

CRANFIELD UNIVERSITY

Xiaolong Wu

Performance Evaluation of UAM Configurations
Cost Estimation for the eVTOLs

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
Aerospace Dynamics MSc

This thesis is submitted in partial fulfilment of the requirements for
the degree of Aerospace Dynamics MSc.
Academic Year: 2020 - 2021

Supervisor: Dr. Linghai Lu

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ABSTRACT

With the development and progress of society, the pressure on road traffic is increasing daily, causing enormous time and economic losses to the public. The concept of electric vertical take-off and landing vehicles (eVTOLs) was proposed in order to identify a speedy and effective way of commuting in congested cities. There are many different categories of eVTOLs on the market and many countries and companies are developing it, however the various types of vehicles have different target scenarios and will incur different operating costs. This research project will identify the most suitable configuration of eVTOL in the given scenario, predict its cost and present the lowest cost optimisation solution. The research project started with a reference and evaluation of the similarities and differences between the cost structure of electric general aviation and eVTOL. Top-down, bottom-up and parametric methods were then used to initially determine the cost structure and cost formula. Furthermore, the Lilium five-seater configuration was identified as the target for this project based on the requirements of the specified scenario. Finally, the operating cost per seat-mile, operating cost per hour, annual operating cost and the optimal trajectory schedule were obtained for the specified scenario.

Keywords:

eVTOL, Lilium, Cost Estimate, Optimal Trajectory

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LIST OF ABBREVIATIONS

CNAS	China National Accreditation Service for Conformity Assessment
DOA	Design Organisation Approval
EASA	European Union Aviation Safety Agency
eHelos	Electric Helicopter
eVTOLs	Electric vertical take-off and landing vehicles
FAA	Federal Aviation Administration
FDOC	Fixed direct costs
IOC	Indirect operating costs
ISA	International standard atmosphere
POA	Production Organisation Approval
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
VDOC	Variable direct costs

1 INTRODUCTION

1.1 Background

The road transport system is already overwhelmed by the increasing pressure on urban traffic. Approximately 123 million workers in the US commuted by car themselves in 2017, with around 20 million people commuting for more than 60 minutes and distances of more than 30 miles [1]. This results in a huge waste of resources, both in terms of energy and human resources. To alleviate these series of pressures, the Urban Air Mobility System be produced. Urban Air Mobility is a safe and efficient urban air transport system. The electric vertical take-off and landing vehicles (eVTOLs) is an excellent choice. This technology has emerged as a result of major advances in electric propulsion and the growing demand for new vehicles for urban air taxis.

Air taxis need a fixed apron, like a taxi stand, for picking up passengers, charging and parking. The current mainstream idea for aprons for air taxis is to use the roof of a building or to build an addition to a building. In the future, additional ground infrastructure will need to be constructed for the air urban mobility system. Due to the UAM (Urban Air Mobility) is a system project, it requires not only the aircraft itself, but the ground facilities are also vital. Recently, a large number of companies are currently developing multi-rotor manned drones such as Joby Aviation, Voorlooper, Lilium and Airbus etc. From this aspect it can be argued that the field of air taxis should have a great prospect. Besides, the capital markets have also been highly favourable to the eVTOLs field.

The future of the urban air transportation market is expected to grow by a huge leap, from US\$3.1 billion to US\$15.5 billion from 2023 to 2030 [2]. Then, projects the global urban air mobility market to reach a staggering \$1.5 trillion [3]. This shows that the capital markets are bullish on this sector and the urban air mobility market will be injected with a large amount of capital. In addition, many of the leading companies in the industry have also expressed their vision for a full commercial rollout beyond 2020. For example, EHang has revealed

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that it hopes to commercialise by end of 2020 [4], and it has estimated in its official blog that its five-seat electric vertical take-off and landing vehicle will be available by 2025.

The certification is one of the most important process for launching an eVTOL, the main certification organisations are currently the European Union Aviation Safety Agency (EASA) in Europe and the Federal Aviation Administration (FAA) in the USA. EASA published the special certification conditions for eVTOL aircraft in 2019, and the criteria for test flights. Lilium has received Design Organisation Approval (DOA) and Production Organisation Approval (POA) from EASA. After completing the design and testing of the aircraft, Lilium will be certified according to the special conditions previously mentioned for small VTOL aircraft. Flight safety is always a top priority and therefore EASA's certification requirements are stringent and Lilium must demonstrate that its aircraft will be free from catastrophic accidents during up to one billion hours of flight [5]. Certification requirements for eVTOLs are essentially the same as those for commercial airliners, but these are challenges that must be experienced for eVTOLs to be more reliable in practical applications. According to the latest news, Joby Aviation has reached an agreement on the basis for G1 certification with the FAA in 2021[6]. Although the exact requirements of the agreement have not been made public, it is considered a significant step forward in its target to be operating eVTOL by 2024. Moreover, eVTOLs of EHang passed the China National Accreditation Service for Conformity Assessment (CNAS) UAS fence test, which stated that its eVTOL aircraft were able to automatically identify and accurately sense the fence of system [4].

This project will investigate different brands of vehicles in detail. Firstly, in the eVTOLs industry, electricity consumption will be the main consumable, which determines part of the usage costs, just like fuel consumption of vehicles. Secondly, the depreciation costs of eVTOLs aircraft, the depreciation costs of batteries, pilot salaries and a range of costs unique to eVTOLs such as the construction of infrastructure, network operations and management will all be included. However, companies in the market are currently in the validation

1.Introduction

phase and do not give detailed performance data or the data given does not materialise and this study requires validation. Furthermore, the research scenario for this research project is for an operating company to complete a defined transport task within a specified scenario with a start-up capital of 50 million dollars. Therefore, a detailed and relatively accurate cost estimate is required, which will result in an annual operating cost, an operating cost per hour and a cost per seat-mile.

1.2 Aims and objectives

1.2.1 Aims

1. To determine which configurations of eVTOLs can perform the flight tasks in the specified scenarios.
2. To identify the cost structure of these configurations and their approximate costs.
3. To establish the lowest cost configuration and determine the specific cost of the best configuration.
4. To develop an optimal trajectory plan and calculate its annual operating costs and operating costs per seat-mile.

1.2.2 Objectives

The objective of this project is to develop a business model for the operation of eVTOLs that analyses in detail the costs of operating a company with regard to various aspects. This is achieved by firstly breaking down the cost structure into its various components and then calculating the results in summary. As no previous research has been carried out in this area, this analysis seems essential to inform the actual operation of eVTOLs

2 LITERATURE REVIEW

2.1 Classification of eVTOLs

There is a growing number of eVTOL companies on the market, with approximately 200 electric airlines receiving over \$1 billion in support since 2018 [7]. Therefore, how to choose the right configuration of eVTOL needs to be discussed. Firstly, the eVTOL can be classified according to the following characteristics: Vectored Thrust, Lift plus Cruise, Wingless, Hoverbikes and eHelos [8] as figure.2-1 shown below.

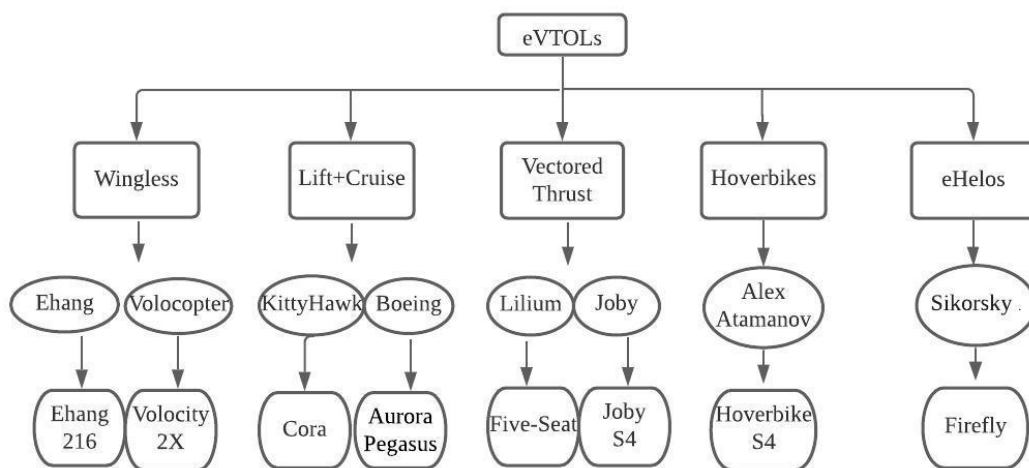


Figure 2-1 Classification of eVTOLs

Different configurations vary in performance and the appropriate choice is determined by the actual situation. Firstly, the vector thrust configuration has the characteristics of speed and long range, making it more capable of handling the transport of people over longer distances such as between cities. However, it has high power requirements for hovering, and requires extremely high-performance batteries to power it, which is not yet possible with current battery technology. There are currently Lilium and Joby on the market that specialise in this configuration. These two companies are using this configuration in order to

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advance inter-city transport, which will be widely adopted with the development of technologies such as batteries.



Figure 2-2 Vector thrust: Lilium 5 seats [5]; Joby S4[6]

Secondly, Lift+Cruise configured eVTOLs use the lift engine only when hovering, and a separate engine when cruising. It is two separate systems. The lift engine is a vertically mounted jet engine that can generate high thrust during the short take-off and landing periods. The Lift+Cruise configuration with wings and engines will introduce significant parasitic drag in the cruise phase. It will affect the speed and range of the cruise, which is lower but requires more energy than the vectoring thrust configuration. Kitty Hawk and Aurora used to launch this configuration of eVTOLs known as Cora and Pegasus. This configuration favours the efficiency of the vertical take-off and landing phase over the efficiency of the cruise, thus setting its target for medium range transport.

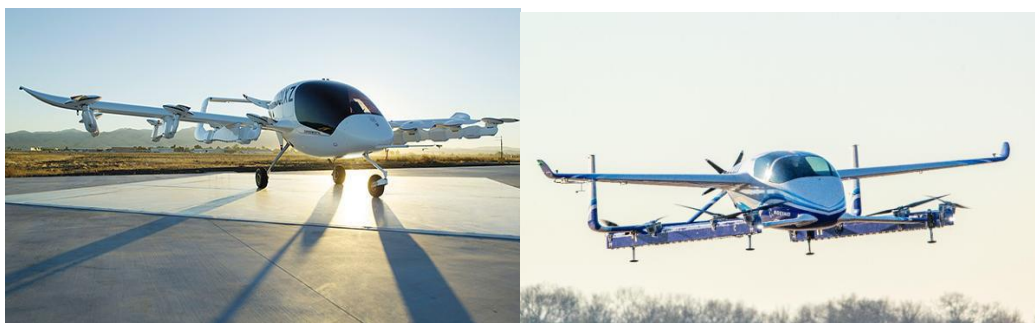


Figure 2-3 Lift plus Cruise: Kitty Hawk Cora [7] and Aurora Pegasus [7]

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Then, the Wingless configuration, also known as multi-rotor eVTOLs, requires very little energy to perform short range missions, and current technology is primed to achieve this. However, due to its very low cruising efficiency, it is not capable of flying longer distances. The Wingless configurations from EHang and Volocopter are the two companies that currently stand out in the market. These two companies are likely to be marketed as intra-city transport, solving internal traffic congestion, and sharing some of the pressure of road traffic, and will not be able to handle longer flights such as the project in this research.



