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Development and production costs estimation methodology for eVTOL

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Abstract

Urban Air Mobility (UAM) is a new, safe and efficient air transport system in which people and goods are transported by crossing urban areas using electric vertical take-off and landing aircraft. In order for this innovative transportation system to be truly deployed worldwide, it needs to be cost-effective compared to ground-based competitors. Therefore, the goal is to develop a development and production cost estimation model for eVTOL.

Several well-known companies are already developing their eVTOL in order to bring them to market as soon as possible.

The design data of the different aircraft (powered lift and multicopter) were first obtained by estimating the weight of the individual components, and then the various models were implemented on MatLab software, obtaining as output the estimated costs of the different subsystems. Finally, again using MatLab software, the data obtained was analysed and the main cost drivers were identified which allow the cost equations to be obtained.

In the end, the results relating to eVTOL aircraft were compared with its main competitor: the helicopter.

1. Introduction

1.1 What is UAM?

Urban Air Mobility (UAM) is a concept that may seem like science fiction but which, year after year, is becoming reality. At the centre are air taxis of flying taxis, vertical take-off and landing flying vehicles capable of making short and frequent trips in urban areas with a small number of passengers. In Italy, on 6 October 2022, the first vertiport was inaugurated in Rome. However, let's take a closer look at what is happening in this futuristic sector.

The sector is currently developing along various lines for which human guided solutions are being studied and tested, as well as technologies that allow remote piloted driving both within the pilot's sight and outside its field of vision, while autonomous driving still seems to represent too great a challenge.

In general, UAM refers to all those means of transport designed for very short-range air travel and at low altitude in urban and extra-urban areas, but very often, it also implies the implementation of innovative solutions for smart mobility that involve the use of silent, clean and safe technologies.

In certain sense, it could be said that the concept has already been realized with the use of helicopters for travel in large cities such as Los Angeles, New York, Tokyo and other cities. Heli taxi services in these megacities have been active for several decades, but have always been associated with high costs, loud noise and high consumption of resources.

UAM, on the other hand, aims to adopt electric motors mounted on cutting-edge vehicles capable of transporting a few passengers, but at prices not very different from those of an ordinary taxi, and above all to arrive practically anywhere thanks to eVTOL (electric vertical take-off and landing) with low sound impact.

1.2 UAM is increasingly necessary

The decarbonisation of city transport, the democratization of the air and the development of innovative technologies are just some of the great challenges that these new means of transport are facing, part of a large picture that aims to revolutionize the way we will move within the next 10-20 years. According to some estimates by 2030 about 60% of the world's population will live in cities or in densely populated urban centres. This percentage will grow and is expected to rise to cover about three quarters of the world's population by 2050.This increase will lead megacities to emit 70% of greenhouse gases and consume two thirds of global energy. If we add to this that already today about half of the public surface area in cities is occupied on average by roads, we understand that to find a solution there is no other way than the third dimension: the air.

In this scenario, UAM presents itself as the next generational leap, something that allows not only to improve the state of health of city environments, but also to broaden the radius of our movements, not unlike what the advent of the automobile has made regarding horse travel at the beginning of the twentieth century. If a car can travel about 20 km in 40 minutes leaving an urban centre like Paris, an air taxi promises to take its passengers up to 150 km in the same time.

For all these reasons, UAM currently represents a fertile ground for experimentation for innovators and investors at the same time, which is imparting an extraordinary transformation to the entire air transport and civil aviation sector and opening up new technological, economic and industrial.

1.3 The challenges of UAM

In order to become a means of mass transport, however, the entire sector must face a series of key challenges that concern various aspects: the creation of futuristic aircraft, equipped with cutting-edge electric motors capable of solving the SWaP riddle, with low noise impact, with low costs to guarantee pricing that is adequate to expectations and above all safe. In addition to the vehicle itself, a series of infrastructures are also necessary - from vertiports to software systems for air traffic management – as well as addressing and clearing two fundamental aspects: the system of rules, standards and certificates, at a bureaucratic level, and the social acceptance of UAM.

Vertical take-off and landing aircraft face the same challenge as the automotive industry: the battery. To date, the eVTOL on which most focus is offered systems with lithium ion (Li-ion) batteries, which still represent the only truly reliable alternative on a commercial level despite having important limitations in terms of weight, capacity and safety. In the future, it will be necessary to find solutions that guarantee greater autonomy and power, lower charging times and weight, so it is hypothesized that the leap could take place with the advent of solid-state batteries. Other options, such as that represented by hybrid engines, appear inadequate in terms of noise and pollution, while hydrogen propulsion as time goes by increasingly seems like a promise that will not be kept.

For the development of low altitude flying vehicles, it is necessary to be able to rely on a very low latency network connection that can allow constant real-time monitoring of traffic at altitude, weather conditions, communication with the mainland and, why not, also entertainment services for passengers. In view of possible autonomous driving applications, the advent of 5G represents an essential step without which UAM could not take hold. The greatest difficulties are of a technical nature, in particular concerning the connection at altitude with very rapidly moving objects, but various experiments carried out between Dubai and Singapore by Volocopter as well as by Vodafone in Spain and AT&T with Uber are bringing encouraging results.

1.4 UAM Management

It was calculated that in 2019 there were around 30.000 drones flying every 24 hours across the European Union, a figure which is expected to rise to 20.000 flights over a single city by 2035. It is therefore immediately clear how the need to structure an urban Air Traffic Management system (ATM) is felt. Unlike self-driving cars, in fact, air taxis and drones will be regulated by special agencies that will operate according to strict safety and efficiency standards. In the United States the FAA created the UTM (Unmanned Aircraft Systems Traffic Management) system together with NASA, while in Europe the EASA (European Aviation Safety Agency) is working on "U-Space". Both aim at automated traffic management, the first cornerstone of a goods transport system using self-driving drones, probably among the first UAM vehicles we will see in operation.
The global urban air mobility market size was USD 2.90 billion in 2020 and is projected to grow from USD 8.91 billion by 2028 at a CAGR of 16.77% in the 2020-2028 period.

1.5 Bureaucracy and security

The new standards should therefore conform to the 10^{-9} rule, i.e. catastrophic accident is considered acceptable once every billion hours flown. On this aspect, however, the emotional considerations of the passengers will weigh heavily: getting on an air taxi is in fact not like getting

on an ordinary taxi. Beyond the small percentage of the population who suffers from the classic "fear of flying", there is however a significant portion of people who are neither used to nor feel comfortable in the air.
For example, statistics say that today around 40% of Americans who fly say they feel a certain sense of anxiety, therefore a change in general mentality will be necessary to be able to allow air taxi travel into one's daily life. The difference will probably be made by the gradual advent of solutions for freight transport and the safety that the system and the vehicles themselves will be able to inspire in their prospects. The most nebulous aspect of the challenge linked to certifications, however, is represented by the political system and its ability to adopt necessary and shared rules.

1.6 Critical issues

The introduction of eVTOL vehicles on the modern market will introduce strong changes in the management of low-altitude airspace, will require new configurations of urban assets, there is already talk of vertipads and vertiports, and a significant rethinking of infrastructure. Below are some of the most significant critical aspects related to eVTOLs:

- Regulations
- Tecnology
- UAM corridors
- Infrastructure

1.6.1 Regulations

Any autonomous vehicle must be subject to regulations before it can be made available to the market.

The complexities related to the regulation of autonomous cars are numerous.
Already today, the regulations relating to autonomous cars are proving to be a significant obstacle.

1.6.2 Technology

The development of eVTOL must take place at the same time as the introduction of 5G, because planes must communicate both with each other and with air traffic control centers. Vehicle sensors and collision avoidance systems must also be integrated into the IoT. Real-time information on location and maintenance requirements is critical.
If autonomous eVTOL vehicles take off, artificial intelligence will play an important role, as they will need reliable networks to transmit large amounts of data.
Furthermore, efficiency is a big sign issue. . for new technologies. The launch is still a point of contention between the parties involved. Key performance factors include:

- cost per kWh
- battery capacity and weight
- charging speed

1.6.3 UAM corridors

The corridors are designed to ensure the safety of air taxis, pilots and passengers, as well as people and property on the ground. They are designed to minimize environmental emissions (such as noise) in densely populated areas, while ensuring efficient traffic flow.

Over bodies of water (such as rivers, large lakes, or oceans) with air taxis, air taxis can be autonomous. . danger to the people and property of the country. However, this route means that the eVTOL vessel must have additional safety equipment and that the pilot and passengers must be briefed on all emergency procedures related to forced landings.
These connect the starting point to the end point of the eVTOL. . The places where such machines can take off and land are called vertiports.

Figure [1.1]: UAM corridors

1.6.4 Infrastructure

Although there are many airports, they are usually not located in the middle of busy cities. Passengers will also use eVTOL to travel increasingly shorter distances, so take-off and landing zones should be established in all large cities with heavy traffic.
Infrastructure changes should also include aircraft loading areas. Currently, electric charging stations for Tesla cars seem the most likely.
However, if other energy systems are preferred in the coming years, these plans could change.
VTOLs need infrastructure even when not in use, and parking lots or parking lots should be built for maintenance close to the hubs.

Some analyses carried out by both public and private research centres hypothesize a division of infrastructure into three categories:

1. Vertihubs: is a self-contained structure with several take-off, landing and parking areas and maintenance facilities with the possibility of retail sales
2. Vertiports: is the specialized infrastructure for landing and take-off for eVTOL. These vertiports need to be strategically located, easily accessible and equipped with facilities for maintenance, charging and passenger services. The global vertiport development segment is estimated at $41.58 million in 2023 and is expected to grow at a CAGR of 8.69% during the forecast period 2023-2033 to reach $103.95 million by 2033.
3. Vertipads: they are the smallest structures and present in more rural or less populated areas. They have a maximum of two take-off and landing areas

Figure [1.2]: vertihubs, vertiport and vertistop

2 eVTOL

2.1 Classification

eVTOLs are particular aircraft that belong to the category of totally electric aircraft; they are able to take off and land in a vertical direction similarly to helicopters, but they are their main competitors. EASA, through the definition of special conditions, makes a clear distinction of this category into two macro categories: wingless and powered lift.

They present two peculiar characteristics common to all types of eVTOL: the vertical take-off and landing capability and the distributed electric propulsion system. This last aspect allows the use of simplified technologies both during the vertical lifting phase and during forward thrust, compared to the traditional jet rotor mounted on conventional aircraft. Subsequently, these propulsion units will be called "lift/thrust units" (LTU), in line with the SC-VTOL nomenclature.

In *Figure [1.3]*, the subdivision of the different types of eVTOLs currently, existing is depicted.

Wingless eVTOL aircraft rely exclusively on the thrust of their TLUs in both phases mentioned above. However, the operation of multicopter aircraft is different: they have multiple LTUs, which can only guarantee vertical lift.

All the eVTOL configurations mentioned can land independently without the aid of a landing strip, as is the case with airplanes.

