POLITECNICO of TORINO

College of Aerospace Engineering

Master's degree Course
in Aerospace Engineering – Aeromechanics and Systems

Master Thesis

Operating cost estimation methodology for eVTOL

Supervisor
Dr. Davide Ferretto

Candidate
Nadia Oteri

April 2025

Abstract

The aviation industry keeps evolving and responding to the needs of urban mobility; a promising solution for efficient transportation is electric Vertical Take-Off and Landing (eVTOL) aircraft. In this thesis, a comprehensive methodology for estimating the operating costs of eVTOL aircraft is described, discussing the various cost analysis methods and ultimately selecting the Roskam model as the most appropriate framework for this analysis. This study examines several scenarios in order to define the mission profile, in this case, the journey from Brussels to Liège, which covers a distance of 93 kilometers is selected.

In the first stage, the research considers different methods of cost estimation, evaluating their relevance and accuracy in eVTOL operations. The Roskam model is preferred due to its strong analytical capability and the capacity to combine the unique parameters related to eVTOL technology. The method involves a thorough breakdown of fixed and variable expenses, such as maintenance, energy, crew, and infrastructure, which are all important for an overall understanding of the operational situation.

This is preceded by the thesis analyzing the mission profile of the Brussels-Liège scenario, main factors that have to be considered are flight time, mission phases and flight total range. The analysis wants to compare eVTOL operations with traditional modes of transport, including ground-based services. The results are that while the operating cost of eVTOL aircraft is generally higher than other modes of transport, the potential for significant time savings renders them an option in the urban transport sector.

Overall, this research not only emphasizes the feasibility of eVTOL technology but also indicates that the strategic cost analysis plays a central role in deciding whether it is feasible. The comparative results show that eVTOLs, although at first considered costly, are extremely advantageous in terms of efficiency and time efficiency.

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1 Introduction

1.1 eVTOL Historical Background

Of late, there have been many new electric Vertical Take-off and Landing ideas, prototypes, and some production aircraft. This must be much like the early, heady days of powered aviation when all those engineers, entrepreneurs, and enthusiasts were building and flying the initial powered airplanes.

Advances in battery technology, electric motors, and power management systems-achieved with enabling by the progress made within the automotive sector and growing demand for sustainable energy solutions-allowed a new family of electric propulsion concepts, hence multiple designs of eVTOL. These aircraft capable of vertical takeoff and landing can be either fully electric or have hybrid propulsion with different forms of energy storage. Generally designed to carry less than ten passengers, these will have a take-off weight of less than 3,175 kg. Some of the drivers that seem to be leading to these new eVTOL aircraft include innovation in energy storage, advancement of distributed electric propulsion technologies, supportive regulatory environment, improvements in vehicle operation and flight control systems, and overall improvements in autonomous navigation.

Ongoing urbanization and rapid metropolitan growth have been putting pressure on the lives of city residents. This results in situations such as traffic congestion and air pollution. The evident effects of climate change, industry development, researchers, and government officials agree that there is a need for clean and sustainable transportation solutions for the future of urban settings. It is because of all these challenges that the workable solution seems to come in the shape of UAS. In NASA's words, it would "safe and efficient air operations in urban areas for a mix of crewed and uncrewed aircraft systems" [2]. Most designs related to eVTOL are tagged to Urban Air Mobility (UAM). The concepts contain elements of both these categories; technically speaking, they would be integrated under advanced air mobility (AAM) [1].

Figure 1-1: Urban Air Mobility

The performing of Urban Air Mobility missions is a routine aspect of air taxi operations. These air taxi flights are forecasted to travel between one city to up to 50km to 100km depending on in the short to medium term across city-to-city distances in the intermediate term, future. As a demonstration, a local UAM service could provide a trans-city service, with a short-range local service e.g., London financial district to Heathrow, without a service break. For example, imagine a day when it's possible to offer a 200km route between London and Birmingham, for which the normal commercial flight offer fares are lower than usual, but also lower than the train journey.

Space missions with a useful range larger than 100 km are highly dependent on technological advances, particularly in the context of battery density in the function of battery powered systems. Meanwhile, hybrid-electric actuation provides a solution to the type of range limitation that is inherent to the energy density of the system until the performance of pure electric battery technologies become both feasibly and commercially available. The potential applications for eVTOL aircraft are rapidly expanding. This includes civil and emergency (law enforcement, ambulance, aerial, surveillance), corporate, logistics, entertainment, telemedicine services, agriculture, emergency grocery delivery, service delivery, transporter animal, incident, search and rescue operations, and so on [3]. This could be the platform on which an idea as a means of transport could be based, permitting savings with respect to travel times in the framework of traffic, road accidents, and road congestion and to which can be applied in the context of point-to-point travel by air between urban centers and city-district residential areas as well as to regional mobility, especially those which are today very limited and poorly covered by standard air trips. Some of the technologies under development, which aid air travel operations are enhanced, and this enables air travel operations to be viewed as an alternative to "traditional" helicopter service [2].

The implementation of UAM, which pertains to the utilization of aerial vehicles for transporting both passengers and cargo in urban settings, deals with a complex set of challenges. These challenges are addressed to ensure its successful operation and integration into current urban transport systems. However, this task is not straightforward, because various factors have to be considered. Although significant progress has been made, the path forward remains intricate and requires careful planning. Furthermore, the need for collaboration among stakeholders is crucial, but it can be difficult to achieve consensus. The success of UAM hinges on overcoming these obstacles, as they are integral to its viability in modern cities [3].

Figure 1-2: eVTOL concept idea

These challenges [4] can be categorized into several key areas:

1. Regulatory Constraints:

   - The regulatory framework surrounding Urban Air Mobility is still predominantly underdeveloped. Current aviation laws do not sufficiently consider the distinct characteristics of urban air traffic. This necessitates the formulation of new regulations that address various aspects, such as air vehicle certification, pilot licensing and operator requirements.

   - Safety and standards are of utmost importance; ensuring the safety of aerial operations is paramount. UAM must comply with rigorous safety standards, which require extensive testing and validation of the vehicles. Establishing clear criteria for airworthiness and operational safety is crucial, however, this remains a complex endeavor.

   - Airspace management presents additional challenges: the integration of UAM into existing airspace necessitates a thorough re-evaluation of air traffic management systems. This is necessary to accommodate both manned and unmanned aerial vehicles while maintaining safe and efficient operations. Although significant progress has been made, the road ahead is fraught with obstacles.

2. Infrastructure Availability:

   - Vertiports and Landing Facilities: for UAM operations, adequate infrastructure is necessary such as the construction of vertiports (limited landing-take-off area) with charging stations on the eVTOL version of aircraft. Building these facilities requires a large investment, urban planning, etc.

   - Integration with Public Transport: this should be able to easily integrate with existing public transport networks to maintain connectivity and ease of use for its end users. This applies to questions about passenger transfer facilities, multi-modal transport networks, and dynamic service coordination, etc.

3. Air Traffic Management Issues:

   - Traffic Coordination: UAM introduces additional layers of aerial movement into urban environments, traffic management systems that can prevent buildup and guarantee safety are highly desirable. Future air traffic management systems, possibly based on the use of artificial intelligence and automation, will be required to manage and regulate the urban airspace.

   - Communication Systems: situation awareness and safety are served by robust communication protocols among UAM vehicles, ground control and other aviation traffic. Reliable communication infrastructure is of paramount importance for enabling these interactions.

4. Environmental Considerations:

   - Noise Pollution: UAM vehicles, especially eVTOLs, need to take into consideration noise radiation (noise emission), since traffic noise in cities can be a problem with the increased number of aviation flights. This question induces the need for an investigation and technological progress with respect to noise minimization during ascent, descent, and flight.

   - Emissions and Sustainability: UAM may have the capacity to alleviate ground traffic bottlenecks, the ecological cost of air traffic rising should be considered. Electric or hybrid propulsion offers the potential to reduce emissions, but life cycle assessments are needed to determine the total carbon emissions of UAM airframes.

5. Community Acceptance:

   - Public Perception: building community acceptance of UAM is essential for UAM's advancement. Concerns regarding safety, noise and operational aesthetic appeal of UAM vehicles can cause public backlash.

   - Equity and Access: UAM services should be available to a broad population without further widening existing inequality is critical. This requires careful thinking about service pricing, service delivery in low income/rural areas, and mode of transportation for individuals lacking private autos.

In other words, the path to UAM is paved with regulatory, infrastructural, environmental, and social hurdles. This requires collaboration at different levels among government authorities, industry players, urban planners, and communities because this collaboration will provide a strategy in addressing these issues. But again, successful implementation of UAM in urban environments is dependent on all these collective efforts. Though obstacles remain, the potential benefits are great [5] [6].

1.2 eVTOL Concepts and Architecture

EASA has defined two key features that are typical of small category eVTOL aircraft through its Special Condition: the ability to take off and land vertically (VTOL) and the use of a distributed electric propulsion system. This electric propulsion system makes the design and potential capabilities more easily achievable for both vertical lift and forward flight as in contrast with complex jet engines and thrust vectoring systems employed on conventional aircraft. EASA argues that this ability distinguishes these aircraft from ordinary ones, and the electric propulsion in the eVTOLs differentiates it from old rotorcraft [7].

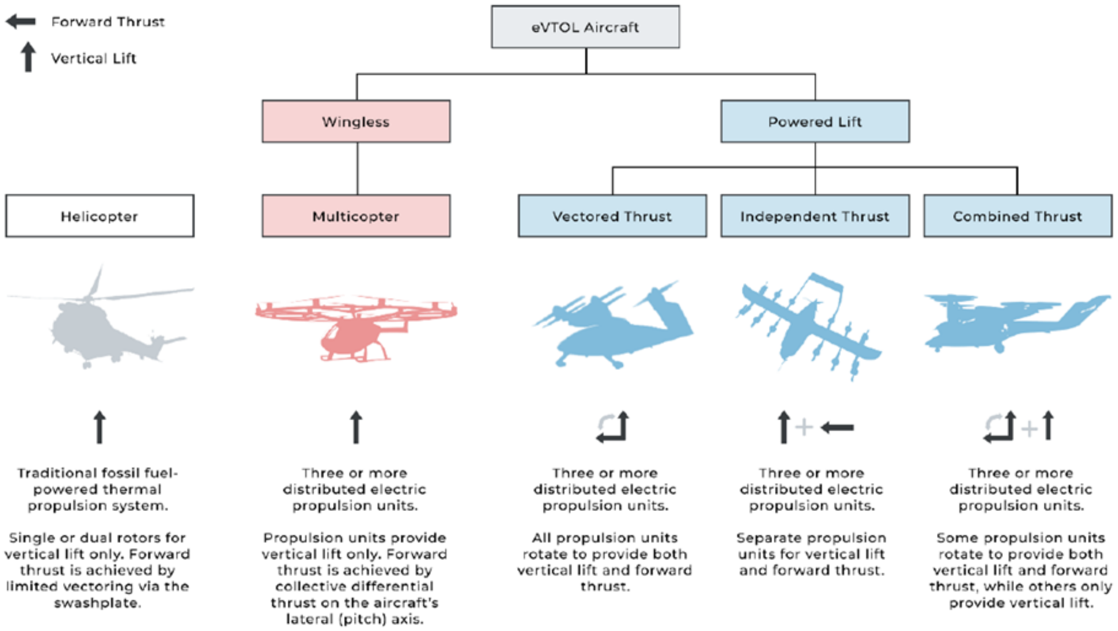

Figure 1-3: Propulsion architectures of eVTOL aircraft.

1.2.1 Powered Lift eVTOL

All types of eVTOL aircraft can land vertically without a runway. The only class of aircraft with the capacity for high-speed cruise flight in the manner of conventional fixed-wing aircraft, in addition to high-altitude flight against ungoverned eVTOLs and helicopters is the powered lift aircraft. This capability allows powered lift aircraft to fly to a greater range of operational reach to be flown more effectively than wingless counterparts, thereby allowing greater cruising speed, payload and range to be realized.

The integration of wings and the systems are part of generating aerodynamic lift while in flight, and the requirement for autonomous propulsion systems. When flying forwards the vertically lift systems (LTUs) become weight and drag which degrades the overall performance of the aircraft. To minimize drag designers may also orient propellers perpendicular to the direction of the air flow while cruising or encapsulate idle LTUs in aerodynamic covers. Implementing these features increases the design intricacies.

A notable example of independent thrust architecture is the Wisk eVTOL, which features a dedicated LTU for forward flight.

However, Vectored thrust systems are not trivial since the force generation path requires a mechanism to modulate thrust from vertical to forward attitude. This problem is hardly new, it has been around since the days of VTOL aircraft in the 1960s. For all these reasons, several thrust vectoring principles have been proposed and implemented in the eVTOL airplanes. Designs of tilt fan and tilt propeller, for example, Lilium and Joby eVTOLs, all are based on the rotation of the lifting machines (fans or propellers) in azimuthal plane and, of course, altitude with vertical lift motion and forward thrusts. With all of the actuators of lift and thrust serving for hover and forward flight modes, vectored thrust and tilt prop schemes, Joby Aviation eVTOL prototype vehicle implements the idea that all of the "actuators" can be active at hover and in forward flight.

Design illustrations of coupled thrusts in which thrust vectoring plays a role for some of the propulsion devices and has a constant thrust direction during vertical flight. This paradigm has the effect of resolving the deadweight issue inherent in the individual thrust systems, in that all of the propulsion systems are active during the vertical launch, whereas the propulsion systems are idle or inactive during the forward flight. An example of such a system of integrated thrust designs is the Vertical Aerospace VX4 considered in the present paper.

1.2.2 Wingless eVTOL

Wingless eVTOL drones provide lift/thrust forces for both vertical takeoff and horizontal flight. The word "multicopters" has been used to describe robots with multiple lift/thrust units designed for vertical lift, that is, helicopters. Multicopters are the leading secondary type of wingless designs. One of the most representative examples is the VoloCity of Volocopter, which is a two-seater multicopter and has 18 lift/thrust actuators. Electric helicopter eVTOL designs with an option of plural units to enhance travelling speed during the main flying mode exist. Nevertheless, these vehicles do not have flight parameters that are restricted to fixed-wing types more comparable to those of helicopters. There are different multicopter designs in the pipeline, most of which are designed for air taxi and rescue applications.

1.2.3 PAVs

Personal Aerial Vehicles (PAVs) are specifically considered as multicopters from a technical point of view but there are differences in terms of the number of passengers on board. PAVs are typically intended for individual use and some are dual-use, single-seat eVTOL vehicles with ground and flight capabilities. As their name implies, PAVs are autonomous, single-passenger level-flight-vehicle unmanned flying machines that can transport individuals who sit or stand during flight. Furthermore, the relatively low price of commercially available electric motors available for this weight class makes PAVs one of the cheapest to manufacture. As a result, many advanced and larger eVTOL designs often begin their development as PAVs until their propulsion systems are thoroughly tested and validated.

Figure 1-4: CES 2016 Highlights - Autonomous Aerial Vehicle Ehang 184

1.2.4 Design Classification

Many different design procedures have been suggested for Advanced Air Mobility applications, including different kinds of vehicles, and propulsion systems. For a systematic review of such designs, they have been ordered into groups according to the rotor configuration and propulsion system structures. The classifications utilized in this review are derived from established sources, including NASA’s repository of Urban Air Mobility (UAM) reference vehicles, the Vertical Flight Society’s industry design directory classifications, and existing scholarly classifications [8].