Figure 2-4 Wingless eVTOLs: EHang 216[4]; VoloCity 2X [7]

Furthermore, the Hoverbike is more of a leisure or personal configuration that needs more development in terms of safety and validation. eHelos simply appear to be an electric helicopter, it is not a disruptive change, just a change in fuel choice and therefore not considered for this project.

2.2 Research Scenario

The study scenario for this project is from London Heathrow Terminal 5 to Coventry, which is a drive of around 160km with a linear distance of around 120km. With Heathrow ranking first in Europe and seventh in the world in terms of total passenger traffic, a station at the airport would bring convenience to a significant number of people [9]. Secondly, Coventry will be the first eVTOLs airport in the world due to its unique location and surrounding advantages, and

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this is a partnership between the Hyundai Group and the UK government, which is highly representative [10].

According to the National Express [11], there will be four bus trips per day between the two locations. With an occupancy rate of 80%, approximately 200 passengers will travel on this route each day. Then, with the proximity of Coventry to Birmingham, the second largest city in the UK and radiation to many cities such as Northampton, Leicester and Nottingham, more passengers will have a new option. Moreover, as there is no detailed data on how many people drive from these cities to Heathrow Airport daily. An assumption is made here that 2000 people per day travel between the two destinations. Initial estimates suggest that around 1000 passengers a day will be potential users of this scenario, due to its higher cost.

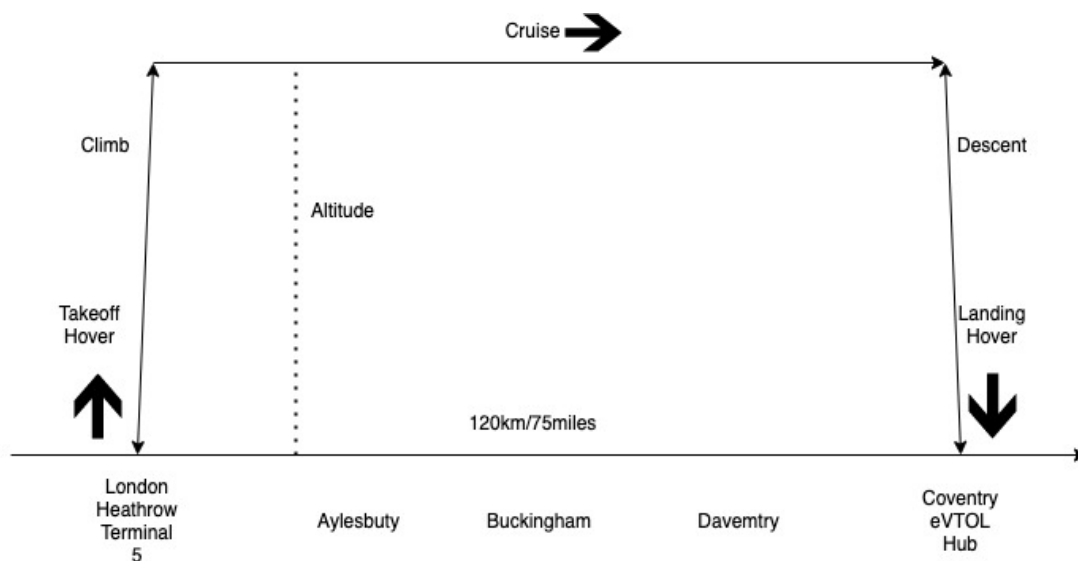


Figure 2-5 Flight Mission Profile

2.3 Factors of Influence

Firstly, the performance comparison of the three previously mentioned configurations will be presented. Table 2-1 illustrates the comparison of the parameters of the six products.

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Table 2-1 Comparison different eVTOL configurations

Products Factors	Lilium	Joby	Kitty Hawk	Aurora	EHang	Volocopter
Capacity	5	5	2	2	2	2
Wingspan	11m	10.7m	11m	8.5m	4.3m	11.3m
Range	300km	241km	100km	80km	35km	35km
Max Speed	300km/h	332km/h	180km/h	180km/h	130km/h	110km/h
Number of Rotors	36	6	12	8	8	18

Table 2-1 reveals that only the Lilium and Joby configurations have a cruising range of more than 100km, enabling them to fly longer distances. These two configurations also have a cruising speed of over 200km/h, which increases the efficiency of long-range transport. In the specified scenario, Due to the impact of these characteristics on cost estimates, the metric for the importance of each factor will be shown in Table 2-2.

Firstly, cruising range is the most important item, as charging or changing mid-transit will not only affect the passenger experience but will also significantly increase operating costs. Secondly, carrying capacity would be a direct measure to reduce the eVTOL's per seat-mile, making it significantly cheaper to ride and more accommodating for multiple passengers. Then, maintenance costs and direct operating costs (i.e., power consumption costs) are then also closely linked to the operations of the operating companies. Moreover, the cruise speed enhances transport efficiency and allows the UAM to operate more round trips, thus serving more passengers. The dimensions of the UAM were considered because of its docking and storage issues, which would be

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linked to the construction of ground infrastructure and could entail additional costs if the aircraft is too large.

Table 2-2 Signification of Factors for this project

Factors	Importance
Range	10
Capacity	8
Manufacturing Costs	7
Direction Operating Costs	7
Cruise speed	6
Max dimensions	6

The metric for this project considers the impact of each factor of eVTOLs on the operating company in the given scenario, from 0 to 10, in increasing order of importance.

However, the actual scenario under consideration has 120 km and only the two products with vector thrust are capable of this task. The operating company has £50 million to develop this project and expects to complete the transport of 50% of potential users, which would require the transport of 1000 person-time per day and approximately 125 round trips. A one-way trip can be managed in about 30 minutes, a round trip means 60 minutes, with an additional adjustment overhaul of about 30 minutes, so a round trip flight takes one and half hours. According to Goel and Holden [12], eVTOL vehicle operates for approximately 2080 hours a year, meaning approximately six hours of operation per day. As approximately 125 round trips are required, each eVTOL consumes 10 hours per day carrying out five round trips, the operating company needs to procure 25 eVTOL vehicles for its daily work. Furthermore, it cannot be ruled out that

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the vehicles will not be operational at certain times of the day, hence the need for an additional 5 vehicles as a back-up option.

Taking these important factors into account, the Lilium five-seater and Joby S4 configurations are initially capable of flying in the given scenario their performance and direct operating costs (assumption of power consumption) will be further investigated.

Table 2-3 Performances of Two Products for this Project

Factors	Lilium	Joby
Range	300 km	241km
Capacity	5	5
Manufacturing cost	1.28M dollars [5]	1.3M dollars [6]
Cruise Speed	300km/h	332km/h
Max dimensions	11m	10.7m

3 IDENTIFY THE PRODUCT FOR THIS PROJECT

This research paper uses a parametric approach and refers to models of general aviation operating costs for the Lilium 5-seater and Joby S4 eVTOLs for cost analysis. When modelling operating costs, the cost of each factor needs to be calculated and ultimately combined into a total operating cost. Therefore, the model requires a detailed design that considers all the costs that the operating company will face afterwards. The difficulty in modelling this is that there are no similar eVTOL operators on the market before, so a part of the operating costs needs to be constructed with reference to general aviation costs, particularly for hybrid general aviation. Secondly, a reasonable range of costs was adopted, combining some past cost data such as pilot wages, local electricity costs etc. Moreover, it is essential to accurately identify the differences between the eVTOL industry and general aviation, and to rely on a suitable baseline for the evaluation and calculation of cost data. Finally, as eVTOL is a new industry, it is inevitable that it will encounter new challenges and it is important to estimate the operational costs that may arise from these new challenges.

3.1 Cost Estimation Methods of General Aviation

Civil aviation, which refers to the utilization of aircraft for aviation activities besides national aviation activities such as defence, police and customs, is also the most easily accessible daily. Civil aviation derived from the aviation economy should be the transport industry, civil aviation security industry, aviation manufacturing, aviation services, air tourism, general aviation industry, space industry and other industries and industries after the collection and integration and generate new derived income effect of economic business and state [13]. In particular, both airline and general aviation cost estimates are informative for the UAM industry. The costs of an airline can be divided into two main components: The costs of airlines can be divided into two main components: objective costs and functional costs. Objective costs can be subdivided into salaries and related fringe benefits, materials. Functional costs

3. Identity the product for this project

can be further divided into aircraft operating costs, aircraft service costs, transportation service costs, passenger service costs, maintenance and sales costs, and other costs [14]. However, the cost reference value is extremely limited since the aircraft used by the airlines are relatively large and fly long distances, which differs significantly from the actual UAM. The aircraft used by general aviation are typically 20 seats or less and the distances can be customised to be more like the eVTOL industry. The next section details the approach to cost estimation for general aviation, allowing it to serve as a preliminary model for cost estimation for eVTOL. The general aviation approach to cost projections would be a relevant reference as no eVTOL companies have operated in the market, making it impractical to access existing cost forecasting models.

There are roughly three approaches to cost estimation in the aviation sector: top-down, bottom-up and analogous cost estimation approach [15]. Firstly, the top-down budgeting method is based on the judgement of managers and the experience and data from previous similar situations. These cost estimates are then passed on to lower-level managers who continue to break down the budget to estimate budgets for each of the tasks and work packages that make up the sub-projects. This process continues until it reaches the bottom of the hierarchy. The advantage of this approach is that operating costs can be planned in an integrated manner, it allows for comprehensive planning of operating costs and has the potential to produce reasonable approximations in a relatively short period of time. However, the difficulty in implementing this technique is that it requires an appropriate baseline and detailed data [16]. Individual factors can lead to large deviations and some aspects are not easily considered for new industries.