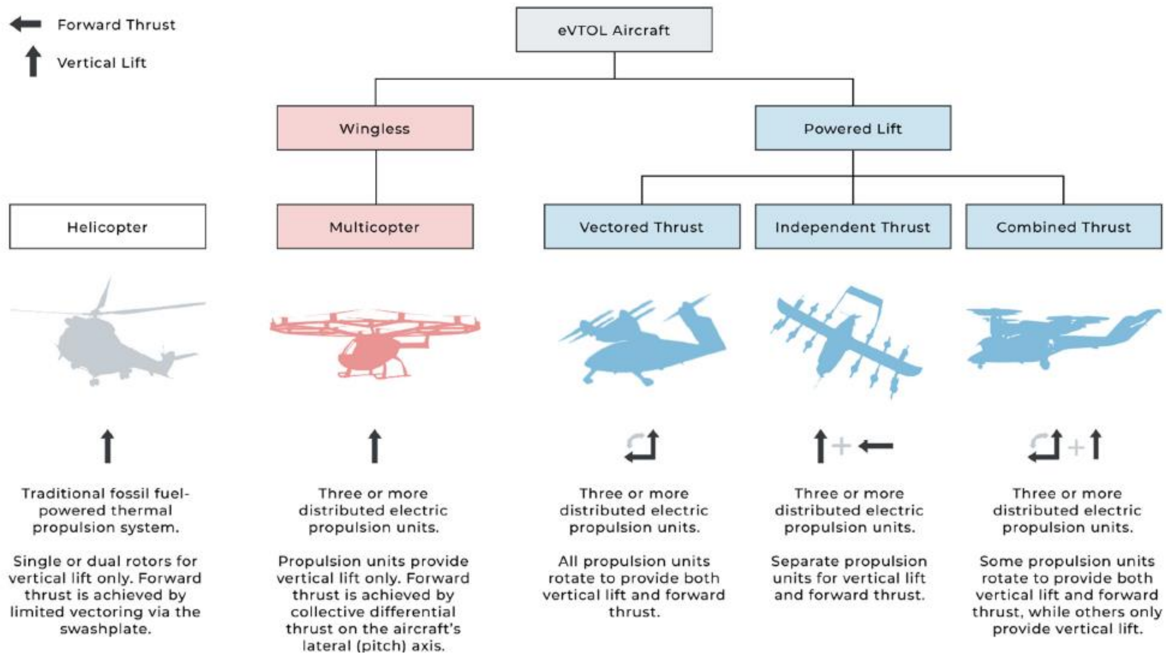

Figure [1.3]: eVTOL classification

Powered lift aircraft, on the other hand, are significantly more complex to design, but obviously also have significant advantages compared to the multicopter category. The complexity is mainly due to two factors:

- the presence of the wing and obviously of the respective control systems to generate the lift during the cruise phase
- additional LTUs necessary for the forward mode.

As can be seen in the figure, there are three different configurations regarding this macro category.

In order, you have the independent thrust eVTOL, which has a separate propulsion that allows forward thrust during the cruise phase while keeping the LTUs for vertical lift turned off. Conversely, during vertical lift the LTUs for forward flight remain deactivated. One of the main advantages of this configuration is the reduction in complexity and overall design cost.

When the LTUs are not activated, they are considered by the aircraft as "dead weight" contributing significantly to the increase in aerodynamic resistance and the overall mass of the aircraft.

Secondly is the vectored thrust configuration, probably the most complex, due to the systems necessary to vectored the thrust between the vertical and forward regime; among other things, this problem already arose at the end of the 1960s when the first VTOL aircraft were developed.

The tilt-rotor and tilt-prop models only rotate the LTUs by lifting propellers or fans, thus activating vertical lift or forward thrust modes. These two categories are probably the most used in the case of vectored thrust configuration.

Regardless of the vectorization approach used, all existing designs belonging to this configuration require additional systems for vectorization control and mitigation, as well as the presence of numerous redundancies due to the critical issues of these systems which add to the empty mass of the eVTOL.

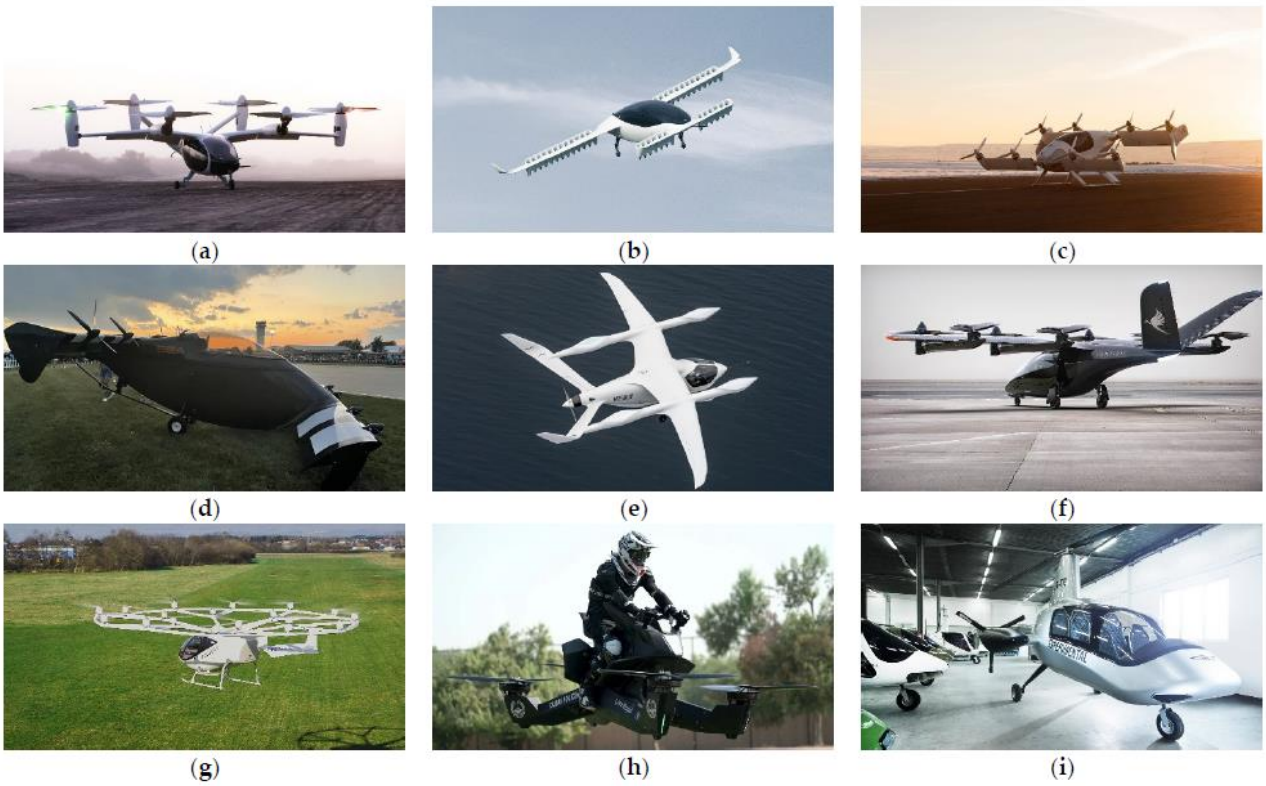

Figure [1.4]: different eVTOL types

Last category, but not least, is the combined thrust which combines thrust vector control for some propulsion units while the remaining units are fixed for the vertical mode.

One of the main advantages concerns the overall weight of the aircraft since in this case the LTUs are not counted as "dead weight", as in the case of the independent thrust since all the units are used during the ascent phase. However, additional LTUs are added to meet the high power demands in portrait mode.

However, some complications of the vector case can also be seen in this category, although to a lesser extent.

An emblematic example of this category is the Vertical Aerospace VX4 aircraft.

2.2 Study cases

To obtain the development and production costs for the next chapter, six different eVTOL aircraft were chosen, two for each existing category to be able to analyze all possible cases. The choice fell on the following eVTOL:

- vectored thrust: 1. Lilium Jet
  2. Joby S4 2.0
- lift and cruise: 1. Cora Generation 5
  2. Beta Alia 250
- multicopter: 1. E-Hang 216
  2. Volocity

2.2.1 Lilium Jet

The aircraft Lilium Jet is a fully electric aircraft, belonging to the category of eVTOL; it has German origin developed by the company Lilium GmbH. Initially the company had hypothesized the realization of a prototype constituted by folding bodies forward able to fly through electric propulsion and able to recharge in some hours by means of a standard socket to 240 V. The first unmanned flight was completed from a two-seater prototype, named Eagle full-size, on 20 April 2017 at Mindelheim-Mattsies airport in Bavaria, Germany. Further flight tests were carried out and the first prototype destroyed due to a fire took place on 20 February 2020. Another incompletely erected prototype was undamaged. Another untreated prototype was abandoned and work began on the seven- figure interpretation. Simplicity is one of Lilium's most important design rudiments. There are numerous affects you can leave out of an aeroplane to keep its complexity as low as possible, which means lower product costs, lower conservation costs, better safety, lower costs, lower weight and advanced effectiveness. The company noted that any element that does not live does not bear development and does not bear conservation. The company also launched an alternate and much larger smart plant compared to the original 3000 square measures, the Lilium Jet series product.. product installations are smart manufactories and grasp, digital from the launch and use adaptive work instructions. With this approach, these product units aim to achieve advanced product volumes than presently produced by aerospace product installations. Lilium aims to produce hundreds of aircraft per time at the launch of marketable service.

Figure [2.1]: Lilium Jet

To allow thrust during the cruise phase and allow take-off and landing the Lilium Jet uses several rather small-ducted propellers that are activated by electric motors: they are 36. Six are mounted on the front canards while twelve on each rear wing. The company wanted to define the eVTOL as a jet because the propellers are enclosed inside the gondolas.

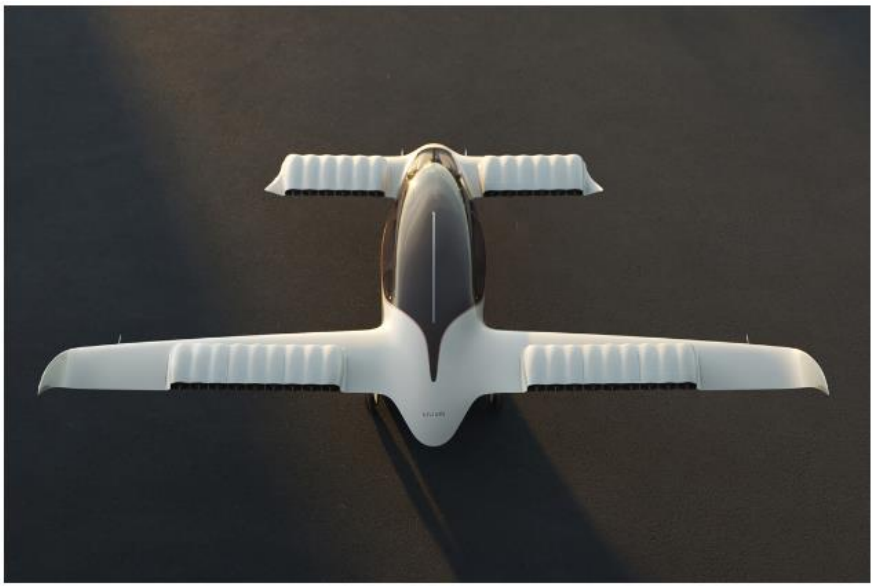

Figure [2.2]: Lilium Jet

During vertical casting, the transmission fins rotate downwards. As soon as you reach the horizontal position, a forward thrust develops.
This configuration allows it to be cheaper than a conventional rotor, actually compared to its main competitors is the most expensive due to very high caries on the disc and power delivery.
With regard to batteries, Lilium has invested heavily on anodic silicon-dominated batteries that offer high energy levels and power densities even at low charging levels (12C with 3.8 kW/kg at 50% charge and 3.0 kW/kg at 30%).

Figure [2.3]: Internal Lilium Jet

General characteristics

- capacity: 7 seater, 1 pilot and 6 passengers
- empty weight: 3100 kg
- maximum take-off weight: 640 kg
- power plant: 36 vertical electric

Performance

- maximum speed: 300 km/h

- cruise speed: 280 km/h
- range: 300 km

2.2.2 Joby S4.0 2.0

Joby Aviation is a start-up founded in 2009 by the CEO and founder JoeBen Bevirt in Santa Cruz and San Carlos, California. Its main objective is to create fully electric vertical take-off and landing aircraft. In addition to this company also founded the company Joby which operates on the telephony market, selling in addition to mobile phones also cameras, lighting accessories and other consumer products.

