the future of aviation. This requires adequate branding and marketing, which is supported by the aircraft appearance.
- **Inspection:** This is the last step in the post-manufacturing phase. The parts or subassemblies are inspected whether they comply with the pre-defined quality standards.

11.4. Assembly Plan

Once the parts and subassemblies have gone through post-manufacturing processes, they are ready for final assembly. In this section, different aspects of the assembly phase are discussed. First, an elaboration on manufacturing divisions and joining methods are given in Section 11.4.1, followed by a description of the assembly jigs in Section 11.4.2. Lastly, the systems integration strategy is briefly discussed in Section 11.4.3

[4]https://www.compositesworld.com/articles/the-outlook-for-carbon-fiber-supply-and-demand

11.4.1. Manufacturing Divisions and Joining Methods

The aircraft is not made in one piece. Rather, it is created in smaller sections that are joined into the final product. These divisions arise for two reasons: Mounting divisions are those that are not permanent. These are used for attachment of components that need frequent replacement. Subassemblies that belong to the mounting divisions are, among others: the tail of the aircraft, battery pack fasteners, engines, or the landing gear. It is important that these divisions can be replaced by making use of the same tools, since this makes replacement possible almost everywhere. Manufacturing divisions are those that are implemented to increase ease of production. They allow the end product to be split into smaller, easier to handle parts, increasing manufacturing efficiency. Manufacturing divisions are permanent after joining. Subassemblies that belong to the production division are, among others: stringers to the wing box skin, firewalls to the fuselage of the aircraft, and the wing-attachment-structure to the fuselage.

There are two ways to join composite components: Mechanical fasteners, can be used if a supporting material is integrated into the composite sandwich structure. This has the advantage that it is a non-permanent bond, but has the disadvantage that it increases the weight. If mechanical joints are used, bolts and nuts of readily available, standard dimensions, should be used, since this among others reduces the price and availability of these components. On the other hand, adhesives can be used to join composite components together. There is also the possibility to use a combination of both[5]. In future design phases, AmpAir will analyse the most appropriate joining method for each joint.

11.4.2. Assembly Jigs

In order to accurately assemble different components and subassemblies, assembly jigs are required. Their function is to protect the components that will be joined together from damage, support them and position them for joining. AmpAir will use aluminium profile systems to build their jigs. An example of this is the RK ROSE+KRIEGER[6]. Some components available are shown in Figure 11.10. These profiles can be assembled into jigs that comply to all jig requirements. These requirements are given below.

- The jig is stiff enough to provide adequate support during assembly.
- The jig is accessible from all positions.
- The jig is as cheap as possible.
- The jig allows for easy removal of the part(s).
- The jig covers minimal space in the workplace.
- The jig is movable.
- The jig should be adaptable, supporting any dimensional changes of the part (including thermal expansion).

11.4.3. Systems Integration

During the systems' integration phase, systems like the engines and propellers are installed. Before implementation, the quality of these components should be confirmed by the supplier or checked by AmpAir. Since the systems integration components are obtained from external companies, they are likely to arrive before the systems integration phase has started. This means that components need to be stored until this phase is initiated. The required conditions of the storage space are defined by the supplier and include, among other things, volume, temperature, humidity and the light exposure of the components. There is one system's integration component that needs extra caution: the batteries, as they pose a potential fire hazard. Extra precautions, by means of a fire protection plan, must be taken during battery storage. The type of cabinet that is to be purchased depends on the battery specifications. This will change over the years, as the battery concept of the AmpAir aircraft is adjusted to innovations in technology (as explained in Section 5.1).

11.5. Production Plan Flow Diagram and Workspace Layout

Finally, the workspace layout and the production plan flow diagram are explained in Section 11.5.1 and Section 11.5.2, respectively. Both are a preliminary prediction and can change throughout future project phases.

[5] https://www.machinedesign.com/fastening-joining/article/21812797/joining-composites
[6] https://www.rk-rose-krieger.com/english/products/profile-system/

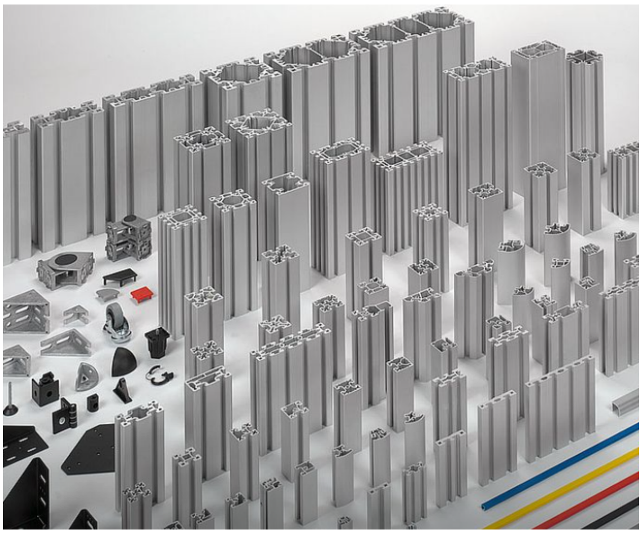


Figure 11.10: Assembly jig components

11.5.1. Workspace Layout

Keeping in mind the lean manufacturing ideology used, and the required components/apparatus, a preliminary workplace layout is set up, and presented in Figure 11.11. The lean manufacturing ideology is applied in the creation of this layout. This means that travel distance between cells is minimised. Furthermore, it is expected that the employees adhere to the rules in terms of the 5S and load levelling methods, as was explained in Section 11.3.

11.5.2. Production Plan Flow Diagram

Figure 11.12 depicts the expected elapse of the production phase, including the end-of-life phase of the aircraft. In the diagram, the rectangles indicate (detailed) tasks, the horizontal squares indicate a task that consist of several sub-tasks, slanted squares indicate that a choice needs to be made with two outcomes (pass/fail or yes/no), and the coloured circles indicate that the diagram continues on the same letter further or more back in the diagram.

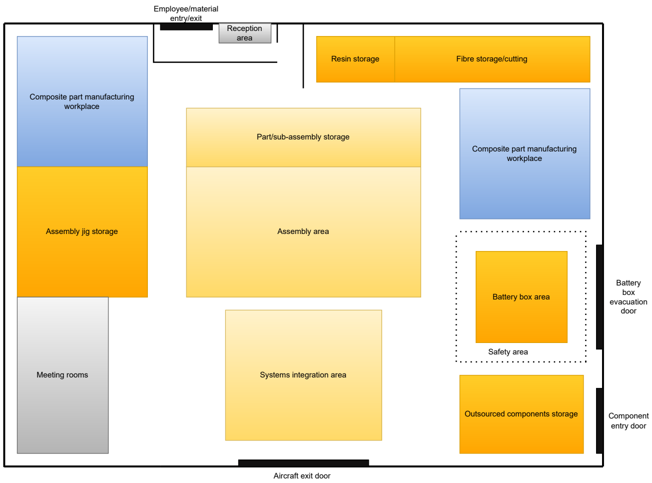


Figure 11.11: Preliminary workspace layout

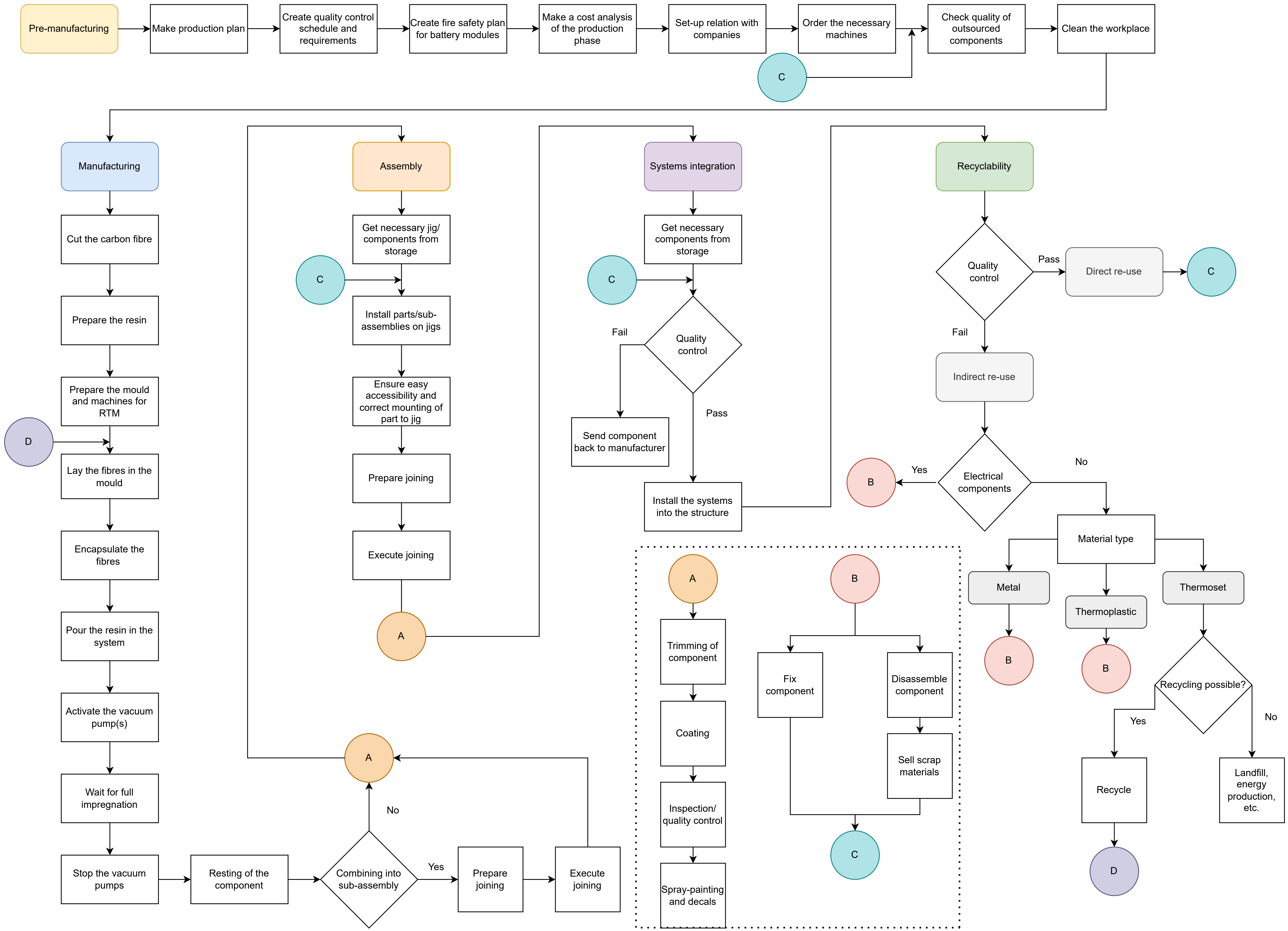


Figure 11.12: Production plan flow chart

12
Cost

In justifying the AmpAir project, the cost requirement plays a major role in making the concept viable. This chapter will detail on a few aspects regarding this cost aspect. It goes into detail on the method used for the estimates, which also forms the basis for the construction of the 4D future-proofing matrix, as discussed in Chapter 5. This is elaborated on in Section 12.1, also detailing on the model's limitations and assumptions. With a clear outline of the model, the first findings may be presented in Section 12.2. Then, most important novel findings such as the cost breakdown, return on investment (ROI) and growth concept implementation are discussed in Section 12.4 and Section 12.3 respectively.

12.1. Adapted Method

The method used for the cost estimation is based upon a method used in previous project stages, using the same model at its core but vastly reworked processing of the calculations [30]. The model at its centre is a modified USAF DAPCA-IV method, including modifications for hybrid-electric aircraft as well as further adjustments to fit the AmpAir project [8, 38]. The model is based on the calculation of the procurement and operating cost of one aircraft, which is then extrapolated to the whole programme and fleet size. The model uses various correction factors for a most accurate estimate, based on design parameters such as the use of retractable landing gear, composites and a pressurised cabin. The model includes equations, most of which are statistically derived, for the calculation of every individual cost segment, as presented also in Table 12.4.

The model makes a number of assumptions, such that it can depict a sufficiently complete overview of the cost for the various considered scenarios, given the limited data available. Model inputs are listed in Table 12.1, however some aircraft parameters such as weight fractions are not listed as they are taken directly from the central parameter file such that they simply correspond with the rest of the project.

Table 12.1: Input parameters used for further calculation using the presented model

Description	Variable	Value	Unit	Comment/Source
Number of seats	N_{seats}	5	[-]	Determined in previous project stages.
Top speed factor	V_f	1.176	[-]	Literature
Number of prototypes	Q_{prot}	1	[-]	Estimate based on similar aircraft
Consumer price index since 2012	CPI	1.34	[-]	CPI ratio for transportation[2]
Tooling rate	R_{tool}	61	[€/hr]	Model source [8]
Engineering rate	R_{eng}	92	[€/hr]	Model source [8]
Manufacturing rate	R_{mnf}	53	[€/hr]	Model source [8]
MNF experience factor	F_{exp}	0.95	[-]	Model source [8]
Profit	prf	5	[%]	Profit margin on aircraft procurement price
Insurance	ins	17.5	[%]	Model source [8]
Charging efficiency	η_{ch}	85	[%]	Model source [8]
Price of electricity	P_e	0.2	[€/kWh]	Literature
Crew (Pilot, operator) rate	R_{crew}	60	[€/hr]	Model source [8]
Observer rate	R_{obs}	40	[€/hr]	Estimate based on role
Noise factor	F_{noise}	1	[-]	Set to 1 for electric aircraft [8]
Maintenance fraction	F_{mf}	0.275	[-]	Hours of maintenance per flight hour [8]
Maintenance rate	R_{lbr}	90	[€/hr]	Model source [8]
Storage rate	R_{stor}	3000	[€/yr]	Model source [8]
Insurance rate	R_{ins}	500	[€/yr]	Model source [8]
Depreciation period	T_{dep}	25	[yr]	Estimate from similar aircraft, global parameter
Depreciation fraction	L_{dep}	80	[%]	Inverse of EOL leftover cost, estimate
Battery depreciation fraction	$L_{dep,bat}$	80	[%]	Inverse of EOL leftover cost
Number of battery cycles	N_{cyc}	1000	[-]	Global parameter
Loan fraction	F_{loan}	80	[%]	Percentage of cost financed, estimate
Yearly number of flights	N_{fl}	730	[-]	Per aircraft per year
Indirect cost fraction	F_{ind}	52	[%]	Percentage of indirect operating cost as a fraction of total
Interest rate	int	2	[%]	Estimate
Fleet size	Q	Variable through stages	[-]	To be determined
Level of autonomy	Aut	[-]	Stage dependant	Determined in Chapter 5
Range	R_{oper}	Stage dependant	[-]	Determined in Chapter 5
Payload	$Payload$	Stage dependant	[-]	Determined in Chapter 5
Battery mass	M_{bat}	Stage dependant	[-]	Determined in Chapter 5
Battery energy density	Rho_{bat}	Stage dependant	[-]	Determined in Chapter 5

Apart from the parameters shown in Table 12.1, the aircraft weight fractions play a major role in the cost estimates. Also note that in further calculations presented throughout this chapter, some parameters will be varied in order to calculate the influence of future changes on the cost and price of the service.