Secondly, the bottom-up approach to cost estimation works by prioritising details at the base level, with the costs of individual activities or tasks being estimated at the detail level and then aggregated through the levels to higher levels to ultimately determine the overall cost budget. This approach requires managers to understand the process [15]. The bottom-up approach is an

3.Identity the product for this project

information-intensive approach as it generates cost estimates from the bottom [16]. Therefore, a detailed design is required, so it is generally applied after the production phase because the design is already fixed. This method aggregates the costs of each new factor to achieve a relatively complete and accurate overall cost estimation.

Furthermore, a statistical method known as the parametric method, is used as the basis for the current project by using a sample of similar previous projects with reference to their scope, cost, budget and other measures of value or size and complexity [17]. It has the advantage of being easy to implement, as it does not rely on physical knowledge and requires only basic input variables. However, this approach is difficult to develop as very precise past model details are required for the cost model itself and technical changes cannot be reflected [15].

For the cost predictions of hybrid general aviation, it is based on a top-down approach [18]. Since the hybrid general aviation cost budget model is built on the cost model of general aviation The costs are broken down from top to bottom based on the previous experience of managers. As there is little difference between the two, this model gives a more accurate forecast for hybrid general aviation. The total operating costs of general aviation can be roughly divided into three components: variable direct operating costs (VDOC), which include energy costs, operator costs, landing fees and maintenance costs; fixed direct operating costs (FDOC), such as aircraft depreciation costs, insurance costs, periodic inspections, and parking costs; and finally indirect operating costs (IOC), which are mainly related to capital expenditure, sales, general and administrative costs [18]. To gain a comparative closer result, hybrid general aviation was chosen as a reference for this research. The following table details the calculation model for each factor.

3. Identity the product for this project

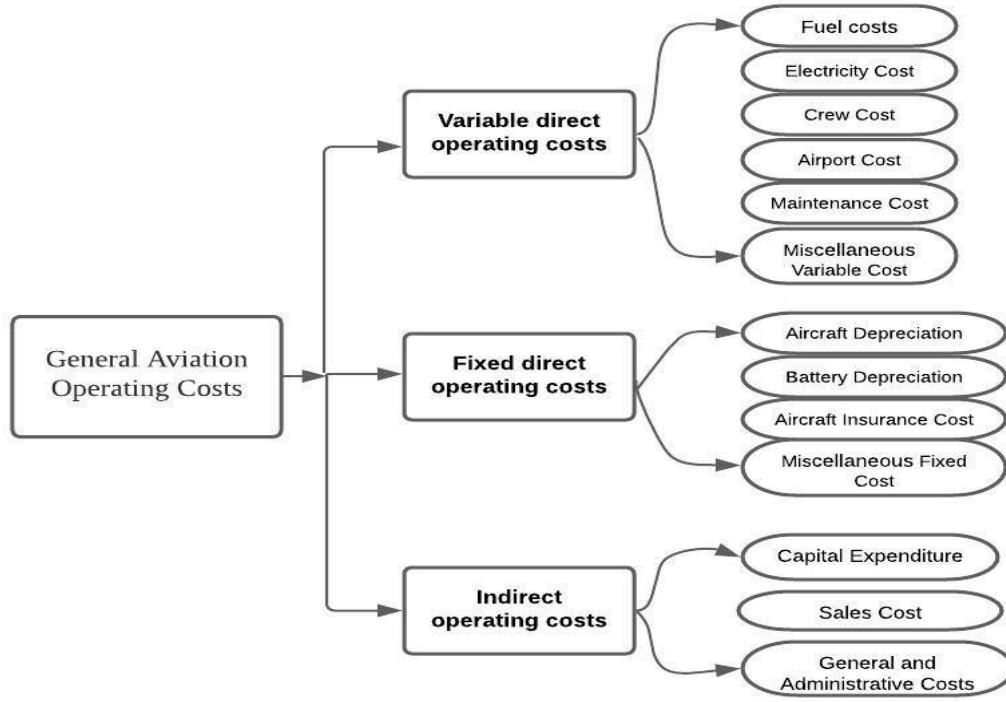


Figure 3-1 Components of Hybrid General Aviation Operating Costs

3.1.1 Variable direct operating costs (VDOC):

Fuel costs (C_{FUEL}) are determined by the price of fuel (τ_{Fuel}) and the quantity used (m_{Fuel}). Fuel prices for general aviation depend on pricing in different regions and have a direct impact on general aviation operating costs.

$$C_{Fuel} = \tau_{Fuel} \times m_{Fuel} \quad (3-1)$$

The cost of electrical energy (C_E) for hybrid general aviation is determined by the local price of electricity (τ_E) and the amount of electrical energy consumed for each flight (E_{flight}). Besides, the charging efficiency has to be considered and an average value of 87% (η_{charge}) will be taken as a condition for estimation in this case [19].

$$C_E = \tau_E \times E_{Flight} / \eta_{charge} \quad (3-2)$$

3. Identity the product for this project

The cost of the crew (C_{CREW}) depends on their hourly rate (R_{Crew}) (approximately £42 per hour), the number of personnel (N_{Crew}) and the number of hours of flying (t_{flight}). Due to the additional waiting time that will be incurred when the aircraft is in operation, costs are generally estimated using 1.5 times the actual flight time.

$$C_{CREW} = R_{Crew} \times N_{Crew} \times 1.5 \times t_{flight} \quad (3-3)$$

Besides, according to the North Central Texas Council of Governments [20], general aviation pilot salaries range from £39k to £76k a year, depending on the experience and ability of the pilot.

Airport take-off and landing costs ($C_{AIRPORT}$) are classified according to noise decibels, if the noise is greater than category A, F_{Noise} will be 1.45 and less than that will be 1. The maximum take-off weight (m_{MTO}) and number of landings ($N_{Landing}$) of a general aviation aircraft will also be considered in this part of the cost.

$$C_{AIRPORT} = 0.01 \times (m_{MTO} - 1100lb) \times F_{Noise} \times N_{Landing} \quad (3-4)$$

The cost of maintenance (C_{MAINT}) is more variable and the value of F_{MF} is determined by the actual aircraft type. It represents the ratio of flight time (t_{flight}) to maintenance time and this ratio takes values ranging from 0.2 to 0.35 depending on the aircraft type. In addition, aircraft mechanics are paid approximately (R_{AP}) £42 per hour.

$$C_{MAINT} = R_{AP} \times F_{MF} \times t_{flight} \quad (3-5)$$

Besides, the ground handling and navigation costs may apply as miscellaneous cost.

3. Identity the product for this project

3.1.2 Fixed direct operating costs (FDOC)

Aircraft are essential as fixed assets and incur a certain amount of depreciation costs. Aircraft depreciation costs (C_{ACD}) are expressed as a linear relationship between the total cost of the aircraft (τ_{AC}) and the number of flights (n_{flight}).

$$C_{ACD} = \tau_{AC} / n_{flight} \quad (3-6)$$

Hybrid aircraft must consider the depreciation costs of the batteries (C_{BATD}), which is a complex estimation process. Firstly, the cost of the battery (C_{BAT}) needs to be considered and secondly at the current level of battery technology, it can be assumed to have 1,000 loop cycles (n_{cycles}) and an end-of-life ($E_{BAT, end - of - life}$) value of 80% or less. If the battery needed to be charged once a day, it would be replaced within three years, a frequency much higher than the depreciation rate of the aircraft itself.

$$C_{BATD} = C_{BAT} \times \frac{E_{flight}}{n_{cycles} \times E_{BAT} \times \left(1 - \left(\frac{1 - \left(\frac{E_{BAT, end - of - life}}{E_{BAT, nominal}} \right)}{2} \right) \right)} \quad (3-7)$$

The cost of insurance (C_{INS}) is essentially the same as the cost model for a conventional aircraft. However, its actual price will vary depending on the actual condition of each aircraft, such as the experience of the pilot and cost of aircraft (τ_{AC}). The formulae presented here are intended only as a general reference.

$$C_{INS} = 500 + 0.015\tau_{AC} \quad (3-8)$$

Furthermore, there are some fixed miscellaneous expenses, such as storage and inspection fees at the airport, its approximately £2500 per year.

3. Identity the product for this project

3.1.3 Indirect operating costs (IOC)

It mainly related to capital expenditure, sales, general and administrative costs. The specific costs can be partially referred to some processes of civil aviation. Civil aviation booking and sales costs account for 14% of total costs, with general and administrative expenses at roughly 6% [14].

3.1.4 Feasibility of a general aviation cost forecasting methodology

Table 3-1 Feasibility of general aviation cost factors

General Aviation	Adoption of UAM
VDOC	
Fuel Costs	⊗
Electricity Costs	✓
Crew Cost	⊗
Airport Cost	⊗
Maintenance Cost	?
Miscellaneous Variable Cost	?
FDOC	
Aircraft Depreciation	✓
Battery Depreciation	✓
Aircraft insurance Cost	?

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Miscellaneous Fixed Cost	⊗
IOC	
Capital Expenditure	⊗
Sales and Reservation	?
General and Administrative Costs	✓

The ⊗ indicates no adoption, ? means partially adopted and requires further discussion, ✓ denotes adoption.

The UAM is powered entirely by electricity, thus there is no need to calculate fuel costs. Airport costs are measured in terms of aircraft weight and noise levels. eVTOLs do not share airports with civil aviation or general aviation, its ground infrastructure is outside the traditional aviation industry and therefore requires a separate cost estimation methodology. Meanwhile, this part also applies to the methodology for forecasting miscellaneous fixed costs. Next, general aviation may also have long-range flights with some crew for it. The eVTOLs require only one pilot to operate and the requirements of that pilot differ slightly from those of general aviation, hence the general aviation crew cost estimation methodology is not applicable to the eVTOL industry. Then, general aviation capital expenditure is closely related to loans, and the eVTOLs aircraft that were purchased with sufficient funds for this project do not require consideration of this component.

Firstly, the structure of maintenance costs for general aviation can be used in eVTOLs, but the ratio of flight time to maintenance time may differ and the cost of maintenance personnel may also vary slightly. Secondly, the miscellaneous variable cost items are ground handling and navigation costs, which are also essential in the operation of eVTOLs but can vary significantly depending on the size of the aircraft and altitude flown. Next, the methodology for estimating the

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cost of insurance for general aviation can be fully referenced and an additional component will need to be added to it. Because eVTOLs is a totally new industry, its operations are heavily influenced by weather and its passengers are relatively untrained, additional consideration needs to be given to this part of the insurance. Furthermore, the cost of the sales and reservation component can be partly referenced, as eVTOLs passenger is more widely accessible and requires more ability to interact with customers.

Cost estimates for electrical energy, aircraft depreciation, battery depreciation and general and administrative costs for general aviation can be applied to the UAM industry, and there are essentially no differences between the two, and the general aviation approach can be used as a suitable reference.