Starting from January 2020, the company has a total of 400 employees and numerous open applications that justify the huge investment that Bevirt is making. The company combines helicopter debris and small aircraft to create extremely quiet and fully electric eVTOL prototypes.

Joby Aviation's first prototypes were the Joby S2, Joby Lotus and Joby Monarch. Starting from the aircraft Joby S2 we arrived at the realization of the Joby S4 2.0, which is an eVTOL capable of carrying five people, including the pilot, equipped with six tilting propellers. The eVTOL features an extremely modern and futuristic design with large openings to allow passengers a fantastic view of the outside world. It also features a classic tricycle landing gear.

Figure [2.4]: Joby S4.0

A distributed electric propulsion system (DEP) allows the aircraft to reach 322 km/h; batteries consisting of lithium-nickel-cobalt-manganese oxide providing a range of 241 km power them.
It also has a flight control system that helps the pilot during the pre-cruise phase.

Figure [2.5]: Joby S4.0

A propulsion system type DEP in addition to ensuring greater stability during flight allows the aircraft to be extremely quiet, limiting emissions, lower weight, lower operating costs, higher efficiency, low weight, no delay in starting or stopping the engine, as well as ensuring high redundancy which translated means more safety for the passenger. In fact, if one or more propellers fail, the remaining ones will be able to land the eVTOL safely.

General characteristics

- capacity: 5 seater, 1 pilot and 4 passengers
- empty weight: 1815 kg
- maximum take-off weight: 2404 kg
- power plant: 6 high performance electric motors

Performance

- maximum speed: 322 km/h
- range: 241 km

2.2.3 Cora Generation 5

Wisk Aero is a start-up founded in 2019 as a challenge between two large aerospace companies: Boeing and Kitty Hawk Corporation. It is based in Mountain View, California. The main objective of the company is the realization of electric aircraft with zero emissions.

Figure [2.6]: Cora Generation 5

Cora Generation 5 is an independent two passenger's eVTOL prototype aircraft. The aircraft smooth egg- type shaped fuselage and has a cover over the cockpit. The company has made multiple prototype aircraft for testing purposes. The aircraft has flown numerous successful breakouts in the USA and New Zealand. It was confirmed in January 2020, that Wisk will only be making the Cora eVTOL as an independent aircraft and there will be no pilot. The aircraft has 12 independent VTOL only propellers powered by 12 electric motors are mounted equidistant thunderclaps, resembling to the fuselage and under its 11 measures long bodies. The low main bodies have flaps and winglets. There is one three- bladed pusher propeller providing thrust for forward flight. There is one binary smash tail with an inverted U vertical stabilizer, the vertical stabilizer having four flaps. The aircraft has fixed tricycle wheeled wharf gear.

Figure [2.7]: Cora Generation 5

General characteristics

- capacity: 2 seater, autonomous and 2 passengers
- empty weight: 2900 kg
- maximum take-off weight: 181 kg
- power plant: 12 high performance electric motors

Performance

- maximum speed: 180 km/h
- range: 100 km

2.2.4 Alia Beta 250

Beta Technologies is a company founded in 2017 by the entrepreneur Kyle Clark with the aim of creating a fully electric aircraft able to take off and land vertically just like helicopters. The company's first prototype was named the Ava XC. In addition to the creation of eVTOL, Clark plans to invest in the

production of charging columns for electric aircraft easily achievable within urban aggregates or cities.
Beta announced in April 2022 that it had raised $375 million to invest in the UAM, bringing its total funding to $796 million. Starting from the first months of 2023, the company has already reached about 450 employees, confirming itself as one of the most developed start-ups in the UAM sector.
The aircraft made by Beta Technologies is called Alia 250, a prototype that took three years of processing and design, obtaining a very special design. Clark has even compared it to the Arctic tern, that is a nice bird able to carry out particular "manoeuvres" in flight and able to emigrate for many kilometres, more than any other bird present on the earth.
Obviously, it is a totally electric aircraft, with a propulsion distributed on the 4 rotors. It currently has a range of about 50 minutes.
Alia 250 was built in two different configurations: cargo or passengers.

Figure [2.8]: ALIA 250

The shape of the V-tail aircraft was designed to reduce drag and stability during manoeuvres at low altitudes. Each set of propellers was mounted with a precise objective; unlike the tilting propellers, they were installed without thinking about the optimization of the design.

The company also produces electric motors directly to ensure that they are as customizable as possible for each eVTOL that will be produced. Finally, regarding the battery packs they are bought by external companies but then customized and adapted for different specific cases.

Figure [2.9]: ALIA 250

General characteristics

- capacity: 5 seater, 1 pilot and 4 passengers
- empty weight: 3175 kg
- maximum take-off weight: 635 kg
- power plant: 5 electric motors

Performance

- maximum speed: 300 km/h
- range: 500 km

2.2.5 E-Hang 216

E-Hang is a Chinese platform company created in 2014 by Huazhi Hu, president and CEO and Derrick Yifang Xiong, director and CFO.

The main objective of the company is the development of personal electric aircraft to transport goods and people. The EH216- S is a two passenger eVTOL multicopter product model aircraft made for advanced air mobility (AAM). The voyage speed of the aircraft is 100 km/ h, has a maximum speed of 130 km/ h and has a maximum altitude of 3,000 m. The range of the E-Hang 216 is 35 km and has a flight time of 21 twinkles. The letter" S" is a common convention in the aeronautics and manufacturing assiduity denoting a product interpretation of a product, indicating it has reached a stage of development suitable for manufacturing and marketable use. The aircraft has 16 propellers, 16 electric motors and is powered by batteries. The battery recharging time is 120 twinkles. The maximum cargo of the aircraft is 220 kg. The multicopter has a cover over the incline and windows on doors furnishing excellent views for the passengers. The aircraft has chump-sect doors. The fuselage is made of carbon fiber compound for high strength to low weight rate. The aircraft has fixed descent wharf gear.

Figure [2.10]: E-Hang 216

General characteristics

- capacity: 2 seater, autonomous and 2 passengers
- empty weight: 600 kg
- maximum take-off weight: 220 kg
- power plant: 16 electric motors

Performance

- maximum speed: 130 km/h
- cruise speed: 100 km/h
- range: 35 km

2.2.6 Volocity

The eVTOL Volocity is realized by the German company Volocopter from 2019. It’s a totally electric aircraft that can take off and land vertically. It is the fourth generation of such aircraft after the Volocopter VC200/2X. It is in line with the SC-VTOL provisions published by EASA in 2019. The first flight

test was carried out in June 2021 and lasted about 3 minutes. In 2024, it is said that it will be used during the inauguration of the Olympic Games to be held in Paris, obviously unmanned.
The Volocity is equipped with 18 electric motors capable of carrying a maximum of two people including the pilot.
To ensure high safety for the crew, this aeroplane has a high number of redundancies.

Figure [2.11]: Volocity

Figure [2.12]: Volocity

General characteristics

- capacity: 2 seater, autonomous and 2 passengers
- empty weight: 700 kg
- maximum take-off weight: 200 kg
- power plant: 18 brushless DC electric motors

Performance

- maximum speed: 110 km/h
- cruise speed: 90 km/h
- range: 35-65 km

3 Cost analysis

This section will examine different parametric methods to derive the development and production costs of the eVTOL that was selected and discussed in the previous chapter. In particular, starting from the literal description of the existing and already used methods in the aeronautical sector and beyond.

Parametric cost estimating models are based on parametric methods, valuating hardware or software costs. Parametric models typically consist of several interrelated CERs and are often computerized.

In the following section, the parametric cost model used for the thesis are summarized.

3.1 Roskam cost model

The parametric cost method is based on the CERs reported in the “Part VIII-Airplane Cost estimation”, first published in 1989 by Dr. Jan Roskam. The purpose of this method is to present preliminary cost estimating methods for newly designed airplanes, both military and commercial.

The idea of LCC (Life Cycle Cost) is defined and its relation to the design decision-making process is outlined. The main costs of LCC are:

- Research, development, technology and evaluation cost (RDT&E cost)
- Manufacturing and Acquisition cost (ACQ cost)
- Operating cost (OPS cost)
- Disposal cost (DISP cost)

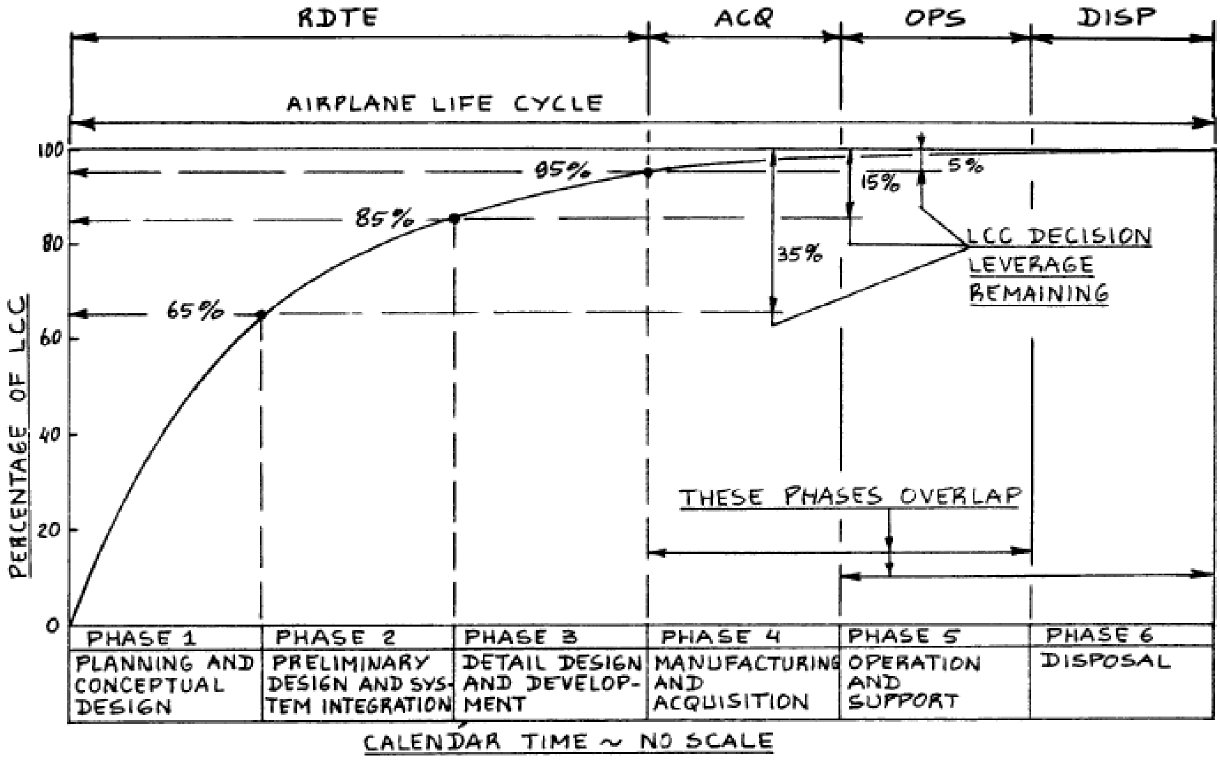

Figure [3.1]: life cycle cost

3.1.1 RTD&E cost

The RDT&E cost is the first cost source and is accumulated during phases 1-3 in *Figure [3.1]*. Phases 1-3 involve those activities that take a new airplane all the way from the planning and conceptual design stage to certification. This applies not only to military, but also to commercial airplanes. Phases 1-3 normally include the design, construction, ground and flight testing of a number of static and flight test airplanes. *Figure [3.1]* shows how the RDT&E activities of phases 1-3 fit into an airplane program. The method for estimating RDT&E cost can be applied to military as well as to commercial airplane programs.