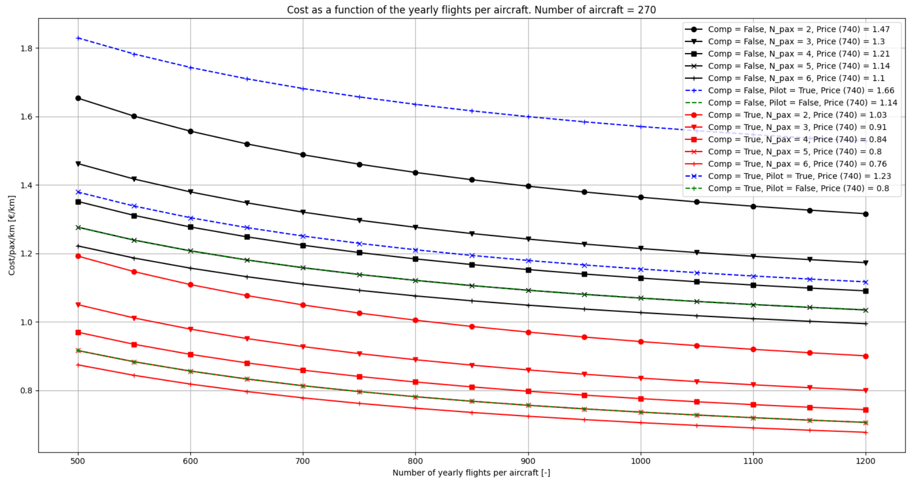


Figure 12.1: An indication of the impact of a change is the seat count of the aircraft on the cost per passenger per kilometre, expressed as a function of the yearly flights per aircraft. The plot contains 2 sets, one for a fully composite aircraft and one for a conventional one. Taken from [30].

The model presented and implemented is based on the calculation of cost for procurement and operation of a single aircraft, which is then extrapolated to attain estimates for a complete fleet. This however bases many things such as overhead, sales, and marketing costs on an accurate indirect operating cost fraction, which is an important point of future improvement. Furthermore, there is still much room for improvement in the quality of input parameters, things such as the indirect cost fraction, financing fraction and interest rates are merely estimates, but may be updated if further development occurs. Most of these limitations would cause the model to underestimate the cost of operation, however it is the best available in the current phase of the project.

Additionally, professional contacts at E-Flight Teuge have presented some insight in the added operating cost for electric aircraft, for example an increase in software cost. Expenses as such are not accounted for in the model, where maintenance plays a smaller role due to the aircraft being electric.

12.2. Sensitivities and Previous Work

In early design stages, the main use of the cost estimation model was to identify the impact of design choices on the cost of the aircraft, and thus the feasibility of reaching the cost requirement as design progressed. From this, a few major choices were made, an important figure for which is re-presented in Figure 12.1. Note that since the implementation of the growth concept a transition was made to using cost per kilogram per kilometre instead of per passenger per kilometre, for consistency with cargo operations, however this is merely the same number divided by a factor of 100. The plot details the difference in cost per passenger per kilometre for varying the use of composites as well as the number of seats, and the use of a pilot. From this, the choice was made to pursue a fully composite, five seat design. Note the numbers have since changed and are thus not representative, however the trends are applicable. A similar drop in price for an increase in the level of autonomy is still much visible in the previously presented matrix in the growth concept. The vast difference in the use of composites can be attributed to the incorporation of the snowball effect, which is exaggerated for electric aircraft due to battery weight.

Moreover, another important plot was the one shown in Figure 12.2, it shows the relation between cost and the fleet size, again plotted against the yearly number of flights per aircraft. The trend-line shows that for a set total number of yearly flights for the entire fleets, as would follow from a market analysis, it is always most profitable to use a small fleet with a maximum utilisation per aircraft. Also, it is important to note the diminishing returns in terms of cost reduction with an increase in the fleet size.

Apart from these main non-linear (with respect to the cost) sensitivities, some other linear parameters were also identified, the main of which were the battery price, the financing fraction and the indirect cost ratio, an overview is presented in Table 12.2. These values should either be subject to further future investigation, or

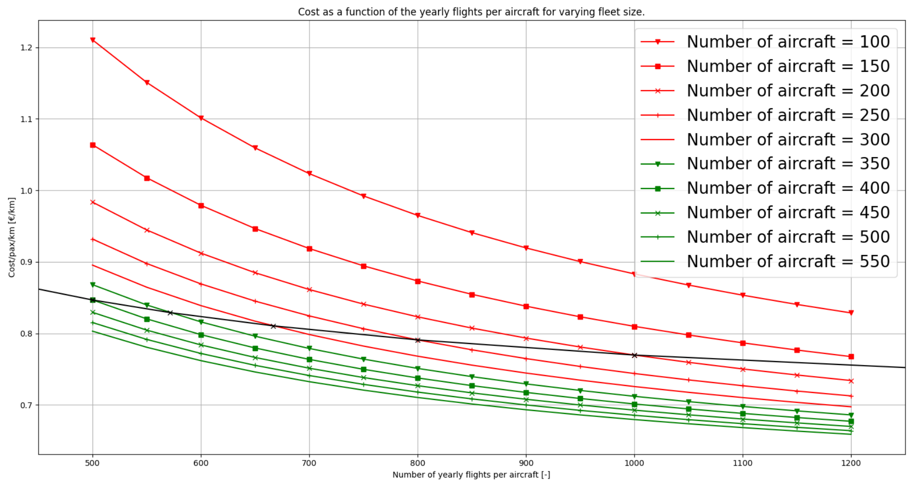


Figure 12.2: In an indication of the sensitivity of the cost with respect to the fleet size, lines are a varying fleet size expressed against the number of flights per year. The trend-line goes through points corresponding to a fixed total number of flights per year for the entire fleet. Taken from [30].

are to be taken into account in design. Furthermore, a strong sensitivity is present with regard to the interest rate, as well as the number of cycles one battery can go through. This last parameter may cause problems in the implementation of lithium sulphur batteries, as this is currently the main shortcoming of the technology. For both, a similar non-linear relation is present, as was also visible for the fleet size. The interest rate is deemed acceptable as long as it remains below 4.0%. Regarding the battery cycles it would optimally be kept above 750 to 1000, however the cost penalty may be offset by an increase in performance, and should thus again be subject to further investigation, depending on the case.

Table 12.2: The sensitivities of cost driver that contribute to uncertainties in the model, having a linear relationship with the cost. Values are expressed in terms of passenger kilometres to prevent them from being excessively small[30]. Applicable to a fleet size corresponding to stages 2-3.

Cost driver	Current estimated value	Unit	Sensitivity	Unit
Profit margin on procurement	5	[%]	0.02	[€ / %]
Indirect cost ratio	52	[%]	0.02	[€ / %]
Insurance rate	17.5	[%]	0.013	[€ / %]
Battery price	100	[€ / kWh]	0.11	[€ / 100]
Maintenance fraction	0.275	[hrs]	0.02	[€ / 0.1]
Financing fraction	80	[%]	0.08	[€ / 10%]

12.3. Return on Investment and Growth

Apart from the procurement cost of an aircraft, which varies greatly throughout the lifetime of the service operation, another important metric for investors is the return on investment, or ROI. This metric shows an investor how much an initial investment is expected to return over a given time period, showing an obvious link to the market analysis. In previous project phases it was already identified that it will always be most profitable to fly a small fleet with the highest possible utilisation, as opposed to a large, stationary fleet. For this reason, a maximum of 2 flights per day per aircraft was assumed throughout its lifetime. Considering this, the market analysis offers a clear vision on the fleet size to attain for full implementation of the concept.

In Figure 12.3 a visualisation is presented on the diminishing cost as time passes. In black, the cost is presented, while the green line indicates the price that customers would have to pay. Note that not a fixed percentage profit margin is used, but rather a fixed absolute value of profit per payload kilometre. A fixed percentage would mean that as the operation size increases, the cost drops but so does profit as a result, this requires more flights for the same absolute profit. From literature, it was found that general air transport services operate with profit margins between 2.7% and 42.9% [101]. The figure assumes a starting margin of 5%, slowly increasing to 15% throughout the first four project stages, this keeps the absolute profit value

Figure 12.3: Timeline depicting the projected cost of operation and price for customers throughout the life of the whole AmpAir service. The red vertical lines depict the boundaries between stages, as mentioned in Chapter 5. Horizontal lines are the cost of FlyAeolus (upper) and the cost requirement (lower)

per kilometre somewhat constant or at a slight increase. After this a sizeable drop in cost, as well as a dive below the 50 cent per passenger per kilometre mark allows for an increase in absolute profit, thus translating to large profit margins of up to 95%. The horizontal lines in the figure show both the cost requirement set (with the higher horizontal line), and the price per passenger kilometre that the main competitor, FlyAeolus roughly uses, as described in Chapter 3. It once again becomes visible that already as soon as cargo operations start, the AmpAir concept may not reach the initial cost requirement, however can still operate in a commercially viable manner. In Figure 12.3 note the initial influence of the fleet size on the cost, where in stage 0 a small decrease is visible but then also the subsequent diminishing returns, having a minor impact in later stages.

As a support to Figure 12.3, the cost, price and fleet size are also presented separately in Table 12.3.

Table 12.3: A numeric overview of the cost, price, and fleet size at the end of every growth stage.

Stage	Cost [€/kg/km]	Price [€/kg/km]	Max fleet size [-]
0	€0.0154	€0.0161	14
1	€0.0109	€0.0117	40
2	€0.0108	€0.0117	197
3	€0.0078	€0.0090	294
4	€0.0020	€0.0031	416
5	€0.0020	€0.0027	538

Tying into the previously outlined implementation of the growth concept is the growth of the fleet size throughout the years, Figure 12.4 shows the increase in fleet size throughout the years. From the TAM as presented in the market analysis and the number of flights, a maximum fleet of 538 aircraft is expected at model end, in 2054. It is assumed that a linear growth is kept between phases, up to the projected maximum for that phase, after which a new slope is maintained. For flights school operations, a maximum fleet size of 14 aircraft is assumed, based on similar flights schools currently operating. For the cargo phase a maximum fleet size of 40 aircraft is assumed, however this estimate requires further investigation due to difficulties in establishing a rigid market analysis for the cargo segment. It should be noted that this varying fleet size is taken into account in the calculation of the cost for each year of operation, thus introducing a varying quantity discount factor (QDF), which may be inaccurate, however goes to more clearly show what the cost would be for a selected data point. This offers the option to see Figure 12.3 not so much as a timeline, but more so as a presentation of different options, as taken from the growth matrix. It should also be noted that the graph starting in 2023 of course makes little sense, however it is included to show that even for today, feasible

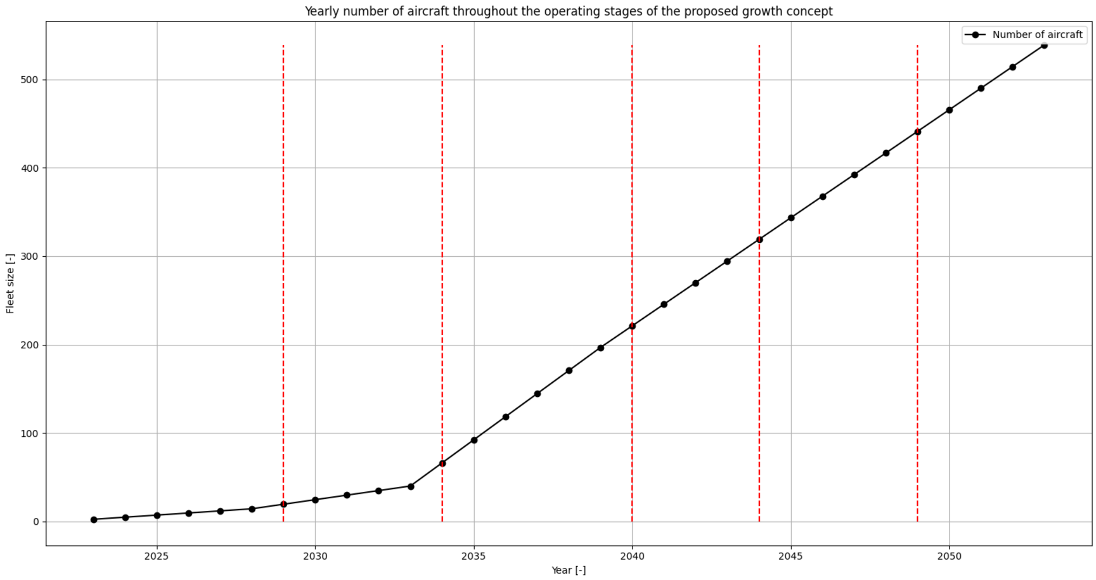


Figure 12.4: Timeline depicting the projected fleet size throughout the life of the whole AmpAir service. Numbers were obtained from technical limits, the market analysis and the maximum number of yearly flights per aircraft.

business options exist.

The presented implementation of the growth concept can, with known costs and profits, be linked directly to an ROI value. As presented, the overarching ROI comes out to a value of 135.2% over the full timeline, providing a profit of almost 1.5 billion euros. While this may not seem like a lot, it should be noted that first, aircraft transport margins tend to be low and serve more of a supporting role in other industries and second, most of the value is created in later project phases. Knowing this, it may be wise to hold off on implementation, possibly until a full phase 2 launch may be possible, depending on the environment. With the current implementation of the model, the ROI per stage would simply be the profit margin assigned to that stage of operation. This means that for the final phase, an ROI as high as 195% may be obtained over a shorter time-span. Furthermore, note that the final two stages are still very affordable for customers, and as such one could also opt for even higher profits, and still remain well under the cost requirement. It should be noted that currently the model assumes that flights always occur at maximum payload to calculate the cost per kilogram kilometre, however for business parties it was previously found that the average party size is approximately three. This would thus introduce inaccuracies into the final stages, and actual prices may be higher than presented.

12.4. Cost Breakdown

For many investors, as well as other operators, the procurement price of an aircraft is an important metric in comparison with respect to other similar aircraft. For this purpose, as well as to identify main cost drivers, a cost breakdown for procurement is presented in Table 12.4. The breakdown presented assumes operation during stage 2, as this corresponds to the originally outlined concept throughout the project.

Note that in previous project phases the price of procurement exceeded two million euros, however due to later iterations and a drop in the MTOW, this is much reduced. Due to the aforementioned strong sensitivity, the procurement cost with the expected fleet size of 538 is expected to drop to values as low as 0.65 million euros. Also note the low cost is as such directly related to the fleet size, and thus leads to quite low segments, for example the engineering cost. As some of the cost segments only occur once in the lifetime of an entire aircraft type, they are split over the entire fleet.