3.2 Factors specific to eVTOLs cost estimation

As eVTOLs are a completely new industry, the cost estimates will not involve the usual considerations as any previous industry, and its innovative nature causes greater difficulty in cost estimates, the overall structure is presented in Figure 7. However, for the current part of this project, it is only necessary to first present a model of the operating costs of the eVTOL aircraft.

When establishing the methodology for cost estimation of eVTOLs, the previously mentioned the parametric approach was applied, using the Hybrid General Aviation methodology for reference, and in addition, a bottom-up budgeting approach was utilised. This is because the details need to be aggregated from the bottom up in order to fully consider the various costs involved in operating eVTOL. Since there are still some differences between the hybrid general aviation and eVTOL industries, new issues and factors arising from them need to be discussed in detail and separately. For instance, eVTOL is purely electrically powered and consumes only electrical energy; secondly, it is a vertical take-off and landing method that does not require a large airport in the traditional sense, and some buildings, or small infrastructures, would make it easier to integrate eVTOL into the city; furthermore, it has a much wider target

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population, and the operational sales and public acceptance of eVTOL companies need to be examined in detail.

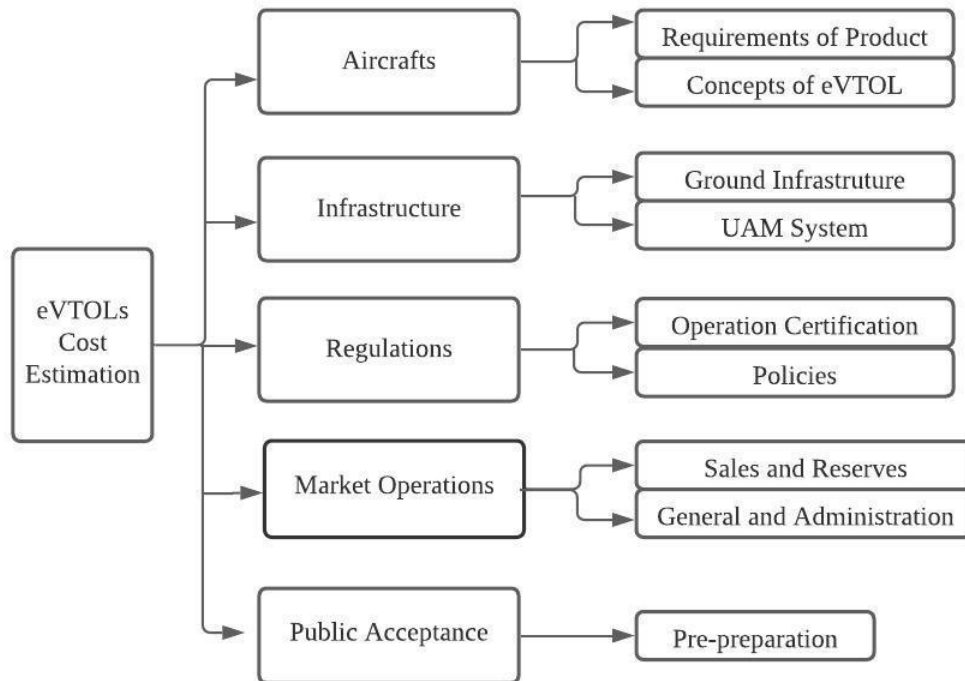


Figure 3-2 Important Fields of eVTOLs Cost Estimation

3.2.1 Aircrafts

Based on the analysis in Chapter Two, two products (Lilium 5-seat and Joby S4) have been obtained that can be applied to this scenario. Currently there is a requirement to focus on the potential cost changes associated with the differences between these two products. It is important to reflect on which factors will contribute to how much difference the cost estimate will cause. Therefore, a further cost analysis is desired based on the specified scenario and the choice of two products. As previously mentioned, in the case where the purchase cost of both products is approximately the similar. Maintenance costs and direct aircraft operating costs will be the main factors affecting operating companies. Vector thrust uses the same propulsion system for both hovering and cruising [5]. Besides, the Joby S4 can be subdivided into a tilting thrust way

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and the Lilium into a tilting duct approach. For the Lilium, it reduces maintenance costs by removing all unneeded devices in order to keep things simple and reduce price and failure rates. The Lilium eliminates folding or tilting propellers, tail fins, rudders, gearboxes, and water-cooling systems etc. [5]. The Joby has a tilting propeller and is equipped with a tail and rudder. However, maintenance costs are currently difficult to predict and the actual failure rate of the tilting propeller and tilting duct configuration, as well as the price of maintenance, will need to be proven in the marketplace. Secondly, the direct aircraft operating costs will need to be obtained from the power assumption results in subsequent chapters and given that there will still be some discrepancies between the power consume results and the actual results, it is inevitable that the accuracy of this part of the cost estimate will need to be verified.

3.2.2 Infrastructure

Goel and Holden [12] state that if it needs to operate eVTOL in a city, it needs to fully understand the local needs and facilities on offer so that it can adapt. Investigate what new infrastructure needs to be built in that location or how existing facilities can be utilised. Based on this article's analysis from an operator's perspective, operators need to communicate and engage well with all levels of government and communities. Many issues will appear in the discussion about how eVTOL fits into the local area. The cost of using existing facilities, the cost of building new stations, and the choice of station scales will affect the cost of building infrastructure and flight routes and thus the cost of change to some extent. Goel and Holden mention the use of different stations (like the current public transport termini and sub-stations) to rationalise the traffic layout and thus increase efficiency. There is no experience regarding the installation of UAM stations before, hence this is a challenge for the industry. There is currently some debate that if a suitable station is chosen from the supply side perspective, they will require that closed airspace is removed from consideration. If the choice is made on both the supply and demand side, needs

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such as population density, job density, per capital income and the combination of ground transportation all need to be considered [12]. The final solution will require further investigation and research. For operators, it is important to consider not only from a professional point of view, but also the cost of building stations in different areas and the efficiency of commuting.

It is satisfying that the UK government is now funding the development of an eVTOL airport, for air taxis using in Coventry [10]. This is a pop-up airport known as Air-One and its biggest advantage is its convenience. With a diameter of just 14 meters, this pop-up airfield is sixty percent smaller than a conventional heliport, takes only a few days to install and achieves zero carbon emissions. The study addresses the issue that there may not be enough eVTOL sites in the city and makes an important contribution to the efficiency of urban air transport system. This provides more possibilities for infrastructure siting, with reduced space requirements and almost omitted construction periods, which will significantly reduce costs for operators. The exact funding required for this new airport project needs to be further validated. However, it is believed that as demand increases and the industry matures, the cost of this segment will become less.

The infrastructure does not only consist in the construction on the ground, but also in the traffic management for the eVTOLs. The current air traffic management system may not be up to the task as it considers the huge growth that the eVTOLs market will see. Urban air traffic systems need to be fully integrated and need to meet many basic principles, such as not requiring additional air traffic system infrastructure, not affecting the use of traditional airspace users, and meeting high standards of safety thresholds, among others [4]. A new air traffic management system could be improved based on previous ATC (air traffic control) systems, continuously updated, and integrated as the density of air traffic increases, and from where a complete system is formed. In particular, the new ATM system will require the use of the 5G network, where EHang states in its white paper that the interoperability of the UAM and the

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capabilities of the control platform will be significantly enhanced [4]. A new ATC system may require a large upfront capital investment, however the convenience it delivers is also significant. This part of the cost may also need to be taken into account by the operator. The specific cost required is unknown and therefore poses some difficulties for operators to budgets for costs.

3.2.3 Regulations

This is not just for eVTOLs operating companies but is a requirement for the development of the industry. Firstly, it is vital that pilots are trained. Even though flying an eVTOL may be less difficult than a general aviation aircraft, it has special characteristics that make it necessary for pilots to have additional knowledge and skills. Secondly, the take-off and landing areas should also follow certain regulations and not affect the existing traffic system as much as possible. Next, a comprehensive database of maps and terrain should be established. Due to the low altitude, pilots need technological means to get a better view. Furthermore, there should be some provisions for passengers to travel with eVTOLs to ensure flight safety. Lastly, the operating company must also be proven to be capable of running eVTOL trips, both technically and in terms of staff operations.

Externally to the eVTOLs industry, if it grows to a certain size, it will create scheduling difficulties or congestion. In addition, it generates additional effects, such as land or housing around the site will become progressively scarce. This will require a third party to regulate it [12]. Compared to the traditional taxi industry, its regulatory system is the granting of operating permits, thus controlling the quality and quantity of its services. The method of regulation for private cars is generally divided into setting fees for congested areas during peak hours (e.g., London Congestion Fee) or restricting some vehicles from driving in (e.g., License plate number restrictions in China). However, the eVTOLs sector has more security and greater influence, and requires a unique

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approach to regulation that considers previous approaches as well as innovations.

3.2.4 Market Operation

In market operations, an operating company plays the role of service provider, but in this project is also the owner of the eVTOLs. The operating company provides UAM transport services to passengers, which it does by scheduling trips and managing the fleet. Depending on the situation of the operating company, customer interaction terminals such as mobile applications, computer web pages etc. can be set up independently. Another way is to completely host the service to an external platform, with the operating company handing over directly to the external platform. However, in the current market it seems that more of the transport industry has its own interactive platform and takes some cooperation with external platforms. For example, passengers can go to the official airline website to book tickets or use a ticketing agency to make purchases. Based on experience, civil aviation companies typically spend 14% of their overall costs on reservations and sales.

Next, many of these cost aspects need to be factored into the operation of the market. Will maintenance, repairs and overhauls need to be outsourced to specialist companies, and as UAMs face high safety standards, specialist maintenance companies will be exposed to high certification standards and must ensure a high level of quality. This will be a challenge for the smaller operating companies in the initial stages. Secondly, the operating company will require a specific agreement with the insurer, which is only available to the eVTOLs industry. Such insurance would need to cover aircraft breakdowns, weather stoppages and losses due to passenger misconduct [3]. Moreover, there are costs associated with the use of infrastructure. The situation in this project is relatively straightforward, requiring the establishment of infrastructure services for only two stations, which can be communicated in detail to public organisations or infrastructure companies.

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At present, there is no practical experience in the relevant field and a great deal of research and investigation is needed to ensure that reliable partners are found. After this, the operating company will need to consider supply and demand and the actual transport situation in order to build and improve the business model.

