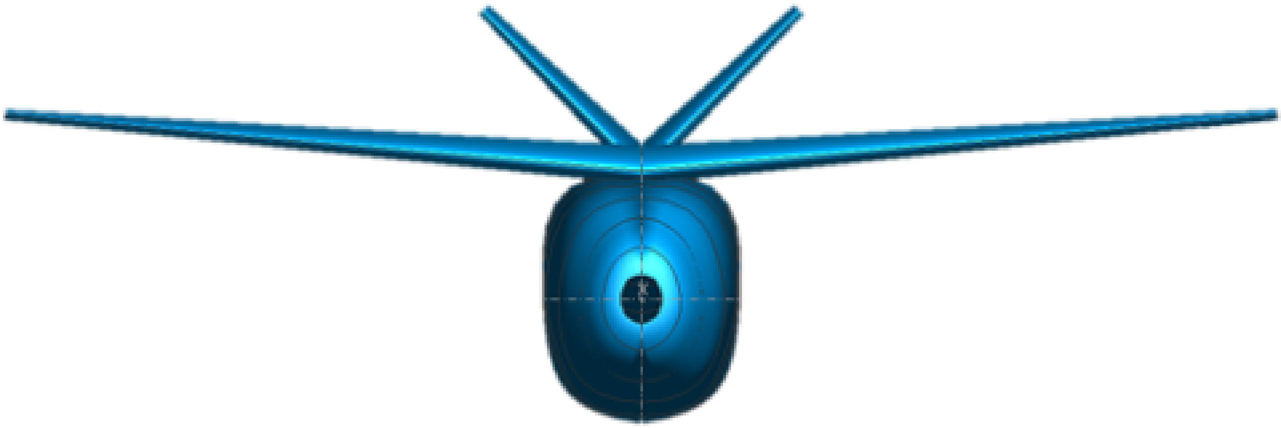
TÉCNICO LISBOA



Conceptual Design of an Urban Air Mobility Solution

Augusto Manuel Frazão Reis

Thesis to obtain the Master of Science Degree in

Aerospace Engineering

Supervisors: Prof. Frederico José Prata Rente Reis Afonso
Prof. Inês Esteves Ribeiro

Examination Committee

Chairperson: Prof. Filipe Szolnoky Ramos Pinto Cunha
Supervisor: Prof. Frederico José Prata Rente Reis Afonso
Members of the Committee: Prof. Elsa Maria Pires Henriques
Prof. Afzal Suleman

December 2020

The present document results from extensive research and all sources are referenced.
This is not a copy.

Acknowledgments

To everyone who ever crossed my path. ”Do something! Just do something” by Mark Manson, this was my mojo whenever I found myself ”between a rock and a hard place.” After all, I hope all the lost hair has turned into fruitful knowledge.

But most of all, I am thankful for:

- the little sister who keeps me emotionally stable;

- the eldest sister who keeps me rationally stable;

- the brother who extended the peace treaty without notice;

- the niece who keeps the childish monster inside well alive;

- the brother-in-law who kept pushing forward by the day;

- the persistent father who unadvisedly wants to be the first passenger;

- the caring mother who hosted me again for nine challenging months;

- at last, all those who kept my sanity.

I owe a debt of gratitude to my supervisors that always showed care for my work and showed all the possible paths. One utter acknowledgement to Filipe Laíns who exceptionally helped his cousin even during his exams weeks and days-off.

To each of you, my sincerest thank you.

Abstract

Urban Air Mobility (UAM) is the aircraft industry answer to the ever-increasing mobility needs in heavily populated cities, where citizens spend up to two hours a day in the traffic jam. Moving oneself from point A to B the fastest way possible, with the minimum environmental and economic impact is the prime goal. Aircraft capable of taking off anywhere and that occupies the smallest land area is a great solution candidate, hence Vertical Takeoff and Landing (VTOL) aircraft are a great fit. Helicopters are the only vehicle that could address this issue if only they were not so noisy and expensive to operate, resulting in an unfeasible solution. Hydrogen is the energy of the future, meanwhile, electricity is in the present, attending the aircraft is to be commercialized in 2024. Nowadays, the greenest, cheapest and widest available source of energy is electricity which results in conceiving an all-electric aircraft granting zero carbon dioxide operation emissions, with expected lower cost of operation than helicopters or any other solution from General Aviation (GA) given the energy cost is lower. Consequently, the estimated pricing for passengers will drop and potentially increase the number of costumers. The current work conceptualizes an aircraft from a set of cost, environmental and aeroacoustics requirements.The resulting proposal is a lift-plus-cruise solution with a Maximum Take-Off Weight (MTOW) of 1434 kg with an estimated energy system of 217kWh, considering a mission profile of three trips of 67 km each at a cruising altitude of 500 meters.

Keywords

Urban Air Mobility, Air-taxi, Conceptual Design, Noise Estimation, Environmental Impact, Operational Cost

Resumo

A Mobilidade Aérea Urbana (UAM) é a resposta da indústria aeronáutica às necessidades de mobilidade incessantes das cidades sobrelotadas, desperdiçando aos seus cidadãos até duas horas diariamente. Deslocar-se entre o ponto A e B o mais rápido possível com o menor impacto ambiental e económico é o objetivo principal. Aeronaves que tenham a capacidade de descolar em qualquer sítio ocupando a menor área possível são excelentes candidatos a serem soluções UAM, consequentemente aeronaves de descolagem e aterragem verticais VTOL apresentam-se como uma possível solução. Os helicópteros são os únicos veículos prontamente capazes de solucionar o problema apresentado, porém são ruidosos e dispendiosos de operar, tornando-os numa solução inviável. O hidrogénio é a energia do futuro, enquanto a eletricidade é o presente, atendendo ao facto da aeronave ser comercializada em 2024. Atualmente, a fonte de energia mais verde, barata e amplamente disponível é a eletricidade, resultando na conceção de uma aeronave totalmente elétrica, garantindo a operação sem emissões de dióxido de carbono, com a expectativa de menor custo de operação comparativamente a helicópteros ou qualquer outra solução da Aviação Geral (GA) dado o custo associado de energia ser menor. Portanto, o preço estimado de viagem será reduzido potencialmente aumentando a carteira de clientes. A tese atual conceptualiza uma aeronave definindo requisitos económicos, ambientais e acústicos, cuja resposta é uma aeronave lift-plus-cruise com um peso máximo de descolagem de 1434 kg com uma necessidade energética de 217kWh, para uma missão de três viagens de 67km à altitude cruzeiro de 500 metros.

Palavras Chave

Mobilidade Aérea Urbana, Táxi Aéreo, Desenho Conceptual, Estimativa Acústica, Impacto Ambiental, Custo Operacional

Contents

List of Figures

List of Tables

Acronyms

AAV Autonomous Air Vehicle

AC Alternate Current

AP Airframe and Powerplant

AR Aspect Ratio

ATC Air Traffic Control

BLDC Brushless Direct Current

BMS Battery Management System

CAAC Civil Aviation Administration of China

CFR Code of Federal Regulations

DC Direct Current

DEP Distributed Electric Propulsion

DNL Day-Night Level

DOA Design Organization Approval

DOD Depth of Discharge

EASA European Space Safety Agency

EOL End of Life

EPNL Effective Perceived Noise Level

EV Electric Vehicles

eVTOL electric Vertical Takeoff and Landing

FAA Federal Aviation Administration

FAR Federal Aviation Regulations

GA General Aviation

GWP Global Warming Potential

GAMA	General Aviation Manufacturers Association
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
LCA	Life Cycle Assessment
L/D	Lift-to-Drag ratio
LEAPTech	Leading Edge Asynchronous Propellers Technology
Li-Air	Lithium-Air
Li-ion	Lithium-Ion
Li-S	Lithium-Sulfur
LSA	Light-Sport Aircraft
MAC	Mean Aerodynamic Chord
MIT	Massachusetts Institute of Technology
MTOW	Maximum Take-Off Weight
NASA	National Aeronautics and Space Administration
NEC	Nippon Electric Company
Ni-Cd	Nickel-Cadmium
Ni-MH	Nickel-Metal-Hydride
OGE	Out of Ground Effect
P/W	Power-to-Drag ratio
RPM	Rotations Per Minute
SEL	Sound Exposure Level
SM	Static Margin
SOC	State of Charge
SPL	Sound Pressure Level
STOL	Short Takeoff and Landing
T	Thrust
TRL	Technology Readiness Level
UAE	United Arab Emirates

UAM Urban Air Mobility

UAS Unmanned Aerial Systems

USA United States of America

VFR Visual Flight Rules

VFS Vertical Flight Society

VPS Visual Positioning System

VTOL Vertical Takeoff and Landing

1

Introduction

Engineering focuses on the big picture when proving concepts and then focuses on small details when making the technology real.

The conceptual design of aircraft is focusing on the big picture of the aircraft industry. Numerous companies are aiming to design all-electric or hybrid aircraft, however, very few models of those have reached the market mainly due to battery technology deficits. The first goal of the present thesis is to develop an Urban Air Mobility (UAM) aircraft solution that may be market-ready by 2024 to meet the market needs and expectations estimated by Uber in 2016 [1].

Uber, in October of 2016 [1], set the goal to have a fleet of air-taxis in service by 2023 by publishing a white-paper, where it showed a worldwide demand for this service. Such publication set UAM into motion. January of 2020 was the turning point as contracts over 600M US$ [2] were established between car manufacturing, aircraft and mobility companies.

Whether the designed UAM solution is hybrid, all-electric or hydrogen-powered the first company to create the less pollutant vehicle possible while being efficient gets ahead on the market establishing the prices for competitors. Hence, the second goal is to produce an aircraft with nonexistent operational emissions. An all-electric solution fits the purpose as there are only emissions associated with the production of the aircraft and the recharging of associated batteries. In 2020, most of the electricity source still comes from fossil fuels, nonetheless, the future of green and cheaper electricity is getting closer by the day due to all research being conveyed. The third goal of the current thesis is to achieve the lowest operational cost possible to allow reasonable pricing for customers and profit for companies.

People want to move from point A to B the fastest way possible, however, when they are living their lives they do not enjoy being bothered, resulting into the fourth goal of the current thesis which is the lowest noise possible, at least lower than helicopters, so that people can keep living their lives with the smallest environment disturbance.

The present document has 5 chapters. Firstly, there is the current introduction, then chapter 2 explains the current UAM market state by 2020 as well as the current associated technology state and future prospects, chapter 3 presents the conceptual design, chapter 4 presents noise and environmental impact and the estimation of the operational cost and chapter 5 concludes while pointing towards the future work.

2

State of Art

2.1 Introducing UAM

The Vertical Flight Society (VFS) started to publicly gathering information for statistical purposes and to centralize all existing and relevant information, in 2016. VFS gathered information on 262 Vertical Takeoff and Landing (VTOL) aircraft [3] (assessed in 20th of January of 2020).

In February of 2018 [4], according to www.eVTOL.news, there were more than 40 eVTOL aircraft projects under development around the world. Almost all, using Distributed Electric Propulsion (DEP) using multiple electric engines each associated with a single propeller. It is important to clarify that there is no best electric Vertical Takeoff and Landing (eVTOL) concept as the design of all aircraft relies on mission profiling and trading-off through all stages from conceptual to production. Hence, the concept of best eVTOL varies from company to company accordingly to the companies goals or points of view.

According to Dr. Steven Daniel at the Embry-Riddle Aeronautical University Eagle Flight Research Center, VTOL designs should aim for the highest endurance possible of the batteries, therefore it needs to be built at the systems level. Despite all the evolution, every technology needs to follow the United States of America (USA) Federal Aviation Administration (FAA). Once aircraft are approved for the USA they can easily be approved elsewhere in the world given that USA has one of the most strict aircraft regulations, which ensures high safety margins, despite delaying progress given their resistance to adapt regulations. Ehang, a Chinese company aiming to create autonomous Urban Air Mobility (UAM) solutions has conducted the ”first-ever U.S. trial flight” successfully [5] on 7th of January of 2020 as part of the company's plan to ”ensure that its Autonomous Air Vehicle (AAV) operates safely and reliably in different areas globally”.

According to Greg Bowles (in February of 2018) from General Aviation Manufacturers Association (GAMA), anyone developing a fixed-wing all-electric aircraft up to 19 passengers and a takeoff weight of 19000 lbs (approx. 6818kg) needs to follow the Code of Federal Regulations CFR 14 Part 23 [4], that sets the ground rules for Airworthiness Standards: Normal, Utility, Aerobatic and Commuter Category Airplanes, such set of rules has already been updated to fit some changes in the industry. Fortunately, in May of 2020, according to Future Planet [6] a Cessna Caravan 208B - eCaravan - with the capacity to seat up to 9 passengers despite only carrying the pilot during the flight became the biggest commercial plane ever to fly all-electric for 30 minutes straight having a fuel cost reduction of approximately 98% (from around 300 US dollars to a mere 6 US dollars). The mentioned experience was possible due to the experience of magniX a company that had already replaced in smaller aircraft the conventional motor for an electric solution [6] and the knowledge brought up by the company AeroTEC.

According to the National Aeronautics and Space Administration (NASA) [7], any UAM solution:

- should require the minimum additional Air Traffic Control (ATC) infrastructure;
- should require the minimal changes to the FAA automation systems (at least to begin with);
- must meet the regulatory requirements for vehicle-level and system-level safety and security;
- must be resilient to a wide range of disruptions (from weather and localized system failures to widespread disruptions);
- must be possible to scale economically for high-demand operations with minimal fixed costs;
- must support flexibility and decision making to the greatest extent possible.

Table 2.1 presents the potential hazards of several UAM domains which helps the reader to put things into perspective.

Table 2.1: UAM domains and its hazards from an article published in 2018 [7].

UAM Domains	**Potential Hazards**
Vehicle, equipage, systems	- Loss of electrical power to control systems - Failure or spoofing of GPS/Receiver Autonomous Integrity Monitoring
Vehicle servicing and maintenance	- Unavailability of necessary replacement part
Communications (voice, datalink, Command-and-Control (C2) link)	- C2 link lost - Degraded Quality of Service (QoS) for critical control commands
Aerial operations, flight procedures, flight management	- Vehicle upset attitude - Vehicle fly-away
Routing, airspace, air traffic management	- UAM route conflicts with existing air traffic - Loss of safety-critical functions on ground station
External environment (weather, obstacles, aerial traffic, birds)	- Convective weather (hail, severe downdrafts) - Buildings, power lines, airborne vehicles
Pilots (on-board and remote)	- Inadequate pilot training for maintaining safety margins - Loss of pilot situational awareness
Dispatch, control center, emergency pilots	- Dispatch understaffed, flight planning delayed - Loss or degradation of the ground control station capability (e.g., displays)
Ground-based operations and infrastructure	- Lack of vertiport availability (occupied, damaged, closed to traffic) - Inadequate ground crew training for maintaining safety margins

Passengers	- Passenger interference with pilot/vehicle operations - Passenger illness during flight
Cybersecurity (including Verification and Validation)	- Inadequate authentication of C2 link (undetected the hijacking of C2 link)

Nevertheless, the current solution and definition of UAM only apply to helicopters that do not pose an elegant solution due to their numerous disadvantages. A UAM solution may either be autonomous or not, hence the designation of AAV. Due to evolution and the current course of technology, it is plausible to believe that UAM solutions posing as air taxis will be autonomous in the long run, to increase system efficiency to the highest level possible, therefore AAV is pointed out as the future of UAM. According to Ehang [8], electric AAV's have higher safety led by DEP with multiple propellers, dispose of full automation to eliminate human errors, support 4G/5G network, have centralized command-and-control, are sold at reasonable vehicle price, eliminate pilot costs, have low repair and maintenance cost, have a small noise foot print, have zero operational emissions, are small in size, easy take-off and landing with better manoeuvrability and are able to carry both passengers and freight with a payload up to 200-600 kg.

2.2 Uber Positioning

Uber´s public intentions to revolutionize the world are not recent as it is a company firmly decided to change the mobility worldwide, specially where humanity is heavily populated. Whether on the road or in the air, they aim to move people between their desired locations as fast as possible on pollute-free vehicles. Hence, to develop a UAM solution one should study Uber's market intention as they may pose one of the possible investors or clients.

The Uber Elevate Summit is an annual event that began in 2017, in 2020 it aims for its 4^{th} edition. In 2016, Uber published a white paper [1] revealing its intentions for On-Demand Urban Air Transportation and stating its limitations named: Fast-Forwarding to a Future of On-Demand Urban Air Transportation [1]. Given that Uber intends to transform a two-hour car drive commute into a 15 minutes flight having in mind that when the technology is launched some hurdles will still be a reality, though not a business impediment.

The biggest market feasibility hurdles identified by Uber's experts [1] are the:

- Certification Process – VTOL technology requires an update of the existing regulations and the creation of new regulations. FAA regulates 50% of the world's aviation activity and European Space Safety Agency (EASA) regulates 30%. Historically, such modifications usually take long though the effort of all the UAM enthusiasts. Retrofitting existing aircraft with an all-electric solution eases the process of certification [9] as it is only energy-focused rather than assessing aircraft at all levels like it is done when certifying brand new aircraft. FAA has started making changes to its electric aircraft certification criteria since at least 2016 [9] but there is still a long way to go.

- Battery State of the Art – one can compare different batteries bearing in mind four factors: specific energy, charge rate, cycle life and cost per kilowatt-hour. Today's batteries are insufficient for long-range commutes and have a large charging time making the vehicles unavailable for too long and increasing the using price time-wise.
- Vehicle Efficiency – helicopters belong to the only fully-developed VTOL technology, nevertheless they are not energy efficient enough to pose as a good solution for the UAM market. The needed solution requires to be designed as much mission-optimized as possible, the combination of a fixed-wing aircraft with DEP works for that goal. However, only several conceptual vehicles have been publicly presented but none ready for commercializing.
- Vehicle Performance and Reliability – reducing and optimizing the time between request, drop-off and charging is the key to the low-cost operation. Such a variable relies on both vehicle performance (specially taking-off and landing times and cruising speed) and system reliability, which may be measured as the time between request and pick-up. Uber Elevate is aiming for one-minute takeoffs and landings, cruising speeds of 240-320 km/h and operation under several weather conditions.
- Air Traffic Control (ATC) – today's regulations allow business at the urban airspace with limitations showing up due to the large drones' usage. Some cities, like Sao Paulo (in Brazil), have around 700 helicopters in between 400 rooftops helipads [10] and around 700 flights per day [11]. Despite helicopters usually flying using Visual Flight Rules (VFR), they can also fly using Instrument Flight Rules (IFR) using the existing ATC systems. On the other hand, an optimized on-demand UAM solution requires an update of the existing ATC regulations because such a solution involves a significantly higher frequency of flights and higher fully autonomous aircraft density operating over a city populated by millions of human beings, and their lives should not be put into danger anymore they already are by a large margin.
- Cost and Affordability – helicopters are expensive to maintain due to their low demand which is converted into low manufacturing volumes, meaning it lacks a scalable economy (917, 968 and 976 units sold worldwide from 2016 to 2018, respectively – despite the small growth of units ordering, these values are really low to be considered mass production [12] when compared to the mass production of cars, for example).
- Safety – proving a UAM is a safer option than a simple car ride is challenging, a metric to be used may be fatalities-per-passenger-mile. Uber's goal is "making VTOL's twice as safe as driving DEP and partial autonomy" meaning 0.3 fatalities per 100 million passenger miles which in turn is four

times less than Uber's car service rate of 1.2 fatalities per a 100 million passenger miles in 2016 [1].

- Aircraft Noise – the helicopter's main sources of noise are the propellers, rotor (main and tail) and motor (turbine or piston) [10]. Ideally, the UAM solutions should be so quiet they blend into the city's background noise, which translates into making any UAM solution half as loud as a medium-sized truck passing a house.
- Motor – firstly, one must know the aircraft requisites to calculate the first approximation of power needed to operate the aircraft. Then, the design team, alongside with the propulsion team need to decide the mean of propulsion power (electric, hybrid, hydrogen, combustion).
- Emissions – any UAM solution is likely to become global, meaning having mass production. Therefore, its production, lifetime and disposal must be carefully thought to have the smallest ecological footprint possible. There are two metrics: operational emissions and life-cycle emissions; the first one accounts for the emissions during flight operation and the second one accounts for the entire energy of an airplane life (from its factory stage to disposal).
- Pilot Training – under 14 Code of Federal Regulations (CFR) Part 135 is required for the pilot-in-command to have at least 500 hours of experience for VFR flight and 1200 hours for IFR flight. A UAM solution is intended to be flown in fully autonomous, meaning no need to waste a seat for the pilot, for such solution legislation needs to change a great deal as the FAA does not have regulations for no pilot passenger's transportation approved. Coming up with a fully autonomous solution is handy because in General Aviation (GA) the number one cause of accidents is the loss of control during flight [13], therefore the mass scale solution will increase a lot the number of aircraft in the skies, making it harder to fly in VFR mode like helicopters do most of the time. A trade-off some companies may be willing to accept is to firstly design considering a pilot and then iterate for a fully-autonomous model due to the regulations constraint.
- Vertiport/Vertistop Infrastructure in Cities – as mentioned above the lack of landing pads for a mass scale solution is a problem to solve on the long-run once a UAM solution is built. At first, this limitation could be faced by adapting the top of living, offices and parking garages buildings as well as using existing helipads only then adapting the city floor to it as the UAM market expands. One solution may be creating infrastructures like one-fit-all for all the companies involved within a range of measurements or create UAM solutions small enough to park on existing heliports and parking buildings with small infrastructure adjustments. Such stations may fit several purposes according to their design and capability, such as single pick-up, landing point, single or multi-hub or charging dock. Vertiport/Vertistop can play a part in the community by allowing electric vehicles to charge as well.

- Command-and-Control Platform – autonomous vehicles require ATC center and though it may not happen in the beginning but certainly in the long run, as low-height air traffic grows. There are several solutions pointed by the industry, one of them being a command-and-control platform where companies have employees monitoring several aircraft taking control whenever needed as a means of redundancy, as even autonomous aircraft can fail. One concern would be the critical case that all aircraft being looked after by one pilot need attention, meaning all systems fail, all redundancy planed fails to assist; another concern is whether or not all companies operating in the same city are under the same command-and-control platform or not, as this raises issues on the secrecy of companies as not all of them are to operate equally or under the same system. Two solutions are presented: sell/rent spots for companies to have their ground commands or; each company is responsible for their command-and-control platform that communicates at all moments with a governmental institution that manages air traffic (for example, associating the Visual Positioning System (VPS) with 5G network will enhance proficiency and purposes of UAM systems with help of computer programs and cluster management techniques), this is crucial when combining on-demand unscheduled and scheduled trips.

2.3 Big Companies know where to bet

As of the beginning of 2020, a lot has changed in the UAM game as major players in the car industry took a step in the future. The following lines are intended to explain some of those big steps into the future.

Zee.Aero is one of the largest companies developing eVTOL being San Francisco based with 10 years of experience [14]. Their proposed UAM solution is Flyer an all-electric airplane (one of its products has already flown over 25.000 times) [15]. The model Heaviside claims to be "roughly a 100 times quieter than a helicopter" and travels from San Jose to San Francisco (90 km [16]) in 15 minutes using "less than half the energy of a car" [17] complying with Uber's desires in terms of time [1]. This last model, however, cannot have four passengers on board despite being human-piloted. Zee.Aero has had backing from Boeing over the years [18].

Joby Aviation is a big player on the market for also 10 years and at the beginning of January of 2020 closed a round of investments of 590M US$ [19], the major part coming from Toyota [18], from the automotive industry, for almost 400M US$. Joby's available model can fly up to 322 km/h, has a range of 241 km on a single charge and claims to be 100 times quieter than a helicopter [20] while producing zero carbon emissions during flight. As of 2017, Joby Aviation started a flight testing and a certification program with the FAA [21] and in December of 2019 they "signed a multi-year commercial partnership to launch a fast, reliable, clean and affordable urban air taxi service" with Uber Elevate committing to a timetable of services by 2023 [22].

EHang is the biggest player at UAM solution at the Asian market and is already conquering ground on the USA by being the first aircraft of its kind to have a trial-flight approved by the FAA [5], at 8 of January of 2020, despite being a non-passenger flight, they are working closely with the FAA to get a passenger flight license. According to the founder and chairman of EHang “Pilotless air taxis have the power to transform everyday life in urban areas since they can lessen pollution, expedite emergency services, and save individuals and businesses time and money through shorter travel times” [5]. Up until January of 2020, EHang had already conducted over 2000 trial flights across the USA, China, Austria, Netherlands, Qatar and United Arab Emirates (UAE) to prove their aircraft are safe and reliable to operate in different scenarios [5]. All points out for EHang to become the first company to produce a large fleet of air taxis for companies such as Uber.

Airbus announced in August of 2016 to be have been working on their eVTOL projects: Vahana and CityAirbus [23], three months later Uber presented a white paper regarding the UAM industry. Although CityAirbus seems to be a proof of concept with a cabin very similar to a helicopter and the main difference being the four big propellers transporting up to four passengers, it represents a bold bet into the future. On the other side, Vahana is a different approach with tilting wings filled with rotors carrying only one passenger and travelling up to 1.6 times faster than CityAirbus.

Siemens, a big player in electrification, automation and digital technologies, developed an electric and hybrid-electric aircraft-propulsion business that was sold to Rolls Royce in June of 2019 [24], one of the biggest players in the aerospace, automotive and defence industries in the world. Such a purchase by Rolls-Royce reinforces that the combustion industry is looking forward to changing to the electric world, as big players start to invest. It is important to state that 180 employees from Siemens eAircraft played a role when developing the CityAirbus by joining forces with Airbus in 2016 [24].

