Politecnico di Torino

Department of Mechanical and Aerospace Engineering

MASTER'S THESIS IN
AEROSPACE ENGINEERING

Conceptual design methodology for eVTOL

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Abstract

The aim of this thesis is to present a design methodology for a category of new aircraft: eVTOLs (electric vertical take-off and landing). This thesis will analyse the potential of sustainable urban mobility solutions through advanced air mobility (AAM). In light of the intensification of urban congestion and the environmental problems caused by increasing air pollution, eVTOL vehicles appear to offer a promising solution to replace or complement urban transport.

In the first part of this thesis, eVTOL technology will be contextualised within the historical trajectory of personal air vehicles, with a particular focus on its potential to reduce carbon emissions in urban transport.

Subsequently, a comprehensive analysis of the various eVTOL configurations currently being designed by various international companies will be carried out.

Starting from some design specifications, including range, payload capacity and regulatory requirements set by government agencies such as EASA, statistical and analytical models will be used to carry out the aircraft sizing. In more detail, the thesis will explore the main design factors – mass estimation, propulsion requirements and battery configuration – in order to obtain preliminary sizing results that will be useful for optimising the performance of the aircraft for urban air mobility.

This research will endeavour to consider the technological challenges and requirements of the transition to eVTOL technology, with a particular focus on the various systems that contribute to the functionality of these aircraft. This will provide a foundation for future design advances that prioritise safety, efficiency and reduced environmental impact.

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Introduction

The rapid increase in urbanisation, coupled with increasingly stringent environmental requirements and targets, has stimulated the search for sustainable and efficient mobility solutions. The scientific and industrial community is working to develop new technologies that meet these requirements, with the goal of reducing the environmental impact and improving the quality of urban life. The process of developing new solutions in the field of aeronautics is particularly complex in comparison to other sectors. This is mainly due to the necessity of ensuring safety, the presence of stringent regulations, and the inherent technological complexity. One of the most promising responses to these challenges may be the development of electric vertical take-off and landing aircraft (eVTOLs), which are regarded as a potentially transformative innovation for urban air mobility (UAM).

These vehicles are distinguished from fixed-wing aircraft by their ability to perform vertical take-offs and landings. They have the potential to address the growing issue of urban congestion while reducing greenhouse gas emissions, due to their electrical propulsion. Mobility-related emissions contribute a significant portion of global pollution in the transport sector. Therefore, a sustainable solution in this area is crucial in reducing the environmental impact in cities.

Although the eVTOL concept was initially inspired by early flying car prototypes, it is now able to benefit from recent advances in battery technology and electric propulsion. Nevertheless, numerous design and operational challenges remain to be addressed, including the standardisation of regulatory frameworks, safety concerns and technological limitations pertaining to energy storage and management.

The objective of this thesis is to develop a systematic approach to the conceptual design of eVTOLs intended for use in urban contexts, with the aim of optimising the operational efficiency of key aircraft components. The objective of the research is to ensure compliance with existing safety and regulatory standards, thereby guaranteeing that the design meets the specific requirements of urban air mobility.

In particular, an in-depth analysis of different eVTOL configurations, from multicopters to powered-lift aircraft, will provide insights into the optimal configurations and performance metrics required for urban applications. The study will employ statistical and analytical methods to investigate the influence of diverse design parameters on mass, propulsion and energy. The design process proposed in this thesis is based on an iterative approach that combines empirical data and theoretical models with the objective of achieving optimal performance for the effective implementation of eVTOL in urban air mobility.

Chapter 1

eVTOL: History and Meaning

The idea of having a personal vehicle that would allow people to optimise their movements by taking off and landing from a specific desired location has always existed, but it has always been a fantasy or a desire that was difficult to achieve. The earliest known example of a personal air vehicle is a flying car, which can be traced back to the early 1990s and Glenn Curtiss's Model 11 Autoplane[1].

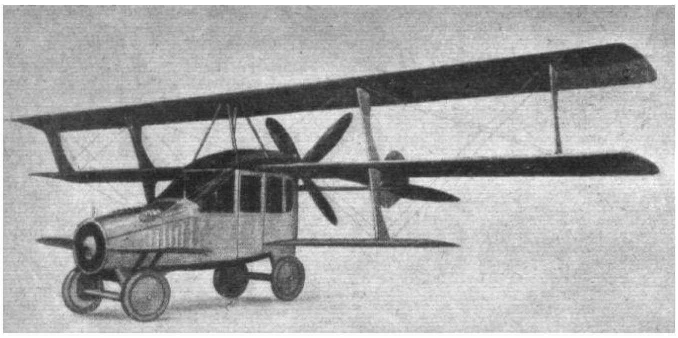

Figure 1.1: Model 11 Autoplane

It was a small aeroplane with a lot of car-like comfort inside. A three-seater with an aluminium body and plastic windows, it was to be the new luxury vehicle of the future, but the entry of the United States into the First World War limited development and production [3].

[1]Glenn Curtiss, born Glenn Hammond Curtiss (Hammondsport, 21 May 1878 - Buffalo, 23 July 1930), was an American entrepreneur and aviation pioneer.

In 1919, a centuary ago, a few months before his *Round the Rim* mission[2], Lieutenant Ernest Emery Harmon[3] of the US Army Air Corps wrote an article in the *New York Sun* in which he expressed his vision of the future of aviation: "I believe the time is not far distant when we shall have aero-garages in every large city where you can buy an aeroplane and learn to fly it, where you can store it overnight, and where you can hire an air-taxi to take you from one city to another, or an air-bus to see the city" [4]. Although Captain Harmon's vision of the future may have appeared to be a mere flight of fancy at the time, nearly a century later it seems to be becoming a tangible reality. The concept of the personal air vehicle, or air taxi, has become an emerging reality as a consequence of technological advances and innovations in advanced air mobility.

Thirty years later, two more remarkable projects filled the pages of the newspapers of the time: the *Taylor Aerocar* and the *Ford Volante Tri-Athodyne*.
The first was a design by Moulton Taylor[4] that turned out to be a real car, capable of removing its wings in a matter of minutes and transforming itself into a two-seater with a propeller engine. Although it was essentially a car and had a number of differences from a traditional aircraft, Taylor's design was classified as a fixed-wing aircraft, but it was the only flying car to be produced in those years, and five examples still exist in some museums.
The second project was an idea/experiment by the Ford Motor Company, representing a car with three ducted fans needed to move through the air. Despite its avant-garde nature, the model (illustrated in the following figure) was never developed.

In the years that followed, interest in the development of personal flying vehicles waned due to the limited attention given to the pioneering prototypes that had been developed earlier. In addition, the rapid development of civil aviation and the increasing emphasis on improving fixed-wing aircraft led designers to focus their efforts exclusively on the latter category, thus slowing progress in the field of personal vehicles.

[2]From July 24 to November 9, 1919, Lieutenant Harmon piloted the first ever flight around the continental United States.

[3]Captain Ernest Emery Harmon, Army Air Corps (February 8, 1893–August 27, 1933) was an aviation pioneer.

[4]Moulton B."Molt" Taylor (September 29, 1912 – November 16, 1995) was an American aeronautical engineer

 

Figure 1.2: Taylor Aerocar and Ford Volante Tri-Athodyne

Although the technical development of personal flying vehicles has come to a halt, the idea and desire for a personal flying vehicle has always remained alive. This is confirmed by the various cultural fields, such as film, literature and art, which over the years have used the image of the personal flying vehicle to depict futuristic and science fiction scenarios.

In literature, one of the most iconic examples is J.K. Rowling's 1998 novel *Harry Potter and the Chamber of Secrets*, in which the flying car, the Ford Anglia, becomes a symbol of magic and adventure.

In the cinematic landscape, films of the 1990s made ample use of the appeal of flying cars. Films such as Robert Zemeckis' *Back to the Future Part II* (1989) had a lasting impact on the 1990s, imagining a future with flying cars that captured the imagination of a generation. Other films, such as Luc Besson's *The Fifth Element* (1997), presented a detailed vision of an urban future where flying taxis are an integral part of the cityscape.

Cartoons in the 1990s also embraced the concept of personal flying vehicles with enthusiasm. *The Jetsons*, originally created in the 1960s, depicted a future in which flying cars completely replaced road cars.

Finally, trade magazines in the 1990s often devoted articles and covers to flying car prototypes, helping to keep the public and engineers interested in the technology. Publications such as *Popular Mechanics* and *Scientific American* explored both the technical achievements and the challenges still to be overcome, bridging the gap between fantasy and scientific reality.

Figure 1.3: References: "The Fifth Element", "The Jetsons", "Popular Mechanics Magazine"

The appeal of the flying car lies not only in its benefits for the everyday lives of citizens, but also in a number of design features, such as: the ability to perform vertical take-off and landing (VTOL) in confined spaces, fast travel, decongestion of road traffic, access to remote and hard-to-reach areas, and environmental impact. The development of helicopters over the last century has accentuated these advantages, especially for certain types of missions and flight areas/environments.

Initially, during the post-war period, attempts were made to apply some of these advantages to some fixed-wing combat aircraft (e.g. the European Harrier), by attempting to exploit the advantages of vertical take-off and landing and fixed-point flight through the orientation of the propulsion jet. This solution, although possible, is very complex and not always feasible, except for high performance aircraft. Moreover, the use of jet-propelled aircraft (a solution adopted by almost all fixed- and rotary-wing aircraft) has limited the development of flying cars because it has proved to be particularly complex and very noisy.

The personal air vehicles and air taxis has remained largely an unattainable goal, despite various attempts at development over the years. However, technological advances and new environmental requirements have put the concept in a new light. In technical terms, such vehicles are now referred to as **eVTOL (Electrical Vertical Take-Off and Landing)** and fall within the broader context of Advanced Air Mobility (AAM), also known as Urban Air Mobility (UAM).
This new type of aircraft is very different from the flying car of the 20th century, and its configuration is somewhere between traditional aeroplanes and helicopters. As currently conceived, eVTOLs are aircraft capable of carrying up to 9 passengers over short distances, mainly within large cities, and using electricity to hover, take off and land vertically.

The concept of the eVTOL emerged in 2009 when NASA released a video of its "Puffin" project [5], created by aerospace engineer Mark Moore, which showed an electric vertical take-off and landing aircraft that looked unusual at the time, but is very close to today's modern eVTOL concept.

Subsequently, the AAM industry underwent a period of rapid development as a consequence of the interest expressed by numerous companies seeking to develop eVTOLs that are fit for purpose and able to gain certification and enter the market. According to a NASA White Paper - *Transformative Vertical Flight Working Group* [6], dated August 2021, over 150 companies are currently engaged in the development of prototypes, including EVE Air Mobility (U.S.), Joby Aviation (U.S.), Lilium (Germany), Vertical Aerospace Group (UK), E-Hang (China), Volocopter (Germany), as well as major corporations such as Airbus, Boeing, Bell (US), Embraer (Brazil) and Uber (US). Some have already obtained certification from government agencies, while others are in the process of doing so. The intention of the latter is to launch their aircraft by 2025.

1.1 Advancing Sustainable and Urban Mobility

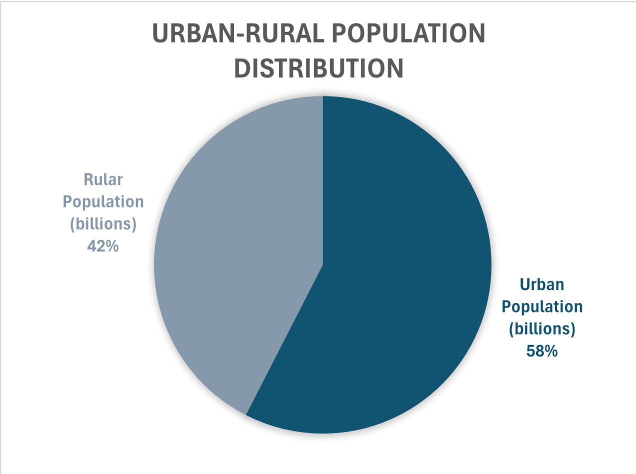

Figure 1.4: Population Distribution

The idea of developing a vehicle for intra-city transportation was derived from the realisation that the majority of the global population resides in urban areas [7], with over 58% of the total world population (approximately 4 billion individuals) currently living in such environments in 2020. This trend will persist and continue to ascend, with projections indicating a 68% prevalence by 2050, with a growing number of people moving to the city due to the better economic and infrastructural conditions..

It is also essential to note that urbanisation varies significantly between continents [8], as illustrated in Figure 1.5.

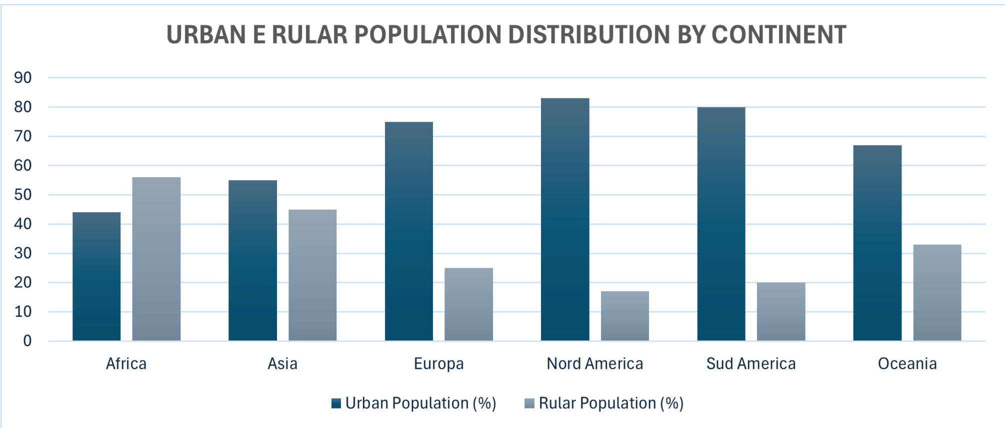

Figure 1.5: Urban-Rules Population Distribution by Continents

For instance, in the most developed continents, such as the United States and Europe, over 75% of the population resides in urban areas. In contrast, in other less developed continents, such as Africa, a considerable proportion of the population continues to live in rural areas.

The environmental impact of the transport sector is significant on a global scale, as illustrated in the graph below, which depicts global greenhouse gas emissions by major sector in 2020 [9].

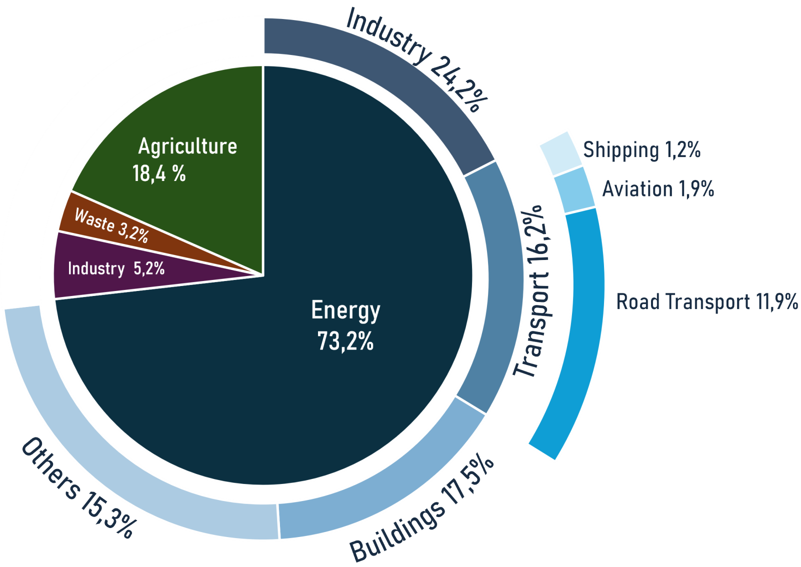

Figure 1.6: Global Greenhouse Gas Emissions

It can be seen that road transport (which includes private transport, commercial goods and intra-city public transport) accounted for 12% of global emissions, which is a significant percentage.
An European Commission's report provides the opportunity to conduct a more detailed analysis [10]. The following figure illustrates that approximately 93% of road transportation is powered by non-renewable sources. These sources have a direct impact on environmental pollution, and thus, a change in this field can have a significant impact.

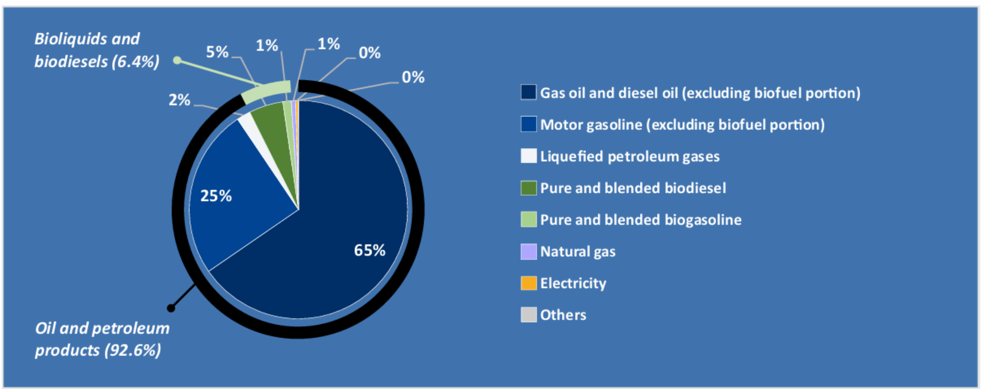

Figure 1.7: Road transport by type of fuel in EU (2022)

In conclusion, an analysis of future projections suggests that road transport will continue to expand in the coming years (from 5500 billion passenger kilometres (pkm)[5] today to around 7000 billion pkm in 2050) [11].

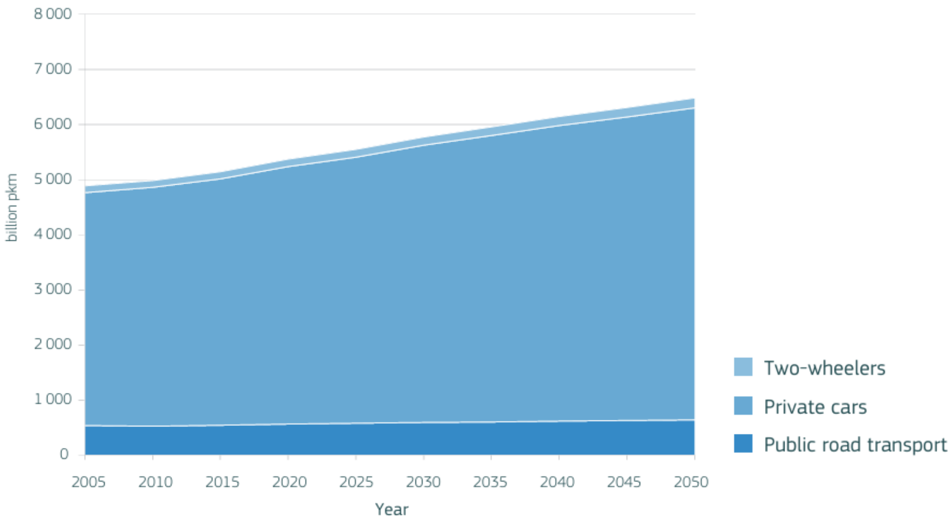

Figure 1.8: Road passenger transport activity evolution since 2005 and up to 2050 (in billion passenger kilometres - pkm)

This scenario is particularly worrying due to the negative impact of road transport on public health and the environment. Therefore, the necessity for innovative, efficient and zero-emission transportation methods is evident. They will undoubtedly play a significant role in the future organization of mobility needs.