RDT&E costs are normally broken down into seven cost categories:

- Airframe engineering and design cost c_{aed_r}
- Development support and testing cost c_{dst_r}

- Flight test airplanes cost c_{fta_r}
- Flight test operations cost c_{fto_r}
- Test and simulation facilities cost c_{tsf_r}
- RDT&E profit c_{pro_r}
- Cost to finance the RDT&E phases c_{fin_r}

Not all airplane programs are aimed at eventual production. Some are started for reasons of developing or demonstrating some aspect of advanced technology.

3.1.2 Manufacturing and Acquisition cost

These costs are incurred during phase 4 in the *Figure [3.1]*. The acquisition cost represents the second source of the Life Cycle Cost. The different between acquisition cost and manufacturing cost is the profit made by the manufacturer, so that:

$$c_{ACQ} = c_{MAN} + c_{PRO}$$

Again, the costs mentioned so far represent program costs. The price paid by the user of an airplane depends on a number of factors:

- The total number of airplanes built by the manufacturer
- The number of airplanes acquired
- The cost of the RTD&E program
- It is possible to negotiate the manufacturer's profit

The total costs associated with the production of the aircraft program can be divided into one of the following categories:

- Airplane engineering and design cost c_{aed_m}
- Airplane production cost c_{apc_m}

- Production flight test operations cost c_{fto_m}
- Cost of financing the manufacturing program c_{fin_m}

The final estimate of the cost of the eVTOL is obtained following the application of the following formula:

$$AEP = \frac{(c_{MAN} + c_{PRO} + c_{RDT\&E})}{N_m}$$

where N_m represents the number of airplanes produced to production standard during program.

3.2 Dapca IV - Raymer cost model

The method reported by Prof Raymer in his manual is essentially based on sets CERs for conceptual design developed by RAND Corporation and known as DAPCA-IV.

This cost model for estimating aircraft acquisition cost is based on Department of Defence data and thus over predicts the cost of general aviation aircraft.

The initial set of equations was taken as listed in Nicolai's text, which the author was using at ERAU at the time. As indicated by the cost model, the process of adjusting this set of cost estimating relationship (CER) equations has begun. This was done by calculating and tabulating the magnitude of various segments of the design and manufacturing process. The equations divide the cost into eight main components:

- engineering hours
- tooling hours
- manufacturing hours
- quality control hours

- development support cost
- flight test cost
- cost of manufacturing materials
- engine production cost.

Each segment is estimated by an equation generated by regression analysis of Department of Defence database information.
The equation for engineering labour hours is typical:

$$E = 0.396 \cdot W^{0.791} \cdot V^{1.526} \cdot Q^{0.183}$$

where W is the airframe weight in pounds, V is the maximum velocity in knots and Q is the total number of aircraft produced.
Therefore, a subjective assessment was made of how time consuming or difficult it is perform each segment on a general aviation aircraft compared to a military aircraft.

Engineering cost

$$H_{eng} = 4.86 \cdot W_e^{0.777} \cdot V^{0.894} \cdot Q^{0.163} \cdot Airframe_{factor}$$
$$c_{eng} = H_{eng} \cdot R_e$$

where c_{eng} includes airframe design and analysis, test engineering, configuration control and system engineering.

Tooling cost

$$H_{tool} = 5.99 \cdot W_e^{0.777} \cdot V^{0.696} \cdot Q^{0.263} \cdot Airframe_{factor}$$
$$c_{tool} = H_{tool} \cdot R_{tool}$$

where c_{tool} includes preparation for production. Design and fabrication of tools and fixtures, production of molds, programming CAD/CAM tools, development and fabrication of production test apparatus.

Manufacturing cost

$$H_{man} = 7.37 \cdot W_e^{0.82} \cdot V^{0.484} \cdot Q^{0.641} \cdot Airframe_{factor}$$
$$c_{man} = H_{man} \cdot R_{man}$$

where c_{man} stands for the direct labor to fabricate the aircraft: forming, machining, fastening, subassembly fabrication, final assembly, routing and purchased part installation.

Quality cost

$$H_{quality} = 0.133 \cdot H_{man} \cdot Airframe_{factor}$$
$$c_{quality} = H_{quality} \cdot R_{quality}$$

where $c_{quality}$ includes receiving inspection, production and final inspection.

Flight Test Aircraft

$$c_{FTA} = 2498 \cdot W_e^{0.325} \cdot V^{0.282} \cdot FTA^{1.21}$$

where c_{FTA} stands for the Flight Test Aircraft costs, so to demonstrate airworthiness and/or compliance with military standards expect for the costs of flight test aircraft themselves.

Material cost

$$c_{mat} = 22.1 \cdot W_e^{0.921} \cdot V^{0.621} \cdot Q^{0.799} \cdot Airframe_{factor}$$

where c_{mat} stands for the raw materials and purchased hardware and equipment from which the airplane is built

Development cost

$$c_{develop} = 91.3 \cdot W_e^{0.63} \cdot V^{1.3}$$

where $c_{develop}$ includes fabrication of mock-ups, subsystem simulators, structural and other test items.

Avionic cost

$$c_{avionic} = Avionic\_factor \cdot W_e$$

where the avionic factor is an input between 5% and 25% of the flyaway cost.

RDT&E cost

$$RDT\&E_{PROD_{cost-preliminary}} = c_{eng} + c_{tool} + c_{man} + c_{quality} + c_{FTA} + c_{mat} + c_{develop} + \left(c_{eng} \cdot N_{eng}\right) + c_{avionic} \cdot Q$$

$$Cost_{RDT\&E\&PROD_{cost-preliminary}} = RDT\&E_{PROD_{cost-preliminary}} \cdot Investment - factor \cdot CEF$$

where 0.9 is a commercial aircraft factor and the investment factor is between 1.1 and 1.4.

Finally the AEP, Aircraft Estimated Price, is

$$AEP = \frac{Cost_{RDT\&E\&PROD_{cost-preliminary}}}{Q} 1.1$$

where 1.1 is the initial spares factor.

3.3 Beltramo cost model

This bottom-up parametric cost method is based on CERs first presented at the 38th annual conference of the Society of Allied Weight Engineers by M.N. Beltramo. Production costs can be divided into design phase costs and production phase costs and are respectively NRC and RC. The model will determine the NRC using the method of Roskam. Roskam calls the design phase the Research, Development, Testing and Evaluation phase. This method is suitable for both commercial and military aircraft.
Beltramo is used to determine RC.
This is accomplished by two-step process:

- weight is first derived basing on performance and design parameters
- cost is then estimated as a function of weight and quantity of aircraft build.

The costs for engines should be obtained from engine manufacturers. The bottom-up method uses engine component prices derived from regression analysis. However, Beltramo offers cost features to cover the car and engine. They are included in the price of the engine using the bottom-up method. From some sample studies presented by Beltramo it appears that, the bonnet and cover affect the price of the engine by 20%. Therefore, the

bottom-up method uses 80% of engine component prices as the engine price. A belt drive requires the weight of several parts of the aircraft.
These weights, in turn, are used to determine the cost of these components, which are:

- wing
- tail
- fuselage
- landing gear
- control surface
- nacelle
- motors
- flight controls
- air conditioning system
- avionics
- battery
- cables

Each cost is multiplied by a particular factor, called CEF, which takes into account the inflation that the currency undergoes, thus discounting the cost.

Wing cost

$$c_{wing} = 2290 \cdot W_{wing}^{0.766} \cdot Q_{wing}^{-0.218} \cdot CEF$$

where c_{wing} is the manufacturing wing cost during production and CEF is the inflation factor.

Tail cost

$$c_{tail} = 2410 \cdot W_{tail}^{0.766} \cdot Q_{wing}^{-0.218} \cdot CEF$$

where c_{tail} is the manufacturing tail cost during production.

Fuselage cost

$$c_{fuselage} = 2730 \cdot W_{fuselage}^{0.766} \cdot Q_{wing}^{-0.218} \cdot CEF$$

where $c_{fuselage}$ is the manufacturing fuselage cost during production.

Landing gear

The cost for the landing gear varies based on the type of gear that the eVTOL mounts: there are three different configurations:

- fixed skid
- tricycle landing gear
- retractable landing gear

The main difference consists in the final weight of the landing gear due to the different technology present. In particular, the weight of the single landing gear is defined as:

- fixed skid: 3% of MTOW
- tricycle landing gear: 0.035% of MTOW
- retractable landing gear: 0.04% of MTOW

$$c_{landing-gear} = 1180 \cdot W_{landing-gear}^{0.766} \cdot Q_{landing-gear}^{-0.218} \cdot CEF$$

where $c_{landing-gear}$ is the manufacturing landing gear cost during production.

Control surface

$$c_{cs} = 195 \cdot W_{cs} \cdot Q_{wing}^{-0.218} \cdot CEF$$

where c_{cs} is the manufacturing control surface cost during production.

Nacelle

$$c_{nacelle} = 4600 \cdot W_{nacelle}^{0.766} \cdot Q_{nacelle}^{-0.218} \cdot CEF$$

where $c_{nacelle}$ is the manufacturing nacelle cost during production.

Engine

$$c_{engine} = 159 \cdot W_{engine} \cdot Q_{engine}^{-0.218} \cdot CEF$$

where c_{motors} is the manufacturing motors cost during production.

Flight control

$$c_{fc} = 205 \cdot W_{fc} \cdot Q_{fc}^{-0.218} \cdot CEF$$

where c_{fc} is the manufacturing flight control cost during production.

Air conditioning system

$$c_{acs} = 268 \cdot W_{acs} \cdot Q_{acs}^{-0.218} \cdot CEF$$

where c_{acs} is the manufacturing air conditioning system cost during production.

Avionics

$$c_{avionics} = 2084 \cdot W_{avionics} \cdot Q_{avionics}^{-0.184} \cdot CEF$$

where $c_{avionics}$ is the manufacturing avionics cost during production.

Cables

$$c_{cables} = 39 \cdot W_{cables} \cdot Q_{cables}^{-0.184} \cdot CEF$$

where c_{cables} is the manufacturing cables cost during production.

4. Application to case studies

The complete configuration of the eVTOL changes according to the design adopted, each aircraft will have different components that will be individually analysed in terms of production and development cost, using the cost estimation methods presented in the previous chapter.
In order to apply these methods, the entire aircraft was first divided into different subsystems and analysed in terms of weight in order to use the equations in the cost models.

4.1 Cost model input

Described the models used and the cost program, an input's overview has been presented in this section for development and production cost. It is important to note that the DAPCA IV cost-method combines the RDT&E and the Production cost.

4.1.1 RDT&E Input

The only cost-method, which divides the flyaway costs analysing the RDT&E and PROD cost separately, is the Roskam one.

Roskam RDT&E Input
Since the model used in Roskam is dated, since it was developed in 1989, a CEF factor has been introduced that can update prices.

Table [4.1]: Roskam model input

Roskam model input							
Input		**Lilium Jet**	**Alia 250**	**Cora Generation 5**	**E-Hang 216**	**Volocity**	**Joby S4.0**
CEF	from 1989 to 2023	4	4	4	4	4	4
MTOW	max take-off weight [kg]	3175	3175	2900	600	900	2404
V_e	cruise speed [Km/h]	300	300	222	130	110	322
N_e	engines number	36	5	12	8	18	6
N_m	number of manufactured aircraft	18650	150	1500	2400	18500	9650
R_e	engineering rate [US$/h]	119	119	119	119	119	119
R_m	manufacturing rate [US$/h]	66,3	66,3	66,3	66,3	66,3	66,3
R_t	tooling rate [US$/h]	85,8	85,8	85,8	85,8	85,8	85,8
$N_{RDT\&E}$	number of RDT&E aircrafts built	5	13	5	5	5	13
N_{ST}	number of airframes built	25	50	200	500	500	200
N_r	number of aircrafts built per month	194,27	1,56	15,63	25	192,71	100,52
F_{mat}	material factor	2,25	2,25	2,25	2,25	2,25	2,25
F_{obs}	low observable factor	1	1	1	1	1	1
F_{diff}	program complexity factor	2	2	2	2	2	2
F_{CAD}	CAD factor	1,2	1,2	1,2	1,2	1,2	1,2
Finance	[%]	15	15	15	15	15	15
Profit	[%]	15	15	15	15	15	15

4.1.2 PROD Input

The two main PROD cost-methods have been the Roskam and Beltramo.