3.2.5 Public Acceptance

Whether the eVTOLs industry will be accepted by the market is a consistently discussed topic. Due to its extremely innovative nature, the public will hold a certain wait-and-see attitude towards the unknown. Studies have shown [21] that the less impact eVTOLs have on non-users, the higher the acceptance of public. They are mainly concerned with issues such as safety, privacy, job security, environmental threats, and noise and visual disruption [21]. Safety will bear the brunt of the problem: some eVTOLs aircraft are flown by a single pilot, while a small number are configured for fully automatic piloting.

The Autonomous Aerial Vehicle (AAV) is represented by the configuration EHang 216, which was designed with safety, intelligence, central platform-based manoeuvring, and online interconnection. Although it has made over 2,000 successful manned and unmanned flights [4], it still takes some courage for the public to attempt it. The attitude of the public towards this technology can be found in unmanned vehicles. In the current data-driven society of today the security risks of autonomous vehicles and the protection of passenger privacy are increasingly being considered by the public. The type, security, and use of data stored in autonomous vehicles can be a concern, for example: whether autonomous cars are able to block hacking attacks and thus safeguard user privacy [8]. Furthermore, autonomous driving accidents are commonplace around the world, this will increase suspicion of the technology. For a new type of public participation in the transport sector, it is important to start with the most fundamental, most secure perspective. In the future, when autopilot and UAM

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technologies are more mature and stable, it is more likely that pilots will be replaced, but for now the role of pilot is significant.

There are several strategies that can be adopted for increasing public acceptance:

1. The operating company can offer a pilot project first, put it within the public view and prove its safety through real-life examples, thus alleviating consumer concerns to some extent.
2. Conduct a large-scale pilot experiment under the influence of local authorities, on the one hand, it enables eVTOLs companies to identify shortcomings or areas for improvement in practice. On the other hand, it will allow the public to become more familiar with this new mode of transport and to develop the same attitude towards it as they do in the traditional transport sector.
3. Local government authorities can cooperate with the aviation regulatory system to establish regulations to control flight areas, times, and altitudes, thus reducing noise and visual impact.
4. Where conditions permit, government departments, such as the police, fire brigade or army, can be served first, leaving the public with no worries.
5. Based on the above strategies, it should be promoted through various media, which should make a greater contribution to increasing public acceptance.

3.3 All Factors of eVTOLs Need to Consider

The methodology used for the eVTOLs cost budget is a combination of the three methods previously used. Top-down, bottom-up and parametric methods. By combining the cost factors affecting hybrid general aviation and eVTOLs, a complete cost items structure for the operation of eVTOLs was established, with its significance.

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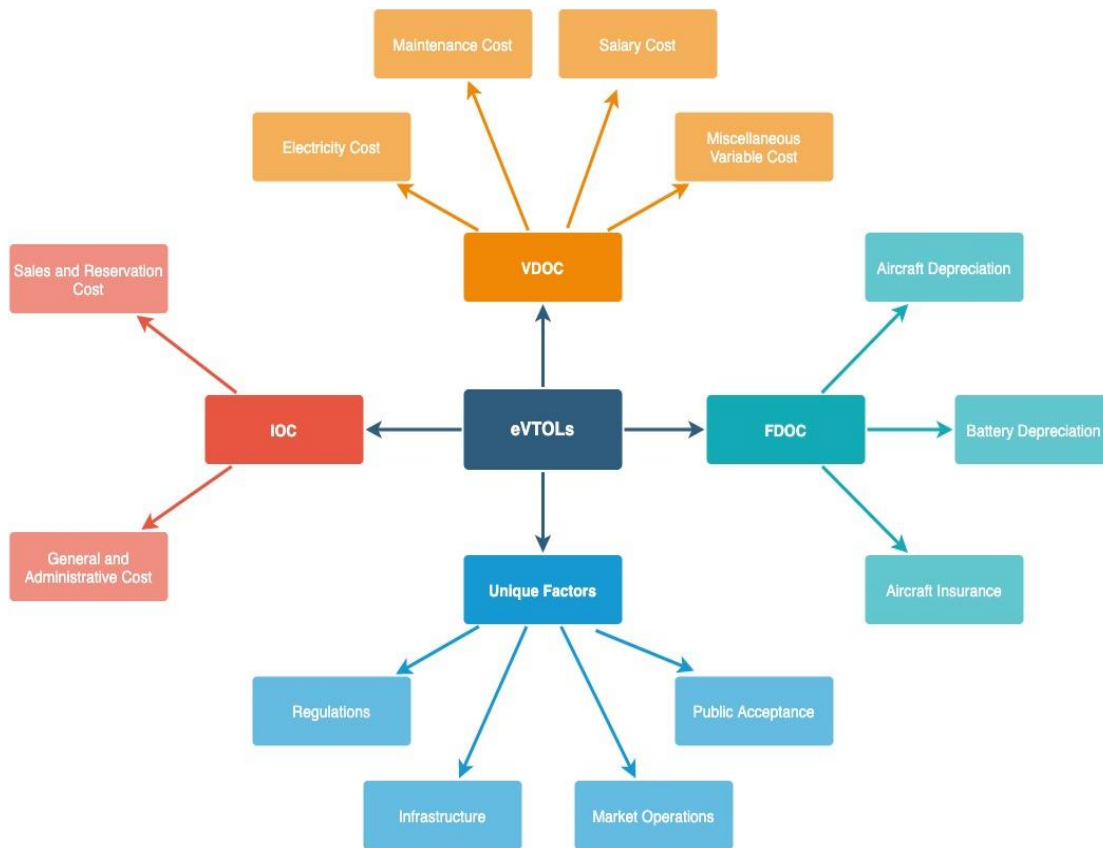


Figure 3-3 Cost Estimation Factors of eVTOLs

The two selected products, the Lilium five-seat and the Joby S4 eVTOLs, will predict their respective cost requirements based on the following factors in order to find the optimal (lowest cost) choice. Table 5 will also indicate the importance of each factor, i.e., the extent to which it affects costs.

Table 3-2 Significance of each Factor about eVTOLs Operation Cost Estimation

Factors	Significance
Electricity Cost	6
Maintenance Cost	7
Pilot Salary Cost	8

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Miscellaneous Variable Cost	6
Aircraft Depreciation	8
Battery Depreciation	7
Aircraft Insurance	5
Sales and Reservation	6
General and Administrative Cost	6
Infrastructure	9
Regulation	9
Market Operation	8
Public Acceptance	8

The metric for this project considers the impact of each factor of eVTOLs on the operating company in the given scenario, from 0 to 10, in increasing order of importance.

3.4 Operation Cost Estimation of Lilium Five-Seat

Firstly, according to the previous Chapter Two, approximately thirty round trips per day are required to operate in the project scenario to cater for 1000 person-time per day. Thus, 30 Lilium five-seater and Joby S4 eVTOL vehicles will cost \$38.4M and \$39M to procure. The fixed direct operation costs of Lilium and Joby eVTOL will be directly calculated.

3.4.1 Fixed Direct Operation Cost

Aircraft Depreciation: The brushless DC motor used in the eVTOLs was expected to last around 60% of its design life [22], a factor that considers the new and harsh environment of air transport in cities. Assuming a motor life of 10,000 flight hours, around 6,000 hours can be used as a reference for now. With daily flights of five round trips per day and 1,825 hours of actual flight time

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per year, the eVTOL vehicle will be available for approximately 3 years. The total flight time is 5,475 hours, and the number of flights is 10,950, based on a flight duration of 30 minutes. This part will not be significantly different for Lilium and Joby as both have a maximum speed of around 300km/h, the Joby S4 is around 10% faster in terms of maximum speed, will only be 1-3 minutes faster than Lilium for the purposes of the research project, therefore the cost of this part can be seen as the same. The formula gives a cost per flight of US\$116.89 for Lilium, and \$118.72 for Joby.

Battery Depreciation: The battery life was assumed to be 1,000 cycles for hybrid general aviation; however, battery life is assumed to be 2,000 cycles based on the same cells used in the Tesla battery pack, namely Panasonic NCR18650B [23], end-of-life value of 80%. If the battery is required charged five times a day, it will be replaced within one years, the number of flights in a year is 3,650 times. Moreover, the cost of the battery is between \$12,000 and \$15,000, with an average of \$13,500 shown, at least two sets of batteries are required to compose the battery pack, at twice the price. As Goel and Holden [12] implicit in the range requirement is the need to retain at least 20% charge in the battery after a transport mission to ensure a high cycle life. 241km cruise range for the Joby S4 and 240km round trip range required in the research project may require the Joby product to be recharged after a single transport. This will increase the depletion of the battery and accelerate the rate of battery replacement in two times faster. Thus, the formula gives a cost of \$7.39 per flight for the Lilium battery replacement and \$14.7 for the Joby S4.

Aircraft Insurance Cost: Based on equation 8, the cost of insurance per flight is \$13.50. Due to the slight disagreement raised earlier, the safety factor for eVTOL may be higher and the factor of 0.015 in the formula may face a decrease of some magnitude. In addition, referring to the data of the Scott and Vegh [18], the cost of insurance is currently about 13 US dollars an hour in the initial phase of eVTOL, i.e., the cost of insurance per flight can be seen as 10 dollars. The flight duration for both eVTOLs is kept to around 30 minutes, therefore the cost of insurance can be considered the same.

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Table 3-3 Fixed Direct Operation Costs of Two Products

Fixed Direct Operation Costs	Cost of Lilium Per seat-mile in Dollar	Cost of Joby Per seat-mile in Dollar
Aircraft Depreciation $C_{ACD} = \tau_{AC} / n_{flight}$	\$0.389	\$0.396
Battery Depreciation $C_{BATD} = C_{BAT} \times \frac{E_{flight}}{n_{cycles} \times E_{BAT} \times \left(1 - \left(\frac{1 - \frac{E_{BAT, end-of-life}}{E_{BAT, nominal}}}{2} \right) \right)}$	\$0.0246	\$0.049
Aircraft Insurance Cost $C_{INS} = 500 + 0.015 \tau_{AC} = \13.49 per flight	\$0.033	\$0.033
Total	\$0.447	\$0.478

3.4.2 Variable Direct Operation Costs

Electricity Cost: Power consumption is mainly generated during take-off and landing, as well as during the cruise phase. To determine the speed and drag of the three phases, it is possible to obtain the required power and thus further establish the electrical power costs.