The objective of eVTOL vehicles is to facilitate a transfer of travel from the road to the air. This has the potential to **reduce traffic congestion**, **improve mobility** and **decrease travel times** for a significant proportion of today's travel demand. A further significant challenge associated with the ongoing process of urbanisation is the reduction of CO_2 emissions, of which the road sector is responsible for a considerable proportion. Consequently, the deployment of electrified propulsion systems for VTOL vehicles has the potential to facilitate the provision of low-emission transport, especially if renewable energy sources are utilised.

[5] Unit of measurement used by the European Commission to quantify passenger mobility. It represents the transportation of a single passenger over a distance of one kilometer across various modes of transport.

This technological feature is now possible thanks to continuous advances in electric propulsion (motors, batteries, electronic controls) combined with the current need for new types of vehicles for urban air mobility [12].

A number of eVTOL prototypes are currently under development for a variety of potential applications. These range from smaller models designed to carry two passengers, which may be considered an evolution of the flying car concept, to larger aircraft capable of transporting multiple passengers on intercity routes, where the eVTOL could be used as a private air taxi. A variety of urban air mobility (UAM) missions have been proposed, covering a range of conceptual approaches, from preliminary designs to more comprehensive studies and even the development of tangible vehicles. Following an in-depth examination of the potential missions, it was determined to present the following options, which encompass a range of macro-areas[13], including:

- **Daily commutes:** Transportation for daily trips within a city, such as commuting to and from work.
- **Airport shuttles:** Fast connections between urban locations and airports, providing efficient transfers for airline passengers, either from their starting point to the airport or from the airport to near their final destination.
- **City-wide transfers:** Enabling passengers to bypass urban traffic by quickly traveling from one side of a city to another.
- **Metro-like services:** Acting as a complement to existing mass transit systems, connecting passengers to other forms of public transportation.

Despite recent advancements, several obstacles remain to be overcome before eVTOLs can be made operational. The primary challenge is the need to develop the infrastructure and aircraft requirements. eVTOLs are technically neither helicopters nor fixed-wing aircraft. The current regulatory framework is insufficient for the description and certification of these aircraft. The process is further hindered by the fact that the various manufacturers are developing designs that are distinct from one another, which makes standardisation particularly complex. Consequently, government agencies must collaborate with manufacturers to establish specific criteria and standards for these innovative aircraft, which will inevitably impact the timing of their market introduction.

The limited size of eVTOLs and the relatively low power of their onboard batteries necessitate frequent landings for both passenger boarding and recharging.

A further significant challenge is associated with the technology itself. In the context of ongoing advancements, developers are directing their attention towards the optimisation of eVTOLs. They a focus on sustainability, in light of the growing interest in reducing the aviation industry's carbon footprint. The use of batteries results in a limited range and it is a focal point of considerable interest. Innovation in this field has the potential to reduce the aircraft weight, thereby increasing the number of passengers that can be accommodated.

Furthermore, it is essential to address the perception to the public of these flights, which must be reassured regarding their safety. This is the main reason of a continued emphasis on safety and flight testing.

While cost and safety are two significant obstacles to the advancement and implementation of eVTOL, this technology holds the potential to provide a solution to several societal challenges, including noise pollution, environmental degradation, and the need for sustainable transportation.

1.2 eVTOLs Architectures

The aviation industry is undergoing a significant transformation as a result of the introduction of new propulsion technologies and energy storage systems. In this context, eVTOLs represent a central element of this technological revolution. In view of the considerable interest in this new category of aircraft, by the end of 2022 more than 500 eVTOL prototypes and production models had been shared with the public, thereby underscoring the accelerated rate of development by the various manufacturers.

The published prototypes are highly diverse, and there is currently no established standard configuration for eVTOLs, in contrast to the established standard configuration for conventional aircraft. In light of this, different manufacturers are studying a variety of configurations in accordance with their respective areas of expertise, with the objective of identifying the optimal configuration.

The objective of this chapter is to provide an overview of the main existing eVTOLs by analysing the main configurations that exist today. The description and analysis of existing configurations will be useful in the following chapters in order to identify the most suitable configuration on which to base the design of new solutions in this field.

eVTOLs can be classified into two principal groups:

- **Wingless**;
- **Powered Lift**.

The following figure presents a schematic overview of the various types of eVTOLs currently available on the global market, comparing them with the well-known helicopters. For each type, the figure includes a reference to the type of propulsion system and direction of thrust vectoring. Subsequently, the existing types will be analysed in detail, illustrating each with a real example of an eVTOL. Finally, the strengths and weaknesses of each type will be discussed.

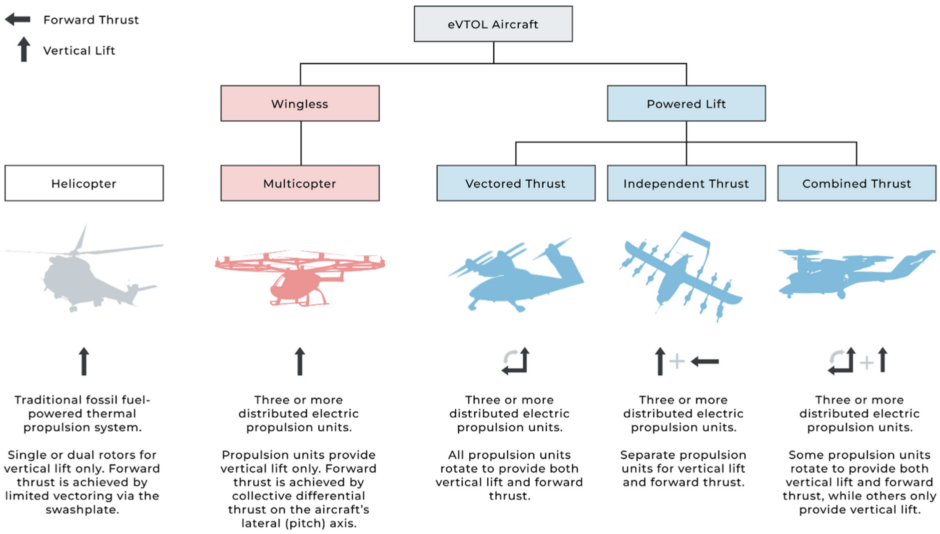

Figure 1.9: eVTOLs Configurations [1]

The wingless configuration is relatively simple and highly efficient for vertical take-off, landing and hovering due to low disc loading. However, multicopters are unable to operate at cruising efficiency without wings, which restricts their application to the UAM market. In contrast, multi-rotor eVTOLs offer a number of significant operational advantages, including a greater degree of control over the aircraft during flight and an increased level of manoeuvrability that allows for highly precise movements in all directions, including the ability to rotate on themselves. This flexibility permits their operation in close proximity to structures and buildings, thereby optimising operational effectiveness and reducing flight time. They also exhibit a number of significant limitations, namely a reduction in both range and speed, which renders them unsuitable for large-scale, long-duration and long-distance operations. Additionally, they are inefficient with respect to the other configurations, resulting in a notable increase in energy demand. The current state of battery technology limits flight time to approximately 20 to 30 minutes with a light payload, while models capable of lifting heavy loads exhibit a considerable reduction in flight time [14].

Figure 1.10: Wingless/Multicopters: Volocopter VoloCity and E-Hang EH216-S

The Powered Lift eVTOL can be further categorised into three distinct groups:

- **Vectored Thrust:** These eVTOLs utilize all of their lift/thrust units for both vertical lift and cruise. This is achieved by rotating the resulting thrust points in various ways, including the rotation of the entire wing-propeller assembly (tilt wing), the rotation of the lift/thrust unit itself (tilt fan for ducted fans and tilt prop for propellers), or the rotation of the entire aircraft frame pivoted on the fuselage (tilt body or tilt frame).

Figure 1.11: Tilt-Wing: Lilium Jet; Tilt-Fan/Prop: Joby S4; Tilt-Body: Aurora Pegasus

- **Independent thrust:** this type of eVTOLs represent a category of powered lift eVTOLs that utilise entirely distinct lift/thrust units for vertical lift and forward flight operations. The thrust points of the lift/thrust units remain fixed against the direction of flight, so they are not vectored. This category of eVTOL is also known as "Lift + Cruise". The rotors associated with cruise thrust are typically singular and situated towards the rear of the aircraft in push mode.


Figure 1.12: Lift + Cruise Type: Eve Air Mobility - Eve and Beta Alia

- **Combined thrust:** Combined thrust eVTOLs represent a fusion of vector thrust and independent thrust eVTOLs. This category of eVTOLs represents a compromise between the practicality of Lift + Cruise aircraft and the desired efficiency of vector thrust aircraft. In this configuration, all rotorcraft units are used for vertical flight, while only some lift/thrust units are used for cruise. To perform the cruise, combined thrust eVTOLs vector only a portion of their lift/thrust units, while the other lift/thrust units remain in the fixed role of increasing vertical lift.

Figure 1.13: Combined Thrust Type: Vertical Aersopace VX4 and Archer Midnight

eVTOL vehicles with a powered-lift configuration offer a multitude of advantages that make them particularly well-suited to advanced air mobility applications. A principal benefit is their capacity to integrate vertical take-off and landing (VTOL) operations with high aerodynamic efficiency during horizontal flight, a characteristic that can be achieved with the presence of wings or load-bearing surfaces. This configuration enables eVTOL powered-lifts to operate in restricted areas, such as densely populated urban zones, without the necessity for extensive runways.
Moreover, the capacity of these aircraft to utilise a single propulsion system for both vertical lift and forward flight optimises overall efficiency, reducing weight in comparison to configurations that employ separate propulsion systems, which, however, entails a slight increase in system complexity.
The reduction in weight results in a greater range and payload, which makes eVTOL-powered lifts particularly effective for the transportation of passengers and cargo in urban environments.
Another significant advantage is the operational flexibility offered by vector thrust configurations, which allow the aircraft to quickly adapt to different phases of flight, while ensuring a high level of control and stability. This capability increases the safety and efficiency of operations, especially in complex flight conditions or congested environments.

This type of vehicle also has a number of disadvantages. One of the main ones is the mechanical and technological complexity associated with the powered lift configuration. This complexity leads to increased production, maintenance and operational costs compared to aircraft with simpler configurations, such as multicopters. The need for advanced vector thrust control systems and integration between different flight modes leads to further technical complexities, increasing the risk of failure or malfunction.
Furthermore, energy efficiency is particularly compromised when switching between vertical and horizontal flight modes as it requires intensive use of energy, limiting the aircraft's range. Finally, the need to balance thrust between the various phases of flight results in less overall stability of the aircraft, requiring complex advanced control systems to ensure safe flight [1].

Initially, eVTOL designers adopted heterogeneous design approaches, proposing different configurations inspired by the success of unmanned drones. However, currently the scientific and engineering community seems to be converging on the *powered lift* configuration. Although this configuration is more complex to develop and to integrate in terms of its structural and aerodynamic characteristics, it offers significant advantages in terms of energy efficiency, payload and range. This makes it particularly suitable for urban and intercity air transport applications. This standardization phenomenon has been described by some experts as a '*Boeing 367-like moment*' [15], as it is reminiscent of civil aviation's transition to a dominant jet aircraft design. In the early years of jet aviation, there was considerable variation in aircraft configurations, with each manufacturer pursuing different technical and architectural solutions. The Boeing 367-80, subsequently marketed as the Boeing 707, established the standard with its tube-and-wing design, characterised by a tubular fuselage, arrow-shaped wings and two or four thrusters mounted under the wings. This configuration was subsequently demonstrated to be optimal for aerodynamic efficiency and long-range operations, exerting a profound influence on subsequent designs and becoming the benchmark for jet aircraft development. Similarly, it seems likely that the powered lift configuration will become a benchmark for the future generation of eVTOLs, establishing a new industry standard.

1.3 eVTOLs Certification

The certification of eVTOLs is a responsibility that has been assigned to the EASA (European Union Aviation Safety Agency) in Europe, while in the United States, this responsibility has been assigned to the FAA (Federal Aviation Administration). In this chapter, an analysis will be presented of the certification process for eVTOLs by EASA, with a particular focus on the documents and requirements established by this agency. It is important to note that although EASA and FAA are distinct entities, the certification processes adopted by both agencies frequently exhibit similarities. Consequently, the descriptions presented in this chapter may also be pertinent outside the European context.

As previously indicated in preceding chapters, a multitude of eVTOL initiatives have been undertaken in recent years, each exhibiting distinctive configurations. As reported in the EASA document *Special Condition for Small-Category VTOL Aircraft* «EASA has reviewed more than 150 VTOL project configurations, at different stages of maturity, all aiming at addressing a potentially new market» [16]. The available data indicate that there is a wide variety of configurations, with limited common characteristics, with the exception of VTOL capability and distributed propulsion. In view of the variety of configurations and the significant differences from conventional aircraft, EASA concluded that it would not be feasible to certify eVTOLs using existing certification specifications.

Indeed, the implementation of existing certification specifications, such as CS-23 (for light aircraft) and CS-27 (for helicopters), with certain adaptations, would not be adequate to ensure the requisite level of safety, given the intrinsic differences between conventional and vertical take-off and landing aircraft. Consequently, the EASA has opted to develop a dedicated *Special Condition (SC)*, which is primarily based on Amendment 5 of CS-23 and is also aligned with the FAA Part 23. This SC incorporates aspects of CS-27 and introduces new requirements where necessary, taking into account the distinctive features of eVTOLs, including electric and hybrid propulsion systems, battery management, and specific requirements pertaining to vertical take-off and landing.

The Special Condition sets forth supplementary technical requirements with the objective of ensuring the operational safety of these aircraft, taking into account their technical innovations. The main areas of focus include the safety of the propulsion system, the management of battery reliability, and the assurance of operational safety in complex flight scenarios. The SC thus provides the requisite guidance for the integration of these vehicles into existing aircraft systems in a manner that is both safe and efficient.

In addition to the Special Condition, the EASA has developed and published a series of Means of Compliance (MOC) and Acceptable Means of Compliance (AMC) to provide greater clarity and transparency for companies wishing to develop and certify eVTOLs [17]. The aforementioned documents provide acceptable methods and approaches for demonstrating compliance with safety requirements, thereby facilitating competition and ensuring a fair and transparent certification process.

The main requirements established by the EASA for eVTOLs are as follows:

- Vertical take-off and landing capability;
- All-electric or hybrid propulsion;
- Capacity to carry less than ten passengers;
- Maximum take-off mass less than 3175 kg.

It is also important to report the management and classification of *Failure Conditions* (FC), which are defined as the failure conditions that an aircraft might face during its operational cycle. In order to guarantee the adoption of appropriate safety levels in the event of malfunctions or failures, the EASA has developed a Failure Condition Classification system specifically designed for eVTOL aircraft.

In terms of certification, EASA distinguishes between two categories for eVTOLs:

(a) **Enhanced Category**, which is dedicated to aircraft intended for commercial operations in urban areas and which must maintain "continuous safe flight" even in the event of a critical failure;

(b) **Basic Category,** which is intended for aircraft that must be capable of making a controlled landing in emergency situations.

The following table, derived from *EASA's Special Condition* document, outlines the primary categories of fault conditions for eVTOLs and the corresponding quantitative safety objectives with respect to the two category (Enhanced or Basic).

Additionally, it presents the levels of function development assurance, also known as Function Development Assurance Levels (FDALs). The FDALs indicate the level of rigour required in the function design, verification and validation process, based on the criticality of the associated failures. This is in accordance with reliability criteria ranging from FDAL A (highest criticality) to FDAL D (lowest criticality).

The table below categorises fault conditions into four groups, from 'Minor' to 'Catastrophic', with each group representing an increasing level of severity and requiring appropriate risk mitigation measures. Each failure condition has a quantitative safety objective expressed in terms of probability of occurrence per flight hour, reflecting the degree of acceptable risk for each function.

		Failure Condition Classifications			
	Maximum Passenger Seating Configuration	**Minor**	**Major**	**Hazardous**	**Catastrophic**
Category Enhanced	**-**	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-7}$ FDAL B	$\leq 10^{-9}$ FDAL A
Category Basic	**7 to 9 passengers**	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-7}$ FDAL B	$\leq 10^{-9}$ FDAL A
	2 to 6 passengers (see note A)	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-7}$ FDAL C	$\leq 10^{-8}$ FDAL B
	0 to 1 passenger (see note A)	$\leq 10^{-3}$ FDAL D	$\leq 10^{-5}$ FDAL C	$\leq 10^{-6}$ FDAL C	$\leq 10^{-7}$ FDAL C
[Quantitative safety objectives are expressed per flight hour]					

Figure 1.14: Failure Condition Classification

The table is a useful tool for understanding how the EASA has established FDALs for each failure level, taking into account configuration, passenger seating and associated risk level. In the case of the most critical failures, such as those classified as catastrophic, an FDAL A is required. This implies the utmost rigour in design and an extremely low probability of occurrence ($\leq 10^{-9}$ per flight hour for advanced configurations). This level of rigour is comparable to that applied to conventional aircraft.
In contrast, failures classified as minor, which do not compromise operational safety, necessitate only an FDAL D. This imposes less stringent but still appropriate design standards to mitigate minor risks.

This classification is of great consequence in the certification process, as it provides the foundation for the design of the requisite safety systems and protective measures, ensuring that each eVTOL meets the necessary operational safety standards. The designation of a failure condition class implies the necessity for specific design responses, including the incorporation of redundancy in critical systems, the adoption of advanced emergency management technologies, and the implementation of rigorous maintenance procedures.

