Integrated Vertiport Design and Flight Scheduling Model for a Future Air Taxi Service in an Urban Area

MSc Thesis Air Transport Operations

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TU Delft

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by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on 03 July 2023.

Student number:	4480651	
Project duration:	04/2022 – 07/2023	
Thesis committee:	Dr. A. Bombelli	TU Delft, supervisor
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Acknowledgements

After moving to Delft for studies in September 2015, I'm finally on the verge of being a TU Delft graduate. Starting at Applied Physics, finishing my bachelors at Mechanical Engineering, and now almost an Aerospace Engineer. During my time as a student in Delft I transformed from being a young insecure adolescent, not knowing what path to follow, to a confident adult ready to take the next steps in life. When I finished my bachelors three years ago, I knew I wanted to do a masters in operations, as logistical problems always seemed to fascinate me - as a structured individual and a bit of a control freak. The master program Air Transport Operations was the key to success. Not that I'm thát hyped about airplanes, but because I liked all the puzzles we were going to solve. My friend Yvor joined me at ATO after our successful bachelor project at 3ME. It was a good call to do this together, as we could motivate each other when the pandemic forced us to do everything from home. It was unfortunate that we couldn't create a personal connection with the faculty and its staff members. When the faculties opened again for students, I was already done with all courses and hadn't got the chance to attend a lecture at the Aerospace Engineering faculty.

Eventually I got to know one lecturer, my supervisor for this thesis, Alessandro Bombelli. His futuristic subject about Air Taxi Services caught my eye and sounded interesting for a thesis project. While the project was first heading towards the in-air safety of the eVTOL aircraft, Alessandro proposed a more fitting research. With my interest in business we created a project about analyzing the profitability of an ATS on his home ground - the Milan metropolitan area. With the help of Sebastian Birolini from the University of Bergamo, we managed to make a great project out of it, while having fun during our calls between Delft and Bergamo. Besides always being helpful, I'd like to thank Alessandro especially for showing interest in to my personal life. It didn't matter if were questions about my weekly improving guitar skills, my job interviews or deeper issues - the personal connection really helped me to stay motivated. Grazie, Alessandro.

Meanwhile I live in Amsterdam with Yvor (PL) and our mutual friend Lauren. Together with my girlfriend Victoria and my parents they supported and motivated me to reach my full potential the past year. They all cannot wait to be transported by an eVTOL aircraft in the future. Three days after my graduation I'm going on vacation to Sicily and Milan with my girlfriend - maybe do some fieldwork in the Milan metropolitan area? I hope you enjoy reading the paper, contact me if you have question regarding the outcome or the model itself.

Thomas Hermans
Delft, July 2023

Contents

List of Abbreviations

ASC	Alternative Specific Constant
ATS	Air Taxi Service
BE	Break-Even
COGS	Cost Of Goods Sold
eVTOL	electric Vertical Takeoff and Landing
GPM	Gross Profit Margin
KPI	Key Performance Indicator
LF	Load Factor
MILP	Mixed-Integer Linear Programming
MNL	Multinomial Logit
O-D	Origin-Destination
TAT	Turnaround Time
TSN	Time-Space Network

Introduction

Urban air transport could be closer than we think, as companies are creating and optimizing eVTOL aircraft, and regulations are starting to be formed by aviation organisations such as the EASE and FAA. This futuristic transportation mode could alleviate road congestions, while transporting passengers much faster to their destination than traditional modes. However, before people will fly with an air taxi service (ATS) over the cities, it is important to know if the benefits from operations will outweigh the costs. During this research a model is created and applied to the Milan metropolitan area, which uses commuting demand data to make eVTOL flight schedules to investigate the revenues obtained by such a network. Additionally, the size of vertiports are determined at each location, which is the ATS infrastructure that gives eVTOLs a place to land and take off, while also providing maintenance and refueling. In the literature studies at the start of this master thesis, the main focus was on understanding urban air mobility and eVTOL aircraft specifications, and on finding appropriate literature that could be applied to the proposed model. After the literature studies, however, the subject was changed from creating a flight schedule with safety as the highest priority, to having the focus on profit maximization and designing the whole network.

The goal of this project is to create an ATS network, which integrates vertiport sizing to each location. The model can choose between a large, medium, and small vertiport per location, depending on what is most beneficial for the total network in terms of profit. The ATS competes with other transportation modes for potential passengers, and a flight schedule is created that optimizes not only the passenger flow, but also the size of the eVTOL fleet. This model could be interesting for governments and investors that are seeking opportunities to construct an ATS network in the future.