Hyundai joins forces with Uber, the first company from the automotive industry to partner with Uber Elevate [25], revealing a real scale model of a UAM solution at CES 2020 - The Global Stage for Innovation (January of 2020, Los Angeles, USA) inspired by both NASA and Uber. The partnership eases on one hand the massive scale production of electric vehicles to decrease the cost by the unit as far as possible, as Hyundai already has several decades of experience in the business of manufacturing vehicles, and, on the other hand, Uber brings the interface for the ride-sharing service, minimizing the time of each trip; Hyundai and Uber are currently working together to think of infrastructures for charging, maintenance and parking on a joint effort to reduce the costs for the passengers, to make such technology available for everyone. The joint design named S-A1 has a cruising speed of 290 km/h, cruising altitude from 0 to 2000 ft above sea level, a range of up to 100 km and allows up to 4 passengers [25]. It is said to be 100% electric using DEP while using several rotors and propellers allow for eVTOL and redundancy. Uber chose Melbourne, in Australia, for its first flight test [26] as it is planned to be a trip from a commercial center of West field to its main airport in just 10 minutes when usually takes up to 30 minutes by car, however, one does not know exactly when are these experimental flights going to happen.

Uber has 8 official partners [27]: Boeing, Bell, EmbraerX, Karem Aircraft Inc, Pipistrel, Jaunt Air Mobility, Hyundai and Joby Aviation; each company was carefully chosen due to its knowledge, area of expertise and will for fast development. Uber also has 12 other companies that are part of Uber's ecosystem [27] some of them from the real estate field to help create vertiports [22]. Last but not least, is the Space Act Agreement signed with NASA to "develop new Unmanned Traffic Management concepts". Such partnerships enhance the air taxi industry breaking boundaries every day. In 2016, Uber set crystal clear goals for 2023 in its white paper. Uber decided that a rider is only eligible to use a VTOL solution if the estimated duration of the route to be taken is at least 40% faster relative to the estimated duration of the ground trip [1], the EHang solution launched at May of 2019 reduced a 40-minute ground trip to a 5-minute air ride meaning it is approximately 87.5% faster than the equivalent ground trip (the test was conducted in China's Zhejiang Province) [8].

Volocopter is the first eVTOL start-up to receive Design Organization Approval (DOA) by the EASA [28], as this guarantees the highest safety standards, and eases the access to get flight test permissions. During September of 2019, it was announced that Daimler (another big player in the automotive industry) and Geely (a leading automotive manufacturer from China, producing Volvo and Lexus vehicles) partnered with the Volocopter with an investment of almost 50M US$ [29].

Not only the corporate world is looking into UAM, some governments, like Japan, are getting involved in developing a UAM solution [30] as it is a starting point to solve the mobility problem it faces, whether of people or goods. Japan is made of 6 852 islands and only 5 of them make the main islands, however, Japan's islands are close enough to be linked using eVTOL hence the government interest on the topic. Japan created the Public-Private Conference for Future Air Mobility in August of 2018 [31].

As one can easily conclude by all the provided evidence, the UAM market is set to grow bigger and bigger. The final proof is the blue paper written by Morgan Stanley [32], published in December of 2018, which states that the UAM industry was at that time worth 1,300M US$ and it is expected to be worth 1,500,000M US$ in 2040 (these are the best-case scenarios and the worst-case scenarios are 733M US$ and 523,000M US$, respectively).

2.4 Market Analyses

Innovation suits needs, hence when thinking of a product-solution one must access if it is likely to be used or if it just market-trash. Though, accessing the market is not the main focus of this thesis it is important to bear in mind. Uber, a worldwide expert on mobility in heavily populated cities claims that there is a clear market for a UAM solution on their white paper [1].

According to TomTom Traffic Index [33] which gathered data from 416 cities, across 57 countries on 6 continents, the car traffic increased in 239 cities decreasing only 63 cities and the average extra time spent in a traffic jam in 2019 was 87 minutes. The index only accounts for 28 cities with over eight million inhabitants and more than half of the inquired cities are in Europe, making this studied more Europe focused than worldwide. The upside is that the biggest cities across the world were considered.

Filtering the ranking within these 28 cities, the ranking shows cities where traffic improved (39%) and deteriorated (35%) [34]. From treating the data present in [34], it is inferred that there seems to be a wide market in China, the USA and India as these countries own 29%, 11% and 11%, respectively, of all cities considered by the source [34].

An important factor when choosing which urban areas to implement an air taxi service is the inequality factor amongst a pre-selection of cities, because such service will be a premium service, to begin with, therefore their urban area needs to be elastic in a way that offers a niche market and then a broader spectrum of people. Another factor is to look not only for over-congested cities but also for high-densely populated cities. These three factors help to decide the implementing cities for the air taxi service.

Regarding the amount of money, clients are willing to pay for such a service like the one presented at Uber's white paper, Uber believes "that in the long-term autonomous case, direct costs per vehicle mile will approach 50 cents per mile (equivalent to 35 cents per ground mile)" [1]. As for the service of pooling "the price for a 45-mile pool VTOL, which would replace a 60-mile automobile trip, could approach as low as 21 US$ for the 15-minute journey" [1]. Hence, Uber believes the prices are very competitive with the ground solution currently offered making it a hopefully viable solution.

A study concerning potential clients needs and desires regarding a UAM solution to enter the market has been presented by NASA [35] which published a technical out brief in October of 2019. The study participants are from several cities across the USA (Houston, Los Angeles, New York, San Francisco and Washington DC). The key takeaways of the study are:

1. neutral to positive reaction to the concept of UAM;
2. preference of sharing a ride with known people rather than unfamiliar people;
3. some openness as well as apprehension to flying alone, specially in autonomous vehicles;
4. strong preference for piloted operations with openness to automated pilot if discounts or mixed fleet is offered;
5. preference for long flights, from 60km to 190km;
6. show of resistance to very short flights given the high costs and convenience restraints;
7. younger people show interest for a premium service to flying alone;

8. some willingness to own and pilot a UAM aircraft;
9. recognition of possible market for services such as Uber and Lyft;
10. existing noise concerns, during the nights and early mornings.

2.5 Aircraft Inventory

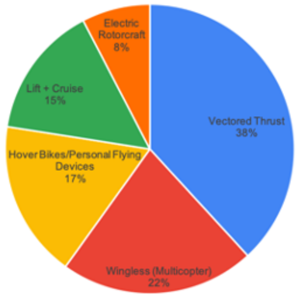


Figure 2.1: Distribution of 262 aircraft according to their propulsion mode

The VFS started to publicly gathering information for statistical purposes and to centralize all existing and relevant information, in 2016. VFS gathered information on 262 VTOL aircraft [3] (assessed in 20th of January of 2020) and organized them under 5 categories: vectored thrust, wingless (a type of multicopter), hover bikes and personal flying devices, lift-plus-cruise and electric rotor-craft; unfortunately only 94 out of the 262 aircraft pages had some relevant information. Some of these aircraft are only a proof of concept, meaning there was no intention to produce it at a large scale, and other aircraft projects became extinct due to lack of investment. Nevertheless, eVTOL is a growing industry and, as mentioned in section 2.3, it is an industry to be worth billions of US dollars in the long-term. Therefore, the number of companies investing in the field is increasing and 2020 has been proof of it. As mentioned previously, there are several big automotive companies creating bonds with the aeronautical industry because the automotive industry already has decades of knowledge for mass-scale production, but lacks the aeronautical expertise to build a UAM solution for on-demand transportation whether for 2 or 20 people.

2.6 Current Associated Technology State and Future Prospects

2.6.1 Misconceptions of electric propulsion

According to Moore and Fredericks [36], in 2014, there were five misconceptions regarding electric propulsion aircraft on emergent aviation markets. The article [36] mentions that some studies fail to compare electric propulsion with reciprocating or turbine engines because such authors do not understand the differences between those means of propulsion; there is not a defined set of metrics to perform a comparison analysis consequently most authors focus only on a single specification rather than seeing the big picture (perspective is the key). The mentioned article [36] states that a mere battery specific energy density of 400 Wh/kg already has a great impact reaching up to 2 to 8-time factor improvements across several metrics (according to NASA Zip studies) such as energy and operational costs, efficiency, community noise, system and safety reliability and Green House Gas emissions. It surely does not allow for commercial aircraft to fly as they do nowadays yet but allows for small aircraft changes either on their current or emergent markets. Innovation has to start somewhere.

Any developing technology should not just be compared through legacy metrics, as the results may be misleading, but also through other important characteristics of future interest [36] (which may provide important latent value). In the case of electric propulsion, it means not only to compare the propulsion system weight to performance but also energy and operational costs, efficiency, community noise, system and safety reliability and gas emissions.

Follows a list of the benefits of electric propulsion: 6x the motor power to weight; 3-4x the efficiency of State-of-art engines; scale-free efficiency and power to weight; high efficiency from 30-100% power; extremely compact; high reliability; safety through redundancy; low cooling drag; produce 100% power for 30-120 seconds; continuously variable transmission; extremely quiet; no power lapse with altitude or hot day; 10x lower energy costs; reduction of engine-out sizing penalty; and zero vehicle operational emissions. On the other hand, the penalties of electric propulsion are: energy storage weight; energy storage cost; certification; and safety.

To sum up, the "electric propulsion is considered to be a classic disruptive technology that has the potential to quickly displace conventional propulsion technologies; but in ways that will likely be perceived as unexpected (but with comparison to other disruptive technologies, are actually quite predictable)" [36].

The title of sections 2.6.1.A to 2.6.1.E are citations of an article by Moore [36].

2.6.1.A "Design of electric aircraft is no different than existing aircraft"

Reciprocating or turbines engines are not scalable as they suffer significant penalties of power to weight, efficiency and reliability when their size is altered. On the other hand, the scale independence of electric propulsion is translated into the fact that the power to weight ratio and efficiency of electric motors be always the same, regardless of the size.

One key difference is "to put the thrust where the drag is" [36] seeking excellent integrated aerodynamics characteristics, which is only possible due to the compactness of electric motors, easing the distribution of propulsion along the air-frame. This also changes the control systems of the aircraft as having multiple independent electric motors on the wing allows aircraft engineers to manipulate the speed of each and change roll, pitch and yaw moments with stronger control forces at lower critical speeds, instead of being solely dependant of wind gusts on aerodynamic-structural control surfaces. This also allows for an infinite set of possibilities to build a constructive or destructive interference to better control aircraft acoustics. All in all, the possibility of DEP scale-free results in an increase of degrees of design freedom which were not available in the past, in turn, increases by far the difficulty of performance analyses requiring new physics-based tools to analyze such complex multi-disciplines interactions.

Resulting, therefore, in a rather different design approach. Programs like NASA CBAero have readily adapted to show good results for DEP by including the actuator disk theory while allowing for a direct import of geometry from the program OpenVSP parametric geometry modeller. Given that CBAero is missing the feedback loop of a closely coupled wing or tail to provide feedback into the open propeller performance, then a new multiple lifting line wing-tail-propeller analyses tool is needed to rapidly capture the wing and propeller aerodynamics, with feedback between each these lifting/propulsive surfaces [36].

2.6.1.B "Electrical and conventional propulsion should be compared on an isolated propulsion system basis to achieve fair comparisons"

Given the increase of degrees in design freedom, an engineer can think of distributing part of the batteries set across the fuselage resulting in very strict relation between the structural, control and propulsion engineers. Such a relationship is highly dependent on the creativity of the engineer. Then, what area should engineers focus first when designing an aircraft using DEP? A poll across NASA Langley [36] experts resulted in a qualitative assessment ranking to prioritize the synergistic potential of DEP in terms of the magnitude of resulting impact across the disciplinary metrics of aerodynamics, acoustics, operations, control and structures. That is precisely the misconception in the discussion as it is unfair to compare a new technology in an isolated way when it asks for "highly integrated coupling with other disciplines" [36]. This is precisely what NASA Langley is trying to do to reduce the associated uncertainty with each part through detailed multi-disciplinary research that captures the tight coupling effects.

There are several potential integration and architectures relating to DEP and their selection relies on specific application intent and mission. In general, conventional propulsion provides low efficiency and emissions benefits; hybrid-electric answers very fast to peak energy demands and delivers smoothly to cruise conditions being a good trade-off regarding energy efficiency; at last, an all-electric system is the most efficient and lowest operating costs though having the limitation of low range. All these propulsion architectures have their advantages and disadvantages which all need to be weighed in when opting or inventing a solution. Once again, it is proven that design aircraft is all about trade-offs.

2.6.1.C ”Just like electric cars, electric aircraft will not make financial sense”

Electric cars using batteries as energy storage suffer from the high price of batteries pushing the maintenance cost of the propulsion to high standards. However, such prices can compensate if one makes a different use of a car. A technology when developed may not suit all needs thought previously but may suit under-thought needs, hence the need for an amortization study. Electric vehicles belong in such categories, the fact that batteries are extremely expensive is compensated with a high frequency of usage. For example, a set of batteries for a Tesla Model S [36] is approximately 30,000 US$ therefore the current usage of 300 h/year instead of 1500 h/year has different amortizations costs. The batteries in question have around 2000 h of useful life hence the current usage makes it possible to have high opportunity costs to solely sit in idle for around 7 years; on the other hand, a higher usage lowers the opportunity cost. Higher usage rates can be achieved via a shared business model which companies should be open to (making the vehicle autonomous may be part of the solution), once again proving how disruptive the electric mobility industry can be.

High usage rates are the key because the time the vehicles spend in idle is reduced as well as the dissipated energy during such time. The more optimized is the usage of the vehicle the better regarding costs and energy efficiencies. In general, maintenance and fuel costs are the major contributors to the operational costs of an aircraft. According to Moore and Fredericks [36] approximately ”50% of GA aircraft total operating costs are energy costs due to a combination of poor aerodynamic and propulsive efficiency of existing aircraft, as well as the high cost of low lead aviation fuel”. They also state that for the same amount of energy (not fuel) electricity is 1.5-time less expensive than low lead aviation fuel. Such decrease along with 8-time less energy use due to Leading Edge Asynchronous Propellers Technology (LEAPTech) concept provides a 12-time reduction in energy cost when comparing to SR-22 airplane. However, when amortization of the battery set is considered the 12-time reduction is reduced to only 4-time improvement. From this, it is easily inferred that there is a potential for dramatic energy costs decreases when using electricity as power instead of conventional fossil fuels.

One other side of the economic feasibility relates to the high acquisition costs of electric aircraft given the very low production volumes. Despite being in the market for over 30 years, small aircraft of internal combustion are still very expensive and their yearly production volumes are very low and it has not increased as expected as it did with the car industry. Therefore, both electric and internal combustion aircraft are very expensive. There is, actually, a better shot for Electric Vehicles (EV) aircraft as they seem to fit several markets as well as open new markets as explained in section 2.6.2 having in mid-term higher production volumes than internal combustion aircraft. Also, the current UAM solution is the helicopter and their production volume (see section 2.2) is very low for the world-wide UAM demand. Hence, the high acquisition cost is not a barrier to the eVTOL industry.

In 2014, when Moore and Fredericks [36] wrote an article there was a big difference in the acquisition cost of an electric car when comparing to an internal combustion car. Fast forward 6 years only to 2020 (year of publication of the present thesis), such difference has decreased and does not pose as a barrier anymore in the automotive industry. Given the huge amount of early adopters of EV's, the industry was able to lower the prices into a more competitive window resulting in higher production volumes and in lowering the prices again. The key is to have a technology appealing enough to captivate investment and early adopters, the UAM industry has mastered in such art.

2.6.1.D "Electric storage energy density is the issue and insufficient for meaningful range"

Moore and Fredericks [36] believe that a battery specific energy density of 400 Wh/kg is "sufficient to enable meaning electric and hybrid-electric aircraft" (and there are more scientits beliving this fact [37]) and that it would be accomplished by 2020. An electric conceptual retrofit of SR-22 was used to study the sensitivity for a battery-electric range of 370 km along with the estimating distribution of trip distances that would be required if such aircraft was an on-demand UAM solution. However, according to an article of December of 2019 [38] "energy densities of 240–250 Wh/kg and 550-600 Wh/L have been achieved for power batteries" and "300 Wh/kg is expected to be realized in 2020 and 500Wh/kg in 2030" so the battery specific energy density is chosen for the conceptual aircraft design of this thesis was 300 Wh/kg.

Once GA using internal combustion chooses their engines they can calculate their maximum range without any additional significant weight penalty. On the other hand, electric aircraft have a much higher gross weight sensitivity to the range due to the fixed batteries weight making the calculation of range with major accuracy of utter importance, as it cannot be simply increased by adding a set of batteries like pouring more fuel into fuel tanks.

Aside from the battery specific energy density, specific power and required charging time also play a key role in the EV industry. Specific power is translated into the "rate at which the batteries can be discharged" [36] and its importance is specially related to Short Takeoff and Landing (STOL) and VTOL far more than energy density, because such aircraft may require a minimum of 5 minutes at full power meaning extracting the power very fast, in case the mission does not ask for a sustained hover (if it does require then it is more than 5 minutes at full power). The charging time, on the other hand, has more impact on the high usage rates, because a high charging time is a barrier for a large usage as a high charging time demands for a bigger fleet for the same clients and results in increased operational costs (which is not desired); low charging time is highly dependent of low internal battery resistance. These last two characteristics are equally important to achieve feasible operational capabilities and they are presented with a C ("C is multiplier of how quickly a battery can expend its energy in relation to its charging time" [36]), although 60C batteries are available (meaning full discharge in 60 minutes) at reasonable but low energy densities.

As an example, Tesla is already able to charge 50% of batteries in a 30 minutes charge having a near-term goal of achieving 80% charge in 60 minutes of charge [39]. Furthermore, according to Moore and Fredericks [36], there is reason to believe that if batteries keep developing at the same pace they have been for the last 30 years (given the mentioned research is from 2014) then in 2021 it is likely that batteries achieve sufficient energy density for reasonable GA solutions to be implemented market-wise. Batteries' state of art is to be discussed in section 2.6.3.

2.6.1.E "Electric aircraft research should focus on large commercial transports with a market introduction"

Many disruptive technology case studies (like the internet or mobile industry) have showcased how important it is to have a highly adaptable/agile research and market plan. When investing in a new technology one needs to understand the business case and opportunities that will present oneself along the "incrementally revolutionary" development path" [36]. Research and development are focused on commercial transportation because "is where the majority of revenue passenger miles and profits currently exist" [36], however, such industry currently poses as a misfit to DEP technology given their long range requirements.

The penetration of DEP technology is highly expectable. Firstly, it is applied to Unmanned Aerial Systems (UAS), secondly to GA markets and only afterwards increasing the scale for bigger aircraft. It is important to reinforce the idea that the application of a given technology does not mean its development is finished as innovation is a never-ending process. This path is also the most likely one given that GA is the market with more room for great improvements on the overall efficiency of the aircraft [36].

Moore and Fredericks [36] estimated that in 2019 the DEP technology would reach the markets what indeed happened. Already in 2018, there were several retrofits showcases by Siemens [40] and in late 2019 by magniX [41] which prove the estimations right and as mentioned in section 2.1 there was an experimental flight test of a Cessna Caravan. Moore and Fredericks also estimate that in 2024 commuter and regional jet aircraft will see some game change due to DEP technology implementation.

When developing a technology it is important to always keep the big picture in mind as narrowing the thought may lead to misguided and unreal conclusions and may miss the opportunity of new markets arise. All frontiers of knowledge are important and deserve to be explored.

2.6.2 Reinventing small aircraft purposes

The proposed aircraft may have several purposes ([8] and [7]) ranging from conventional to new markets. It is designed to be an air taxi posing as a UAM solution. However, with a few changes, it may have suit other needs, such as private luxury transportation, tourism for sightseeing or hotel transportation, air ambulance as an emergency medical service provider or a medical transporter for routine consults, rescue teams, humanitarian missions, fire fighting, law enforcement operations, forest protection, agriculture and material transportation helping with factories and stores with logistics, news gathering, weather monitoring and ground traffic assessment.

With the never-ending development of battery, DEP, LEAPTech technologies as well as many other technologies still waiting to be invented, the purposes that aircraft like the one to be presented by this thesis have are also ever-changing. Therefore, the mentioned purposes may also change in a few years. The author of this thesis believes that the future is as much predictable as unpredictable, relying only on estimations may misguide the disputers of the today's world. As one must question every step of the way seeking for improvement.

Regarding civil purposes, it is important to reduce flight boredom during the flight inside the cabin [42]. For example, design the aircraft in such a way that allows hosting a comfortable conversation, reading, writing, eating, drinking, sleeping or relaxing; having Wi-Fi onboard improves the user ride experience, in particular, for long flights.

2.6.3 Li-ion Battery Technology

2.6.3.A Brief Explanation of a Li-ion Battery

Though existing immense information published on Lithium-Ion (Li-ion) batteries, there is still plenty more to be written. According to the Clean Energy Institute of the University of Washington [43], Li-ion battery uses lithium as the main component for the electro-chemistry. For a discharge cycle, lithium atoms present in the anode are ionized and then separated from their electrons; the lithium ions move from the anode to the cathode through the electrolyte, a permeable separator given their extremely small size [43]. When in the cathode, the lithium ions are recombined with their electrons and electrically neutralized [43]. A Li-ion can use several materials as electrodes. A typical choice for a set is cobalt oxide, as a cathode, and graphite, as an anode [43]. Another common set is manganese oxide, used in hybrid-electric and electric vehicles, as well as iron-phosphate [43].

2.6.3.B Specifications of Current Li-ion Batteries

According to Bacchini and Cestino [44], it is worth to salient that the mentioned values of energy density and specific power of the Li-ion batteries used for VTOL may be conservative as the assumed values are at pack level; meaning they consider additional weight for thermal management, connections and casings. Such a conservative approach can be seen as a safety measure to ensure there is plenty of power for takeoff and landing even after several years of use. This can possibly result in a bigger user window as the battery may take longer than expected to self-discharge.

As mentioned in section 2.6.1.D, Moore and Fredericks [36] believe that a battery specific energy density of 400 Wh/kg is sufficient to enable meaning electric and claim such batteries will be available by 2020. However, according to Wenzhuo Caoa, Jienan Zhanga and Hong Lian [38] specific and volumetric energy densities of 250 Wh/kg and 600 Wh/L, respectively, have already been achieved and in 2020 it is expected to reach 300 Wh/kg and by 2030 it is expected to be 500 Wh/kg. Hence, the battery specific energy density chosen for the conceptual aircraft design of this thesis was 300 Wh/kg. Table 2.2 presents some of the characteristics of a Li-ion battery in 2020.

Table 2.2: Characteristics of a Li-ion battery in 2020.

Characteristic	Units	Value
Volumetric Energy Density	Wh/L	550-600 [38]
Specific Energy Density	Wh/kg	240-260 [38]
Specific Power Density	W/kg	1300 [44]
Voltage	V	3.6 [43]

According to Bjorn Fehrm [45], in 2017, 1 kg of Jet fuel could store 70 times as much energy as the best Lithium-Ion battery at the time. One and a half years later, in 2019, the energy relation was about 50 times [45], meaning an improvement of 29%. Ideally, this relation should be equal or smaller than one, meaning Li-ion based batteries specific energy would have to be, at least, equal to Jet fuel specific energy. Regarding space efficiency, in 2017, “Jet fuel stores 20 times as much energy as one litre of Lithium-Ion battery” [45]. When designing an aircraft weight is more relevant than space [45] due to calculations of the center of gravity and pressure, neutral point and static margin given all contribute to the maneuverability of the aircraft.

2.6.3.C Comparing Li-ion to other Battery Technologies

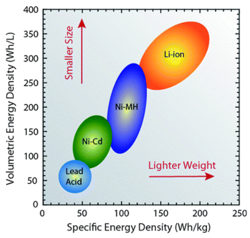


Figure 2.2: A graphical representation of the specific energy density and volumetric energy density of various battery types [43].

Li-ion is the most mentioned battery in the present thesis and the reason can be seen in figure 2.2. Such figure compares specific and volumetric energy densities, but another comparative value is the voltage delivery of Li-ion which is 3-time higher than Nickel-Cadmium (Ni-Cd) or Nickel-Metal-Hydride (Ni-MH) technologies.

Nevertheless, there are other batteries worth mentioning such as Lithium-Sulfur (Li-S) and Lithium-Air (Li-Air) that have not yet reached market but present excellent battery pack test values between 300 and 500 Wh/kg ([46] and [47]).

2.6.3.D Advantages and Disadvantages of Li-ion Battery Technology

Li-ion batteries are widely used in mobile phones, digital cameras, laptops and electric vehicles [48]. Another proof that Li-ion battery technology is a game-changer within the mobility industry is that, in 2015, 28 EV and plug-in vehicles used LG Chem's Li-ion batteries [48]; for instance, Tesla Models S, 3 and X use Li-ion batteries by Panasonic and Nissan Leaf uses Li-ion batteries produced by Nippon Electric Company (NEC) [48].

Given Li-ion batteries being the prime choice for several mobility companies, assessing their advantages and disadvantages is adequate, hence table 2.3.

Table 2.3: A list of advantages and disadvantages of Li-ion battery technology [43].