The eVTOL certification process represents a crucial step in the integration of this new class of aircraft into the commercial aviation landscape. The specific technical requirements for eVTOLs are therefore being defined by the approach taken by government certification bodies, such as the European Aviation Safety Agency and the Federal Aviation Administration, with the objective of ensuring high standards of operational safety. The objective of this process is twofold: firstly, to regulate a rapidly evolving sector, and secondly, to establish the foundations for the safe use of these aircraft within the existing aviation system.

Chapter 2

Aircraft Modelling

The eVTOL development process is based on the same workflow used for conventional and unconventional fixed-wing aircraft. However, the models and methods outlined in the following paragraphs have been specifically updated to address the design of eVTOL aircraft.
The modelling cycle can be summarised as follows:

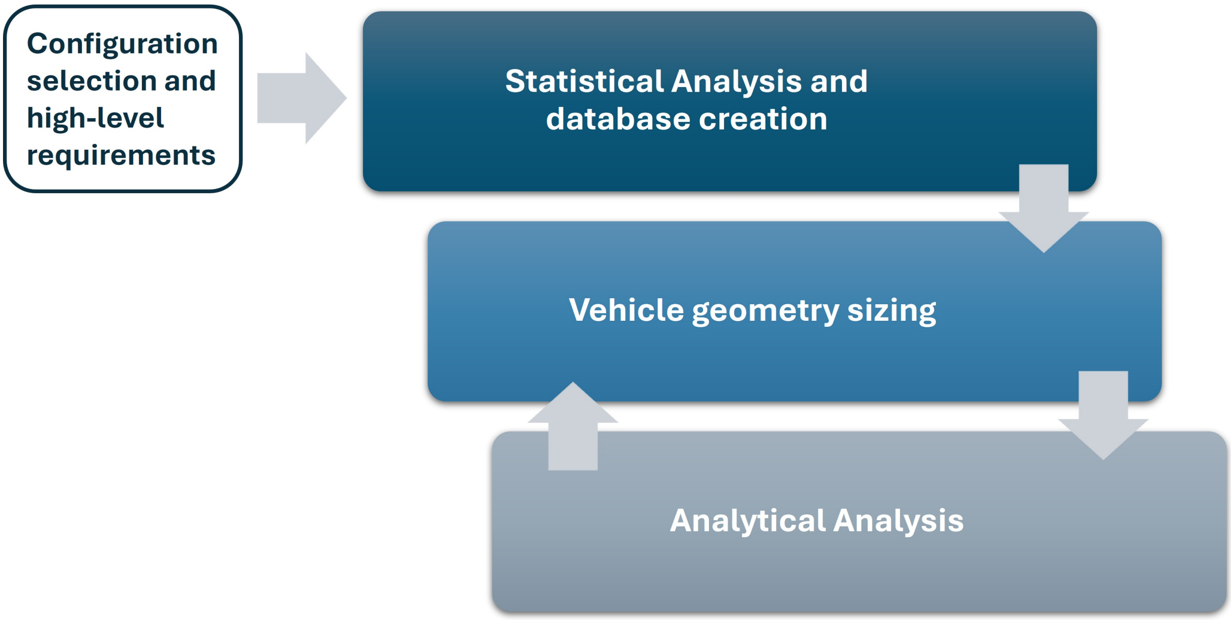

Figure 2.1: Aircraft Modelling Cycle

2.1 High-level Requirements

The preliminary specifications of the model, upon which its development is based, are outlined below:

- **Range:** 100 miles ($\sim$160 km);
- **Payload:** 4 passengers + 1 pilot;
- Obtain **Type Certification** from the European Aviation Safety Agency (EASA);
- Enter into service between 2024 and 2026.

These requirements represent the foundations of the European project 'eVTOLUTION', to which this thesis refers. The project has received financial support from the European Union's Horizon Europe program, as outlined in grant agreement No 101138209. Further details about the project can be found at [18].

In accordance with the specified parameters, a preliminary statistical analysis will be conducted to identify the initial geometric and performance parameters. Subsequently, analytical methods will be employed to estimate the massive components of the aircraft. It should be noted that the entire development process is iterative, and thus the parameters will be updated at the conclusion of each analysis.

2.2 Statistical Analysis

The preliminary design of a new aircraft can be based on an analysis of the various eVTOL aircraft designs that have been developed by competitors around the globe. This phase is crucial, as it provides the opportunity to gain insight into existing trends in aircraft design and performance, thereby establishing a robust basis for the preliminary design of new aircraft and optimizing the design process. A statistical study conducted at the beginning of an aircraft design offers two key advantages. Firstly, it provides an overview of existing technologies and configurations, providing insights that influence initial design assumptions. Secondly, it allows for the extrapolation of trends that can be used to define future technologies and configurations.

At this preliminary stage, particularly for newer aircraft designs such as eVTOLs, for which comprehensive technical specifications are not yet available, it is not feasible to conduct precise and detailed analyses pertaining to the specific design of the aircraft. It is therefore essential to carry out a statistical analysis of known data relating to similar aircraft. This approach allows the identification of specific reference parameters and correlations between geometric and performance factors that are not explicitly defined as requirements and for which there are currently no established estimation methods.

In the following paragraphs, the various mass components of the aircraft will be referred to as either "masses" or "weights," as the terms are used interchangeably despite the fact that they differ by a factor of 9.81 m/s^2.

The implementation of the statistical analysis is based on the following sequence of steps:

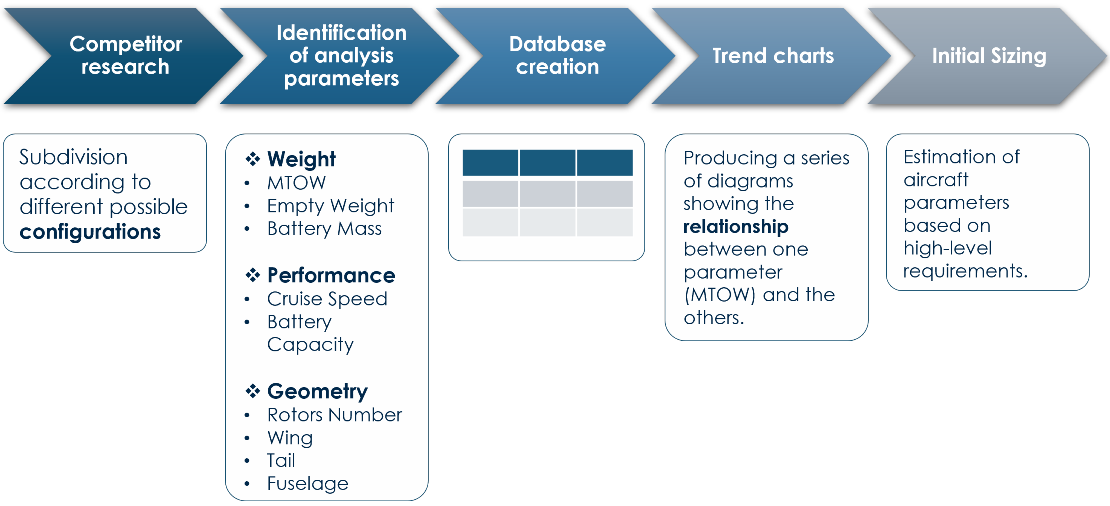

Figure 2.2: Statistical Analysis

A wide range of eVTOL configurations was selected for analysis, with a view to examining the most relevant international projects. In particular, it was decided to focus on **powered lift configurations**, as these are the configurations chosen internationally by the various manufacturers, as they are the most advantageous from various points of view.

The fundamental parameters were collected from a variety of sources, including magazines, articles and web pages. These parameters included:

- **Geometric characteristics:** fuselage length, wingspan, wing surface area and number of rotors;
- **Performance characteristics:** cruise speed, range, load capacity, number of passengers and take-off mass;
- **Massive characteristics:** MTOW, empty weight, battery mass.

Once the data had been collected regarding the various eVTOL designs, the subsequent step was to collate this information and store it in a table in an organised manner. This table correlates the different eVTOL models with their respective performance, geometric and mass characteristics. The organisation of the data enabled direct comparisons to be made between the various eVTOL configurations. This permitted the analysis of correlations between the geometric and performance characteristics of the aircraft, and provided a foundation for further statistical and design analysis.

2.2.1 Maximum Take-Off Weight (MTOW)

The initial correlations subjected to analysis were those between **payload mass-MTOW**[1] and **range-MTOW**, given that the payload mass and range were defined by the specifications. These statistical relationships thus permitted the calculation of take-off mass as an average of the two outcomes:

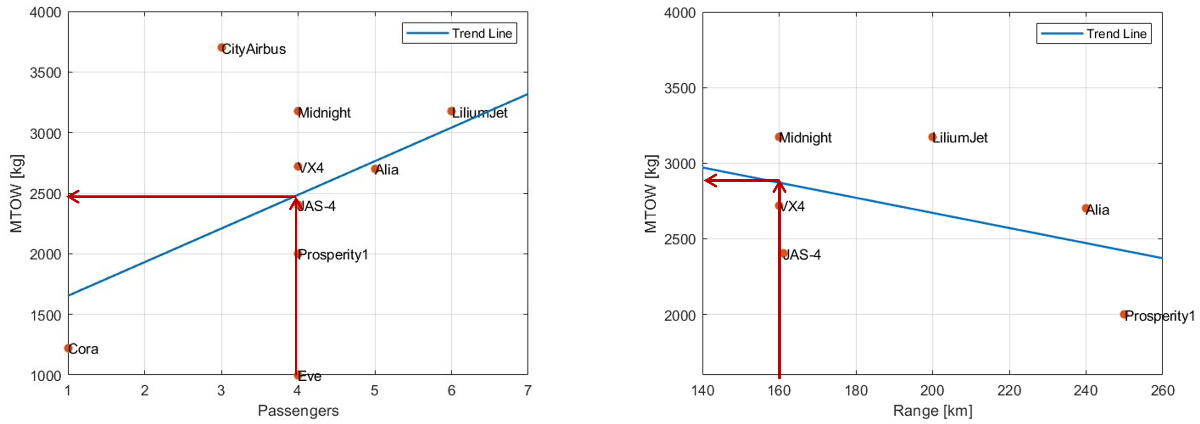

Figure 2.3: MTOW estimation

The mean result, representing a preliminary estimate of the take-off mass of the eVTOL aircraft under examination, is 2700 kg.

Preliminary Estimation		
Variable	**Value**	**Unit**
MTOW	2700	kg

Table 2.1: MTOW first estimation

The mass founded is subsequently employed as the dimensional variable for the calculation of all other geometrical and performance parameters.

[1]The payload mass is defined by the specifications assuming 80kg for the pilot and 115kg for passengers (35kg for luggage)

2.2.2 Massive and Performance parameters

The statistical analysis permitted the evaluation of the relations between **MTOW-EW** and **MTOW-W$_B$** thus enabling the estimation of the empty mass of the aircraft (EW) and the mass of the batteries (W_B).

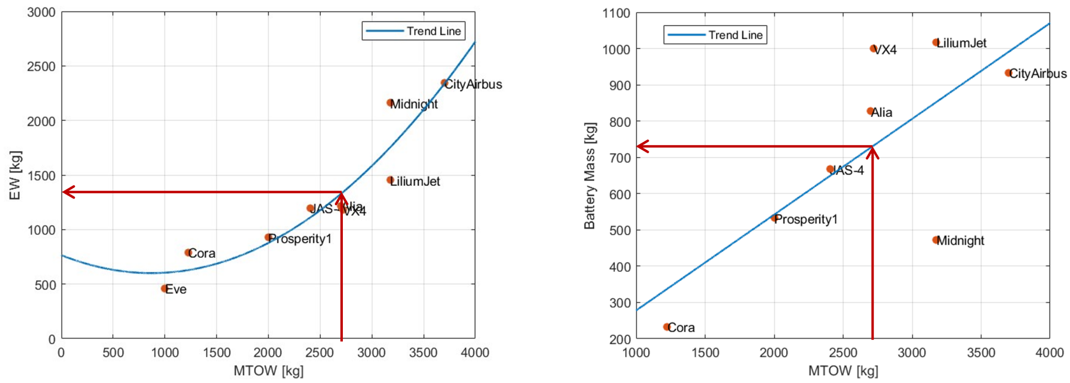

Figure 2.4: Massive parameters estimation

Moreover, in order to evaluate the battery capacity (C_B) and disk load[2] (K_d), the relationship between the **MTOW-C$_B$** and the **MTOW-K$_d$** was examined.

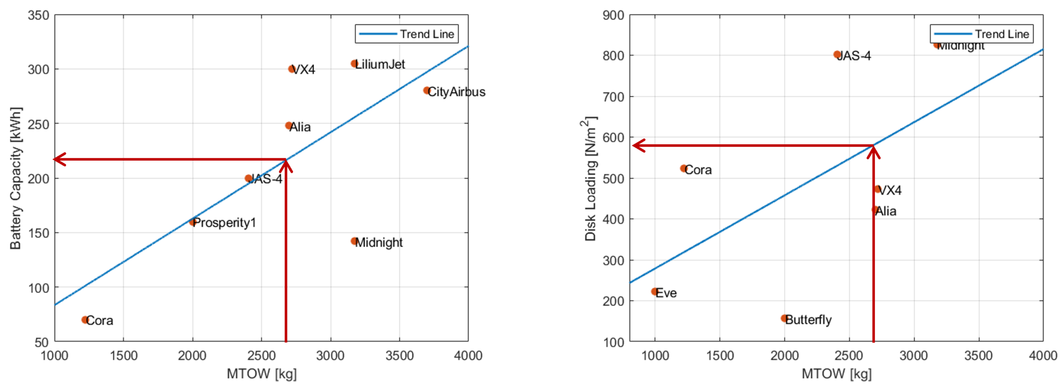

Figure 2.5: Performance parameters estimation

The results of the previous analysis are summarised in the following table.

Preliminary Estimation		
Variable	**Value**	**Unit**
EM	1400	kg
W$_B$	720	kg
C$_B$	220	kWh
K$_d$	590	N/m^2

Table 2.2: Mass and Performance components first estimate.

[2] The disk loading was normalized with respect to the single rotor

2.2.3 Geometric parameters

Similarly, the geometric parameters estimated from the statistical analysis were:

- Wing span (b);
- Fuselage length (L_f);
- Rotor diameter (D_R);
- Rotor number (n_R).

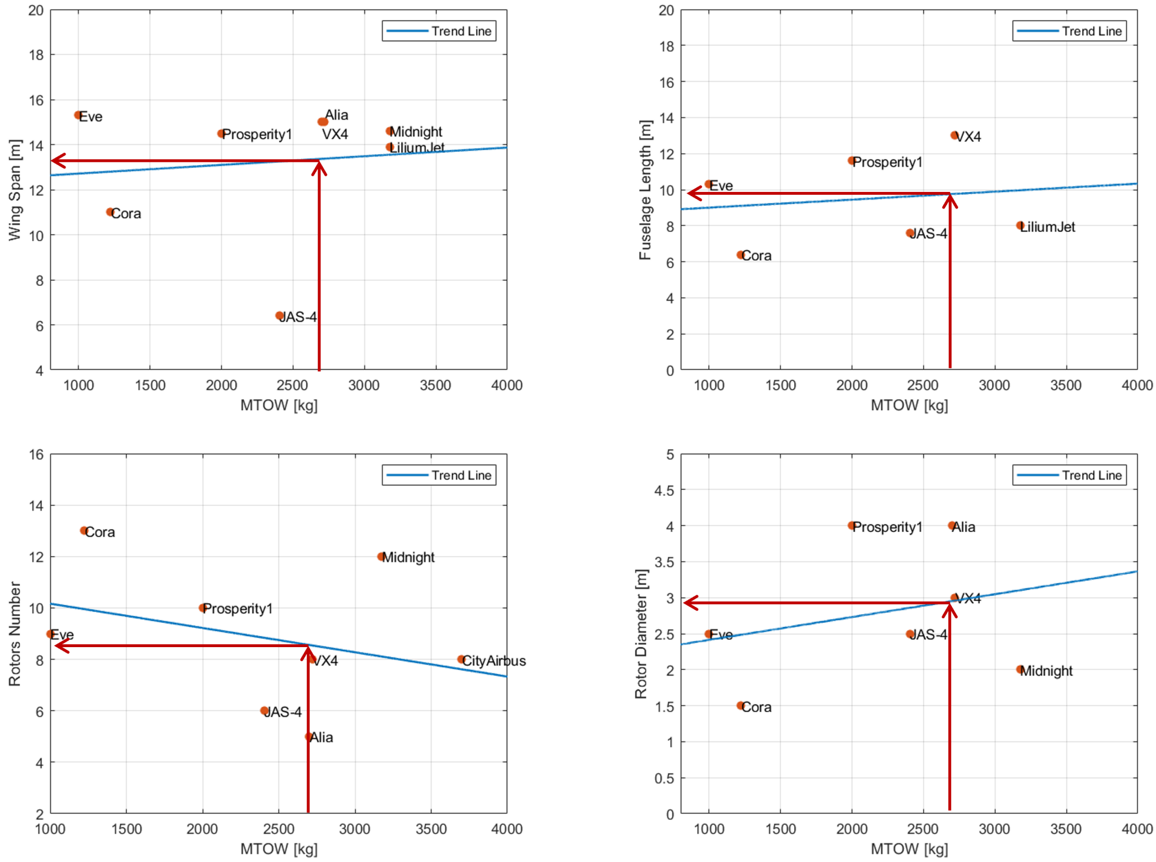

Figure 2.6: Wing Span, Fuselage Length, Rotor number and diameter estimation

Preliminary Estimation		
Variable	**Value**	**Unit**
b	13	m
L_f	10	m
n_R	8/9	-
D_R	3	m

Table 2.3: Geometric components first estimate.

2.2.4 Results and Preliminary Sketches

Once the statistical analysis was complete, the collected geometric data were employed in the development of a preliminary sketch of the eVTOL aircraft, with particular focus on the top and frontal views (Fig.3.8). This step enabled the generation of a graphical representation of the overall dimensions of the aircraft, including wingspan, fuselage length and rotor arrangement.

However, it is important to note that the size of the tail of the aircraft was not determined through statistical analysis, as the data collected did not include specific information on this element. Consequently, the proportions and dimensions of the tail were approximated based on general design assumptions, but cannot be considered reliable.