4.1.2.1 Roskam PROD Input

As can be seen in *Table [4.2]*, some input are the same as the RDT&E one, but some values are different. For instance, the cost-rate were changed because the cost associated during PROD phase are slightly lower than during RDT&E.

Table [4.2]: Roskam PROD Input

Roskam model input							
Input		Lilium Jet	Alia 250	Cora Generation 5	E-Hang 216	Volocity	Joby S4.0
CEF	from 1989 to 2023	4	4	4	4	4	4
MTOW	max take-off weight [kg]	3175	3175	2900	600	900	2404
V_e	cruise speed [Km/h]	300	300	222	130	110	322
N_{pax}	number of passengers	7	5	2	2	2	5
N_e	engines number	36	5	12	8	18	6
N_m	number of manufactured aircraft	18650	150	1500	2400	18500	9650
R_e	engineering rate [US$/h]	119	119	119	119	119	119
R_m	manufacturing rate [US$/h]	66,3	66,3	66,3	66,3	66,3	66,3
R_t	tooling rate [US$/h]	85,8	85,8	85,8	85,8	85,8	85,8
$N_{RDT\&E}$	number of RDT&E aircrafts built	5	13	5	5	5	13
N_r	number of aircrafts built per month	5	5	5	5	5	5
F_{over}	overhead factor	4	4	4	4	4	4
F_{mat}	material factor	2,25	2,25	2,25	2,25	2,25	2,25
F_{obs}	low observable factor	1	1	1	1	1	1
F_{diff}	program complexity factor	2	2	2	2	2	2
F_{CAD}	CAD factor	1,2	1,2	1,2	1,2	1,2	1,2
FTh	flight test hour [h]	2	20	2	2	2	2
F_{int}	interior factor [US$/pax]	1000	0	1000	1000	1000	0
Finance	[%]	15	15	15	15	15	15
Profit	[%]	10	10	10	10	10	10

4.1.2.2 Beltramo PROD Input

In order to apply the Beltramo model it is first necessary to analyse the weight of the single subsystem.

The weights at the subsystem level will be different depending on the selected configuration due to the different design type.

The entire structure is divided into different subsystems.

Landing Gear

1. Fixed skid $W_{fix\_skid} = 0.03 \cdot MTOW$
2. Tricycle landing gear $W_{tri} = 0.035 \cdot MTOW$
3. Retractable tricycle landing gear $W_{ret} = 0.04 \cdot MTOW$

Fuselage

To determine the weight of the fuselage, the literature always uses conventional aircraft. For the specific case of eVTOL, several formulae exist in the literature, including:

$$W_{fus} = 14.86 \cdot MTOW^{0.144} \cdot \frac{L_f^{0.778}}{P_{max}} \cdot L_f^{0.778} \cdot N_{pax}^{0.455}$$

where:

- L_f is the fuselage length
- P_{max} is the maximum fuselage perimeter
- N_{pax} is the passengers number

Esistono delle relazioni che permettono di stimare il peso della fusoliera in funzione del MTOW:

- 7% of MTOW for Multicopter configuration
- 9%-10% of MTOW for Vectored Thrust and Combined Thrust configuration
- 12% of MTOW for Independent Thrust configuration

Wing

The wing can be considered with similar considerations as the fuselage. In particular, the weight of this component is expressed as

$$W_w = 0.04674 \cdot MTOW^{0.397} \cdot S_w^{0.36} \cdot \eta_w^{0.397} \cdot AR_w^{1.712}$$

where

- S_w is the wing surface
- η_w is the load factor
- AR_w is the wing aspect ratio

Also in this case it is possible to express the total weight of wing with the MTOW of the single eVTOL:

- 8% of MTOW for Independent Thrust configuration
- 10%-12% of MTOW for Vectored Thrust and Combined Thrust configurations

Due to the different configuration of eVTOL compared to conventional aircraft (lack of arrow angle, tanks…), the empirical equation above was not applicable for certain eVTOLs. In the case of the Multicopter configuration the wing is not present.

V-Tail

In eVTOL aircraft, the most commonly used tail configuration is the V-Tail on because it can enclose three tails thanks to the differential use of its control surfaces in two tails.

The empirical formula used in the treatment

$$W_{V-tail} = 0.039 \cdot MTOW^{0.567} \cdot S_v^{1.294} \cdot AR_v^{0.482} \cdot \frac{t_v^{0.747}}{15.6}$$

where

- S_v is the tail surface
- AR_v is the tail aspect ratio
- t_v is the tail thickness

Control Surface

The weight of the control surfaces is estimated as

$$W_{cs} = 0.4 \cdot MTOW^{0.684}$$

Arms

These components are only inside the Multicopter configuration due to the lack of wings, tail and control surfaces. The main difference in this configuration is the number and shape of the arms.

The weight of the arms is calculated

$$W_{arms} = n_{arms} \cdot k \cdot S_{wetted} \cdot t \cdot \rho_{material}$$

where

- n_{arms} is the number of the arms
- k is loading structural factor
- S_{wetted} is the external wetted surface
- T is the arm thickness
- ρ is the material density

E-Motors

As previously mentioned, eVTOL are completely electric aircraft with electric motors, which are powered by electric current.

Each eVTOL usually has several electric motors; it tends to be fitted with identical or very similar motors. Each engine must therefore provide the same power as the others in nominal conditions.

Having the power generated by each individual engine, you can derive its weight as

$$W_{motor} = \frac{1}{5} \cdot P_{motor}$$

where

- P_{motor} is the power engine generated

Cables

They have as their main function to bring electricity from the accumulator to the electric motors.

In general, the total weight of the cables is expressed as

$$W_{cables} = S_c \cdot L_c \cdot \rho_c \cdot 4 \cdot n_{motor}$$

where

- S_c is the cables section
- L_c is the cables lenght
- ρ_c is the cables material density

Battery

Lithium-ion batteries are the current batteries used. They can reach high energy densities of the order of 200 Wh/kg.

To derive the mass of batteries use

$$W_{battery} = \frac{1}{200} \cdot E_{battery}$$

where

- $E_{battery}$ is the energy density of the battery in Wh

Fuel Cell

An alternative method to the batteries used are fuel cells that are mounted on certain types of eVTOL.

The total weight of the fuel cells is calculated as

$$W_{fc} = 70.326 + (0.9404 \cdot P_{motor})$$

where

- P_{motor} is the power motor generated

Liquid Tank

A liquid tank is necessary for fuel cells to operate. On the market, the two most used tanks weigh respectively 16 kg and 32 kg.

Air Conditioning System

Per poter determinare la massa di questo sottosistema è stato considerato un classico sistema installato a bordo degli elicotteri. Utilizzando la seguente formula empirica si è ricavato il peso del sottosistema

$$W_{acs} = 0.015 \cdot MTOW$$

Flight Control System

There are two different configurations of this system:

- system for *wingless* configuration
- system for *powered lift* configuration

The technology used is simpler in the wingless configuration, which has a simpler and lighter system than the powered lift counterpart due to the absence of moving parts. However, given the lack of information on the subject, it was decided to assume the same technology for both configurations and assume the weight of the subsystem equal to

$$W_{fcs} = 12.92\ kg$$

Avionics

Per quanto riguarda l'avionica è possibile utilizzare la seguente formula

$$W_{avio} = 18.1 + 0.008 \cdot MTOW$$

The *Table [4.3]* summarizes all the Beltramo weight inputs used to estimate the PROD eVTOL cost and finally obtain the AEP.

Table [4.3]: Beltramo model input

Beltramo model input							
Input		**Lilium Jet**	**Alia 250**	**Cora Generation 5**	**E-Hang 216**	**Volocity**	**Joby S4.0**
CEF	from 1989 to 2023	4	4	4	4	4	4
N_m	number of manufactured aircraft	18650	150	1500	2400	18500	9650
W_{wing}	wing weight [kg]	349,25	349,25	319,00	0,00	0,00	264,44
$W_{fuselage}$	fuselage weight [kg]	317,50	317,50	290,00	290,00	90,00	240,40
W_{tail}	tail weight [kg]	0,00	39,61	0,00	0,00	0,00	80,00
W_{lg}	landing gear weight [kg]	127,00	95,25	101,50	87,00	27,00	93,16
W_{nac}	nacelles weight [kg]	50,00	50,00	50,00	0,00	0,00	50,00
W_{mot}	motors weight [kg]	104,00	289,60	69,12	38,00	90,00	40,00
W_{fcs}	flight control system weight [kg]	12,92	12,92	12,92	12,92	12,92	12,92
W_{acs}	air conditioning system weight [kg]	38,36	30,04	17,57	17,57	17,57	30,04
W_{avio}	avionics weight [kg]	43,50	43,50	41,30	41,30	25,30	37,33
W_{cs}	control surface weight [kg]	99,37	99,37	93,40	93,40	41,95	82,15
W_b	battery weight [kg]	240,00	470,00	400,00	0,00	0,00	600,00
W_{fc}	fuel cell weight [kg]	0,00	0,00	0,00	249,00	305,00	0,00
W_{lt}	liquid tank weight [kg]	0,00	0,00	0,00	32,00	0,00	0,00
W_{cables}	cables weight [kg]	152,93	27,00	47,52	11,58	61,56	25,49
W_{arms}	arms weight [kg]	0,00	0,00	0,00	24,36	50,00	0,00
I.T. Factor	initial spares [%]	10,00	10,00	10,00	10,00	10,00	10,00
Finance	[%]	10,00	10,00	10,00	10,00	10,00	10,00

DAPCA IV-Raymer Input

The last one has been the DAPCA IV-Raymer cost method for both RDT&E and PROD cost. It is important to note that method was just as a comparison because it is optimized for military and/or civil long-range aircrafts.

Table [4.4]: RAND DAPCA model input

RAND DAPCA model input							
Input		**Lilium Jet**	**Alia 250**	**Cora Generation 5**	**E-Hang 216**	**Volocity**	**Joby S4.0**
CEF	from 1989 to 2023	4	4	4	4	4	4
N_m	number of manufactured aircraft	18650	150	1500	2400	18500	9650
MTOW	max take-off weight [kg]	3175,00	3175,00	2900,00	600,00	900,00	2404,00
V_e	cruise speed [km/h]	300,00	300,00	222,00	130,00	110,00	322,00
R_e	engineering rate [US$/h]	119,00	119,00	119,00	119,00	119,00	119,00
R_m	manufacturing rate [US$/h]	60,00	60,00	60,00	60,00	60,00	60,00
R_t	tooling rate [US%/h]	85,80	85,80	85,80	85,80	85,80	85,80
R_q	quality rate [US%/h]	67,32	67,32	67,32	67,32	67,32	67,32
FTA	flight test hours [h]	250,00	50,00	200,00	500,00	500,00	200,00
T_{FF}	time first flight	2019	2023	2022	2022	2022	2021

4.2 Cost model output

Obtained and controlled all data input with the software MatLab have been implemented different algorithms to obtain the desired output. The results of the various estimation methods analysed above are given below.