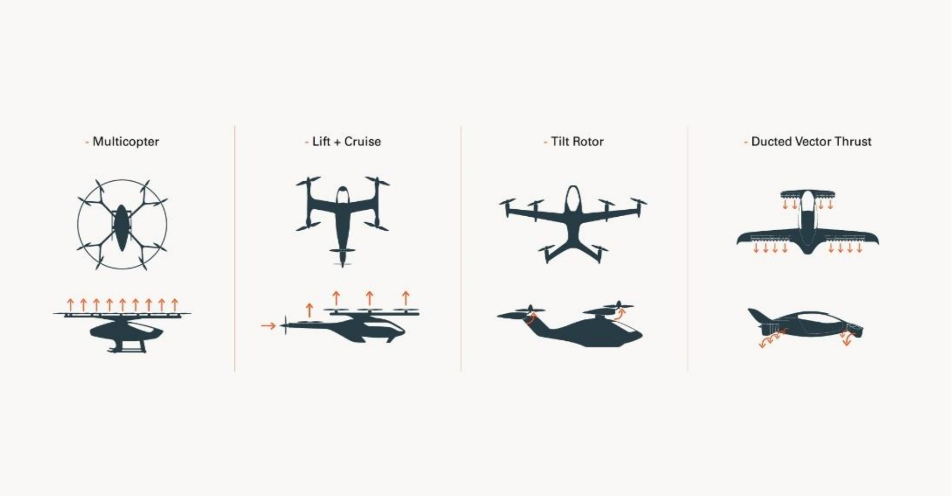

Figure 1-5: eVTOL Design Proposal

After constructing these classification systems, it has been identified that five major rotor schemes can be classified into a rotary-wing or fixed-wing. Under the rotary-wing category, there are divided also the "multi-rotor" and "rotorcraft" configurations. Multi-rotor vehicles produce lift only through changing the revolutions per second of their multitude of propeller units. In contrast, rotorcraft designs rely on a single rotor mast, and thus they differ from multi-rotor aircraft.

Fixed-wing designs are sub-categorized into "lift + cruise," "tilt-wing," and "tiltrotor" configurations. The lift + cruise design is split into two distinct propulsion systems: one dedicated to vertical lift and the other to provide thrust for horizontal flight. Tiltrotor and tilt-wing vehicles are classified as vectored-thrust designs, allowing for propulsion system manipulation that can direct thrust in multiple orientations, enabling the use of a single propulsion system for both vertical takeoff and landing (VTOL) as well as forward flight. For the purposes of this review, the tilt-rotor category also includes tilt-duct designs, characterized using rotating ducted fans instead of conventional rotors, providing both thrust and lift capabilities.

In examining propulsion system architectures, the designs have been categorized into three principal types: internal combustion engines, hybrid-electric systems, and all-electric configurations. Internal combustion engines are the main option for the majority of commercial aircraft. However, the vast majority of UAM designs require all-electric power systems in order to meet low noise requirements that are appropriate for urban use. Nevertheless, current battery technology constraints make electric aircraft less practical than alternative propulsion architectures for regional flights. The turboelectric powertrain is a promising powertrain that has been proposed by academia and NASA, in which a combustion engine is used to produce electrical power to drive the onboard electric motors.

Hybrid propulsion systems may consist of either series or parallel configurations that combine battery systems with internal combustion engines or hydrogen fuel cells, thereby enabling cooperative functionality for energy storage and power production. Of these hybrid architectures, those architectures combining internal combustion engines are currently most found in development and will represent the hybrid systems in relative assessment of the different propulsion architectures. Where any striking differences with respect to design or measurement data for hydrogen systems have occurred, this will be acknowledged. In the next few years, these advances in hydrogen technologies might be very applicable to the AAM operation too.

Subsequent categorization may arise from considerations of how aircraft are brought under control, hull shapes, materials involved, tail geometries, propeller arrangements, and a host of related auxiliary characteristics, among others. Yet, no detailed information exists on such characteristics in academic studies and industrial design specifications, mostly due to the high level of confidentiality of information contained in AAM vehicles that are currently under development and due to the lack of global modeling schemes within AAM applications to such classifications. The focus could be on rotor designs and propulsion designs. These vehicles first appeared in Electric VTOL News, Vertical Flight Society (now with >700 VTOL concepts).

1.3 Thesis Scope

The aim of the present work is to find and to describe the best approaches for the calculation and analysis of costs that may be employed in the aerospace industry for the eVTOL operative life.

Having examined and calculated the cost for the full operational life cycle of this novel air transport technology, the cost component of the current technology, i.e., systems used to address the same scenario, will be compared and calculated. At this evaluation stage, the advantages and potential limitations of this new transport mechanism will be discussed, not only to introduce the scope and challenges of the current situation, but also to provide a framework for future research and development of this new transport method.

1.4 Thesis Out of Scope

Although a rough estimate of the costs related to the development of this technology can be obtained, the main attention will be given to the operational life of the vehicle. In addition, the case study on which the development of these calculations is based will be peculiar and will be specially chosen for this purpose so that the analysis will be accurate and pertinent.

2 Operative Cost Analysis and Mission Scenarios

2.1 General overview of cost analysis

Cost analysis is an activity of analyzing and assessing the cost incurred by that activity, project, or operation in a company. The primary goal is to understand how and where money is being spent, identify areas where costs can be reduced, and improve overall economic efficiency [9].

Components of Cost Analysis:

1. Cost Identification: this involves gathering information about the various costs involved. These can be divided into:
    - Fixed Costs: costs that do not change with the volume of production (e.g., rent, salaries).
    - Variable Costs: expenditures which vary or are driven by production volume (such as inputs, production expenses).
    - Direct Costs: costs that can be directly attributed to a product or service (e.g., materials used for a product).
    - Indirect Costs: cost cannot be assigned to a product (e.g., overhead cost).
2. Cost Evaluation: analysts shall make the calculations of total costs and compare them with the revenue generated or the benefits received.
3. Cost-Benefit Analysis: in this phase, costs are compared with what has been expected by its virtues. The goal is to determine whether a project is financially sustainable.
4. Monitoring and Control: After the data analysis is finished, it is also necessary to track costs over time to prevent costs from getting out of control and to adjust accordingly if any aberrations are detected.

Cost analysis is closely related to several operational areas in an organization:

- Production: the cost of production is evaluated in the shop by the analysis of the cost of production. All this may affect, for example, decisions along the lines of production process optimization and procurement of raw materials.
- Marketing: cost analysis can also impact on marketing strategies. Understanding the costs associated with different advertising campaigns helps evaluate the return on investment (ROI) and choose the most effective strategies.
- Finance: Decisions regarding financial matters, for example, the allocation of new projects and the purchase of equipment, are also largely driven to cost analysis. Companies should ensure that projects are financially sustainable.

- Human Resource Management: cost analysis can also include employee compensation and benefits, etc. Measuring personnel costs, which supports planning and managing human resources, informs medical insurance and government healthcare policies.
- Supply Chain: in supply chain management, cost analysis provides the "means to understand" where procurement and logistics costs can be minimized.

Cost analysis of different methodologies in the aeronautical field:

- Roskam
- Allen's Operation Cost Model
- Benchmarking Model
- Wright's Cost Model
- Kermode's Cost Model
- Zedlitz's Cost Model

To sum up, cost analysis is a crucial tool for business management, as it provides a clear view of expenses and helps make informed decisions across various operational fields. Cost comprehension allows companies to increase their profitability and run for the long term [10].

2.2 Airplane program and life cost

The area of "aircraft program and life cycle cost" is complex and involves many economic, technological and operational considerations. Program cost in aircraft is defined as the sum of all costs which have to be paid during development and production and market launch of a new aircraft model [11]. This includes: Research and Development (R&D): seed funding given to the development and testing of new technologies and concepts; Prototyping: expenses linked to the construction and certification of prototypes; Production: expenses related to large scale production (i.e., material costs, labor costs, and machine costs); Marketing and Sales: costs for marketing of the aircraft and early sales campaign; Support and Training: costs incurred for training personnel and providing post-sales support [12].

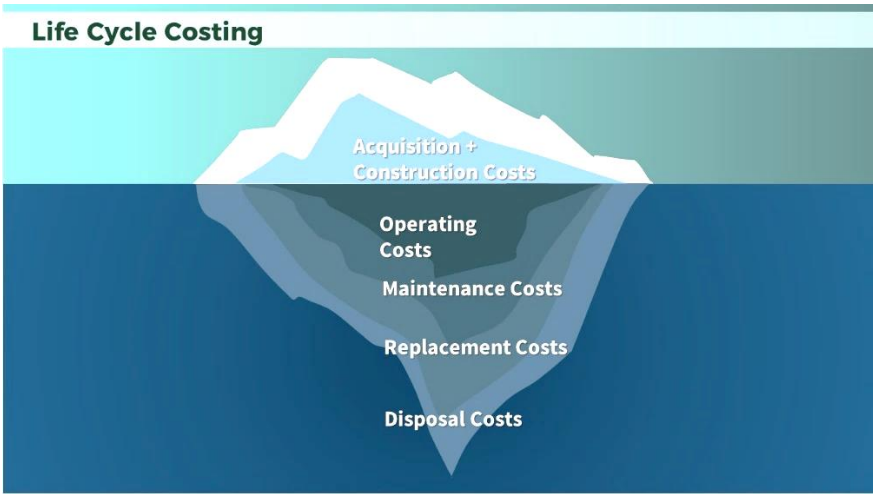

Figure 2-1: Life Cycle Cost iceberg

The life cycle cost of an aircraft is defined as the sum of all the costs incurred due to the aircraft for its entire operational period. This comprehensive financial assessment encompasses several key components. To begin with, it is possible to consider the operating costs, that is, the daily operating cost of the aircraft. It encompasses the basic costs, for example, fuel, maintenance, insurance and crew member salaries. Then, we discuss maintenance costs that consist of regular and special maintenance tasks such as repair and technology replacement/refurbishment Works.

Depreciation, which represents the reduction in the book value of an aircraft overtime, is another factor that needs to be considered. Furthermore, when the aircraft is on lease instead of fully owned, leasing costs are added to the costs, the monthly rental payments included in the lease agreement. In the end, of course, it is possible to consider scrapping costs, i.e., the unit costs of breaking down the aircraft at the end of its service life. Specifically, this includes disposal cost and recycling cost of materials. All these factors collectively impact on the lifecycle cost of an airplane, giving a picture of its cost implications throughout its life span, from acquisition to retirement [13].

2.3 Roskam ’s model

The Roskam model, applicable in the aviation industry to cost calculation, is a sophisticated methodology which considers a multitude of economic, operational, and technical variables. Despite there being no global and conclusive definition of the Roskam framework, I can offer you a comprehensive account of the above general principles that define it, given the wider practice of cost calculation in the air travel sector [14].

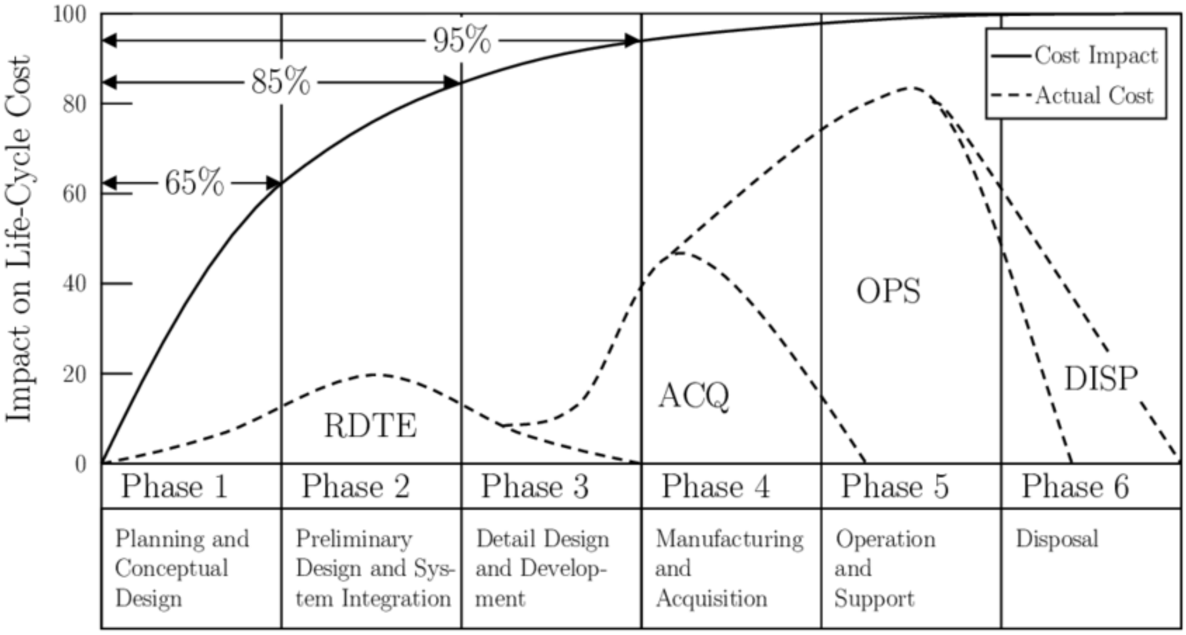

Figure 2-2: Impact of Airplane Program Phases on Life-Cycle Cost

The Roskam model is developed on the following main ingredients that affect the cost of operation of an air operation. These components can be divided into main categories:

a. Fixed Costs: those costs do not depend on the number of air operations and consist of:

- Depreciation of aircraft: the aircraft purchase cost divided by its useful life.
- Insurance: premiums paid to cover the risks associated with the operation of aircraft.
- Leasing costs: if the aircraft is on lease the monthly or annual payments must be taken into account.
- Ground staff costs: salaries and benefits for personnel not directly involved in flying, such as administrative and support staff.

b. Variable Costs: those costs vary with the number of flying flights performed and represent:

- Fuel: the fuel cost is a major cost variable and may be in relation to the market values of oil.
- Maintenance: expenses associated with scheduled and unscheduled maintenance, which may differ based on aircraft utilization.

- Crew costs: salaries and related expenses for the crew, which can differ for the number of flights and flight hours.
- Airport costs: charges and costs incurred for the sharing of airport infrastructure, including ramp charges.

In the Roskam model, cost is calculated using both mathematical and statistical formulas. Variables are typically quantified, and this is done by employing historical data and future projections to estimate costs, for example cost per kilometer flown (derived by dividing total cost by the distance traveled); cost per flight hour (calculated by dividing total costs by the number of flight hours); cost per passenger (total costs are then divided by number of passengers).

The Roskam model could also incorporate sensitivity analysis in which changes from sources of fuel costs, airport fees, or personnel wages influence in turn the total operational costs. This helps airlines in planning and making strategic decisions. The model can also be applied to benchmarking and comparing the costs of similar tasks between different airlines or operational contexts. This enables businesses to recognize where they can improve, and to make their operations as efficient as possible.

It is important to note that the Roskam model, like any economic model, has its limitations. Cost estimations may be affected by uncontrollable exogenous components (e.g., fuel price changes, changes in regulation, and global events), such as pandemics. As an integrative strategy, the Roskam model for cost calculation in the aviation industry comprehensively takes effect on a variety of economic and operational elements. Knowing how this model works is key to effective air operation management and to airline strategic planning.

2.4 Allen ’s model

This approach is built on a set of parameters and factors that affect the final cost of a project and, in particular, it is applicable to examine the economic viability of emerging projects as well as production cost optimization. Now, it is possible to explain in detail the work of this model.

The structure of the Allen Model is composed by:

1. Cost Components: this model considers various cost components, including:

- Research and Development (R&D) Costs: resource, (financial) investments required for the design and realization of new aircraft or systems.
- Production Costs: expenses associated with manufacturing components, assembly, and testing.
- Operational Costs: costs of the aircraft's operation, such as fuel, maintenance, and labor.
- Disposal Costs: costs related to the decommissioning or recycling of the aircraft at the end of its life.

2. Input Parameters: the model requires several input parameters, including:

- Size and Weight: information concerning the physical dimensions and weight of the aircraft.

- Technology: The technology used (which can affect the production/operational cost).
- Production Volume: the forecasted number of products to be made, that may lead to a decrease in unit costs as a result of economies of scale.
- Materials: type and cost of materials used in the construction of aircraft.