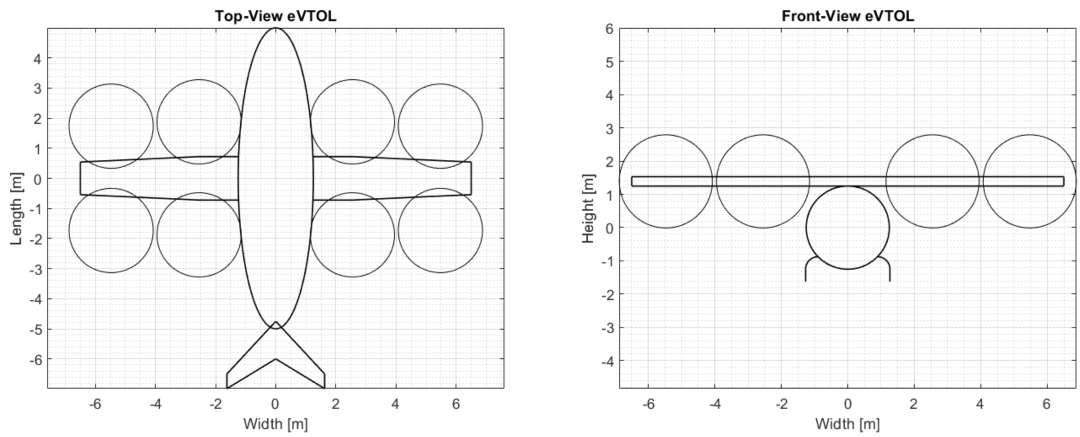

Figure 2.7: Top View and Front View

The following tables present a summary of the results of the statistical analysis:

Preliminary Estimation		
Variable	**Value**	**Unit**
MTOW	2700	kg
b	13	m
L_f	10	m
n_R	8/9	-
D_R	3	m
EW	1400	kg
W_B	720	kg
C_B	220	kWh
K_d	590	N/m^2

Table 2.4: Statistical analysis results

2.3 Analytical Analysis

The objective of analytical analysis is to construct a mathematical model that accurately reflects the characteristics of the aircraft under investigation. This method enables the evaluation of the relationships between design parameters and desired performance, thereby providing a foundation for the investigation of the aircraft's behaviour under different operating conditions. By analysing these relationships, designers are able to optimise various aspects of the aircraft at an early stage of the development process. This is one of the primary benefits, as it allows designers to obtain information at the initial stages of the project that is either more or less reliable and detailed regarding the characteristics that the aircraft will possess. This preliminary data is indispensable for the continuation of the subsequent study and analysis.

In the context of conventional fixed-wing aircraft, the sizing methods employed for estimating an aircraft's mass, layout, geometry and power requirements to meet mission requirements are well established. However, these conventional methods are inadequate for eVTOL aircraft sizing for two principal reasons:

- firstly, the distributed electric propulsion systems and energy storage technologies utilised in these aircraft;
- secondly, the vertical take-off and landing capability of these aircraft.

Furthermore, traditional aircraft design methods are based on the assumption that liquid fossil fuels lose mass during flight. Batteries, which are the sole power source for eVTOL aircraft, do not exhibit this characteristic. Consequently, the overall weight of an eVTOL aircraft remains relatively constant throughout its flight. This characteristic significantly alters the performance dynamics and requires innovative analytical approaches. It is therefore evident that a new model is required which is capable of providing a comprehensive description and facilitating the eVTOL study.

The analysis will be founded upon a series of fundamental steps, the objective of which is to estimate and optimise the mass and performance characteristics of the eVTOL aircraft, as represented in the following diagram.

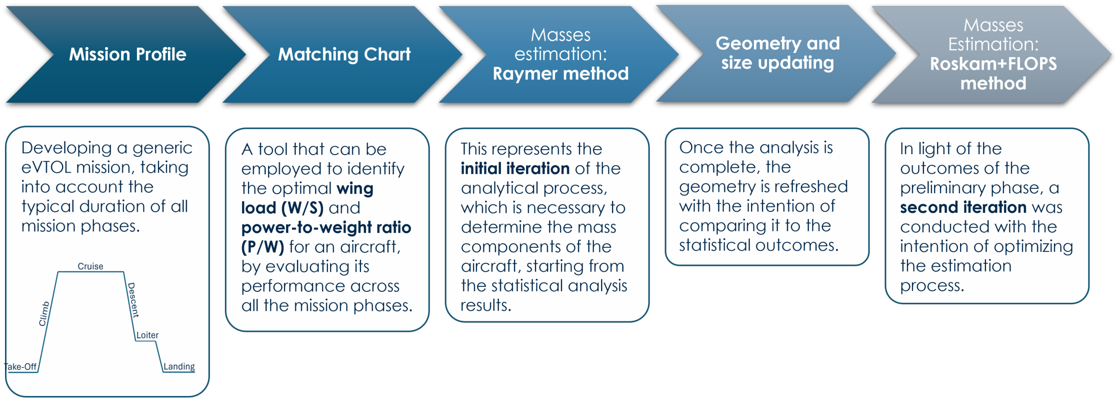

Figure 2.8: Analytical Analysis

Firstly, in order to calculate the mass of the aircraft, it is necessary to construct a mission profile to which the aircraft will be subjected. Secondly, a matching chart will be created. The purpose of this chart is to allow the selection of optimal performance values that reflect the requirements for the entire mission.
Based on the mission profile and the matching chart, the mass analysis will be carried out in the two following steps.
In the initial phase of the development, the Raymer method will be used to obtain results in an easy and efficient manner through the utilisation of statistical relationships. This approach may lead to potential inaccuracies. However, if used correctly, the results can be closer to reality. Based on these mass results, the geometry and dimensions of the aircraft are updated and compared with the statistical output to verify the accuracy of the design.
Subsequently, in the second stage, the geometric results will be employed in a further iteration utilising a hybrid approach, combining the Roskam method with the NASA FLOPS method, with the objective of further optimising the results obtained in the preliminary phase.

2.3.1 Mission Profile

The mission profile on which the analysis will be based represents a ’constrained intracity’ mission. The scenario represents an aircraft connecting locations within congested urban areas and in more adverse operating conditions. The take-off and landing require an extended period of vertical flight, with additional time spent in low-speed manoeuvres to comply with the departure and arrival route. Some holding time is required due to air traffic or weather, and a high cruise speed is needed to overcome headwinds or minimise flight time.

To provide a more detailed description, the mission profile is structured as follows:

Mission Profile				
Phases	**Duration (min)**	**Range (km)**	**Start Altitude (m)**	**End Altitude (m)**
Take-off	2	0	0	30
Manoeuvres	0.5	0	30	30
Initial Climb & Transition	4	10	30	300
Climb	3	20	300	610
Cruise	15	90	610	610
Descent	3	20	610	300
Hold	4	10	300	300
Approach & Transition	3	10	300	30
Manoeuvres	0.5	0	30	30
Landing	2	0	30	0

In conclusion, the eVTOL has a total range of 160 km (100 miles), a maximum altitude of 610 m (2,000 ft) and a duration that can vary between 25 and 35 minutes, in compliance with the specified requirements.

The subsequent images illustrate a graphical representation of the mission profile as a function of time and range.

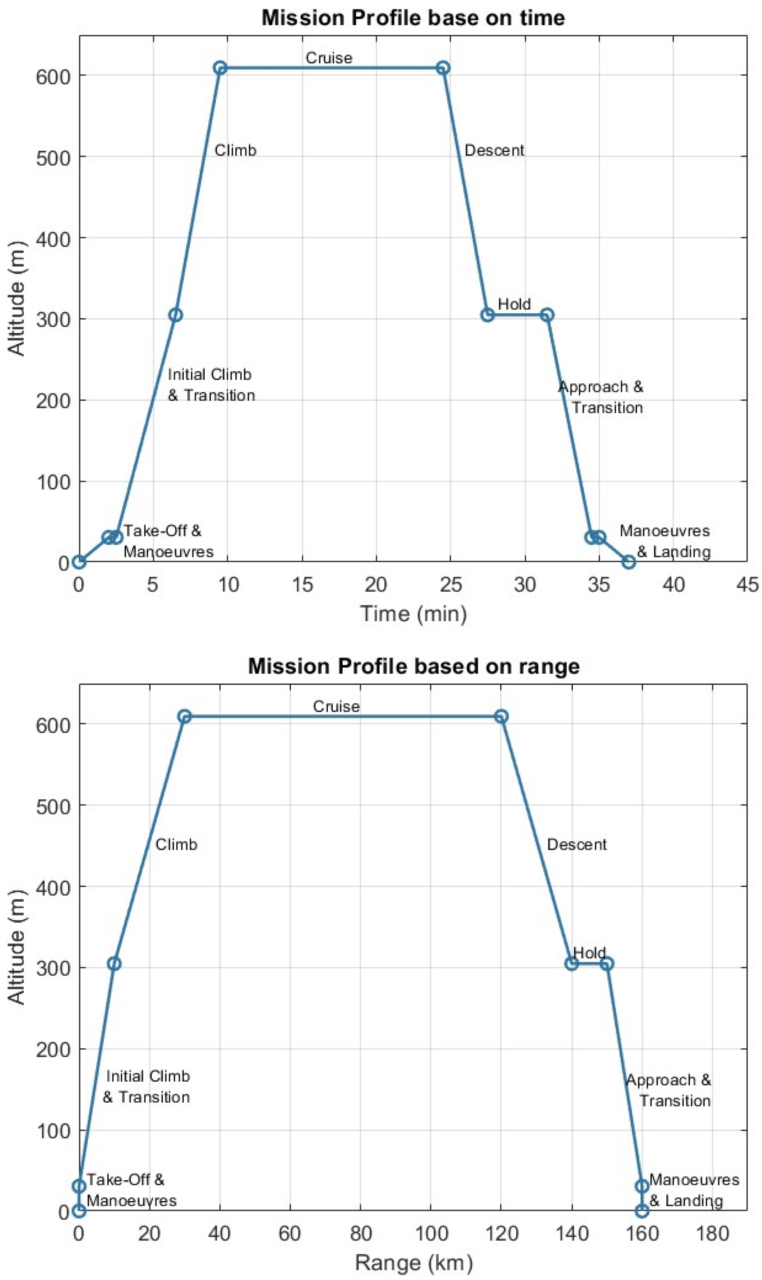

Figure 2.9: Mission Profile

2.3.2 Matching Chart

In order to identify the optimal geometric and performance requirements for the aircraft, a simple and intuitive tool is employed: the Matching Chart. This chart depicts a set of lines, each of which refers to the flight performance of a specific mission phase. Furthermore, each line is expressed as a function of two key design parameters: the **weight-to-power ratio** and the **wing load**. By employing this approach, a combination of design parameters can be defined in order to optimise performance and achieve the desired outcomes.

The chart was constructed on the basis of four main flight conditions: take-off, cruise, climb, descent and stall. These conditions encompass the various phases of flight that an eVTOL will experience, each with unique aerodynamic and performance requirements. The analysis of the flight performance referred to all the main flight conditions allows a more refined development and an efficient integration of the aircraft's systems. This analysis provides the design with greater robustness and reliability.

The equations used to describe these mission phases in the matching chart plot are outlined in detail in [19] and are presented below:

- **Take-Off:** during this phase, the aircraft operates in multi-rotor mode. To estimate the required power, the disk actuator theory has been employed. The characteristic equation given by:

$$\left(\frac{P}{W}\right)_{TO} = \sqrt{\frac{\frac{T}{A}\,g}{2\rho}}\;\frac{k_T}{FoM\;\eta_{prop}} \tag{2.1}$$

  where T/A is the disk load, g is the gravitational acceleration, ρ is the air density abd η_{prop} is the propeller efficiency.
  The actuator disc theory does not consider certain drag components; therefore, a parameter (FoM - Figure of Merit) has been added to account for all the necessary power components. FoM is defined as the ratio between the induced power and the total power given by induced speed.
  Additionally, in take-off, the propeller thrust is greater than the weight of the aircraft; thus, a further parameter has been added to account for this (k_T – ratio between T and W).

The take-off specific power does not depend on the wind loading W/S but on the disk loading T/A. This is because during the take off the aircraft is in multirotor mode.

- **Climb:** the requested power during climb phase can be easily obtained by using classical flight mechanic equation. The following equation can be used:

$$\left(\frac{P}{W}\right)_{CL} = \frac{1}{E_{CL}\,\eta_{prop}}\sqrt{\frac{2g}{\rho\, CL_{CL}}\frac{W}{S}} + \frac{ROC}{\eta_{prop}} \tag{2.2}$$

  where E_{CL} is the lift-to-drag ratio in climb, CL_{CL} is the lift coefficient during climb phase and the ROC is the rate of climb.

- **Cruise:** the cruise characteristics equation can be readily derived from the flight mechanic equation by setting the aircraft's rate of climb (ROC) to zero.

$$\left(\frac{P}{W}\right)_{CR} = \frac{1}{E_{CL}\,\eta_{prop}} V_{CR} \tag{2.3}$$

- **Stall:** to compute maximum wing loading two parameters have to be introduced: the stall speed (V_{stall}) and the maximum lift coefficient with flap deployed (CL_{max}). Considering the aircraft in level flight (L = Wg), the following equation can be obtained:

$$\left(\frac{W}{S}\right)_{max} = \frac{\frac{1}{2}\,\rho\, V_{stall}^2\, CL_{max}}{g} \tag{2.4}$$

The aforementioned equations were implemented in MATLAB to produce the graph P/W - W/S (Figure 2.10). The values used to construct the graph are given in the Appendix A.1.

Once the chart has been created, the next step is to identify the most critical combination of wing load and weight-power ratio (**design point**) in order to ensure that the aircraft meets the performance requirements in all operational phases.
The design point[3] is selected by identifying the most stringent condition from the various curves in the corresponding chart. As illustrated in Fig.2.10, the sizing curve corresponds to the take-off phase (P/W = 255 W/kg). This result is in

[3]Marked by a star in Fig.2.10

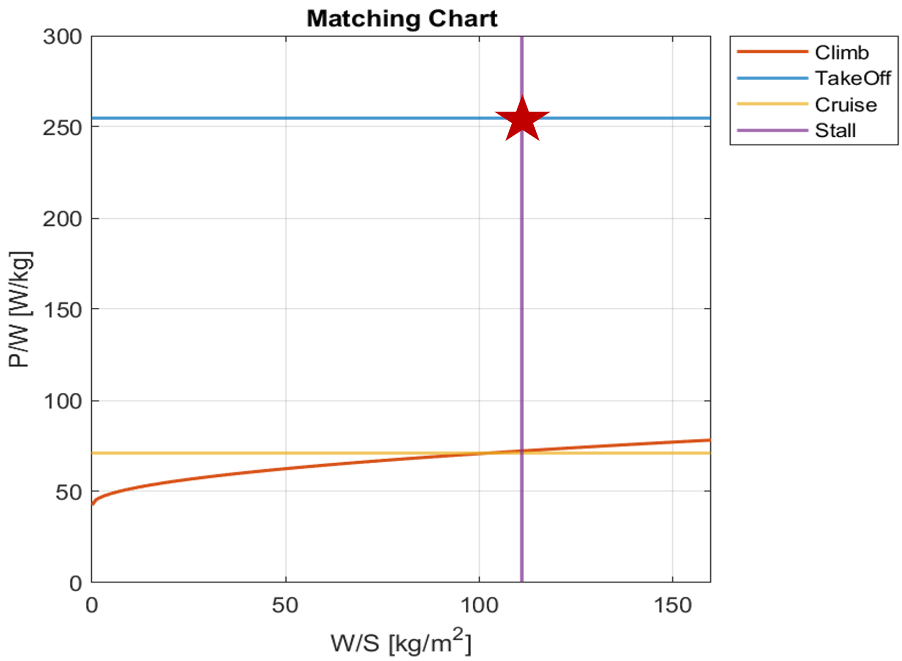

Figure 2.10: Matching Chart

accordance with the operational characteristics of an eVTOL, since take-off occurs in vertical mode, necessitating high thrust from the rotors. In this phase, the thrust-to-weight ratio (T/W) assumes a significant role, resulting in a higher power demand than in the other flight phases.

In order to optimise the overall aircraft design, the point corresponding to the wing load determined by the stall condition is selected ($W/S = 110\ kg/m^2$). The advantage of this approach is that it permits the attainment of a value of W/S that ensures an adequate wing surface area, thus avoiding the necessity for wings that are excessively large or ineffective for the cruise phase. This results in an equilibrium between the aircraft's operational requirements, optimising both aerodynamic performance and overall efficiency.

2.3.3 Masses Estimation: Raymer Method

The initial method employed for analytical analysis is founded upon the approach put forth by Raymer[4] for estimating the masses of electric aircraft. Raymer proposes a model for dividing the overall aircraft mass into three main components:

- the **empty mass**, which includes the aircraft structure, on-board systems

[4]Daniel P. Raymer, Chapter 20 of [20]

and other fixed equipment;

- the **payload mass**, which represents the payload, such as passengers, crew, or cargo;
- the **mass of the batteries**, which is the primary energy source for the electric aircraft.

$$MTOW = m_{pay} + EM + m_{battery} \tag{2.5}$$

Raymer's approach is particularly useful for conceptual design of electric aircraft as it provides empirical formulae based on historical data from previous designs, allowing for precise preliminary estimation of masses. Furthermore, this method enables the assessment of the impact of different design configurations on the total mass and, consequently, the operational performance of the aircraft.

Using empirical equations and an iterative process, the method allows the masses to be calculated progressively, evaluating the influence of different design configurations on the aircraft's total mass.

Payload Mass The payload mass can be easily calculated by determining the number of passengers the aircraft is designed to accommodate. In accordance with the design specifications, the aircraft is constructed to accommodate a total of four passengers, in addition to the pilot. Thus, assuming a mass of 115 kg for each passenger (80 kg for body weight and 35 kg for any baggage) and a mass of 80 kg for the pilot (with no baggage), the total mass of the payload is equal to:

$$m_{pax} = (80 + 35) \cdot pax + 80 \tag{2.6}$$

Batteries Mass The calculation for an electric aircraft (eVTOL) is conducted through an iterative process that determines the proportion of the aircraft's mass that must be allocated to batteries to meet the energy requirements of the mission. In contrast to the methodology employed for combustion-powered aircraft, whereby the calculation is based on fuel consumption and weight variation during flight, electric aircraft utilize an approach based on the parameter known as **Battery Mass Fraction (BMF)**. The Battery Mass Fraction (BMF) is an index that represents the fraction of the battery mass relative to the total mass of the aircraft, taking into account the energy consumption for each segment of the flight mission.

To calculate the batteries mass, the following steps have been implemented:

1. The BMF for each mission segment (such as cruise, loitering, climb, and descent) is calculated using specific formulae that consider the energy consumption required for that segment.

   - Cruise:

   $$BMF_{cruise} = \frac{R\ g}{3.6 \cdot ED_{battery} \cdot \eta_{batt2mot} \cdot \eta_{prop} \cdot L/D_{cruise}} \tag{2.7}$$

   where: R is the total range, $ED_{battery}$ is the energy density of the battery, η_{prop} is the propeller efficiency, L/D is the lift to drag efficiency in cruise and $\eta_{batt2mot}$ is the total system efficiency from battery to motor.