Advantages	Disadvantages
- 3-Time higher than Ni-Cd or Ni-MH; - Comparatively low maintenance; - Not required scheduled cycling to maintain their battery life; - No memory effect; - The low self-discharge rate of around 1.5-2% per month; - Not made with toxic cadmium; - Best selling cars, Nissan Leaf and Tesla Model S;	- A tendency to overheat; - Can be damaged at high voltages; - It has happened to lead to thermal runaway and combustion; - The fleet of Boeing 787 has been grounded due to combustion risks in equipment with Li-ion batteries; - Several shipping companies refuse to perform bulk shipments of batteries by plane; - Require safety mechanisms to limit voltage and internal pressures, which increase weight and reduce performance; - Batteries are subject to ageing losing capacity and frequently fail after some years; - Cost is approximately 40% higher than Ni-Cd; - Best batteries store about 40-time less energy per unit-weight than jet fuel (though usable is only about 14-time less);

2.6.3.E State and Depth of Charge

An all-electric battery-based aircraft has no weight variation during flight easing its control and avoiding a constant correction of the center of gravity. When comparing to combustion propulsion, the weight is ever-changing during flight as fuel is burned during the flight [49] making the aircraft substantially lighter during flight while asking for a permanent control lookout. Such weight variation may be perceived as both an advantage as a disadvantage depending on the reader's beliefs.

Figure 2.3 helps understanding the concept of State of Charge (SOC) for Li-ion batteries and shows that a battery may be considered empty for calculations purposes when SOC is between 10-20% meaning a Depth of Discharge (DOD) of 90-80% in every use [50]. However, the design team may opt for a more conservative DOD of 60-70%.

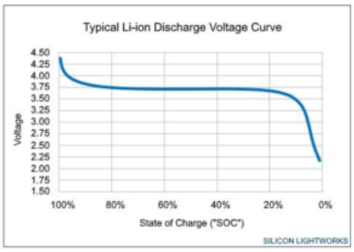


Figure 2.3: Typical Li-ion battery discharge Voltage Curve [50].

2.6.3.F Disposal of Li-ion Batteries

Table 2.3 mentions a ”Low self-discharge rate of around 1.5-2%” what helps do calculate when to dispose and replace Li-ion batteries. The self-discharge rate results from the bonding of lithium ions with the electrodes when in continual charge and discharge cycles, reducing the number of lithium ions available for the battery system and, consequently, the battery holds a charge for less amount of time [48].

Accelerated degradation of batteries is usually caused by improper use and handling, like fast charging, inadequate charge and discharge (according to manufacturer's advice) and operating at a different range of temperatures than those set by the manufacturer. For an EV, a Li-ion battery may ”last anywhere from “5 to 20 years depending on many factors”” [48].

Despite not being of good use to EV after some use, Li-ion batteries still have a lot of potential afterwards in other areas, hence instead of the disposal batteries can be adapted for new purposes. Despite the research [48] in this field, there are no large scale practical applications yet.

According to an article of 2018 [51], in just two years the mindset of the industry regarding recycling and reusing Li-ion batteries has gone from ”lack of economic viability” to ”profitable and convenient” which is not surprising due to the rapid growth of the EV industry, whether air or land vehicles. According to Kushnir and Sandén [52] and to Zackrisson et al. [53], legislation and resource supply awareness concerns are likely to drive the recycling rate (including collection rate) to as much as 80%, however, such effort will only avoid 50% of the environmental impacts of virgin material production [53]; this 50% results from the statement from Zackrisson et al. [53] ”recycled materials are often of inferior quality and cannot fully replace virgin materials, and partly because the recycling processes need resources and cause environmental burden”.

Zackrisson et al. [53] states that the battery cells is built as follows: electrolyte are 54% and 18% for sealing gasket; and both them are assumed to be incinerated and ”only 28% of the total cell weight will be recycled as material (copper, lithium, cobalt and polypropylene)” [53].

The production and disposal of batteries have impact when assessing the overall equivalent emissions in section 4.2, in accordance with Zackrisson et al. [53].

2.6.3.G Important Definitions regarding Battery Specifications

The definitions of battery basics, condition and technical specifications are as described by Massachusetts Institute of Technology (MIT) [54].

2.6.4 Electric Engine

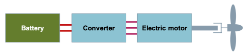


Figure 2.4: Simple scheme of an all-electric aircraft propulsion, composed by a battery, a converter and the electric motor [55].

Assessing energy conversion efficiency into shaft work is the next step and figure 2.4 reveals a simple scheme of an all-electric aircraft propulsion system, where the shaft is right before the propeller. A propulsion system made of a modern gas turbine is around 55% [45] and one modern all-electric propulsion system by Siemens is 95%, using the Siemens model SP260D [55].

All-electric propulsion systems need a power, which has an efficiency of around 99% [56], in 2017, according to research for large subsonic transports according to NASA [57]. Despite that, the mentioned Siemens model SP260D has the overall mentioned efficiency.

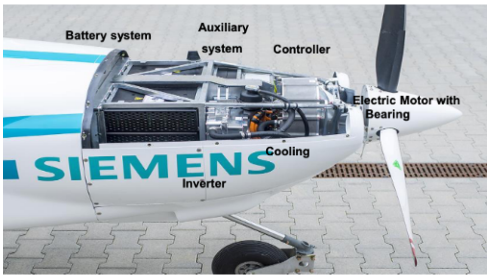


Figure 2.5: Real application photograph at Siemens eAircraft Magnus eFusion (at maiden flight Summer 2016) an all-electric propulsion system composed by a battery, a converter and the electric motor [55]. This e-aircraft is a collaboration of Magnus Aircraft, a company based in Hungary, with Siemens [58].

The mentioned Siemens all-electric motor, SP260D, was already used in Siemens eAircraft Extra 330LE [59] and its specifications are presented in table 2.4. This e-aircraft results from a partnership of Extra Aircraft, Siemens, MT-Propeller and Pipistrel [58]).

Other factors when designing an aircraft are their range and endurance, given their high sensitivity to the propulsion system. For a non-combustion aircraft, the existing methods for its estimationt are not as precise as they should be due to the lack of historical data on all-electric and hybrid aircraft, as such methods are based both on physics and collected data through the decades. GAMA published, in 2017, as a solution, the “Hybrid & Electric Propulsion Performance Measurement” [60] to set a common frame of reference for all the developers [4]. From tables 2.3 and 2.2, it is clear both power and energy density

Aircraft Data	
MTOW	1000 kg
Wingspan	8.0 m
Height	2.6 m
Length	7.5 m
Wing area	10.7 m^2
Propulsion System Data*	
$P_{cont.}$	260 kW
N_{max}	2250 rpm
$M_{cont.}$	1000 Nm
U_{zk}	580 VDC
η_{Motor}	max. 95%
$m_{motor\ including\ propeller\ bearing}$	50 kg

* As rated in the Extra 330L

Table 2.4: Siemens eAircraft Extra 330LE specifications [55].

of Li-ion batteries need to increase at least one order of magnitude, to make flights longer than 15 to 30 minutes commercially possible. Though, a 30 minutes flight was performed in 2020 as mentioned in section 2.1, despite not carrying passengers and being only a flight, test it is proof of a hard-working industry and its great results proving the viability of all-electric aircraft.

Given the claim “all the automotive industries are going to e-cars” [4] by Colucci, therefore there is reason to believe that there is still a lot of innovation to be seen in the GA industry due to the consequent faster development of the battery technology, as Li-ion batteries are of great interest of both industries.

Given the facts provided, some engineers believe that the future is hybrid-electric rather than all-electric. Both parties have advantages and disadvantages, for the scope of this thesis only an all-electric option was considered. A hybrid-electric solution usually uses electric energy stored in batteries for takeoff and landing as they pose as the segments of the mission profile that use most of the energy and a typical combustion engine to suit the cruising needs, given the type of aircraft like the one being proposed by this thesis as shown by mission 1 presented in figure 3.12. This presents a good compromise between both technologies but still poses as a polluting solution during operation.

Another solution highly promising is hydrogen-based. Hydrogen poses as the greenest source of energy for the future. One big issue with this solution is the conceptual design given the heavy tanks to store the hydrogen and also to correlate that with the mass variation along with the flight. This technology, in 2020, falls a few years behind of an all-electric solution regarding implementation and certification. FAA has started making changes to include fuel cell-powered vehicles certification criteria since at least 2017 [61] committing to further investigation into such technology to adapt their certification process. Nevertheless, companies such as HyPoint [62] already have a functioning solution and the same company has retrofitted successfully aircraft with their solution. Having Hydrogen Fuel Cell systems as HyPoint's mission and being one of the first companies to deeply research in the field, they conceived a technical white paper [62] on the matter. Alex Ivanenko, an employee of HyPoint, announced (on an unrecorded webinar on the 7th of April of 2020) a 9% mass ratio (equation 2.1), a safety factor of 1.8, 1MW cell and an energy density of 1000 Wh/kg. It is undoubtedly a better solution than Li-ion but still needs further research and certification developments.

$$\frac{mass_{H_2}}{mass_{H_2} + mass_{tank}} = 9\% \qquad (2.1)$$

The current thesis, as mentioned in the section 1, aims to develop a conceptual aircraft that could be ready for the market in 2024. Such a model is to design for 30 years of operations, having zero operation emissions and lowest operation costs. Hence, an all-electrical solution seems to be the best fit given all the published research by the year of publication of the current thesis, 2020. All-in-all it all comes down to trade-offs, if the year of the market launch was to be 2030, then a rather different solution would be designed.

2.6.5 Overall Aircraft's Noise

Current VTOL vehicles most used as a UAM solution are helicopters and they come as loud as they get. According to Brown and Harris [63] from MIT, the prime sources of noise in a helicopter, by decreasing order of importance, are blade slap, piston-engine exhaust noise, tail-rotor rotational noise, main-rotor vortex noise, main-rotor rotational noise, gearbox noise and turbine engine noise.

Any on-demand UAM solution looking to enter the market should be as quiet as possible to allow the widest operation time frame as the purpose of an on-demand solution is to suit population needs at any given time, hence cruise cities' skies both day and night.

Another reason for the aircraft's quietness is the fact that when an on-demand UAM solution comes to market, it is likely to come at large scale meaning an increase in aircraft traffic, with the skies becoming densely populated. All over the world, governments have rules setting an accepting range of values regarding overall population health and concerns in the field of electromagnetic radiation, noise, pollutant emissions, airspace field, field management and several others, varying from city to city within the same country. Consequently, the shortest path for the widest acceptance rate is to aim for the quietest vehicle possible, bearing in mind all the necessary trade-offs.

NASA [35] sets its limits, under 50dB as "quiet" operations and higher than 50dB as "non-quiet" due to NASA's "Societal Barriers focus groups which indicated low public acceptance of a large number of high-noise Air Taxi operation."

Uber believes that "67dB(A) at ground level from a VTOL at 250ft altitude" as Uber believes to be achievable, this is equivalent to "a Prius at 25ft from the listener, driving by at 35mph"(56km/h)[1]. By 2018, according to Brown and Harris [63] from MIT, a 62dB(A) noise was not possible, even when postulating the most generous long-term technological assumptions, showing a clear need for improvement and effort to reduce noise.

Uber also states the direct consequence for real-estate market as properties on "busy or noisy" communities are often valued less compared to properties in ”quiet” areas [1]. Noise footprint has existed for a long time the goal is to reduce it or increment infinitesimally, which according to Uber [1] translates into ”not increasing the long term average Day-Night Level (DNL) by more than 1 dB, which is the smallest change in loudness that a person can detect.”

DNL is the averaged sound pressure level for a 24-hours, with a sensitivity offset of 10 dB between 10 PM and 7 AM, hence a constant sound of 60dB(A) in the daytime and 50 dB(A) at night would define a neighbourhood with 60dB DNL [1]. For example, the FAA uses a yearlong running average of DNL when reporting the noise impact of airports [1].

Long-term annoyance is via DNL, while the short-term is via Sound Exposure Level (SEL). The target for short-term annoyance is to increase night-time awakenings by no more than 10% at maximum, ideally to increase by 5% is thought to be possible [1].

According to Jaunt Air Mobility, on information traded via e-mail with an employee in 2020, a 20dB reduction in sound is equivalent to a 100-time decrease in sound intensity (W/m). By October 2019, Jaunt's aircraft was the quietest solution in the market, if considering Effective Perceived Noise Level (EPNL), with exception to hot air balloons.

Siemens eAircraft Extra 330LE featuring the electric engine Siemens SP260D shows great noise reduction when compared to Siemens Extra 330LT featuring internal combustion. Such differences are visible on the company's public videos published on YouTube [64]. The videos allow to see graphical differences and hear them for takeoff, fly-over at 50ft and 1000ft. Proving that an all-electric solution of two similar aircraft is quieter than the internal combustion solution.

There is plenty to pay attention to in the future as data is collected over the years. The next steps into noise perception, according to International Civil Aviation Organization (ICAO) [65], are:

- monitoring and reporting on research goals and milestones programs worldwide;
- evaluate and postulate new noise reduction technologies;
- reviewing progress towards achievements in 2020 and 2030;
- update certification procedures and research for supersonic flight.

2.6.6 Overall Aircraft's Emissions

All-electric aircraft have zero operational-emissions [1], meaning zero emissions when performing a mission. All they have is emissions regarding their building, recharging, maintenance and disposal/recycling/reusing processes, which all are part of the life-cycle of aircraft. Though recharging related emissions may be brought to zero if green energy is used for this purpose, as it depend on the electric generation mix [66]. The higher the battery energy density then the energy needs by mission lower, as single charge takes the aircraft further away.

According to Fu et al. [67], UAM's environmental impact has not been properly studied yet, Fu et al. [67] raises awareness to the problem of assuming a UAM solution is energy efficient, emission free and quiet rather than thoroughly studying those and assess the real impact. According to Afonso et al. [56], noise studies have been performed because noise is one of the most critical constraints [68] regarding community acceptance of the UAM industry. Such statment is in agreement with a study by Eißfeldt [69].

André and Hajek [70] submitted a paper in 2019 stating that eVTOL vehicles can compete environmentally with internal combustion solutions as long as "the required energy is provided by a sufficiently clean energy grid", "the UAM mission profile has a small hover" time regarding the whole mission (approximately a maximum of 20% of hover time over the overall mission's profile time), the occupancy of the seats is at its maximum (6 passengers in an autonomous solution would be ideal. However, they also state the constraints of this due to regulations), the trip distance saving is high in comparison to the road-bound mission and the batteries hold at least 1000 cycles. This paper also mentions that a battery specific energy of 650 Wh/kg would be better rather than a 400 Wh/kg as it may be risky to work on the limbo, going against what has been mentioned in section 2.6.3. However, the authors recognize they played conservatively choosing a power train efficiency of between 0,7 and 0,8 when it is usually 0,9 (and some consider this last value as conservative). Showcasing conservative publications is beneficial has it puts things into perspective and aids keeping it real.

Emissions of EV are controversial, one knows that despite operational emissions being zero all the other sources of pollutants of vehicles' lifetime may surpass the emissions of an internal combustion solution. The source of the energy that charges the batteries of electric vehicles (whether boats, aircraft or cars) needs to be green otherwise all this effort may be for nothing. Once more, it is addressed that it needs to be a global change of mentality as populations in general need to optimize all resources usage.

It is a question of marketing! For companies operating EV's, it is about zero operational emissions to market the vehicle as a green solution. For the EV's seller, it is important to suit clients needs. For the manufacturer and designer, it is important to suit the clients' needs and meet all the regulations, hence it all comes down to regulators. It is best to consider the overall impact of an EV even if the operational emissions are zero given the first bears in mind the second. It is precisely this that public institutions and companies need to research to better understand the long-term impact and solution viability of EV solutions whether land or aerial.

2.6.7 The Reality of Autonomous Vehicles

Autonomous vehicles are getting closer, the biggest barrier being people as they are concerned whether such vehicles are reliable enough. From the engineering perspective, it seems easier to have autonomous air vehicles rather than land, as on-air there are no passers-by and no signals to read. Despite this, autonomous land vehicles seem to be ahead of aerial solutions, companies like Tesla are making huge efforts and advancements poking the industry at all levels. Nevertheless, there have been some military drones fully autonomous performing data acquisition missions since the XIX century [71], however, such vehicles still require a command center to analyze data and take control in-flight in case anything goes wrong. Only in 2014, was publicly announced the intention of using drones for purposes other than military, Amazon [71] took that leap of faith by showing their will to have drones delivering their clients' orders. A Cessna 172, in September of 2019, and a Cessna 208 Caravan, in June of 2020, made the first take-off, 15-minute flight and landing autonomously by the company Reliable Robotics [72], with the intention to create a business of small cargo transportation between neighbour airports.

There are 6 levels recognized worldwide for autonomous land vehicles ([73] and [74]), from level 0 of "no automation" to level 5 of "full automation". In 2020, there are plenty of car manufacturers offering level 2 "partial automation" solutions meaning such vehicles can assist in controlling speed and steering. Despite not being on the market, the project Waymo by Google is an example of level 4 "high automation" meaning the car can drive itself without human interactions.

On the other hand, the aeronautics industry has not yet come up with a grading system for autonomous vehicles for the whole mission profile. Only a system for assisted landing (Instrument Landing System (ILS)) [75] (composed by 5 levels) has been developed for commercial flights, as for GA, not even such has been published.

ICAO has investigated and published about integrating autonomous aircraft within communities [76], since at least 2016. Such an institution believes that ATC, navigation and surveillance systems, manned and autonomous aircraft and control and command center need to be connected to ground telecommunications as well as other aircraft being operated in the same airfield and satellites. This joint effort aims to optimize performance, enhance reliability, data accuracy and availability and allow for extremely consistent information exchange.

ICAO mentions C2-link technology as part of the solution for autonomous flight ([77] and [76]) to connect the remote controller at the control and command center to the aircraft and all their surroundings. C2-link solutions have been trusted successfully to mission-critical applications by the USA government and defence industries [78].

ICAO published a working paper [79] in 2018 for a conference to study "4G\5G mobile technology application in civil aviation" and one of the first drawn conclusions is that such technology has a "bright prospect and great potential". The same paper states that the Civil Aviation Administration of China (CAAC) is to actively cooperate with mobile operators and related industry to readily apply this technology to civil aviation. This is reinforced by some companies such as Ericsson [80] as they state that 5G technology connections are the way to go due to their great characteristics [81] like massive machine-type communications (great for smart cities and remote monitoring) and ultra-reliable communications and low-latency communications (excellent for autonomous vehicles). There are already some applications in aviation, as examples are Manchester [82] and Brussels [83] airports operating fully with 5G technology and the demo of baggage claim of Rome's Leonardo da Vinci airport [82]. Ehang stated in their white paper in, 2020, that 5G network technology seems to be a good fit to UAM [8].

C2-link and 5G are promising technologies and some believe the path towards success is the joint effort of both technologies [84]. Nevertheless, one must state that regulations need to be ever-updated and communities must be duly informed so that technology can be implemented in commercial solutions and build-up people's confidence.

2.6.8 The Next Big Steps for e-Aircraft

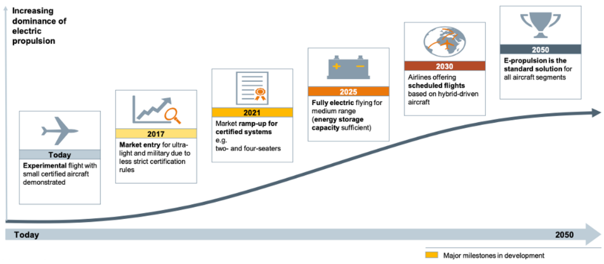


Figure 2.6: Siemens future beliefs for the eAircraft market [55].

Figure 2.6 wraps up the aviation industry present beliefs for the mid and long-term future. According to Siemens [55] by 2050 electric propulsion will be the standard of aviation and become the new conventional technology in the industry. Although such belief may be wrong in case there are breakthroughs with hydrogen-based technology regarding the aviation industry given all the available research in 2020 [85].

In April of 2016 was announced a joint effort from Boeing and Siemens [55]. Another collaboration publicly announced 1.5 years later, in November of 2017, was the joint effort of Siemens, Airbus and Rolls-Royce [55] to produce the 100-seater E-FanX [86] planned to be launched in 2021. Though such a partnership was said to be cancelled [86] according to news published in April 2020. According to the same news [86], both Rolls-Royce CTO Paul Stein and Airbus CTO Grazia Vittadini said that "decarbonization of aviation remains a major goal for both companies" and according to the mentioned Rolls-Royce CTO "E-Fan X was always designed to be a demonstrator only and never for actual use as a product in service". Despite having been cancelled, it is a project worth mentioning as it had already achieved several milestones.

It is important to state that business partnerships like the ones mentioned in the current section and section 2.3 are a major signal that a great change in the industry is about to come! It is better to join forces to fight the unknown, multidisciplinary is the key factor for success.

Public acceptance and regulations are the main disadvantages of UAM (according to what has been written in the present document so far and according to several speakers of the event "Urban Air Mobility Virtual" from 11st to 13th of August 2020 by the Aviation Week Network [87]). How to change this? Companies and governments need to create awareness campaigns to show community members the broad value of UAM solutions.

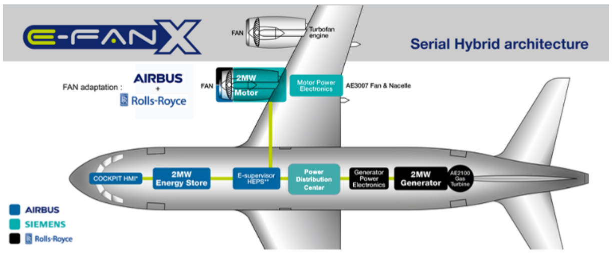


Figure 2.7: Initial concept of the joint effort resulting in E-FanX [55].

3

Conceptual Design

Designing aircraft demands for creativity, physics, market assessment and hope. Once the designing team considers that the conceptual design is optimized then the team looks for investment to produce a scale model for small size testing and iterate. Step by step the model grows bigger until it reaches the scale 1:1 and another round of testing and iterations begins. From a simple idea to commercialization several years can go by, up to 10 years [88].

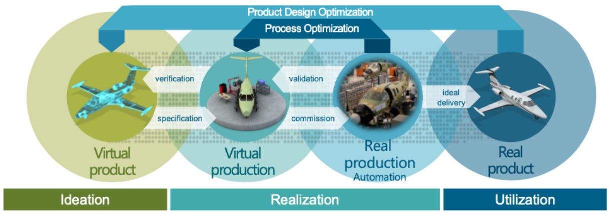


Figure 3.1: From ideation to utilization, according to Siemens [55].

3.1 Fundamental Phases of the Aircraft Design Process

Designing aircraft is a form of art and though there is a method to do so, it is only a guide helping to set directions. The fundamental phases of the aircraft [89] designing process are, by order of doing, requirements, conceptual design, preliminary design, detail design and proof-of-concept aircraft construction and testing. Now, follows a little explanation of each phase by Snorri Gudmundsson.

1. Requirements [89] - like a wish list of what the aircraft should include, high-hopes and expectations to the aircraft mission are expected to be presented here. It can specify regarding range, endurance, cruising speed and altitude, seats, loading, propulsion type, operation and maintenance costs, environmental impact or any other thing the designing team desires. Requirements can either be a few lines document or a long one.

2. Conceptual Design [89] - it involves engineering to provide a reliable assessment of likely performance, possible looks, marketability, labour requirements and expected costs.

3. Preliminary Design [89] - ultimately answers if the idea is viable by exposing potential problems

and respective solutions. A small prototype may be built to ease the assessment of aerodynamic features. At the end of the present phase, a decision must be made to carry on with the program, make major changes or cancel it.

4. Detail Design [89] - having decided to keep the program, the design team needs to detail every detail possible regarding structures, systems, avionics, mechanics and ergonomics. A profound study of the technologies available must be made to facilitate the next phase.

5. Proof-of-concept Aircraft Construction and Testing [89] - it is used to refine all areas of the aircraft. Quality and safety assurance protocols should be followed as then follows flight-testing, build of all user and maintenance manuals and overall certification.

Given the emphasis of the present thesis is developing a UAM solution, then the Conceptual Design phase shall be further explained according to Snorri Gudmundsson's beliefs [89]. Such a phase is used to define:

- the type of propulsion - piston, turboprop, turbojet/fan, electric, hydrogen, hybrid;
- type of lift - vectored thrust, lift-plus-cruise, multicopter or rotor-craft;
- the mission profile;
- the technology on-board - avionics, material, engines;
- the aesthetics;
- the occupant comfort conditions and ergonomics - pressurization, galleys, lavatories, WiFi, luggage and leg space;
- special aerodynamic features - flaps, slats, wing sweep, amongst several other;
- certification basis - Light-Sport Aircraft (LSA), FAA Part 23, for GA, or FAA Part 25, for transport aircraft, military;
- ease of manufacturing - provide an idea of the processes involved;
- maintenance - periodicity, methods, labour, tools;
- and initial cost estimation and market estimation.

There is plenty said and written worldwide regarding which areas an engineer should focus on first during the conceptual design stage. Siemens [55] sums it all up beautifully in figure 3.2.

3.2 Set Project Objectives

Requirements can be technical aspects of the aircraft as well as operational timelines and costs or safety marks. When developing a non-research project the goal is either sustainability or profit.

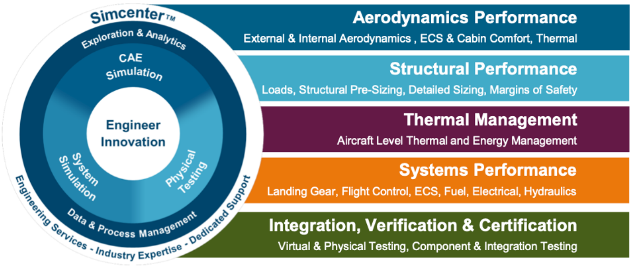


Figure 3.2: Engineer innovation for aircraft performance, according to Siemens [55].