Lilium five-seat:

Firstly, Nathen [24] states that the cruise and climb drags of Lilium are 1705N and 1698N, respectively. Secondly, the eVTOL is assumed to fly at an altitude of 3000m above sea level, at a speed of 300km/h and in an international standard atmosphere (ISA). There are four components of drag at cruise: cabin, wings, flaps, and induced drag Nicolosi et al. [21] point out the equation of cabin drag:

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$$D_{c,ideal} = C_{D,c} \times \rho_{cr} \times S_{c,\emptyset} \times V_{cr}^2 = 248N \quad (3-9)$$

Where, $C_{D,c}$ is cabin drag coefficient 0.039, and frontal area of the cabin of Lilium ($S_{c,\emptyset}$) is $2.01m^2$, as the wing design of the Lilium interferes with the cabin drag increasing it by 30%, the overall cabin drag is 322N.

Equation of wing drag:

$$D_w = C_{D,w} \times 0.5 \times \rho_{cr} \times S_w \times V_{cr}^2 = 374N \quad (3-10)$$

Where $C_{D,w}$ is the wing drag coefficient 0.014, and wing area of the wing is $8.464 m^2$.

Equation of flaps drag:

$$D_f = C_{D,f} \times 0.5 \times \rho_{cr} \times A_{flap,o} \times V_{cr}^2 = 399N \quad (3-11)$$

Where $C_{D,f}$ is the drag coefficient of the flaps 0.017, and $A_{flap,o}$ is surface area of the flaps $7.434 m^2$.

Equation of induced drag:

$$D_i = 2 \times (MTOM \times g)^2 / \rho_{cr} \times \pi \times V_{cr}^2 \times s_w^2 = 610N \quad (3-12)$$

Where e of Oswald factor is $e = 0.83$.

Total Cruise Drag:

$$T_{CD} = D_c + D_w + D_f + D_i \quad (3-13)$$

Then, the power during the cruise of Lilium:

$$Powe = T_{CD} \times Cruise Speed \quad (3-14)$$

Which is 142kW, and the work done for 26 minutes cruising is 61.5kWh, according to the data from UK Power [25], average UK electricity cost of \$0.167

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per kWh, and the electricity cost during cruising is \$10.3. Meanwhile, Nathen [24] states the climbing speed is around 275km/h, climbing drag is 1698N, and the climb power is approximately 2.25 times the cruise power and an overall take-off and descent time of four minutes is assumed. Thus, the work done for take-off and descent is 21.3kWh, and the electricity cost is around \$3.56. Finally, the electricity cost per sear-mile is around \$0.046 for Lilium five-seat.

Joby S4:

As Moller [26] points out cruise power of Joby S4 is around 174kW at 320km/h, and the VTOL (take-off and descent) power is 642kW. Assumes cruise time and take-off and landing times of 26 minutes and 4 minutes consistent with Lilium. The work done of these two phases are 75.4kWh and 42.8kWh, the total electricity cost is \$19.7, and the electricity cost of per sear-mile is \$0.066.

Maintenance Cost: The maintenance costs presented according to equation 5 need to be calculated based on the actual aircraft model to arrive at a result, unfortunately there are currently no quotes available for maintenance labour costs for this model. Therefore, the Vegh et. al states the maintenance cost of Cora is \$69.75 per hour, it can only be used as a reference [27], and the actual cost of maintenance for a five-hour flight per day would be around \$34.88 per flight. Certainly, for the two different eVTOLs, the points of difference need to be identified to obtain a more accurate estimate. The Cora is powered by a 6 rotors system with 12 propellers and an additional propeller for forward propulsion, similar to the previous Lift+Cruise system, which is technically backward and therefore relatively inexpensive to maintenance.

The OTA (Office of Technology Assessment) [28] stated that a tilting propeller aircraft will increase operating costs by 14% to 18% over a 200-mile trip compared to an open propeller aircraft. The main difference between the Joby and the Cora is the power configuration, the size of the airframe and other data are relatively similar, and this difference in maintenance costs can be seen simply as the difference in maintenance costs between the open propeller and

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the tilting propeller. According to Scott and Vegh [29], maintenance costs are around 28% of the operating costs, which means that the maintenance costs of the Joby are around 5% higher.

As mentioned in Chapter Two, the Lilium is powered by 36 motors driving 36 rotatable ducted electric fans, while the rest of the body has been designed in a minimalist way, eliminating some of the redundant design and thus reducing maintenance costs to a certain extent. At present, the main maintenance costs appear to be for the 36 motors and fans. Firstly, there are four times as many motors and fans as the Cora, and even though they have a higher service life and are smaller, the daily maintenance costs should be at least 20% higher. Secondly, the Lilium is a ducted electric fan, and cleaning its ducts takes extra time. Therefore, it is assumed that the maintenance cost of the Lilium should be 30% higher than the maintenance cost of the Cora, which is approximately \$45.34 per flight.

Pilot Salary Cost: Scott and Vegh [29] indicate that the salary expenditure for a pilot is approximately \$180 a flight hour. In this project, five round trips would take five hours and the pilot would be paid \$900 per day to complete five round trips per day. It should be noted that the actual operating time is 10 hours per day but considering that half of the time pilots are not expected to drive, including this in the flight time would significantly increase the cost to the operating company, resulting in it being excessive. An additional allowance can be considered, assuming \$60 an hour for a break, costs the pilot an additional \$300 per day. For each flight, the cost to the pilot is \$120 per flight. In the future, as unmanned technology advances, regulations are perfected and public acceptance increases, the cost of this part can be eliminated.

Miscellaneous Variable Cost: The costs in this section are for ground services and navigation, the costs of ground infrastructure are detailed next, thus the variable miscellaneous costs are for navigation only. According to Birmingham Airports [30] navigation fee description, a navigation fee of £4.09 per ton is payable for a Lilium five-seater with a maximum take-off weight of less than or equal to 1 ton. However, considering the different altitudes of flight, the cost of

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navigation as a new field may increase and this item is calculated about £6 per flight. For both products, the miscellaneous cost of this component is the same.

Table 3-4 Variable Direct Operation Costs of Two Products

Variable Direct Operation Costs	Cost of Lilium Per seat-mile in Dollar	Cost of Joby Per seat-mile in Dollar
Electricity Cost: $C_E = \tau_E \times E_{flight}$ $l\eta_{charge}$	\$0.046	\$0.066
Maintenance Cost: $C_{MAINT} = R_{A\&P} \times F_{MF} \times t_{flight}$	\$0.151	\$0.116
Pilot Salary Cost: \$120 per flight	\$0.4	\$0.4
Miscellaneous Variable Cost: \$6 per flight	\$0.02	\$0.02
Total	\$0.617	\$0.602

3.4.3 Indirect Operation Costs

Sales and Reservation Cost: Civil aviation expenditure on this component is 14% of overall operating costs, according to ICAO [14], with an overall one-hour operating cost of \$357, cost of per seat an hour is \$1.93. If applied fully to the eVTOL scenario, it would be \$0.97 per seat per flight, however, given the distance flown, the duration of the flight, and significantly fewer passengers this component could be kept at around five times higher of its level, which is around \$0.065 per seat-mile.

General and Administrative Cost: Similarly, according to ICAO data [14], this component accounts for 6% of the overall operating costs (\$153), which is also considered to be five as much as civil aviation expenditure, considering that the eVTOL project has significantly fewer passengers when compared to civil aviation.

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Table 3-5 Indirect Operation Costs of Two Products

Indirect Operation Costs	Cost of Lilium Per seat-mile in Dollar	Cost of Joby Per seat-mile in Dollar
Sales and Reservation Cost	\$0.065	\$0.065
General and Administrative Cost	\$0.028	\$0.028
Total	\$0.093	\$0.093

3.4.4 Unique Factors Costs

Infrastructure Cost: Infrastructure costs, mainly considered as physical construction costs and network management costs in this project. The infrastructure is built primarily based on the number of passengers it serves and the location of the destination. One type of facility, known as Vertibases, is more appropriate for the scenario of this research project. It is a medium-sized structure that can be either newly built or retrofitted to an existing structure [31]. It has three active take-off and landing spaces, and six additional spaces that can be used for parking eVTOLs or maintenance inspections. The Vertibases cost between \$500,000 and \$800,000 to build, have a design life of 30 years and a further \$3 million to \$5 million a year to operate, considering the overall purchase of 30 eVTOLs by the operating company, with each of two stations being built at Coventry Hub and Heathrow Airport. The operating costs are based on location and traffic levels, and with the current target of 125 round trips per day, the operating costs are not expected to be significant in terms of traffic levels, it costs around \$0.44 per seat-mile.

Moreover, Johnston et.al [31] state that the network cost, i.e., the management cost, can be considered as \$15 to \$20 million for the infrastructure network construction, with a lifetime of about 30 years and an annual operating cost of between \$35 and \$50 million. It is important to note that the network here serves one large eVTOL airport vertihubs (which is the size of three vertibases), ten vertibases, and five small airport vertipads (which is about one-third the size

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of a vertibase). For the four vertibases used in this research project the construction cost was approximately \$0.13million and the operating cost was approximately \$9.3 million a year. Therefore, the network operating cost is approximately \$0.34 per seat-mile and the overall infrastructure operating cost is \$0.35 per seat-mile.

Regulation Cost: The cost of the regulations for an eVTOL operating company is mainly to obtain an operating license, which is established based on the needs of the local authorities, the traffic management, the regulatory authorities and the eVTOL participants. As there are no actual examples of this, references can only be made to the UK Civil Aviation Authority (CAA) [32] for the price of a single engine helicopter. Firstly, the basic charge for each helicopter operating application is approximately \$10,315, plus an annual operator target charge of approximately \$13,166 and a per helicopter target charge of \$1535. Thus, the cost of regulations per flight can be kept to around \$0.187.

Market Operation Cost: The cost of operating the market is an investment of up to \$5 billion in 2020 for the taxi operator Uber [33], and it accomplished the task of making approximately 3.9 billion journeys. This means that every time a trip is completed it will cost \$1.28 to operate the marketplace, and eVTOL operating companies can also refer to this rate as an implementation.

Public Acceptance Cost: The cost of this component is something that the industry needs to consider, and for a small operation it is not a huge expense to offer discount codes to attract customers during the initial operation, apart from advertising in busy areas etc. Assuming this would cost \$1,000,000 a year, it will involve a cost of approximately \$10.95 per flight.

Table 3-6 Unique Factors Costs of Two Products

Unique Factors Costs	Cost of Lilium Per seat-mile in Dollar	Cost of Joby Per seat-mile in Dollar
Infrastructure Cost:	\$0.79	\$0.79
Regulation Cost:	\$0.006	\$0.006

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Market Operation Cost:	\$0.004	\$0.004
Public Acceptance Cost:	\$0.037	\$0.037
Total	\$0.837	\$0.837

Based on the above analysis, the operating costs per kilometre per seat for an eVTOL can be roughly derived.

