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Cost Per Flight Analysis Of Tilt-Wing Evtols For Urban Mobility

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Abstract

Electric Vertical Take-Off and Landing (eVTOLs) aircrafts have been a subject of immense interest over the past decade. The promise of a mode of transportation that enables utilization of 3D space to alleviate traffic congestions while being environmentally friendly is the primary reason behind this added interest. In addition, this mode of transportation also has advantages such as enabling true point-point transportation, enhanced autonomy etc. These features make it ideal for urban transportation. There are certainly a few disadvantages to current designs of eVTOLs. For example, the eVTOLs being designed today only have a short range which is not ideal for intercity transfers. They can only host a few passengers, thereby it is not an ideal mode of transportation to enable mass transit. Since we already know that these aircrafts are mostly for individual or shared use and not meant for mass transit, it must be designed in such way to make it affordable and must be made efficient to operate with low-cost overheads. Most of the eVTOLs being talked about today are currently in conceptualization or design phase which means that there are many opportunities for design improvements. This work focuses on optimizing the design of eVTOLs to minimize the cost per flight and then compares the cost with commercial ride hailing services.

Keywords**—***eVTOLs, Optimization, design, MDO, tilt-wing.*

I. INTRODUCTION

Over the last few decades, there has been an increased focus on reducing carbon emissions to limit the increase in global temperature to 1.5°C above pre-industrial levels [1]. Transportation accounts for over 19.2% of the overall greenhouse gas emissions [2]. Any improvement made towards making the transportation more sustainable by making it more environmentally friendly or even by making the existing transport infrastructure more efficient will have a significant impact on the global greenhouse gas emissions. Although transportation accounts for only 19.2% of the overall sustainability goals, it is also important to make the whole energy transport supply chain more environmentally friendly to achieve the peak impact on reducing greenhouse gas emissions and that includes even the source of energy production. For example, the advent of electric cars and other modes of transportation that uses electricity as the source of power will only benefit the global warming goals if the primary source of energy is also as environmentally friendly as possible. Use of wind, solar or geothermal energy will be the most ideal sources of energy in this case because they have minimal greenhouse gas emissions. Although usage of electric cars is one way to significantly reduce greenhouse gas emissions from transportation sector, another way of reducing greenhouse gas emissions that is relatively untapped is electrification for air travel. Traditionally flying is only associated with travelling long distances but it can very well be used for short distance transport if it is commercially viable. Air transport for short distances has been challenged by high costs owing to the high cost of acquisition and also the availability of more affordable point to point road travel in the form of commercial ride hailing services.

However, over the last few years battery technology has enabled reduction in cost per KWh of batteries to an extent where battery powered cars have become affordable for most of the population [3]. This reduction in battery costs also enables the possibility of designing electric air transportation that can be made affordable for the masses. It is not yet possible to have electric air transport that can be used for long distance travel as the energy density of the best batteries we have today is only 220 Wh/kg[4], while jet A1 fuel has an energy density of 11.99 kWh/kg, which is roughly 50 times the best battery density. Therefore by a conservative estimate, the best means of electric air transportation can only travel short distances between 50-200km. Although this is not the best news for long range transport it certainly allows for a short means of air transport that can be electrified.

In addition to the feasibility of electric air travel, it is also important to analyze the cost of per flight and compare it with traditional means of transport. Since this work only discusses point to point urban travel, it is only fair to compare the cost per flight to a commercial ride hailing services instead of mass transit, which is not truly point to point. Since this is an electrified means of transport, there is going to be a huge advantage over the cost of energy as compared to a traditional ride hailing services. In an equivalent land mode of transport comparison, electric cars are cheaper to own than the gas equivalents even with the cost of financing (that includes high acquisition costs of electric cars over gas cars) [5]. This actually translates well in air transport. Even though more energy is required for air travel, the cost of energy can still be comparable to gas powered ride hailing services. Another means of reducing the overall cost is through autonomy. Usage of algorithms that can autonomously pilot the aircraft can drastically improve the safety as well as the affordability of the ride. Usually, the costs incurred by the driver overhead forms a significant share of the ride hailing fare and elimination of this cost gives a huge advantage for electric air transport. Besides autonomy in land based transportation, air transport is relatively easier to achieve owing the huge expanse of available space and also the availability of structured environment.