4.2.1 RDT&E Output

The only method analysed that makes it possible to derive the development costs of the aircraft analysed is the Roskam model. As can be seen in the following *Table [4.5]* the largest item is FTA costs.

Table [4.5]: RDT&E Output

ROSKAM RDT&E cost						
Output	**Lilium Jet**	**Alia 250**	**Cora Generation 5**	**E-Hang 216**	**Volocity**	**Joby S4.0**
Airframe engineering & Design cost	$ 52.453.000,00	$ 46.857.000,00	$ 4.671.000,00	$ 292.850,00	$ 299.460,00	$ 16.184.400,00
Development Support & Testing cost	$ 3.960.300,00	$ 5.512.000,00	$ 418.720,00	$ 57.965,00	$ 57.404,00	$ 7.661.400,00
FTA cost	$ 175.950.000,00	$ 221.570.000,00	$ 26.362.000,00	$ 2.490.100,00	$ 2.961.700,00	$ 99.810.000,00
Cost of engines and avionics	$ 303.500,00	$ 3.492.500,00	$ 205.200,00	$ 328.000,00	$ 363.000,00	$ 5.296.500,00
Manufacturing cost	$ 63.349.000,00	$ 104.520.000,00	$ 10.152.800,00	$ 865.980,00	$ 1.025.100,00	$ 34.089.000,00
Material cost	$ 8.223.400,00	$ 1.527.000,00	$ 1.291.360,00	$ 452.240,00	$ 518.780,00	$ 23.281.800,00
Tooling cost	$ 94.440.000,00	$ 82.142.000,00	$ 13.233.400,00	$ 815.770,00	$ 1.021.500,00	$ 36.036.000,00
Quality control	$ 8.235.300,00	$ 13.587.000,00	$ 1.319.880,00	$ 28.144,00	$ 33.316,00	$ 1.107.900,00
Flight test operational cost	$ 929.260,00	$ 3.395.600,00	$ 77.692,00	$ 13.884,00	$ 16.582,00	$ 4.246.200,00
Test & Simulation facilities cost	$ -	$ -	$ -	$ -	$ -	$ -
RDT&E program cost	$ 469.020.324,00	$ 554.993.565,00	$ 66.391.859,80	$ 6.146.672,95	$ 7.241.368,30	$ 261.870.180,00

4.2.2 PROD Output

The production costs shown here are calculated using both the Roskam model and the Beltramo model. While with the first you get results at the level of macro categories with the second you can estimate the single cost of the components of the structure.

Table [4.6]: Roskam PROD Output

ROSKAM PROD cost						
Output	**Lilium Jet**	**Alia 250**	**Cora Generation 5**	**E-Hang 216**	**Volocity**	**Joby S4.0**
Manufactured aircrafts	18650	150	18650	2400	12200	10000
Airframe eng & Design Man cost	$ 183.810.000,00	$ 60.397.000,00	$ 16.368.200,00	$ 833.160,00	$ 1.173.200,00	$ 50.560.200,00
Aircraft production cost	$ 13.858.000.000,00	$ 1.611.300.000,00	$ 2.163.200.000,00	$ 237.580.000,00	$ 1.196.100.000,00	$ 6.321.600.000,00
Cost of engine and avionics	$ 303.500.000,00	$ 381.000.000,00	$ 1.594.575.000,00	$ 196.800.000,00	$ 1.107.200.000,00	$ 4.815.000.000,00
Interior production cost	$ 522.200.000,00	$ 24.000.000,00	$ 29.840.000,00	$ 16.800.000,00	$ 24.400.000,00	$ 300.000.000,00
Manufacturing cost	$ 4.492.600.000,00	$ 977.510.000,00	$ 720.040.000,00	$ 21.052.000,00	$ 58.767.000,00	$ 1.063.440.000,00
Material cost	$ 5.552.500.000,00	$ 648.740.000,00	$ 871.920.000,00	$ 15.139.000,00	$ 62.609.000,00	$ 1.129.680.000,00
Tooling cost	$ 313.800.000,00	$ 101.670.000,00	$ 43.972.000,00	$ 2.244.200,00	$ 3.839.200,00	$ 108.606.000,00
Quality control cost	$ 584.040.000,00	$ 127.080.000,00	$ 93.604.000,00	$ 684.210,00	$ 1.909.900,00	$ 34.561.800,00
Flight test operations cost	$ 4.972.800.000,00	$ 319.968.000,00	$ 99.456.000,00	$ 159.984.000,00	$ 813.252.000,00	$ 3.999.600.000,00
PROD cost	$ 35.400.737.500,00	$ 4.889.414.750,00	$ 6.477.921.480,00	$ 748.784.055,50	$ 3.759.637.845,00	$ 20.496.505.200,00

The Beltramo model results will be presented individually for each eVTOL for better reading and clarity.

Table [4.7]: ALIA 250 PROD Output

ALIA 250			
Output	**Weight [kg]**	**$/kg**	**Prod Cost [US$]**
Manufactured aircrafts	150		
STRUCTURE			
Wing	349,25	$ 257,76	$ 90.023,00
Fuselage	317,50	$ 313,85	$ 99.648,00
V-Tail	36,61	$ 83,68	$ 3.063,60
Control Surface	99,37	$ 310,68	$ 30.872,00
Nacelle	50,00	$ 1.080,10	$ 54.005,00
Multicopter fuselage	0,00	$ -	$ -
Multicopter arms	0,00	$ -	$ -
Fixed skid	95,26	$ 86,81	$ 8.269,60
Tricycle landing gear	0,00	$ -	$ -
Retractable landing gear	0,00	$ -	$ -
POWERPLANT			
E-Motors	289,60	$ 253,33	$ 73.363,00
E-Motors Multicopter	0,00	$ -	$ -
Cables	27,00	$ 62,14	$ 1.677,70
Battery	470,00	$ 106,38	$ 50.000,00
Fuel Cell	0,00	$ -	$ -
LH2 Tank	0,00	$ -	$ -
SUBSYSTEMS			
AC System	34,20	$ 426,99	$ 14.603,00
Flight control system	12,92	$ 326,62	$ 4.219,90
Avionics	43,50	$ 902,87	$ 39.275,00
Total PROD cost			$ 469.019,80

Table [4.8]: Lilium Jet PROD Output

Lilium Jet			
Output	**Weight [kg]**	**$/kg**	**Prod Cost [US$]**
Manufactured aircrafts	18650		
STRUCTURE			
Wing	349,25	$ 216,39	$ 75.575,32
Fuselage	317,50	$ 211,45	$ 67.134,23
V-Tail	0,00	$ -	$ -
Control Surface	99,37	$ 258,54	$ 25.691,00
Nacelle	50,00	$ 690,78	$ 34.539,00
Multicopter fuselage	0,00	$ -	$ -
Multicopter arms	0,00	$ -	$ -
Fixed skid	0,00	$ -	$ -
Tricycle landing gear	0,00	$ -	$ -
Retractable landing gear	127,00	$ 332,98	$ 42.288,68
POWERPLANT			
E-Motors	104,00	$ 210,81	$ 21.924,00
E-Motors Multicopter	0,00	$ -	$ -
Cables	152,93	$ 51,71	$ 7.907,70
Battery	240,00	$ 37,12	$ 8.909,80
Fuel Cell	0,00	$ -	$ -
LH2 Tank	0,00	$ -	$ -
SUBSYSTEMS			
AC System	38,36	$ 355,29	$ 13.629,00
Flight control system	12,92	$ 271,80	$ 3.511,70
Avionics	43,50	$ 1.092,05	$ 47.504,00
Total PROD cost			$ 348.614,43

Table [4.9]: CORA GENERATION 5 PROD Output

Cora Generation 5			
Output	**Weight [kg]**	**$/kg**	**Prod Cost [US$]**
Manufactured aircrafts	18650		
STRUCTURE			
Wing	319,00	$ 168,38	$ 53.714,00
Fuselage	290,00	$ 205,02	$ 59.457,00
V-Tail	37,21	$ 161,32	$ 6.002,70
Control Surface	93,40	$ 258,53	$ 24.147,00
Nacelle	50,00	$ 690,78	$ 34.539,00
Multicopter fuselage	0,00	$ -	$ -
Multicopter arms	0,00	$ -	$ -
Fixed skid	0,00	$ -	$ -
Tricycle landing gear	101,50	$ 150,15	$ 15.240,00
Retractable landing gear	0,00	$ -	$ -
POWERPLANT			
E-Motors	57,60	$ 461,15	$ 26.562,00
E-Motors Multicopter	0,00	$ -	$ -
Cables	47,52	$ 51,71	$ 2.457,20
Battery	400,00	$ 37,13	$ 14.850,00
Fuel Cell	0,00	$ -	$ -
LH2 Tank	0,00	$ -	$ -
SUBSYSTEMS			
AC System	17,57	$ 355,36	$ 6.243,60
Flight control system	9,00	$ 390,19	$ 3.511,70
Avionics	41,30	$ 1.092,06	$ 45.102,00
Total PROD cost			$ 291.826,20

Table [4.10]: E-Hang 216 PROD Output

E-Hang 216			
Output	**Weight [kg]**	**$/kg**	**Prod Cost [US$]**
Manufactured aircrafts	2400		
STRUCTURE			
Wing	0,00	$ -	$ -
Fuselage	0,00	$ -	$ -
V-Tail	0,00	$ -	$ -
Control Surface	93,40	$ 108,15	$ 10.101,00
Nacelle	0,00	$ -	$ -
Multicopter fuselage	290,00	$ 74,82	$ 21.699,00
Multicopter arms	24,36	$ 7,44	$ 181,30
Fixed skid	87,00	$ 74,66	$ 6.495,20
Tricycle landing gear	0,00	$ -	$ -
Retractable landing gear	0,00	$ -	$ -
POWERPLANT			
E-Motors	0,00	$ -	$ -
E-Motors Multicopter	38,00	$ 138,22	$ 5.252,30
Cables	11,58	$ 62,12	$ 719,39
Battery	0,00	$ -	$ -
Fuel Cell	249,00	$ -	$ -
LH2 Tank	32,00	$ 228,94	$ 7.326,00
SUBSYSTEMS			
AC System	17,57	$ 427,02	$ 7.502,80
Flight control system	0,00	$ -	$ -
Avionics	41,30	$ 889,20	$ 36.724,00
Total PROD cost			$ 96.000,99

Table [4.11]: Volocity PROD Output

Volocity			
Output	**Weight [kg]**	**$/kg**	**Prod Cost [US$]**
Manufactured aircrafts	12200		
STRUCTURE			
Wing	0,00	$ -	$ -
Fuselage	0,00	$ -	$ -
V-Tail	0,00	$ -	$ -
Control Surface	41,95	$ 268,58	$ 11.267,00
Nacelle	0,00	$ -	$ -
Multicopter fuselage	90,00	$ 295,73	$ 26.616,00
Multicopter arms	50,00	$ 8,14	$ 407,02
Fixed skid	27,00	$ 224,53	$ 6.062,20
Tricycle landing gear	0,00	$ -	$ -
Retractable landing gear	0,00	$ -	$ -
POWERPLANT			
E-Motors	0,00	$ -	$ -
E-Motors Multicopter	50,00	$ 21,90	$ 1.094,90
Cables	61,56	$ 53,71	$ 3.306,60
Battery	0,00	$ -	$ -
Fuel Cell	305,43	$ -	$ -
LH2 Tank	32,00	$ 228,94	$ 7.326,00
SUBSYSTEMS			
AC System	15,00	$ 432,37	$ 6.485,60
Flight control system	0,00	$ -	$ -
Avionics	25,30	$ 1.180,75	$ 29.873,00
Total PROD cost			$ 92.438,32

Table [4.12]: JOBY S4.0 PROD Output

Joby S4.0			
Output	**Weight [kg]**	**$/kg**	**Prod Cost [US$]**
Manufactured aircrafts	10000		
STRUCTURE			
Wing	264,44	$ 201,54	$ 53.296,00
Fuselage	240,40	$ 357,72	$ 85.995,00
V-Tail	0,00	$ -	$ -
Control Surface	82,15	$ 273,40	$ 22.460,00
Nacelle	50,00	$ 791,32	$ 39.566,00
Multicopter fuselage	0,00	$ -	$ -
Multicopter arms	0,00	$ -	$ -
Fixed skid	0,00	$ -	$ -
Tricycle landing gear	0,00	$ -	$ -
Retractable landing gear	96,16	$ 174,19	$ 16.750,00
POWERPLANT			
E-Motors	40,00	$ 835,95	$ 33.438,00
E-Motors Multicopter	0,00	$ -	$ -
Cables	25,49	$ 54,67	$ 1.393,60
Battery	600,00	$ 149,31	$ 89.583,00
Fuel Cell	0,00	$ -	$ -
LH2 Tank	0,00	$ -	$ -
SUBSYSTEMS			
AC System	30,04	$ 375,77	$ 11.288,00
Flight control system	75,00	$ 49,51	$ 3.713,40
Avionics	37,33	$ 1.224,81	$ 45.722,00
Total PROD cost			$ 403.205,00

Knowing at this point of the treatment is the development costs that of production will be possible to derive the total cost of the single eVTOL, defined like AEP, Aircraft Estimated Price. Within this item is already considered the profit margin for the company, i.e. the gain, which usually settles between a 10% and a 20%: in this case, we opted for a gain of 15% average.