Therefore there is a great concern to the financial engineering front of such projects. Important to remember that depending on trade-off choices made along with the project, requirements are going to be subjected to constant keen observation and questioning, making them malleable. Their main goal is to keep the designing team on the right path to success.

One of the purposes of the current thesis is to develop a UAM solution and despite the coordinators not setting requirements, the aircraft must address several needs of the UAM market. The starting point is Uber [1] as they were one of the first companies to publicly set the impetus of the UAM industry. However, several companies, such as Uber [1], Volocopter[90], Ehang [8] and HyPoint [91], have independently published white-papers on the UAM market, assessing market needs and prospecting about the future.

Usually, design teams establish a list of well defined requirements to be followed throughout the whole project. The current project preferred to establish objectives rather than well defined requirements, though some of them may seem requirements given their spelling. Here follow the chosen goals of this project, remember they are malleable and that they are intend to guide the design team, written by order of importance:

1. Air taxi - as the main aircraft purpose [1];
2. At least 2-passenger aircraft, if possible a 4-passenger, with respective cargo up to 10 kg each;
3. All-electric aircraft - to have zero operational emissions [1];
4. Power-train efficiency of, at least, 92% [1];
5. Energy costs account for 15% of the baseline direct operating costs, a maximum of 20%;
6. Thrust-to-Maximum Take-Off Weight (MTOW) of 1.15, at least [1];
7. Range of, at least, 200 km [1] - such value is slightly higher than twice the size of the longest trip showcased by Uber Elevate [1] (the longest trip being 83 km long). This choice is also based on two articles ([44] and [92]) of Bacchini and Cestino, from 2019, where it is stated that the current battery technology on the market allows for 200 km commutes [92][1];

[1] Tesla Model S has a well-functioning battery with an energy density of 160 Wh/kg ([1] and [93]).

8. Cruising speed of, at least, 275 km/h [1];
9. L/D of 15 for a cruising speed of 275 km/h [1];
10. Possibility of serving 5 trips of 40 km or 2 trips of 80 km on a single battery charge;
11. Include a 10-minutes emergency energy storage - according to MIT research such a reserve was used for a battery specific energy of 200 Wh/kg [94] for aircraft posing as UAM solutions. A jet fuel reserve for GA has to be able to provide 30 min cruise-reserve for day-time and 45 min for night-time ([95] and [96]). Given that GA has almost zero engine redundancy and that electric DEP adds a lot of redundancy, then a 10-minutes reserve may be considered reasonable;
12. At least, 90 minutes endurance to perform the mission;
13. Battery specific energy of 300 Wh/kg, see section 2.6.3.B, at the pack level [1];
14. Battery pack with, at least, 2000 life-cycles [1];
15. 80% maximum battery energy discharge limit [94];
16. Save, at least, 40% of time relative to the homologous ground-trip [1];
17. 3-minute riders loading and 2-minutes riders unloading, both considering riders cargo loading and unloading [1];
18. Fully Autonomous - to ease ATC [1], avoid fuel management errors [1], reduce the loss of control problems [1], have improved trajectory flight profiles [1], minimize any additional power required [1];
19. Use DEP technology - to increase propulsion redundancy [1] to achieve a fully digitally controlled fly-by-wire control system (once combined with autonomous flight) [1], to reduce the risk of auto-rotation [1] and ease manoeuvrability;
20. Use Automatic Ground Collision Avoidance System - to reduce collision risk [1];
21. Near 75-80 dB(A) at 50 ft or, equivalently, 62 dB L_{Amax} at 150 m distance [1] in hover;
22. 67 dB(A) at ground level from an aircraft at 250 ft altitude [1];
23. Do not exceed a maximum of 5% increase in the night-time awakenings - for short-term annoyance [1];
24. Do not increase more than 1dB in DNL - for the long-term annoyance, as it is the minimum variance for a human to detect [1];
25. A 100-times quieter than a helicopter [16];
26. Technology Readiness Level (TRL) of, at least 7, [97] for commercial availability in 2024;

27. 0.3 fatalities per 100 million passenger miles - 2-times better than a driving car and 4-times better than the current air-taxi solution, both values are referenced to 2016 [1];

28. Use a Ballistic Recovery System - a parachute to be deployed in case of emergency to safely land aircraft [1];

29. Accomplish aircraft availability of, at least, 3500 hours/year[2] and an expected maximum of 4700 hours/year[3];

30. A cost of 2.5 US$ per passenger-kilometer [8];

31. Depreciation cost of 10% of the baseline direct operating cost [1];

32. 20% of all flights are of dead-flights [1] - no revenue is expected from such flights as they serve to re-position aircraft to an area with more potential clients than where it was left;

33. Be available for, at least, 13 years of service - if used 2080 hours/year [1] for 640-thousand km yearly [1]

34. Salvation after 13 years of usage with 30% of residual value [1] - being about 20-times greater than a car [1];

35. The acquisition price of aircraft between 200-300k US$ [1];

36. Annual overhaul cost between 90-95k US$ for an airplane lifespan of 13 years [1].

At last, it is important to see these as guiding lines and goals to achieve rather than strict and exclusive factors as aircraft designers must bear it in mind throughout the whole designing process mentioned in section 3.1.

3.3 The Trade-offs

Whatever decision a person makes, it is all about trading, no matter what field it is. Aviation is full of trade-offs. The current section only reveals a few of the immense trade-offs. According to Dr. Raymer [98], an expert in aircraft design, when designing an aircraft it is better to rely on a high Aspect Ratio (AR) to improve aerodynamics and then decide on other characteristics. Finally, testing with computational models and scale models in small wind tunnels can help with trade-offs.

Trade-offs are presented and explained in numerous textbooks, articles or websites, references [98] and [89] explain most of them. For example, for the same wing area, the increase of the AR decreases induced drag increasing, in turn, Lift-to-Drag ratio (L/D) and potentially reducing the energy needs.

[2] Considering 11 hours availability window from Friday to Sunday and 9 hours from Monday to Thursday all year long, stopping 2 weeks [1] a year due to maintenance or bad weather purposes.

[3] Considering 14 hours availability window from Friday to Sunday and 13 hours from Monday to Thursday all year long, stopping 2 weeks [1] a year due to maintenance or bad weather purposes.

However, the mentioned increase of AR as disadvantages such as the increase of the root bending moment, correction of such negative effect implies adding-on structural weight.

The wing position - low, mid or high, on fixed-wing aircraft is of major importance when designing aircraft. Some state, that regarding aerodynamics, the location of the wing should be the first specification to be chosen [42]. Table A.1 enlightens the reader on the different wing configurations.

The method to produce lift may also be subjected to deep questioning as there are several ways to produce it: vectored thrust or tilt-wings, lift-plus-cruise, wingless (a type of multicopter) and rotor-craft. No one can say one is better than the other as it depends on perspectives and the end-mission of aircraft. Table 3.1 mentions the advantages and disadvantages of each configuration.

Table 3.1: Advantages and disadvantages of vectored thrust or tilt-wings, lift-plus-cruise, wingless and rotor-craft lift configurations [44].

Type of Lift	Advantages	Disadvantages
Vectored Thrust	- Rotating the propeller in hover avoids the impinging of the propeller slipstream on it [44]; - The lift produced by the wing is augmented, at high angles of attack, by the blowing effects of the propellers [44]; - Use duct fans which reduce blade tip loss while producing higher thrust for the rotor diameter [44]; - Use wings for an efficient cruise [44]; - Use the same propulsion system for both cruise and hover [44], meaning optimal propulsion weight.	- May suffer from control problems due to low-pitch control power [44]; - The loss of an engine may cause catastrophic roll upset [44]; - Use the same propulsion system for both cruise and hover [44] lacks safety redundancy in case of engine failure.
Lift-plus-Cruise	- Use wings for an efficient cruise [44], easing medium to long-range missions; - Use different engines for lift and cruise [44], adding safety redundancy; - Usually have a tail to provide more stability and increase range and payload [92]; - Sets a compromise between vectored thrust and wingless configurations [92].	- Use different engines for lift and cruise [44], adding dead weight to the propulsion system; - The tail adds on dead weight.
Wingless	- Large disk actuator surface makes it hover efficient [44]; - Suits short-range needs.	- Do not have wings for cruise efficient flight [44], only allows for short-range flights; - Control is similar to helicopters.
Rotor-craft	- Their behaviour is very well-known, reducing control risks.	- Noisier aircraft.

Bacchini and Cestino [44], published in 2019 a comparison of three aircraft configurations (vectored thrust, lift-plus-cruise and wingless) regarding the following five factors: disk loading, total hover time, cruise speed, practical range and flight time. These values used for comparison purposes were computed considering three reference missions, differentiating in the range: urban (7 km), extra-urban (30 km) and long-range (100 km). The main conclusion is that lift configuration is highly correlated to the aircraft's mission. The evidence points out that multicopter works best for hovering missions, vectored thrust is more cruise efficient and lift-plus-cruise is a compromise between the previous two. Another drawn conclusion from the same paper is that the aircraft studied with the vectored thrust lift configuration is, out of three cases, the most energy and time-efficient throughout the three different missions.

Bacchini and Cestino [92] state that aircraft designed for missions with a much shorter hover time than a cruise, should have the smallest vertical thrust area possible to reduce the drag produced by those surfaces during cruise flight. Furthermore, in such case, the wings of VTOL aircraft have to be sized and optimized for a cruise rather than takeoff and landing to have the smallest size possible [92].

3.4 Primary Conceptual values by assessing similar solutions

Using historical data is a common basis to design aircraft, however eVTOL industry is very recent and has not been on the market long enough to have historic data. The majority of current UAM solutions have not reached the market yet, hence few details are readily available for data compilation and analyses. Very few companies make their data publicly or provide it when asked by email so that their competition does not get a hold of their data. There is a common saying "secrecy is the core of business" however it can delay the fast development of technologies.

3.4.1 Assessing the Type of Propulsion

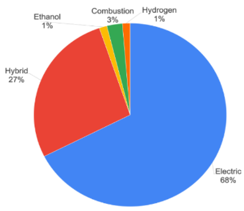


Figure 3.3: Energy source of 77 aircraft [99].

Figure 2.1 results from information made available to VFS to define a database [99] of the VTOL industry and all the analyses in the current research were made considering such database [99]. VFS also published a "Commercial Intra-city on-demand electric-VTOL status of Technology" [100], in January of 2018 in a partnership with NASA and the University of Maryland, showcasing 55 aircraft and some of their characteristics at the time of publishing. Worth of mentioning is that since January 2020 when the author of the current thesis first looked into such a database it has grown. As section 2.5 mentions, although there were, at the time of research, 263 registered aircraft on the database only 94 of them had useful information. At last, not all 94 aircraft had the same information, therefore the caption of figures

3.3 to 3.10 mention how many aircraft was used to build the respective figure. Also, the universe sample is adapted to fit all the choices up until the step before, when possible.

Analyzing figure 3.3, one states that the aircraft should be all-electric which follows as mentioned in section 2.6.4. One should think ahead of time as several countries across Europe are making big efforts to reduce or eliminate combustion engines cars in the city centers ([101], [102] and [103]), therefore any UAM solution to be applicable in major cities across Europe should follow the same path, towards a world of clean energy, at least from the operating point of view.

3.4.2 Assessing the Number of Passengers

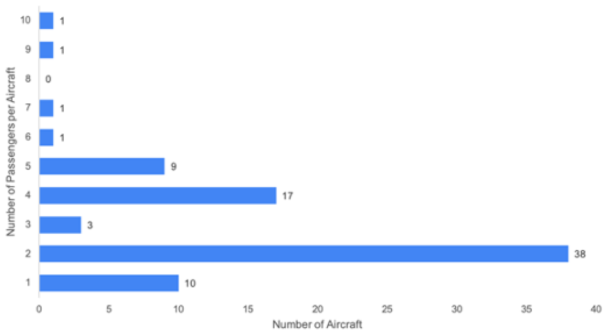


Figure 3.4: Number of passengers per aircraft, given data of 81 aircraft [99].

From figure 3.4, aircraft should have either 2 or 4 passenger seats. Considering the main purpose of this UAM is being an air-taxi, as mentioned in section 3.2, then it should have 4 passengers, the same as an Uber car on average [1]. From here forward it will be presented information regarding all-electric aircraft with 2 to 4 passenger seats with useful information, therefore the aircraft universe drops from 94 to 31.

3.4.3 Assessing Lift Configuration

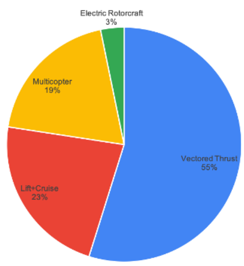


Figure 3.5: Type of lift used, given data of 31 aircraft [99].

Figure 2.1 uses data 262 aircraft and figure 3.5 was built considering four types of lift of all the

31 aircraft considered: vectored thrust, lift-plus-cruise, multicopter or wingless and rotor-craft. Local efficiency-focused people may jump to the statement that vectored thrust is the prime choice as it represents more than half of the population and, if given a second thought, they may lean to a lift-plus-cruise or multicopter lift consideration. Nevertheless, there are a lot of considerations to be made when choosing the lift consideration, for instance, due to mission profile, range, endurance and efficiency. The advantages and disadvantages of each lift configuration are presented in table 3.1.

The goal range of the UAM solution being designed, as mentioned in section 3.2, is closer to the long-range mission given the range distribution in section 3.3. Consequently, the UAM solution to be designed has a cruise focused mission, therefore the lift configuration should be either vectored thrust or lift-plus-cruise. Regarding the differences in those configurations, one choice needs to be made.

Studying the mission profile, presented in section 3.2, eases not only the analyses of the chosen range, endurance and cruise speed target values, mentioned in section 3.2 but also the lift configuration as it is highly related to the number of take-off and landings the aircraft is designed to withstand. Aircraft performing several take-offs and landings by mission requires better hover capacity without disregarding cruising capacity. Considering such aircraft perform extra to long-range missions (30 to 100 km respectively, see section 3.3), hence a lift-plus-cruise configuration seems to better fit the purpose of the UAM solution being designed.

There is no information regarding the mission profile of the 31 aircraft being studied, so it will be considered the case study by Uber Elevate [1]. Even though, Uber shows a clear desire to perform missions of 160 km [1] they also show a clear desire to have three hours endurance of smaller paths of 40 km [104]. Given the current UAM solution range is 200 km, as mentioned in section 3.2, split it into 40 km courses means 5 take-offs and landings each mission, on average. Therefore, the lift-plus-cruise configuration is the best lift configuration as it is a good compromise between hover and cruise aircraft capabilities.

3.4.4 Assessing if Piloted or Autonomous Aircraft

From the 94 relevant aircraft only 75 of those had information regarding the need or not for a pilot, 80% is said to either be autonomous or to be converted into autonomous. However, when comparing to the analysis of the same information but regarding only the electric aircraft for either 2 to 4 passengers that value raises to 90%. Consequently, the UAM solution being design should be autonomous, however, if the autonomous technology TRL [97] is 7 or lower than the design team should consider the possibility of having a pilot at first and then adapt the aircraft to autonomous flight once such technology has a higher TRL level. All in all, such a decision is related to the year of commercial release and it is 2024, as mentioned in section 3.2, as one needs to estimate the technology available at the time in future.

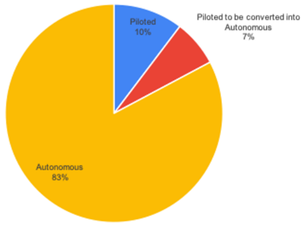


Figure 3.6: Assessment of autonomous flight in electric aircraft for either 2 to 4 passengers, given data of 29 aircraft [99].

3.4.5 Assessing Weight Ratios

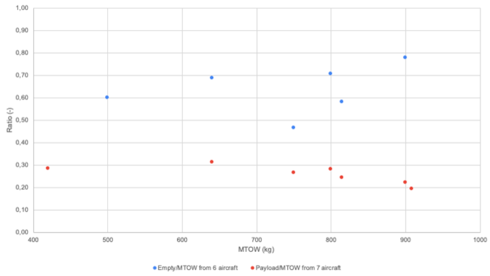


Figure 3.7: Assessment of autonomous flight in electric aircraft for either 2 to 4 passengers, given data of 7 aircraft for payload weight and 6 aircraft for empty weight [99].

Figure 3.7 analyses the empty-to-MTOW ratio[4] of 6 aircraft out of the reduced universe of 31 aircraft and analyses the payload-to-MTOW weight ratio of 7 aircraft from the same reduced universe. This is clear evidence of the lack of data share from companies that is understood given market competitiveness. Figure 3.7 shows the most likely weight distribution of aircraft (between MTOW, empty and payload weights) considering MTOW to be the highest weight and the reference value: 25% for payload, 60% for empty weight and the remaining 15% may be used for batteries or additional payload. It is important to reinforce the major importance of the battery-to-MTOW ratio as it strongly affects both range and hover aircraft capabilities [92]. This remaining 15% may be the outcome of differences between definitions across companies' weight definitions in the aircraft industry, for instance, confusion between gross weight with MTOW, net with empty weight and payload with cargo and crew weight. On the source of information, the term used was not explained especially for net versus empty weight and payload versus cargo weight, hence some errors may result from such vague use of terms. A non-established criterion in the electric aircraft industry is whether or not to consider batteries as part of empty weight. Given the batteries' weight not changing with time it should be considered an empty weight for operational reasons as the term payload usually accounts for all the weight of the components that may change each flight, such as jet-fuel, cargo, crew and passengers.

[4]The empty-to-MTOW ratio is also known as the structural factor.

3.4.6 Assessing Rotor-to-Motor Relation

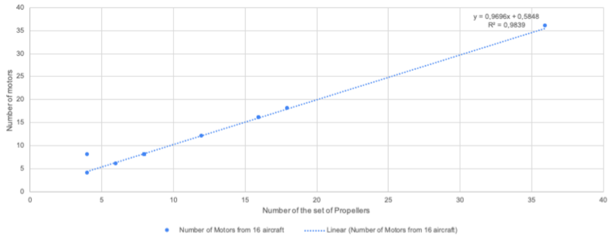


Figure 3.8: Assessment of number of motors needed for a set of propellers, given the data of 16 aircraft [99].

According to the figure 3.8, built from 16 aircraft out of the reduced universe of 31, 98% of the data agrees with a linear relationship of almost one-to-one between the number of the set of propellers and the number of motors present in each aircraft. Therefore, for each set of propellers demands its motor.

3.4.7 Estimating MTOW

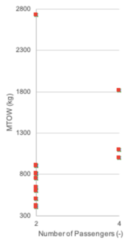


Figure 3.9: Assessment of the impact of the number of passengers in the MTOW, given the data of 11 aircraft for 2-passenger aircraft and 3 aircraft for 4-passenger aircraft [99].

Due to requirements presented in section 3.2 and because the aircraft may suit other purposes rather than being an air-taxi, the choice of designing a 4-passenger aircraft was made. The geometric weighted MTOW average is 1412 kg and the simple average of the 3 aircraft is 1305 kg. The three 4-passenger aircraft considered for the MTOW analyses were: Joby S4 from the company Joby Aviation with MTOW of 1815 kg, carrying 4 passengers and 1 pilot [20]; Bartini Flying Car from the company Bartini.Aero with MTOW of 1100 kg, carrying 2 to 4 passengers [105];and, EmbraerX DreamMaker from the company Embraer with MTOW of 1000 kg, carrying 4 passengers [106].

Both Joby Aviation and Bartini.Aero have unveiled much more information than Embraer, which may indicate their project is ahead of Embraer and that their data may be more solid. Hence, performing a weighted average seams fairer rather than a simple average reducing the risk of granting the same relevance to conceptual design and flight-tested prototype (Joby S4 [20] and Bartini Flying Car [107]). The author of the present thesis decided to give twice the importance to Joby S4 and Bartini Flying Car for the mentioned reasons, resulting in the following distribution o importance 45% to both tested vehicles and 10% for EmbraerX DreamMaker. The result of the weighted MTOW average is 1412 kg.

3.4.8 Assessing Range, Endurance and Cruise Speed

Figure 3.10 was obtained by arranging data of 21 out of 31 aircraft to study range relationship to cruising speed and 9 aircraft to evaluate the relation between cruising speed and endurance. Given the requirement of 200 km of range, mentioned in section 3.2, the cruise speed is calculated from the linear relation obtaining 288 km/h. Despite figure 3.10 showing a maximum endurance of 90 min and an average of 40 min, the author has decided to aim for the maximum endurance possible, considering that the aircraft used to build figure 3.10 have a battery specific energy much smaller than the one being used for the current UAM solution given the expected battery technology improvements [38].

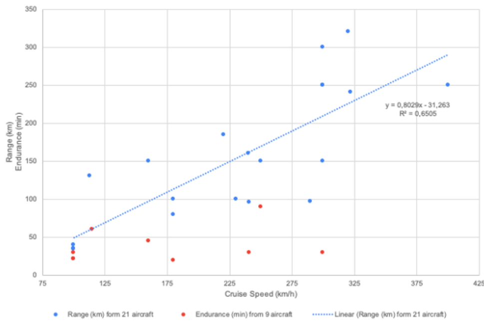


Figure 3.10: Assessment of the relationship of cruising speed of aircraft in their range, given the data of 21 aircraft, and their endurance, given the data of 9 aircraft [99].

3.4.9 Summarizing All Findings

All in all, the figures presented in the current section are a key part of the decision-making process of setting reasonable initial concept values of the UAM solution being designed in the current thesis: all-electric propulsion; 4-passenger of 80 kg each with cargo up to 10 kg each; lift-plus-Cruise configuration; fully-autonomous; empty-to-MTOW ratio around 0.6 (also known as structural weight); payload-to-MTOW ratio around 0.25; one motor for each set of propellers; MTOW of 1410 kg; range of 200 km; cruise Speed of 290 km/h, rather than the 275 km/h presented in section 3.2; endurance of 90 min; and, at least 40% faster than a ground-trip.

At this is stage is natural for the design team to have some sketches of the aircraft to be built like figure 3.11 showcasing several possibilities for exterior and interior design.

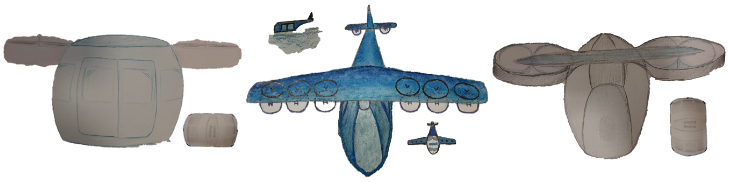


Figure 3.11: Conceptual sketches of the UAM solution, from left to right: multicopter, lift-plus-cruise, tilt rotor.

3.5 MTOW estimation by Several Methods

After assessing current UAM market solutions one needs to start choosing aerodynamic values, starting with AR, given Dr. Raymer beliefs presented in section 3.3. Given the choice of lift-plus-cruise configuration, explained in section 3.4. A design similar to GA would not come as shock given the extensive research and the years of perfecting such body form. Using the conventional GA body-frame still requires an aerodynamic study because using DEP combined with a lift-plus-cruise configuration is a synonym of having multiple sets of propellers in neutral mode during most of the aircraft mission profile which in turn will change the stream body of the aircraft. Also, using DEP will immensely change aircraft's control, therefore the designing team must consider it in their decisions.

3.5.1 MTOW with Dr. Raymer's estimation

Given the choice of a design similar to GA then performing Dr. Raymer weight assessment can be helpful [98]. Despite the used historical aircraft data being related to conventional propulsion (using jet-fuel and similar types of fuel) and conventional runway takeoff, Dr. Raymer analyses and estimation may still achieve good weight results. This section presents in detail the weight estimation following Dr. Raymer and then sums up all the other estimations (given their similarities to Dr. Raymer estimation) so that the current thesis does not become extensive. The method created by Dr. Raymer is thoroughly explained in the book entitled "Aircraft Design: a Conceptual Approach" [98].

Dr. Raymer [98] provides the estimate of the wetted-area ratio of 4, given the resemblance of the drawn UAM solution to the Cessna Skylane RG. The choice of a wetted-area ratio along with the AR produces a more reliable estimate of L/D [98], which is highly dependent on the wingspan and the wetted area. Hence, a new parameter comes up - the Wetted Aspect Ratio - resulting from the wingspan squared divided by the total aircraft wetted area [98].

The span of the aircraft was chosen considering the maximum space the aircraft might occupy when parked in an over-crowded city. The design team plans the aircraft may use from 2 to 3 car-parking spots, hence the wingspan is between 6 to 9 meters, which is acceptable for an aircraft of this size. After several iterations and more research, the decision of 9 meters for the primary wingspan was made. Dr. Raymer provides the first AR value of 7.5 [98]. The wing area is then calculated to be 10.8 m^2.

Choosing passengers' weight depends on the estimation of people's weight average on the locations of operation as the average weight of a person differs from country to country. Given this project followed FAA for reference values then following Federal Aviation Regulations (FAR) weight recommendation is acceptable. FAR Part 23 Section 25 states " Each seat occupied, assuming a weight of 170 pounds for each occupant for normal and commuter category airplanes" [96] which is equivalent to 77 kg, however, given the importance of this value for MTOW calculations, then raising the value to 80 kg seems fair. Also, such value is based on elevators designing companies that consider the weight per person to be between 75-80 kg [108]. Considering the aircraft to be fully-autonomous, then the crew weight is 0 kg.

Cargo weight was chosen according to cabin baggage weight limit of low-cost airlines of Europe, such as Transavia [109], Ryanair [110] and Easyjet [111], which set the weight limit between 10-15kg. Given the main purpose of the present UAM solution, then a cargo weight of 10 kg per passenger seems to suit the overall needs. Consequently, the maximum payload of the current UAM solution is 360 kg, resulting from the sum of the weight of 4 passengers and respective cargo.