Table 3-7 Operation Costs of Lilium and Joby (double check)

Type of Costs	Lilium per seat-mile	Joby per seat-mile
Fixed Direct Operation Costs	\$0.447	\$0.478
Variable Direct Operation Costs	\$0.617	\$0.602
Indirect Operation Costs	\$0.093	\$0.093
Unique Factors Costs	\$0.837	\$0.837
Total Costs	\$1.994	\$2.001

In summary, the actual operating cost per mile per seat of the Lilium five-seat eVTOL is lower than that of the Joby S4, so the Lilium was established as the actual operating target for this research project. In terms of indirect costs and unique factor costs, the operating costs are the same for the two. The main differences are the following: the depreciation costs of the batteries, the Joby S4 has a cruising range of approximately 240km and in order to strictly enforce the flight standards and guarantee the safety of the flight it has to be recharged during a round trip transport mission, which leads to faster battery consumption; secondly the maintenance costs, the Lilium, due to its higher number of motors and fans, leads to additional time and expenses for maintenance. Finally, there is a slight difference in the cost of power consumption between the two, with the

3. Identity the product for this project

Lilium having less power in its vertical take-off and landing phase and thus less power consumption than the Joby S4.

4 DETERMINE THE OPTIMAL TRAJECTORY

4.1 The eVTOLs operational details

The flight trajectory of the eVTOL is assumed to be as follows: hover phase, a vertical climb and descent phase, transition and re-transition phase, and the cruise at required altitude on the path between Heathrow and Coventry Hub. The objective of the operating company is to maximise profits by controlling costs and expenditure while satisfying project missions. The first is the hover phase, which occurs during the initial take-off and landing of the eVTOL, when the power demand of the batteries is constant. In order to control costs, the pilot should move towards the transition or re-transition phase in time. The second phase is mainly the period when the eVTOL is converted to forward thrust through the hover phase, or from forward thrust to hover, and the power of the eVTOL decreases rapidly over time, it should be noted that this part will proceed rapidly. This is followed by the climb and descent phases, such that the power of the eVTOL is considered constant until it reaches the corresponding cruising altitude and cruising speed. Furthermore, the most important cruise phase, which occupies around 90% of the flight time, is also constant in its power.

The Lilium has a maximum cruising speed of 300km/h, based on which it will also incur maximum energy consumption. Moreover, to allow more time for the other stages to reach cruising altitude, a little cruising time is sacrificed. Thus, the operating speed of the Lilium can be assumed to be 280km/h with a cruising time of 26 minutes and 4 minutes for the other phases such as hover and climb. This speed may be relatively fast; however, speed and efficiency will always be the most profitable aspect of eVTOL, and the time requirements of passengers will need to be satisfied. The daily operation requires 1,000 passengers to be carried (assuming full seats) and a minimum of 250 one-way flights per day.

4. Determine the optimal trajectory

4.2 Operation Cost Estimation of Lilium per year

Depending on the project scenario and the target number of people to be carried, how to minimise costs while maximising profit is what is being considered. A detailed arrangement is required in terms of power consumption costs, maintenance costs, pilot and management operation cost, etc. to identify the optimum flight schedule. In particular, factors that fluctuate significantly in cost with flight time will need to be highlighted.

Table 4-1 Factors of Optimal Trajectory

Factors	Cost per seat-mile	Percentage
Electricity Cost	\$0.046	2.3%
Maintenance Cost	\$0.151	7.6%
Aircraft Depreciation	\$0.389	19.5%
Pilot Cost	\$0.35	17.6%
Infrastructure Operation Cost	\$0.79	39.6%
Total Relevant Cost	\$1.29	64.6%
Total Operation Cost	\$1.994	100%

From Table 4-1, it can be concluded that three factors account for a large proportion of the overall costs under commercial optimal route planning, which are aircraft depreciation, pilot salaries and infrastructure operating costs. Therefore, these three factors will greatly influence the cost of the final scheme, and how to achieve the most benefits while controlling the lowest costs is currently under discussion.

Based on the above analysis, the cost function of each factor has been listed and the next step is to prioritise its importance. This metric allows for the cost impact of the factors planned for the Lilium trajectory on the operating company in a particular scenario, from 0 to 1, in increasing order of importance.

4.Determine the optimal trajectory

Table 4-2 Metric of Factors in Trajectories Planning

Factors	Weighting
Electricity Cost	0.03
Maintenance Cost	0.09
Aircraft Depreciation	0.23
Pilot Cost	0.2
Infrastructure Operation Cost	0.45

The cost of electricity consumption is \$13.82 per flight, which is 2.3% of the overall operating cost, and its cost varies constantly and only in relation to the number of flights, hence its importance is rated at 0.03. Secondly, the importance of maintenance costs is rated as 0.09, since Lilium required inspection and maintenance after every two flights at a cost of \$45.36 per round trip flight. Next is the cost of depreciation of the aircraft at approximately \$117 per flight, which accounts for 19.5% of the operating share, although the cost of the aircraft decreases linearly in a regular manner, and considering its greater importance, this section is assigned a significance of 0.23. Then, the cost of pilot salaries is more than 20% of the overall operating costs, with an average of \$105 per flight being paid to pilots, hence its importance as an 0.2 out of 1. The actual flight time salary is fixed, and a more efficient planning of pilot breaks would reduce costs to some extent. Moreover, the operating costs of the infrastructure are virtually composed of the operating costs of the physical facilities and the operating costs of the network, which account for approximately 40% of the overall operating costs, with an importance ratio of 0.45.

4. Determine the optimal trajectory

4.3 Non-linear optimisation of various costs

4.3.1 Routine maintenance

As mentioned in the third chapter, the Lilium is expected to be 30% more expensive to maintain than the Cora due to its relatively large number of motors and fans, and its culverted configuration, requiring maintenance costs of \$45.34 per hour of flight. For a project mission with an expected flight time of 30 minutes, maintenance would be required after one round trip. The annual maintenance cost is shown in Equation 4-1.

$$C_M = 45.34 \times 0.5n_{flight} \times 365 \quad (4-1)$$

Firstly, it is assumed that each Lilium requires at least 15 days of maintenance to ensure it operates safely and efficiently. Then, assuming that the number of Lilium flights per day is x_1 ; the number of Liliums requiring maintenance is x_2 ; and the number of eVTOLs operating per day is $30-x_2$. Thus, the cost of daily maintenance can be expressed as:

$$C_M^2 = (680.4x_1x_2)^2 - (22.68x_1x_2^2)^2 \quad (4-2)$$

4.3.2 Maximum operating capacity per hour

A one-way flight takes 30 minutes, and once at the destination it takes 10 minutes to pick up and drop off passengers or adjust for the return flight; and assuming that it takes at least 110 minutes after the return flight to recharge for the next flight. It means that a Lilium takes 180 minutes from the first take-off to the next mission, thus it allows 8 return flights per day. Based on the previous assumptions that there are at least two Lilium aircraft undergoing maintenance each day and at least 250 flights per day, each Lilium aircraft would need to complete at least 8.9 one-way flights, which should be seen as 5 round trips or 10 flights per day depending on the actual situation. If this condition is satisfied,

4. Determine the optimal trajectory

no more than 5 eVTOLs should be serviced per day. Hence, it can therefore be expressed in Equation 4-3.

$$\begin{cases} 250 \leq (30 - x_2) \times x_1 \\ 10 \leq x_1 \leq 16 \\ 2 \leq x_2 \leq 5 \end{cases} \quad (4-3)$$

4.3.3 Electricity Cost

Other relevant factors also need to be discussed, starting with the cost of electrical energy consumption. The Lilium has a maximum cruising speed of 300km/h, based on which it will also incur maximum energy consumption. Moreover, to allow more time for the other stages to reach cruising altitude, a little cruising time is sacrificed. Thus, the operating speed of the Lilium can be assumed to be 280km/h with a cruising time of 26 minutes and 4 minutes for the other phases such as hover and climb. This speed may be relatively fast; however, speed and efficiency will always be the most profitable aspect of eVTOL, and the time requirements of passengers will need to be satisfied. The total electricity consumption was 82.8 kWh, at a total cost of \$13.82. The annual cost of electrical energy consumption required is shown in Equation 4-4 and C_E is the cost of electrical energy, n_{flight} is number of flights per day.

$$C_E = 13.82 \times n_{flight} \times 365 \quad (4-4)$$

The daily cost of electricity required is:

$$C_E^2 = (414.6x_1)^2 - (13.82x_1x_2)^2 \quad (4-5)$$

4.3.4 Aircraft Depreciation

The cost of depreciation of the aircraft is 20% of the overall operating cost, with a working life of approximately 6,000 hours for the brushless motors and other power equipment, and the required flight time of half an hour for this project will

4. Determine the optimal trajectory

incur a depreciation cost of \$117 per flight. The annual depreciation cost can be derived from Equation 4-6, with C_{AD} being the depreciated cost of the aircraft.

$$C_{AD} = 117 \times n_{flight} \times 365 \quad (4-6)$$

The daily cost of depreciation required is:

$$C_{AD}^2 = (3510x_1)^2 - (117x_1x_2)^2 \quad (4-7)$$

4.3.5 Pilot Cost

With pilot salaries contributing around 18% to overall operating costs, it will be the most influential factor in costs. The actual pilot will be paid \$180 per hour and will be given 30 minutes to rest and adjust after each single flight. The operating company will also be required to pay for this time, which is estimated at \$60 per hour, resulting in an overall payment of \$105 per flight to the pilot. Equation 4-8 indicates the annual cost that the operating company has to pay to the pilot.

$$C_P = 105 \times n_{flight} \times 365 \quad (4-8)$$

The daily cost of pilot required is:

$$C_P^2 = (3150x_1)^2 - (105x_1x_2)^2 \quad (4-9)$$

4.3.6 Infrastructure Operation Cost

The operating costs of the infrastructure amount to over 40 percent, as it covers not only the operating and management expenses but also the network services. Based on the previously assumed target of 125 round trips, the infrastructure and network structure are built for a 30-year lifetime and the route schedule only requires consideration of the annual operating costs of both. The

4. Determine the optimal trajectory

cost of building and operating the infrastructure is approximately \$132.2 per flight and the cost of building and operating the network is \$103.4 per flight, for a total cost of \$235.6. Therefore, the annual cost of infrastructure and network operation and construction can be expressed as Equation 4-10.

$$C_I = 235.6 \times n_{flight} \times 365 \quad (4-10)$$

The daily cost of infrastructure operation required is:

$$C_I^2 = (7068x_1)^2 - (235.6x_1x_2)^2 \quad (4-11)$$

Thus, the overall costs are:

$$\begin{aligned} C_O^2 &= 0.09C_M^2 + 0.03C_E^2 + 0.23C_{AD}^2 + 0.2C_P^2 + 0.45C_I^2 \\ &= (5225.9x_1)^2 + (106.4x_1x_2)^2 - (6.8x_1x_2^2)^2 \end{aligned} \quad (4-12)$$

$$s.t \begin{cases} 250 \leq (30 - x_2) \times x_1 \\ 10 \leq x_1 \leq 16 \\ 2 \leq x_2 \leq 5 \end{cases}$$

The optimal solution is obtained in MATLAB using the fmincon function [34] as $x_1 = 10$, $x_2 = 2$, and $C_O = 52302$. Furthermore, with a flight cycle of 180 minutes and 28 Lilium aircraft operating daily, it can be concluded that with a take-off time of 6.4 minutes for a Lilium aircraft, it can be expected that the frequency of take-offs from the two destinations would be 12 to 15 minutes a vehicle, which, based on a daily flight count of 280, would result in an operating time of 17.5 hours per day. This represents 64.6% of the overall operating costs, with a total operating cost of \$80,963 per day. To achieve the mission target, a minimum of \$29.55 million in annual operating costs would be required, with an operating cost of \$4,626.5 per hour, \$289.1 per flight, and \$0.96 per seat-mile.