Currently, a single Cirrus SR22 costs around 0.7 to 0.9 million euros, still with approximately 4000 aircraft already having been built[1]. With this number in mind, again, the AmpAir aircraft offers a competitive alternative, both in procurement and operation.

[1] https://wikiwings.com/how-many-airplanes-has-cirrus-aircraft-sold-2020/

Table 12.4: Cost breakdown for the five passenger, composite aircraft, according to stage 2 level of autonomy. Corresponding to stage 2 a fleet size maximum of 196 is used, setting the QDF to 0.68.

Cost segment	**Price**
Engineering	€185,245
Tooling	€87,451
Manufacturing	€549,735
Development support	€6,131
Flight test operations	€897
Quality control	€370
Materials	€50,553
Electric motors	€57,082
Power management system	€49,209
Battery	€28,015
Propellers	€41,069
Misc	€13,686
Total cost to produce	€1,069,444
Insurance	€187,152
Profit	€62,830
Procurement price	€1,319,426
Price per kilogram, kilometre	€0.0108

13 Technical Risk Assessment

This chapter identifies, categorises, quantifies and mitigates the technical risks that might occur during the design and operational phase of the aircraft. The chapter starts with a section on risk identification (Section 13.1). This is followed by Section 13.2, which further details the categorisation and quantification of these risks. Findings from these sections are combined and presented in Section 13.3 and Section 13.4 in the form of a risk register and a risk map respectively. After mitigation, a posterior risk map is presented, showing how the risk severity is decreased.

13.1. Methods

As described in the midterm report [30]:

This project shall follow a classical "plan-do-check-act" approach. This chapter contains the "plan" section of this cycle, and outlines how to perform the other steps. The risk mitigation strategy contains the following steps: identify, analyse, plan, track, and control [49]. Using this method, most global technical risks are identified, after which they will be analysed and thus categorised. Based on this, a plan for mitigation shall be made. Tracking and controlling will not be covered in this report. However, it is an essential part of all project stages, meaning all risks are continuously reassessed and, if necessary.

To identify all present risks, various methods exist. Risks can be deducted by looking at the top level risks and hazards of similarly sized aircraft or any historical occurrences. More formal approaches can be applied to identify and mitigate potential hazards and risks. The most complete risk overview can be attained through a Hybrid Hazard Identification Process (HHIP) [65]. However, to prevent constraining the design, more focus is put on a conventional Hazard and Operability Analysis (HAZOP) [14]. It should be taken into account that the HHIP is limited to the identification of hazards, and therefore risks, in the operational environment. Modifications to the method are needed for the design phase risk assessment.

13.2. Parameter Categorisation

As described in the midterm report [30]:

For careful and consistent indexation of all risks as presented in Table 13.1, a clear framework on impact and likelihood categorisation is required. For this purpose, the ICAO SMM are adhered to, for which the definitions are depicted in Table 13.1 [14]. It should be noted that these norms are mostly applicable for operational risk events, while for the design risk events the indexations are slightly different. Design phase technical risks are indexed according to the following definitions; A level 5 categorisation means that the consequence of this risk causes major loss of resources or cause reduction in performance. In contrast to this, level 1 is assigned if the consequences do not incur a significant loss in performance or resources. The indexation for likelihood of occurrence remains the same and is defined as the chance a risk will occur during the lifespan of the entire air-taxi fleet.

Table 13.1: ICAO SSM (ICAO 2009) indexation of frequency and impact pertaining to risks [14]

Index	***Likelihood***	***Impact/Consequence***
1	Extremely improbable - Almost inconceivable that the event will occur	Negligible - Little consequences
2	Improbable - Very unlikely to occur (not known to have occurred)	Minor - Nuisance; Operating limitations; Use of emergency procedures; Minor incident
3	Remote - Unlikely to occur, but possible (has occurred rarely)	Major - A significant reduction in safety margins, a reduction in the ability of the operators to cope with adverse operating conditions as a result of increase in workload, or as a result of conditions impairing their efficiency; Serious incident; Injury to persons
4	Probable - Likely to occur sometimes (has occurred infrequently)	Hazardous - A large reduction in safety margins, physical distress or a workload such that the operators cannot be relied upon to perform their tasks accurately or completely; Serious injury; Major equipment damage
5	Frequent - Likely to occur many (has occurred frequently)	Catastrophic - Equipment destroyed; Multiple deaths

13.3. Risk Register

As described in the midterm report [30]: Following the earlier outlined methods for risk identification and classification, Table 13.2 presents all risks identified, that are relevant for the current design stage. Furthermore, the original likelihood and impact are indicated, the numbers between the brackets give the likelihood and impact after risk mitigation.

Table 13.2: Risk register presenting identified risks[30]

Index	Category	Cause/Risk event	Consequence	Mitigation	L	I
TL-DES-01	Top level design	Inaccurate coefficient/design budget estimates.	Wrongly determined design targets, possibly leading to not meeting requirements.	Perform a study on similar aircraft to ensure budgets make sense. Implement an iterative design process, such that coefficients may be adjusted.	4(3)	3(3)
PERF-DES-01	Performance design	Sub-optimal aircraft layout selected.	Problems later on in the design process, inability to ensure stability and meeting of requirements.	Maintain a fluid design process, staying open-minded on possible late stage changes. Seek feedback from experts.	2(1)	4(3)
TL-DES-02	Top level design	Subsystem Technology Readiness Level (TRL) below projected.	Insufficient performance of system at the time of design completion.	For each selected technology, a multi-horizon approach is used such that a future-proof design is attained, opening possibilities for retrofitting when technologies reach the required TRL.	2(2)	2(1)
TL-DES-03	Top level design	Sub-optimal subsystem solution selected.	Lack of performance in certain areas, waste of time due to redesigning. Possible infeasible complete system.	Maintain a fluid design process, staying open-minded on possible late stage changes. Seek feedback from experts.	3(2)	3(2)
SI-DES-01	System integration design	Poor subsystem integration throughout.	Possible sub-optimal performance or even missing of performance targets. Possible infeasible total system.	Appointment of a systems engineer to ensure smooth integration throughout subsystems.	2(1)	4(4)
AERO-DES-01	Aerodynamic design	Wrong selection of simulation parameters.	Simulation results fail to correspond to external sources. Inadequate aerodynamic performance or excessive noise emissions.	Ensure plenty verification and validation data on selected method in similar applications. Possibly seek feedback from experts.	3(3)	2(1)
AERO-DES-02	Aerodynamic design	Excessive simplifications throughout the design process.	Unforeseen performance phenomena due to applied concept interference.	Design verification through CFD analyses, possibly backed up by experts.	4(3)	3(2)
EM-DES-01	Emissions design	Environmental effects insufficiently taken into account in design process.	Reduced performance or system lifetime, increase in operational and maintenance cost.	Evaluate selected design options in a wide range of environmental conditions, and implementing adequate processes to ensure resistance.	3(2)	4(3)
TL-DES-04	Top level design	Improper attention for power source degradation throughout lifetime in initial sizing estimates.	Reduced performance or system lifetime, increase in operational and maintenance cost.	Implement power source degradation in initial estimates for adequate sizing of aircraft systems.	3(2)	4(3)
PROP-OPER-01	Propulsive operation	Power source failure.	Loss of thrust, inability to maintain level flight.	Implement a level of reliability and/or redundancy to meet industry standards.	3(2)	5(4)
PROP-OPER-02	Propulsive operation	Tractive system failure.	Loss of thrust, inability to maintain level flight.	Implement a level of reliability and/or redundancy to meet industry standards.	4(3)	5(4)
PROP-OPER-03	Propulsive operation	Power delivery system failure.	Loss of thrust, inability to maintain level flight.	Implement a level of reliability and/or redundancy to meet industry standards.	4(3)	5(4)
PROP-OPER-04	Propulsive operation	Power source puncture/ignition.	Possible fire or other hazardous situation on-board.	Implement measures to prevent or suppress fire, or to reject the source from the system.	3(2)	5(4)
STRUC-OPER-01	Structural operation	Improper cabin sealing/closing.	Hazardous situation for passengers	Feature redundant on-board systems such as oxygen masks or other solutions to ensure passenger health.	2(2)	2(1)
PROP-OPER-05	Propulsive operation	Bird strike.	Possible (partial) failure of aircraft structures.	Implement impact load cases into structural design process to ensure likely impact areas are able to absorb without critical failure.	4(4)	2(1)
CONT-OPER-01	Control operation	Power distribution system failure.	Possible loss of subsystem workings or control. Possibly loss of level flight ability.	Implement a level of reliability and/or redundancy to meet industry standards.	4(3)	4(3)

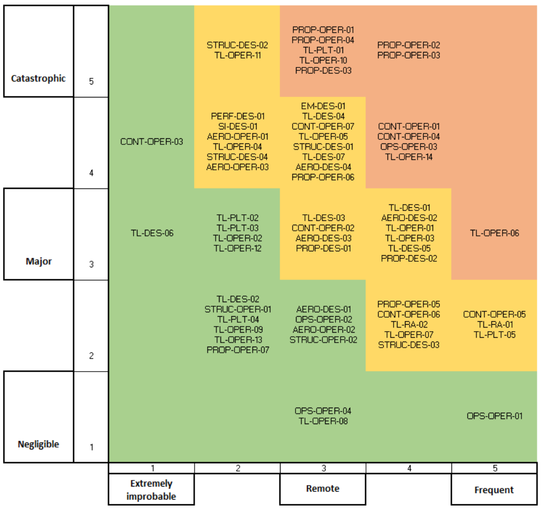
CONT-OPER-02	Control operation	Mechanical control operation failure.	Loss of control surface operation ability.	Implement a level of reliability and/or redundancy to meet industry standards.	3(2)	3(2)
CONT-OPER-03	Control operation	Passenger malignant intent.	Complete loss of control of aircraft trajectory and operation. Endangerement of direct environment.	Implement systems such that pilot is shielded from the passenger, or such that the passenger is incapacitated from piloting the aircraft.	1(1)	4(2)
CONT-OPER-04	Control operation	Flight control system failure.	(partial) Loss of aircraft control.	Implement a level of reliability and/or redundancy to meet industry standards.	4(3)	4(3)
CONT-OPER-05	Control operation	Unsafe flight path.	Potentially dangerous proximity to obstacles, weather or other air traffic.	Implement monitoring and intervention systems for potential obstacles or traffic.	5(4)	2(2)
CONT-OPER-06	Control operation	Unavailable landing area.	Necessitates other landing options or deviation from flight plan.	Implement emergency range capability or systems such that the aircraft is able to land on various terrain types.	4(4)	2(1)
CONT-OPER-07	Control operation	Landing gear system failure.	Landing gear (partially) fails to extend.	Implement a level of reliability and/or redundancy to meet industry standards.	3(2)	4(3)
OPS-OPER-01	Operations system operation	Damage sustained outside of system operation.	Mission delays or increase in maintenance cost.	Implementation of proper pre-flight checking procedures, as well as designing for maintainability.	5(5)	1(1)
OPS-OPER-02	Operations system operation	Communication system failure.	Loss of contact with ground station. No possibility for remote control.	A level of autonomy or overrideability needs to be present such that the aircraft is never left uncontrolled.	3(3)	2(1)
OPS-OPER-03	Operations system operation	Pilot is incapacitated during flight.	Pilot is no longer able to fly the a/c by themselves.	A level of autonomy or overrideability needs to be present such that the aircraft is never left uncontrolled.	4(4)	4(3)
OPS-OPER-04	Operations system operation	Aircraft is unable to return to home airfield.	Possible inability to perform planned missions. Possible need for alternative support.	Measures in operations and system design are to be implemented such that no aircraft is left to be stranded, or infrastructure is such that it poses no further problem.	3(2)	1(1)
TL-RA-01	Overarching risk analysis	Oversight of risks.	Unforeseen problems throughout design process. Unconsidered hazards in product operation.	Perform a careful risk analysis, following existing and proven methods for risk identification.	5(3)	2(2)
TL-RA-02	Overarching risk analysis	Improper tracking of identified risks.	Identified risks improperly taken into account in furhter design. Mitigation measures failed to be implemented.	Perform periodic updates on the risk assessment, including further identification, categorisation and mitigation. Check mitigation procedures.	4(2)	2(2)
TL-PLT-01	Aircraft piloting	Autonomous system views human intervention as a threat.	Improper aircraft control.	Implement a clear operational control structure. Pilot shall be able to disengage autonomous and remote pilot at all times.	3(1)	5(5)
TL-PLT-02	Aircraft piloting	Autonomous system failure.	Loss of autonomous control.	Implement pilot and remote control possibilities. Implement "highway-in-the-sky" system to ensure ability of passenger to always take over control confidently.	2(2)	3(2)
TL-PLT-03	Aircraft piloting	Loss of communication with ground station.	Loss of remote piloting possibility.	Implement pilot and autonomous control possibilities. Implement "highway-in-the-sky" system to ensure ability of passenger to always take over control confidently.	2(2)	3(2)
TL-PLT-04	Aircraft piloting	Pilot insecurity of ability to perform required control tasks.	Loss of direct aircraft control by pilot on board.	Implement "highway-in-the-sky" system to ensure ability of passenger to perform basic flight operations confidently. Enable pilot to ask for remote piloting assistance.	2(2)	2(1)
TL-OPER-01	Overarching operation	No battery present at airport of destination.	Unable to recharge aircraft in time for following flights.	Enable the aircraft to recharge using ever-present facilities such as the general power network. Implement a transparant communication towards passenger on flight possibility.	4(1)	3(2)
TL-OPER-02	Overarching operation	No charging possibility at destination airfield.	Unable to recharge aircraft in time for following flights.	Incorporate a battery supply to airfields in logistics concept, or have a basic number of batteries stored at pre-determined fields.	2(1)	3(2)
AERO-OPER-01	Aerodynamic operation	Stuck control surfaces.	Loss of aircraft control in one or more directions.	Design control surfaces such that compensation is possible through other surfaces.	2(2)	4(3)
TL-OPER-03	Overarching operation	No replacement parts available at destination airfield.	Inability to perform required maintenance by contractor. Aircraft grounded.	Incorporate a maintenance service such that more complex maintenance may be carried out at any location.	4(4)	3(2)
TL-DES-05	Overarching design	Insufficient volume estimates for subsystems.	Packaging problems due to false estimates.	Maintain an iterative design process. Implement sufficient verification and validation measures in the design.	4(2)	3(3)
TL-DES-06	Overarching design	Improper gear positioning.	Ground maneuvering stability problems, possible tip-over cases.	Iterate on landing gear design through various design phases to account for shifting weight balance estimates.	1(1)	3(1)
TL-OPER-04	Overarching operation	Lack of certified maintenance personel available.	Inability to maintain the required fleet size.	Implement an in-house or outsourced process to certify maintenance personel.	2(1)	4(4)
TL-PLT-05	Aircraft piloting	Passenger/pilot becomes sick during flight.	(Partial) loss of accurate aircraft control by the on board pilot.	Implement a "highway-in-the-sky" system such that passengers can perceive lateral and vertical movement to reduce sickness.	5(3)	2(2)
TL-OPER-05	Overarching operation	Flight data sensors give non-sensical readings.	Loss of accurate autonomous and remote control capability.	Implement "highway-in-the-sky" system to ensure ability of passenger to perform basic flight operations confidently.	3(3)	4(3)
TL-OPER-06	Overarching operation	A/C has to divert from route due to inclement weather.	Inability to fulfill the planned mission.	Implement monitoring system to evaluate nearest reachable airfield.	5(5)	3(2)
TL-OPER-07	Overarching operation	Passenger arrive late or fail to show up.	Inability to fulfill the planned mission.	Implement fees for passengers not showing up for scheduled flights.	4(1)	2(2)
TL-OPER-08	Overarching operation	Passengers being overweight or unable to board aircraft due to physical reasons.	Inability to fulfill the planned mission.	Ensure passengers are physically capable during pre-flight courses. Implement a basic level of aircraft accesibility.	3(2)	1(1)
STRUC-DES-01	Structural design	Gear fatigue insufficiently accounted for.	Possible need for landing gear system redesign or increase in maintenance load.	Sufficiently consider loading due to ordinary and crabbing landing cases during design.	3(2)	4(3)
AERO-DES-03	Aerodynamic design	HLD performance under-estimation.	Inability to meet performance requirements in T/O and landing. Possible inability to meet certification requirements.	Perform careful analysis on the preliminary design. Implement CFD verification and validation in design process.	3(1)	3(3)
STRUC-DES-02	Structural design	Battery placement and dynamic behaviour insufficiently taken into account in wing structure design.	Increase in vibrational and/or bending loads in wing structure.	Maintain an iterative design process. Implement sufficient verification and validation measures in the design.	2(1)	5(5)
TL-OPER-09	Overarching operation	Foreign object debris (FOD) ingestion or impact.	Damage to aircraft, possibly resulting in loss of propulsion or control.	Analyse sensitive and likely areas, and design for local mitigation in such locations.	2(2)	2(1)
TL-DES-07	Overarching design	Cooling problems due to battery placement.	Battery overheating problems, possible safety hazard for passengers. Increased risk of energy source ignition.	Implement, verify and validate sufficient cooling systems in design. Design for emergency heat shedding towards other areas than the passenger cabin.	3(2)	4(3)