This comparison of cost between electric air transportation for urban mobility and commercial ride hailing services is critical for the wide adoption of eVTOLs. Since the objective here is to conceptualize an air taxi with the minimum cost per flight, the best means to design eVTOLs is optimize the design for cost per flight. The subsequent sections of this study talk about detailed modelling of each component and finally using this detailed model to optimize for minimum cost per flight.

II. PRIOR LITERATURE

The emphasis on meeting global warming reduction goals has led to a lot of funding for research on topics involving electrification of transport. While most of the focus has been on electric cars, there is a burgeoning interest on design of eVTOLs.

Airbus urban mobility group along with its parent company started a project known as Vahana in 2016. The main goal of this project was to conceptualize the feasibility of eVTOLs as a mode of urban transportation. Significant progress was made in the design of eVTOLs and a prototype had been built with the conceptualized design. While the project was ceased a few years later, one of the major contributions of this project was the open source eVTOL model [6] that came out of this program. This model included detailed designs of each component of eVTOLs and took it even further to optimize all these components using a single level optimization. The result of this study was that it was found to be feasible to design eVTOLs with 1-5 passenger capacity that can travel short ranges between 50 – 200km. This paved the way for establishment of many startups with a primary goal of building a commercially viable eVTOLs. Just like the autonomous electric vehicle market, it might be possible initially to develop eVTOLs tuned towards ride hailing services and not going the route of ownership based travel.

Based on the Vahana eVTOL study, another approach of optimizing the design is demonstrated by Chinthoju et. al. [7]. Typically any system optimization of practical engineering applications happens in a sequential manner. Although optimizing for low level design is as easy as using an optimizer that does the computation for us, it is not practically feasible to follow a single level optimization workflow in actual engineering organizations. A single level optimization workflow demands an unstructured interfacing among all subcomponents and this is difficult to be realized in practical engineering organizations. Another problem faced in implementing this is that the system level optimizer decides the design decisions of all subcomponents using a single optimization function but there might be some subcomponents that are well suited to be optimized by a specific kind of optimizer. A single system level optimizer will not allow a choice in the selection of individual optimizers since there is only one optimizer being used for all the sub systems. In [7], Chinthoju et. al, demonstrate the use of a specific case of decomposition based Multi-disciplinary Optimization technique known as Analytical Target Cascading (ATC) [8] to split the design optimization of eVTOLs into different subsystem optimizations while maintaining the synergy between them to optimize for the system level objective function. This enables the use of individual optimizers for the design of each subcomponent and hence can easily be scaled to work with engineering design organizations. Another bi-product of this study was a generalized ATC MATLAB application that fits the entire ATC algorithm into a user friendly GUI [9].

In [10] Zhang et. al, focus on overall design of the aircraft which includes even stability and control aspects of eVTOLs. This is an important aspect of eVTOLs that is left out in the current work but will be part of future studies. The optimization of controls and stability within design optimization is a problem that is well studied. This sub section of optimization algorithms are known as control co design optimizations. Several methods have been formulated to tackle this problem and one of the most popular approaches is to use nested optimization which has an inner loop that optimizes for control design and an outer loop that optimizes for system level design.

In [11], O'Reilly et. al, demonstrate the economic viability of eVTOL for urban mobility applications. The findings of this paper show that eVTOLs have a lower acquisition cost than helicopters while also boasting significantly lower operational costs. Thus it argues for the development of eVTOLs as a commercially viable mode of transport which can make urban air mobility accessible to a bigger demographic than current modes of urban air travel.

Another aspect of a well designed urban mobility system is traffic management. In [12], Kleinbekman et al. discuss an arrival and departure sequencing algorithm that can handle on demand requests. One of the main reasons for making the case for directly developing autonomous eVTOLs and in the process, skipping manually piloted eVTOL is the added advantage in scheduling. The use of autonomy paired with utilization of 3D space significantly enhances the avoidance of traffic congestion. Less traffic congestion equates to more availability time and thus eVTOLs can outperform traditional means of transportation even when considering utilization metrics. This very fact would make it highly attractive for applications such as air taxis.