   - Loiter:

   $$BMF_{loiter} = \frac{E\ V\ g}{3.6 \cdot ED_{battery} \cdot \eta_{batt2mot} \cdot \eta_{prop} \cdot L/D_{cruise}} \tag{2.8}$$

   where E is the loiter endurance (loiter time – hrs).

   - Climb/Descent:

   $$BMF_{climb/descent} = \frac{h_{MAX}}{3.6 \cdot ROC \cdot ED_{battery} \cdot \eta_{batt2mot}} \frac{P/W_{TO}}{1000} \tag{2.9}$$

   where ROC is the eVTOL rate of climb and P/W_{TO} is the take-off power-to-weight ratio.

2. The total BMF required for a complete mission is obtained by summing the BMFs of all mission segments.

   $$BMF_{TOT} = BMF_{cruise} + (BMF_{climb/descent} \cdot 2) + BMF_{loiter} \tag{2.10}$$

   This sum represents the total energy required to complete the entire mission, from take-off to landing.

3. Once the total BMF is known, an iterative method can be applied to calculate the total weight of the aircraft and, consequently, the weight associated with the batteries alone.

Empty Mass The empty mass of the aircraft is calculated using an empirical formula proposed by the Raymer method by which the EW is estimated statistically from historical trends. This formula estimates the empty mass as a function of the maximum take-off weight and certain coefficients derived from statistical data on similar aircraft. The equation is generally of the form:

$$EM = A \cdot MTOW^C \tag{2.11}$$

where: EM is the empty mass of the aircraft, MTOW is the maximum take-off weight of the aircraft, A and C are empirical coefficients specific to the category of the aircraft (see Appendix B.1). To adapt this formula to the eVTOL, the coefficients are chosen assuming that the aircraft under consideration is a general aviation aircraft with two engines.

The data required for the application of the method are provided in Appendix B.2. The results of the method are summarised below:

Masses Estimation: Raymer Method		
Variable	**Value**	**Unit**
m_{pax}	540	kg
$m_{battery}$	887	kg
EM	1827	kg
MTOW	3253	kg

2.3.4 Geometry and size updating

In light of the mass parameters obtained, the geometric parameters that had previously been estimated[5] were updated.

By employing the MTOW determined through Raymer's methodology as the sizing parameter, the following results are obtained:

Geometry updating				
Variable	**Old Value**	**Unit**	**New Value**	**Unit**
Wing Span	13	m	14	m
Fuselage Length	10	m	10.00	m
Rotor Diameter	2.8	m	3.13	m

Table 2.5: Comparison of old and new geometric component values

The figures illustrate a comparison between the previous estimation of the geometry and the present results.

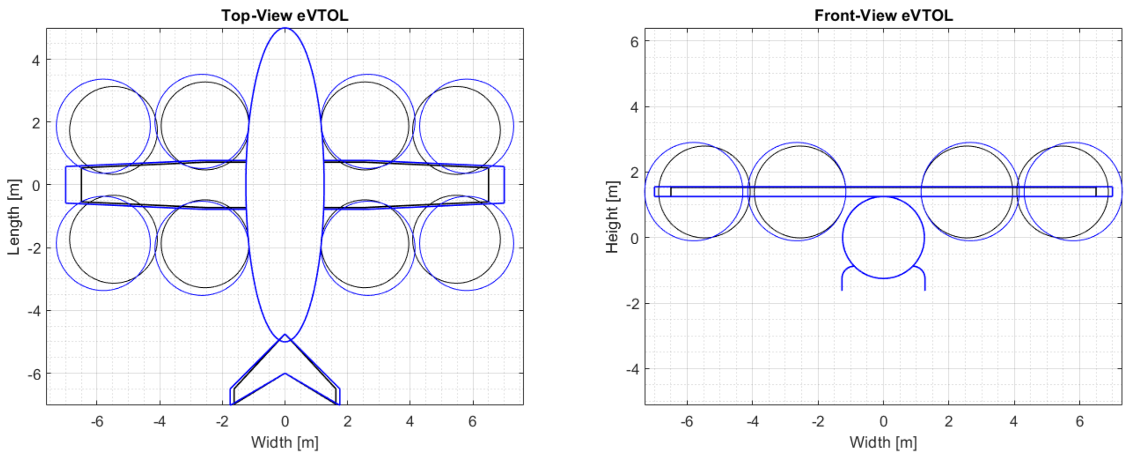

Figure 2.11: Geometry Updating: Top View and Front View

The black graph depicts the initial estimate derived from the data obtained through statistical analysis, whereas the blue graph represents the updated geometric representation.

[5] On the basis of statistical MTOW

2.3.5 Mass Estimation: Roskam + Flops Method

After defining the main aircraft weights, a second method was employed to obtain a more detailed estimation of the aircraft components. This second method is based on an approach that combines the Roskam method [1] with the FLOPS (Flight Optimisation System) method developed by NASA [21]. These two methods are similar to the Raymer in that they also use iterative approaches based on statistical formulae, but they provide a more detailed assessment of the masses of the various components. In Raymer's method, these components are generally combined into the empty weight; however, Roskam's method and the FLOPS method break down the estimates into more specific categories. By combining these two methods, mass estimation becomes not only more granular than that proposed by Raymer, but also more adaptable to specific design needs, which could result in greater accuracy for eVTOL aircraft.

Batteries Mass Roskam's method begins with the estimation of the mass of the aircraft by analysing the specific energy required to complete the flight mission for which the aircraft is designed. This is achieved by calculating the power required in various flight conditions and the flight time for each phase, which allows for the total specific energy needed to be calculated as follows:

$$E_{sp} = \sum P_i \, t_i \tag{2.12}$$

In order to accurately estimate the mass of the battery, it is essential to consider not only the energy density of the batteries, which has been set at 300 Wh/kg in anticipation of future technological developments, but also:

- the usable capacity of the battery is typically set below its total capacity to preserve its lifespan. This is correlated with the **depth of discharge (DoD)**, which indicates the percentage of the battery's total capacity used during a cycle. A higher DoD means a larger portion of the battery's energy is being utilized, but it can also accelerate the battery's degradation over time. Typically, a DoD of 80% is considered standard, meaning 80% of the battery's energy can be used before it needs recharging. DoD is the complementary value of the State of Charge (SoC), so both parameters can be used.

- the **end-of-life (EoL)** capacity of the battery. This is the point at which the degraded battery reaches a lower storage capacity than its original capacity and is no longer efficient for its designated use. Degradation of a battery is caused by a series of charge/discharge cycles and compromises both performance and safety;
- the **efficiency** of the batteries themselves, determined by their ability to convert stored energy (chemical energy) into usable energy (electrical energy) during charge and discharge cycles, with minimal energy loss.

In accordance with the aforementioned, the battery mass equation is augmented with the minimum state of charge (SOC_{MIN}), which is set at 20% and the end-of-life (EOL), which is fixed at 85%.

The mass of the battery is calculated as follows:

$$m_{battery} = \frac{E_{sp}}{SED} \cdot \frac{(1 + SOC_{MIN})}{(\eta_{battery} \cdot EOL)} \tag{2.13}$$

where SED is the Litium-Ion Specific Energy Density.

Fuselage Mass The majority of eVTOL concepts include a fuselage. To estimate the mass of the fuselage, a number of parameters must be considered, including the length of the fuselage (L_f), the maximum perimeter of the fuselage section (P_{max} - see Appendix C.1) and the number of passengers (Npax):

$$m_{fuselage} = 14.86 \cdot (MTOW)^{0.144} \cdot \frac{L_f^{1.161} \cdot (N_{pax} + N_{Crew})^{0.455}}{P_{MAX}} \tag{2.14}$$

Wings Mass Similarly, the mass of the wing components is calculated in accordance with the following formula:

$$m_{wings} = 0.04674 \cdot MTOW^{0.397} \cdot S_w^{0.36} \cdot \eta_w^{0.397} \cdot AR_w^{1.712} \tag{2.15}$$

where S_w is the wing surface[6], η_w is the wing load design factor and AR is the Aspect Ratio.

[6]Evaluated on the assumption that the wing is rectangular with a chord equal to the mean chord. See Appendix C.2

Landing Gear Mass It is calculated based on the length of the landing gear structure (L_{LG}) and the landing gear design load factor (η_{LG}):

$$m_{LG} = 0.054 \cdot L_{LG}^{0.501} \cdot (MTOW \cdot \eta_{LG})^{0.684} \tag{2.16}$$

Propulsive System Mass The propulsive system can be modelled as a series of electric motors and rotors/propellers connected in a network.
The following formula was employed to estimate the mass of electric motors:

$$m_{mot} = 0.165 \cdot P/W_{TO} \cdot MTOW \cdot (1 + PM) \tag{2.17}$$

The motors are sized to the maximum power requirement for the entire mission. This is usually in the Take-Off phase (P/W_{TO}). The formula also includes a power margin (PM) and the number of motors (N_{mot}) that are installed on the aircraft.

The mass of the propellers is calculated in the following manner:

$$m_{prop} = 0.144 \cdot \left(d_{prop} \cdot \frac{P/W_{TO} \cdot MTOW}{1000} \cdot N_{BL}^{0.5}\right)^{0.782} \tag{2.18}$$

Where N_{BL} is the blade number and d_{prop} is the propeller diameter. The equations used also include the total mass of the aircraft (MTOW), so an iterative method is required for resolution.

Electrical System Mass The mass of the electrical system was calculated using the equations proposed by the FLOPS method:

$$m_{el-sys} = [92 \cdot (L_f \cdot 3.28)^{0.4} (d_f \cdot 3.28)^{0.14} N_{eng}^{0.69} (1 + 0.044 \cdot N_{crew} + 0.0015 \cdot N_{pax})] \cdot 0.4536 \tag{2.19}$$

where d_f is the fuselage diameter.

Avionic System Mass Similarly, the avionic system mass is determined through the application of the following equation:

$$m_{avionic} = [15.8 \cdot (Range \cdot 0.62137)^{0.1} \cdot (F_{Area} \cdot 10.764)^{0.43}] \cdot 0.4536 \tag{2.20}$$

where F_{Area} is the fuselage area[7].

[7] Estimated using the formula set out in eq.(62) of the Flops Method. See Appendix C.4

Anti-Ice System Mass The mass of the anti-ice system was calculated as follows:

$$m_{AI} = \frac{b}{cos(sweep\_angle)} + 3.8 \cdot (d_{prop} \cdot 3.28) \cdot N_{eng} + 1.5 \cdot (d_f \cdot 3.28) \qquad (2.21)$$

The data required for the application of the method are provided in Appendix C.5.

The results of the second iteration are summarised below:

Masses Estimation: Roskam + Flops Method		
Variable	**Value**	**Unit**
Avionic Mass	136	kg
Anti-Ice Mass	88	kg
Payload Mass	540	kg
Battery Mass	700	kg
Fuselage Mass	150	kg
Wing Mass	124	kg
Landing Gear Mass	22	kg
Motor Mass	168	kg
Propeller Mass	117	kg
Electrical System Mass	1024	kg
MTOW	3089	kg

Table 2.6: Roskam+Flops Mass Estimation

2.4 Results and Final Considerations

In consideration of the outcomes obtained from the two methodologies employed in the preceding paragraphs, some observations can be made.
Raymer's method categorizes the mass components as follows

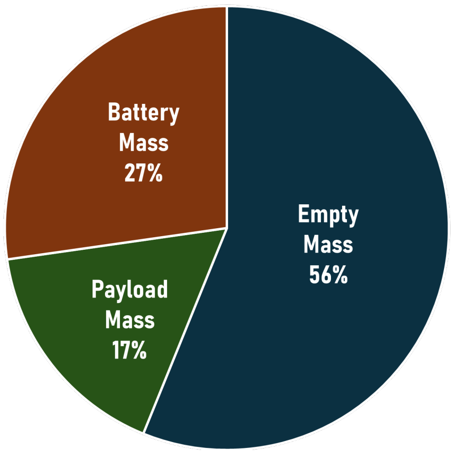

Figure 2.12: Estimated Mass Breakdown Using the Raymer Method

The alternative approach, designated as the Roskam+Flops method, led to the following outcomes:

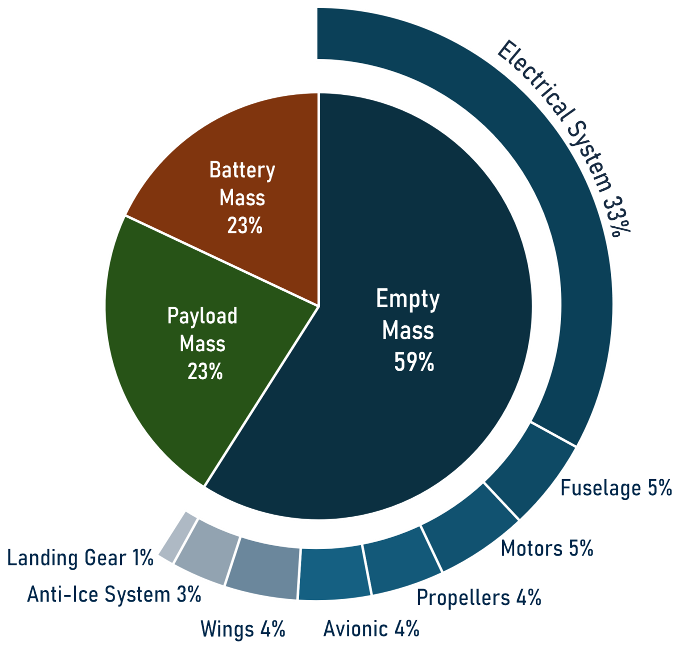

Figure 2.13: Estimated Mass Breakdown Using the Roskam+Flops Method

A primary observation is the similarity in the percentage distribution of the various mass components between the two methods.

The calculated empty mass (EM) exhibits minimal discrepancy between the two methods, exhibiting a high degree of similarity in absolute terms[8] and also in percentage terms. It is important to note that the EM estimate of the second method is undoubtedly more reliable than the first. This estimate was calculated on the basis of the mass of each of the main components of the eVTOL, although the second method is also based on statistical formulations, as in the first case. The fact that the same value is obtained for the empty mass confirms that the estimate is reliable.
A detailed analysis of the EM of the second method reveals that the preponderant mass component is the electrical system. This is an unsurprising result, given that this system is the most important on an eVTOL and powers the entire aircraft.

Furthermore, it should be noted that the anti-icing system was also considered in the mass study for the aircraft under consideration. The system has a notable impact on weight, and thus it is essential to consider the following factors when estimating this mass component: firstly, the method used, which is based on statistical data from fixed-wing aircraft, may yield unreliable results due to the differences between the fixed-wing configuration and eVTOL. Secondly, given the low flight altitude and short duration of eVTOL flights, this subsystem could be excluded from the analysis. A more detailed investigation of this aspect, which was not conducted in this thesis, is recommended.

There is also a discrepancy in the estimated percentage of battery, resulting in a difference of almost 200 kg in absolute terms. This discrepancy is significant as this is a significant amount of weight that has an impact on aircraft performance, especially in the case of a relatively small aircraft such as the eVTOL. The discrepancy in Raymer's estimate can be attributed to the inherent characteristics of the model itself. The model was developed several years ago and does not reflect the technological advances of recent years. In addition, the methodology was devel-

[8] The sum of the mass components of avionics, engines and propellers, fuselage, wings, anti-ice, landing gear and electrical system is the empty mass of the aircraft. The estimate of empty mass using the second method gives a value of 1891 kg. The empty mass estimate with the first method was 1830 kg.

oped for electric fixed wing aircraft and not specifically for eVTOLs. This results in a less accurate estimate as the energy consumption of an eVTOL is completely different to that of a fixed wing aircraft due to the vertical take-off and landing..

The payload mass is identical for both models. The discrepancy in percentage terms is attributable to the difference in the estimated total aircraft mass.

The final dimensions of the eVTOl are illustrated in the following sketches.

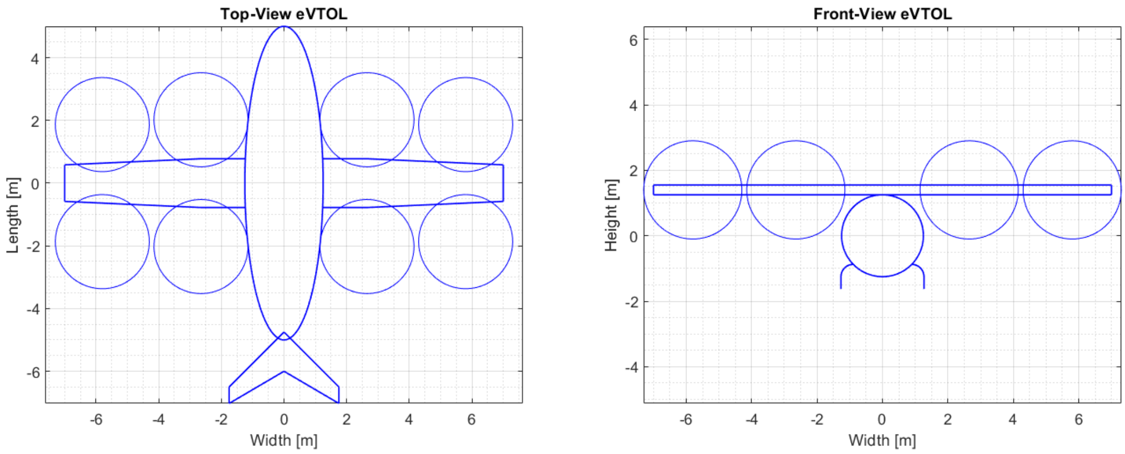

Figure 2.14: Final Geometry: Top View and Front View

The dimensions and geometric detail are presented in the table below.

Final Size and Geometry		
Variable	**New Value**	**Unit**
Wing Span	14	m
Fuselage Length	10.00	m
Rotor Diameter	3.13	m

Table 2.7: Final geometric component values

Chapter 3

PowerTrain and Battery Configuration

The objective of this chapter is to conduct a comprehensive analysis of specific components within the aircraft's electrical system. In particular, a more detailed examination will be conducted on the sizing of the batteries and the determination of the number of cells required, taking into account the performance requirements and regulations in case of failure.

Following the sizing of the battery, the resulting data will be subjected to analysis, serving as the basis for a series of sensitivity analyses. These analyses will evaluate the impact of specific key parameter variations on the system, considering the potential influence of future technological developments on aircraft design and performance.