TL-OPER-10	Overarching operation	Power source failure.	Loss of thrust, inability to maintain level flight.	Implement a level of reliability and/or redundancy to meet industry standards.	3(2)	5(4)
TL-OPER-11	Overarching operation	Energy source puncture or ignition.	Loss of energy supply. Obvious fire hazard for passenger and structural integrity.	Implement systems for fire suppression or energy source ejection. Implement fire retardant materials surrounding passenger cabin.	2(1)	5(4)
AERO-OPER-02	Aerodynamic operation	HLD failure.	Reduced lift, necessitating more T/O or landing distance.	Implement a level of reliability and/or redundancy to meet industry standards. Divert to a different airfield.	3(3)	2(1)
AERO-DES-04	Overarching design	Improper control surface estimates.	Lack of aircraft control, possible inability to meet certification requirements.	Maintain an iterative design process. Implement sufficient verification and validation measures in the design.	3(2)	4(3)
TL-OPER-12	Overarching operation	People or objects impacting wing structure or accessories.	Damage to aircraft, possibly resulting in grounding of aircraft.	Implement clear outlines on aircraft ground handling in pre-flight training courses.	2(2)	3(2)
TL-OPER-13	Overarching operation	Uneven power distribution.	Reduction of aircraft control and performance.	Design such that control surfaces may compensate, or such that shutdown of a selection of motors is possible.	2(2)	2(1)
PROP-OPER-06	Propulsive operation	Loss of cooling for engine.	Loss of engine performance	Ensure redundancy by utilising separate cooling system.	3(2)	4(3)
TL-OPER-14	Overarching operation	Loss of cooling for power-providing subsystems.	Loss of power-providing system capabilities.	Ensure redundancy by utilising separate battery management system and cooling system.	4(3)	4(3)
PROP-DES-01	Propulsive design	Propulsion induced loading insufficiently taken into account in wing structure design.	Increase in vibrational and/or twisting loads in wing structure.	Maintain an iterative design process. Implement sufficient verification and validation measures in the design.	3(2)	3(2)
PROP-DES-02	Propulsive design	Unforeseen design problems due to propulsion technology readiness.	Loss of resources in design process. Possible budget overruns.	Investigate complexity and feasibility prior to final concept selection.	4(3)	3(3)
PROP-OPER-07	Propulsive operation	Uneven power distribution.	Reduction of aircraft control and performance.	Design such that control surfaces may compensate, or such that shutdown of a selection of motors is possible.	2(2)	2(1)
PROP-DES-03	Propulsive design	Concept offers insufficient performance.	Performance requirements failed to be met.	Thoroughly evaluate the feasibility of the proposed concepts, if unreasonable, adapt these as fit.	3(2)	5(5)
STRUC-DES-03	Structural design	Landing gear storage space problem	More complexity of the structure and increased drag.	Iterative design usage to efficiently incorporate the landing gear into the design.	4(3)	2(2)
STRUC-OPER-02	Structural operation	Access difficulties	Parts that need replacement/ removal cannot be replaced or removed.	Design in a way that the components are removable /replaceable from the top of the wing.	3(2)	2(2)
STRUC-DES-04	Structural design	High torsion loads not sufficiently taken into account.	Loss of functionality of the tail.	Thoroughly evaluate the configuration and the load characteristics.	2(1)	4(4)
AERO-OPER-03	Aerodynamic operation	Unfavourable stall behaviour and recovery	Poor flight handling, unsuitable for inexperienced pilots	Thoroughly evaluate the configuration and the stall characteristics.	2(1)	4(4)

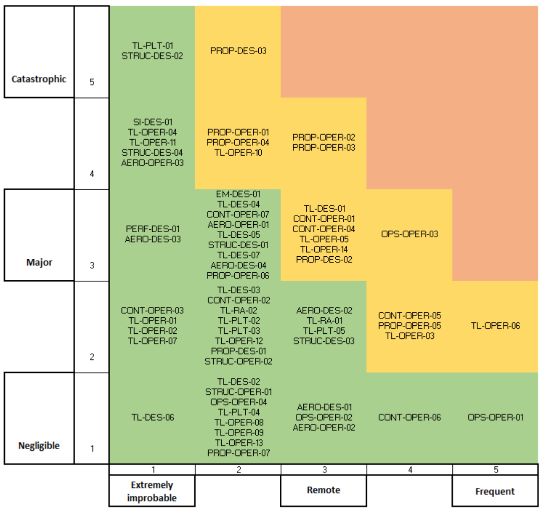
13.4. Risk Indexation and Mitigation

As described in the midterm report [30]:

All risks previously presented have been indexed according to their likelihood and the severity of their consequences. Visually, a risk map is presented following the same indexation in Figure 13.1a. This risk map broadcasts the risks before any mitigation is executed. The red, orange and green cells indicate high, medium, and low risk respectively. If mitigation as given in Table 13.2 is executed, this leads to the risks relocating within the risk map, shown in Figure 13.1b.



(a) Technical risk map (before risk mitigation)



(b) Technical risk map (after risk mitigation)

Figure 13.1: Risk mitigation maps

14 Verification and Validation Procedures

This chapter describes the execution of verification and validation done throughout the report, as planned in previous design stages [30]. Firstly, Section 14.1 describes how model verification and validation and assumption validation is performed. The verification of the product, which includes the compliance with the product requirements, is presented in Section 14.2. Finally, Section 14.3 covers an initial compliance analysis of the stakeholder requirements. A testing procedure is included, which will be used to physically test the compliance of the design with each stakeholder requirement.

14.1. Model Verification and Validation

The process of model verification and validation is done continuously throughout the design. Firstly, models taken from literature are always checked on stated deficiencies and discrepancies to be able to determine the correctness of the outcome. It is also verified, that models must always be backed-up by multiple studies. If this is not the case, a model is not used for design purposes.

Furthermore, there are models applied through coding using the Python programming language[1], which structure and performance are verified. Unit tests are performed on every function in the code, using the Pytest framework[2], to check the operating of each function happens correctly. The code of an example unit test, to verify the output type of a function that calculates the density at a certain altitude, is shown below.

```
from test_par import test_par # Import class containing test parameters.
test_par = test_par() # Create object containing test parameters.
def test_unit_rho(): # To test the density function to have a float type as output.
    # rho function inputs are altitude [m] and object with test parameters.
    assert type(rho(0, test_par)) == float
```

The output of a unit test is either a pass, failure, or error. Unit tests are simple to understand and are used to discover small coding mistakes that are easy to fix. Unit tests are not only performed on functions, but also on inputs. Before an input is used, it is checked if it is for example the right object type or that it contains information and is not a 'Nonetype'. Output behaviour tests are performed to verify the outputs change as expected, when changing the inputs. For the unit test example, shown above, this could mean increasing the altitude, which should result in a lower density. Both input tests and output behaviour tests are also performed using the Pytest framework. Additionally, calculation verification is done for model verification. Every time a calculation is performed using a model, it is checked by hand using a calculator and using the code in which the model is written. This ensures that a calculation is always checked twice, using different methods.

Finally, code debugging is done continuously and has taken up most of the time spend on model verification. Code debugging consists mainly of running the code, through which errors are discovered. When an error is discovered, the process of debugging starts by inspecting the code for mistakes that are easier to spot. If the mistake is not detected right away, a debugging-tool is used, which are included with most integrated development environments (IDE's). A final measure that is taken, in case the previous methods were not successful, is running small parts of the code separately. However, this method was not used often, as the before mentioned unit-test methods are already written before a code is used.

Throughout the design process, all assumptions have been analysed for model validation. Whenever an assumption was used, it was analysed through literature research or by consulting field experts. The analysis includes the reason the assumption is used, and it clarifies the effect each assumption has on the design and how the effect will be analysed in future detailed design. Furthermore, the results that were obtained by using the models were compared to the model outcomes mentioned in the literature of the model. These comparisons were made as a sanity check.

[1] https://en.wikipedia.org/wiki/Python_(programming_language)

[2] https://docs.pytest.org/en/7.3.x/

14.2. Product Verification

Product verification is done by confirming each product requirement is met. The verification of the product is presented in a compliance matrix, shown in Table 14.1.

The compliance with the requirements is checked for stage 2 in the growth concept in Chapter 5, as this is the stage that aimed for in the aircraft design and deemed achievable. In Table 14.1, it can be seen that most requirements are met, indicated in green, or that the compliance is undetermined in this design stage, indicated in grey. The compliance with some requirements is highly dependent on development of technology and certification. The adaptability of the design on these developments is explained in Chapter 5, and the compliance with these requirements is indicated with orange. Five of the product requirements are unmet and are depicted in red. **REQ-CN-RAMS-04** states that the aircraft must be available for 8 hours a day. This requirement is only met when fast charging is possible, which is included in hubs only for stage 2 of the growth concept. Future technology can improve charge time of the aircraft, while solid-state battery technology will open up the possibility of swapping batteries. **REQ-TP-FPP-19** is not met as individual oxygen systems are not needed for aircraft flying below 3000 m [43]. However, a cabin fire extinguisher system is included in the design of the aircraft. **REQ-TP-CS-18**, is considered unachievable as a robot would be need to be available at every airport. This would increase the cost of the service to an unfeasible extent. Having a parachute for every passenger on board, as demanded by **REQ-TP-OPE-14**, is shown to be unnecessary. The aircraft itself already has a ballistic parachute, which will deploy in case of emergency. It would also be needed to train each passenger individually on the use of parachutes, including children and elderly. It is thus considered more safe to only have a ballistic parachute for the aircraft itself. **REQ-TP-COMS-02** is not met as the data transmission system, needed for creating a secured video broadcast between the aircraft and ground control, is too complicated with current technology. All five unmet requirements are considered to not be killer requirements [4], and do not drive the design to an unacceptable extent.

Table 14.1: Compliance Matrix

Identifier	Requirement Description	Compliance	Justification	Reference section
REQ-CN-COST-01	The total cost of the manufacturing shall not exceed 2,000,000 euros per vehicle.	Compliant	Estimated cost is 1,320,000 euros	Section 12.4
REQ-CN-COST-02	The operational cost of the vehicle shall not exceed 0.5 euros per passenger per kilometre (€/pax/km).	Compliant in future	Stage 4 estimate: 0.314 (€/pax/km)	Section 12.4
REQ-CN-COST-03	The vehicle design shall be completed within 10 weeks by 10 students.	Compliant	Preliminary design completed	Chapter 15
REQ-CN-SCH-01	The vehicle shall be able to arrive at the departure location at most 2 hours after passenger request.	Compliant	400 km covered under 2 hours at cruise speed	Section 2.2
REQ-CN-SCH-02	The vehicle shall be operable within 10 years from the start of the project.	Compliant	Stage 2 design, operable in 11 years	Section 5.1
REQ-CN-SCH-03	The vehicle shall have an operational lifetime of at least 25 years.	Compliant	Vehicle lifetime of 25 years	Section 6.1
REQ-CN-SUS-01	The vehicle shall have no emissions.	Compliant	0% Emissions during flight	Section 10.1
REQ-CN-SUS-02	The end-of life waste shall be less than 10 %.	Compliant in future	Depended on composite recyclability	Section 10.4
REQ-CN-SUS-03	The vehicle shall not cause noise higher than 60dB at 1000 ft.	Compliant	51.9 dB in cruise	Section 10.5
REQ-CN-LEG-01	The vehicle shall comply to the CS23 certification standards.	Not determined	Partly covered in current certification	Chapter 4
REQ-CN-LEG-02	The vehicle shall comply to the IFR standards.	Compliant	IFR standards covered	Section 4.3
REQ-CN-LEG-03	The vehicle shall be capable of autonomous flight during taxiing, take-off, cruise, and landing.	Compliant	Performed by autopilot	Section 6.8
REQ-CN-RAMS-01	The probability of catastrophic failure of the vehicle shall not exceed 10^{-9} per flight hour.	Compliant	Less than 10^{-9}	Chapter 6
REQ-CN-RAMS-02	The vehicle shall be equipped with a means to exit the vehicle in case of an emergency.	Compliant	Normal and emergency exit present	Section 7.4
REQ-CN-RAMS-03	The vehicle shall adhere to the airspace restrictions of the local government where it is operating.	Compliant	Flight plan accounts for restrictions	Section 6.2
REQ-CN-RAMS-04	The vehicle shall be available for use during 8 operating hours per day.	Non-compliant	Only when fast-charging is available	Section 6.4.2 Section 6.8