III. EVTOL CLASSIFICATIONS

eVTOLs are classified based on different configurations of wings and rotors as shown in Figure 1. The first mode of classification is based on whether the aircraft is winged or wingless. Wingless aircrafts encompasses electric helicopters and electric aircraft with multiple static rotors. Note that the word static in this context means that the rotor configuration is fixed and it does not tilt. These types of aircraft are typically less efficient than aircrafts with thrust vectoring and wings because these aircrafts lack the flexibility of using the entire power generated to channel a horizontal thrust and have to rely on whole body pitch to generate the horizontal component of thrust. Hence this paper primarily focuses on winged eVTOLs and their optimization.

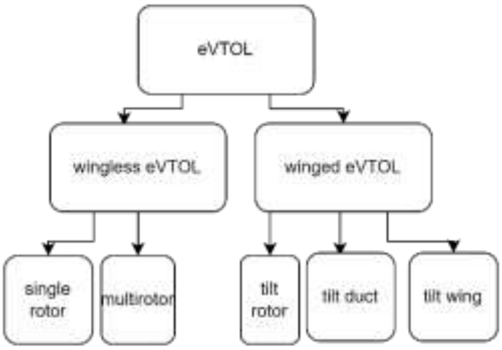

Figure 1: eVTOL classification

On the other end of the spectrum are eVTOLs that use movable wings and rotors. This category includes types of eVTOLs such as tilt wing, tilt rotor and tilt duct.

Tilt rotor eVTOLs only have rotors that can tilt about their axis and thereby provide thrust vectoring while the wings stay fixed to the fuselage. Since there can be multiple rotors mounted on a single wing, each rotor can have its own titling actuators. This configuration is similar to helicopters but instead of having tilt range of under 30deg, these rotors can be tilted to make them perfectly horizontal or beyond. The advantages of this configuration of eVTOLs is the high level of controllability. Since each tilt rotor can be actuated separately, VTOL (vertical takeoff and landing) phases of the flight are relatively easier to maintain. The transition from vertical flight to horizontal flight which is challenging in other configurations is also relatively easier to control in tilt rotor eVTOLs. A combination of a few vertically titled and a few horizontally titled rotors can handle this transition without the requirement of complex trajectory planning algorithms. However this configuration typically comes with a higher acquisition cost owing to the requirement of multiple rotor titling actuators. Thus tilt rotor is not an ideal configuration if minimizing the cost per flight is the primary objective.

Tilt duct eVTOLs are similar to tilt rotors with each rotor having its own tilting actuator. In a tilt duct eVTOL, the rotor is surrounded by a duct or a shroud that tilts along with the rotor to transition between vertical takeoff and landing and cruise mode. The advantages of this configuration is that it is easier to achieve the transition from VTOL to cruise modes because of individual rotor tilt actuation (just like tilt rotors) and a more compact design compared to other configurations. The disadvantages are that it is more expensive to build than tilt wing and it has less operational efficiency (especially in cruise mode due to the drag from the shroud or duct).

As name implies, in tilt wing configuration eVTOLs, the entire wing pivots and tilts to shift from horizontal to vertical flying. This design typically features a fixed wing with a hinge, allowing the wing to rotate around a central axis. The wings' angle of attack changes to produce lift during vertical takeoff and landing (VTOL) and thrust during cruise, thereby avoiding the need for separate equipment for both. Since this configuration also has only limited number of actuators for tilt, the cost of acquisition is also lower compared to other configurations. This however also comes with its own disadvantages. This configuration of eVTOLs has all the rotors on a fixed wing and this individual rotor axis pitch controllability is lost. This means that the control algorithms have to be robust to allow for the lack of individual controllability [13]. This in turn necessitates the utilization of advanced actuators that can be quick to respond and are more reliable but it still does not add up to the cost of multiple actuators used in other configurations. Thus when looking at from the perspective of optimizing for cost per flight, tilt wing is the ideal configuration of eVTOLs. Hence this paper primarily focuses on tiltwing eVTOLs.