5 DISCUSSION

5.1 Project results

The purpose of this research project was to develop an estimate of the operating costs of eVTOLs. Firstly, the prospects of the UAM and in particular of the eVTOLs industry are presented, demonstrating the importance and necessity of the experimental objectives. Secondly, a preliminary analysis of the different configurations of eVTOLs available on the market was performed to understand the power configuration, number of passengers, cruise speed and range of the various vehicles, thus identifying two configurations, the Lilium 5-seater and the Joby S4, that able to perform the flight task in the given scenario. The feasibility of each of these factors for eVTOLs was then analysed by reference to the cost structure of electric general aviation, leading to the establishment of a cost structure specific to eVTOLs. Furthermore, this cost structure was used to initially predict that the Lilium 5-seater would be a lower operating cost option. Therefore, it was further explored, within the mission scenario, to determine the daily transport tasks of the operator, to optimise the trajectory required by the operator, to calculate the daily operating costs (\$80,963), the annual operating costs (\$29.55 million), and the operating costs per seat-mile (\$0.96).

5.2 Compared with other reported figures

According to Goel and Holden [7], Uber Elevate projected a price per passenger per mile of \$0.84 to \$1.19 in the initial stages of this industry. This figure is in line with the data obtained for this research project. However, the results of Goel and Holden are for the entire eVTOLs industry. The \$0.96 price is based on the cost of operating the Lilium five-seat in the scenario specified in this paper. Secondly the Uber Elevate data spreads out the cost structure more finely, with extra consideration of salvage value, occupancy, capital expenditure etc., without considering the cost of the network system significantly. The current project has made more assumptions in this area, excluding capital, occupancy and salvage value components.

5. Discussion

Furthermore, from the analysis provided by Santha et. al [35] from LEK consulting, the cost of eVTOLs would be \$43 per 20 km (12.4 miles) and \$71 per 70 km (43.5 miles) per passenger. This can be converted to \$3.46 per seat-mile for 12.4-mile journey and \$1.6 per seat-mile for 43.5-mile journey. Compared to the results of this paper, if the flight distance is extended to about 75 miles or 120km, this price also produces a significant drop and approaches the level of one dollar, following the trend of its distance to price ratio. Overall, the results of this research project are highly credible and provide a relatively accurate estimate of the operating costs of eVTOLs.

5.3 Limitations and solutions

Although the results achieved the desired objectives, the methodology and operational process still have various limitations and shortcomings. As mentioned above a number of assumptions have been made for this project. Firstly, it does not require consideration of capital expenditure, which can take up around four percent of the total cost [7]. Secondly, the carrying rate is not accounted for due to start-up funding constraints. This is because it may require the procurement of additional vehicles to meet the sufficient number of passengers to be transported. Then, the investment costs in terms of regulatory costs, market operations and public acceptance are relatively difficult to predict, and the value of referenceable targets is not high. Furthermore, rounding in the process of building some formulas and calculations may also have had an impact on the final results. Finally, as the project scenario has a flight distance of 120km and the electrical energy costs are not a significant proportion of the cost, this allows for a reduction in the cost per seat-mile.

The above issues will probably affect the final operating cost results to some extent, hence further improvements will be necessary in the future during the resolution of related issues. Firstly, it would appear more reasonable and realistic for an operating company to have a capital expenditure

5. Discussion

component. Secondly, there should be a more detailed consideration of the occupancy rate. It would be more accurate to analyse this part after the actual operation. The eVTOLs industry is new to transport and its acceptability and stability of service quality is still unknown. Then, cost projections of public acceptance may require surveys of residents in different regions and countries. Areas with low acceptance may require a significant increase in upfront investment in this area. Moreover, the results obtained at each step of the calculation process could be more accurately documented and an estimation method could be used at the end to reduce errors. Finally, cost estimates can be made for different distances to obtain a more comprehensive result regarding the impact of cruising range on specific costs.

6 CONCLUSION

In this project, a cost estimation model of eVTOLs' operation company has been established. It first refers to the model structure of general aviation and cuts out some elements that are not highly reliable. Following this, each of the factors required to forecast costs for eVTOLs was uncovered through three various cost estimation methods. Besides, each factor was ranked in order of importance and the optimal trajectory arrangement for the operating company and the specific operating costs were finally obtained. Despite the different prediction models adopted, the operating costs per seat-mile match those predicted by the larger companies Uber Elevate and LEK consulting.

This research did not consider many industrial cost factors and its predictive model tended more towards providing a commercial operating model to the eVTOLs operating companies. This research could provide a reference for start-up companies to gain a more accurate and detailed cost structure and could also provide them with some help on how to control or reduce costs. The most significant limitation of the current project is that the cost estimates are only relevant for missions within the specified scenarios. Although the choice of scenarios is highly practical and relevant, the scope of the experiment is not sufficiently comprehensive. It does not account for all scenarios in which eVTOLs operate, which may result in different operating costs for various configurations of eVTOLs in different scenarios.

Further research is recommended in the following areas: cost projections for the Lilium five-seater within short and medium range flight scenarios. Next, to identify the respective most cost effective eVTOL configurations for short and medium range flight scenarios where conditions permit. This will probably need to be completed once the market is more developed and there is more demand. This will enable a transport market for eVTOLs across the full range of distances, further reducing the pressure on ground traffic and allowing for less wasted resources.

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APPENDICES

Appendix A

A.1 MATLAB CODE

% objective function

function f=fun(x)

f=((5225.9^2)*x(1)^2)+((106.4^2)*x(1)^2*x(2)^2)-((6.8^2)*x(1)^2*(x(2)^2)^2);

end

function [c,ceq]=fun2(x)

c=(30^2*x(1)^2-x(1)^2*x(2)^2-250^2);

ceq=[];

x =

10.0000

2.0000

fval =

2.7355e+09

.

Appendix B

B.1 Cost Analysis

For the individual research project cost estimates, Cranfield University provided costs for various factors. The main cost of this project is student time, which costs £400 per day. The time period is expected to run from 17th February to 18th August, with a total of 134 days excluding weekend time, the cost of student time is £53,600. Furthermore, Cranfield University will charge 20% of the cost as an administration fee (£10,760), therefore the overall cost is £64,360.

Table_Apx 1 Cost Analysis Summary

	Student Time	Administrative charge	Total Cost
Cost	£53600	£10,760	£64,560

Appendix C

C.1 Risk assessment of individual research projects

Consequences		Probability				
		Unlikely	Possible to occur over time	Probably will occur under routine conditions	Will occur under current conditions	Frequent/Regular / Continuous Occurrence
People		1	2	3	4	5
Fatality(s) / Chronic Illness with no recovery	5	*				
Injury/Illness requiring personnel to be hospitalized/off work for extended period of time	4	*				
Injury/Illness requiring medical treatment by a medical professional beyond first aid / no time off work required	3	*	Medium Risk		High Risk	
Injury/Illness requiring first aid treatment by non-medical personnel	2	*				
Minimal - no medical treatment or assistance needed.	1	*	Low Risk			

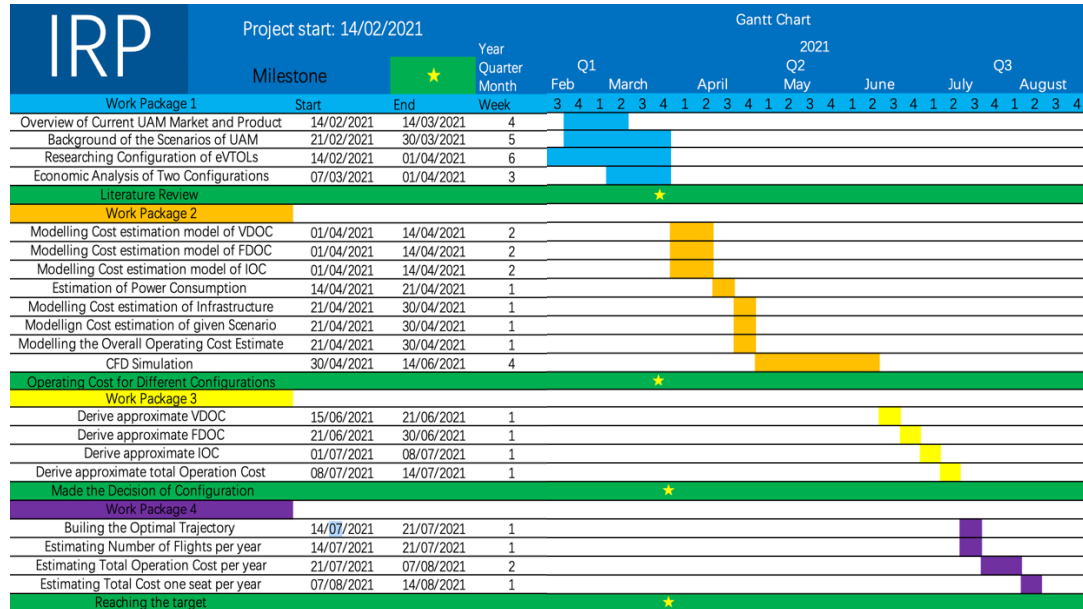
Figure_Apx 1 Risk Assessment

The possible risks associated with the development of this individual research project are shown in Figure C-1 and the level of risk associated with each hazard is represented by an "*".

Appendices

Appendix D

D.1 Tasks and project plan



Figure_Apx 2 Gantt Chart