Finally, potential failure conditions, such as rotor failure scenarios, will be examined. Rotor failure presents a critical challenge for eVTOLs, as rotors are essential for maintaining balance, especially during vertical flight. In the event of a rotor failure, the aircraft loses balance, and a control system must be implemented to restore stability by adjusting power distribution among the remaining rotors.

3.1 Battery Sizing

In light of the previously calculated data, the batteries were sized to meet the requisite specifications.

The analysis was conducted starting from the specific energy required to complete the mission, which was determined using equation (2.12). By combining the maximum take-off mass (MTOW), the end-of-life (EOL), the state of charge (SOC) and the battery efficiency, it is possible to calculate the total energy required to complete the mission using the following relationship:

$$E_{tot} = E_{sp} \cdot MTOW \cdot \frac{(1 + SOC)}{\eta_{battery} \cdot EOL} \tag{3.1}$$

In order to calculate the mass of the battery, it is necessary to consider the specific energy density (SED). This step is purely for the purpose of verification, as the value in question has already been established in Chapter 2.

$$m_{battery} = E_{tot} \cdot SED \tag{3.2}$$

The value of the mass of the batteries obtained is perfectly in line with the results of the previous sections, despite the use of a slightly different equation than previously applied.

Furthermore, calculating the volume of the batteries at this stage is also beneficial. This parameter is of significant consequence, as an unsatisfactory result could have a considerable impact on the overall aircraft sizing. In the event that the volume is found to be excessive in relation to the available space on board the aircraft, a revision of the sizing would be necessary. Potential solutions to this issue include:

- a reduction in the operating range (a smaller range would necessitate less energy);
- a reduction in the mass of the aircraft (a lighter aircraft would require less energy);
- an increase in the volumetric energy density (VED) in order to reduce the volume of the batteries.

The following equation was employed to calculate the volume of the batteries:

$$V_{battery} = \frac{E_{tot}}{VED} \tag{3.3}$$

3.1.1 Battery composition and cells configuration

In selecting the optimal power source for the aircraft in question, it was determined that solid-state batteries would be the most suitable option. At present, they represent one of the most promising technologies in comparison to conventional lithium-ion batteries, particularly for use in aircraft such as eVTOLs [22].

The subsequent illustration depicts the principal contrasts between a conventional lithium-ion battery (on the left, Figure A) and a solid-state battery (on the right, Figure B). Furthermore, the image illustrates the existence of four cells in series in both configurations.

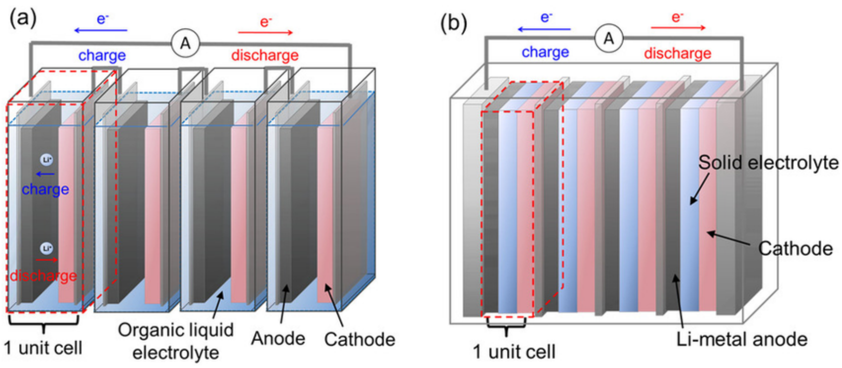

Figure 3.1: Comparison of a conventional Li-Ion battery and a solid-state battery [2].

The principal advantages of a solid-state battery are as follows:

- **Energy density:** they are able to store more energy than lithium-ion batteries. A higher energy density results in a longer flight time or greater payload capacity, thereby reducing the number of required recharges;
- **Safety:** the use of solid-state batteries eliminates the necessity for flammable liquid electrolytes, a characteristic inherent to lithium-ion batteries. This consequently reduces the risk of fire or explosion;
- **Life cycles:** they demonstrate a markedly higher resistance to degradation than other battery categories. They offer a longer service life and greater stability even after numerous charge and discharge cycles, thereby reducing maintenance and battery replacement costs;
- **Recharge time:** The batteries allow for a faster recharge than conventional batteries, which is a significant advantage for improving the operational efficiency of eVTOLs.

The development of a battery is founded upon an analysis of its internal components, specifically the cells, and the manner in which these cells are connected to one another.

Each cell is composed of three fundamental components: the anode (negative electrode), the cathode (positive electrode) and electrolyte (allows the transfer of ions between the anode and cathode during the charging and discharging cycles).

The configuration of the cells may be either in series or in parallel, according to the requisite voltage and capacity. The connection of cells in series results in an overall increase in battery voltage. In this configuration, the voltages of each cell are summed, while the capacity remains constant at the value of a single cell. In contrast, when cells are connected in parallel, the battery capacity increases, while the voltage remains unaltered.

In the majority of complex systems, including those utilised in eVTOLs, the cells are configured in a mixed manner, comprising both series and parallel arrangements. This technique is useful for achieving an acceptable result in terms of both voltage and capacity.

In order to ascertain the number of cells that constitute a battery and the manner of their interconnection, it is first necessary to calculate the energy associated with each individual cell. The cell energy is dependent upon two key factors: the capacity C and the nominal cell voltage V. The following equation can be used to find the total energy E stored in a cell [23]:

$$E_{cell} = C \cdot V \tag{3.4}$$

The energy stored in an individual cell plays an important role in this process. An increase in the capacity or voltage of the individual cell results in a proportional growth in the energy stored by each cell, leading to an overall increment in the battery's total energy storage capacity. The cell energy influences the total number of cells and, consequently, the number of cells in parallel. It can be observed that an increase in energy results in a decrease in the number of cells in parallel, while still meeting the minimum energy requirements (see Appendix D.2).

Once the energy of a single cell is known, the total number of cells required to meet the energy demands can be calculated using the following equation:

$$N_{c,battery} = \frac{E_{battery}}{E_{cell}} \tag{3.5}$$

where $E_{battery}$ is defined as the maximum amount of energy that can be stored in the battery, which is necessary to complete the mission. The battery energy capacity is calculated by dividing the total energy (calculated with Eq.3.1) by the number of batteries carried on the aircraft.
Equation 3.5 provides the total number of cells present within each battery pack.

It should be noted that the energy component sizing presented in this thesis is limited to the energy requirements of the propulsion system. In this sizing process, any additional energy demands for other electrical components of the aircraft are not considered. To address these needs, an additional battery could be integrated to power these subsystems.

The number of cells in series is calculated based on the voltage requirements of the electric motors that the batteries must supply. The formula for calculating the number of cells in series is as follows:

$$N_{c,ser} = \frac{V_{mot}}{V_{cell}} \tag{3.6}$$

Once the total number of cells and the number of cells in series have been determined, the number of cells in parallel that are contained in each battery can be calculated by this formula:

$$N_{c,par} = \frac{N_{c,battery}}{N_{c,ser}} \tag{3.7}$$

In order to ensure consistency and accuracy, the calculated values must be rounded up to the nearest whole number, given that cells are discrete components.

3.2 Evaluation of Battery System Configurations and Failure Scenarios

Following the initial battery sizing, this section presents an analysis of the optimal configuration of the aircraft's electrical system.

The objective is to identify the optimal number of batteries with which the aircraft should be equipped in order to meet performance and safety requirements, particularly in the context of various operational and failure scenarios. A variety of configurations will be presented, and the associated advantages and disadvantages will be evaluated. The aspects that will be analysed include redundancy, weight efficiency, uniformity of power delivery and the management of possible failures. For each configuration, the total number of cells in parallel required to meet the energy demands will be determined. As previously stated, this varies depending on the number of batteries the aircraft will be equipped with.

In the initial configuration, a straightforward approach utilising four batteries is proposed, with each battery responsible for powering two rotors arranged in tandem on one edge of the wing.
As a preliminary estimation, the sizing of each battery can be conducted by dividing the total energy required to complete the mission equally among the four batteries. An allocation such as this would be sufficient for the completion of the different phases of the mission under nominal conditions. However, in order to ensure an adequate level of safety and reliability, it is necessary to consider failure scenarios that make sizing more complex.

The present study aims to analyse two main failure conditions:

1. the failure of a rotor/motor;
2. the failure of a battery.

This thesis will not consider combined failure effects or those of other components of the electrical system.

Furthermore, specific attention will be devoted to the take-off and landing phases, which are the most critical for the system.

The first type of failure, namely the loss of a rotor assembly, is not a particularly critical issue. In the event of a rotor failure, the loss of thrust can be compensated for by switching off the diagonally opposite rotor, thus rebalancing the pitch and roll moments. Any yaw torque imbalance can be managed by the control system, which compensates by modulating the torques on the remaining operational rotors.

In the event of battery failure, the safety of the system is significantly compromised. The equal division of energy between the four batteries, in conjunction with the failure of one of them, would result in the complete loss of two rotors. It can be seen that, particularly in the critical phases under consideration, the aircraft would be unable to complete the required operations, thus rendering this configuration impractical.

In order to ensure continuity of power supply even in the event of a battery failure, it is necessary that each of the four batteries be of a size capable of supplying power to four rotors [24]. In this way, even in the event of a failure condition, the aircraft would be able to complete the mission safely, meeting established reliability requirements. A graphical representation of this, with a particular emphasis on the interconnections between the various battery groups, is presented in the subsequent figure.

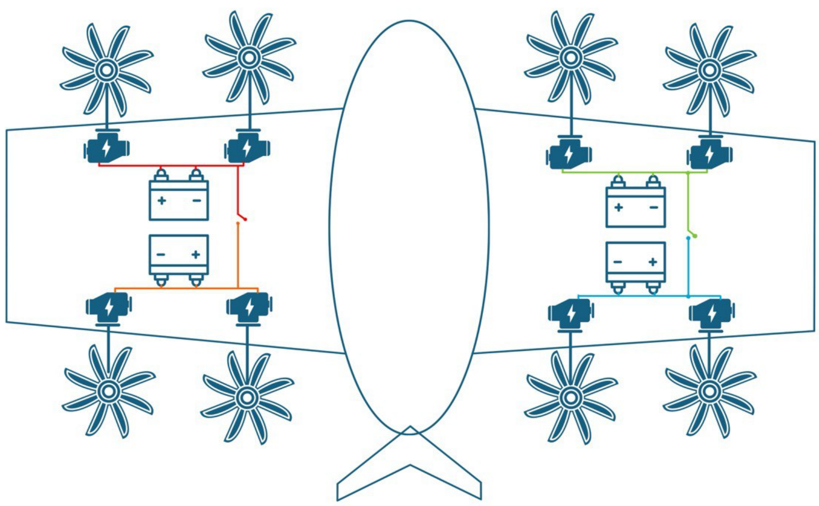

Figure 3.2: Battery Configuration: I case

It is important to note that the open connection between the different batteries indicates the possibility of activating a switch in the case of failure. Furthermore, it should be highlighted that the electrical system is not accurate and that the elements in the electrical connection are not as in the real system. Therefore, it is essential to use this representation as a tool for illustrative purposes only.

This configuration presents a number of advantages.
From a logistical point of view, the use of a reduced number of batteries reduces the time needed for recharging and handling, which makes maintenance much simpler. This enables more rapid and effective operations, thereby reducing downtime and optimising the aircraft's overall operational activities. Furthermore, the reduction in the number of components results in a proportional decrease in potential failure points, with the additional benefit of facilitating the detection and resolution of such failures.

Nevertheless, this configuration presents a number of considerable disadvantages.
The most significant issue is the increase in MTOW. An increase in battery size will inevitably lead to a significant increase in aircraft weight. If each battery is required to possess twice the energy previously estimated (in order to power its own rotors plus potentially two additional rotors in the event of failure), the total weight of the batteries would consequently double. This would result in a weight increase of approximately 700 kg, which is not compatible with the operational requirements of an eVTOL.
Furthermore, the considerable dimensions and substantial weight of each battery pack would necessitate the involvement of specially trained personnel and sophisticated equipment for battery replacement or handling operations, thereby impeding the efficiency of rapid replacement procedures. Finally, batteries with such an elevated energy capacity may necessitate extensive recharging periods. This is of particular consequence for eVTOLs, as these aircraft are designed to operate with a certain degree of continuity in flight, which requires rapid recharging times to ensure mission frequency.

One solution to this problem would be to add a fifth battery pack, which would only be used if one of the other four failed.

A graphical representation of this configuration is provided in the figure below.

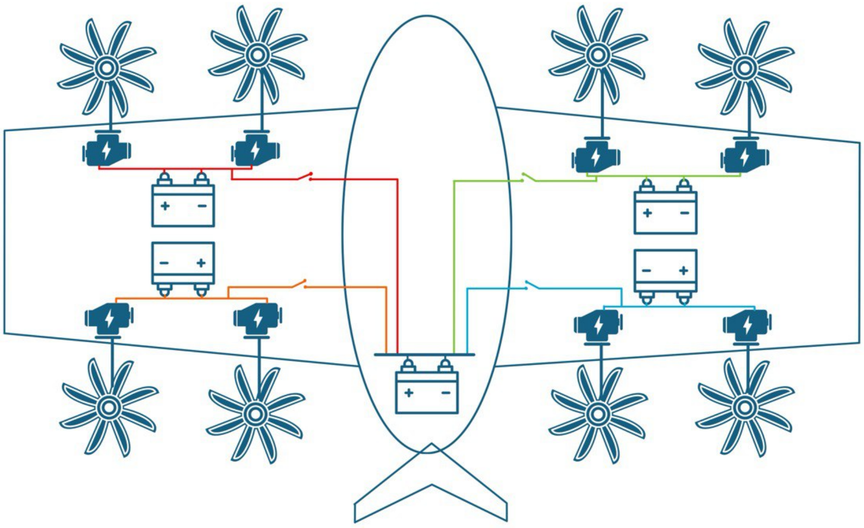

Figure 3.3: Battery Configuration: II case

This solution offers important advantages in terms of overall weight compared to the previous configuration. In fact, the addition of the fifth battery, which is required to hold enough energy to power two rotors, adds approximately 200 kg of weight.
With the introduction of the back-up battery, the main batteries would therefore be sized to power only two rotors each, thus reducing over-sizing. In addition, the presence of a back-up battery ensures greater safety in the event of a failure, guaranteeing the aircraft's ability to maintain balance without overloading the other batteries.

It is specified that the backup battery is only to be used to replace one battery that undergoes a failure. The combination of two or more battery failures is not covered by this type of backup for two reasons:

- firstly, the stored energy may be insufficient to drive four motors;
- secondly, the output battery voltage is sized to guide only two motors.

Another configuration was developed with the objective of reducing the overall weight of the system while maintaining compliance with the requisite safety standards.

In this configuration, each rotor will be powered by an electric motor, which in turn will be powered by two separate batteries, as proposed by [23]. This configuration is therefore optimal in the event of a battery failure, as it reduces the potential for catastrophic consequences, given that the remaining battery is still able to power the rotor.
This is guaranteed by the specific sizing of the batteries: they are sized to provide half the power required by each electric motor. Consequently, even in the event of a battery failure, each rotor continues to be powered by the remaining battery, and the aircraft is able to make a safe landing.

A graphical representation of this is provided in the following figure:

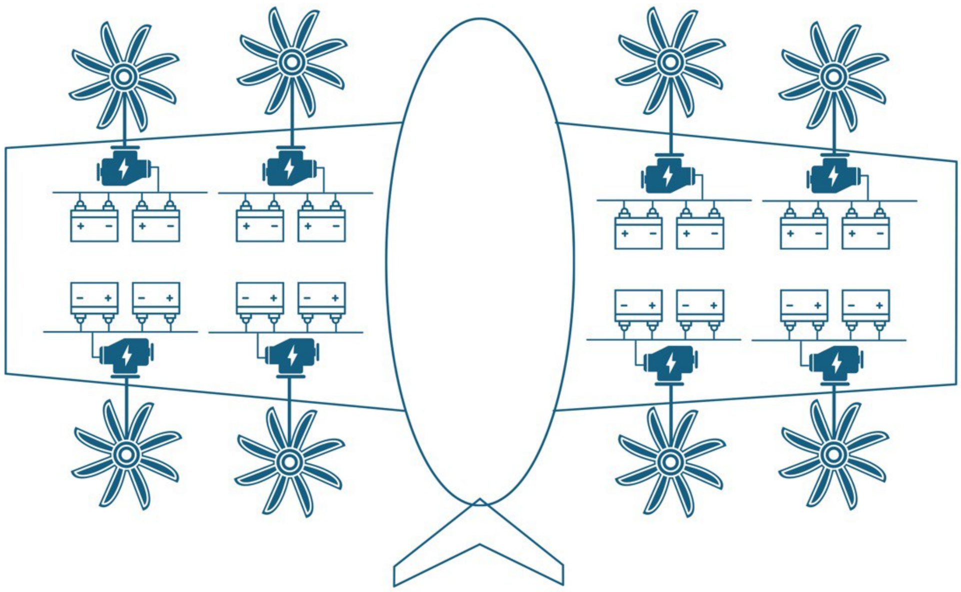

Figure 3.4: Battery Configuration: III case

The division of energy into a larger number of batteries presents a number of advantages and disadvantages, necessitating a careful and detailed analysis in order to optimise the aircraft's energy system.

The initial consideration is the overall weight of the system. A greater energy distribution results in the elimination of the necessity for supplementary backup batteries, which has a beneficial effect on the overall reduction of weight. Each battery is designed to contain the requisite amount of energy, with an additional reserve to ensure uninterrupted functionality in the event of a failure.

Nevertheless, the use of a greater number of batteries gives rise to a number of logistical challenges. The management of the charging and replacement of multiple batteries may result in an increase in downtime on the ground. However, this disadvantage is offset by the shorter charging time required for each battery due to their low weight, which also facilitates handling and maintenance.
It is also important to consider that an increase in the number of components will result in an increased probability of failure.

Moreover, in order to guarantee the most effective management of this complex system, it is essential to implement an advanced battery and energy control system. The control system is responsible for a number of critical tasks, including the detection and isolation of any failed batteries and the reconfiguration of the system to ensure the continued operation with functioning batteries. Moreover, the control system is responsible for ensuring a balanced consumption between the two batteries powering each rotor, thereby guaranteeing a safe landing even in the event of a battery failure.
To illustrate, the significance of maintaining a balanced consumption between the two batteries assigned to each rotor is underscored. In the event that the power of one battery is entirely consumed previous to switching to the secondary battery, a failure of the second battery would result in a total loss of power for that rotor, with a critical impact on the mission. In contrast, distributed consumption between the two batteries allows the rotor to maintain power at all times, ensuring operational continuity even in the event of a failure.