IV. SIMPLE AND RESERVE MISSIONS

The focus of this paper is to understand the cost per flight of eVTOLs for relevant comparisons with other modes of transport. To simplify the computations, without loss of generality, we can assume the use of a simple mission to understand the cost per flight requirements. The simple mission is designed in such a way that it can be configured to work with different payloads and different point to point distances (ranges). It encompasses a vertical takeoff phase, a combination of transition and cruise phases and finally a vertical landing phase as shown in Figure 2.

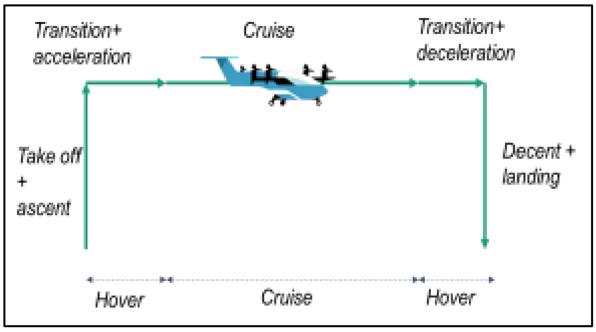

Figure 2: simple mission used in eVTOL design optimization

As a general target the aircraft is designed to be able to ascend in 90sec and descend at the same rate. During this phase the wing will be tilted vertically and all the rotors will generate lift. For ascent or descent, the lift generated by all the rotors should match the weight of the aircraft. This typically is the most power hungry phase of the mission. The operational altitude of eVTOLs for low level flight is around 500m [14]. To achieve this attitude in 90seconds, the aircraft must ascend at the rate of ~6m/s.

This is followed by transition and cruise where the wing is tilted back horizontally and all the rotors now generate thrust while the wing generates the lift to keep the aircraft air borne. The power needed in this phase is only needed to cancel out the effects of drag on the aircraft and to keep the aircraft cruising at a constant speed. This power requirement is minimal as compared to the ascent and descent phases. However, most of energy expenditure in the mission is spent during this phase owing to the time spent in cruise mode. Thus any improvements to efficiency in this phase go a long way in reducing the overall cost per flight.

Another aspect of designing a successful eVTOL concept is the safety. For this reason, reserve mission modelling is also included in this study. This involves additional 20 min loiter at cruise velocity to allow for multiple landing attempts in case of challenging conditions or equipment failure. The 20 min of loiter will add significantly more battery capacity requirement but this is necessary to maintain the rigorous safety requirements for air borne travel.

V. COMPONENT MODELLING

eVTOLs are highly sophisticated aircrafts that consists of several critical components to ensure safe operation. Different configurations of eVTOLs have different component requirements but the core concept of eVTOL design remains the same. Achieve lift using propellers, transition to cruise and descend using the lift from propellers. In a tilt wing eVTOL, which this paper focuses on, the main components are:

1. Rotors
2. Wing
3. Battery
4. Motor
5. Gearbox

Other components such as control surfaces, fuselage etc. are also important but optimizing the above components gives us the most impact on cost per flight. For the formulation of the cost per flight object function, all the other components are also modelled but they are either not optimized or they are optimized with a low fidelity model. The following section describes the modelling approach for each of the main components.

A. Rotors:

Rotors are the thrust providing devices in traditional aircrafts. However, they also provide lift in the take-off and landing phases of eVTOL flight. This lift is unique in that a takeoff velocity is not needed and the rotor can simply hover the aircraft in place. This implies that no runway is needed for takeoff and thus this mode of travel is truly point to point, requiring minimal infrastructure to operate.

Since the rotors have two different requirements for two different phases (lift and cruise), the rotors must be optimized for both the phases. The transition phase is only going to be a short phase which doesn't necessarily impact either the maximum power requirement (this is usually highest in VTOL phases and is dictated by those requirements) or the efficiency (this is dictated by the cruise phase which consumes the highest energy). In essence, the rotors must be designed for maximum power demanded during lift off and the must operate at maximum efficiency during the cruise phase.