3. Mathematical Relationships: Allen's model uses mathematical functions to link the multiple costs of the system with the input parameters. In an example, it may apply regression functions to calculate total cost as a function of weight and technology. These associations may be derived from histories of analysis and archival data from previous studies.

4. Economies of Scale Analysis: the model also considers economies of scale on the product unit cost, i.e., the unit cost is reduced by increasing production. This is especially true in the aerospace sector, in which economies of scale can help minimize the cost of mass production.

5. Simulation and Sensitivity: this is a key part of the model, where changes in input parameters are used to change final costs.

There are also different limitations of this Model:

- Historical Data Required: model accuracy will depend upon the quality and amount of historical data that is available.
- Market Variability: costs may differ a lot depending on service and age because of variations in the price of materials and developments in technologies.
- Non-Quantifiable Factors: there are others that are hard to measure and model, for example, technological advancement or regulatory shifts.

The Allen model is a useful asset to the aerospace sector, as the model provides detailed estimates of the cost of work on complex projects. Due to its capability to incorporate a range of variables and parameters into the cost estimates, it is a valuable technique for engineers, managers, and strategic decision-makers. Yet indispensable is the integration of the model with other analyses and factors, in order to get a complete and accurate picture of the real costs brought about by an aerospace project.

2.5 Others analysis-cost models

2.5.1 Benchmarking Model

The Benchmarking Model for operational cost calculation in the aviation industry is a formal methodology to assess and compare the costs of airline operations. This model can advise airlines on where to save costs, enhance performance, and thus increase profitability. A short description of the main components of the model is provided here.

Key Components of the Benchmarking Model:

- Cost Categories: Direct Operating Costs (these are fuel, maintenance, crews' wages, landing charges and aircraft leases); Indirect Operating Costs (these costs include administration, marketing and overhead that are not specific to the operation of flights).

- Data Collection: collecting information from all the airlines and the industry reports is very important, etc. This may take the form of financial statements, operational data or performance numbers).

- Performance Metrics: metrics like Cost per Available Seat Kilometer and Revenue per Available Seat Kilometer are frequently applied to evaluate efficiency and profitability.

- Comparative Analysis: with a dataset of cost and performance characteristics, airlines are able to plot their results against industry estimates (or estimates for similar airlines) in order to pinpoint deficiencies and opportunities for optimization.

The model also motivates the implementation of industry standard measures, the consequence of which can be improved operational effectiveness and cost savings.

Benchmarking is a continuing process; airlines need to continually check their performance and adjust their approaches so as to remain competitive.

2.5.2 Wright Cost Model

The Wright Model, or Wright Cost Model, is one of the most prevalent cost estimation models in the aviation sector to calculate operational costs. Conceived by economist William D. Wright, the model offers a structured framework for the grasp and quantification of the wide range of costs in managing an aircraft.

Key Components of the Wright Model:

- Fixed and Variable Costs: these are costs that do not vary with the level of output or flight operations. These include costs, for example, aircraft depreciation and insurance rate, labor cost of permanent staff, etc.

- Variable Costs: these expenses vary directly depending on the scale of operations. These are fuel charges, maintenance, landing fees, and crew charges that are incurred as functions of the number of flights (or flight hours).

- Cost Drivers: the model lists unique cost drivers that affect the operational cost of the system. These can also include aircraft type, operational behaviors, route configuration and load factors.

- Cost Estimation: the Wright Model derives costs from historical data and statistical techniques. It sometimes uses regression analysis in an attempt to establish relationships between the different cost elements and the operational variables.

- Economies of Scale: the model elaborates on the idea of economies of scale, in which the mean cost per flight tends to decline with the scale of flights. This is especially important for airlines with large fleets, from which fixed costs can be spread across a greater number of flights.

- Operational Efficiency: the model highlights the role of operational efficiency in cost savings. Use of aircraft (utilization, route optimization, and proper maintenance procedures) can have a dramatic effect on the running operational and maintenance costs.

- Sensitivity Analysis: through the Wright Model, sensitivity analysis can be performed by the operators to determine the impact of an alteration of various inputs (e.g., fuel price, labor costs) to the total operational cost.

The Wright Model is employed by airlines, aviation advisors and governmental authorities to: develop budgets and financial forecasts and determine the cost efficiency of various types of aircraft and operation models.

2.5.3 Kermode Cost Model

The Kermode model is a process within the aviation sector that allows the determination of operational cost incurred for aircraft flights. The model, developed by aviation specialist John Kermode, offers a profile for the assessment of the several costs associated with the use of an aircraft.

Key Components of the Kermode Model:

- Direct Operating Costs: the model emphasizes the direct costs related to the operation of the aircraft, which include: Fuel Costs (fuel cost is one of the major parts, which are affected by the fuels' prices and consumption rates); Maintenance Costs (this includes routine maintenance, repairs, and parts replacement; Crew Costs (salaries, training, and benefits for pilots and cabin crew); Insurance Costs (costs associated with insuring the aircraft against various risks).

- Indirect Costs: while the model primarily focuses on direct operating costs, it may also consider indirect costs such as: Overhead Cost (operational costs incurred in running the airline or aviation enterprise); Depreciation (decreasing value of the aircraft over time, affecting the total costs).

- Operational Factors: the model considers a number of operational parameters which can influence costs, including Flight Distance and Duration (longer flights may incur higher fuel and crew costs); Aircraft Utilization (the frequency and volume of aircraft operation can dictate maintenance schedules and expenses).

- Cost Allocation: the Kermode study provides a tool to assign operating costs to individual flights or routes, so that airlines can estimate their performance on a per flight basis.

The Kermode model is particularly useful for airlines and operators in planning and budgeting, as well as for financial analysis and forecasting. Through the development of a unified structure for understanding and controlling operational costs, the model leads aviation enterprises to a better financial performance and competition.

2.5.4 Zedlitz Cost Model

The Zedlitz Model is a procedure to estimate operational costs in the aviation sector. It is specifically designed as a method to decompose a number of cost elements involved in aircraft operations.

Overview of the Zedlitz Model:

- Cost Components: the Zedlitz Model disaggregates operational costs into several major elements, such as: Fixed Costs (these are expenses that do not vary with the level of flight activity, such as aircraft depreciation, insurance, and salaries for permanent staff); Variable Costs (costs which depend on the amount of activity, such as fuel, maintenance, and crew pay); Overhead Costs (these are covering administrative and operational expenses for the general running of the airline but not for the individual flights).

- Calculation Methodology: the model takes a serialized procedure to determine the cumulative operational cost per flight/ per hour. It considers both fixed and variable costs, allowing for a comprehensive understanding of the cost structure.

The Zedlitz Model is employed by airlines and aviation businesses to: Estimate the cost-effectiveness of different operational strategies and determine ticket prices on the basis of an explicit definition of the cost structure.

Like any model, it can lack the generality and the robustness to be a reliable predictor across all of the situations for which it is relevant, and it can lack the robustness in other meanings to account for the limits of accessible data and the choices made in calculations that lead the model to behave the way it does. The accuracy of the model relies on the quality of the input data and the operational context.

2.6 Mission scenario

The eVTOL is designed for general use in a wide range of operational scenarios, offering the capability and flexibility to be highly effective in a wide range of application scenarios.

Its core functionalities are:

- Airport Transit: air travel will provide high speed travel (i.e., urban and feeder aircraft networks). It is very well suited for high-frequency traffic at distances from 10 to 50 miles and offers rapid turn-around time for minimal ground time (core than 15 min). This capability will lead to an increase in interconnectivity and hence of passenger traffic in any highly populated airport environment.

- Inter-City and Point-to-Point Routes: on long trips, the aircraft will make inter-city flights and inter-city intermediate trips with distances ranging from 50 -to100 miles. Although this feature is envisaged as a seamless travel experience, the possibility of reducing artificial interruption at intermediate waypoints and optimizing travel efficiency, poses novel challenges. However, the design aims to address these issues effectively.

- Tourism and Leisure Services: (the aircraft will be also used for some form of tourism activities) like island cruising or luxury tourism destinations with high tourism value. Such leisure-like flights up to 100 km from the ground will contribute to improving access to the apparently most visited locations and will, in turn, contribute toward the travel experience for leisure. While such flights are convenient due to the comforts they bring, they also cause worries in the realm of sustainability. However, as demand for unique experiences increases, the sector has to evolve.

Information about distribution of mission type is of critical relevance for planning and resource management in organizational operations. The scope of the review to characterize the kinds of missions undertaken by entities, assess their respective effects and illuminate strategic factors that shape their distribution.

- Airport Transit: 60% of operations will prioritize airport transit, this highlights a robust demand for seamless connectivity within major travel hubs.

- Inter-City and Point-to-Point: 30% of missions will be reserved for inter-city mobility, that addresses an economic need for a viable long-distance travel option.

- Tourism and Leisure: 10% of flights and will be supporting tourism and leisure services, which promote exploration and travel to beautiful places.

The aircraft can provide optimum support to a number of transportation needs; it enhances not only passenger convenience but operational robustness through the different phases of travel.

2.6.1 VX-4

To conduct the analysis, with consistent reference to the eVOLUTION project, the VX4 aircraft is taken into consideration.

Figure 2-3: VX-4

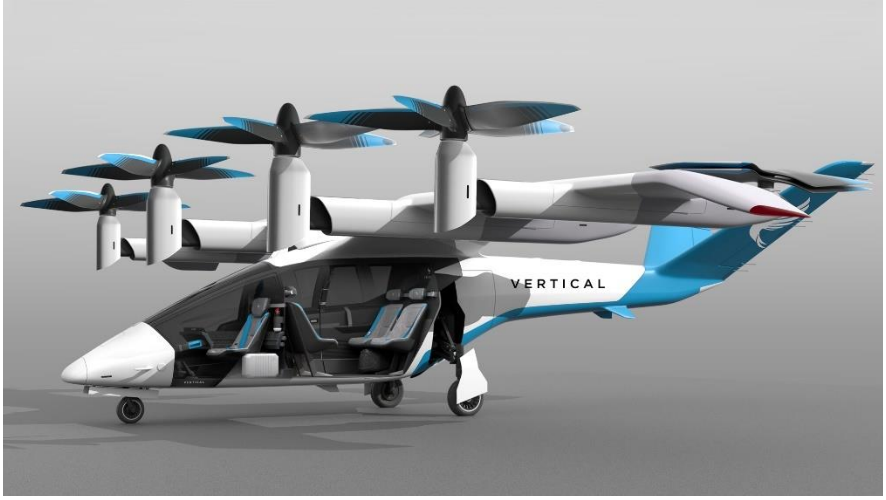

Figure 2-4: VX-4 interior

The characteristics of the VX-4 are as follows:

Parameter	Value
Gross Mass	3150 kg
Empty Mass*	1827 kg
Battery Mass*	887 kg
Power-to-weight*	250 W/kg
Wing Loading*	110 kg/m2
Disk Loading	550 N/m2
Wingspan	15 m
Fuselage length	10 m
Rotors	8
Rotor Diameter	3 m
*Assumptions	

Table 1: VX-4 Parameters

The geometrical design is assumed as follows:

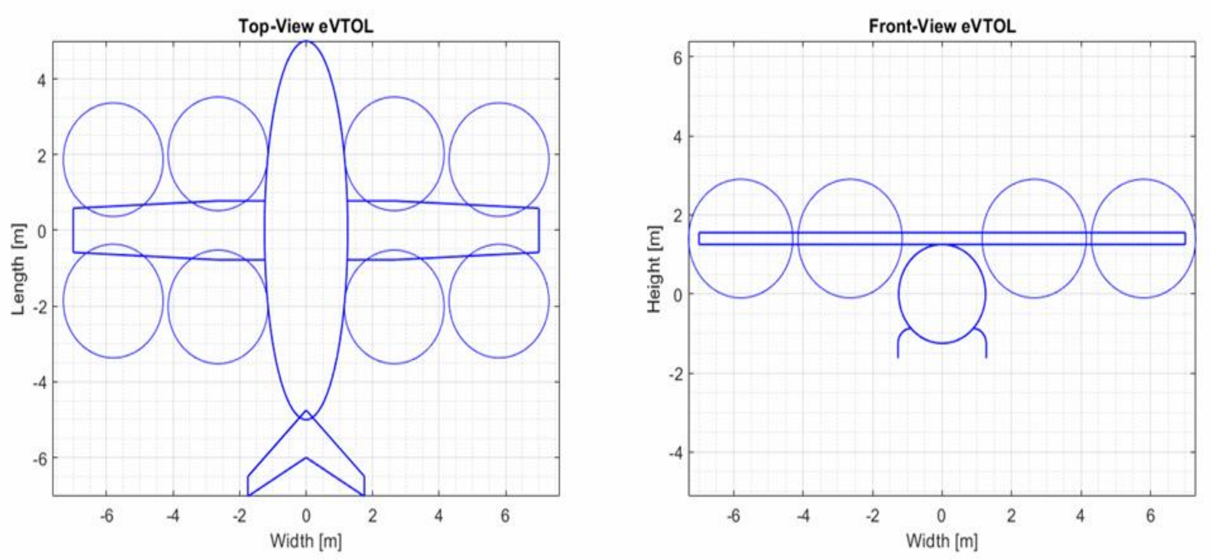

Figure 2-5: VX-4 Top View and Front View

2.6.2 Use Case

In practice, realistic flight routes are rarely straight as arising from the need to take account of airspace restrictions, traffic jams or existing helicopter flight tracks. In the case of routes in the (urban) city center this can drive an increase in travelling time of up to 30% and in the case of routes outside the city center an increase of up to 10% is more typical.

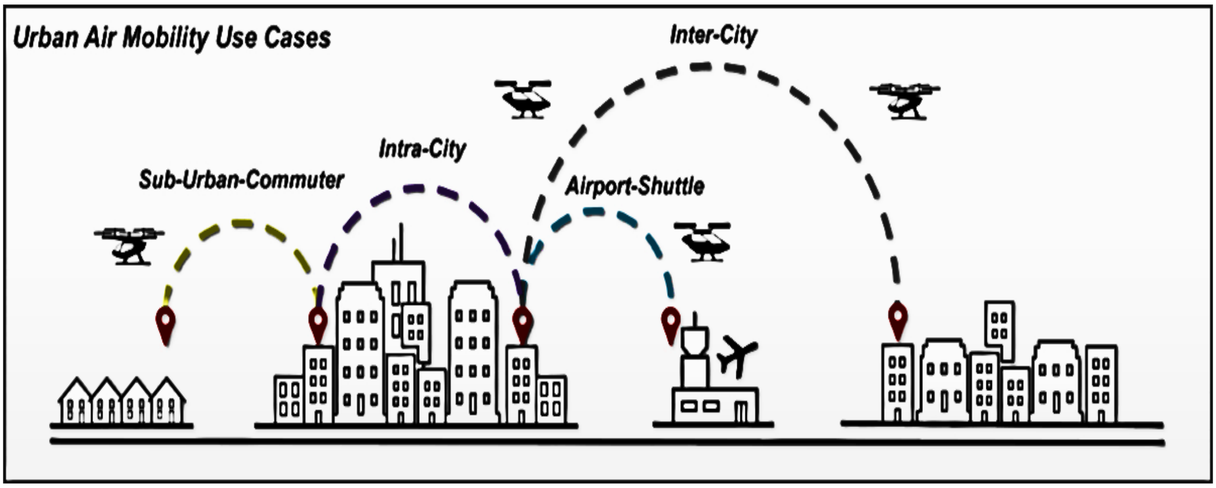

Figure 2-6: UAM Use Case Example

An approximate measure of the route lengths can be established by summing the direct distance and adding 20%.

In order to exploit the technology in the optimal way (as judged by previously established missions) the following have been considered for below. This paper introduces concrete examples that may be used as a starting point for further analysis. Recognizing these examples, as reported by eVTOLUTION Aircraft Mission [4], an opportunity arises to use knowledge of technological applications and their effects to guide further studies.