It is important to note that if the decision is made not to provide each battery with a high energy reserve, the overall weight of the aircraft is reduced. However, this reduction in weight is achieved at the cost of the aircraft's ability to complete the mission. In this configuration, the failure of a battery during specific time phases of the mission may result in the aircraft being unable to reach its final destination, necessitating an alternative landing site. While this scenario ensures the safety of passengers, it may result in logistical and organizational inconvenience. Moreover, in a network of landing pads distributed in an urban environment, there is no guarantee that they will always be in close proximity or available to accommodate the aircraft in the event of a failure, thereby further limiting operational flexibility.

Therefore, although this configuration is advantageous from a weight perspective, further analysis is required to determine the optimal amount of energy reserve to be allocated to each battery. It is therefore essential that the reserve be calibrated in order to maximise the operational range of the aircraft in the event of a failure, thereby ensuring both in-flight efficiency and passenger safety.

The two configurations proposed in the second and third cases are both acceptable according to the preliminary analysis. Furthermore, both are suitable for handling possible failure conditions of the different components analysed. Following the preliminary analysis of the battery system, it will be necessary to conduct more detailed design phases in order to select the optimal configuration. This will entail carrying out additional in-depth or trade-off analyses.

3.2.1 Input Parameters and Results

This section will present an overview of the principal input parameters and the outcomes derived from the analysis conducted in the preceding sections.

The solid-state lithium-ion battery selected for analysis has an internal capacitance of 5 Ah for each cell and a nominal voltage of 3.7 V [23].

As reported in Appendix D.1 the volumetric energy density (VED) employed for the calculation of volume is 1000 Wh/L.

The reference electrical motors selected for sizing operate at a supply voltage of 400 V [25]. In the case of configurations that utilise a battery to power two rotors, it is essential to consider a voltage of 800V when determining the appropriate battery size. Consequently, the number of cells in series will be greater.
It is also important to note that each electric motor weighs approximately 8 kg. In addition, each motor is coupled with a motor controller, which weighs around 11 kg [23]. As a result, the total weight associated with each motor setup is approximately 20 kg, which aligns with the results presented in the previous chapter and is summarised in Table 2.6.

The total energy required to complete the mission is 217 kWh, calculated using the formula provided in equation (3.1). The total weight of the batteries will be approximately equal to 720 kg with a total volume of 0.2165 m^3, values obtained from equations (3.2) and (3.3).

The aforementioned quantities (mass, volume and energy) will be distributed equally between the batteries that constitute the aircraft, contingent on the configuration selected. The following section presents the results for the two configurations analysed in the preceding chapters:

- I case: Four batteries in series with one backup battery;
- II case: Sixteen batteries in series.

In the initial case, the inclusion of a backup battery results in a 25 % increase in both the total energy capacity and the total battery volume, as compared to the calculated values.

The energy and geometric results of the batteries for the two cases under consideration are presented in the following tables.

Battery sizing results				
	I case		**II case**	
Variable	**Value**	**Unit**	**Value**	**Unit**
E_{tot}	271	kWh	217	kWh
$E_{battery}$	54.2	kWh	13.56	kWh
E_{cell}	18.5	Wh	18.5	Wh
$m_{battery}$	900	kg	720	kg
$v_{tot,batteries}$	0.2706	m^3	0.2165	m^3
$v_{single\ battery}$	0.0541	m^3	0.0135	m^3

Table 3.1: Battery Sizing Results

In light of the reported results, it is crucial to underscore that in the 'I case', the reported results include the backup battery. Consequently, the values of energy, mass and volume are greater than those observed in the preceding paragraphs.

Once the energy capacity of each battery and the supply voltage of the electric motors have been established, the internal configuration of the batteries can be determined by calculating the number of cells in series and in parallel required to meet the specified requirements. Finally, following the determination of the number of cells in series and parallel, the final total number of cells can be calculated using the following formula:

$$N_{c,tot2} = N_{c,ser} \cdot N_{c,par} \tag{3.8}$$

The results are presented in tabular form below.

Battery internal configuration results				
	I case		**II case**	
Variable	**Value**	**Unit**	**Value**	**Unit**
$N_{c,ser}$	217	-	109	-
$N_{c,par}$	17	-	7	-
$N_{c,total}$	3689	-	761	-

Table 3.2: Battery internal components

Again, the reported results are inclusive of any backup batteries. Consequently, the values shown have already been rounded and include the additional capacity provided by the reserve battery.

In summary, using the initial case as a point of reference, each battery will contain 217 cells in series, with each cell consisting of 17 cells in parallel. Consequently, the capacity of each battery will be as follows:

$$C_{b,each} = E_{cell} \cdot 14 \cdot 217 = 56.2\ kWh \tag{3.9}$$

resulting in a capacitance value that was slightly higher than the value indicated in the Tab.3.2 as the required value. An identical example can also be carried out for the second case.

In conclusion, as illustrated in the table, the number of cells in series and in parallel differs significantly between the two cases. This discrepancy can be attributed to the varying output voltages and energy capacitance that the batteries are required to provide in each configuration. In the initial configuration, each battery is required to supply two rotors, necessitating an output voltage of 800V and a battery capacitance of approximately 55 kWh. In the second case, however, only one battery is supplied with a voltage of 400 V and the capacity is 75% lower.

3.2.2 Sensitivity analysis of Battery Mass and Volume

The purpose of this section is to examine the influence of specific parameters on battery sizing.

The initial step consists of analyzing the dimensions of batteries in terms of mass and volume. Equations (3.2) and (3.3) reveal that these parameters are dependent on the specific energy density (SED) and volumetric energy density (VED). The subsequent figures illustrate the impact of variations in these two parameters on the final result.

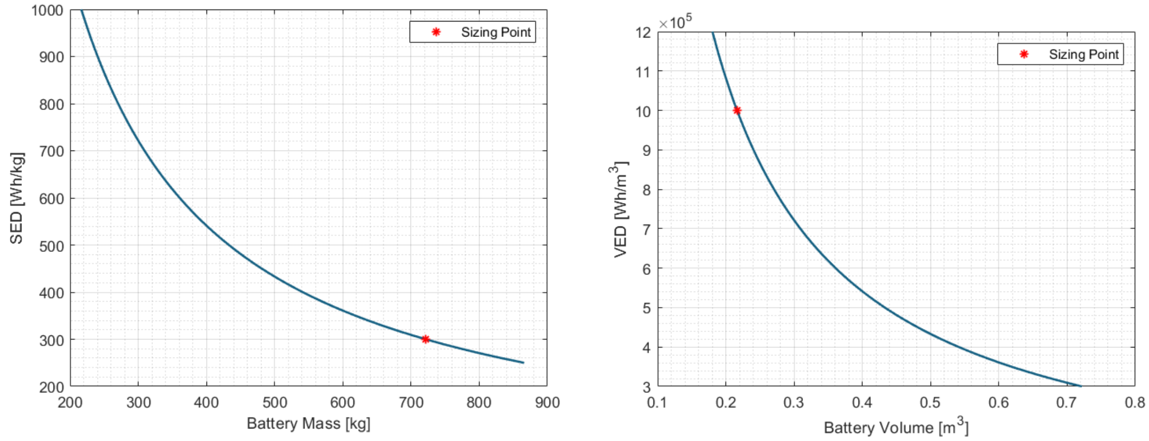

Figure 3.5: Variation of Battery Mass and Battery volume with SED and VED

The values employed in the analytical process are indicated by a red star.

The graphs illustrate that the doubling of the SED or VED results in a reduction in battery size by approximately 50%.
To illustrate, an increase in the SED from 300 Wh/kg to 600 Wh/kg results in a reduction of the mass by half, from 720 kg to 360 kg. Similarly, a doubling of the VED (from 500 Wh/m^3 to 1000 Wh/m^3) results in a volumetric saving of 48.5%.

By acting on these two parameters, it is possible to limit the weight of the battery pack, which represents a significant advantage. A reduction in the weight of the batteries or the overall size of the aircraft will result in a decrease in mass. This could result in enhanced performance, range, and passenger capacity.

However, it is important to emphasise that the ability to act freely on these parameters is constrained by technological advances in the sector. Nevertheless, an analysis of current trends suggests that significant developments in battery technologies are anticipated in the near future, enabling the aforementioned parameters to be increased and battery sizes to be further optimised.

The variation in battery mass and volume is also dependent upon the end-of-life (EOL) and state-of-charge (SOC) values. It should be noted that the sizing values employed are EOL=85% and SOC=20%. Accordingly, the following graphs will analyse the combined impact of EOL and SOC variations on battery sizing.

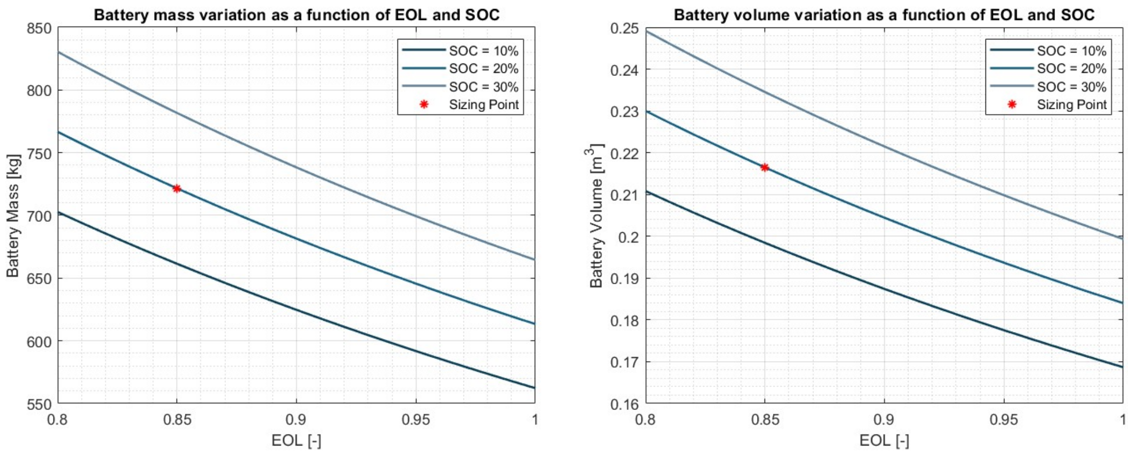

Figure 3.6: Variation of Battery Mass and Battery volume with EOL and SOC

The two graphs illustrate a decreasing trend in battery mass and volume as the EOL factor approaches a value of 1. This trend indicates that elevated EOL values result in a more compact and lightweight battery system, as the batteries are capable of operating at a capacity closer to their maximum capacity, thereby reducing the necessity for supplementary cells to maintain the requisite energy output over time.

It is important to highlight the significance of the efficiency of this parameter. In fact, an increase in the EOL by 10% results in a reduction in battery mass of approximately 80 kg.

Similarly, the state of charge (SOC) has a considerable impact on both the mass and volume of the battery, as evidenced by the three distinct curves. A higher state of charge (SOC) necessitates the reservation of a greater capacity within each battery cell to ensure the maintenance of safe operating levels. Consequently, a

greater number of cells are required to achieve the same effective capacity.
A reduction in the state of charge (SOC) from 30% to 10% results in a corresponding decrease in both the mass and volume of the battery system. The resulting mass reduction is approximately 150 kg, while the volume decreases from 0.25 m^3 to 0.2 m^3.

The combined effect of higher EOL and lower SOC results in considerable battery efficiency. For example, going from the case with EOL=0.8 and SOC=30% to a battery case with EOL=0.9 and SOC=10% results in a saving of 200kg.

The conclusion of the analysis reveals that the combination of the two parameters underscores the importance of balancing EOL and SOC when designing battery systems. This can optimise the battery system with regard to weight and space efficiency, which is of particular significance in aviation applications such as eVTOLs, where weight and space are limiting factors.

3.2.3 Sensitivity analysis of the cells configuration

This section analyses how the variation in capacitance and voltage of each cell affects the number of cells in series, in parallel and the total number of cells.

First the number of cells in series is analyzed. According to Eq. (3.6), the number of cells in series depends on the total voltage required by the actuator and the voltage supplied by each cell. The voltage of each cell is determined by the battery technology used; here we refer to solid state Li-Ion batteries as described in the previous chapters.

Changing the voltage of each cell directly affects the number of cells required in series to power the motor. Consequently, as shown in the graph below, the number of cells in series decreases as the voltage increases. It is important to note that the curve in the variable voltage graph is not perfectly linear. This is because the number of series cells has been rounded up to the nearest integer, as cells are discrete units.

The capacity of the cells does not directly affect the number of cells in series. It only affects the amount of energy each cell can store and the lifespan of the battery. For example, switching from 4 Ah cells to 10 Ah cells only increases the amount of energy stored, while the output voltage of each cell remains constant. Therefore, as shown in the right graph in Fig.3.7, the number of cells in series remains the same as the capacity of each cell varies.

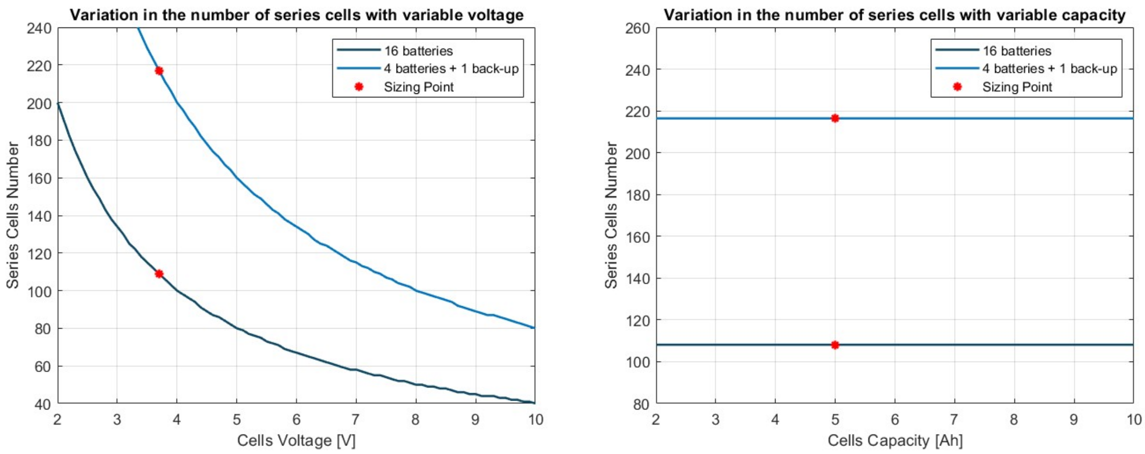

Figure 3.7: Variation in the series cells number with variable nominal Voltage (sx) and variable Capacity (dx)

Similarly, the variation of the number of cells in parallel as a function of the same parameters can be subjected to analysis.
By combining equations (3.7) and (3.5), an alternative expression for the number of cells in parallel can be derived:

$$N_{c,par} = \frac{E_{tot}}{V_{cell} \cdot C_{cell}} \cdot \frac{V_{cell}}{V_{mot}} = \frac{E_{tot}}{C_{cell} \cdot V_{mot}} \tag{3.10}$$

However, this expression leads to the same result as that obtained in previous chapters. It is evident from the presented equation that the number of cells in parallel is determined exclusively by the cell capacity, as shown in the graphs below.

The analysis of the variation in the number of cells in parallel reveals two key trends. As demonstrated in the graph on the left, the variation in cell voltage has no impact on the number of cells in parallel. This phenomenon can be attributed to the fact that, as demonstrated by the equation, the influence of cell voltage on the number of parallel cells is offset, making the voltage irrelevant in determining the number of parallel cells.

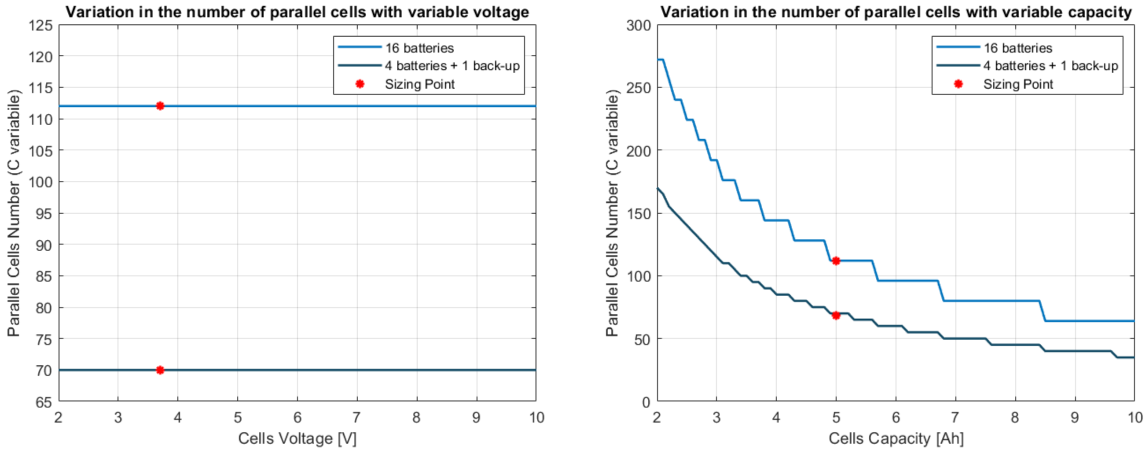

Figure 3.8: Variation in the parallel cells number with variable nominal Voltage (sx) and variable Capacity (dx)

In contrast, the graph on the right demonstrates a clear correlation between the number of cells in parallel and the capacity of each cell. As the capacity of the cells increases, the number of cells in parallel decreases significantly. This can be explained by the fact that as the capacity of a single cell increases, it is capable of storing more energy. Consequently, a reduced number of cells are required in parallel in order to meet the total energy demand of the system.

Moreover, the non-linearity of the curve is more evident in this context. This non-linearity can be attributed to two main factors:

- rounding to the next multiple, as the cells are discrete elements;
- rounding to a multiple of 16 (value identifying the batteries present on the aircraft, 2 for each of the eight engines).

These factors together produce the step-like behavior observed in the graph.

A further substantial analysis can be conducted on the total number of cells by calculating the percentage change in relation to the combined effect of voltage and capacitance. The resulting data are presented in the following fig. 3.9.