In this study, the rotors are modelled using actuator disk theory (AD). The propulsion system in total includes eight rotors with four rotors on each wing. Each rotor has four blades. The time allotted for both ascent and descent is 90 seconds each respectively. During both of these phases, the rotor needs to produce enough lift to counter the weight of the aircraft which is take off mass times the acceleration due to gravity. The power generated by the rotor using actuator disk theory depends on vehicle design parameters such as radius, chord length of the blade, and RPM [16] as shown in equation (3) .Thus an equation involving the power and these design parameters can be used with an optimization function to find the most optimal design parameters for minimizing the system level objective function (i.e. minimizing the cost per flight).

$$\sigma = \frac{\eta_{\mathrm{prop}} c_{\mathrm{prop}} r_{\mathrm{prop}}}{\pi r_{\mathrm{prop}}^2} \tag{1}$$

$$\mathrm{T}_{\mathrm{hover}} = \frac{\mathrm{W}}{\eta_{\mathrm{prop}}} \tag{2}$$

$$P_{hover,max} = \eta_{prop} T_{prop} \left(k \sqrt{\frac{T_{prop}}{2\pi \rho_\infty r_{prop}^2}} \right) + \sigma \frac{C_{d0}}{8} \frac{v_{tip}^2}{\frac{T_{prop}}{\pi \rho_\infty r_{prop}^2}} \tag{3}$$

Here, T_{hover} is the thrust generated during hover, C_{d0} is the sectional drag coefficient and ρ_∞ is the density of free air stream. In this study, a drag coefficient of 0.012 is considered based on a NACA0012 airfoil blade profile. k , is an emprical correction factor used to match the findings of experimental results to results from actuator disk theory. The torque required to generate this power while the propeller is spinning at an angular rate of ω is then given by

$$Q_{hover,max} = \frac{P_{hover,max}}{\omega} \tag{4}$$

Another approach that can be used is Blade Element Momentum Theory. This approach involves sectioning the blade into a cross sectional element and integrating the lift and the drag from each of these elements over the entire length of the blade. This process is little more complex than using actuator disk and hence is avoided in this work to simplify computations. However, this method has a higher fidelity than actuator disk theory and hence can be used to optimize the model better if more computational devices are at disposal.

At this sub component level, this eqn. (3) will be used in computing the total energy expenditure that will be required in the simple and the reserve missions and eqn. (4) will be used to constraint the design with the maximum torque.

B. Motor

In this study, all the motors are sized using a sizing map [7]. This is the most simplistic approach as modelling a motor will required heavy computation and possibly simulation linked optimization in order to be the most accurate. The sizing of the motor used in this study is as follows

$$m_{motor} = 0.03928\, T_{motor}^{0.8587} \tag{5}$$

Using this equation the motor mass that forms a part of the overall mass and the cost of the eVTOL can be computed

Another parameter that is important to model the motor is the efficiency of the motor. Again, to simplify things, the efficiency of the motor is taken from a torque-RPM-efficiency map. Thus for any given mode of operation, the efficiency of the motor for that specific phase can be calculated using this mapping. Since each tilt wing has four rotors, each of them will require a motor and this is also considered while computing the total mass of the eVTOL.

C. Wing

The wing of the eVTOL is modelled using a constant lift NACA profile. The tunable parameters here are the chord length and wingspan which when multiplied together result in entire area of the wing. Using this area of the wing, the lift generated by the wing can be computed as follows

$$L_{wing} = C_{Lwing}\frac{1}{2}\rho v_{\infty}^{2}.c.b \tag{6}$$

Here c is the chord length of the NACA profile and b is the wingspan of the wing. This computed lift is used in a constraint to limit the maximum take-off weight of the aircraft (w_{mtow}) Similar to eqn. (6), the drag generated by the wing can be computed as

$$D_{wing} = C_{Dwing}\frac{1}{2}\rho v_{\infty}^{2}.c.b \tag{7}$$

The drag here is used to compute the power required during cruise mode. In cruise mode, the entire thrust of all the propellers balances out the drag due to the wing and the fuselage. Thus, the power consumed can be computed by the product of the overall drag on the aircraft and the cruise velocity (which is also a design parameter).