REQ-CN-RAMS-05	The vehicle shall be operational both during daylight conditions and in low-visibilty or no-visibility conditions.	Compliant	IFR standards covered	Section 4.3
REQ-CN-RAMS-06	The vehicle shall be equipped with easy-to-access maintenance panels and hatches to facilitate maintenance and repair work	Not determined	Completed in future design	-
REQ-CN-RAMS-07	The vehicle shall be designed such that routine maintenance tasks can be performed within a time limit of 17 minutes per flight hour and with minimal tools and equipment	Compliant	Subsystems designed for low maintenance	Section 6.10
REQ-TP-STR-01	The vehicle shall sustain a positive limit manoeuvring load factor of no less than 2.1+24000/(W+10000) but less than 3.8 (CS23.337).	Compliant	Positive limit of 3.65	Section 11.2.1
REQ-TP-STR-02	The vehicle shall sustain a negative limit manoeuvring load factor not less than 0.4 times the positive load factor (CS23.337).	Compliant	Negative limit of -1.459	Section 11.2.1
REQ-TP-STR-03	The vehicle shall withstand loads resulting from gusts on each lifting surface (CS23.341).	Not determined	Completed in future design	-
REQ-TP-STR-04	The vehicle shall have an ice protection system for normal operations under Vmo (CS23.2165).	Not determined	Completed in future design	-
REQ-TP-STR-05	The vehicle shall be strong enough to withstand the flight loads combined with pressure differential loads (if any) from zero up to the maximum relief valve setting (C23.365).	Not determined	Completed in future design	-
REQ-TP-STR-06	The vehicle shall have at least one emergency exit on the opposite side of the cabin from the main door (CS23.807).	Compliant	Emergency exit with dimensions: 48-by 51 cm	Section 7.4
REQ-TP-STR-07	The vehicle shall support limit loads without interference with the safe operations of the vehicle (23.305).	Not determined	Completed in future design	-
REQ-TP-STR-08	The vehicle shall support ultimate loads for at least 3 seconds without failure (23.305).	Not determined	Completed in future design	-
REQ-TP-STR-09	The vehicle shall not fail due to corrosion during its mission operation.	Compliant	Designed for corrosion resistance	Section 11.1.2
REQ-TP-STR-10	The vehicle shall not fail due to fatigue during its mission operation.	Not determined	Completed in future design	-
REQ-TP-STR-11	There shall be a clearance gap between the engine rotating blades and the fuselage of 25 mm.	Compliant	Clearance gap of 25 mm included	Section 8.4
REQ-TP-STR-12	The nose gear shall be loaded between 8% and 15% of MTOW.	Compliant	Nose gear is loaded with 15% of MTOW	Section 7.6
REQ-TP-STR-13	Tyres shall be pressurised between 310kPa and 410kPa to be able to land on hard grass runways.	Compliant	Tyre pressure in allowable range	Section 7.6
REQ-TP-STR-14	Landing gear shall be positively kept in landing gear position in case of failure (CS.2305).	Compliant	Landing gear possitively kept	Section 7.6
REQ-TP-STR-15	The scrape angle shall be no less than 15 degrees.	Compliant	Scrape angle of 15 degrees included	Section 7.4
REQ-TP-STR-16	The overturn angle shall not be greater than 55 degrees.	Compliant	Overturn angle is 52.4 degrees	Section 7.4
REQ-TP-STR-17	The Center of Gravity shall not exceed a position further aft than the location of the main landing gear at any point. Including loading procedure.	Compliant	Center of Gravity in front of main landing gear	Section 7.7.1
REQ-TP-STR-18	The energy storage shall be designed such that leakage or failure due to fatigue has a lifetime of 10000 flights minimum.	Not determined	Completed in future design	-
REQ-TP-STR-19	Each removable fastener shall include 2 retaining devices if loss of fastener could lead to structural failure (CS23.607).	Not determined	Completed in future design	-
REQ-TP-STR-20	All control surfaces hinge design shall have a safety factor of 6.67 from ultimate bearing strength (CS23.657).	Not determined	Completed in future design	-
REQ-TP-STR-21	All push-pull controls using angular displacements shall have a safety factor of 3.33, expect cable control with a safety factor of 2 (CS23.693).	Not determined	Completed in future design	-
REQ-TP-STR-22	The structure shall minimise damage in case of an uncontained engine or rotating-machinery failure (CS23.2240).	Not determined	Completed in future design	-
REQ-TP-FPP-01	With all engines operating during climb a minimum climb gradient of 8.3% shall be possible (CS 23.2120).	Compliant	Overdesigned due to excess power	Section 7.1
REQ-TP-FPP-02	The vehicle shall account for stall speed safety margin, a minimum control speed and climb gradients. This must include the determination of ground roll and climb distance up to 15 m above the surface.	Not determined	Completed in future design	-
REQ-TP-FPP-03	The vehicle shall have controllable stall characteristics in straight flight, turning flight, and accelerated turning flight (CS23.2150).	Not determined	Completed in future design	-
REQ-TP-FPP-04	Safe limits of the Center of Gravity (COG) of the vehicle shall be determined for operations (CS23.2100).	Compliant	Determined in potato diagram	Section 7.7.1

REQ-TP-FPP-05	Determination of safe limits of the Center of Gravity (COG) of the vehicle shall be easily repeatable (CS23.2100).	Not determined	Completed in future design	-
REQ-TP-FPP-06	The vehicle shall have a climb gradient of 1.5% at a pressure altitude of 1524 m in cruise in case of critical loss of thrust (CS 23.2120).	Compliant	Climb gradient of 38%	Section 8.11
REQ-TP-FPP-07	The vehicle shall be able to have a climb gradient of 3% at balked landing without creating undue pilot workload, with landing-gear extended and flaps at landing (CS 23.2120).	Not determined	Completed in future design	-
REQ-TP-FPP-08	Climb and descent performance shall be determined when all engines are operating and also during critical loss of thrust during take-off and on route phase flight (CS 23.2125).	Not determined	Completed in future design	-
REQ-TP-FPP-09	Vehicle shall not go into unintentional stalling, also during a critical loss of thrust (thrust-asymmetry) (CS23.2150).	Not determined	Completed in future design	-
REQ-TP-FPP-10	The vehicle shall have a clear warning to prevent unintentional stalling (CS23.2150).	Compliant	MAU warning system	Section 9.3
REQ-TP-FPP-11	Fuel lines shall be designed redundantly in case of failure.	Compliant	Including two battery packs	Section 7.3
REQ-TP-FPP-12	Cooling subsystem shall have a smaller failure rate than any other engine subsystem.	Compliant	Cooling subsystem fails last	Section 7.8.2
REQ-TP-FPP-13	Cooling subsystem shall comply with both gaseous (CS23.1041) and liquid (CS23.1061) requirements.	Compliant	Requirements accounted for	Section 7.8.2
REQ-TP-FPP-14	Power shall be provided to other subsystems of the aircraft by the energy source converter used in the power and propulsion system.	Compliant	Energy source converter included	Section 7.8.1
REQ-TP-FPP-15	Engine start up and shut down shall be an autonomous process.	Compliant	Done by autopilot/passenger pilot	Section 6.6
REQ-TP-FPP-16	Propeller aerodynamics shall be optimized for cruise advance ratios such that take-off performance is only reduced to 80% of cruise thrust.	Compliant	Overdesigned due to excess power	Section 8.3
REQ-TP-FPP-17	All exhausts shall minimize exit temperature to reduce unwanted chemical reactions such as NOx production.	Not determined	Completed in future design	-
REQ-TP-FPP-18	Cabin shall be implemented with individual oxygen systems and cabin fire extinguisher system.	Non-compliant	Oxygen systems not included	Section 7.4
REQ-TP-FPP-19	The aircraft systems integration shall be implemented with redundancy to ensure hydraulics or electric failures do not lead to catastrophic failure.	Not determined	Completed in future design	-
REQ-TP-FPP-20	The tail loading shall be adaptable to provide sufficient controllability to perform all necessary manoeuvres.	Not determined	Completed in future design	-
REQ-TP-FPP-21	The tail shall comply with balancing loads regulations during design (CS 23.421).	Not determined	Completed in future design	-
REQ-TP-FPP-22	The tail shall comply with manoeuvre loads regulations during design (CS 23.423).	Not determined	Completed in future design	-
REQ-TP-FPP-23	The tail shall comply with gust loads regulations during design (CS 23.425).	Not determined	Completed in future design	-
REQ-TP-FPP-24	The engines shall be mounted in such way that they can be removed and swapped without requiring to ground the aircraft.	Not determined	Completed in future design	-
REQ-TP-CS-01	Vibration and buffeting (up to Vd/Md) shall not interfere with control or cause fatigue (S23.2160).	Not determined	Completed in future design	-
REQ-TP-CS-02	The control forces itself shall not fatigue the pilot in any situation (CS 23.2140).	Not determined	Completed in future design	-
REQ-TP-CS-03	The vehicle shall have static longitudinal stability in normal operations (CS23.2145).	Compliant	Determined in scissors plot and potato plot	Section 7.7.2 Section 7.7.1
REQ-TP-CS-04	The vehicle shall have static lateral stability in normal operations (CS23.2145).	Not determined	Completed in future design	-
REQ-TP-CS-05	The vehicle shall have static directional stability in normal operations (CS23.2145).	Not determined	Completed in future design	-
REQ-TP-CS-06	The short period shall be stable (CS23.2145).	Not determined	Completed in future design	-
REQ-TP-CS-07	The Dutch roll shall be stable (CS23.2145).	Not determined	Completed in future design	-
REQ-TP-CS-08	The control system shall provide stable feedback (CS23.2145).	Not determined	Completed in future design	-
REQ-TP-CS-09	The vehicle shall have controllable longitudinal and directional handling characteristics during taxi, take-off, and landing (CS23.2150).	Not determined	Completed in future design	-
REQ-TP-CS-10	The pilot or the flight control system shall be able to maintain lateral and directional trim in cruise (CS 23.2140).	Not determined	Completed in future design	-

REQ-TP-CS-11	The pilot or the flight control system shall be able to maintain longitudinal trim in climb, level flight, descent, and approach without needing a control force (CS 23.2140).	Not determined	Completed in future design	-
REQ-TP-CS-12	The vehicle shall be directionally stable during ground operations.	Compliant	Overturn angle accounted for	Section 7.4
REQ-TP-CS-13	The vehicle shall be controllable and manoeuvrable for an average pilot within the flight envelope (CS23.2135).	Compliant	Highway in the sky system included	Section 6.1.3
REQ-TP-CS-14	The autopilot shall always engage before take-off, and disengage after landing, except emergency disengagement operated by the ground control.	Compliant	Depended on pilot level	Section 6.11.2 Section 6.1.3
REQ-TP-CS-15	The vehicle shall not go into inadvertent bad stall conditions after critical loss of thrust and in case of thrust-assymtry (CS23.2150).	Not determined	Completed in future design, parachute for emergency	Section 6.11.5
REQ-TP-CS-16	In case of automatic ground operations, the vehicle shall be able to taxi itself from hangar to the runway and vice versa.	Compliant	Automatic taxiing included	Section 6.8
REQ-TP-CS-17	The vehicle shall be able to perform built in checks to determine its airworthiness.	Compliant	Central Maintenance Computer	Section 6.10.1
REQ-TP-CS-18	In case of automatic ground operations, the vehicle shall be able to recharge itself.	Non-compliant	Person required for recharging	Section 6.4.2
REQ-TP-CS-19	The vehicle shall be able to send diagnostic data to the operational centre at all times.	Compliant	Data-link included for sending data	Section 9.1
REQ-TP-CS-20	The vehicle shall be able to stop at all times during ground operations.	Compliant	Emergency stop included in design	Section 6.11.2
REQ-TP-CS-21	The vehicle shall perform collision detection during flight.	Compliant	Detection system and radar/transponder	Section 6.2
REQ-TP-MAT-01	90% of the operational empty mass of the vehicle shall be recyclable.	Compliant in future	Depended on thermoset recyclability	Chapter 10
REQ-TP-MAT-02	All materials used in the cabin structure shall be fire-resistant.	Compliant	Completed in future design	Section 11.1.2
REQ-TP-MAT-03	Design and manufacturing processes for joining parts shall be maximised.	Compliant	Optimised in design and production plan	Section 11.4.1
REQ-TP-MAT-04	Choice of recycled materials shall be implemented in all non-critical structural parts if design tolerance allows it.	Compliant	Optimised in design and production plan	Section 11.5.2
REQ-TP-MAT-05	Interior cabin design shall avoid usage of new complex shapes with high cost and manufacturing efforts.	Compliant	Optimised in design and production plan	Section 11.3
REQ-TP-MAT-06	Avionics equipment and electrical equipment shall be fire-resistant (CS23.2330).	Not determined	Completed in future design	-
REQ-TP-MAT-07	The energy storage shall have a fire-protection material coating or laminating protecting from external heat sources (CS23.2325).	Compliant	Firewall deemed sufficient	Section 11.1.2 and Section 11.2.2
REQ-TP-MAT-08	The structure material shall protect the structure from weathering, corrosion and abrasion, including ventilation and drainage surfaces (CS23.609).	Not determined	Completed in future design	-
REQ-TP-MAT-09	90% of the cost spent on aircraft materials shall be recuperated at end-of-life.	Compliant in future	Depended on thermoset recyclability	Chapter 10
REQ-TP-OPE-01	The vehicle shall be able to determine its position during the mission.	Compliant	Using GPS and air data computer	Section 9.3
REQ-TP-OPE-02	The vehicle shall be able to determine its attitude during the mission.	Compliant	Using GPS and air data computer	Section 9.3
REQ-TP-OPE-03	The vehicle shall be able to determine its airspeed during the mission.	Compliant	Using GPS and air data computer	Section 9.3
REQ-TP-OPE-04	The vehicle shall be able to determine its altitude during the mission.	Compliant	Using GPS and air data computer	Section 9.3
REQ-TP-OPE-05	The vehicle shall be able to follow flight plan during the mission.	Compliant	Accounted for in operations	Section 6.2
REQ-TP-OPE-06	The vehicle shall be able to contact the ATC at all times during the mission.	Compliant	Using VHF	Section 9.1.1 Figure 9.5
REQ-TP-OPE-07	The vehicle shall be able to share its position during the mission with ATC.	Compliant	Using VHF	Section 9.1.1 Figure 9.5
REQ-TP-OPE-08	The vehicle shall be able to share its altitude during the mission with ATC.	Compliant	Using VHF	Section 9.1.1 Figure 9.5
REQ-TP-OPE-09	The vehicle shall be able to contact the operational centre at all times during the mission.	Compliant	Using satellite and VHF	Section 9.1.1 Figure 9.5
REQ-TP-OPE-10	The vehicle shall be able to taxi from storage to the hangar and vice versa.	Compliant	Automatic taxiing included	Section 6.8
REQ-TP-OPE-11	Landing gear design shall be adequate for tarmac and grass runway landings.	Compliant	Correct tire size and pressure	Section 7.6
REQ-TP-OPE-12	The battery structure shall support sharp vibrational damping.	Not determined	Completed in future design	-