The graph illustrates that the total number of cells required for a battery decreases as the individual cell voltage increases, independent of the selected capacity.
Each curve represents a specific cell capacity (varying between 4 Ah and 10 Ah),

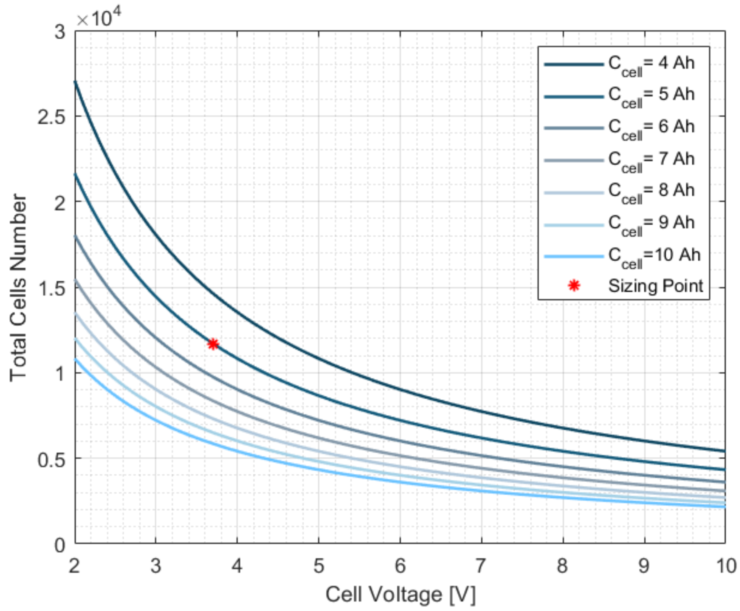

Figure 3.9: Variation of the total cell number

with a progressively decreasing trend as the voltage increases. It is evident that the number of cells required varies considerably depending on the size parameters under consideration.

To illustrate, for low values of voltage and capacity (e.g. $V_{cell} = 3$V and C_{cell}=4Ah), the number of cells required can reach values close to 27,000. In contrast, for higher values (e.g. $V_{cell} = 10$V and C_{cell}=10Ah), the total number of cells is significantly reduced to around 2,000, representing a reduction of 92.6%. This illustrates the crucial role of selecting an optimal combination of voltage and capacity to minimise the total number of cells, thereby enhancing the efficiency of the battery pack configuration. However, as previously stated, the selection of these parameters is contingent upon technological advancements and the specific battery type.

Final Remarks

The research conducted in this thesis focuses on eVTOL as one of the most promising solutions to address the growing challenges of urban mobility and sustainability needs.

The thesis has highlighted how eVTOL technology, although still in its development phase, can be an innovative response to urban congestion, the reduction of CO_2 emissions and the need for flexible and fast transport in densely populated cities. Analyses have shown that eVTOLs can offer significant advantages over traditional road transport systems by using advanced electric propulsion configurations and energy storage technologies. However, technical and operational challenges remain, including the need to increase battery efficiency and energy density, develop appropriate supporting infrastructure and ensure high safety standards.

By developing a conceptual design methodology, this thesis identified the primary geometric and mass characteristics of eVTOLs, evaluating the most effective configurations and essential elements to enhance flight performance and reduce energy consumption. A variety of methodological approaches were employed to develop a robust model for reliably estimating aircraft characteristics. These included the use of statistical and analytical models for estimating mass and performance, with a particular focus on battery configuration and size. The results obtained with these methods confirm the importance of an iterative design process that optimises performance through a combination of empirical models and theoretical simulations. This approach allows for the adjustment of main parameters over time, enabling a balance to be achieved between range, payload and safety.

This research contributes to the study of eVTOL design and development, establishing a foundation for future improvements in urban air mobility. A multidisciplinary approach was employed in the preparation of this thesis, integrating aerodynamic modelling, performance analyses, and safety and reliability assessments to provide an in-depth view of design variables and specifications. This approach renders the work valuable not only for the design of powered lift eVTOLs, but also for the development of other types of eVTOLs, thereby facilitating the accelerated adoption of sustainable technologies in the aviation industry.

This thesis also represents a valuable starting point for future developments. In light of the results and analyses presented, a series of implementations, in-depth research and development projects could be undertaken with the aim of facilitating a more detailed development of the aircraft. In particular, future research could focus on the sectors outlined below.

Detailed subsystem development A comprehensive examination of all subsystems on board the aircraft would facilitate a substantial advancement in the design of eVTOLs. This approach would facilitate more precise estimation of weights and dimensions, thereby enhancing the reliability of the calculations presented in this thesis and optimising the overall design.

Acoustic analysis Given the relatively low cruising altitude of eVTOLs in comparison to conventional aircraft, it would be of significant importance to conduct an acoustic performance analysis. An estimation of the noise impact, in conjunction with an optimisation analysis aimed at minimising noise, would be of particular benefit in facilitating public acceptance and the successful integration of these aircraft into urban environments.

Detailed development of the electrical system This thesis only presents a preliminary analysis of the battery configuration. A detailed investigation of this topic would be advantageous, including an evaluation of the intermediate and supporting components of the batteries, which are crucial for powering the rotors and on-board systems. Furthermore, a trade-off study would be beneficial in order to identify the optimal battery configuration, balancing capacity, weight and range.

Structural Analysis A structural analysis of aircraft components could have a significant effect on the overall structure in terms of weight and safety. The selection of lighter and stronger materials would result in a reduction of the overall weight of the aircraft, thereby enhancing its efficiency and reducing energy consumption.

Infrastructure Analysis A comprehensive analysis of the existing infrastructure and the necessary recharging requirements is essential. In order to ensure the effective integration of eVTOLs in urban environments, it is vital to conduct a detailed analysis of the infrastructure required for the refuelling and maintenance of these aircraft. An analysis of the requirements for rapid charging stations, parking logistics and maintenance could enhance the viability and accessibility of the air mobility system.

In conclusion, eVTOL represents an emerging frontier of sustainable mobility. Despite the considerable obstacles, the prospective advantages in terms of diminished environmental impact and pioneering advances in urban transportation render these vehicles a subject worthy of further investigation and advancement. The objective of this thesis is to make a contribution to this exploration by providing a methodological and analytical basis for addressing the future technological, operational and regulatory challenges that eVTOLs will face.

Appendix A

Matching Chart

A.1 Input Parameters

This section presents the key parameters used in the construction of the matching chart, an essential tool for determining the optimal combination of wing loading and power-to-weight ratio.

Matching Chart Inputs			
Variable	**Value**	**Unit**	**Description**
g	9.81	m/s^2	Gravity Acceleration
S_p	7.06	m^2	Propeller Surface (estimated with a radius of 1.5 m)
Range	160	km	Range (From requirements)
L/D_{climb}	12	-	Lift to Drag Ratio in climb
L/D_{cruise}	10	-	Cruise Efficiency
ρ	1.225	kg/m^3	Air Density (Sea Level)
V_{cr}	66.67	m/s	Cruise Speed (240 km/h)
V_{stall}	33.33	m/s	Stall Speed (From [19])
$C_{L_{max}}$	1.6	-	Maximum Lift Coefficient (From Raymer – Clean Airfoil)
k_T	1.2	-	Extra Thrust Coefficient (From [19])
FOM	0.75	-	Figure of Merit of the rotors (ratio between induced and total power)
T/A	55.71	kg/m^2	Disk Loading (referred to a single rotor equivalent) (Estimated in Statistical Analysis)

Table A.1: Summary of Environmental and Design Parameters

Appendix B

Raymer Method

B.1 Empty Weight Fraction

This section presents the empirical coefficients used to estimate the empty weight, as described in Chapter 3 of reference [8]. The following figure illustrates a summary of the various coefficients based on different aircraft configurations. In estimating the empty weight of an electric vertical take-off and landing (eVTOL) aircraft, these coefficients were adapted by considering a general aviation-twin engine aircraft as a point of reference.

$W_e/W_0 = A W_0^C K_{vs}$	A	{A-metric}	C
Sailplane—unpowered	0.86	{0.83}	−0.05
Sailplane—powered	0.91	{0.88}	−0.05
Homebuilt—metal/wood	1.19	{1.11}	−0.09
Homebuilt—composite	1.15	{1.07}	−0.09
General aviation—single engine	2.36	{2.05}	−0.18
General aviation—twin engine	1.51	{1.4}	−0.10
Agricultural aircraft	0.74	{0.72}	−0.03
Twin turboprop	0.96	{0.92}	−0.05
Flying boat	1.09	{1.05}	−0.05
Jet trainer	1.59	{1.47}	−0.10
Jet fighter	2.34	{2.11}	−0.13
Military cargo/bomber	0.93	{0.88}	−0.07
Jet transport	1.02	{0.97}	−0.06
UAV—Tac Recce & UCAV	1.67	{1.47}	−0.16
UAV—high altitude	2.75	{2.39}	−0.18
UAV—small	0.97	{0.93}	−0.06

Figure B.1: EW Fraction

To adapt this formula to the eVTOL, the coefficients are chosen assuming that the aircraft under consideration is a twin turboprop.

B.2 Input parameters

The parameters that were used to implement Raymer's method are summarised in the following table:

Raymer Inputs			
Variable	**Value**	**Unit**	**Description**
ROC	4	m/s	eVTOL Rate of Climb
Npax	4	-	Passenger number (From Requirements)
η_{prop}	0.92	-	Propeller Efficiency (From [19])
$\eta_{batt2mot}$	0.93	-	Total system efficiency from battery to motor output shaft (From Raymer [20])
t_{loiter}	0.1	hrs	Loiter time
h_{MAX}	610	m	Max Altitude
$ED_{battery}$	300	Wh/kg	Energy Density Battery (from literature, Li-Ion Battery)

Table B.1: Input data to estimate the aircraft's masses using Raymer method

Appendix C

Roskam+Flops Method

This appendix provides a description of the geometric parameters that are necessary for the estimation of aircraft masses using the Roskam+Flops method. The calculations and formulae employed to determine the dimensions of the fuselage, wings and other critical components are outlined in the following section.

C.1 Maximum Fuselage Perimeter

The maximum perimeter of the fuselage cross-section is calculated as follows:

$$P_{max} = 2\pi \frac{d_f}{2} \tag{C.1}$$

Where:

- P_{max} is the maximum perimeter of the fuselage section [m],
- d_f is the fuselage diameter [m].

This parameter is used in Eq.(2.14).

C.2 Wing Surface Area

The wing surface area is computed using the wing span and the mean chord:

$$S_w = b \cdot c_{mean} \tag{C.2}$$

Where:

- S_w is the wing surface area [m^2],
- b is the wing span [m],
- c_{mean} is the mean chord length of the wing [m].

The wing surface area is used as a basis for estimating the mass of the wing in Eq.(2.15)

C.3 Wing Aspect Ratio

The aspect ratio of the wing is defined as the ratio between the wing span and the mean chord, and is given by the equation:

$$AR_w = \frac{b}{c_{mean}} \tag{C.3}$$

Where:

- AR_w is the aspect ratio of the wing,
- b is the wing span [m],
- c_{mean} is the mean chord length of the wing [m].

The aspect ratio is a significant factor in determining the aerodynamic efficiency of the wing. It is used in Eq.(2.15).

C.4 Fuselage Surface Area

The surface area of the fuselage is calculated by multiplying the fuselage length by its diameter:

$$F_{Area} = L_f \cdot d_f \tag{C.4}$$

Where:

- F_{Area} is the fuselage surface area [m^2],
- L_f is the fuselage length [m],
- d_f is the fuselage diameter [m].

C.5 Input parameters

The parameters that were used to implement the method are summarised in the following table:

Roskam+Flops Inputs			
Variable	**Value**	**Unit**	**Description**
L_f	10	m	Fuselage Length
d_f	3	m	Fuselage Diameter
N_{crew}	1	-	Crew number
c_{mean}	2	m	Wing mean chord
b	14	m	Wing span
η_{wing}	1.5	-	Wing design load factor
η_{lg}	2.5	-	Landing gear design load factor
η_{batt}	0.95	-	Battery Efficiency
L_{lg}	0.8	m	Landing gear Length
N_{mot}	8	-	Motor/Propeller number
PM	0.3	-	Power Margin
d_{prop}	3	m	Propeller diameter
N_{bl}	5	-	Number of blades on the propeller
SOC	0.2	-	Minimum battery State of Charge
EOL	0.85	-	Battery End Of Life
sweep_angle	15	deg	Wing Sweep Angle

Table C.1: Geometric and design parameters for the eVTOL aircraft

Appendix D

Battery Sizing

D.1 Volumetric Energy Desnity - VED

The figure illustrates the volumetric energy density of diverse battery types. With regard to solid-state batteries, the focus of this thesis, it can be observed that they exhibit a volumetric energy density (VED) that ranges from a minimum of 300 Wh/L to a maximum of 1000 Wh/L. The value of 1000 Wh/L has been selected for sizing purposes, reflecting a realistic projection of the technological capabilities of this battery type. For further details, please refer to the following source: [26].

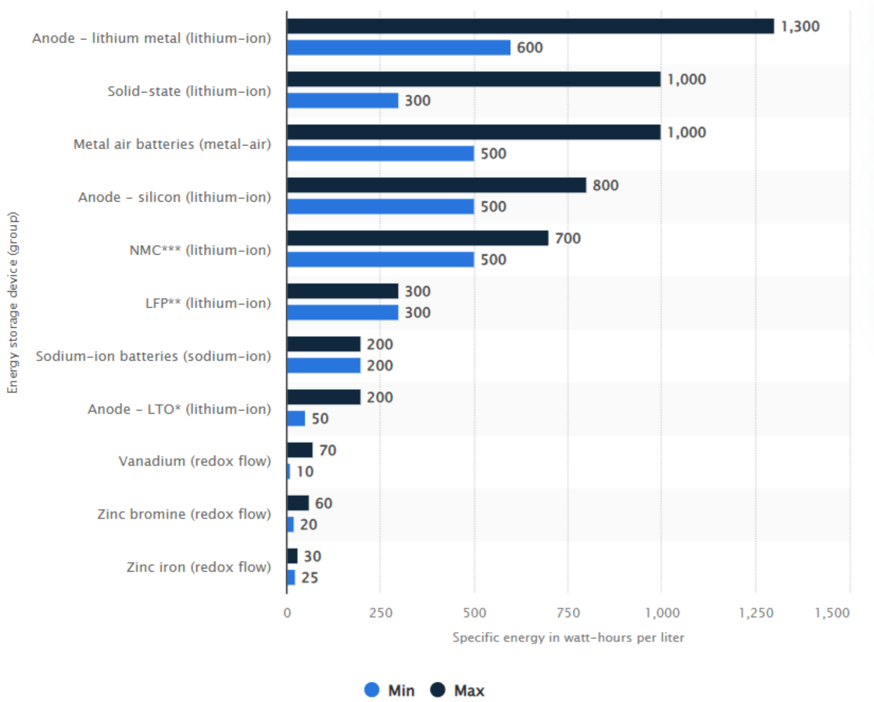

Figure D.1: Volumetric Energy Density

D.2 Effects of battery capacity and voltage increase

This section reports a sensitivity analysis extracted from the document *Preliminary Propulsion and Power System Design of a Tandem-Wing Long-Range eVTOL Aircraft* [23], as it is highly relevant to the topics covered in this thesis. This analysis examines how battery cell capacity and voltage rating affect the number of cells required in the propulsion system of an eVTOL aircraft.

The analysis demonstrates that as the capacity of individual cells increases, the total number of cells required to meet the energy requirements of the system decreases. This occurs because a higher capacity per cell allows each cell to store more energy, thus reducing the total number of cells. However, the reduction process is not linear, as the cell configuration must meet the system's voltage requirements, which leads to fluctuations in the optimal configuration of cells in series and parallel. As illustrated in the Fig. D.2, an increase in cell capacity results in a reduction in the total number of cells, thereby leading to an overall increase in the cell count.

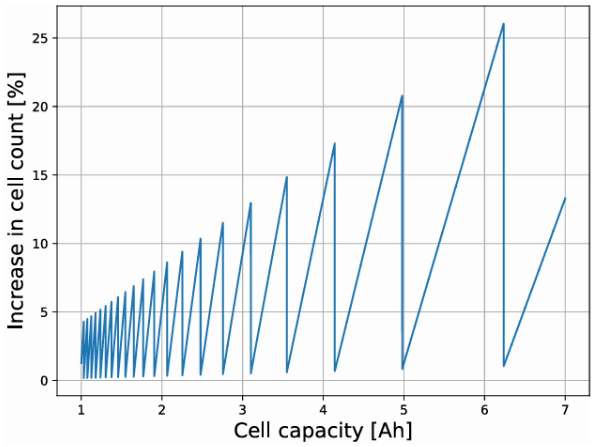

Figure D.2: Relation between cell capacity and the increase in the number of cells

Furthermore, it is essential to examine the correlation between the percentage growth in cell count and the nominal cell voltage. As illustrated in Fig. D.3, a minor alteration in the nominal voltage can result in a considerable change in the number of cells required. For example, an increase in the nominal voltage from 3.70 V to 3.71 V has been observed to result in a notable rise in the number of cells, with the percentage increase reaching 20.75% in comparison to the previous value of 1.27%. This phenomenon can be attributed to the following factors:

- It is essential that the battery pack provides a precise total voltage (for example, 400 V, in accordance with the analysis presented in this document). The cells are connected in series in order to achieve the desired voltage. A slight change in the voltage of each cell will result in a corresponding change in the number of cells required in series to reach the total voltage. This can lead to a significant variation in the total number of cells.

- As the number of cells must be an integer, a minor change in voltage may necessitate the addition or removal of an entire cell, resulting in an amplified effect on the total number. This phenomenon is particularly evident when working with low nominal voltages, where even minor variations have a relatively large impact.

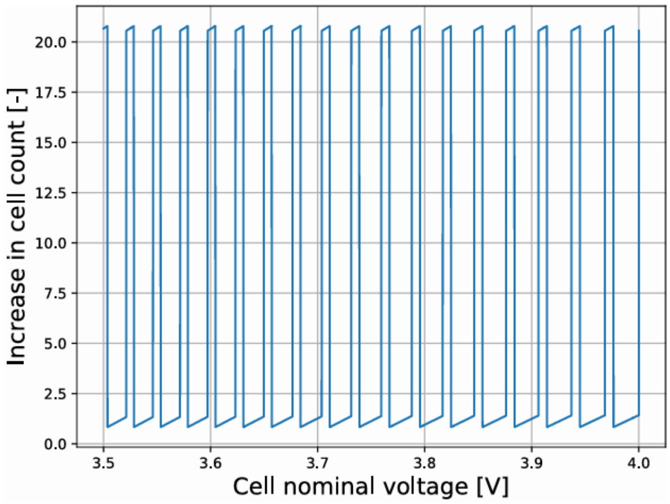

Figure D.3: Relation between cell voltage and the increase in the number of cells

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