D. Gearbox

The gearbox modelling in this study is also from a mass sizing model [7]. The mass sizing model links the output torque of the transmission and the input and output angular velocities of the gearbox.

$$m_{gb} = 0.453592\kappa\frac{(hp^{0.76})\omega_{motor}^{0.13}}{\omega_{prop}^{0.89}} \tag{8}$$

where κ is an index given by the current development progress as 94 and hp is the power transmitted in HP

This is a component that was originally not included in the vahana study all together. Although gearboxes add weight to the overall system, the additional weight can sometimes reduce the weight of the motors and the rest of the aircraft significantly and thus yield a lower overall mass of the aircraft. A simple strategy to evaluate this theory is to include it in the model and optimize the overall system with the possibility of choosing a zero-mass gearbox (no gearbox). Thus, if the optimizer function finds a better solution with the gearbox, it has the liberty to use the sizing from this model or it can completely exclude the gearbox from the system if the addition of gearbox is adding more cost to the system.

VI. OPTIMISATION FORMULATION:

The primary objective of the optimization function is to find a set of design variables which minimizes the cost per flight of the eVTOL design. Thus the objective function is simply the cost per flight of the eVTOL. Along with this objective function, there are also constraints that correspond to component analyses discussed in the previous section. The overall optimization problem formulation that includes the objective function and the constraint is as shown in equation below:

$$\min_{x}: \quad \text{cost per flight} \qquad (9)$$

$$w.r.t \quad x = [r_{prop}, V_{cruise}, m_{batt}, m_{motor}, w_{mtow}, E_{reserve}, S_{wing}, RPM_{motor}, \eta_{motor}, m_{gb}]$$

$$subject\ to: \quad m_{total} < MTOW$$

$$E_{Reserve} < \mathrm{m_{Batt}\ batt_{\frac{Wh}{kg}}} \frac{\mathrm{dischargeDepthReserve}}{1000}$$

$$0.3928 * (\mathrm{T}^{0.8587}) < \mathrm{m_{Motors}}$$

$$\mathrm{V_{stall}} < \mathrm{V_{cruise}}$$

$$\mathrm{S} = \frac{\mathrm{w_{mtow}}}{\frac{1}{2}\rho \mathrm{V_{Stall}^2 C_{Lmax}}})$$

$$\mathrm{m_{motor}} = 0.03928\ \mathrm{T_{motor}^{0.8587}}$$

$$\mathrm{m_{gb}} = 0.453592\kappa \frac{(\mathrm{hp}^{0.76})\omega_{\mathrm{motor}}^{0.13}}{\omega_{\mathrm{prop}}^{0.89}}$$

In this formulation, there are 10 design variables being optimized which are described in Table 1 . Different upper and lower bounds have been set for these 10 variables along with a sensible initial guess of the solution and this formulation was optimized using fmincon function of MATLAB.

Table 1: Design variables for eVTOL optimization

Design Variable	Description
$\mathrm{r_{prop}}$	Radius of each propeller
$\mathrm{V_{cruise}}$	Cruise Velocity
$\mathrm{m_{batt}, m_{motor}}$	Mass of battery
$\mathrm{m_{batt}, m_{motor}}$	Mass of motor
$\mathrm{w_{mtow}},$	Maximum take-off weight
$\mathrm{E_{reserve}}$	Energy reserve
$\mathrm{S_{wing}}$	Wingspan
$\mathrm{RPM_{motor}}$	RPM of motor during cruise

η_{motor}	Efficiency of motor
m_{gb}	Mass of gear box

Besides the one time optimization within the upper and lower bounds with an initial estimate, three other runs of the same formulation are performed with different initial guess for the design variables to simulate a different starting point for the optimization function. These three different guesses are computed by randomizing the value of the design variable between the upper and lower bounds. All the results from such random starts are compared with each other to infer that the final solution arrived upon is the global minimum and not just a local minimum. Although this is does not ensure a strict global minimum, yet it is an effective method used to make sure that the solution computed is not just highly localized to the initial guess.

With this optimization solution result, it is straightforward to extract the mass of each of the important components. For components that do not have the mass as one of the design variables of the optimization problem formulation, some empirical computations are used to estimate the mass (for e.g. components like mass of wiring, mass of fuselage etc.). Along with the component masses, the cost of building up each component is also estimated using some empirical relationships that are also used in the Vahana model [17]. The same model also include relationships between other operating costs and the mass, range and payload of the aircraft (such as facility, insurance and maintenance costs). These costs are also included in this study but are not detailed here as these are mostly empirical and can be found in the Vahana model GitHub repository.