REQ-TP-OPE-13	The aircraft shall provide safe exit in case of emergency.	Compliant	Normal and emergency exit present	Section 7.4
REQ-TP-OPE-14	Certified parachutes shall be provided for each passenger onboard.	Non-compliant	Shown to be unnecessary	Section 4.4
REQ-TP-OPE-15	The vehicle shall be able to detect a potential collision during the mission	Compliant	Done by ADS-B, TCAS-II and radar/transponder	Section 6.2 Figure 9.5
REQ-TP-OPE-16	The vehicle shall be able to avoid a potential collision during the mission	Compliant	Done by autopilot or passenger pilot	Section 6.2
REQ-TP-OPE-17	The vehicle shall be able to retrieve weather conditions during the mission	Compliant	Done by WX radar	Figure 9.5
REQ-TP-COMS-01	A communications channel shall provide a bit rate of 50 kbit/s	Compliant	Bit rate is 50 kbit/s	Section 9.1
REQ-TP-COMS-02	In case of emergency situations, the data rate shall be sufficient for transfer of at least 1 video-broadcast, 2 voice channels and 10 telemetry channels, while operating within the operating radius.	Non-compliant	No video-broadcast possible	Section 9.1
REQ-TP-COMS-03	The secondary communications channel shall provide communication between the aircraft and ATC for the given frequency.	Compliant	Using CPDLC	Section 6.3
REQ-TP-COMS-04	Internal communication channel shall be provided between passengers.	Compliant	Headphones present	Section 10.5
REQ-TP-AERO-01	The total aerodynamic lift combined by the wing shall not exceed at any point during the mission the maximum loading factor.	Not determined	Completed in future design	-
REQ-TP-AERO-02	The control surface devices must respond to control inputs within a time frame of 0.01 seconds.	Not determined	Completed in future design	-
REQ-TP-AERO-03	The control surfaces shall not exceed specific deflections set by aerodynamic loading factors.	Not determined	Completed in future design	-
REQ-TP-AERO-04	High lift devices shall provide excess lift required to reduce speed to approach/landing speed (1.3*V_stall).	Compliant	$V_{stall} < 61knots$ (sufficiently low)	Section 8.9.2
REQ-TP-AERO-05	In no place on wings or propeller/rotor surfaces shall the airflow exceed velocities of Mach 1.	Compliant	Maximum velocity of Mach 0.66 reached	Section 8.6
REQ-TP-AERO-06	Aerodynamics shall feature favourable and predictable turbulence performance.	Not determined	Completed in future design	-
REQ-TP-AERO-07	Aerodynamics shall feature favourable and predictable gust performance.	Not determined	Completed in future design	-
REQ-TP-MAN-01	The vehicle data shall be provided for each design process used (CS23.2250).	Not determined	Completed in future design	-
REQ-TP-MAN-02	All parts to be inspected shall be accessible (CS 23.2250).	Not determined	Completed in future design	-
REQ-TP-MAN-03	All necessary placards and markings shall be displayed (CS23.2610).	Not determined	Completed in future design	-
REQ-TP-MAN-04	Marking and placard information shall be given in the Aeroplane flight manual (CS23.2610).	Not determined	Completed in future design	-
REQ-TP-MAN-05	For any casting manufacturing processes, casting factors shall comply with CS 23.621.	Compliant	No casting required, full composite	Section 11.3.3
REQ-TP-MAN-06	Removable parts shall be able to be detached and attached with the same tool(s).	Compliant	Accounted for in production plan and manufacturing	Section 11.4.1
REQ-TP-MAN-07	The aircraft shall be treated to prevent impact from environmental conditions on the aircraft.	Compliant	Aircraft parts treated with coating	Section 11.1.2
REQ-TP-MAN-08	Sustainability of the manufacturing process shall be maximised.	Compliant	Accounted for in production plan and manufacturing	Chapter 11
REQ-TP-SYS-01	All subsystems shall be able to communicate between each other.	Not determined	Completed in future design	-
REQ-TP-SYS-02	All subsystems shall be connected to each other necessary subsystem to perform its function.	Not determined	Completed in future design	-
REQ-TP-SYS-03	All subsystems shall communicate critical information to other subsystems.	Not determined	Completed in future design	-
REQ-TP-SYS-04	All subsystems shall be compatible with each other.	Not determined	Completed in future design	-
REQ-TP-SYS-05	All bolts used shall be of standard dimensions.	Compliant	Accounted for in production plan	Section 11.4.1
REQ-TP-SYS-06	All wiring shall be sufficient to carry the design electrical current.	Not determined	Completed in future design	-

14.3. Product Validation

Stakeholder requirements are to be validated using physical testing, for which a procedure is made in previous design stages [30]. However, with the design analysis that is performed up until now, an indication can be given on the compliance with the stakeholder requirements. The compliance matrix for the validation of the stakeholder requirements is presented in Table 14.2.

Table 14.2: Stakeholder requirements validation

Identifier	Requirement Description	Compliance	Design Justification	Reference section
REQ-STK-USR-01	The cabin noise shall be no higher than 60 dB(A) during cruise, including damping devices.	Compliant	53 dB due to damping of the cabin plus active noise-cancelling.	Section 10.5
REQ-STK-USR-02	The vehicle shall not be louder than 60 dB(A) at 1000 ft.	Compliant	51.9 dB due to limited rotation of the propellers and optimisation.	Section 10.5
REQ-STK-USR-03	The cabin noise shall at no point be higher than 85 dB(A).	Compliant	83 dB when not using a headset with active noise-cancelling.	Section 10.5
REQ-STK-USR-04	The price shall be no more than €0.5 /km/pax for a passenger for maximum payload flight.	Compliant in future	Stage 4 of design: 0.314 (€/km/-pax)	Chapter 12
REQ-STK-USR-05	The total trip length shall be shorter than alternatives.	Non-compliant	Faster but costlier alternatives available	Section 5.2.1
REQ-STK-USR-06	The aircraft shall be ready at the airport when the passengers arrive.	Compliant	Logistical concept design	Section 3.1
REQ-STK-USR-07	The aircraft shall store a complete first aid kit.	Compliant	Safety aspects from RAMS	Section 6.11
REQ-STK-USR-08	The vehicle shall have enough space to carry at least 4 passengers.	Compliant	5 passengers maximum inside the cabin.	Section 7.4
REQ-STK-USR-09	The vehicle shall have enough storage space for at least 100 kg of luggage.	Compliant	20 kilograms per passenger allows for 100 kg total cargo weight for passengers.	Section 7.4
REQ-STK-USR-10	The minimum range of the aircraft with maximum payload shall be 400 km.	Compliant in future	Stage 3 of design.	Chapter 5
REQ-STK-USR-11	The aircraft shall be able to take off and land on 500 m runways.	Non-compliant	Overestimation of maximum lift coefficient, thus underestimation of stall speed and landing distance.	Section 8.9
REQ-STK-USR-12	The aircraft shall have a maximum stall speed of 50 kts.	Non-compliant	Overestimation of maximum lift coefficient, thus underestimation of stall speed.	Section 8.9.2
REQ-STK-USR-13	The aircraft shall have no in-flight emissions.	compliant	No emissions during flight.	Section 10.1
REQ-STK-DES-01	The preliminary design shall take no more than 10 weeks for 10 people.	Compliant	Performed by design team.	None
REQ-STK-DES-02	The maximum total manufacturing cost per aircraft shall be 2,000,000 euro.	Compliant	Estimated cost 1,320,000 euros	Chapter 12
REQ-STK-OPE-01	The operating costs shall be lower than the passenger price.	Compliant	Operating cost of 1.08 (€/km/-pax) for a pax price of 1.17 (€/k-m/pax) for stage 2 design.	Section 12.4
REQ-STK-OPE-02	The aircraft shall be able to land on both grass and gravel.	Compliant	Landing gear design contains such design aspects.	Section 7.6.2
REQ-STK-OPE-03	It shall be possible for the aircraft to safely fly when passengers have maximally received 25 hours of pilot training.	Compliant	Remote piloting included.	Section 4.4
REQ-STK-OPE-04	At the end of the service life, 90% of the aircraft should be reused or recycled.	Compliant in future	Depends on thermoset recyclability.	Section 11.3
REQ-STK-AIRP-01	The aircraft shall be able to maintain sufficient performance throughout all the segments of the take-off climb up to 1500ft above the field elevation (WAT limit).	Compliant	Performance throughout mission.	Section 8.11
REQ-STK-AIRP-02	The aircraft shall have a climb rate of 200 ft per nautical mile (0.033 m altitude per m).	Compliant	Overdesigned.	Section 8.11
REQ-STK-AIRP-03	The aircraft shall fly at a minimum altitude of 1,000 feet above the highest obstacle, within a horizontal radius of 2000 feet of the aircraft.	Compliant	Cruise at a 2000 m	Section 2.2
REQ-STK-AIRP-04	The aircraft shall fly at a minimum altitude of 500 feet above ground for sparsely populated areas.	Compliant	Cruise at a 2000 m	Section 2.2
REQ-STK-AIRP-05	The landing approach shall comply with the Instrument Approach Chart according to airport.	Compliant	Destinations included in database	Chapter 4, Section 6.1.1

REQ-STK-AIRP-06	The airport shall provide a safe boarding path from the airport hall to the aircraft.	Compliant	Airport selection consideration.	Section 6.1.1
REQ-STK-AIRP-07	The airport shall provide a refilling/refuelling system for the appropriate fuel type required.	Compliant	Battery charging, swappable for solid-state.	Section 6.4
REQ-STK-AIRP-08	The airport shall provide ground staff to help the passenger disembark and handle cargo.	Non-compliant	Not included in current logistics.	-
REQ-STK-AIRP-09	For airports in cold countries, de-icing systems shall be available.	Compliant	De-icing system fully accounted for in design.	Section 7.8.6
REQ-STK-APP-01	The aircraft shall have a clear and distinguishable connection with air traffic control during operations.	Compliant	Communication channels provided.	Section 6.3
REQ-STK-APP-02	The operation of the aircraft shall be limited to 400 km horizontal radius of a ground station to ensure constant successful communications.	Compliant	Logistics and operations design.	Section 6.1.1
REQ-STK-APP-03	Failure rate of connection between aircraft and ground stations shall be less than 10^{-9}.	Not determined	Insufficient analysis performed.	-
REQ-STK-APP-04	The application shall be simple, easy to use, and fully functional.	Compliant	Simplified controls and operation for a user-friendly experience.	Section 6.7
REQ-STK-APP-05	The application shall operate using Wi-Fi/wireless internet to make a booking, and remain operational without access to internet by establishing a connecting to the aircraft.	Compliant	Application capabilities to establish connections.	Section 6.7
REQ-STK-APP-06	The application shall remain operational without access to internet.	Compliant	Information still accessible directly from the aircraft.	Section 6.7
REQ-STK-APP-07	The application shall establish direct connection between the user and the operator through the internet or through an established connection between the aircraft and ground station	Compliant	Application capabilities to establish connections.	Section 6.7
REQ-STK-APP-08	The processing and storing of user data shall comply with the regulation 2016/679 of the European Parliament and of the Council.	Not determined	Completed in future with application design.	Section 6.7
REQ-STK-FUEL-01	The refilling/refuelling company shall deliver the energy source safely and in adequate pressure and temperature.	Compliant	Logistics for recharging as well as battery design.	Section 6.4
REQ-STK-FUEL-02	The energy source shall be contained in safe and sealed tanks in the case of liquids and gasses or stored safely and isolated in the case of solids.	Compliant	Battery design isolated the cells from the structure for isolation.	Section 7.3.2
REQ-STK-FUEL-03	The refilling/refuelling systems shall be safe and reliable with minimal failure.	Not determined	Completed in future in the implementation of recharging infrastructure.	Section 6.4
REQ-STK-ATC-01	The aircraft shall have radio communication with air traffic control stations at all time.	Compliant	Link budget and the telecommunication channels are designed to maintain constant connection.	Section 6.3
REQ-STK-ATC-02	The air traffic control stations shall have access to the logbooks and flight planning of each flight.	Compliant	Logistical implementations such as the flight plan being sent.	Section 6.2
REQ-STK-ATC-03	The air traffic control shall have a method of connection directly to operational ground stations of the aircraft fleet, either directly or relayed through the aircraft telecommunication systems.	Compliant	Connection established through telecommunications subsystem.	Section 6.3
REQ-STK-MAI-01	The maintenance crew shall have a workstation in one of the base airports for the fleet where maintenance routine can be performed.	Compliant	Maintenance crew logistics included in the design.	Section 6.10
REQ-STK-MAI-02	The maintenance crew shall have a fixed schedule. All the aircraft operating in the fleet shall follow this schedule.	Compliant	Logistics implemented to consider operations of the crew.	Section 6.10
REQ-STK-STFG-01	The ground staff shall be minimized without compromising workload	Compliant	Sufficient personnel employed.	Section 11.3
REQ-STK-STFG-02	The ground staff shall have direct connection to the ground station	Compliant	Logistical implementation	Chapter 6
REQ-STK-STFG-03	The ground staff shall handle and clean the aircraft at the end of daily operations once it has returned to base.	Non-compliant	Not included in current logistics for this stage of design.	-
REQ-STK-STFO-01	The ground station staff shall be divided into morning, evening and night shifts	Non-compliant	Not included in current logistics for this stage of design.	-
REQ-STK-STFO-02	The ground station staff shall be readily available to intervene in case of emergency.	Compliant	Accounted for in logistics and operations.	Chapter 6
REQ-STK-STFO-03	The ground station staff shall have contact with local emergency services for safety.	Compliant	Accounted for in logistics and operations.	Section 6.11

Five of the stakeholder requirements are given as non-compliant. **REQ-STK-USR-05** is not met, because it takes time for customers to travel to and from the airport. This influences the possible market that can be addressed, which is accounted for in the market analysis, described in Chapter 3. Due to an overestimation of the maximum lift coefficient in choosing the design point, **REQ-STK-USR-11** and **REQ-STK-USR-12** concerning the take-off and landing distance, and the maximum stall speed, is not met for landing. The effects of distributed propulsion on high-lift performance are also preliminary and need further analysis to determine the exact increase in lift coefficient. These requirements are considered critical stakeholder requirements, that must be analysed further in future design which should allow for satisfaction of such requirements. **REQ-STK-AIRP-08**, demanding ground staff for assisting passengers, is not included in the design to cut down operations costs and complexity. This requirement is considered less critical, and will not impede the concept thus is ot to be considered a requirement in the future. **REQ-STK-STFG-03** and **REQ-STK-STFO-01** have not been included in the logistics concept in this stage of the design, but will be added in a later stage when a employee plan is designed.