Use Case	Example by eVOLUTION
Airport Transit	• Heathrow to Central London or Cambridge. • Kansai International to Yumeshima. • Sao Paolo Garulhos to Congonhas Airports. • Brussels Zaventem to Brussels City Centre.
Inter-City and Point-to-Point	• Liverpool to Leeds. • Kobe to Osaka. • Brussels to Antwerp or to Liege. • Fort Worth to Plano.
Tourism and Leisure	• Ibiza to Palma. • Naples Airport to Capri or Amalfi. • Yumeshima to Kobe.

Table 2: Use Case example

2.6.3 Flight profiles

Many of the objectives will influence the flight profile for any given mission. In order to help vehicle design, the following table (data taken by [4]) describes three flight mission profiles aimed at representing a mixture of real-world scenarios.

These profiles are defined as follows:

A) The "constrained intracity" mission provides an example of a mission where the aircraft connects cities in densely populated urban areas and with more restrictive operating conditions. This profile requires a longer vertical phase during the take-off and landing and lower speed flight phase on both departure and arrival. There is usually some waiting time because of air traffic or weather conditions and a high cruising speed is necessary for both to beat wind resistance or decrease flight duration.

B) The "unconstrained intercity" mission represents a case study to maximize vehicle range. Here, take-off and landing take place in unrestricted, non-heavily trafficked areas, with only limited airspace constraints, low air traffic density and no hostile weather effects and therefore flexible timing is possible. Direct departures and direct arrivals are possible.

C) The "partially constrained intercity" mission is an intermediary case.

Phase	constrained intracity	unconstrained intercity	Partially constrained intercity
Take-off	Lift off and vertical climb to 100ft AGL, remain over FATO with wind gusts/turbulence Hover turn 180°	Lift off and vertical climb to 15ft AGL, still air (No hover turn)	Lift off and vertical climb to 100ft AGL, remain over FATO with (moderate) wind gusts/turbulence Hover turn 180°
Initial climb	Low speed maneuvers at 40 KEAS for 30 seconds Transition to wing-borne, climb gradient 12.5% Wing-borne climb to 1000ft AGL	(No low-speed maneuvers) Transition to wing-borne, climb gradient 4.5% Wing-borne climb to 1000ft AGL	Low speed maneuvers at 40 KEAS for 30 seconds Transition to wing-borne, climb gradient 12.5% Wing-borne climb to 1000ft AGL
En-route	Wing-borne climb to 2000ft AGL Cruise at 150 KEAS, 2000ft AGL Wing-borne descent to 1000ft AGL Hold at speed for best endurance for 5 mins	Wing-borne climb to 2000ft AGL Cruise at speed for best range, 2000ft AGL Wing-borne descent to 1000ft AGL (No hold)	Wing-borne climb to 2000ft AGL Cruise at 150 KEAS, 2000ft AGL Wing-borne descent to 1000ft AGL Hold at speed for best endurance for 3 mins
Approach	Wing-borne descent to conversion height Conversion to thrust-borne, descent gradient 12.5% Low speed maneuvers at 40 KEAS for 30 seconds	Wing-borne descent to conversion height Conversion to thrust-borne, descent gradient 4.5% (No low-speed maneuvers)	Wing-borne descent to conversion height Conversion to thrust-borne, descent gradient 4.5% (No low-speed maneuvers)
Landing	Hover turn 180° Vertical descent from 100ft to touchdown, remain over FATO with wind gusts/turbulence	(No hover turn) Vertical descent from 15ft to touchdown	(No hover turn) Vertical descent from 15ft to touchdown

Table 3: Missions phases and requirements from eVOLUTION [4]

The data which are made available by the eVOLUTION [15] project, are fundamental to analysis. This data will be used as input for assessing costs; however, it depends on the scenario considered in the next chapter.

3 Methodology

In this chapter, the selection of the reference scenario, which is going to furnish the mission-level input data, is described. The chosen scenario is important from the viewpoint of data accuracy and data covariance for cost analysis. In the chapter, the methodology for cost analysis is also described, which is carefully selected to suit the nature and the quality of the input data that can be accessed from the literature so far and from parallel analysis studies.

The study aims to create a strong base which enables deep analysis of cost factors for supporting decision-making processes. The chapter intends to establish a detailed and organized framework for dependable cost analysis by meticulously examining and selecting data sources which support mission success [16].

3.1 Mission Scenario - Brussels to Liege

Based on the scenario types discussed in the previous chapter, this analysis will focus on a scenario within the Inter-City and Point-to-Point category. Initially, the Brussels-Antwerp scenario received initial consideration. This option was thought to be suitable due to its relevance and accessibility. However, upon further examination and the creation of the mission profile, it became clear that the short distance between Brussels and Antwerp would not yield competitive results in terms of time (and then costs) when compared to traditional means of transportation currently available. The short range limits the potential benefits, which renders it unsuitable for our needs.

Considering this, the analysis changed focus but remained in a European context. The Brussels-Liege option became a better choice. This option has a longer distance, which helps in looking at time and cost efficiency more closely. The use of Brussels-Liege seeks to create a realistic model that can be more easily compared to current transportation methods, ensuring the findings are useful and applicable.

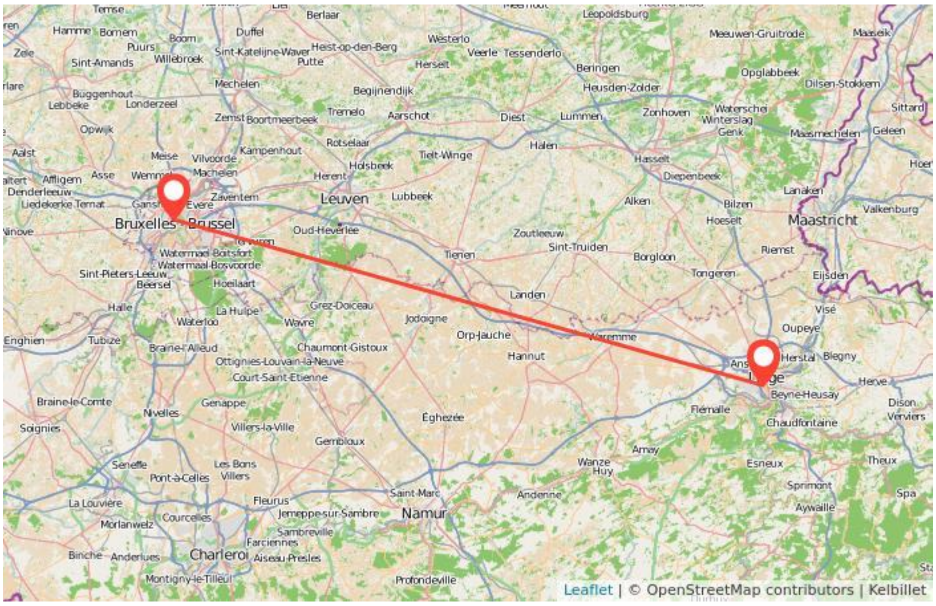

Figure 3-1: Brussels - Liege Scenario

3.1.1 Mission Input Data

The following table represents the main input data to plot the mission profile. All data are essential to give a full and precise list of the mission parameters.

The input data covers various measures such as distance, altitude, speed, and fuel consumption, among others. The measures are of great importance in plotting the mission path, measuring performance, and making wise decisions. By combining and contrasting this data, it is possible to create a complete mission profile that will serve as the foundation for later analysis and optimization.

Parameter	Symbol used	Numerical value	Units of measurement
Drag Coefficient	coeff_drag	0.05	-
Wing Surface	Wing_surface	26.4	m^2
Cruise Velocity	Cruise_velocity	66.67	m/s
Stall Velocity	Stall_velocity	33.33	m/s
Max Altitude	Alt_max	2000	ft
Total Range	Total_range	93	Km
Initial Climb Gradient	Gradient_initial_climb	0.045	-
Climb Gradient	Gradient_climb	0.04	-
Takeoff Altitude	altitudine_takeoff	15	ft

Table 4: Mission Numerical Input Data

3.1.2 Mission profiles

The following graphs show the mission profile. These graphs represent altitude as a function of time and altitude as a function of the range to be covered. The phases that can be observed are 'Take off', 'Initial climb', 'Climb', 'Cruise', 'Descent', 'Loiter', 'Approach', and 'Landing':

- Takeoff: the initial phase where the aircraft gains speed, it is vertical.
- Initial climb: after the takeoff is accomplished, eVTOL begins to climb to a greater altitude. It is a phase that is significant in climbing to altitude efficiently and safely.
- Climb: at this phase, the aircraft continues to climb until cruise altitude.
- Cruise: eVTOL maintains a steady altitude and speed. This is the longest phase of the flight.
- Descent: as the aircraft is coming to its destination, it begins to descend from the cruise altitude. This is a time of controlled slow reduction in altitude.
- Loiter: in some situations, it goes into a loiter, where it remains at some altitude, holding out for authorization to proceed with the approach and land. This may be due to air traffic or operational conditions.
- Approach: at this stage, eVTOL prepares to land and decreases altitude progressively.
- Landing: the final stage is vertical as the Takeoff one. This stage concludes the flight.

All these phases give a general description of the mission profile, representing the significant stages of the flight from takeoff to landing [15].

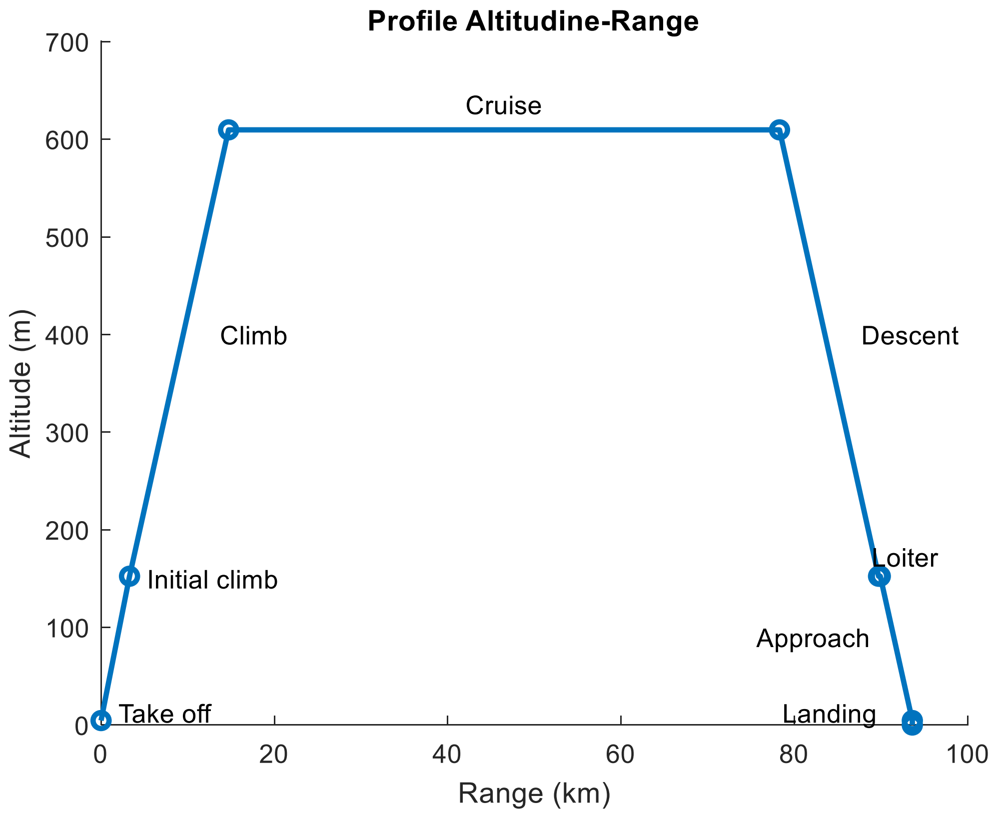

Figure 3-2: Mission Profile Altitude-Range

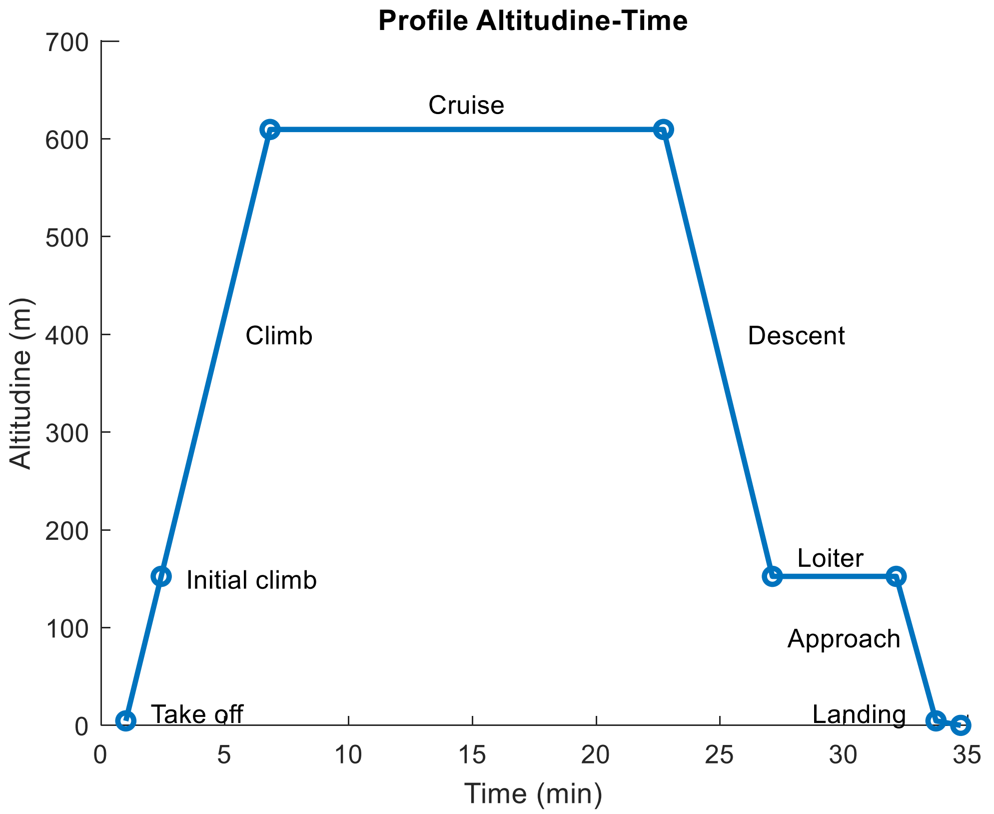

Figure 3-3: Mission Profile Altitude-Time

Data describing these two graphs that came up with the profile analysis are:

Phase	Velocity [m/s]	Range [m]	Time [s]
Take off	33.33	0.00	60.00
Initial climb	38.33	3285.07	85.70
Climb	43.33	11430.00	263.79
Cruise	66.67	63569.87	953.50
Descent	43.33	11430.00	263.79
Loiter	33.33	200.00	300.00
Approach	38.33	3695.70	96.42
Landing	33.33	0.00	60.00

Table 5: Brussels-Liege Mission Profiles Data

3.2 Roskam Model and Input data

Among cost models that were addressed in the previous chapter, the Roskam model is most suitable to conduct an analysis of an eVTOL airplane's operational costs. The Roskam model is selected because it covers a wide range of inputs, which vary from direct operating costs like insurance, crew, and maintenance to indirect expenses like financing and depreciation [13].

The numerical data, presented in the following table, will serve as inputs for the cost calculation model that has been previously selected for application. Some of them are extracted by using existing formulas as part of the analysis of aviation subjects and tasks and others that are still calculated presuming the evidence available for review [17].