Other aerodynamic values need to be given the first estimates. The zero-lift drag C_{D_0} is 0.0315 according to Snorri Gudmundsson [89] assuming the typical values for GA trainer. The lift-plus-cruise configuration usually allows for lower values of C_{D_0} and higher values of L/D, hence the chosen values are conservative regarding what some companies in the industry have been using.

To calculate the induced drag coefficient the design team uses the Oswald Span efficiency, which is usually some value from 0.7-0.85 [98]. According to a formula by Glauert and Weissinger presented by Dr. Raymer [98] considering sweep leading edge angle inferior to 30°and any aspect-ratio, the calculated Oswald efficiency is 0.825.

Then follows the estimation of propeller specific fuel consumption (C_{bhp}), needed for conventional fueled aircraft, like the ones assessed by Dr. Raymer presented method [98]. The value was calculated using Dr. Raymer formula considering the loiter movement of a piston-prop engine of variable-pitch and the propeller efficiency of 0.8 [98].

Dr. Raymer also provides the maximum L/D of 15 for cruise [98], which is retrieved from a graph using the wetted aspect ratio mentioned above and then the L/D for loiter of 13 considering Dr. Raymer formula for propelled propulsion.

Next follows a set of calculus to obtain the weight fraction for warm-up and takeoff, climb, landing, loiter and cruise first estimates considering Dr. Raymer's formulas [98]. Before, starting the iteration process one attains both the final weight fraction at the end of the mission and the ratio of fuel available at the end of the mission [98].

The iteration process requires several initial values, that are provided by Dr. Raymer [98] considering fixed sweep and an initial estimate for MTOW is 1410 kg as mentioned at the end of section 3.4. Given the ageing aircraft that made the statistical relations being used, Dr. Raymer suggests a decrease of 5%

in the empty-to-MTOW ratio to be updated to more recent air-frame materials such as composite [98]. The iteration process first uses equation 3.1 and then equation 3.2 and within 5 iterations the absolute error had 10^{-5} of magnitude.

$$\frac{W_{empty}}{\text{MTOW}} = A \times (\text{MTOW})^{\text{C}} \times K_{vs} \tag{3.1}$$

$$\text{MTOW} = \frac{W_{crew} + W_{payload}}{1 - \frac{W_{fuel}}{\text{MTOW}} - \frac{W_{empty}}{\text{MTOW}}} \tag{3.2}$$

3.5.2 Presenting MTOW estimations

All the methods used to obtain table 3.2 are referenced with the exception to the ”Logarithmic Regression of Conventional Aircraft Data” method that is made of conventional propulsion twin engine aircraft for 4 passengers data collected in November of 2019. Despite the value resulting from this method being 25% higher than the initial value it was still considered because it uses data of aircraft currently in the market and widely used.

Table 3.2: Presenting the results for the 6 methods used to estimate MTOW.

Dr. Raymer [98]	Dr. Raymer Adapted [112]	Snorri Gudmundsson [89]	Logarithmic Regression of Conventional Aircraft	Nicolai and Carichner [113]	UAM selection from section 3.4
1 423 kg	1 432 kg	1 256 kg	1 759 kg	1 323 kg	1 410 kg
Average MTOW considering all the values above					
1 434 kg					

The average value in table 3.2 is only 1.7% higher than the initial value of 1410 kg obtained in section 3.4. Nevertheless, the author decided to use an average weight of 1434 kg for the conceptual design.

3.6 Constraint Analyses

The importance of the mission profile has been stated several times throughout the present document. The mission profile aids in assessing cruise altitude, range and power needs. As mentioned in section 3.4, the current UAM solution being developed aims for trips of 30-100 km long and, as mentioned in section 3.2, the mission should be made of 5 trips or a cruise range of 200 km. However, mission energy requirements of 5 trips results in unbearably high energy needs, hence the designing team reduced the number of trips to 3. Consequently, the designing team conceived the following missions all at the same cruising speed:

- Mission 1 - 3 trips of 67 km each, ranging 200 km, at 500 m of cruise altitude;

- Mission 2 - 2 trips of 100 km each, ranging 200 km, at 1000 m of cruise altitude;
- Mission 3 - 1 trip of 60 min, at 500 m of cruise altitude;
- Mission 4 - the total range of 200 km, split into 5 trips, at 500 m of cruise altitude.

To estimate the battery system weight it was used the formula 3.3 by Bacchini and Cestino [92]. The battery specific energy density (E^*) of 300 Wh/kg as mention in section 2.6.3.B, a total propulsion efficiency (η_{total}) of 76% (electric motors pose an efficiency of around 95% [92] and the propellers' efficiency is around 80% [92]), g being the earth gravitational constant, R stands for range and MTOW of 1434 kg as stated explained in section 3.5.2. From the calculus results a first battery-to-MTOW ratio of 18%, such value would only be possible for a a battery density of 800 Wh/kg, which is extremely far from the used value.

$$R = E^* * \eta_{total} * \frac{1}{g} * \frac{L}{D} * \frac{W_{battery}}{\text{MTOW}} \tag{3.3}$$

Boarding and unloading times were defined considering the requirements presented in section 3.2. Given the main purpose of the current project, as mentioned in the requirements in section 3.2, the aircraft needs to operate smoothly so that passengers do not get airsick on-board. Hence, the chosen acceleration of 4 m/s^2 once it is the average acceleration in the car industry [114].

Table 3.3: Time split of a single trip for all missions.

Units	Part of the trip	Mission 1	Mission 2	Mission 3	Mission 4
min	t_boarding	3.0			
	t_TO	0.5			
	t_transition	0.5			
	t_acc	0.3			
	t_cruise	13.5	20.4	60.0	8.3
	t_deacc	0.3			
	t_transition	0.5			
	t_landing	0.5			
	t_unloading	2.0			
	t_total_trip	21	28	68	12

Given all the information already provided in the current section, the profile of all missions gained shape in figure 3.12.

The power estimation of each mission part needs to be calculated using equation 3.4 to 3.6 [56]. For board and unloading the aircraft does not use energy, takeoff and landing using equation 3.5, transition used equation 3.4 and acceleration, deceleration and cruise used equation 3.6. Remember that the cruising speed has been changed to 290 km/h and the vertical speed of 60 km/h was calculated according to the intention of climbing 500 meters in 30 seconds. The values of C_{d0} and σ were updated to match the values used at [63] and [56] and the k_i was updated to 1.016 [115] to match a 0.25 tapered

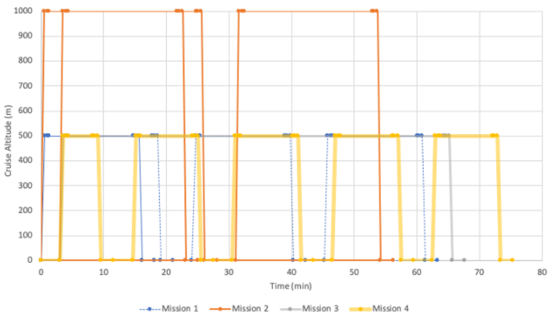


Figure 3.12: Mission profile presentation of four possible missions, given that total mission time and trip time are calculated considering boarding and unloading.

wing value.

$$P_{hover_{\text{OGE}}} = \sum_{j=1}^{NR} T_j \left[k_i \sqrt{\frac{DL}{2 * \rho}} + \frac{\rho V_{tip}^3}{DL} \left(\frac{\sigma C_{d0}}{8} \right) \right] \tag{3.4}$$

$$P_{hover_{climb}} = \sum_{j=1}^{NR} T_j \left[V_y - \frac{k_i}{2} V_y + \frac{k_i}{2} \sqrt{V_y^2 + \frac{2DL}{\rho}} + \frac{\rho V_{tip}^3}{DL} \left(\frac{\sigma C_{d0}}{8} \right) \right] \tag{3.5}$$

$$P_{cruise} = \frac{\text{MTOW} g V_{cruise}}{L/D \eta_{propeller}} \tag{3.6}$$

The design team has chosen to use propellers with rotors as their efficiency has been widely studied and improved through time, its current value is 82.3% [56]. To convert power into the Thrust (T)-to-MTOW force ratio the designed team used the much used formula 3.7. The rotors used have a Mach tip of 0.3 and a radius of 0.4 meters, following the same characteristics as Brown rotors [63]. Lift configuration uses 6 rotors and cruise configuration uses only 2 rotors, all in all the aircraft has 8 propellers.

$$\eta_{propeller} = \frac{T * V_{cruise}}{P} \tag{3.7}$$

Table 3.4: T-to-(MTOW*g) ratio of 3 mission profile stages: hover with OGE, hover in climb and in cruise flight.

	Units	Hover Out of Ground Effect (OGE)	Hover Climb	Cruise
$\frac{T}{\text{MTOW} * g}$	[-]=[N/N]	0.44	0.54	0.37
Power	kW	623	765	109

The following step is designing the power profile, as presented in figure 3.13 for each mission. To do so the team assesses the energy used through time without considering the battery discharge cycle being reduced to 80%, as mentioned in section 3.2. However, a 10-minute cruise reserve, as mentioned when describing requirements (see section 3.2) was considered and, according to calculations, it accounts for 18.2 kWh in each power profile.

As table 3.4 shows the hover OGE needs are 5.7-times higher than cruise needs and hover for climb and landing is 7.0-times higher than cruise as well. This gigantic difference in energy needs is what makes several aircraft companies and experts turn to hybrids, using batteries for take-off, landing and hover OGE and conventional jet-fueled propulsion for cruise, given it is the flight stage with less energy needs.

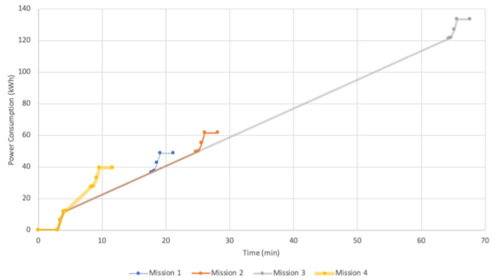


Figure 3.13: Power consumption by mission profile, excluding the 10-minute cruise reserve and considering 100% battery discharge. All missions are explained in the beginning of the current section and present several trips except mission 3, which is a single trip and uses a total of 133 kWh.

On the other hand, table 3.5 considered the 80% discharge rate, as seen in its line four. The same table also shows the needed battery-to-MTOW ratio, the range and duration of a single trip and the maximum range possible using all the power calculated for each mission but only performing one takeoff and landing.

Table 3.5: Power consumed each stage for all for mission. Both total mission and trip time are calculated considering boarding and unloading.

		Mission 1	Mission 2	Mission 3	Mission 4
P_H_OGE	kW	623			
P_cruise		109			
P_H_climb		765			
E_bat,r	-	20%			
n_ES		95%			
t-climb	min	3	2	1	5
t_hover_OGE		3	2	1	5
t_endurance		42	42	61	45
t_total-mission		63	56	68	75
t_reserve		10			
t_trip		21	28	68	12
E_battery/mission	kWh	217	186	199	283
E*_bat	Wh/kg	300			
W_battery	kg	722	619	665	944

W_battery/MTOW	-	50%	43%	46%	66%
Range using all the battery	km	327	263	290	459
Range/trip		67	100	290	40

Mass ratios for each mission profile were calculated, and presented in table 3.6, using battery weight as the starting point, calculated in table 3.5, and considering payload is the same for all missions. There is a clear need to enlighten the reader upon some weight definitions, hence the following explanation:

- Battery Weight - accounts solely for the battery packs weight and their implementation in the aircraft;
- Payload Weight - accounts for the weight that may change from flight to flight, if the UAM solution is used an air taxi then the passengers and their cargo are the sole contributors;
- Empty Weight - accounts for avionics, flight control systems, instrumentation, environmental control systems, furnishing, engine and batteries;
- Operating Weight - accounts for the minimum weight for aircraft to fly; for autonomous aircraft this is the sum of battery and empty weights, if not auto-piloted then the pilot weight must be added here;
- MTOW - it is the maximum weight for takeoff that aircraft are designed to operate, if they are all-electric aircraft then takeoff and landing weights are the same.

At the end of section 3.4, it was stated that the design team was aiming for an empty-to-MTOW of 60%, however, the definition of ”empty weight” was not clear at the time, as explained in the same section. The same section mentions 15% of unknown weight locations which, according to table 3.6 seems to be part of operational weight as, regardless of the mission profile, the operational-to-MTOW ratio is always 75% because the design team chose the payload of 360 kg to remain constant, which is equivalent to 25% of the MTOW.

Table 3.6: Weight ratio distribution according to the analysis of power consumption by each mission, considering an an MTOW of 1434 kg.

Ratio to MTOW	Units	Mission 1	Mission 2	Mission 3	Mission 4
W_battery	[-] = [kg/kg]	0.50	0.43	0.46	0.66
W_Payload		0.25			
W_(empty without batteries)		0.25	0.32	0.29	0.09
W_operational		0.75			

Mission 4 energy analyses show that the mission required by section 3.2 is inconceivable due to the massive battery weight needs. This results from the high number of takeoffs and landings rather than the time spent cruising. From table 3.5 it is clear the extremely high energy needs for takeoff, landing and hover. Both mission 2 and 3, on the other hand, are energetically conceivable and of lower energy need than mission 1. Thus, designing the aircraft for mission 1 allows completion of missions 2 and 3, as well, and provides a comfortable endurance of 60 minutes to a cruising speed of 290 km/h.

The design team must decide on a mission or combination of missions to proceed with calculations and further analyses. Mission 1 seems to be a righteous fit and is then decided to be used. If further analyses show unsatisfying results then the design team should use the present section to iterate. For example, a combination of missions 1, 2 and 3 may be thought as well as the increase of MTOW. Stability assessment is usually a game-changer in re-evaluating MTOW [98].

3.7 Choosing an Engine

Regardless of the type of combustion, the choice of an engine should be based on performance criteria and propeller requirements to create the needed thrust, power, Rotations Per Minute (RPM) and torque [116]. Despite those being the main parameters, there are others to be considered such as acquisition and maintenance cost, lifespan and efficiency.

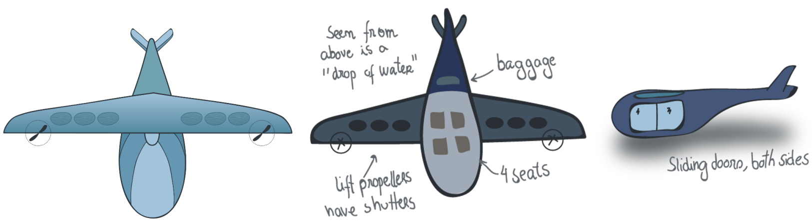


Figure 3.14: Iteration of the conceptual lift-plus-cruise configuration draw presented in the middle-figure 3.11. The autonomous aircraft has 6-lift rotors which dispose shutters to be closed during cruise, reducing considerably the associated drag; the aircraft has 2-cruise rotors. The image was drawn in using the program Adobe Illustrator.

The number of lift rotors choice presented in table 3.7 influences the aircraft's hover efficiency. Given the choice of 6 propellers for lift and the MTOW of 1434 kg then the disk loading is 475 kg/m^2. Consequently and using the power for hover OGE and climb presented in table 3.5, the hover efficiency for OGE is 2.3 kg/kW and for climb is 1.9 kg/kW. Historical data is used to compare the obtained values against some well known aircraft. The obtained values fall within the tilt-wing area of figure 3.15. The higher the number of lift rotors the higher the hover efficiency, however the current UAM solution is being design for both cruise and hover, preferably cruise, therefore the hover optimization is not the focus. The obtained value of disc loading, thus the choice of number of rotors was based on the equilibrium of engine power availability with hover efficiency. Consequently, the obtained values are neither "high disc loading and low hover efficiency" as direct lift aircraft (Maisel et al. [117]) nor "low disc loading and high hover efficiency" as helicopters (Maisel et al. [117]). According to Maisel et al. [117], disc loading selection is one of the challenges "The challenge of finding an aircraft type that meets both the hover and cruise mode performance criteria, while also meeting other operational, economic, and environmental requirements was the major task encountered by the developers of VTOL technology."

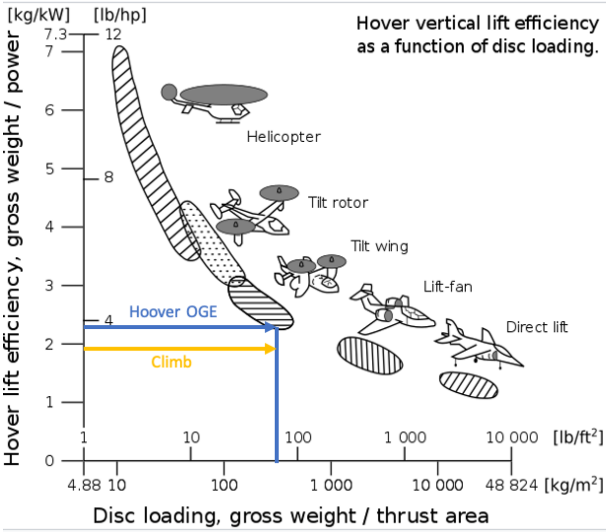


Figure 3.15: Assessing UAM solution hover efficiency using the historical data of Maisel et al. [117]. In blue is the value for hover OGE and in yellow for climb.

From the conceptual sketches presented in figure 3.11, the center sketch is the only one presenting a lift-plus-cruise configuration. Such sketch is now displayed in figure 3.14 hosting some differences after careful reading of expertise literature, assessing the market [118] and trading off on the analyses in section 3.6. Figure 3.14 displays 6 propellers to lift and 2 propellers to cruise and, as presented by figure 3.8 each set of propellers has its motor, hence 6 electric engines are needed. The chosen propeller is the "Ultra Prop II" made of solid carbon fiber composite costing 350 US$ each mounting set and weighing 2.7 kg [119], which amounts to a total cost of 2800 US$ and total weight of 21.6 kg. The lift rotors dispose shutters to be closed during cruise flight, reducing considerably the associated drag. Table 3.7 presents the needs of power by the motor by stage flight.

Table 3.7: The number of engines to be used in each stage of flight and power need by each engine.

Stage of Flight	Number of Motors	Power/motor [kW]
P_H_climb	6	127.5
P_H_OGE		103.5
P_cruise	2	54.5

As mentioned several times through the current document, propulsion is set to be all-electric. Electric motors can either be Alternate Current (AC) or Direct Current (DC), DC motors are said to be lighter [116] than AC motors. In the aircraft industry weight is a major player therefore DC motors are the choice solely based on weight. Anyhow, both AC and DC need additional components to operate: AC needs an AC-DC converter and the DC needs a medium voltage controller [116]. From the several types of existing DC motors, the Brushless Direct Current (BLDC) motor seems to suit the needs accordingly. After looking into several electric motors available in the market ([120], [121], [122] and [123]) a comparison was made considering continuous and peak power, as well as respective Power-to-Drag ratio (P/W), engine net weight and cost, as presented in table 3.8.

Table 3.8: Electric engines specifications from Freerchobby [121]. Though the featured engines do have fulfill the exact needs, the industry estimations point to the development of the costumed-made engines by companies such as Magnax [123].

Engine	Continuous		Maximum		Torque	Net Weight	Price	Thrust
	Power/Weight	Power	Power/Weight	Power				
	[kW/kg]	[kW]	[kW/kg]	[kW]	[Nm]	[kg]	US$	[kg]
MP154120	3.0	18	6.7	40	-	6	835	85
MP240150	3.1	50	6.3	100	180	16	3400	230
MP240100	3.0	40	6.0	80	130	13	2300	200

One factor the design team may consider is the business model of aircraft construction. The author considers it valuable to have all the engines produced by the same company, despite the different energy needs showcased in table 3.7, because when placing massive orders it is more likely to achieve a higher discount on the overall contract. That is the reason table 3.8 only presents engines of the same company. Other companies were looked into, however, Freerchobby [121] presented the best overall fit.

Given the values presented in table 3.7, the best choice is having all engines the same, despite the cruise energy need being substantially lower than the other stage flights. Electric engine industry estimations point into costumed-made engines, hence once the project enters the physical prototyping stage, then a new market search is needed to assess the best choice. Hence, the current UAM solution which has 8 engines of the model MP240150 - 6 engines for lift and 2 engines of for cruise - with a total cost of 27 200 US$ and a total engine net weight of 128 kg.

Finally, the engines need a cooling system to maintain the best operation at all times. Given the main purpose of the current UAM proposal presented in section 3.2, an air cooling system is adequate with the upside of being the simplest of the cooling systems, the cheapest, lightest and the easiest to maintain.

3.8 Battery Selection

Redundancy is a major player throughout the whole designing process, but overdoing it may be prejudicial to the aircraft as a whole. With eVTOL betting on redundancy in the engine, a battery pack selection is a golden rule for safety reasons given it is an opportunity to provide extra energy. According to research [116], the designing team may expect a battery efficiency of around 96%.

An important feature of all-electric aircraft powered by batteries is not having weight variations from take-off to landing, therefore there is no need to release fuel for emergency landings like conventional aircraft have to because their maximum landing weight is much smaller than the MTOW.

Battery-powered aircraft need both a Battery Management System (BMS) and a battery thermal management system. The BMS built-in the propulsion system architecture is used to control and register voltage, current, temperature, SOC amongst others [88]. The battery thermal management system is used to regulate the temperature of the battery module with the help of a built-in cooler or heater. Li-ion batteries' performance is highly dependent on the temperature of operation, hence batteries should be kept within a range of temperatures. The present solution is to be operated any city worldwide then the fluid should be able to generate heat and cold, therefore the water-cooling/heating system is implemented due to its high specific heat capacity.

However a single battery cell is not yet enough to power the aircraft, therefore the need of table B.1 that presents the calculation of a battery cell and a battery pack having the fuel cell Panasonic NCR18650GA [124] as the starting point to achieve a battery pack with a specific energy density of 300 Wh/kg as requested in section 3.2, using the method thoroughly explained at [125].

The results from table B.1 indicate that it is likely the battery pack will be made of 14 580 battery cells occupying around 0.256 m^3, each one costing 3.99 US$ [126] (unit price lowers for orders bigger than 1 000 battery cells) resulting in a battery pack cost of 58 175 US$ resulting in 269 US$ per kWh. If there are any space restrictions the battery pack can be properly disassembled into smaller modules. According to Uber [1] and Brown and Harris [63], batteries are expected to hold 2 000 cycles, as mentioned in section 3.2, therefore the same is applied to these batteries[5].

The expected acquisition price of aircraft is presented in table 4.10. The cost of the aircraft's propulsion system, considering engines (see section 3.7), propellers (see section 3.7) and batteries, is 88 175 US$ and accounts for 11% of the total acquisition price estimation (around 830k US$ to be presented in section 4.3.1). The weight of the propulsion system is 871 kg, around 61% of the MTOW. Consequently, 61% of the aircraft weight accounts for only 11% of the acquisition price.

A study using a battery density of 400 Wh/kg is presented in appendix C.

3.9 Aircraft Initial Measures Assessment

The computational model presented by figure 3.17 was calculated using both Snorri Gudmundsson [89] and Dr. Raymer [98] methods. The design team, as well as both methods mentioned, state that the process of assessing aircraft measures is as much science as art. Trade-offs, mentioned in section 3.3, play a great deal in balancing science and design. In the end, a design must be visually appealing to be

[5]The battery was calculated in such a way that each battery cycle allows the completion of one mission profile.

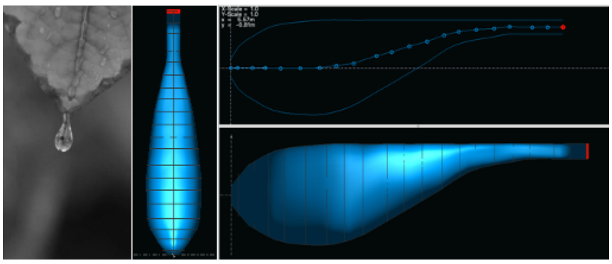


Figure 3.16: Comparing the aircraft's body, from xflr5 [127] to a drop of water falling. The author of the current thesis owns the image rights of the image of the drop of water.

easily accepted, efficient for the lowest operational cost allowing maximization of profit, safe to protect the cargo and adaptable to the ever-changing aircraft industry.

Firstly, all calculations were made considering a conventional t-tail, as close to the middle solution of figure 3.11 as possible. Secondly, the model was tested using xflr5 software [127]. After assessing the resulting values, the airplane was modelled, starting by perfecting the body of the fuselage to resemble a drop of water, given such shape being the ”Holy Grail” regarding aerodynamics. A comparison is presented in figure 3.16.

At this point, the design team has tried some tail configurations using the software xflr5 [127]. After computational calculations of a V-tail, using equation 3.8 by Dr. Corke ([128] and [129]) to calculate the dihedral angle, as shown in figure 3.17, a v-tail configuration was chosen because it obtained similar values to the conventional T-tail. The decision of V-tail was aesthetics and increased stability based, given the results of V-tail and t-tail configurations being similar according to xflr5 software [127].

Dr. Corke ([128] uses the dimensions of vertical and horizontal tail areas, 1.98 m^2 and 3.38 m^2, respectively, obtained following the method presented by Snorri Gudmundsson [89] with the assumptions of table 3.9. Applying equation 3.8 the dihedral angle obtained is 71 degrees, making the aircraft too unstable, hence the value was decreased to a more stable; good results were obtained at 45 degrees.

$$\phi = \left(180 - \arctan\left(\sqrt{\frac{Area_{Vertical}}{Area_{Horizontal}}}\right)_{tail}\right)/2 \tag{3.8}$$

Table 3.9: Values used to achieve the mentioned tail areas using the method presented by Snorri Gudmundsson [89]. To state that the presented values are the result of several iterations

Element	Vertical Tail	Horizontal Tail
Aspect Ratio	1	3
Taper Ratio	0.90	0.45
Span Efficiency	1.06	0.97
Volume Coefficient	0.07	0.80

Table 3.10 only showcases the final measures of the wing and the adapted V-tail shape. Despite Dr. Corke ([128] and [129]) stating that the v-tail surface area should be the sum of both vertical and horizontal areas, such value is too high. Hence the aircraft testing using xflr5 [127] started at that value and decreased up to the value presented in table 3.10 always considering the trade-off of lift, drag and stability.