VII. RESULTS:

Since the main objective of this study is to compare the cost of urban road transportation with cost of eVTOL flight, the optimization of the design of eVTOL is carried out for a set of different operating ranges. To keep the problem relevant to the urban transportation phase, the ranges chosen in this study are 50km,100km,150km and 200km. All these designs include a requirement to carry 5 passengers. As discussed in the above section, the design of each of these range specific eVTOLs has been rigorously optimized to identify the best possible solutions for minimizing the cost per flight. The results of optimization are as shown in Figure 3.

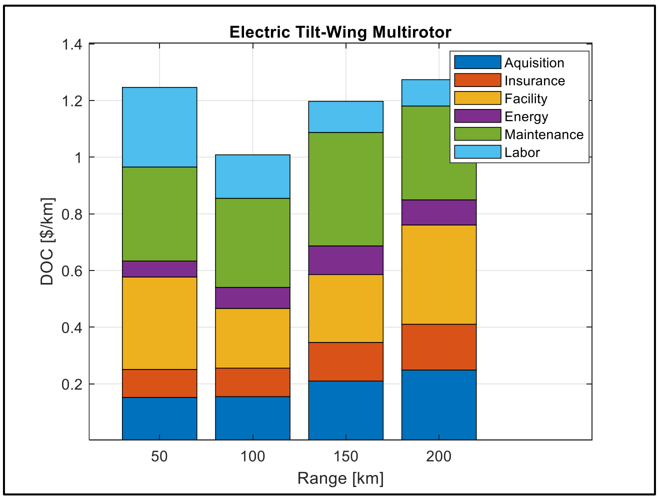

Figure 3: Direct operating cost per flight for different ranges

In Figure 3, the Direct operating cost per flight is plotted against the specified operating range of the aircraft. These results are particularly interesting because along with determination of the optimal design, it also sheds some light on what is optimum range at which this aircraft can be operated in a cost efficient way. The 100km range is the most ideal for eVTOLs and there are primarily two reasons for that. As the range is increased, the acquisition cost and the labor (which includes cost of crew members) is distributed over a larger range and thus decreases. However, the operating costs, which include cost of fuel, facility, insurance and maintenance increase and at 100km we find a minimum in cost per flight computation.

The results tell another compelling story that energy costs which are typically one of the highest costs associated with travel are lower in eVTOLs. The primary reason here is the low cost of energy in the form of electricity. With the reduction in energy costs, costs such as facility costs, insurance and maintenance become significant. Its important to note that although empirical relations have been used to determine these costs, these costs also depend on the design choices made for the aircraft (which are modelled into the empirical relations). For example, the facilities costs is modelled on the basis of the footprint of the aircraft. This again depends on the wingspan of the aircraft and thus it is expected that wingspan reduction would have played a bigger role in optimizing cost per flight instead of traditional factors associated with costs such as efficiency of the propulsion system.

The component masses for the optimal designs with different ranges are as shown below

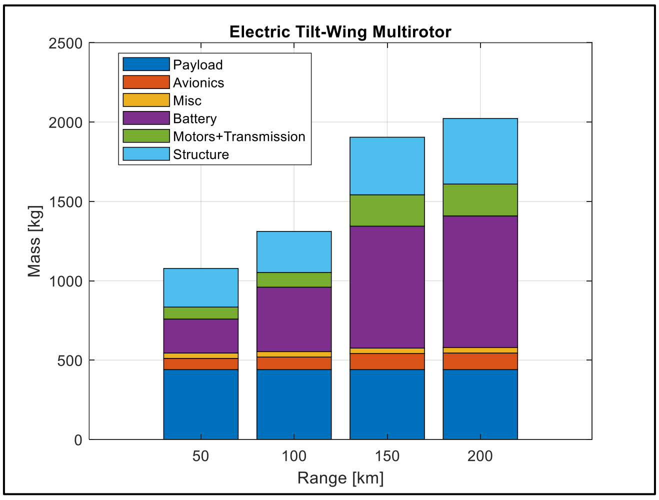

Figure 4: Mass breakdown for optimal cost designs for different ranges

The inference from this plot is much more straightforward and it tells that most of the increase in the component mass comes in the form of battery size increase as range is increased. Other components also increase proportionally to support the additional weight of the battery, however, the increase in battery mass is the biggest contributor to this trend.