Parameter	Symbol used	Numerical value	Units of measurement
takeoff weight of the airplane	Wto	6795.8	Lbs
number of airplanes acquired	Nacq	1	-
Number of engines per airplane	N_e	8	-
Number of propellers per airplane	N_p	8	-
block distance measured in nm	R_{bl}	50.21	Nm
time required to climb	t_{cl}	0.097	Hrs
projected horizontal speed of the airplane during the climb	V_{cl}	79.37	Kts
projected horizontal speed of the airplane during the descent	V_{de}	84.23	Kts
time required to descent	t_{de}	0.073	Hrs
maneuvering due ATC constraints	V_{man}	250	Kts
design cruise speed of an airplane in nautical miles per hour	V_{cr}	129.60	Kts
number of years during which the airplane is operated	Nyr	5	-
Number of captains	$n_{capitain}$	1	-
Number of copilots	$n_{copilot}$	0	-
Number of flight engineer	$n_{\text{flightengineering}}$	0	-

vacation pay, cost of training, crew premium, crew insurance, and payroll tax	K_j	0.26	-
Salary value for 1989	SAL_{1989}	75000	USD
Cost Escalation Factor from 1989 to 2024	CEF	2.53	-
Energy Used for a mission	Energy_used	200	Kwh
Energy Price in European Union	PE	0.15	USD/Kwh
annual hull insurance	f_{ins_hull}	0.015	USD/USD/airplane/year
airplane market price in USD	AMP	2250000	USD
airplane maintenance labor rate per manhour in USD/hr	Rl_{ap}	150	USD/hr
number of engine maintenance hours needed per block hour per engine	MHR_{meng_bl}	0.07	M_Hrs/blhr
engine maintenance labor rate per man hour in USD/hr	Rl_{eng}	16	USD/hr
airframe and systems maintenance materials cost per airplane block	$\mathrm{Cmat}_{\mathrm{apblhr}}$	70.72	USD/hr
number airframe and systems maintenance materials men hours needed per flight	MHR_{map_flt}	0.07	M_Hrs/blhr
number of engine maintenance hours needed per flight per engine	MHR_{meng_flt}	0.07	M_Hrs/blhr
engine maintenance materials cost per engine per airplane block hour	$\mathrm{Cmat}_{\mathrm{engblhr}}$	30	USD/hr
overhead distribution factors for labor cost	$\mathrm{famb}_{\mathrm{lab}}$	1	-
overhead distribution factors for material	famb_{mat}	0.35	-
number maintenance hours needed per block hour per engine	MHR_{eng_bl}	0.07	M_Hrs/blhr

number maintenance material men hours needed per block hour per engine	$MHR_{\mathrm{mat\_engblhr}}$	0.07	M_Hrs/blhr
airframe depreciation factor	F_{ap}	0.25	-
Airplane estimated price	AEP	2000000	USD
engine price (per engine) in USD	EP	15000	USD
price per propeller in USD	PP	9000	USD
avionics systems price per airplane in USD	ASP	150000	USD
airplane depreciation period	DP_{ap}	5	Ys
engine depreciation factor	F_{deng}	0.25	-
engine depreciation period	DP_{eng}	5	Ys
avionics systems depreciation factor	F_{dav}	0.15	-
avionics systems depreciation period	DP_{av}	5	Ys
propeller depreciation factor	F_{dprp}	0.03	-
propeller depreciation period	DP_{prp}	5	Ys
airplane spare parts depreciation factor	F_{dapsp}	0.25	-
airplane spare parts factor	F_{apsp}	0.10	-
airplane spare parts depreciation period	DP_{apsp}	5	Ys
engine spare parts depreciation factor	F_{dengsp}	0.25	-
engine spare parts factor	F_{engsp}	0.25	-
engine spare parts price factor	ESPPF	1.5	-
depreciation period for engine spare parts	DP_{engsp}	5	Ys

Table 6: Input Data

3.3 Direct Operating Cost

Direct operating costs refer to the expenses that are directly attributed to the operation of an aircraft. These costs are essential for maintaining operational efficiency and financial health of aviation activities.

The Roskam model gives a full picture of how to figure out the direct operating costs. It highlights 4 main categories:

- Direct operating cost of flying.
- Direct operating cost of maintenance.
- Direct operating cost of depreciation.
- Direct operating cost of landing fees, navigation fees and registry taxes.

3.3.1 Direct operating cost of flying

In this sub-chapter, there are listed flying's Direct Operating Costs as postulated by the Roskam model:

- Time spent on ground maneuvers: this is a variable that estimates the time an aircraft spends on the ground taxiing, loading, and unloading.

$$t_{gm} = 0.51 \times 10^{-6} \times Wto + 0.125$$

- Distance to climb and to accelerate to cruise speed: the distance an airplane needs to climb to cruising altitude and accelerate to its destination speed is relevant to how much energy it uses.

$$R_{cl} = V_{cl} \times \ t_{cl}$$

- Distance covered during the descent: similar to the ascent, the distance required for descending impacts consumption efficiency and the amount of time spent in flight.

$$R_{de} = V_{de} \times \ t_{de}$$

- Time spent in ATC maneuvering: ATC regulations can make aircraft spend longer periods in flight. This has implications for flight schedules.

$$t_{man} = 0.25 \times 10^{-6} \times Wto + 0.0625$$

- Distance covered while maneuvering due to ATC constraints: this parameter calculates the additional distance covered due to ATC regulations and restrictions, which can increase consumption and expenses.

$$R_{man} = V_{man} \times t_{man}$$

- Design cruise speed for an airplane: the ideal speed for an airplane to cruise efficiently at high altitude is important to save energy.

$$V_{cr} = V_c$$

- Block time: this refers to the total time from the moment an aircraft leaves the gate until it arrives at its arrival gate, incorporating all elements of the flight. It is a key measure used for planning operations.

$$t_{bl} = t_{gm} + t_{cl} + t_{cr} + t_{de}$$

- Block speed: this refers to average speed for block time.

$$V_{bl} = \frac{R_{bl}}{t_{bl}}$$

- Annual utilization in block hours: this states how many block hours an aircraft is used in a year, giving information on how much it is being used and how productive it is.

$$U_{ann\_bl} = 10^3 * (3.4546 * t_{bl} + 2.994 - \sqrt{(12.289 * t_{bl}{}^2 - 5.6626 * t_{bl} + 8.964)})$$

- Total annual block miles flown: it indicates the distance planes fly during block time. It is a significant metric for examining how much work is being performed and the expenses incurred.

$$R_{ann\_bl} = V_{bl} * U_{ann\_bl}$$

- Number of crew members: the quantity of individuals in the flight crew is central to determining labor costs, which influences the overall cost of operations.

$$n_{cj} = n_{capitain} + n_{copilot} + n_{flightengineer}$$

- Salary for crew members: this is what crew members earn, and it has a direct impact on the financial aspect of flight operations.

$$SAL_j = SAL_{1989} * CEF$$

- Crew total cost: the total amount of crew wages, benefits, and other incidental costs.

$$C_{crew} = n_{cj} * \frac{1 + Kj}{V_{bl}} * \frac{SAL_j}{AH_j}$$

- Total cost insurance: aircraft and operating liability insurance costs play an important role in risk management and financial planning.

$$C_{ins} = \frac{F_{ins\_hull} * AMP}{U_{ann\_bl} * V_{bl}}$$

- Energy total cost: energy costs, which make up the majority of direct operating costs, are affected by a number of factors including how efficiently energy is consumed and market prices.

$$C_{en} = \frac{Energy_{used} * PE}{R_{bl}}$$

- Direct Operating cost of flying: this is inclusive of all of the above factors; it gives an overall indication of the money needed to run an aircraft.

$$DOC_{flt} = C_{crew} + C_{en} + C_{ins}$$

3.3.2 Direct operating cost of maintenance

In the aviation industry, it is important to understand how aircraft maintenance costs affect managing a fleet and operating well [18] [19]. The Direct Operating Costs of maintenance, as explained in the Roskam model, provide a complete way to look at the costs related to keeping an aircraft in good condition.

- Flying time: this is a significant metric for the determination of maintenance costs as it has a direct relation to the wear and tear of aircraft components and systems. The accumulated flying hours determine how often and to what extent maintenance is needed.

$$t_{flt} = t_{cl} + t_{cr} + t_{de}$$

- Number of airframe and systems maintenance man hours needed per block hour: this metric measures the labor needed to maintain the airframe and its systems per block hour of flying time.

$$MHR_{map\_bl} = MHR_{map\_flt} * \frac{t_{flt}}{t_{bl}}$$

- Labor cost of airframe and systems: this cost reflects the expenditure on skilled labor that keeps the airframe and systems of the aircraft in good condition. It includes wages, benefits, and other expenses related to maintenance staff, and therefore it is a major part of the overall DOC.

$$Clab_{ap} = 1.03 * \frac{MHR_{map\_bl} * Rl_{ap}}{V_{bl}}$$

- Labor cost of engine(s) maintenance: like airframe labor costs, this item deals with the cost of aircraft engine maintenance. Given that engine performance is critical, having knowledge of such costs is essential for proper budgeting and planning of resources.

$$Clab_{eng} = \frac{1.03 * 1.3 * N_e * MHR_{meng\_bl} * Rl_{eng}}{V_{bl}}$$

- Number man hours needed per flight hour: it compares total man-hours needed to perform work to total flight hours allows operators to ascertain levels of performance and areas for improvement.

$$MHR_{flthr} = \frac{MHR_{map\_bl} * t_{bl}}{t_{flt}}$$

- Cost of maintenance materials for the airframe and systems: costs related to parts, components, and materials needed to keep the airframe and systems in good condition.

$$Cmat_{ap} = \frac{1.03 * Cmat_{apblhr}}{V_{bl}}$$

- Cost of maintenance materials for the engines: this subsection presents the costs for material maintenance used for engines. Knowing these costs helps in preparing for maintenance in advance and estimating future expenditure on equipment.

$$Cmat_{eng} = \frac{1.03 * 1.3 * N_e * Cmat_{engblhr}}{V_{bl}}$$

- Applied maintenance burden: it is the added cost of maintenance operations, for example, building expenses, utility expenses, and office overheads. It gives a broader picture of real maintenance expenses, over and above direct labor and materials.

$$Camb = 1.03 * (famb_{lab} * MHR_{map\_bl} * Rl_{ap} + N_e * MHR\_eng\_bl * Rl_{eng} + famb_{mat} * (Cmat_{apblhr} + N_e * Cmat_{engblhr})) / V_{bl}$$

- Direct operating cost of maintenance: it adds up all the items described above.

$$DOC_{maint} = Clab_{ap} + Clab_{eng} + Cmat_{ap} + Cmat_{eng} + Camb$$

3.3.3 Direct operating cost of depreciation

This segment will discuss the different elements of the DOC of depreciation:

- Cost of airplane depreciation without engines and without propellers: this cost represents the depreciation associated with the airframe, excluding engines and propellers.

$$Cdap = \frac{F_{dap} * (AEP - N_e * EP - N_p * PP - ASP)}{DP_{ap} * U_{ann_{bl}} * V_{bl}}$$

- Cost of engine depreciation: engines are very vital parts of an airplane. This cost explains how engine depreciation affects the overall operating costs.

$$Cdeng = \frac{F_{deng} * N_e * EP}{DP_{eng} * U_{ann_{bl}} * V_{bl}}$$

- Cost of depreciation of propellers: for an eVTOL, this cost describes the financial impact of the depreciation of propellers based on their replacement and maintenance schedules.

$$Cdprp = \frac{F_{dprp} * N_p * PP}{DP_{prp} * U_{ann_{bl}} * V_{bl}}$$

- Cost of depreciation of avionics systems: new aircraft, as eVTOL, have complex avionics systems. This cost describes the depreciation of these systems that are critical to the understanding of how they add to the operational capability of the aircraft as well as general safety.

$$Cdav = \frac{F_{dav} * ASP}{DP_{av} * U_{ann_{bl}} * V_{bl}}$$

- Cost of depreciation of airplane spare parts: spare parts are an essential aspect of maintaining aircraft readiness. This cost area reflects the depreciation of these parts.

$$Cdapsp = \frac{F_{dapsp} * F_{apsp} * (AEP - N_e * EP)}{DP_{apsp} * U_{ann_{bl}} * V_{bl}}$$

- Cost of depreciation of engine spare parts: the same as for general spare parts, this section is solely reserved for engine spare parts and how their depreciation affects operational budgeting.

$$Cdengsp = \frac{F_{dengsp} * F_{engsp} * Ne * EP * ESPPF)}{DP_{engsp} * U_{ann_{bl}} * V_{bl}}$$

- Cost of depreciation of battery:

$$Cbattery = \frac{F_{deng} * ASP}{DP_{av} * U_{ann_{bl}} * V_{bl}}$$

- Direct operating cost of depreciation: it is possible to combine the different factors to provide a result of the Direct Operating Cost of depreciation. By looking at all of the costs mentioned above and how they work together it is possible to understand how they affect the financial aspect of flying an eVTOL.

$$DOC_{depr} = Cdap + Cdeng + Cdprp + Cdav + Cdapsp + Cdengsp + Cbattery$$

3.3.4 Direct operating cost of landing fees, navigation fees and registry taxes

This chapter explores three important elements: airplane landing fees, navigation fees, and registry taxes.

- Airplane landing fees: these charges imposed by airports to allow planes to land. The charges can change depending on the weight, on where the airport is situated, and on the time of day.

$$Caplf = 0.002 * Wto$$

- Direct operating cost due to landing fees: this is a part of DOC that involves the payment of fees for landing services. This cost is directly related to the number of flights landing at different airports.

$$Clf = \frac{Caplf}{V_{bl} * t_{bl}}$$

- Cost of navigation fees: charges for the use of air navigation services, such as air traffic control and route management. These charges are essential for safe flight operations, and they can change depending on flight routes and airspace usage.

$$Cnf = \frac{Capnf}{V_{bl} * t_{bl}}$$

- Factor depending on airplane size: charges that depend on the size and weight of the aircraft. Larger aircraft tend to have higher charges, so planning is required for fleet management and route selection.

$$f_{rt} = 0.001 + 10^{-8} * Wto$$

- Direct cost of registry taxes: these are fees imposed by governmental authorities for the registration of aircraft, which can vary significantly based on jurisdiction.

$$Crt = f_{rt} * DOC$$

- Direct operating cost of landing fees, navigation fees and registry taxes: this overall cost entails the amount incurred in landing fees, navigation fees, and taxes for aircraft registration.

$$DOC_{lnr} = Clf + Cnf + Crt$$

3.3.5 Direct operating cost of financing

This chapter aims to explain the concept of Direct Operating Costs of Financing as outlined in the Roskam model.

- Direct operating cost of financing: it represents the direct costs involved in financing aircraft operations, which can greatly affect profitability.

$$DOC_{fin} = 0.007 * DOC$$

3.4 Indirect Operating Costs

Indirect operating costs are essential, and this chapter wants to clarify the concept of indirect operating costs as described in the Roskam model, focusing on their components and the factors that affect them.

- Indirect operating cost for passenger services: this section represents costs linked to passenger services, such as customer support, ticketing, and check-in processes.

$$IOCpax = Cmls + Cpax\_ins + Ccat + Cpax\_gen$$

- Indirect cost for maintaining and depreciating ground equipment and ground facilities: ground equipment and facilities are essential for airport operations. This part discusses the expenses related to the maintenance and depreciation of these assets

$$IOCsta = Cmgef + Cdgef$$

- Indirect operating costs for airplane and traffic servicing: this section explains the costs involved in servicing airplanes.

$$IOCascf = Caps + Capctrl + Cfrt$$

- Indirect Operating Costs: these costs are related to expenses that cannot be directly linked to a specific flight or service but are vital for the airline's functioning.

$$IOC = IOCpax + IOCsta + IOCascf + IOCpse + IOCgaa$$

Now it is possible to discuss challenges posed by the limited availability of data on indirect costs.