Table 3.10: Aircraft generic measures, calculated using methods from [89] and [98], used to create the computational model presented in figures 3.14 and 3.17. For V-tail it was also considered [130] and Dr. Corke ([128] and [129]).

Specification	Units	Wing	V-tail
Surface Area (S)	[m^2]	10.8	3.4
Span (b)	[m]	9	3
AR	[-]	7.5	3
Taper ratio	[-]	0.25	0.45
Root's chord	[m]	1.92	1.45
Tip's chord	[m]	0.48	0.66
Average chord	[m]	1.20	1.06
Mean Aerodynamic Chord (MAC)	[m]	1.34	1.11
Sweep root-to-tip angle	[º]	-5	-7
Sweep at quarter of the chord angle	[º]	17	17
Tip twist angle	[º]	3	0
Dihedral angle	[º]	5	45

Table 3.11 and 3.12 reveal the position of the main elements of the aircraft and the main measures of both the aircraft and cabin, respectively. The values presented in the mentioned tables result from several iterations using program xflr5 [127].

Table 3.11: Main reference measures of the aircraft with the referential position on its nose.

	Position of the elements [m]		
Aircraft Part	x	y	z
Nose	0.00	0.00	0.00
Wing - start	1.14	0.00	0.90
Tail - start	4.70	0.00	0.90

Table 3.12: General aircraft and cabin measures.

	Units	Length	Width	Height
Overall	[m]	6.13	9.00	2.72
Cabin	[m]	1.60	1.40	1.76

At last, the resulting computational model obtained from xflr5 [127] is showcased in figure 3.17. If further analyses shows reduced overall efficiency due to engines close alignment, then a high T-tail may be considered again, therefore increasing the misalignment, reducing the associated drag and increasing the overall efficiency.

3.10 Weight Distribution

Estimating the overall weights of the airplane is made by the historic-based formulas of Dr. Raymer [98]. The weight of the vertical and horizontal tail was summed to obtain v-shape tail weight. The weight of the main and nose landing gears was also summed once it is planned to have landing gear similar to helicopters, along the body.

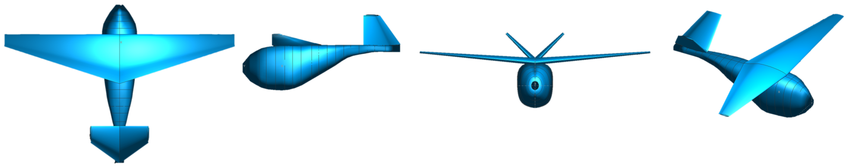


Figure 3.17: A computational model of the UAM solution being designed was obtained using xflr5 software [127]. From left to right, the figure presents the top, side, front and iso aircraft views.

Table 3.13 presents the results of such a method after applying a correction factor to all values calculated using Dr. Raymer's method so that the propulsion-to-MTOW[6] and payload-to-MTOW ratios were kept unchanged as presented at the end of section 3.6. The resulting values are very low for some aircraft parts, so here is stated the need to maybe review aircraft's MTOW considering some aircraft elements have very low weight available, but only after the stability analyses is done. Other hypothesis is increasing the battery energy density considered as once it increases less battery weight is needed and the weight difference can be distributed to other aircraft elements. Rising the battery density from 300 to 400 Wh/kg provides substantial differences, as table C.2 shows.

Table 3.13: Total weight distribution according to Dr. Raymer historic-based formulas [98] but with a correction factor to suit the weight ratio decision made at the end of section 3.6.

Part of the Aircraft	[kg]	Part of the Aircraft	[kg]
Wing	14.2	Hydraulics	0.3
V-Tail	3.8	Electrical	63.9
Fuselage	44.3	Avionics	43.3
Landing Gear	9.3	Air conditioning & Anti-ice	10.6
Batteries & Engine & Propellers	871.5	Furnishings	11.5
Flight Controls	1.3	Payload	360.0
Total [kg]			
1434.0			

3.11 Stability Analysis

Using xflr5 [127] to introduce the results from section 3.5.2 to section 3.10 it is possible to assess the aerodynamic viability of the current UAM solution being developed as figure 3.19 showcases. Though

[6]The propulsion-to-MTOW considers the weight of batteries, electric engines and propellers and their mounting parts.

the results presented are better than the theoretical values considered, the rotors and their alignment influence have not been considered, therefore these results lack accuracy. Using the wing loading formula to calculate stall speed [56] and using the air density at 500 m above sea level, lift coefficient of 0.5 (from figure 3.19) and a wing loading of 1302 N/m^2, then the calculated stall speed is 130 kts, above the minimum certifying speed of 65 kts [56] and 17% inferior relative to the cruise speed of 157 kts (290 km/h).

Using the weights from table 3.13 and equation 3.9 it is possible to assess the Static Margin (SM) as presented in figure 3.18.

$$\text{SM} = \frac{x_{Neutral\ Point} - x_{Center\ of\ Gravity}}{\text{MAC}} \tag{3.9}$$

The considerations for such calculations are: each passenger weights 80 kg and carries a cargo of 10 kg; passengers are divided on the x-axis (longitudinal) in groups of 2, hence, from no passengers to full capacity there are only 9 seat configurations (in reality, there is 2 seats in the front row and 2 seats in the back row); cargo is always carried inside the luggage cabin behind the passengers' cabin; are divided into four packs all placed under the passengers' cabin; engines weights are placed in the wings and elevators; and landing gear was placed bellow the passengers' cabin.

Figure 3.18 reveals a minimum static margin of 6.6% when there are only 2 passengers in the back row and the highest of 18.5% when there are only 2 passengers in the front row. The static margin for empty flight is 9.7% and MTOW flight is 14.7%. According to Professor Vural [131], a static margin should range from 5-15% regarding MAC[7]. Visual observation of figure 3.18 shows some values outside such range but most of them fall within. Though it seams the aircraft may be manoeuvrable, more accurate computational calculations are needed to support such statement.

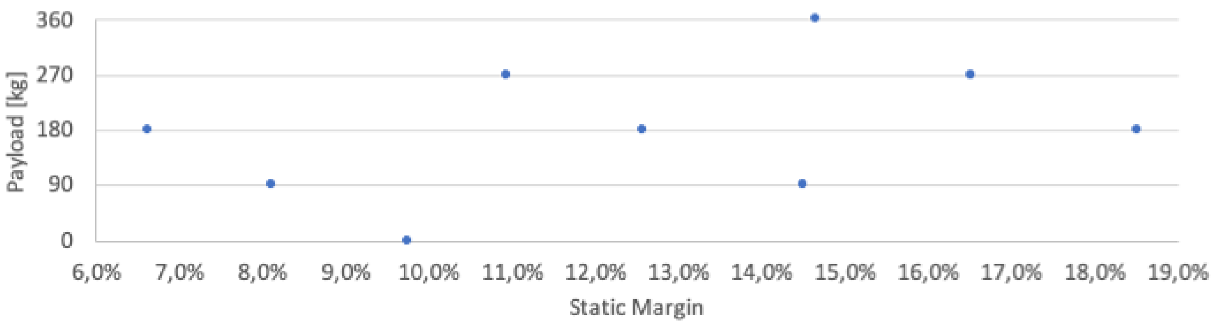


Figure 3.18: Range of static margin form computational results using xflr5 [127].

Lateral stability is to be made using the several rotors available at all time. By adjusting the speed of each rotor independently it is possible to induce yaw, roll and pitch, though with pitch is more difficult

[7] A considerable part of the aircraft industry does not agree to what value, or range of values, of the static margin indicate good longitudinal stability.

to do so. Varying the dihedral angle of the v-tail also helps with lateral stability ([132], [133] and [134]), though this also influences longitudinal stability, therefore the static margin will also change - this is another trade-off. This theory needs to be tested using computational programs.

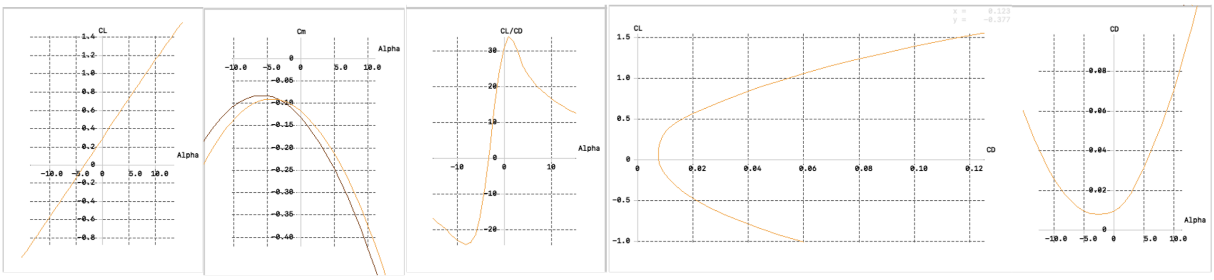


Figure 3.19: The computational results obtained using xflr5 [127]. The light color is the empty airplane and the darkened color is the MTOW, when only one color is visible it means they perfectly match. From left to right, the y and x axis represent: lift coefficient versus angle of attack alpha; pitch moment coefficient versus angle of attack alpha; L/D coefficient versus angle of attack alpha; total drag coefficient versus angle of attack alpha and lift coefficient versus drag coefficient.

4

Brief Aeroacoustic, Environmental and Cost Analyses

4.1 Aeroacoustic Analyses

4.1.1 Aeroacoustics Model

Current VTOL vehicles most used as a UAM solution are helicopters and they come as loud as they get. According to Brown and Harris [63] from MIT, the prime sources of noise in a helicopter, by decreasing order of importance, are blade slap, piston-engine exhaust noise, tail-rotor rotational noise, main-rotor vortex noise, main-rotor rotational noise, gearbox noise and turbine engine noise. However, the method presented here only considers the noise generated by the rotors neglecting all the other sources as it follows the methodology proposed and explained by Brown and Harris [63] and Afonso et al. [56].

According to Johnson [135], considering the rotor noise as impulsive, rotational and vortex by increasing frequency is acceptable. Johnson [135] also states that though a rotational noise usually leads to the highest Sound Pressure Level (SPL) of the sound spectrum, conventional helicopters have rotational noise at such low frequencies that may even be bellow the human hearing range. According to Afonso et al. [56], UAM solutions usually display rotors considerably smaller than helicopters, hence UAM rotors work at frequencies higher than helicopters becoming a considerable noise source. Afonso et al. [56] also states that impulsive noise (also known as blade slap phenomenon) is generated when propeller blades enter stall due to the shock waves formation or the blade-vortex interactions become strong enough. Brown and Harris [63] explain that such penalties can be mitigated by proper airfoil blade design with lowest Mach number at the tip blade (usually ranging from 0.3-0.5, the design team chose 0.3) and by applying the adequate flight procedures. Hence, impulsive noise is neglected. According to Johnson [135], vortex noise (as known as broadband noise) results from the interaction between turbulent flow and fluctuations loads on the blades and occurs at high frequencies.

All in all, the aeroacoustics model presented by Afonso et al. [56] and Brown and Harris [63] only considers two semi-empirical models: rotational noise (by Gutin [136] and Deming [137]) and vortex noise (by Schlegel et al.[138] and Marte and Kurtz [139]). These two contributions are summed up in a logarithmic scale.

4.1.2 Aeroacoustics Results Discussion

Following the method presented by Brown and Harris [63] and Afonso et al. [56] and using the values from table 4.1 as input, the aeroacoustic model estimates 80.6 dB SPL for an observer at a distance of 500 ft.

Table 4.1: Inputs used in the aeroacoustics model.

Rotor Radius	0,4	[m]
Rotor solidity ([56], [63])	0.2	[-]
Mach at Blade Tip ([56], [63])	0.3	[-]
Thickness-to-Chord Ratio ([56], [63])	0.12	[-]
Lift Number of Rotors	6	[-]
Number of blades per rotor	2	[-]

Noise estimations using the aeroacoustics model mentioned are presented in table 4.2. The rotational noise estimations were made for hover OGE flight considering an observer at a distance of 250 ft, 500 ft and 1635 ft (or 500 m), the first two being from Uber [1] and from requirement section 3.2 and the third being the cruise altitude. The overall noise estimation results are as follows for an observer at: 250 ft 86.1 dB SPL; 500 ft 80.1 dB SPL and 1635 ft 69.8 dB SPL.

Given the resulting noise estimations using the aeroacoustics model mentioned were not as good as expected. Hence the performance of a sensibility analyses, which results are as follows: reducing hover OGE power needs by 100 kW, adding one lift rotor and increasing the radius in 0.05 m all have approximately the same positive effect of reducing noise by 1.0 dB SPL, 0.7 dB SPL and 1.0 dB SPL, respectively; using 3 blades rather than 2 blades per rotor causes a decrease of 5.5 dB SPL. Due to the high variation of noise due to the increase of the number of blades per rotor and that doing so does not influence any other field of the current project, the design team has decided to use a 3-blade rotor rather than a 2-blade rotor. Noise estimation of the aircraft is as follows in table 4.2. The aircraft design presented in figure 3.14 is then updated in figure 4.1 (in the end of the current section).

Table 4.2: Noise estimation of a 3-blade rotor from the aeroacoustics model and comparison to daily activities.

Altitude ft	Noise dB SPL	Comparison [140]	[141]	[142]
250	80.6	Alarm clock	Vacuum cleaner	Garbage disposal and city traffic noise
500	74.6	Dishwasher / Toilet flushing	Halfway between busy traffic and vacuum cleaner	Dishwasher

1635	64.3	Halfway between conversational speech and Air conditioner	Halfway between normal conversation and busy traffic	Laughter

The estimations show that though Uber [1] and project (section 3.2) requirements are not met, they are very close to being achieved for an observer at 500 ft.

The noise estimation for an observer at 250 ft may provoke hearing damage if the exposure is much higher than 16 hours [143] and, according to Zhang [141], the observer at a distance of 500 ft and 1635 ft from the aircraft does not suffer from hearing impairment as the noise estimation is considered to be ”moderate to quiet”.

The peak frequency obtained is 544 Hz which falls into the category of mid-range frequencies [144]. The human ear is, on average, capable of hearing frequencies ranging 20-20,000 Hz and is usually more sensible to high frequencies. Once a prototype is done, several experiments must be done to assess the presented values.

Though these results present themselves as plausible, it is important to mention they are not obtained testing a prototype and that the method uses historical data of helicopters. According to the Helicopter Association International, helicopter noise perception ranges from 87-78 dB when in heights from 500-1000 ft [145], which is the same as standing next to a working Washing machine [142] to riding the subway or a motorcycle [142]. Comparing to those values, the range of decibels SPL of 74.6-68.6 obtained for the current solution, from the altitude range of 500-1000 ft respectively, is appealing and seem to be harmless [146].

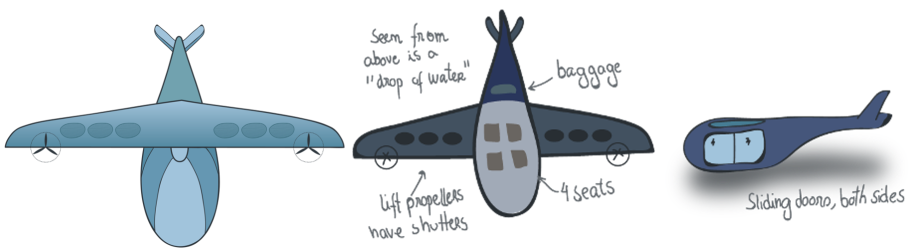


Figure 4.1: Iteration of the conceptual lift-plus-cruise configuration draw presented in the figure 3.14. The autonomous aircraft has 6-lift rotors dispose shutters to be closed during cruise, reducing considerably the associated drag; the aircraft has 2-cruise rotors, each rotor has 3 blades. The image was drawn in using the program Adobe Illustrator.

4.2 Environmental Analyses

4.2.1 Pollutant Emissions Assessment Method

Operational pollutant equivalent carbon dioxide emissions are zero because the aircraft is all-electric, however there are pollutant emissions in several regarding several aircraft elements. Afonso et al. [56]

and Brown and Harris [63] thoroughly explain the method used by the design team to assess the equivalent tonnes of pollutant carbon dioxide emissions of the solution being developed, considering both production and End of Life (EOL) of the used batteries as well as the energy used to recharge throughout their whole lifetime, considering the battery holds 2000 cycles[1].

According to Afonso et al. [56], methane and dinitrogen monoxide are also contributors to the greenhouse effect and are expressed as kg CO_2eq through characterization factors assessing their relative impact to climate change. The environmental impact estimation presented as follows is assessed using a metric for Global Warming Potential (GWP) of the Life Cycle Assessment (LCA), the kilogram of carbon dioxide equivalent per functional unit (kgCO_2eq), as stated by Afonso et al. [56]. The most extensively used metric is GWP, being mentioned in most of the LCA articles and papers, to address the carbon foot-printing [147].

Equation 4.1 follows the methodology presented by Afonso et.al [56] which computed the GWP through the "ReCiPe Midpoint/Endpoint (H) V1.11 / Europe Recipe H method with the support of LCA software (SimaPro) and the Eco Invent database". The production and EOL of the battery emission constant values are in accordance to Zackrisson et al. [53] and presented in table 4.3.

$$\begin{aligned} Emissions_{total} &= Emission_{Production} + Emission_{Battery\ Use} + Emission_{\text{EOL}} \\ &= \frac{Energy_{battery}}{1000} * [Battery_{Production} + Electric_{mix} * N_{cycles} + Battery_{EOL}] \end{aligned} \tag{4.1}$$

4.2.2 Environmental Results Discussion

Applying the explained method to the mission and battery needs presented in table 3.5 results in the equivalent pollutant carbon dioxide emissions are presented in table 4.3.

Table 4.3: On the left, input constant values to the method explained in the current section. On the right, pollutant emissions results from the method explained in the current section.

Input Constants			Emissions Results		
Electric mix [148]	13[2]	gCO_2eq/(kW.h)	Production & EOL	5.633	tons CO_2eq
Battery Production	148480 [3]	gCO_2eq/(kW.h)	Battery Lifetime	32.190	tons CO_2eq
Battery EOL [53]	97	gCO_2eq/(kW.h)	Total	37.82	tons CO_2eq

In the end, this means the emission of 87 gCO_2eq/(kWh). Hence one trip of mission 1, as mentioned in table 3.5, emits to the atmosphere around 6.3 kgCO_2eq, as shown in table 4.4. Considering mission 1 lasts for 63 min plus the 10-minute reserve, as stated in table 3.5, thus follows a pollutants emission of 15.5 kg CO_2/h.

[1] In reality, there are no operational emissions given the aircraft is fully electric.

[2] The method used considered the electricity mix of 13 gCO_2eq/kWh [148] from Sweden in 2016, which may be considered a highly optimistic value considering the European average of 296 gCO_2eq/kWh [148] by 2016. Nevertheless, the aircraft is due to 2024, hence the global European is expected to dramatically decrease given all the investments being made into greener energies.

[3] Resulting from an average of the values presented by Zackrisson et al. [149].

Table 4.4: Emissions results obtained following the method explained in the current section. All values include the 10-minute energy reserve.

Energy Mission1	217	kWh	Energy of 1 trip of Mission 1	72	kWh
Total emissions per Mission 1	18.9	kg CO_2eq	Emission/trip_of_mission 1	6.3	kgCO_2eq
Emission/kWh			87		gCO_2eq/(kW.h)

These pollutant emissions result 85% from the energy used to recharge batteries, hence this ”operational emission” may be reduced to approximately zero if the batteries are charged with totally green electricity instead of electricity produced by transforming fossil fuel.

The widely used Cessna 172 Skyhawk, which is a 4-seat aircraft, is part of the GA family and it is estimated to emit around 75 kgCO_2/h [150]. The UAM solution is a 79% decrease in CO_2eq when compared to Cessna 172 Skyhawk. Despite being theoretical, this result leads the reader to believe the current UAM solution being developed pollutes much less than the homologous solution presented by the conventional GA industry. Nevertheless, further assessment is needed to validate the presented data and confirm these estimations. Also, the industry is still in need of further assessment of the life-cycle of Li-ion batteries because it is still not clear if the zero operational emissions that they allow overcomes their heavily polluting production processes.

4.3 Cost Analyses

4.3.1 Yearly Costs Breakdown

There are several methods to estimate operational cost, each with their own benefits and disadvantages. The author of the current thesis decided to articulate several methods: Brown and Harris [63], Snorri Gudmundsson [89] and Ploetner et al. [151]) and showcase the results in table 4.10. Brown and Harris [63] consider the deadhead mission (mission without payload to relocate aircraft), Snorri Gudmundsson [89] is made for conventional GA and Ploetner et al. [151] is electric-powered focused. The resulting method accounts with the following costs: Airframe and Powerplant (AP) maintenance, storage and operation at vertiport, command controller, energy, insurance, overhaul and airplane investment as presented in equation 4.2. The costs considered are based on the heavily studied costs of GA.

$$\begin{aligned} C_{total} = C_{\text{AP}} + C_{Storage} + C_{Command\ Controller} + C_{Energy} \\ + C_{Insurance} + C_{Overhaul} + C_{Investment} \end{aligned} \tag{4.2}$$

Energy costs are of major importance and are highly related with the results of table 3.5. Charging times used for energy cost calculations considered Tesla V3 Supercharger, commercially available since 2019, because it provides a peak power rate of 250 kW per car ([152], [153] and [154]) resulting in the charging times presented as follows.

Follows an enlightenment to better understand the missions presented in section 3.6:

- Mission 1 - Considering MTOW of 1434 kg and a mission energy need of 217 kWh, then follows a 63-minute mission split into 3 trips, each with 67 km. The battery charging time for Mission 1 is 58 minutes. This represents a charging-to-flight time ratio of 82%, therefore, for every minute of flight the aircraft has to stop 50 seconds to charge.
- Mission Deadhead - Without any payload and zero time for boarding and unloading and a mission energy need of 118 kWh, then follows a 28-minute mission split into 3 trips, each with 33 km. The battery charging time for Mission Deadhead is 28 minutes. This represents a charging-to-flight time ratio of 100%, therefore, for every minute of flight the aircraft has to stop one minute to charge.

The daily flight window considered is from midnight to 7 a.m. considering in such window that the aircraft does not fly for 1.7 hours because there are no clientele. This means the operational costs model analyses does not consider the case of the maximum daily operations possible. Regardless of the number of missions to be performed each day of the week, two of them are always deadhead missions. Also, from Friday to Sunday there is one more mission than from Monday to Thursday, as there is usually more Uber rides during the weekends. The yearlong operation is possible because the aircraft is autonomous, hence, the cost model only accounts for 3 weeks a year of non-operation for maintenance purposes as seen in table 4.5.

Table 4.5: Daily and yearly flight time estimation.

Daily Flight Estimation		
Number of Daily deadhead missions	[-]	2
Daily missions including charging (Friday to Sunday)	[-]	9
Daily missions including charging(Monday to Thursday)	[-]	8
Maximum missions 1 a day	[-]	12
Number of Yearly Missions	[missions/year]	2891
Hours available/day considering only flights from 7am to midnight	[hours/day]	17.0
No flight time/day	[hours/day]	1.7
Yearly Flight Hours		
Daily Flight hours from Friday to Sunday	[h]	8
Daily Flight hours from Monday to Thursday	[h]	7
Flight Hours by year	[h/year]	2652
Daily Charging hours from Friday to Sunday	[h]	7
Daily Charging hours from Monday to Thursday	[h]	6
Charging Hours by year	[h/year]	2233
Weeks/year	[Weeks/year]	52
Weeks/year without Flying	[Weeks/year]	3
Charging to Flight hours ratio	[-]	84%

With the hours of aircraft usage presented in table 4.5 and the charging and mission times explained above, it is possible to estimate the the cost of all the energy being used to charge the aircraft using equation 4.3 that considers the different energy needs of mission 1 and deadhead mission. The results are displayed in table 4.6.

$$\frac{C_{Energy}}{year} = \frac{\$}{kWh}\frac{Weeks}{year} \Big[(Days * Number_{Mission_1})_{Friday\ to\ Sunday}\, Energy_{Mission_1} + (Days * Number_{Mission_1})_{Monday\ to\ Thursday}\, Energy_{Mission_1} + (Days * Number_{Mission_{Deadhead}})_{Weekly}\, Energy_{Mission_{Deadhead}}\Big] \tag{4.3}$$

Table 4.6: Energy cost estimation of the aircraft.

Cost of Energy		
Hours of charging by year	[h/year]	2233
Average Price of Electricity [155]	[$/kWh]	0.13
Yearly Energy Cost	[$/year]	$ 73 642

The acquisition price of the aircraft was calculated using the empty weight cost approximation of 772 $/kg [63], given the empty weight of the current project being 1 074 kg then the overall cost of the aircraft is estimated to be 828 686 US$. The designing team considered the payment of the aircraft in 10 years with an interest rate of 7.5% [156] to estimate the acquisition cost as seen in table 4.7. The acquisition price of the aircraft is around 2.8 times the highest expected value mentioned in section 3.2.