Table [4.13]: AEP

Output	Lilium Jet	Alia 250	Cora Generation 5
AEP	$ 1.904.615,65	$ 2.188.096,29	$ 265.331,96
Estimated cost	$ 2.285.538,78	$ 2.516.310,73	$ 305.131,75
Declared cost	$ 2.500.000,00	$ 2.500.000,00	$ 300.000,00
% difference	**-8,58%**	**0,65%**	**1,68%**

Table [4.14]: AEP

Output	E-Hang 216	Volocity	Joby S4.0
AEP	$ 273.525,63	$ 268.487,47	$ 1.221.080,90
Estimated cost	$ 314.554,47	$ 308.760,59	$ 1.404.243,04
Declared cost	$ 302.000,00	$ 300.000,00	$ 1.300.000,00
% difference	**3,99%**	**2,84%**	**7,42%**

Observing the percentage differences between the declared cost and the actual cost, it can be concluded that the used method is the most effective considering the observed differences between +7.42% and -8.58%.

4.2.3 RDT&E and PROD cost output

The RAND DAPCA-IV model makes it possible to derive both production and development costs for eVTOL. The results obtained by applying this method are shown below.

It will be used only as a comparison with the other two methods because it is not optimal for the study of the aircraft analysed.

Table [4.15]: RAND DAPCA Output

RAND DAPCA Output			
Output	**Lilium Jet**	**Alia 250**	**Cora Generation 5**
Number of aircraft	18650	1500	18650
Engeneer Hours	$ 65.127,00	$ 61.184,00	$ 38.562,00
Tooling Hours	$ 41.167,00	$ 39.605,00	$ 33.373,00
Manufacturing Hours NR	$ 12.566,30	$ 10.899,20	$ 9.978,65
Manufacturing Hours R	$ 60.043,00	$ 58.875,00	$ 47.852,00
Manufacturing Mat Hours R	$ 4.225,12	$ 2.563,21	$ 2.180,24
Quality control Hours	$ 9.912,80	$ 9.609,30	$ 8.318,50
Development support	$ 158.710,00	$ 125.630,00	$ 182.302,00
Flight test	$ 1.721.100,00	$ 2.706.400,00	$ 223.600,00
Avionics	$ 36.026,00	$ 87.503,00	$ 36.026,00
AEP	**$ 2.108.877,22**	**$ 3.102.268,71**	**$ 582.192,39**
Estimated cost	$ 2.425.208,80	$ 3.567.609,02	$ 669.521,25
Declared cost	$ 2.500.000,00	$ 2.500.000,00	$ 300.000,00
% difference	**-3%**	**43%**	**123%**

Table [4.16]: RAND DAPCA Output

RAND DAPCA Output			
Output	**E-Hang 216**	**Volocity**	**Joby S4.0**
Number of aircraft	2400	12200	10000
Engeneer Hours	$ 13.459,00	$ 14.338,00	$ 59.301,00
Tooling Hours	$ 36.354,00	$ 11.197,00	$ 35.829,00
Manufacturing Hours NR	$ 1.040,30	$ 1.060,70	$ 6.986,30
Manufacturing Hours R	$ 17.141,00	$ 20.804,00	$ 51.242,00
Manufacturing Mat Hours R	$ 1.604,77	$ 1.469,35	$ 2.146,20
Quality control Hours	$ 2.603,40	$ 3.124,40	$ 8.569,60
Development support	$ 191.900,00	$ 189.250,00	$ 130.670,00
Flight test	$ 94.851,00	$ 123.740,00	$ 1.020.360,00
Avionics	$ 39.071,00	$ 38.952,00	$ 40.670,00
Total RDT&E and PROD cost	**$ 398.024,47**	**$ 403.935,45**	**$ 1.355.774,10**
Estimated cost	$ 457.728,14	$ 464.525,77	$ 1.559.140,22
Declared cost	$ 302.000,00	$ 300.000,00	$ 1.500.000,00
% difference	**52%**	**55%**	**4%**

Since it is not possible to know exactly how much the development costs affect the total, because not made available by the companies, it is assumed in order to make the comparison with the RAND DAPCA Method, that part of the development is included in the total sales price. Unlike the other methods in which the final price is assessed in relation to the cost of production.

4.3 Equation PROD cost

Having obtained all the production and development costs of the various eVTOL chosen, we proceed by introducing a particular concept typical of the aeronautical sector: learning curve.

The learning curve is a tool that can be used both for strategic assessments related to production competitiveness and to design production systems taking into account changes in time following the learning phenomenon.

It is the basic concept that, translated into appropriate mathematical models, allows us to predict with reasonable precision, of course if applied with criterion, the variation in time of quantities dependent on learning such as the unit cost of a product, the time needed to build it, the maintenance hours required for units of production volume, etc.

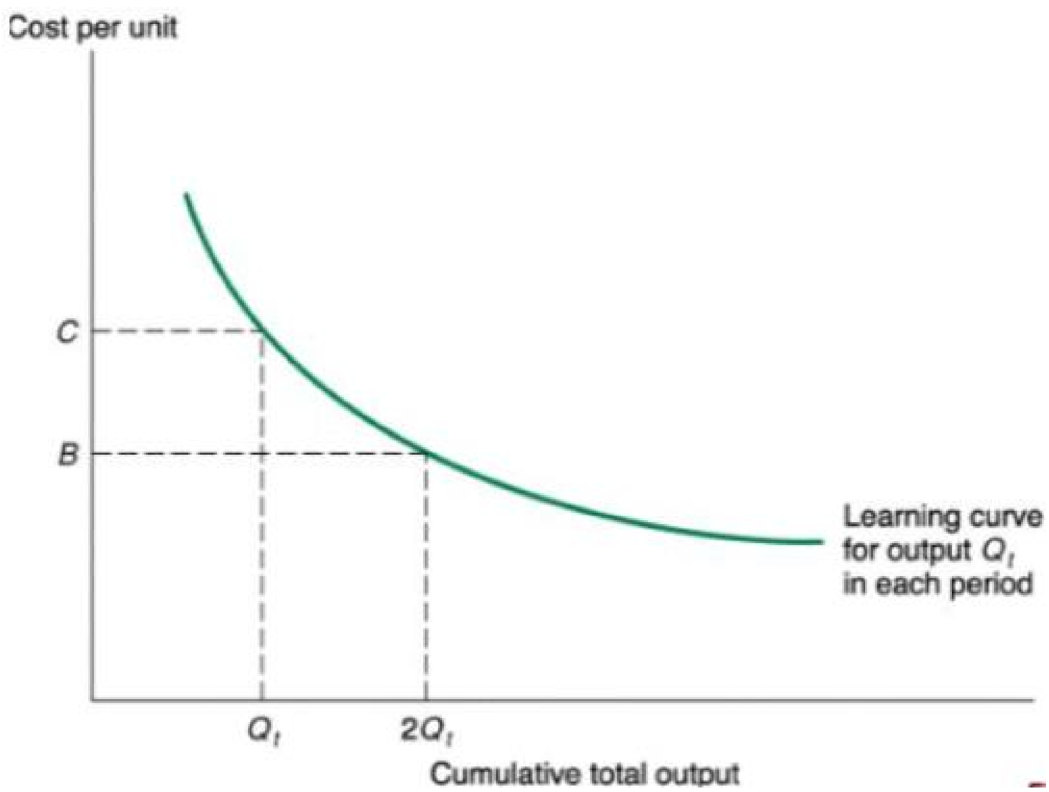

Figure [4.1]: learning curve

The equation governing the learning curve is shown below

$$Y = A \cdot X^b$$

where

$$b = \frac{\log(slope)}{\log 2}$$

In this case, we opted for a gradient of 83% for all the main components or more used, while for the components ad hoc or less used a slope less than about 90%.

In *Table [4.17]* it is possible to observe the equations obtained for all subsystems characterizing the complete eVTOL structure. Within the equation, there are three terms:

- a constant term that has a certain cost drive variable
- a constant term referring to the number of pieces produced
- the last term consisting of the number of pieces to be produced and the slope of the learning curve.

Table [4.17]: PROD equation cost

Production equation cost	
Components	**Production cost**
STRUCTURE	
Wing	$ = (199,1551+245,7051*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Fuselage	$ = (261,3887-47,7578*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
V-Tail	$ = (123,1318+4898,5*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Control Surface	$ = (243,6786+231,3833*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Nacelle	$ = (813,2450+813,2450*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Multicopter fuselage	$ = (94,2316-24,5850*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Multicopter arms	$ = (8,0065+8,8034*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Fixed skid	$ = (87,2947+22,9733*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Tricycle landing gear	$ = (150,1478+150,1478*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Retractable landing gear	$ = (154,0297+43,5798*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
POWERPLANT	
E-Motors	$ = (264,9900+186,4509*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
E-Motors Multicopter	$ = (64,4859-346,4500*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Cables	$ = (52,2979+50,6589*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Battery	$ = 28*kg*N^(log(%)/log(2))
LH2 Tank	$ = (838+202,7*kg)*0,9^(-log(%)/log(2))*N^(log(%)/log(2))
SUBSYSTEMS	
AC System	$ = (387,6319+359,7504*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Flight control system	$ = (67,8829-0,2343*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))
Avionics	$ = (1042+685,0759*kg)*Q^(-log(%)/log(2))*N^(log(%)/log(2))

4.4 Comparison between method used

Since the development costs of eVTOL cannot be found in the literature and therefore it is not possible to verify the correctness of the costs obtained, it was decided to compare the results obtained between the Roskam method and the RAND DAPCA method.

The following *Table [4.18]* shows the percentage results.

Table [4.18]: Roskam Model vs RAND DAPCA Model

% difference			
Output	**Lilium Jet**	**Alia 250**	**Cora Generation 5**
Roskam Model	$ 35.521.081.849,00	$ 5.444.408.315,00	$ 6.544.313.339,80
RAND DAPCA Model	$ 39.330.560.153,00	$ 4.653.403.065,00	$ 10.857.898.144,50
% difference	**-10%**	**17%**	**-40%**
Output	**E-Hang 216**	**Volocity**	**Joby S4.0**
Roskam Model	$ 754.930.728,45	$ 3.766.879.213,30	$ 20.758.375.380,00
RAND DAPCA Model	$ 955.258.728,00	$ 4.928.012.490,00	$ 13.557.741.000,00
% difference	**-21%**	**-24%**	**53%**

4.5 eVTOL vs Helicopter

The main competitor of the eVTOL is the helicopter. In this section, we will analyse the main characteristics of helicopters, from a propulsive and structural point of view, as well as a comparison in terms of development and production costs.