Considering this limitation and the demonstrated effectiveness of the following formula, this study decided to combine all previously mentioned indirect costs into a more representative formula. This method not only simplifies the analysis but also improves the capacity to derive meaningful insights from data. By concentrating on this simplified model, the aim is to offer a clearer perspective on the indirect costs involved and their influence on the overall findings.

$$IOC = 0.3 * DOC$$

3.5 eVTOL Total Operating Costs

This sub-chapter discusses total operating costs.

It will use formulas that have already been presented and focus on the inclusion of direct and indirect costs.

To calculate the total direct and indirect operating costs, the factor of total annual block miles flown and the years in which the vehicle is expected to be used are taken into account.

Specifically, it will combine direct costs and total indirect costs and then multiply by the units purchased.

$$Cops_{dir} = DOC * R_{ann\_bl} * N_{yr}$$

$$Cops_{ind} = IOC * R_{ann\_bl} * N_{yr}$$

$$Cops = Cops_{dir} * N_{acq} + Cops_{ind} * N_{acq}$$

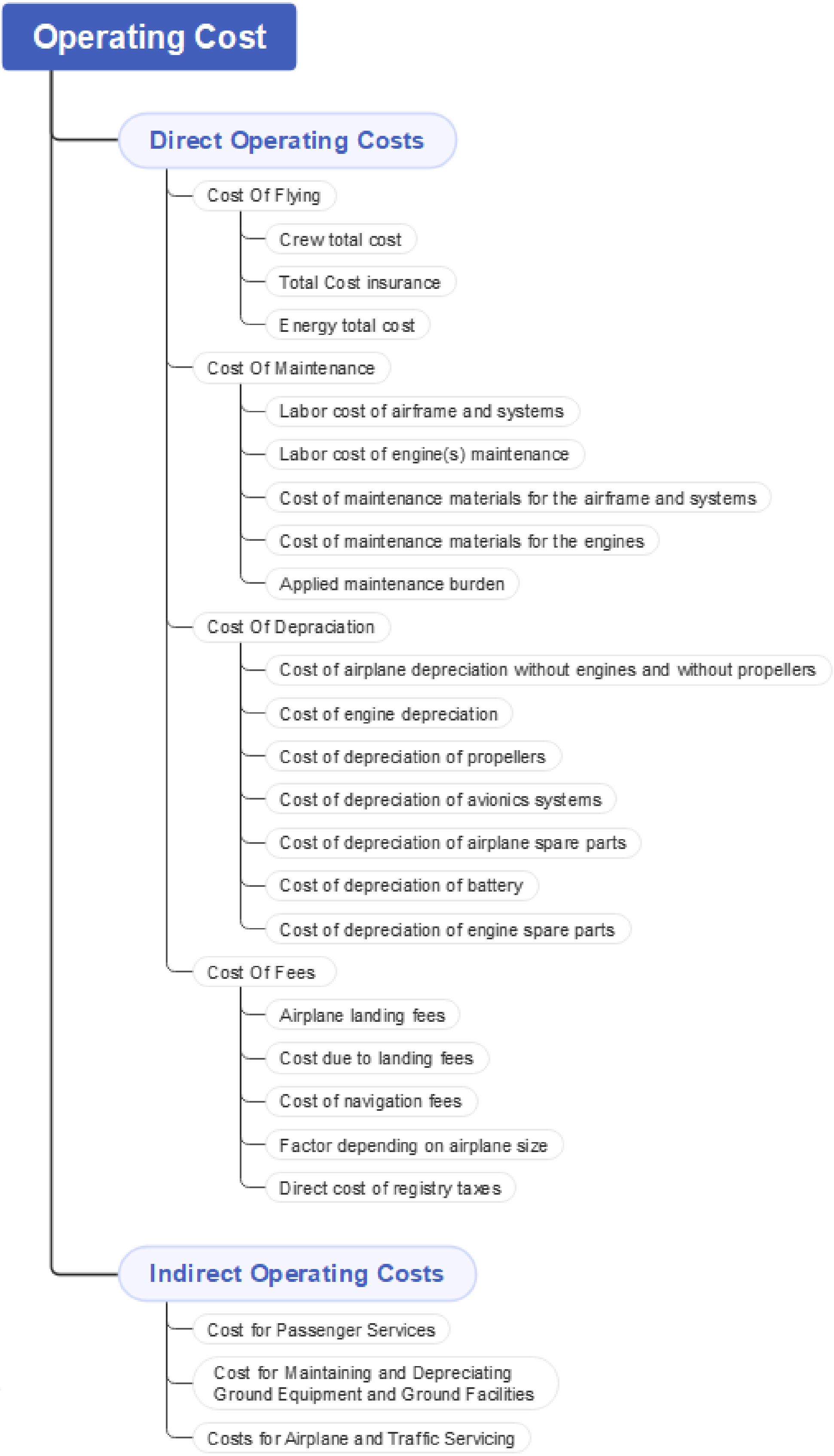

Figure 3-4: Operating Cost Parameters

4 Results and Discussion

This chapter will present the results of the cost approach outlined above with a focus on the chosen scenario. The analysis will give a clear image of the economic effect related to this approach.

This analysis will also contrast it with other scenarios that include consistent increases or decreases in the distance to be covered. By comparing these differences, it is possible to learn important things about the strengths and weaknesses of the chosen method under different conditions. The comparison will show how effective the cost method is and will also show how variations in distance can affect the results. This will ultimately allow to understand the multifaceted aspects of cost management in real-life conditions.

4.1 Operating Costs Percentages

Applying the formulas presented herein, based on the Brussels and Liege case data, the proportions for the different direct and indirect cost categories are shown in the figures below:

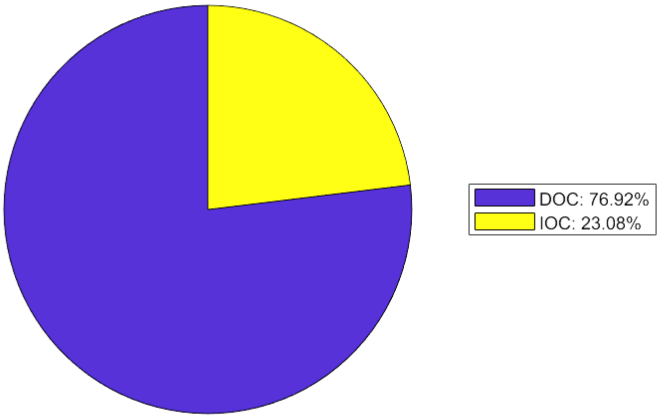

Figure 4-1: Direct and Indirect Cost Percentages

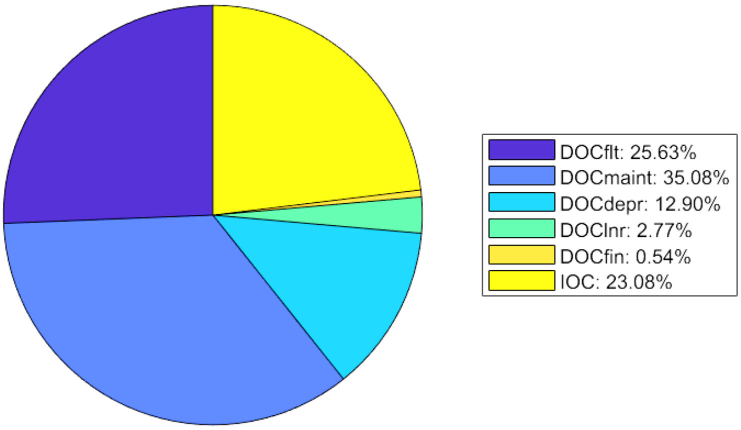

Figure 4-2: Specific Operating Costs Percentages

The direct costs are said to be three times larger than the indirect costs. Among all the categories of costs, maintenance costs constitute the highest element, while the direct operating financing costs constitute the lowest element. This breakdown shows the impact of maintenance costs on the overall costs, demonstrating the importance of efficient maintenance management. On the other hand, the low percentage of direct financing costs shows that they have a less dominant effect on the overall costs. It is essential to know these distributions for better cost control and improvement in the chosen situation.

Numerical results, expressed in USD/nm, are:

Costs	Value [USD/nm]
Direct Operating Costs of flying	2.5936
Direct Operating Costs of maintenance	3.5496
Direct Operating Costs of depreciation	1.2287
Direct Operating Costs of landing fees, navigation fees and registry taxes	0.2807
Direct Operating Costs of financing	0.0539
Direct Operating Costs	7.7061
Indirect Operating Costs	2.318

Table 7: DOC and IOC Values

4.2 Cost per Passenger

To calculate the cost per passenger per trip, firstly it is needed to consider the aircraft's total lifespan, which is 5 years, and determine the annual costs. After that, it is possible to calculate the mission costs.

This method provides a clearer picture of the financial implications of operating the aircraft throughout its entire life cycle. By segmenting the costs annually, it is possible to achieve a more precise and realistic estimate of the cost per passenger per trip.

The result, for a range of 93Km is:

$$C_{per_{pass}} = 127 \, \$$$

4.3 Cost per Nautical Mile

Based on the obtained cost results, it is possible to calculate the cost per nautical mile per passenger.

By examining the cost per nautical mile, a more precise measurement of the financial implications for each passenger can be achieved; an understanding of the cost per nautical mile per passenger is crucial for evaluating the economic viability and competitiveness of the aircraft:

$$C_{per_{nm\_per\_pass}} = 2.52 \, \$$$

4.4 Cost per Block Hour

Based on the findings, it is possible to highlight the total block-hour cost associated with the vehicle's use. This value is obtained by dividing the annual cost by the annual utilization measured in block hours. This metric offers a clear perspective on cost efficiency relative to eVTOL’s operating time.

$$C_{per_{bl}} = 901.4 \, \$$$

4.5 Brussel – Liege: eVTOL vs Conventional Transport

This discussion examines how time impacts road construction and how it influences traffic in the city. The Idaho Transportation Department report "Economic Impact of Work Zone Travel Time Delays" [10] provides a definite method to evaluate these delays.

- Finding Work Zones: first of all, one has to find out where the work zones in the city are. This means finding out the duration of the construction/road working and what exactly is being built, along with which roads will be affected.

- Traffic Flow Analysis: the report suggests traffic flow analysis before, during, and after the implementation of the work zone. This involves gathering data on the volume of traffic, speed of traffic, and levels of congestion. Through analysis, it is possible to measure changes in travel time and peak delay periods.
- Travel time delays calculating: using traffic flow information, it is possible to determine the travel time delays due to work zones. then measure the additional time it takes for vehicles to pass through or around construction zones. Delays are typically expressed in average minutes per vehicle.

- Economic Impact Analysis: the second main step is to examine the impact of these travel time delays on the economy. Various costs are enumerated in the report, such as the consumption of additional fuel, increased vehicle expense, and lost productivity due to increased travel time. The total economic expense is calculated by multiplying the additional travel time by the number of affected vehicles and the monetary value of time.

- Comparative Analysis: the report highlights the significance of comparing travel time delay and economic impacts in different work zone scenarios. By examining the duration of construction, the size of the impacted area, and the degree of traffic congestion. Then it is possible to determine the main factors related to delays and costs.

- Mitigation Strategies: based on the report, mitigation strategies are needed to come up to reduce travel time delays. This can involve solutions as: better scheduling of construction times, having traffic management strategies in place and using alternative routes to keep traffic away from work zones. The objective is to reduce travel delays and the costs associated with them.

- Conclusion: examination of delays in travel time within work zones is essential in understanding how they affect city traffic and the economy. From using the suggested framework, it is possible to recognize the major causes of delays, evaluate their economic effects, and create efficient plans to curb them. This maintains transport systems efficiently and prevents unwanted economic effects.

4.5.1 Time Consideration

The next step involves examining the actual travel times using conventional modes of transportation for the selected itinerary. It is assumed that the eVTOL is taken immediately upon disembarking at the airport, and for this reason it will eliminate additional transfer times. In contrast, potential traffic congestion due to road work is considered for traditional transportation methods such as trains and cars [20]

- By eVTOL:
    - Mission Time: 35 min
    - Time to get off the plane: 5 min
    - Baggage recovery time: 10 min

  The total time needed is about 50 minutes, but this result is not affected by traffic congestion.

- By Train:
    - Mission Time: 75 min
    - Time to get off the plane: 5 min
    - Baggage recovery time: 10 min
    - Time to get off at the airport: 15 min
    - Train waiting time: 15 min
    - Traffic Congestion Delay: 25 min

  The total time is about 100 minutes considering that the result is affected by traffic congestion (75 standard minutes plus 25 minutes delay).

- By Car:
    - Mission Time: 68 min
    - Time to get off the plane: 5 min
    - Baggage recovery time: 10 min
    - Time to get off at the airport: 15 min
    - Train waiting time: 15 min
    - Traffic Congestion Delay: 40 min

The total time is about 153 minutes. This result is affected by traffic congestion (113 standard minutes plus 40 minutes delay).

Before proceeding and calculate cost for Conventional Trasport (train and car) it is important to understand how road work delays could be considered for calculate the effective costs.

The "Economic Impact of Work Zone Travel Time Delays" report by the Idaho Transportation Department [10] provides a framework for evaluating the cost of travel time delays.

To estimate the cost of a delay, it’s essential to consider several factors, such as the value of time, increased fuel consumption (for using a car), and other associated costs.

- Value of Time: it is often calculated using wage rates. The average hourly wage In Belgium, is approximately $25.13 USD [11]. This data is based on the most recent data available and provides a general idea of the average earnings for workers in the country.

- Fuel Consumption: increased fuel consumption occurs due to additional idling and reduced speeds. The additional fuel costs can be estimated and added to the value of time.

- Other Costs: additional vehicle operating costs, such as increased wear and tear.

Hereafter a simplified way for calculating these costs:

- Value of Time:

$$\text{Average Hourly Wage } \left[\frac{USD}{hours}\right] \times \text{ Delay [hours]} = \text{ Cost per Person [USD per person]}$$

- Increased Fuel Cost:

  to estimate the additional fuel cost for a half-hour delay, we need to consider the average fuel consumption rate and the current fuel price in Belgium.

  - Average Fuel Consumption Rate: it is possible to assume an average fuel consumption rate of 8 liters per 100 kilometers (a common rate for many vehicles).

  - Current Fuel Price: the current gasoline price in Belgium is approximately $1.75 per liter.

  If a vehicle idles or moves slowly it might consume around 1 liter of fuel, assuming an additional fuel cost of $2 per person for the delay.

- Other Costs:

  it is possible to estimate an additional $1 per person for vehicle wear and tears.

4.5.2 Cost Comparison

Total estimated cost per person for different transport:

Transport	Transport Cost	Additional Delay Cost	Additional Fuel Cost	Additional Other Cost
eVTOL	125.76 $	0 $	0 $	-
Train	32 $	10 $	2 $	1$
Car	22 $	13 $	4 $	1$

Table 8: Additional Costs Considerations

Based on all the previous considerations, the total costs that can be determined in relation to the time required are as follows:

Transport	Total Time – Total Cost
eVTOL	35 min - 127 $
Train	125 min - 45 $
Car	172 min - 40 $

Table 9: Time-Total Cost Results

Analyzing the obtained data, it can be observed that using eVTOL vehicles incurs significantly higher costs compared to traditional modes of transportation such as cars and trains.

However, the travel times are reduced to one-third of what is typically experienced with these conventional methods. This highlights a clear trade-off between cost and efficiency, suggesting that while eVTOL offers rapid transit solutions, the financial implications have to be considered.

4.6 Different Scenario

It is essential to contrast previously done work with various scenarios. The contrasting will assist in verifying if the established findings are valid and can be applied under various conditions.

By comparing research together with different situations, patterns and variations become clearer that are not evident when looking at a single situation alone.

This process enables future analysts to gain a clearer understanding of the concepts involved. Learning from various circumstances facilitates improved decision-making and developing plans that can be modified based on new results.

In conclusion, a look at the previous work done in other contexts is an useful way of confirming research results and verified applicability.