The physical testing procedure for each stakeholder requirement is explained in the list below:

- **REQ-STK-USR-01**: The cabin noise is to be measured during a cruise procedure using a decibel meter for different flying altitudes at cruise velocity.
- **REQ-STK-USR-02**: During a flight test procedure flying at an altitude of 1000 ft, the ground noise is measured using a decibel meter.
- **REQ-STK-USR-03**: The cabin noise is to be measured during a take-off procedure using a decibel meter and during a maximum velocity procedure. This tests the highest engine noise and highest propeller noise.
- **REQ-STK-USR-04**: Cost estimation using all known parameters is performed to obtain the true operational cost.
- **REQ-STK-USR-05**: Measure the total trip time from point to point and compare to different methods of transportation consisting of car taxi, train, bus, commercial flights.
- **REQ-STK-USR-06**: Logistical timings and planning from detailed analysis using ATC and airport operations. To be validated, the aircraft shall be able to land at the airport and be recharged to operate maximum range before the user is cleared for boarding.
- **REQ-STK-USR-07**: A first aid kit is present and easily accessible inside the cabin of the aircraft.
- **REQ-STK-USR-08**: There are sufficient passenger seats with sufficient legroom and accessibility to minimum standards as commercial airlines offer.
- **REQ-STK-USR-09**: There is sufficient cabin storage volume to store the required cargo safely without shifting.
- **REQ-STK-USR-10**: Aircraft prototype shall perform standard flight profile at maximum payload, and range flown will be measured.
- **REQ-STK-USR-11**: Validating final runway performance of the prototype aircraft.
- **REQ-STK-USR-12**: Measuring stall speed of the prototype aircraft.
- **REQ-STK-USR-13**: Propulsion emissions are checked using an opacity meter, a CLD analyser and a carbon dioxide meter.
- **REQ-STK-DES-01**: The maximum working limit is to not exceed 10 weeks.
- **REQ-STK-DES-02**: True manufacturing cost including all aspects related to manufacturing are recorded during production of the first aircraft.
- **REQ-STK-OPE-01**: Once in operation, operational cost are recorded in order to determine passenger cost in order to make profit.
- **REQ-STK-OPE-02**: Successful landings on both grass and gravel are to be performed under below average weather safety conditions and, for higher safety rating, successful landings under full wet conditions.
- **REQ-STK-OPE-03**: All passengers have mandatory requirements to give the total flight hours, determining whether they are able to fly the aircraft by themselves.
- **REQ-STK-OPE-04**: Validate recyclability plan by consulting companies with expertise.
- **REQ-STK-AIRP-01**: Take-off performance is tested up to 1500 ft at maximum propulsive performance.
- **REQ-STK-AIRP-02**: Take-off performance is tested up to 1500 ft at maximum propulsive performance.
- **REQ-STK-AIRP-03**: Maximum physical altitude achieved through test and maximum flight envelope capabilities calculated through analysis.
- **REQ-STK-AIRP-04**: Minimum altitude manoeuvrability test as well as flight envelope capabilities.
- **REQ-STK-AIRP-05**: Instrument testing on board.
- **REQ-STK-AIRP-06**: Inspection of all operating hub airports for appropriate boarding methods. Further testing to be implemented in the case of boarding stairs attached to aircraft door.
- **REQ-STK-AIRP-07**: Airport logistics inspection for all airport hubs and appropriate recharging system on board.
- **REQ-STK-AIRP-08**: Logistics inspection of possibilities with ground personnel available.
- **REQ-STK-AIRP-09**: Airport logistics within operations to be inspected before clearance.
- **REQ-STK-APP-01**: Communications system use to be tested.
- **REQ-STK-APP-02**: Tested ground control telecommunications range.
- **REQ-STK-APP-03**: Tested ground control telecommunications reliability.

- **REQ-STK-APP-04**: Sensitivity and extreme inputs testing when operating the applications (verification of the application).
- **REQ-STK-APP-05**: Sensitivity and extreme inputs testing when operating the applications (verification of the application).
- **REQ-STK-APP-06**: Sensitivity and extreme inputs testing when operating the applications (verification of the application).
- **REQ-STK-APP-07**: Sensitivity and extreme inputs testing when operating the applications (verification of the application).
- **REQ-STK-APP-08**: Numerical analysis and verification of data storage.
- **REQ-STK-FUEL-01**: Validation of refuelling/refilling company operations.
- **REQ-STK-FUEL-02**: Fatigue analysis of energy storage structure.
- **REQ-STK-FUEL-03**: Safety and reliability analysis to be performed on the recharging system.
- **REQ-STK-ATC-01**: Communications system reliability to be tested.
- **REQ-STK-ATC-02**: Data transferring capabilities to be tested for maximum data transfer capabilities.
- **REQ-STK-ATC-03**: Data transferring capabilities to be tested using auxiliary connecting equipment.
- **REQ-STK-MAI-01**: Logistics inspection for fulfilment of operational requirements.
- **REQ-STK-MAI-02**: Logistics inspection for fulfilment of maintenance requirements.
- **REQ-STK-STFG-01**: Operations inspection to validate if appropriate contracting for personnel is done.
- **REQ-STK-STFG-02**: Communications reliability testing for important communication channels such as ground station bandwidth and air traffic control bandwidth.
- **REQ-STK-STFG-03**: Logistics inspection for fulfilment of operational requirements.
- **REQ-STK-STFO-01**: Logistics inspection for fulfilment of operational requirements.
- **REQ-STK-STFO-02**: Data transferring maximum limit for different ranges to optimise for data transferring content in the scenario remote control is required.
- **REQ-STK-STFO-03**: Data transferring capabilities to be tested for maximum data transfer capabilities for the ground station with different bandwidths at the same time.

15 Conclusion

The aim of this report is to show the final AmpAir air taxi design and operational & logistics concept. The aircraft will enable flexible and emission-free travel for customers that seek privacy and time-efficiency. To achieve the optimal design and business strategy, the current and future predictions of the market were analysed, after which a logistics and operational concept was established. Throughout the final phase of the Design Synthesis Exercise, a high-wing aircraft with distributed battery electric propulsion and a conventional tail was optimised for the AmpAir mission.

The aircraft concept had to be optimised for the target audience, which was determined through a market analysis. AmpAir will mainly attract passengers business travellers, environmentally conscious tourists and flight enthusiasts, who will be attracted by AmpAirs flexibility, emission-free travel and experience, respectively. From the market analysis, it is estimated that AmpAir will have 1,250,000 annual passengers. Additionally, a sustainable development strategy was created to reduce emissions and waste all throughout the AmpAir life cycle. Here, it is emphasised that AmpAir will not only apply an emission-free propulsion system, but will also lobby and encourage improvements in recycling and manufacturing practices.

After the midterm phase of the project, the team concluded that a high-wing aircraft with battery electric distributed propulsion and a conventional tail is the best option to fulfil the mission. The high-wing provides clearance on the unprepared landing surfaces, such as grass, as it makes the wing and engines less susceptible to debris. The distributed propulsion was chosen for its high-lift, providing performance and low noise pollution. Furthermore, the conventional tail does not add any unnecessary weight to the aircraft structure. By implementing verification and validation procedures, it was ensured the final aircraft complies with all stakeholder requirements. The aircraft includes 14 high lift propeller, each 0.71 m in diameter, powered by an EMRAX 188 motor with a continuous power of 37 kW. These propellers are only used during take-off and climb, they fold during cruise to reduce drag. There are 2 wing tip cruise motors, that are sufficient for this flight condition. They help counteract the wing tip vortices and thus reduce the drag. The propellers are 1.87 m in diameter, powered by EMRAX 268 motors producing 117 kW.

During the technical design phase, the aircraft was optimised based on power requirements, aerodynamic considerations, and reliability. These were analysed for the determined cruise altitude of 2000 m. Flying higher gives a higher safety margin, but it also requires much more energy to climb the additional 1000 m. Flying lower, at 1000 m means a lower safety margin, but requires less energy. The cruise altitude of 2000 m was found to be a good compromise between the two. Passenger safety is also ensured by means of parachute, which can be deployed in case of an emergency.

The aircraft is optimised for a battery density of 900 Wh/kg which will come at some point in the future. However, the current assumption for a battery density, coming in the next few years, is 450 Wh/kg. Thus, given a battery with 450 Wh/kg, the range was found to be 403 km with a payload of 278 kg, empty mass of 1540 kg, battery mass of 682 kg, while the maximum take-off weight (MTOW) is 2500 kg. The payload-range diagram of AmpAir aircraft can be found in Figure 1. When battery technologies improve, the batteries mass can be traded for payload mass, while maintaining the range. When carrying out a ferry flight, the aircraft can fly up to 470 km. Furthermore, when flying one or two passengers only, it has a range of 445 km and, 420 km respectively.

With the current battery technology, the electrolyte is liquid, and the batteries require cooling. In the future, as solid states batteries of 900 W h kg^{-1} become available, the batteries become lighter, smaller and require no cooling. At this point, the swapping of batteries becomes an option. With liquid cooling, this is not possible, as all the cooling lines prevent the battery from being removed easily.

The aircraft includes a de-icing system, ensuring safety and reliability in all weather conditions. The cabin is a 2-2-1 layout and the temperature is controlled by an ECS, with heated seat. There is an EPU that provides enough energy to land in case of total loss of power to the electromechanical actuators that are used to move the control surfaces and the landing gear. The system is designed to be fully redundant, so there is no single point of failure. One battery pack is located in the nose, while a second one is located behind that passenger compartment.

It was found that because of the implementation of distributed propulsion, the effective aspect ratio increased by 45.8%, significantly lowering the induced drag. The C_{D0} is equal to just 0.012. The design risks were assessed, and a mitigation plan was set up for the remainder of the design and operational phase of AmpAir. The wing loading of the aircraft was found to be $1418\,\text{N}\,\text{m}^{-2}$, when using distributed propulsion.

Throughout the design process, careful attention was devoted to safety and certification aspects, significantly influencing various facets of the aircraft. This encompassed the development of wing loading diagrams, the evaluation of trade-offs, and the strategic employed in the subsystem design. A paramount objective of the aircraft is to ensure passenger survival under all circumstances. Consequently, no single mode of failure can result in the aircraft entering a hazardous state. Moreover, even in worst-case scenarios, a robust recovery system is in place to avert any potential dangers.

The aircraft will cost €1.35 million at the start of production, projected to decrease to just €650000 as the production numbers increase. One passenger, together with their luggage, weighs $100\,\text{kg}$. When carrying about three passengers, the aircraft can fly at a range of $403\,\text{km}$. At this range, the aircraft can carry approximately $278\,\text{kg}$ payload, at a price of €1.17 per km, while in the future a price of just €0.27 per km should be possible. This depends on the level of autonomy allowed by the regulatory agencies, which is beyond the control of AmpAir. AmpAir can start its operations as a flight school and progress through cargo to passenger transport. The luggage volume is a comfortable $1\,\text{m}^3$, also allowing for autonomous cargo operations if that proves profitable.

The aircraft can operate in fully piloted, and eventually also in fully autonomous mode. The aircraft is fun to fly and should appeal to people that want to try it, but never had the funds to do so. They can simply download the app and sign up. All it requires is a one-day training course and the customer can start flying. As they get more experience, their star ranking increases, and they have more and more control over the aircraft. They perform the pre- and post-fly checks and can really feel like a proper pilot. The aircraft is fitted with a highway in the sky system, which makes following the direction simple and intuitive.

The operations concept is based on a hub-and-spoke model. The hubs have maintenance and fast charging facilities, while the spokes are the destinations that do not have these facilities, but can still charge overnight.

The AmpAir aircraft meets the noise requirement of 60 dB at 1000 ft in cruise configuration, producing just 51.9 dB. Inside the cabin, the sound pressure level is equal to 83 dB, which will be lowered using noise-cancelling headphones to 53 dB. The noise emission outside during climb is significantly higher, with a sound pressure level of 77.2 dB at 1000 ft. This mainly stems from the fact that high-lift propellers are also being utilised in this stage. The noise generated by the high-lift propellers can, however, be improved by introducing a higher number of blades. This will in turn reduce the rotational speed required and result in a significant decrease in the noise intensity. The frequency of the noise will increase, however, resulting in a more annoying tone of the sound. A trade-off needs to be made therefore to decide on the optimal number of the blades, compromising between thrust performance and noise. For future implementations of distributed propulsion, to increase the axial induced thrust, both the distribution over the propeller and the magnitude of thrust. Larger propellers with more blades will increase the averaged axial induced velocity. Furthermore, to minimize weight, implement engine coupling power to rotors for a given thrust required to minimise the engine excess power and minimise the weight of the engines. As recommendation, RANS implementation to BET would be the most accurate methodology to quantify the thrust generation of the rotors without complex CFD. Custom design of the high lift propellers is necessary, as the desired properties differ significantly from conventional props. While the desired effect is a uniform axial velocity profile, conventional props maximise thrust, as that is the way they generate lift. Maximum axial velocity is how distributed propulsion produces lift. The propellers are in general thicker towards the root and more slender towards the tip than conventional props.

The airfoil chosen is the NACA 65(3)-618. The clean wing lift coefficient is assumed to be 1.14. Fowler flaps were designed, which are estimated to increase the lift coefficient to 2. On top of this, the effects of the high-propellers on the wing were quantified and an approximate increase of 33% in lift has been found. This results in an expected maximum lift coefficient of 2.66. It is assumed here that the distributed propulsion has the same effect on the flaps as it does on the wing. This lift coefficient leads to a stall speed of 57.3 kts. The required landing distance is approximated to be $514\,\text{m}$ using this value. The surface area of the wings is $17.3\,\text{m}^2$, the span is $14.4\,\text{m}$, the MAC is $1.27\,\text{m}$ the aspect ratio is 12, while the effective aspect ratio is 17.5, due to the effect of the propellers.

However, a maximum lift coefficient of 3.5 was assumed when determining the required wing loading. An overestimation of this value coefficient of the aircraft led to the failure to meet the 50 kts stall speed requirement, as well as the REQ-STK-USR-11 runway length requirement of 500 m. While the CS23 requirement of a stall speed of 61 kts is met, and the difference between the required runway length and the expected landing distance is not significant, a further design iteration can be done with increased wing area to ensure the compliance that the stall speed decreases from the current value of 57.3 kts to below 50 kts. Furthermore, the team will perform analysis on the increase of lift on the flaps due to the high-lift propellers to find a better estimate of the maximum lift coefficient, as it is highly likely that the propulsion has a larger gain on the deployed fowler flaps than it does on the clean wing. A more detailed model will also be used for the interaction of the slipstream of the high-lift propellers on the wing, supported by computational fluid dynamics (CFD) modelling. This will also provide information on the effects and accuracy of the used assumptions.

The use of power per flight phase is quite conservative. The depth of discharge is assumed to be 80%, even for the case that a full mission, including a reserve of 30 min is flown. That means that after the end of the flight, the battery charge is still at 20%. This assumption could be changed to assume a full depth of discharge in an emergency, in which case the size of the battery could be reduced.