Table 4.7: Breakdown of the acquisition cost.

Cost of Airplane Acquisition Investment		
Interest Yearly Rate [156]	[-]	7.5%
Number of Years	[-]	10
Yearly Investment Cost	[$/year]	$ 120 728

Insurance cost was firstly calculated considering the value provided by an Insurance provider in Portugal and compared to a simple relation of insurance cost to aircraft acquisition price, which is about 2.3%. Snorri Gudmundsson [89] only insures 1.5% of the aircraft, such value is for GA commonly used aircraft. Given the higher risk associated to the implementation of new technologies, this percentage should be higher, the author decided upon 2.5% and used the formulation of Snorri Gudmundsson [89] as follows in equation 4.4. Such equation considers the fixed price of 500 US$ to begin with. In the end, the yearly insurance cost of each aircraft amounts to 21 217 $.

$$C_{Insurance} = 500 + 0.025 * C_{Acquisition} \tag{4.4}$$

Following the method presented by Snorri Gudmundsson [89] the cost of AP can be estimated using equation 4.5 and the results presented in table 4.8. The cost of a battery pack is 58 175 US$ as explained in section 3.8 where is stated that each battery cycle suits the needs of one complete mission 1. For redundancy purposes, the calculation of AP costs considered that the completion of a deadhead mission uses a full cycle as well. The maintenance man-hours per flight hour (MF) considered was 0.6 in accordance to Brown and Harris [63], though the author believes it is conservative.

$$C_{\text{AP}} = MF * \frac{Man \; \$}{h} \frac{hours \; of \; flight}{year} + \frac{Missions_{yearly}}{Battery \; Life \; Cycle} \frac{\$}{Battery \; Pack} \tag{4.5}$$

Table 4.8: Cost estimation of AP using Snorri Gudmundsson method [89]

Cost of Airframe and Powerplant (AP)		
Maintenance man-hours per flight hour (MF) [63]	[-]	0.6
Hourly rate for a certified AP mechanic [63]	[$/h]	60
Battery Life - Number of Cycle [63]	[-]	2000
Hours of flight by year	[h/year]	2652
Yearly Cost of Airframe and Powerplant	[$/year]	$ 179 558

The estimation of a command and controller pilot cost to be sat at the vertiport controlling 8 aircraft, according to Brown and Harris [63], was done following equation 4.6 and presented in table

$$\begin{aligned}\frac{C_{Command+Controller}}{year} = \frac{Man_{hour} \; \$}{kWh} \frac{Weeks}{year} & \Big[(Days * Number_{Mission_1})_{Friday \; to \; Sunday} Hour_{Mission_1} \\ & + (Days * Number_{Mission_1})_{Monday \; to \; Thursday} Hour_{Mission_1} \\ & + (Days * Number_{Mission_{Deadhead}})_{Weekly} Hour_{Mission_{Deadhead}} \Big]\end{aligned} \tag{4.6}$$

Table 4.9: Estimation of command and controller cost per aircraft yearly.

Cost of Command Controller		
Number of aircraft per controller [63]	[-]	8
Salary of Controller [63]	[$/hour]	$ 70
Yearly Cost of Command Center per aircraft	[$/year]	$ 23 204

Storage costs consider 86 000 US$ yearly for a place in a vertiport, according to Uber [1], including lease fees, maintenance, security personnel and support. The overhaul yearly cost of 90 000 US$ considered is in accordance with Uber [1].

4.3.2 Yearly Costs Summarized and Discussion

Finally, all the costs are summarized in table 4.10 where it is showcased the operational hourly cost of 224 US$ and stated that for each minute of flight the aircraft needs to charge for 50 seconds.

Table 4.10: Subtotals of the yearly costs considered as well as overall charging to flight time ratio and hourly operational cost.

Acquisition Airplane Value	$ 828 686	
Yearly Cost Breakdown		
Cost of Air-frame and Power-plant (AP)	$ 179 558	30%
Cost of Airplane Acquisition Investment	$ 120 728	20%
Cost of Overhaul	$ 90 000	15%
Cost of Storage	$ 86 000	14%
Cost of Energy	$ 73 642	12%
Cost of Command Controller	$ 23 204	4%
Cost of Insurance	$ 21 217	4%
Total Yearly Cost	$ 594 350	100%
Charging Hours Yearly	2233	
Operating Hours Yearly	2652	
Charging to Flight hours ratio	84%	
Hourly Operational Cost	$ 224	

Figure 4.2 shows the distribution of costs resulting from the model used. Energy accounts for 12% being lower than value of 15% set in the requirements in section 3.2. The cost of AP is high because the aircraft needs 1.4 battery pack renovation each year, meaning having to pay for an entire pack at least once a year (7 battery packs every 5 years). AP, energy and command controller are highly dependant hours of operation a year, therefore, if increasing or decreasing the hours of operation these costs will also increase or decrease, respectively.

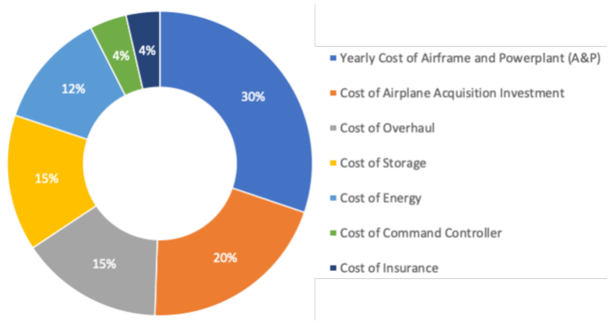


Figure 4.2: Operational costs distribution resulting from the calculations presented in table 4.10

In section 3.6 it was chosen to design the battery to suit mission 1 needs, given mission 1 and 2 could be achieved as well as. Hence, table 4.11, presents the cost of each trip per hour and per kilometer. A 21-minute 67 km trip of mission 1 costs 79 US$, with an equivalent 1.18 $/km and the higher the range the lower the price. This results from the fact that mission 2 and 3 have higher range due to lower number of takeoffs and climbing.

Table 4.11: Price per trip and equivalent price per km according to trip range.

		Mission 1	Mission 2	Mission 3
Time of Trip	[min]	21	28	68
Time Trip Cost	[$/trip]	$ 79	$ 105	$ 253
Range of trip	[km]	67	100	290
Price per kilometer	[$/km]	$ 1.18	$ 1.05	$ 0.87

There was an utter care in the formulation of the problem and as well as with the values considered in the model. Considering the cost of 224 US$/hour the base value of the following results are a comparison to such case:

- using the maintenance man-hour ratio of 3.5 commonly used for helicopters [157], then the operational costs is 398 US$/hour, representing an increase of 78%;
- using the maintenance man-hour ratio of 0.2, resulting from Snorri Gudmundsson [89], then the operational costs is 200 US$/hour, representing a decrease of 11%;
- temoving the 1.7 hours daily ban, explained above, the operation costs are reduced to 211 US$/hour, representing a decrease of 6%;
- keeping operation 24h/day, the operation cost is 177 US$/hour, representing a decrease of 21%;
- a piloted version of the aircraft would make the costs increase by 27%.

Comparing the results to Uber desired estimated pricing for initial operation in San Francisco, Sao Paulo and New Dehli [1], though Uber does not clearly defines ”initial” operation window, there is a profit margin of 25% for all cities, as shown in table 4.12. Uber desires to operate UAM vehicles by 2023 [1] and the current solution would only be made available in 2024, as mentioned in section 2.6.4, therefore it may not included in the initial period of operation. The reader is led to believe the current UAM solution being developed is either commercially viable or that Uber may need to lower their estimated pricing estimation.

Table 4.12: Margin of profit estimation when compared to Uber initial estimated pricing [1].

City	Uber Elevate Trip Initial Estimated Pricing [1]	Uber Trip [km] [1]	UAM solution by $/km	Margin of Profit
San Francisco	$ 129	80	$ 95	26%
Sao Paulo	$ 153	95	$ 112	27%
New Delhi	$ 37	23	$ 27	27%

5

Concluding Remarks

5.1 Conclusion

After conducting an extensive and thorough UAM market analyses, an all-electric lift-plus-cruise solution is presented with an MTOW of 1434 kg as part of a conceptual project.

All in all, the overall results point to solutions like the one proposed by the current document as the way forward. Nevertheless, there are a few important considerations before stating without a doubt that electric vehicles are viable. Firstly, the battery-to-MTOW ratio is much higher than initially estimated resulting in inaccurate weight distribution, therefore it would be better to consider an energy density 400 Wh/kg rather than the used 300 Wh/gh which is in accordance with Moore and Fredericks [36] estimations. The design team is in need of a structural study to better estimate body weight and assess structural safety. At last, further aerodynamic, stability and noise studies are also needed, which are the next steps when designing an aircraft.

The design team chose an all-electric aircraft regardless the fact that hover OGE and climb power needs being 5.7-times and 7.0-times higher than cruise energy needs, respectively. Therefore, hybrid aircraft, using batteries for take-off, landing and hover OGE and conventional jet-fueled propulsion for cruise, given it is the flight stage with less energy needs. Despite, those energy needs, the energy costs are much lower than using all-conventional jet fueled GA aircraft.

Overall, the designed aircraft may not be possibly available by 2024, given the most likely case scenario of having to change the battery energy density as mentioned above, as it is a key element throughout the whole project. Battery energy density influences battery needs to comply with the required mission profile which, in turn, influences the cost assessment because it controls the number of missions possible in one day and influences environmental. The operational carbon dioxide emissions can be reduced in 85% if using green energy to recharge batteries or else the aircraft presents a 79% lower operational emissions when compared to a homologous conventional solution. The presented solution is also quieter than helicopters. When heard at a distance of 500 ft, the helicopter may be felt like standing next to a lawnmower, on the other hand the current solution feels like standing next to a working dishwasher. The main setback is the fact that there is no certification for fully autonomous aircraft, reducing the TRL of the aircraft, hence it would need to be adapted to be initially piloted if to be sold in 2024 and the operational costs would increase due to the cost of pilot.

5.2 Future Work

Extensive data validation and verification are needed via computational programs to analyze the aerodynamic shape, including rotors, define all systems locations and weights to further study of lateral and longitudinal stability and structural viability. Only afterwards would scale prototypes testing begin.

As battery technology develops, the energy density of battery packs increases. The future is not necessarily in Li-ion batteries, but any source of energy cleaner than fossil fuels. Running all-electric vehicles does not produce operational emissions but the energy used to charge the batteries needs to be clean otherwise there is still consumption of fossil fuels. Further study is needed to fully understand the environmental impact of electric vehicles life-cycle and to compare results with conventional combustion vehicles. The automotive industry has a major role has it already has several electric and hybrid cars on the road for several years.

The aircraft industry should design a scale and regulations for manned autonomous aircraft similar to the car industry so that companies can compare and assess their true technology state of art, thus better TRL assessment.

Bibliography

[1] J. Holden and N. Goel, "Fast-Forwarding to a Future of On-Demand Urban Air Transportation," 10 2016. [Online]. Available: http://inrix.com/scorecard/

[2] "UAM Insight: 23 January 2020: $1B Investment in UAM Already in 2020 ≫ AirInsight," accessed: 2020-01-31. [Online]. Available: https://airinsight.com/uam-insight-23-january-2020-1b-investment-in-uam-already-in-2020/

[3] "eVTOL Aircraft Directory," accessed: 2020-09-09. [Online]. Available: https://evtol.news/aircraft

[4] F. Colucci, "Turning Volts to VTOL," *Vertiflite*, p. 4, 1 2018.

[5] "EHang EHang Conducts First-Ever U.S. Trial Flight of Pilotless Air Taxi at North Carolina Transportation Summit," accessed: 2020-08-01. [Online]. Available: https://www.ehang.com/news/605.html

[6] C. Baraniuk, "The largest electric plane ever to fly," accessed: 2020-06-18. [Online]. Available: https://www.bbc.com/future/article/20200617-the-largest-electric-plane-ever-to-fly

[7] D. P. Thipphavong and et al., "Urban Air Mobility Airspace Integration Concepts and Considerations," in *2018 Aviation Technology, Integration, and Operations Conference*, Atlanta, Georgia, 6 2018.

[8] "The Future of Transportation: White Paper on Urban Air Mobility Systems by EHang," accessed: 2020-02-28. [Online]. Available: https://bit.ly/38EVbFL

[9] "Electric planes are the future of aviation, but they haven't taken off - Business Insider," accessed: 2020-07-28. [Online]. Available: https://www.businessinsider.com/electric-planes-future-of-aviation-problems-regulations-2020-3

[10] "Low-cost helicopters, a growing transport segment in Sao Paulo — Business — English edition — Agencia EFE," accessed: 2020-08-09. [Online]. Available: https://www.efe.com/efe/english/business/low-cost-helicopters-a-growing-transport-segment-in-sao-paulo/50000265-3414571

[11] “São Paulo: the world’s biggest helicopter fleet Latin America Bureau,” accessed: 2020-03-17. [Online]. Available: https://lab.org.uk/sao-paulo-the-worlds-biggest-helicopter-fleet/

[12] “Quarterly Shipments and Billings – GAMA,” accessed: 2020-05-30. [Online]. Available: https://gama.aero/facts-and-statistics/quarterly-shipments-and-billings/

[13] J. Wood, “Top 10 causes of fatal GA accidents,” 6 2019, accessed: 2020-03-30. [Online]. Available: https://generalaviationnews.com/2019/06/24/top-10-causes-of-fatal-ga-accidents/

[14] “Zee.Aero,” accessed: 2020-03-13. [Online]. Available: https://www.crunchbase.com/organization/zee-aero

[15] “Flyer by Kitty Hawk,” accessed: 2020-03-20. [Online]. Available: https://flyer.aero/

[16] A. J. Hawkins, “Kitty Hawk says its third electric aircraft has a 100-mile range,” 10 2019, accessed: 2020-04-1. [Online]. Available: https://www.theverge.com/2019/10/3/20897336/kitty-hawk-electric-aircraft-heaviside-mile-range-flight-time-google-larry-page

[17] “Kitty Hawk,” accessed: 2020-03-20. [Online]. Available: https://kittyhawk.aero/

[18] G. Martin, “Toyota Invests $394 Million in Electric Air Taxi Company Joby Aviation,” accessed: 2020-04-20. [Online]. Available: https://www.forbes.com/sites/grantmartin/2020/01/18/toyota-invests-590-million-in-electric-air-taxi-company-joby-aviation/

[19] “Joby Aviation raises $590M for electric air taxi,” accessed: 2020-01-31. [Online]. Available: https://www.phocuswire.com/joby-aviation-raises-590-million

[20] “Joby S4,” accessed: 2020-03-20. [Online]. Available: https://evtol.news/joby-s4/

[21] “Joby Aviation,” accessed: 2020-04-01. [Online]. Available: https://www.jobyaviation.com/

[22] “Uber and Joby Aviation announce aerial ridesharing partnership,” accessed: 2020-03-14. [Online]. Available: https://evtol.news/news/uber-and-joby-aviation-announce-aerial-ridesharing-partnership

[23] F. Colucci, “Given advances in power generation, storage and control, Distributed Electric Propulsion opens new design opportunities for vertical flight.” vol. 62, no. 6, p. 5, 2016.

[24] “Siemens sells electric aircraft-propulsion business to Rolls-Royce,” accessed: 2020-03-10. [Online]. Available: https://press.siemens.com/global/en/pressrelease/siemens-sells-electric-aircraft-propulsion-business-rolls-royce

[25] H. Portugal, "Hyundai e Uber anunciam parceria de ridesharing aéreo," accessed: 2020-01-31. [Online]. Available: https://www.hyundai.pt/hyundai-e-uber-anunciam-parceria-de-ridesharing-aereo/

[26] C. Rocha, "Uber escolhe Melbourne para testar serviço de táxi-aéreo," 6 2019. [Online]. Available: https://insider.dn.pt/noticias/uber-escolhe-melbourne-para-testar-servico-de-taxi-aereo/19440/

[27] "Uber Elevate Network Partners," accessed: 2020-03-31. [Online]. Available: https://www.uber.com/in/en/elevate/partners/

[28] "Volocopter First eVTOL Startup to Receive Design Organisation Approval by EASA," accessed: 2020-03-01. [Online]. Available: https://press.volocopter.com/index.php/volocopter-first-evtol-startup-to-receive-design-organisation-approval-by-easa

[29] C. Rocha, "Táxi aéreo da Volocopter recebe financiamento da Daimler e da Geely," 9 2019. [Online]. Available: https://insider.dn.pt/noticias/taxi-aereo-da-volocopter-recebe-financiamento-da-daimler-e-da-geely/21631/

[30] "Japan's Roadmap for Flying Cars - IEEE Spectrum," accessed: 2020-02-20. [Online]. Available: https://spectrum.ieee.org/cars-that-think/transportation/alternative-transportation/japan-wont-be-grounded-when-it-comes-to-flying-cars

[31] "Public-Private Conference for Future Air Mobility to be Established," accessed: 2020-03-20. [Online]. Available: https://www.meti.go.jp/english/press/2018/0824_001.html

[32] A. Sinkevicius and et al., "Flying Cars: Investment Implications of Autonomous Urban Air Mobility," 2018, accessed: 2020-04-17. [Online]. Available: https://www.reportsearcher.com/detail/1948036

[33] "TomTom Traffic Index," accessed: 2020-03-15. [Online]. Available: https://www.tomtom.com/en_gb/traffic-index/

[34] "Traffic congestion ranking TomTom Traffic Index," accessed: 2020-03-15. [Online]. Available: https://www.tomtom.com/en_gb/traffic-index/ranking/

[35] Booz, Allen, and Hamilton, "UAM Market Study - Technical Out Brief," accessed: 2020-08-13. [Online]. Available: https://ntrs.nasa.gov/citations/20190000517

[36] M. D. Moore, "Misconceptions of Electric Aircraft and their Emerging Aviation Markets," in *52nd Aerospace Sciences Meeting*, National Harbor, Maryland, 1 2014.

[37] "Electric Airplanes Need Better Batteries—Which Should Arrive in 30 Years — WIRED," accessed: 2020-07-31. [Online]. Available: https://www.wired.com/2017/05/electric-airplanes-2/

[38] W. Cao, J. Zhang, and H. Li, “Batteries with high theoretical energy densities,” *Energy Storage Materials*, vol. 26, pp. 46–55, 4 2020.

[39] “Rapid charging at a Tesla EV ”Supercharge” station,” 1 2013, accessed: 2020-06-14. [Online]. Available: https://www.consumerreports.org/cro/news/2013/01/rapid-charging-at-a-tesla-ev-supercharge-station/index.htm

[40] “[Siemens eAircraft] - Fly it before you build it with Simcenter - YouTube,” accessed: 2020-07-21. [Online]. Available: https://www.youtube.com/watch?v=T2g1iIvBzXM

[41] “Harbour Air and magniX Announce Successful Flight of World’s First Commercial Electric Airplane,” accessed: 2020-07-21. [Online]. Available: https://www.prnewswire.com/il/news-releases/harbour-air-and-magnix-announce-successful-flight-of-worlds-first-commercial-electric-airplane-300972566.html

[42] L. R. Jenkinson, P. Simpkin, and D. Rhodes, *Civil jet aircraft design*. American Insitute of Aeronautics and Astronautics, 1999.

[43] “Lithium-Ion Battery Clean Energy Institute,” accessed: 2020-07-29. [Online]. Available: https://www.cei.washington.edu/education/science-of-solar/battery-technology/

[44] A. Bacchini and E. Cestino, “Electric VTOL Configurations Comparison,” *Aerospace*, vol. 6, no. 3, p. 26, 2 2019.

[45] leehamcoeu, “Bjorn’s Corner: Why e in ePlane shall stand for environment, not electric. Part 1.” 12 2019, accessed: 2020-01-30. [Online]. Available: https://leehamnews.com/2019/12/13/bjorns-corner-why-e-in-eplane-shall-stand-for-environment-not-electric-part-1/

[46] K. Zhu and et al., “How Far Away Are Lithium-Sulfur Batteries From Commercialization?” *Frontiers in Energy Research*, vol. 7, no. 123, p. 123, 11 2019. [Online]. Available: https://www.frontiersin.org/article/10.3389/fenrg.2019.00123/full

[47] “OXIS Energy Li-S Cells: Almost At 500 Wh/kg, New Target 600 Wh/kg,” accessed: 2020-09-10. [Online]. Available: https://insideevs.com/news/394309/oxis-cells-almost-500-wh-kg/

[48] “Energy, Batteries, and Secondary Use,” accessed: 2020-07-29. [Online]. Available: https://mdmurbach.github.io/cei-demo-tutorial/index.html

[49] leehamcoeu, “Bjorn’s Corner: Why e in ePlane shall stand for environment, Part 2.” 12 2019, accessed: 2020-01-30. [Online]. Available: https://leehamnews.com/2019/12/20/bjorns-corner-why-e-in-eplane-shall-stand-for-environment-part-2/

[50] "Module 6 - Battery - Drona Aviation," accessed: 2020-09-09. [Online]. Available: https://www.dronaaviation.com/learn-module-6-battery/

[51] "Lithium battery reusing and recycling: A circular economy insight," accessed: 2020-07-30. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6582158/

[52] D. Kushnir and B. Sandén, "The time dimension and lithium resource constraints for electric vehicles," *Resources Policy*, vol. 37, pp. 93–103, 2012.

[53] M. Zackrisson and et al., "Life cycle assessment of lithium-air battery cells," *Journal of Cleaner Production*, 6 2016.

[54] "A Guide to Understanding Battery Specifications," *MIT Electric Vehicle Team*, 12 2008.

[55] F. Anton and et al., "Siemens eAircraft - Disrupting the way you will fly!" accessed: 2020-05-02. [Online]. Available: https://bit.ly/37TD0g9

[56] F. Afonso, A. Ferreira, I. Ribeiro, F. Lau, and A. Suleman, "On the design of environmentally sustainable aircraft for urban air mobility," submitted to Transportation Research Part D: Transport and Environment, 2020.

[57] R. H. Jansen, C. Bowman, A. Jankovsky, R. Dyson, and J. L. Felder, "Overview of NASA Electrified Aircraft Propulsion Research for Large Subsonic Transports." [Online]. Available: https://ntrs.nasa.gov/search.jsp?R=20180000361

[58] "Magnus eFusion Light Sport Aircraft - Aerospace Technology," accessed: 2020-07-31. [Online]. Available: https://www.aerospace-technology.com/projects/magnus-efusion-light-sport-aircraft/

[59] "Extra 330LE Electric Aircraft - Aerospace Technology," accessed: 2020-07-31. [Online]. Available: https://www.aerospace-technology.com/projects/extra-330le-electric-aircraft/

[60] "GAMA PUBLICATION NO. 16-HYBRID & ELECTRIC PROPULSION PERFORMANCE MEASUREMENT," accessed: 2020-04-26. [Online]. Available: https://gama.aero/facts-and-statistics/consensus-standards/publications/gama-and-industry-technical-publications-and-specifications/

[61] "Federal Aviation Administration International Aircraft Systems Fire Protection Working Group Fuel Cell Industry Working Group Updates," accessed: 2020-04-15. [Online]. Available: http://www.fire.tc.faa.gov

[62] "HyPoint," accessed: 2020-07-28. [Online]. Available: https://hypoint.us/

[63] A. Brown and W. Harris, "A Vehicle Design and Optimization Model for On-Demand Aviation," in *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Kissimmee, Florida, 1 2018.

[64] "Reduce noise with electric propulsion - technical comparison - YouTube," accessed: 2020-07-31. [Online]. Available: https://www.youtube.com/watch?v=WylLWeDtPy0&index=7&t=0s&list=PLw7lLwXw4H53YUddJ99vzOVFgn-o4f17U

[65] J. Hupe and et al., "ICAO - Environment - 2013 Environmental Report - Destination Green," accessed: 2020-05-02. [Online]. Available: https://cfapp.icao.int/environmental-report-2013/files/assets/basic-html/index.html#1

[66] A.-W. Schãfer and et al., "Technological, economic and environmental prospects of all-electric aircraft," *Nature Energy*, pp. 160–166, 4 2019.

[67] M. Fu and et al., "Exploring preferences for transportation modes in an urban air mobility environment: Munich case study," *Transportation Research Record*, pp. 427–442, 10 2019.

[68] P. D. Vascik and et al., "Analysis of urban air mobility operational constraints,," *Journal of Air Transportation 26*, pp. 133–146, 4 2018.

[69] H. Eißfeldt, "Sustainable urban air mobility supported with participatory noise sensing," *Sustainability*, 4 2020.

[70] N. André and M. Hajek, "Robust Environmental Life Cycle Assessment of Electric VTOL Concepts for Urban Air Mobility," in *AIAA Aviation 2019 Forum*, Dallas, Texas, 6 2019.