4.6.1 Ibiza to Palma

An example of a scenario that is analyzed for comparison with previously found data is the route from Ibiza to Palma. Currently, traveling this distance requires over 6 hours by car and ferry for a total range of 154 kilometers. The goal is to see how the cost variables vary by taking into account this longer trip compared to the Brussels-Liège route.

In the calculation, the gradient of climb is 12.5%, and the cruise speed is 150 KEAS (Knots Equivalent Airspeed) at a height of 2000 feet above ground level. This scenario allows for a thorough examination of the operational costs associated with different travel routes, considering both the time and distance involved.

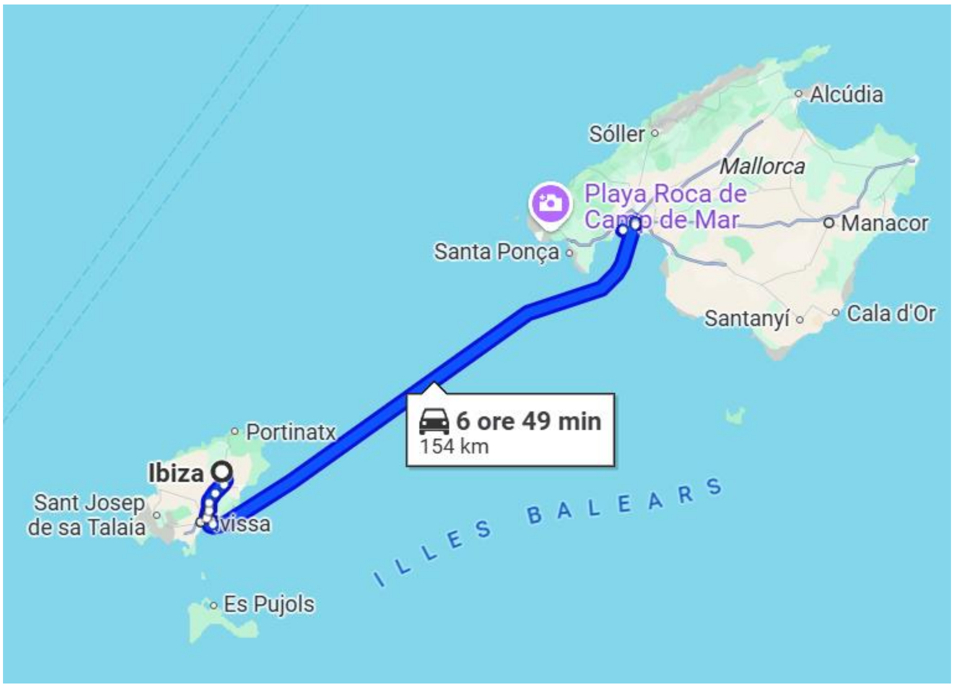

Figure 4-3: Long-Range Scenario

Hereafter, the mission profiles for this scenario:

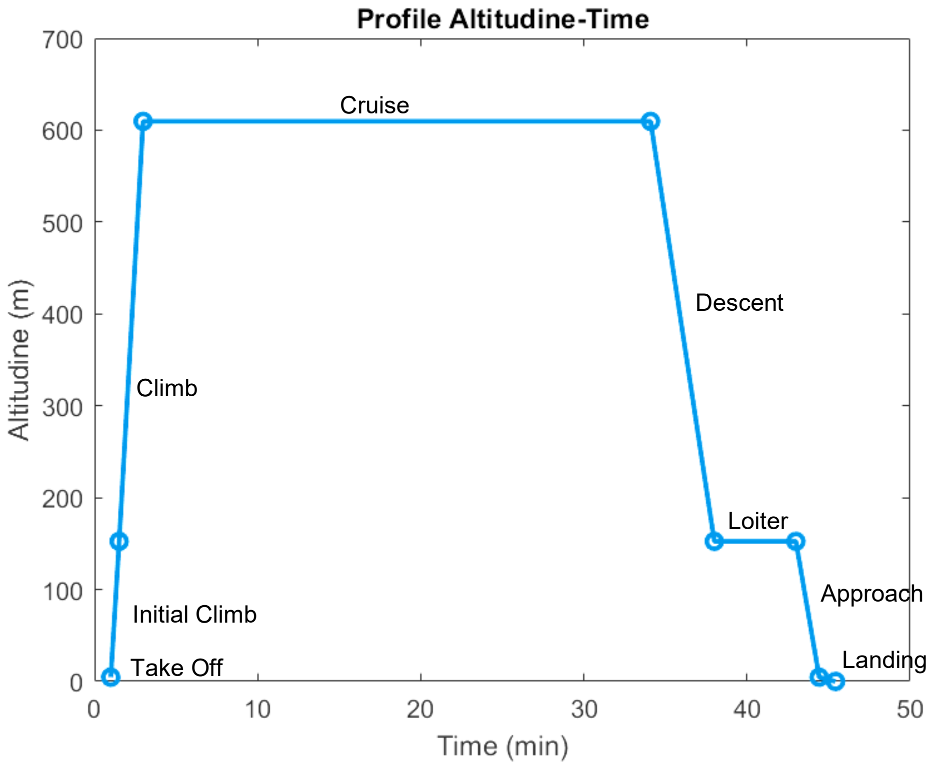

Figure 4-4: Long-Range Profile Altitude Time

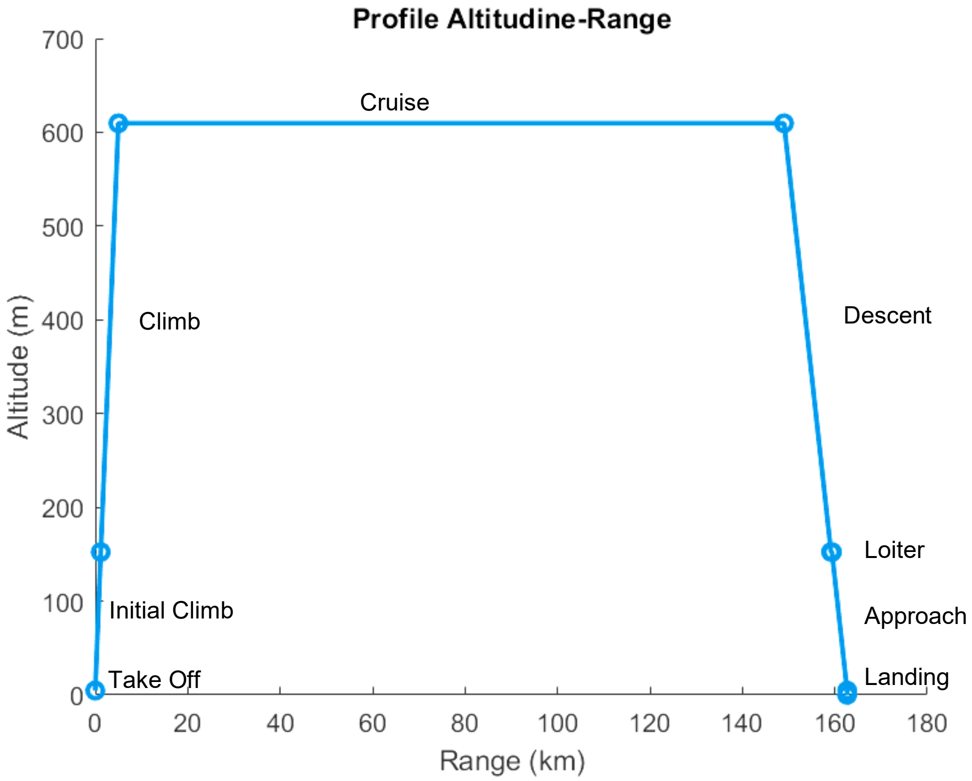

Figure 4-5: Short-Range Profile Altitude Range

Data results from these profiles are:

Phase	Velocity [m/s]	Range [m]	Time [s]
Take off	33.33	0.00	60.00
Initial climb	38.33	1182.62	30.85
Climb	43.33	3810.00	87.93
Cruise	77.16	144014.75	1866.44
Descent	43.33	10160.00	234.48
Loiter	33.33	200.00	300.00
Approach	38.33	3285.07	85.70
Landing	33.33	0.00	60.00

Table 10: Ibiza-Palma Mission Profiles results

The percentages of direct and indirect costs corresponding to these profiles are depicted in the following figure.

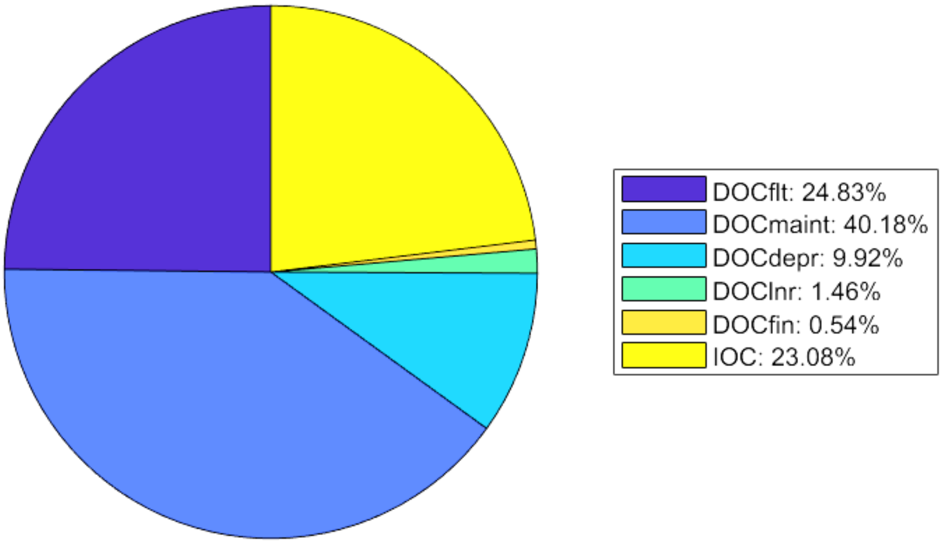

Figure 4-6: Long Range Profile - Costs Percentages

Based on the previously used data and the new values obtained from this scenario, the cost per passenger and the cost per passenger per nautical mile are as follows:

$$C_{per_{pass}} = 247 \$$$

$$C_{per_{nm\_per\_pass}} = 2.97 \$$$

4.6.2 Heathrow to Central London

An example of a scenario analyzed for comparison with previously found data is the route from Heathrow to Central London. Currently, traveling this distance covers a total range of 28 kilometers. The goal is to see how the cost variables vary by taking into account this shorter trip compared to the Brussels-Liège route.

In this calculation, the altitude is maintained at 1000 feet above ground level due to the very short range to be covered. This scenario allows for a thorough examination of the operational costs associated with different travel routes, considering both the time and distance involved.

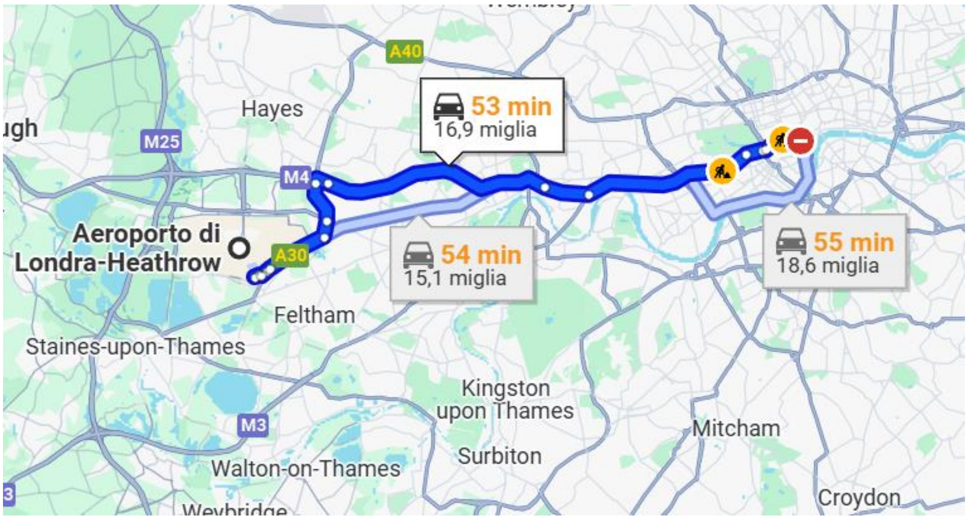

Figure 4-7: Short-Range Scenario

Hereafter, the mission profiles for this scenario:

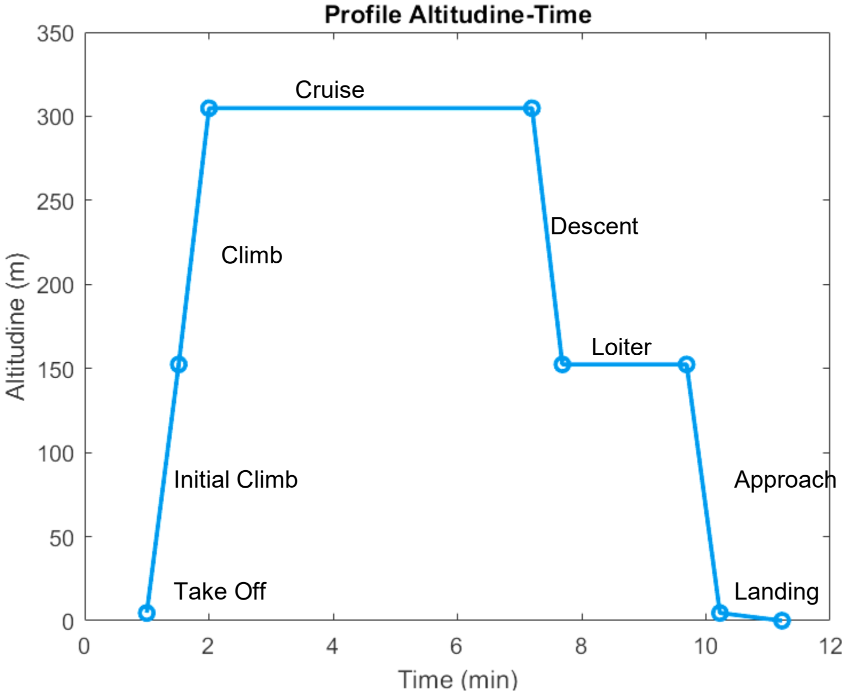

Figure 4-8: Short-Range Profile Altitude Time

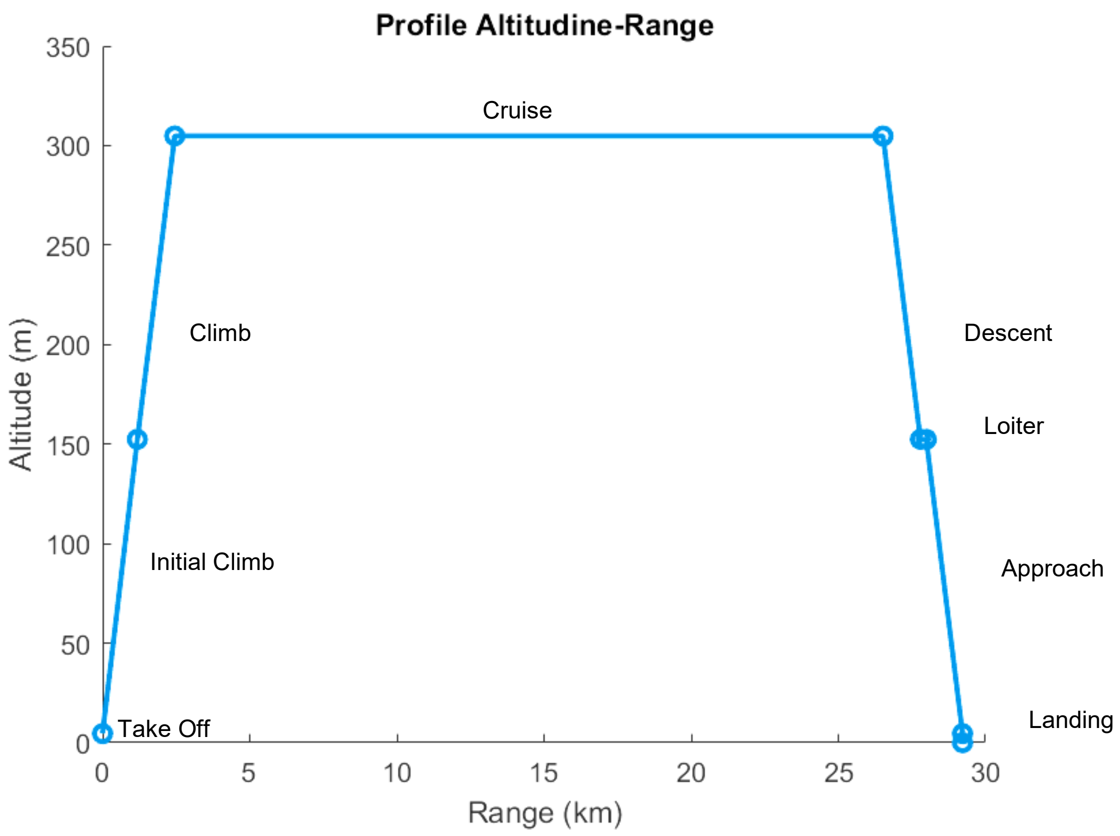

Figure 4-9: Short-Range Profile Altitude Range

Data results from these profiles are:

Phase	Velocity [m/s]	Range [m]	Time [s]
Take off	33.33	0.00	60.00
Initial climb	38.33	1182.62	30.85
Climb	43.33	1270.00	29.31
Cruise	77.16	24064.75	311.88
Descent	43.33	1270.00	29.31
Loiter	33.33	200.00	120.00
Approach	38.33	1231.90	32.14
Landing	33.33	0.00	60.00

Table 11: Heathrow-London Mission Profiles results

The percentages of direct and indirect costs corresponding to these profiles are depicted in the following figure.