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A
Gantt Chart

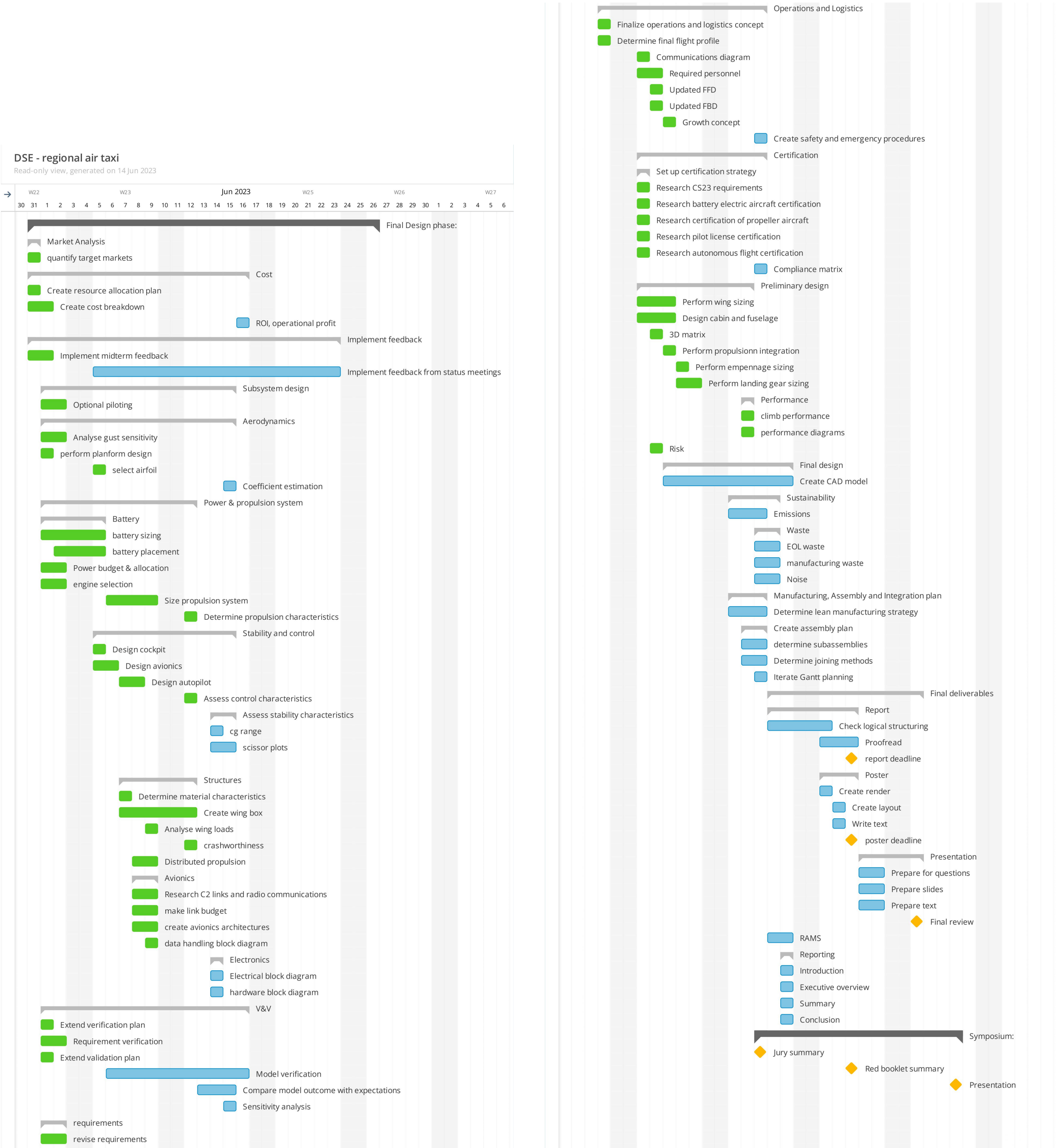

Figure A.1: Gantt chart of the final phase

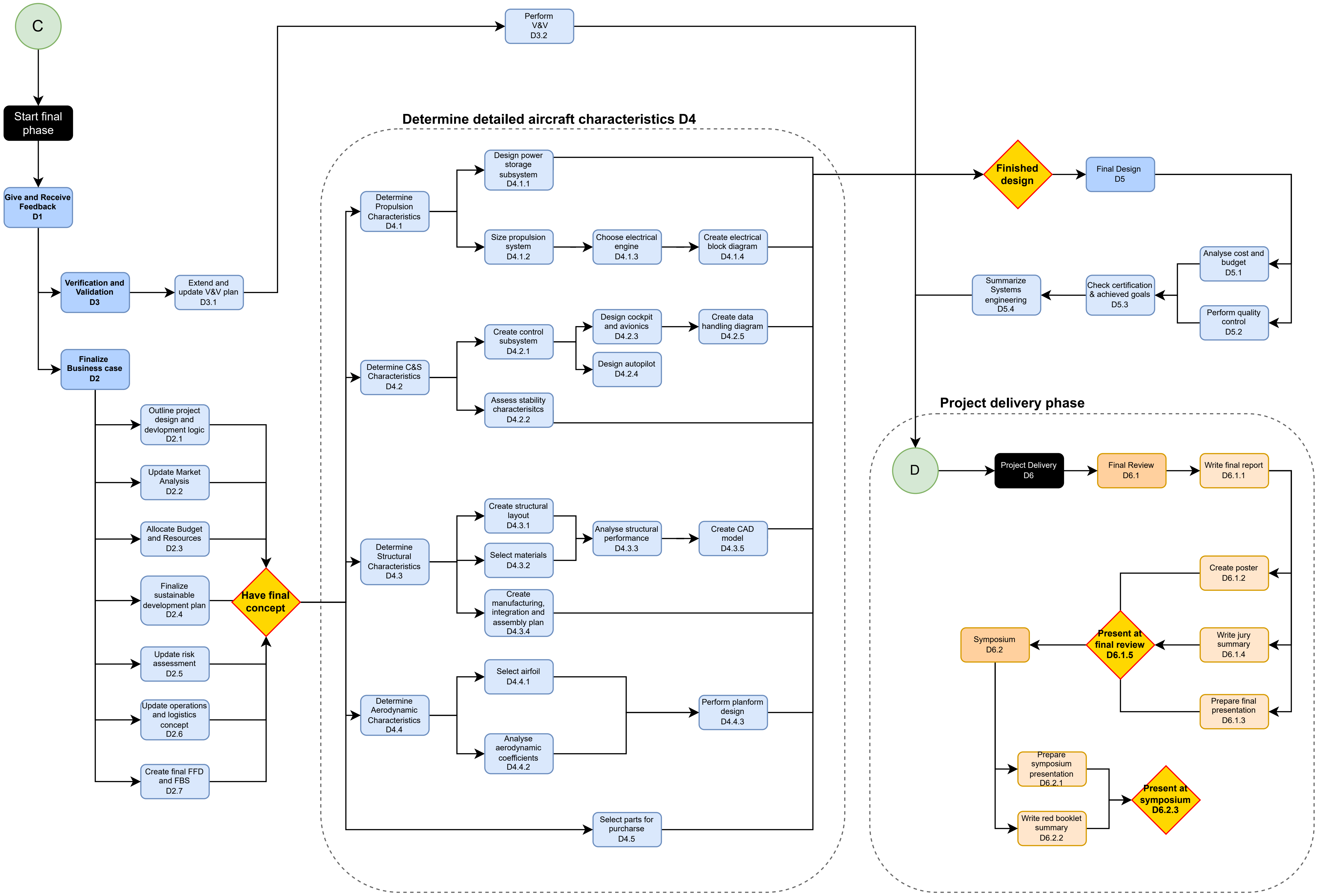

Figure A.2: Project Planning

B
Terms and Conditions

Declaration on Oath

All passengers that may pilot the aircraft will sign the following declaration on oath, indicating they agree and confirm the following statements:

1. *"I have successfully obtained a one star rating by following the AmpAir one day baseline course."*
2. *"Under no circumstances shall I fly under the influence of alcohol, drugs or other substances that can reduce my ability to pilot."*
3. *"I do not have any medical conditions that could impair my ability to fly."*
4. *"I declare that I am personally liable for all damage to the vehicle or third parties if I did not comply with the AmpAir terms and conditions."*
5. *"I will cooperate with any investigation about damage or losses of the aircraft or its components"*
6. *"I will cooperate with any investigation that concerns actions that resulted into unsafe situations or caused harm to other people."*

Approval as Authorised Driver

AmpAir will at all times be able to request additional background information on the passengers, for example identification documents. An applicant can initially or based on ongoing judgement be found unfit to pilot the aircraft. This would mean they will not receive the one star rating or their licence can be (temporarily) withdrawn.

To judge the eligibility of a passenger to pilot, AmpAir will be given permission to consult insurance companies, government instances and other identity-verification services.

User Prohibitions

The passenger is under no circumstances allowed to do the following things:

- Bring alcohol or other substances aboard the cabin compartment.
- Drive while under the influence of alcohol or drugs.
- Smoke or use electric cigarettes.
- Carry any dangerous, toxic, flammable or other hazardous substances
- Transport more than five passengers
- Transport animals that are not enclosed in a cage.
- Commit any criminal or immoral acts
- Use a mobile devices

In case the user undergoes any of the previous actions, they will receive penalties, fines or have their piloting licence be degraded or taken away.

Only passengers that indicated during booking that they will pilot the aircraft are allowed to do so during flight.

Personal Data and Privacy

AmpAir requires personal documents, like ID and drivers license. On top of that, AmpAir is allowed to look into passenger background, which includes insurance information or criminal record.

In order to ensure the safety of the passenger and its surroundings, there are several monitoring systems on board: cameras and audio recorders.

AmpAir is open in the data they collect and informs the user on the personal data that is collected. In the agreement that will be signed by the passengers it will clearly be explained how AmpAir collects, uses and protects this personal data, to which the user has to give explicit permission. All these actions will comply to the European legislation on privacy and data collection.

Liability

The passenger will be held responsible:

- If the general terms and conditions were violated.
- If the final warning is ignored.
- If the aircraft is lost, stolen or damaged.
- If the aircraft accessories or components are lost, stolen or damaged.
- If the aircraft has been damaged due to criminal, deliberate or negligent acts
- For penalties related to non-compliance to airspace regulations

AmpAir will be responsible:

- for accidents that are related to a defect that could not have been detected by the passenger
- for initiating an investigation and set up a report in case of damage, loss or harm and will communicate this clearly with the people involved.

C
Avionics Subsystem

IRS

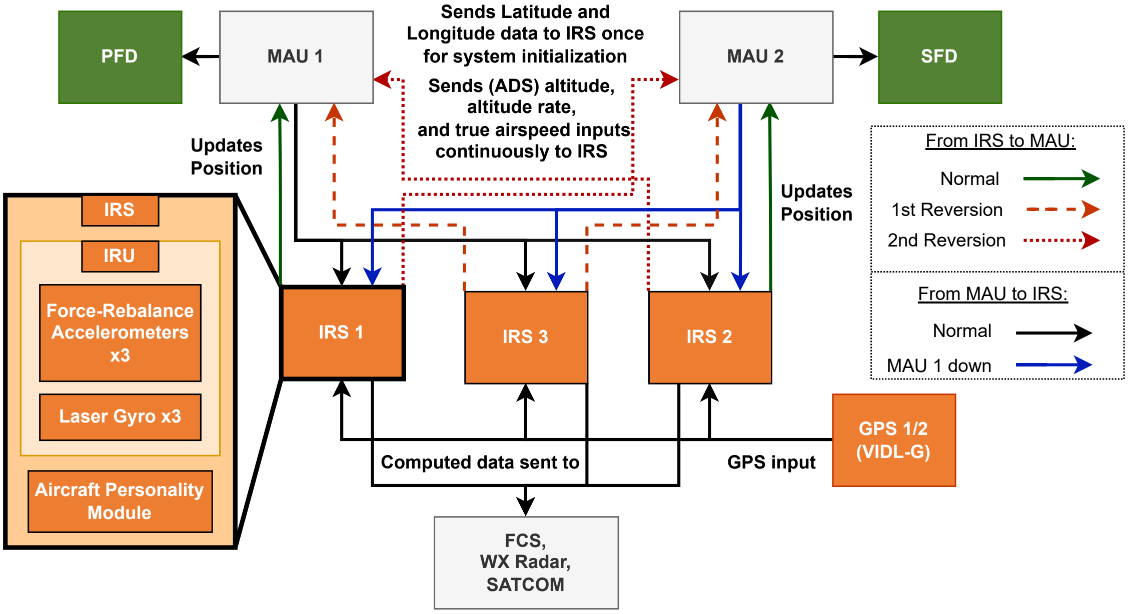

Figure C.1: Physical architecture of the IRS

ADS

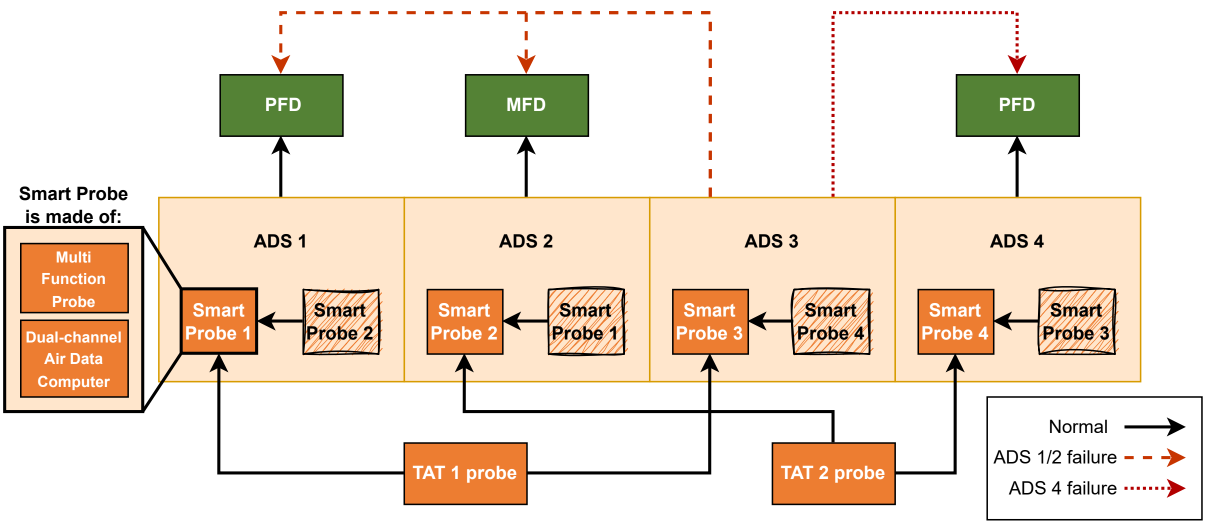

Figure C.2: Physical Architecture of the ADS