[71] "A Short History of Unmanned Aerial Vehicles (UAV) - Consortiq," accessed: 2020-08-16. [Online]. Available: https://consortiq.com/short-history-unmanned-aerial-vehicles-uavs/

[72] "Cessna autônomo decola, voa e pousa sozinho," accessed: 2020-09-01. [Online]. Available: https://olhardigital.com.br/carros-e-tecnologia/video/cessna-autonomo-decola-voa-e-pousa-sozinho/105995

[73] "The 5 Levels of Autonomous Vehicles - TrueCar Blog," accessed: 2020-08-15. [Online]. Available: https://www.truecar.com/blog/5-levels-autonomous-vehicles/

[74] "The 6 levels of autonomous driving, explained as fast as possible," accessed: 2020-08-15. [Online]. Available: https://thenextweb.com/shift/2020/02/27/6-levels-autonomous-self-driving-explained-tesla-waymo-autopilot/

[75] "ICAO Standards Holding Position Markings and Mandatory Instruction Signs ICAO Annex 14, 5th Edition Aerodrome Design and Operations," accessed: 2020-05-03. [Online]. Available: https://www.icao.int/NACC/Documents/Meetings/2016/ACI/D2-02HoldingPositionSigns.pdf

[76] ICAO, "REMOTELY PILOTED AIRCRAFT SYSTEM (RPAS) CONCEPT OF OPERATIONS (CONOPS) FOR INTERNATIONAL IFR OPERATIONS," 2016, accessed: 2020-06-01. [Online]. Available: https://www.icao.int/safety/UA/Documents/ICAO%20RPAS%20Concept%20of%20Operations.pdf

[77] ——, "Unmanned Aircraft Systems (UAS)," 2011, accessed: 2020-07-09. [Online]. Available: https://www.icao.int/Meetings/UAS/Documents/Circular%20328_en.pdf#search=ISBN%20978%2D92%2D9231%2D751%2D5

[78] "Creating Secure C2 Links for UAVs — Intelligent Aerospace," accessed: 2020-08-16. [Online]. Available: https://www.intelligent-aerospace.com/atc-atm/article/16541697/creating-secure-c2-links-for-uavs

[79] "4G/5G MOBILE TECHNOLOGY APPLICATION IN CIVIL AVIATION." [Online]. Available: http://www.caac.gov.cn/en/HYYJ/NDBG/201802/P020180227616856973062.pdf,

[80] "Ericsson 5G: Unleash the power of easy - YouTube," accessed: 2020-08-16. [Online]. Available: https://www.youtube.com/watch?v=0CP13u68_MY

[81] "Setting the Scene for 5G: Opportunities & Challenges," Tech. Rep., 2018. [Online]. Available: https://www.itu.int/dms_pub/itu-d/opb/pref/D-PREF-BB.5G_01-2018-PDF-E.pdf

[82] "5G Takes Off At World's Airports And In The Skies - World Aviation Festival Blog," accessed: 2020-08-16. [Online]. Available: https://worldaviationfestivalblog.com/5g-takes-off-at-worlds-airports-and-in-the-skies/

[83] "June/July 2020 - What Will 5G Bring to the Aviation Industry? — Avionics Digital Edition," accessed: 2020-08-16. [Online]. Available: http://interactive.aviationtoday.com/avionicsmagazine/june-july-2020/what-will-5g-bring-to-the-aviation-industry/

[84] N. Hosseini and et al., "UAV Command and Control, Navigation and Surveillance: A Review of Potential 5G and Satellite Systems," *IEEE Aerospace Conference*, 2019.

[85] "Why This Hydrogen-Powered Engine Could Be the Future of Flying – Robb Report," accessed: 2020-06-01. [Online]. Available: https://robbreport.com/motors/aviation/hydrogen-engine-future-aviation-2922721/

[86] "Rolls-Royce and Airbus cancel E-Fan X project — The Engineer The Engineer," accessed: 2020-07-31. [Online]. Available: https://www.theengineer.co.uk/e-fan-x-project-cancelled/

[87] "Aviation Week's Urban Air Mobility," accessed: 2020-08-13. [Online]. Available: https://uam.aviationweek.com/en/home.html

[88] NASA, "URBAN AIR MOBILITY (UAM) MARKET STUDY," 11 2018, accessed: 2020-06-01. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/bah-uam-executive-briefing-to-post.pdf

[89] S. Gudmundsson, *General Aviation Aircraft Design: Applied Methods and Procedures*, 2014.

[90] "Volocopter publishes white paper on urban air mobility," accessed: 2020-03-01. [Online]. Available: https://press.volocopter.com/index.php/volocopter-publishes-white-paper-on-urban-air-mobility

[91] A. Ivanenko, "HyPoint Technical White Paper," 4 2020, accessed: 2020-05-15. [Online]. Available: https://docsend.com/view/t9aw2mk

[92] A. Bacchini and E. Cestino, "Key aspects of electric vertical take-off and landing conceptual design," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 234, no. 3, pp. 774–787, 3 2020. [Online]. Available: http://journals.sagepub.com/doi/10.1177/0954410019884174

[93] "Tesla Model S," 3 2020, accessed: 2020-08-08. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Tesla_Model_S&oldid=945409983

[94] C. B. Courtin and R. J. Hansman, "MODEL DEVELOPMENT FOR A COMPARISON OF VTOL AND STOL ELECTRIC AIRCRAFT USING GEOMETRIC PROGRAMMING," 2019, accessed: 2020-06-11. [Online]. Available: https://arc.aiaa.org/doi/abs/10.2514/6.2019-3477

[95] FAA, "CFR - Visual Flight Rules," 2012, accessed: 2020-07-03. [Online]. Available: https://www.govinfo.gov/content/pkg/CFR-2012-title14-vol2/pdf/CFR-2012-title14-vol2-sec91-151.pdf

[96] "Federal Aviation Regulation Sec. 23.25 - Weight limits." accessed: 2020-08-31. [Online]. Available: https://www.risingup.com/fars/info/part23-25-FAR.shtml

[97] "Technology Readiness Level — NASA," accessed: 2020-08-27. [Online]. Available: https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

[98] D. P. Raymer and American Institute of Aeronautics and Astronautics., *Aircraft design : a conceptual approach*. AIAA, 1989.

[99] "eVTOL Aircraft Directory," 5 2017, accessed: 2020-09-09. [Online]. Available: https://evtol.news/aircraft/

[100] A. Datta, "PREPUBLICATION COPY Subject to Further Editorial Correction COMMERCIAL INTRA-CITY ON-DEMAND ELECTRIC-VTOL STATUS OF TECHNOLOGY," 2018.

[101] "How can we now reduce CO2 emissions from cars? — France Stratégie," accessed: 2020-08-26. [Online]. Available: https://www.strategie.gouv.fr/english-articles/how-can-we-now-reduce-co2-emissions-cars

[102] "In Drive to Cut Emissions, Germany Confronts Its Car Culture - Yale E360," accessed: 2020-08-28. [Online]. Available: https://e360.yale.edu/features/in-drive-to-cut-emissions-germany-confronts-its-car-culture

[103] "Reducing emissions from aviation — Climate Action," accessed: 2020-08-28. [Online]. Available: https://ec.europa.eu/clima/policies/transport/aviation_en

[104] "Uber Elevate eCRM-004," 9 2019, accessed: 2020-08-10. [Online]. Available: https://evtol.news/aircraft/uber-elevate-ecrm-004/

[105] "Bartini Flying Car," accessed: 2020-08-28. [Online]. Available: https://evtol.news/bartini/

[106] "EmbraerX DreamMaker," accessed: 2020-08-28. [Online]. Available: https://evtol.news/embraer/

[107] "Russian air taxi prototype passes flight tests — Aerospace Testing International," accessed: 2020-08-28. [Online]. Available: https://www.aerospacetestinginternational.com/news/drones-air-taxis/russian-air-taxi-prototype-passes-flight-tests.html

[108] "Passenger Lift Sizes & Dimensions — Stannah," accessed: 2020-08-31. [Online]. Available: https://www.stannahlifts.co.uk/products/passenger-lifts/passenger-lifts-range-sizes

[109] "Hand luggage— Transavia," accessed: 2020-09-01. [Online]. Available: https://www.transavia.com/en-EU/faq/hand-luggage/

[110] "Ryanair 2020 Baggage Allowance — My Baggage," accessed: 2020-09-01. [Online]. Available: https://www.mybaggage.com/shipping/airlines/ryanair-baggage-allowance/

[111] "Cabin bags and hold luggage — easyJet," accessed: 2020-09-01. [Online]. Available: https://www.easyjet.com/en/help/baggage/cabin-bag-and-hold-luggage

[112] D. Raymer, *Aircraft Design: A Conceptual Approach, Sixth Edition and RDSwin Student SET*. American Institute of Aeronautics and Astronautics, Inc., 1 2019.

[113] L. M. Nicolai and G. E. Carichner, *Fundamentals of Aircraft and Airship Design*. American Institute of Aeronautics and Astronautics, 1 2010.

[114] "Acceleration of a Car - The Physics Factbook," accessed: 2020-09-08. [Online]. Available: https://hypertextbook.com/facts/2001/MeredithBarricella.shtml

[115] M. R. Nabawy and W. J. Crowther, "Is flapping flight aerodynamically efficient?" in *32nd AIAA Applied Aerodynamics Conference*, 2014.

[116] T. Addarkaoui and et al., "Graduate Team Aircraft Design Competition: Electric Vertical Takeoff and Landing (E-VTOL) Aircraft Mistral Air Taxi," 2018, accessed: 2020-05-30. [Online]. Available: https://www.aiaa.org/docs/default-source/uploadedfiles/education-and-careers/university-students/design-competitions/3rd-place-grad-team-aircraft.pdf?sfvrsn=5d49f2cf_0

[117] M. D. Maisel and et al., "The History of the XV-15 Tilt Rotor Research Aircraft: From Concept to Flight," 2000, accessed: 2020-02-1. [Online]. Available: https://www.researchgate.net/publication/24295050_The_History_of_the_XV-15_Tilt_Rotor_Research_Aircraft_from_Concept_to_Flight/stats

[118] "Pipistrel," accessed: 2020-10-08. [Online]. Available: https://evtol.news/pipistrel/

[119] "Ultra Prop Low Cost Carbon Composite Propellers," accessed: 2020-10-08. [Online]. Available: https://www.ultraprops.com/

[120] "EMRAX 208 Technical Data Table (dynamometer test data)," 3 2020, accessed: 2020-02-28. [Online]. Available: https://emrax.com/wp-content/uploads/2017/01/emrax_208_technical_data_4.5.pdf

[121] "freerchobby–provide wide range brushless dc motor and controller – Dongguan Freerchobby Co.,Ltd," accessed: 2020-09-13. [Online]. Available: https://www.freerchobby.cc/

[122] "HAWK MOTORS — DHXmachines," accessed: 2020-09-13. [Online]. Available: https://www.dhxmachines.com/hawk-motors

[123] "Magnax - Yokeless Axial Flux Motors for Electric Vehicles," accessed: 2020-09-13. [Online]. Available: https://www.magnax.com/

[124] "NCR18650GA - Lithium-ion Batteries - Secondary Batteries (Rechargeable Batteries) - Industrial Devices & Solutions," accessed: 2020-09-13. [Online]. Available: https://industrial.panasonic.com/ww/products/batteries/secondary-batteries/lithium-ion/models/NCR18650GA

[125] R. Schröder and et al., "Comparatively Assessing different Shapes of Lithium-ion Battery Cells," *Procedia Manufacturing*, vol. 8, pp. 104–111, 2017.

[126] "Panasonic/Sanyo NCR18650GA Flat Top 10A 3500mAh 18650 Battery - Genuin – Liion Wholesale Batteries," accessed: 2020-09-14. [Online]. Available: https://liionwholesale.com/products/panasonic-sanyo-ncr18650ga-flat-top-1?variant=12534245700

[127] "XFLR5," accessed: 2020-09-13. [Online]. Available: http://www.xflr5.tech/xflr5.htm

[128] T. C. Corke, *Design of Aircraft*. Prentice Hall, Upper Saddle River, NJ, USA, 2003.

[129] ——, "Data to size the Tail," accessed: 2020-10-09. [Online]. Available: https://bit.ly/3nZxoXD

[130] M. Sadraey, *Aircfrat Design - a Systems Engineering Approach*. WILEY, 2013.

[131] "STATIC PITCH STABILITY of an AIRPLANE," accessed: 2020-09-01. [Online]. Available: https://mypages.iit.edu/~vural/Pitch%20Stability.pdf

[132] A. Sanchez-Carmona and C. Cuerno-Rejado, "Vee-tail conceptual design criteria for commercial transport aeroplanes," *Chinese Journal of Aeronautics*, vol. 32, no. 3, pp. 595–610, 3 2019.

[133] N. A. Musa and et al., "Effect of tail dihedral angle on lateral directional stability due to sideslip angles," in *53rd AIAA Aerospace Sciences Meeting*, 2015.

[134] H. Stettmaie, "V-Tails for Aeromodels," 11 2001, accessed: 2020-02-28. [Online]. Available: https://www.fmsg-alling.de/wp-content/uploads/2013/09/V-Leitwerke.pdf

[135] W. Johnson, *Rotorcraft Aeromechanics*. Cambridge University Press, New Year, NY, USA, 2013.

[136] L. Gutin, "On the sound field of a rotating propeller," NACA, Tech. Rep., 10 1948.

[137] A. F. Deming, "Propeller rotation noise due to torque and thrust," NACA, Tech. Rep., 1 1940.

[138] R. Schlegel and et al., "Helicopter rotor noise generation and propagation," US Army Aviation Material Laboratories, Fort Eustis, VA, USA, Tech. Rep., 10 1966.

[139] J. E. Marte and D. W. Kurtz, "A review of aerodynamic noise from propellers, rotors, and lift fans," Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, Tech. Rep., 1 1970.

[140] "Levels Of Noise In Decibels (dB) Level Comparison Chart." [Online]. Available: https://soundproofingguide.com/decibels-level-comparison-chart/

[141] X. Zhang, "Noise Prediction of a NACA 0015 Airfoil with Gurney Flap A study based on Time-Resolved Particle Image Velocimetry," *Delft University of Technology*, 12 2015. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3A8f0aa772-4129-4ff7-a2af-6484cdea4720

[142] "Decibels Explained — TLC Electrical," accessed: 2020-09-21. [Online]. Available: https://www.tlc-direct.co.uk/Technical/Sounds/Decibles.htm

[143] "Conversion of Sound Levels," accessed: 2020-10-12. [Online]. Available: https://bit.ly/3n0xgpa

[144] M. Massaro, "Thesis for the Degree of Licentiate of Philosophy. Radio Spectrum Regulation in the European Union: A three-level context," 2017.

[145] "Helicopter Noise," accessed: 2020-09-19. [Online]. Available: https://hearinghealthmatters.org/lawandhearing/2011/helicopter-noise/

[146] "Human Auditory Range," accessed: 2020-09-28. [Online]. Available: http://www.cochlea.org/en/hear/human-auditory-range

[147] N. Jungbluth and C. Meili, "Recommendations for calculation of the global warming potential of aviation including the radiative forcing index," *The International Journal of Life Cycle Assessment*, vol. 24, pp. 401–411, 2019.

[148] "Overview of electricity production and use in Europe — European Environment Agency," accessed: 2020-09-28. [Online]. Available: https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4

[149] M. Zackrisson and et al., "Life cycle assessment of lithium-air battery cells," *Journal of Cleaner Production*, vol. 135, pp. 436–443, 6 2016.

[150] "cessna 172 — Communicate Science," accessed: 2020-09-19. [Online]. Available: https://communicatescience.com/zoonomian/tag/cessna-172/

[151] K. O. Ploetner and et al., "Operating cost estimation for electric-powered transport aircraft," in *2013 Aviation Technology, Integration, and Operations Conference*.

[152] "Tesla's next-gen Supercharger can add 75 miles of range in just 5 minutes – BGR," accessed: 2020-09-15. [Online]. Available: https://bgr.com/2019/07/20/tesla-supercharger-v3-range-model-3/

[153] "Introducing V3 Supercharging — Tesla," accessed: 2020-09-15. [Online]. Available: https://www.tesla.com/blog/introducing-v3-supercharging

[154] "Tesla Model 3 On Supercharger V3: Here Are The Charging Specs," accessed: 2020-09-15. [Online]. Available: https://insideevs.com/news/343622/tesla-model-3-on-supercharger-v3-here-are-the-charging-specs/

[155] "Electricity Rates by State (Updated April 2020) – Electric Choice," accessed: 2020-16-09. [Online]. Available: https://www.electricchoice.com/electricity-prices-by-state/

[156] "Sample Aircraft Loan Rates - Aviation Finance — AOPA," accessed: 2020-09-15. [Online]. Available: https://finance.aopa.org/resources/2016/july/12/sample-aircraft-loan-rates

[157] "Rotary Aircraft," accessed: 2020-09-16. [Online]. Available: https://www.globalsecurity.org/military/systems/aircraft/rotary.htm

A

Trade-off of wing position

Table A.1 presents the advantages and disadvantages of different wing positions on the fuselage height: low, mid and high.

Table A.1: Advantages and disadvantages of low, mid and high-wing configurations ([42], [98] and [89]

Wing Position	Advantages	Disadvantages
Low	- Structurally it is simple, as the main wing structural items can pass beneath the cabin floor [42]; - Wing mounted engines and control surfaces are more easily accessed for servicing [42]; - The wing shields the fuselage in the event of aircraft striking in the water or ground [42].	- The upper surface of the wing is distorted thus affecting the ability to generate lift [42]; - Requires a suitable wing-fuselage fairing to minimize the interference drag [42]; - Engine installation is harder due to likely insufficient space for ground clearance to avoid debris on the floor [42]; - In certain seats in the cabin, the downward view is obscured by the wing [42]; - May require a bigger vertical tail to avoid dutch roll with excessive dihedral angle [98]; - The dihedral angle is defined considering the aircraft does not hit the ground on a bad landing rather than being the best aerodynamic choice [98]; - Increased landing gear weight due to its stowage [98].
Mid	- Aerodynamically easier to fair into the fuselage but no better than the low-wing [42]; - Engine installation and its servicing is a compromise between low and high-wing [42]; - Landing gear layout is also a compromise between low and high-wing [42]. - If the fuselage is approximately circular then no fairings are needed and drag of fairings is the lowest of all three configurations [98]; - It is probably better for aerobatic maneuvers [98].	- Structurally is much worse than either of low and high-wing [42] as it needs either an extension of the wing-box inside the aircraft [98] or a set of massive ring frames built into the fuselage [98] for reinforcement; - The wing structure has to be terminated at the fuselage size [42]; - Need to reinforce the fuselage [42].

High	- The upper surface of the wing in undisturbed, relative to low-wing [42]; - Structurally it is simple, as the main wing structural items can pass above the cabin ceiling [42]; - The aircraft center of gravity is lower than the wing plane, hence increasing the natural stability of the aircraft [42]; - Allows placing the fuselage closer to the ground [98]; - Eases loading and unloading of cargo and passengers [98]; - Propellers have sufficient ground clearance without excessive landing gear [98]; - When in nose-high rolled attitude, the wings are not as likely to hit the ground as the low-wing configuration [98]; - Lighter landing gear because it is fuselage-based [98].	- Wing-fuselage is probably more difficult to manufacture compared to low-wing [42]; - Wing mounted engines and control surfaces are of difficult access for servicing [42]; - Increased difficulty in the design and installation of the landing gear, it may be easier to set it in the fuselage [42]. - Use of external struts to ease wing support adding weight and substantial drag [98]; - If the wing-box passes through the fuselage, then the fuselage may need to be stiffened [98]; - If the wing-box is set on top of the fuselage, it adds on drag [98]; - Despite the reduction of landing gear weight, the overall weight of the aircraft is expected to increase due to all the reinforcement needed [98]; - Can block the pilot's visibility when performing a turn [98].

B

Method of Battery Size Estimation

Following the methodology presented by using the method presented by Schröder [125], table B.1 presents the estimation of the battery size to be used in the current project, using a battery density of 300 Wh/kg.

Table B.1: Assessing the size of the battery pack using the cell Panasonic NCR18650GA [124] as starting point and then adjusting the cell to the 300 Wh/kg requirement, as mentioned in the section 3.2, using the method presented at [125] by Schröder. Calculations assume a range of 327 km according to the choice of mission 1 in section 3.6 and a battery pack voltage of 500 V.

Cell Type					
Specification	Units	Panasonic NCR18650GA	Increase Voltage	Increase Current	Increase Voltage and Current
Nominal Voltage	[V]	3.6	**4.3**	3.6	**4.0**
Nominal Capacity mininum	[mAh]	3350			
Nominal Capacity typical	[mAh]	3450	3450	**4126**	**3713**
Diameter, with tube	[mm]	18.5			
Height, with tube	[mm]	65.3			
Thickness, without tube	[mm]	-			
Width, without tube	[mm]	-			
Height, without tube	[mm]	-			
Weight maximum	[g]	49.5			
C-rate	[-]	1			
All values bellow result from calculus using the method presented at [125] by Schröder.					
Volume by cell	[m^3]	1.8E-05	1.8E-05		
Battery Cell Energy	[Wh]	12.42	14.85		
Volumetric Energy Density	[Wh/l]	708	846		
Gravimetric Energy Density	[Wh/kg]	251	300		
Single Cell Cost	[$/cell]	3.99			
Battery Pack					
Battery Pack Total Energy	[Wh]	216564			
Considering several strings connected in parallel.					
Number of Battery Cells connected in Series	[-]	139	116	139	125
Energy of a String	[Wh]	1725	1725	2063	1857
Number of Strings of the Battery Pack	[-]	126	126	105	117
Battery Pack Capacity	[Ah]	433			
Number of Cells of the Battery Pack	[-]	17437	14581	14580	14580
The following calculations do not account for electronic and cooling circuits, battery casing and wiring.					
Battery Pack Mass	[kg]	863	722		
Volume of the Battery Pack	[m^3]	0.31	0.26		
String Peak Current	[A]	3.45	3.45	4.13	3.71

Battery Pack Peak Current	[A]	433	433		
Battery Pack Peak Power	[kW]	217	217		
String Continuous Current	[A]	3.45	3.45	4.13	3.71
Battery Pack Continuous Current	[A]	433			
Battery Pack Continuous Power	[kW]	217	217		
Cost of Battery Pack					
Battery Cost	[$/pack]	$ 69 572	$ 58 179	$ 58 175	
Cost by kWh	[$/kWh]	$ 321	$ 269		

C

Experimenting with battery density of 400 Wh/kg

As mentioned in section 2.6.3.B, Moore and Fredericks [36] believe that a battery specific energy density of 400 Wh/kg is sufficient to enable meaning electric and claim such batteries. Hence, the present section presents the comparison of results obtained when using such battery energy density and a 300 Wh/kg (the one used throughout the whole project) and keeping MTOW constant (1434 kg). The resulting values are expected to be substantially better (from section 3.6 to 3.11) except for the static margin, which the design team expects to be very similar.

Mission power needs presented in table 3.5 and summarized in table 3.4 do not change at all, because the battery density is not a variable in equations 3.4 to 3.6 as it is only accounted for battery weight calculations. Thus, the choice of engines and propellers is also not influenced as it is based on both power needs and number of rotors for each mission stage.

Table C.1 shows a decrease of 24% of battery-to-MTOW ratio comparing to ratio presented in table 3.6 and an increase of 48% of the empty-to-MTOW ratio (reducing from 722 to 542 kg). These results allow for a smaller battery pack and a much balanced and realistic weight distribution.

Table C.1: Weight ratio distribution according to the analysis of power consumption by each mission, considering an an MTOW of 1434 kg, considering a battery energy density of 400 Wh/kg.

Ratio	Units	Mission 1	Mission 2	Mission 3	Mission 4
W_battery/MTOW	[-]	0.38	0.32	0.35	0.49
W_Payload/MTOW		0.25			
W_empty/MTOW		0.37	0.43	0.40	0.26
W_operational/MTOW		0.75			

Following the methodology presented in table B.1 the battery cost is reduced in 25% dropping from 58.2k US$ to 43.7k US$ if the single battery cell has a nominal voltage of 4.5 V and a minimum nominal capacity of 4.4 Ah. There is a decrease of 25% in the the number of battery cells used (from 14,580 to 10,940) which results in the same percentage of decrease of volume (from 0.256 to 0.192 m^3). To state that these batteries are nowhere close to reach the market, some literature points such availability after 2025, consequently using this battery energy density would not comply with the requirement of having the aircraft market ready by 2024.

The aircraft dimensions would remain essentially the same at this project stage. On the other hand, the weight distribution would see great improvements, as seen in table C.2.

Table C.2: Total weight distribution according to Dr. Raymer historic-based formulas [98] but with a correction factor to suit the weight ratio of mission 1 presented in table C.1. The variation regarding the values from the homologous table 3.13 which considered a battery density of 300 Wh/kg.

Part of the Aircraft	[kg]	Variation	Part of the Aircraft	[kg]	Variation
Wing	27.7	95%	Hydraulics	0.6	95%
V-Tail	7.4	95%	Electrical	113.2	77%
Fuselage	86.1	95%	Avionics	84.3	95%
Landing Gear	18.1	95%	Air conditioning & Anti-ice	20.5	95%
Batteries & Engine & Propellers	691.2	-21%	Furnishings	22.4	95%
Flight Controls	2.5	95%	Payload	360.0	0%
Total [kg]					
1434.0					

Regarding the aircraft stability, the same study as explained in section 3.11 was performed and the results are presented in figure C.1. Such figure shows a horizontal translation of 6.9% to the left, meaning a decrease in stability. With the present analyses, the stability range is (-0.1)%-11.7% which is not totally within the preferred range of 5%-15% in accordance with Professor Vural [131]. To better assess stability one may extensively specify weight positioning.

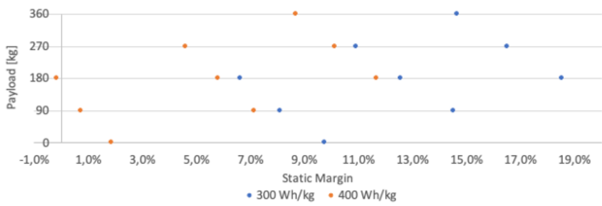


Figure C.1: Range of static margin form computational results using xflr5 [127].

Environmental, aeroacoustics and operational costs analyses presented in chapter 4 do not see any change as none of them depends directly from the battery energy density as it explained in such chapter but rather from the mission profile energy needs.