From these results the operating cost per flight ranges from $0.8-$1.2 per km. A typical fare of ride hailing services in the US is also similar considering five passengers. Thus with the current capabilities, eVTOLs are comparable to traditional gas powered point to point urban transit.

VIII. CONCLUSION:

With the results achieved in this study, we can conclusively say that urban point to point transport using eVTOLs is a commercially viable and environmentally friendly mode of transportation. Although this is an exciting statement on its own, there are plenty of challenges still being faced in the mission of developing commercially viable eVTOLs. Additionally, this study also does not delve into the depths of improvement to traffic congestion which is another big advantage in the use of eVTOLs for urban transit. There can always be a case made for improvement in cost of land based urban transit with electrification and autonomous driving technologies being adopted in the past few years but it will always face the challenge of traffic congestion and the need for heavy infrastructure development to alleviate the congestion. This is where eVTOLs excel because they can use the entirety of 3D space including the height dimension to travel without any collision risk. With this opportunity also comes the necessity for development of urban air travel traffic control strategies, which should be the logical next step to take the eVTOL development space further.

REFERENCES

[1] Masson-Delmotte, Valérie, et al. "Global warming of 1.5 C." An IPCC Special Report on the impacts of global warming of 1 (2019): 93-174.

[2] Abraham, Sarin, et al. "Impact on climate change due to transportation sector–research prospective." Procedia engineering 38 (2012): 3869-3879.

[3] Berckmans, Gert, et al. "Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030." Energies 10.9 (2017): 1314.

[4] Kulova, Tatiana L., et al. "A brief review of post-lithium-ion batteries." International Journal of Electrochemical Science 15.8 (2020): 7242-7259.

[5] Orvis, Robbie. "Most electric vehicles are cheaper to own off the lot than gas cars." Energy Innovation Policy and Technology LLC. May (2022).

[6] Ha, Tae H., Keunseok Lee, and John T. Hwang. "Large-scale design-economics optimization of eVTOL concepts for urban air mobility." AIAA Scitech 2019 Forum. 2019.

[7] Chinthoju, Prajwal, et al. "Optimal Design of eVTOLs for Urban Mobility using Analytical Target Cascading (ATC)." AIAA SCITECH 2024 Forum. 2024.

[8] Allison, James, et al. "On the use of analytical target cascading and collaborative optimization for complex system design." 6th World Congress on Structural and Multidisciplinary Optimization Rio de Janeiro. Vol. 30. 2005.

[9] Chinthoju, P., "ATC application," url: https://github.com/chinthojuprajwal/ATC_application, 2022.

[10] Zhang, Jiechao, Yaolong Liu, and Yao Zheng. "Overall eVTOL aircraft design for urban air mobility." Green Energy and Intelligent Transportation 3.2 (2024): 100150.

[11] O'Reilly, Peter, et al. "Operational feasibility and mobility outcome from eVTOL based on existing air infrastructure." (2024).

[12] Kleinbekman, Imke C., Mihaela A. Mitici, and Peng Wei. "eVTOL arrival sequencing and scheduling for on-demand urban air mobility." 2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC). IEEE, 2018.

[13] Chauhan, Shamsheer S., and Joaquim RRA Martins. "Tilt-wing eVTOL takeoff trajectory optimization." Journal of aircraft 57.1 (2020): 93-112.

[14] Hagag, Nabil, et al. "Maximum total range of eVTOL under consideration of realistic operational scenarios." 2021,

[15] Leishman, J. G., Principles of Helicopter Aerodynamics, 2nd ed., Cambridge University Press, Cambrige, 2016.

[16] Das, Ghanendra Kumar. Multidisciplinary design optimization of an eVTOL aircraft using analytical target cascading. Diss. University of Illinois at Urbana-Champaign, 2021.

[17] Chinthoju, Prajwal Kumar. Optimal design of eVTOLs for urban mobility using analytical target cascading (ATC). Diss. University of Illinois at Urbana-Champaign, 2022.