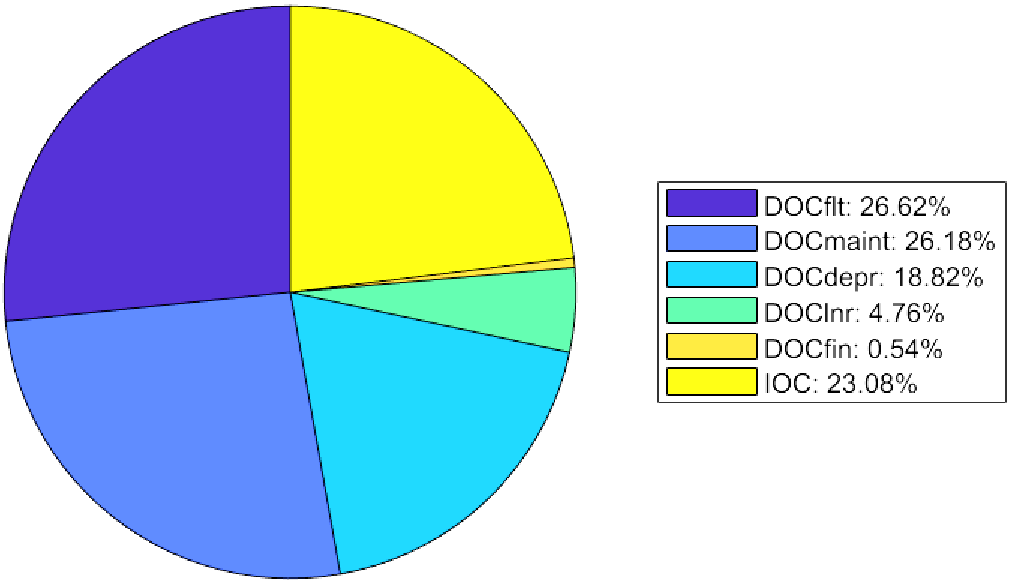

Figure 4-10: Short Range Profile - Costs Percentages

Based on the previously used data and the new values obtained from this scenario, the cost per passenger and the cost per passenger per nautical mile are as follows:

$$C_{per_{pass}} = 72.18\ \$$$

$$C_{per_{nm\_per\_pass}} = 4.61\ \$$$

4.6.3 Scenarios Data Comparison

Hereafter, it is possible to compare data from the different scenarios by exploring with the use of graphs. The graph shows differences in many operational costs, and it is easy to see how the costs change with each mission. The goal is to see how and why these costs change based on the specific mission requirements and resources available.

By looking at the data graphically, it is easier to analyze trends and fluctuations according to the needs of each mission.

This analysis provides valuable insight into how each circumstance affects finances and explains how individual mission goals affect total operating costs.

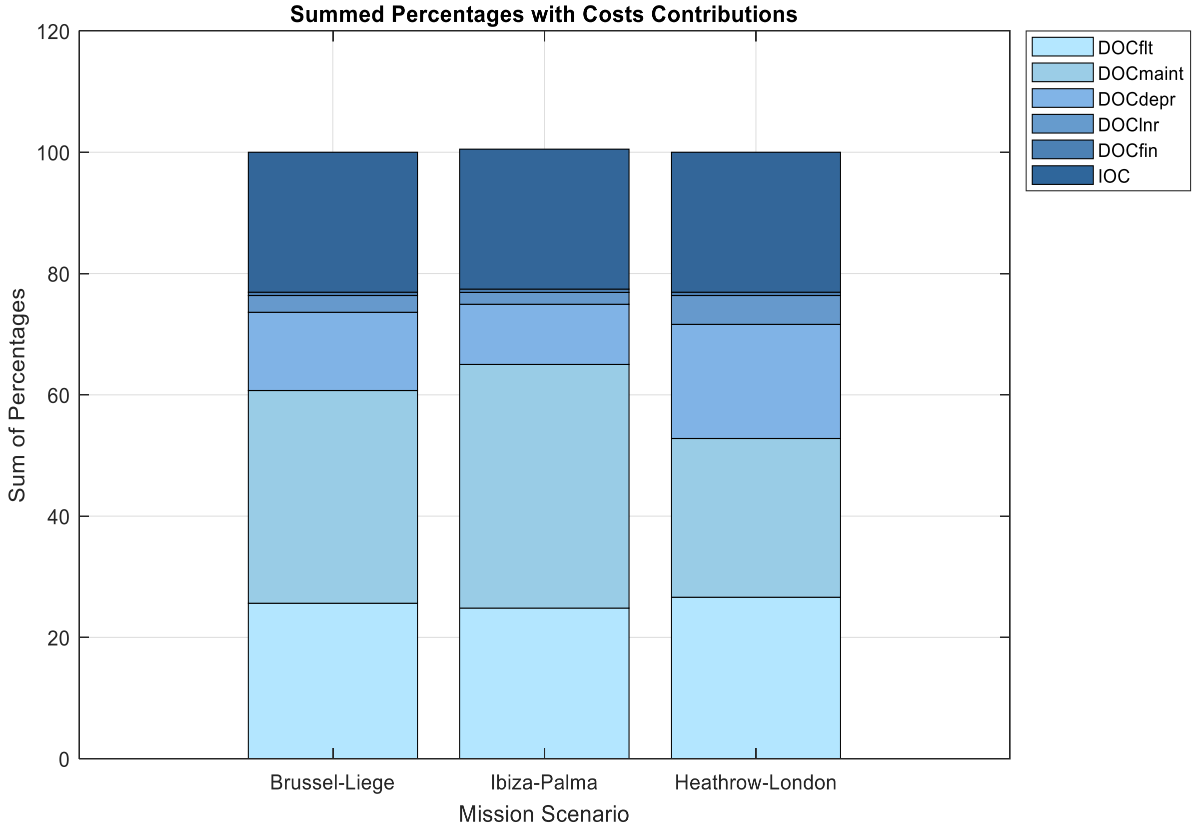

Figure 4-11: Mission Scenario Costs Contributions

It is quickly realized that the proportion assigned to indirect operating costs is always constant in each of the three situations. It is a solid percentage that results from the model under consideration, where indirect costs have been established as 30% of direct operating costs. Even if the figures for direct cost vary, the proportion between direct and indirect costs remains constant.

In effect, even as the absolute levels of direct costs change according to changing mission parameters, the model demands that the indirect costs also change proportionally—always at 30% of the direct costs.

This fixed proportionality simplifies the overall cost estimation by decoupling the effect of mission-specific variables on direct costs while scaling the indirect costs in a consistent manner. This uniform structure simplifies comparison across scenarios as the variation in the overall cost profile can be ascribed to differences in the direct cost components, and not to the volatility in the percentage of indirect costs.

Looking at the types of direct costs, it is possible to highlight that the more the mission range is extended, the more that is spent on maintenance operations. The reason is that equipment and systems are used more and wear out faster for longer ranges and must be maintained more often or more extensively.
So, the longer the mission range, the larger the direct costs for maintenance.

Within the direct costs, depreciation shows an opposite trend. While maintenance costs rise with longer missions, the percentage of depreciation costs within the total direct costs falls as the mission range rises. The opposite trend is seen because depreciation remains constant; as total direct costs rise with more maintenance needed on longer missions, the percentage of depreciation is lower.

5 Conclusion

The results in the previous chapters prove that eVTOLs can be a great transportation method in the future because they are very efficient. A closer look at these vehicles shows that they can greatly cut down on travel time and make transportation in cities easier. Their design and functionality permit individuals to move more quickly and conveniently than through traditional transportation means.

The research also shows that not many individuals will be prepared to utilize eVTOLs. There are several costs and infrastructural issues presently making it challenging for more people to utilize them. Further technological innovation will need to occur to enhance their safety, reliability, and performance for regular city utilization. Furthermore, the development of strong regulations and the building of infrastructure are essential to incorporate this novel technology into current transport networks. Lastly, enabling eVTOL transportation to be accessible to all relies on becoming more efficient at manufacturing and reducing operational and production costs.

In conclusion, eVTOLs will be a valuable component of transportation systems in the future. These benefits will, however, take time to materialize as technology advances, regulations evolve, and infrastructure is developed. This gradual transformation will ensure that more individuals are able to benefit from the benefits of eVTOLs.

Keep in mind that this technology is in its very beginning phases of research and development at this time, and a great deal can be expected to evolve in the years to come. Most of the design, operational, and performance characteristics are presently the subject of active research and may alter as new findings are integrated and more innovations are introduced. This is a time of discovery and refinement, as people find out what eVTOL can do and how it may be improved. So, while this report offers useful insight into current models and cost regimes, these results need to be viewed as part of a development phase that will change considerably going forward.

For future developments, the possibility of using eVTOL without an onboard pilot, rendering them uncrewed, is an area of interest. Advances in automation, sensor technology, and artificial intelligence could drive this evolution, reducing operational costs and minimizing human error. Transitioning to uncrewed systems requires significant developments in autonomous flight control systems. Such a development would mark a major shift in urban air mobility, underscoring the dynamic nature of the technology as it continues to mature through ongoing research

6 Appendix

6.1 Mission Scenario - MATLAB Core-Code

```
% Altitude and range max
alt_max = 2000 * 0.3048;          % from ft to m
range_tot = 93 * 1000;            % from km to m

% Gradient initial climb and climb
gradient_initial_climb = 0.045;
gradient_climb = 0.04;

% Mission Phases
phases = {'Take off', 'Initial climb', 'Climb', 'Cruise', 'Descent', 'Loiter', 'Approach', 'Landing'};

% V Phases
v_phases = [v_stall, v_stall + 5, v_stall + 10, v_cruise, v_stall + 10, v_stall, v_stall + 5, v_stall];

time_phases = zeros(1, length(phases));
altitude_phases = zeros(1, length(phases));
range_phases = zeros(1, length(phases));

% Vertical TO
altitude_takeoff = 15 * 0.3048;        % 15 ft in m
time_phases(1) = 1 * 60;               % 1 min in s
altitude_phases(1) = altitude_takeoff;
range_phases(1) = 0;

% Initial Climb
altitude_initial_climb = 500 * 0.3048;    % 500 ft in m
distance_initial_climb = (altitude_initial_climb - altitude_takeoff) / gradient_initial_climb;
time_fasi(2) = distance_initial_climb / v_phases(2);
altitude_phases(2) = altitude_initial_climb;
range_phases(2) = distance_initial_climb;
```

```
% Climb
altitude_climb = alt_max - altitude_initial_climb;
distance_climb = altitude_climb / gradient_climb;
time_phases(3) = distance_climb / v_phases(3);
altitude_phases(3) = alt_max;
range_phases(3) = distance_climb;

range_cruise = range_tot - sum(range_phases) - (distance_initial_climb + distance_climb + range_phases(5) + range_phases(7));
time_phases(4) = range_cruise / v_cruise;
altitude_phases(4) = alt_max;
range_phases(4) = range_cruise;

% Descent
altitude_descent = alt_max - 500 * 0.3048;
distance_descent = altitude_descent / gradient_climb;
time_phases(5) = distance_descent / v_phases(5);
altitude_phases(5) = 500 * 0.3048;
range_phases(5) = distance_descent;

% Loiter
range_loiter = 0.2 * 1000;              % 200 m
time_phases(6) = 5 * 60;                % 5 min into s
altitude_phases(6) = 500 * 0.3048;
range_phases(6) = range_loiter;

% Approach
altitude_approach = 15 * 0.3048;
distance_approach = (500 * 0.3048 - altitude_approach) / gradient_climb;
time_phases(7) = distance_approach / v_phases(7);
altitude_phases(7) = altitude_approach;
range_phases(7) = distance_approach;

% Landing
time_phases(8) = 1 * 60;
altitude_phases(8) = 0;
range_phases(8) = 0;
```

```
% Profile altitude-time
figure;
plot(cumsum(time_phases) / 60, altitude_phases, '-o', 'LineWidth', 2);
xlabel('Time (min)');
ylabel('Altitudine (m)');
title('Profile Altitudine-Time')

% Profile altitude-range
figure;
hold on;
plot(cumsum(range_phases) / 1000, altitude_phases, '-o', 'LineWidth', 2);
xlabel('Range (km)');
ylabel('Altitude (m)');
title('Profile Altitudine-Range');
```

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8 Sitography

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9 Acknowledgments

I wish to express my deepest gratitude to my family, uncles, cousins, and all relatives, and to my niece Alice, whose constant support has been invaluable.

My sincere thanks go to my mother for her boundless patience, strong support, and "comforting meringues" throughout these years. I am profoundly grateful to my father, who has used every means at his disposal to ensure that I was always in the best possible position to pursue my aspirations, and to my brother for serving as a continuous example of success and determination.

A very special thanks is extended to my grandmother, Ciccina, who, whether over a plate of lasagne or for moments shared with a condor bleu, has always been my number one supporter.

Thanks are also given to the families that I have gained along the way: to Elena, who stuck with me through the tough moments and never left me alone; to my favorite vegetarian friends Alice and Giorgia, for being reliable travel companions over the years and for offering good support; and to Vittoria, whose friendship at Poli and in moments of crisis always gave me a way forward to go.

Gratitude is also due to my colleagues in the professional sphere, especially the “Tipiessini” with whom the often-traumatic entry into the working world was transformed into an enriching and supportive experience; and the “Leonardiani,” who have consistently enriched my skills and recognized my efforts.

A heartfelt thank you goes to Tambo, who shared every moment of this journey with me. Tambo has demonstrated that, with the right company, anything is possible. Throughout these intense and sometimes desperate years of study, Tambo’s presence, filled with love and warmth, has enriched every moment we spent together.

Finally, I want to say a heartfelt thank you for my hard work. Despite many long hours of work and many challenges, I did not make any excuses that stopped progress, and this determination has taken me on a journey that looks forward to a future full of happiness and success.