The helicopter chosen for the comparison is the Eurocopter EC145.

Figure [4.2]: Eurocopter EC145

The Eurocopter EC145 is a twin-engine light utility helicopter manufactured by Eurocopter. Originally, referred to as the BK 117 C2, the EC145 is based upon the MBB/Kawasaki BK 117 C1, which became a part of the Eurocopter line-up in 1992 when the company was formed through the merger of the

Messerschmitt-Bolkow-Blohm helicopter division of Daimler-Benz and the helicopter division of Aérospatiale-Matra. The EC145 can carry up to nine passengers along with two crew, depending on customer configuration. The helicopter is marketed for passenger transport, corporate transport, emergency medical services (EMS), search and rescue, parapublic and utility roles. Below are some specific characteristics of the chosen helicopter compared with the eVTOL Lilium Jet, as the most similar in terms of structural size and number of passengers transported.

Table [4.19]: helicopter vs eVTOL

Helicopter VS eVTOL		
	Helicopter	**eVTOL**
Category	Rotorcraft	Vectored Thrust
Company	Airbus Helicopter	Lilium
Name	Eurocopter EC145	Lilium Jet
Declaration cost [M$]	8,7	2,5
Motor's type	turboshaft	electric (Li-ion battery)
# pilot	2	1
# passengers	7	6
# motors	2	36
Maximum velocity [km/h]	280	300
MTOW [kg]	4000	3175
Payload [kg]	2000	640
Range [km]	750	300
Production number	1500	18650

To analyse the development and production costs of the helicopter, the Roskam estimation model is used, input data as in the case of eVTOL are obtained from the output data required below in *Table [4.20]*.

Table [4.20]: RDT&E and PROD cost, Lilium Jet vs Helicopter

Output	**Lilium Jet**	**Eurocopter EC145**
Airframe engineering & Design cost	$ 52.453.000,00	$ 34.556.000,00
Development Support & Testing cost	$ 3.960.300,00	$ 1.034.500,00
FTA cost	$ 175.950.000,00	$ 134.340.000,00
Cost of engines and avionics	$ 303.500,00	$ 25.000,00
Manufacturing cost	$ 63.349.000,00	$ 44.210.000,00
Material cost	$ 8.223.400,00	$ 2.259.700,00
Tooling cost	$ 94.440.000,00	$ 64.618.000,00
Quality control	$ 8.235.300,00	$ 1.436.800,00
Flight test operational cost	$ 929.260,00	$ 266.440,00
Test & Simulation facilities cost	$ -	$ -
RDT&E program cost	$ 469.020.324,00	$ 325.158.406,00
Manufactured aircrafts	18650	1500
Airframe engineering & Design Manufacturing cost	$ 183.810.000,00	$ 89.500.000,00
Aircraft production cost	$ 13.858.000.000,00	$ 1.717.200.000,00
Cost of engine and avionics	$ 303.500,00	$ 25.000,00
Interior production cost	$ 522.200.000,00	$ 135.000.000,00
Manufacturing cost	$ 4.492.600.000,00	$ 837.740.000,00
Material cost	$ 5.552.500.000,00	$ 523.100.000,00
Tooling cost	$ 313.800.000,00	$ 16.220.000,00
Quality control cost	$ 584.040.000,00	$ 27.227.000,00
Flight test operations cost	$ 4.972.800.000,00	$ 999.900.000,00
PROD cost	$ 30.480.053.500,00	$ 4.997.798.800,00
AEP	$ 1.904.615,65	$ 3.548.638,14
Estimated cost	**$ 2.285.538,78**	**$ 4.693.073,94**
Declared cost	$ 2.500.000,00	$ 4.900.000,00
% difference	**-8,58%**	**-4,22%**

5. Conclusions

The main objective of this thesis was to derive the development and production costs of six different eVTOL, two for each existing category, starting from cost estimation models already present in the literature. While for the production costs it has been possible to derive both the specific equations and the actual cost of production of the single element constituting the eVTOL, as far as the development costs are concerned, only values have been obtained at the level of macro categories. This is mainly because it is not possible to know how the capital invested by the company is divided during the development phase.
As you can see in the previous tables, there was an error between 10% mainly because you do not know exactly the margin that each company has decided to earn from the sale of its aircraft.
Since the exact development costs of each individual eVTOL could not be found in the literature, a comparison was made between the outputs data of the different methods used. Obtained a maximum percentage difference of -8%.
It has not been possible to make a direct comparison with the real costs of production and development because not made available by the different companies it was decided to check the final selling price with that obtained following the application of the methods chosen exposed in the treatment. Finally, a check was made between two different methods to further verify the validity of the numbers obtained.
The most cost-effective configuration in terms of development and production costs is the *Multicopter* configuration due to the absence of large wing surfaces and movable surfaces; however, this will be offset by a likely increase in operating costs due to the absence of load-bearing surfaces. However, since operating costs are not covered within this argument, it is difficult to estimate how much they will affect the final cost of eVTOL.

Production cost equations were then calculated for each single component that makes up the complete eVTOL structure through the implementation of an algorithm through the MatLab software. Inside these equations, there is a cost drive that acts as the main variable for obtaining the final cost of the single subsystem; if one or more components are not present just place a mass equal to 0 kg so as not to consider it. By adding all these equations it is possible to derive the final price of eVTOL.

It is estimated that the total development cost of all these eVTOL is almost 1.5 billion dollars; if the UAM market reaches the expected size between now and the next 7-8 years, the slope of the learning curve is destined to increase and this will provoke a net decrease of the costs.

As a last resort, we wanted to make a comparison between the eVTOL and its main competitor: the helicopter.

The comparison between these two categories was made only through the Roskam cost estimation model, as the two aircraft are different in configuration. The results obtained indicate a percentage error of -4.22%; here too the validity of the method used can be confirmed.

Annex A - Roskam CERs

A.1 RDT&E

$$W_{ampr} = 10^{(0.1936+0.8645 \cdot \log_{10}(MTOW))} \cdot 1.25$$

where 1.25 is a coefficient added because this weight estimating relationships underestimate the manufacturer empty weight.

$$MHR_{aed} = 0.0396 \cdot W_{ampr}^{0.791} \cdot V_{max}^{1.526} \cdot N_{rdte}^{0.183} \cdot F_{diff} \cdot F_{CAD}$$

$$c_{aed} = MHR_{aed} \cdot R_e$$

where c_{aed} is the Airframe & Design Engineering Cost.

$$c_{dst} = 0.008325 \cdot W_{ampr}^{0.873} \cdot V_{max}^{1.89} \cdot N_{rdte}^{0.346} \cdot F_{diff} \cdot CEF$$

where c_{dst} is the Development, Support & Testing cost.

$$c_{fta} = c_{ea} + c_{man} + c_{mat} + c_{tool} + c_{qc}$$

where c_{fta} is the Flight Test Airplanes cost.

$$c_{ea} = (N_{rdte} - N_{st}) \cdot (c_e \cdot N_e + c_{avionic})$$

where c_{ea} is the avionic and engines acquisition cost.

$$MHR_{man} = 28.984 \cdot W_{ampr}^{0.740} \cdot V_{max}^{0.543} \cdot N_{rdte}^{0.524} \cdot F_{diff}$$

$$c_{man} = MHR_{man} \cdot R_m$$

where c_{man} is the production cost for the flight test vehicle.

$$c_{mat} = 37.632 \cdot W_{ampr}^{0.689} \cdot V_{max}^{0.624} \cdot N_{rdte}^{0.792} \cdot F_{mat} \cdot CEF$$

where c_{mat} is the material cost for the flight test vehicle.

$$MHR_{tool} = 4.0127 \cdot W_{ampr}^{0.764} \cdot V_{max}^{0.899} \cdot N_{rdte}^{0.178} \cdot N_r^{0.066} \cdot F_{diff}$$

$$c_{tool} = MHR_{tool} \cdot R_t$$

where c_{tool} is the tooling cost for the flight test aircraft.

$$c_{qc} = 0.13 \cdot c_{man}$$

where c_{qc} is the quality control cost for the flight test aircraft.

$$c_{fto} = 0.001244 \cdot W_{ampr}^{1.16} \cdot V_{max}^{1.371} \cdot (N_{rdte} - N_{st})^{1.281} \cdot CEF \cdot F_{diff} \cdot F_{obs}$$

where c_{fto} is the Flight Test Operations cost.

$$c_{tsf} = 0$$

where c_{tsf} is the Test & Simulation Facilities cost, relevant for innovative program only.

$$c_{RDT\&E} = (c_{aed} + c_{dst} + c_{fta} + c_{fto} + c_{tsf}) \cdot Finance \cdot Profit$$

A.2 PROD

$$MHR_{aed} = 0.0396 \cdot W_{ampr}^{0.791} \cdot V_{max}^{1.526} \cdot N_{rdte}^{0.183} \cdot F_{diff} \cdot F_{CAD}$$

$$c_{aed_m} = (MHR_{aed} \cdot R_{e_m}) - c_{aed_{RDT\&E}}$$

where c_{aed_m} is the Airframe & Design Engineering cost during production.

$$c_{apc} = c_{ea_m} + c_{int_m} + c_{man_m} + c_{mat_m} + c_{tool_m} + c_{qc_m}$$

where c_{apc} is the Airplane Program Production cost.

$$c_{int_m} = F_{int} \cdot N_{pax} \cdot N_m \cdot CEF$$

where c_{int_m} is the interior cost during production.

$$MHR_{man_{program}} = 28.984 \cdot W_{ampr}^{0.740} \cdot V_{max}^{0.543} \cdot N_{program}^{0.524} \cdot F_{diff}$$

$$c_{man_m} = (MHR_{man_{program}} \cdot R_{m_m}) - c_{man_{RDT\&E}}$$

where c_{man_m} is the manufacturing labor cost during production.

$$c_{mat_{program}} = 37.632 \cdot W_{ampr}^{0.689} \cdot V_{max}^{0.624} \cdot N_{program}^{0.792} \cdot F_{mat} \cdot CEF$$

$$c_{mat_m} = c_{mat_{program}} - c_{mat_{RDT\&E}}$$

where c_{mat_m} is the material cost during production.

$$MHR_{tool_{program}} = 4.0127 \cdot W_{ampr}^{0.764} \cdot V_{max}^{0.899} \cdot N_{program}^{0.178} \cdot F_{diff}$$

$$c_{tool_{program}} = MHR_{tool_{program}} \cdot R_{t_m}$$

$$c_{tool_m} = c_{tool_{program}} - c_{tool_{RDT\&E}}$$

where c_{tool_m} is the tooling cost during production.

$$c_{qc_m} = 0.13 \cdot c_{man_m}$$

where c_{qc_m} is the quality control for production.

$$c_{fto_m} = N_m(c_{ops_{hr}} + t_{pft} + F_{ftoh})$$

where c_{fto_m} is the Flight Test Operations Cost during production.

$$c_{MAN} = (c_{aed_m} + c_{apc} + c_{fto_m}) \cdot Profit \cdot Finance$$

where c_{MAN} is the Production cost.

Finally,

$$AEP = 1.1 \cdot \frac{(c_{MAN} + c_{RDT\&E})}{N_m}$$

where AEP is the Aircraft Estimated Price. A coefficient 1.1 is added in order to take into account initial spares.

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