This thesis report is divided in two parts. Part I presents the scientific paper with the proposed model. In this part, more detailed explanations are given about the subject and how the model is created. Also, the results of of the model are presented, which are obtained from sensitivity analyses. In Part II the Literature Study is written related to the ATS.

I

Scientific Paper

Integrated Vertiport Design and Flight Scheduling Model for a Future Air Taxi Service in an Urban Area

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Abstract

With rising numbers in traffic congestions throughout the world, especially in urban areas, implementing an air taxi service (ATS) could be a way to alleviate this problem. Efficient scheduling of an ATS in a metropolitan area is critical to get a sense for the feasibility of ATS networks in the future. This paper presents a comprehensive electric Vertical Takeoff and Landing (eVTOL) aircraft passenger scheduling model, that also integrates the sizing of each vertiport as a strategic decision. The eVTOLs operations are discretized with a time-space network (TSN) and the underlying problem is modeled as a mixed-integer linear program (MILP) with the goal of maximizing the network's profitability within a densely populated urban environment. The TSN takes flight time and other factors into consideration, such as maintenance, eVTOL charging, and passenger (de)boarding. The TSN representation enables the integration of spatial and temporal constraints to accurate model the passenger distribution. To model mode competition, car and public transport services are introduced to compete with eVTOLs. The probability for a commuter to travel with the eVTOL is captured with a passenger discrete choice model. The proposed model is applied to a real-world case - the Milan metropolitan area. The fare is used as a variable parameter to perform a sensitivity analysis. The outcome of every fare is connected to a functioning ATS network, including an optimal eVTOL fleet and a choice on the size of each operated vertiport. An optimal fare of €11/pax·km is obtained which results in a network profit of €72k per day. Starting from multiple benchmark values, different ad-hoc pricing strategies were evaluated that addressed the length of the routes and time of the day. Despite the results, this research gives an impression on how a functioning ATS network will behave in an urban area.

1 Introduction

With a significant drop in commuting during the COVID-19 pandemic due to governmental restrictions, the number of traffic jams is increasing again. [Hu et al., 2020] even predicted that traffic levels will rise even more than before this period as the number of privately-owned cars increases. A new approach is needed to tackle this problem as it not only costs cities enormous amounts of money, but traffic also has negative effects in terms of greenhouse gasses, air pollution and noise. For some companies, the sky is certainly not the limit, as they see these congestions as an opportunity to use electric vertical take-off and landing aircraft (eVTOLs) to reduce them. As some parcel companies focus on aerial package delivery to get trucks off the road, others seek to transport passengers through the air, a so-called air taxi service (ATS). The reason these companies focus on eVTOL aircraft instead of using modern helicopters is because eVTOLs have far less noise pollution and operate on batteries without emitting any greenhouse gasses during operations.

Before this transportation mode can be applied to cities, a whole new infrastructure must be built to support the operations as stated in [Meyers, 2022]. Additionally, the eVTOL aircraft needs to be designed according to the regulations set by organizations as the FAA and EASA in [Talke and Brieger, 2021]. Because of the novelty of this subject, there is little research done on flight scheduling for a future ATS. The few studies done on ATS are solely based on developing a schedule for flights, serving as an airport shuttle service while using fictional data. The research proposed in this paper takes it some steps further. The model presented is applied to the Milan metropolitan area, a region with high traffic density. The input data for the model includes the commuting demand of the year 2020 in the area between ten fixed locations, which serve as the origin and destination of each commuter - thus also the locations of the vertiports. A time-space network (TSN) representation is used to create all potential flights than can be flown from location to location on a certain time step, and a mixed-integer linear programming (MILP) formulation is developed to model the flight schedule. To better mimic real operations, the ATS competes with other existing modes, which are cars and public transport. This is implemented in the model with a passenger discrete choice formulation. Besides handling the passenger choice for transport mode, the formulation additionally incorporates the opportunity for a commuter to be

*Msc Student, Air Transport and Operations, Faculty of Aerospace Engineering, Delft University of Technology served by eVTOL flights later or earlier than the preferred departure time. On top of this, this research focuses on deciding the best size of each vertiport by endogenizing such decision variables as part of the model. The proposed model thus outputs a flight schedule with an optimal vertiport configurations and eVTOL fleet size. With a range of values of fares a sensitivity analysis is performed to find the optimal fare and investigate the behaviour of the model.

The remainder of the paper is organized as follows. Section 2 gives a summary of the literature used for creating the model presented later on. Section 3 elaborates on the problem tackled by this research. This is followed by the methodology in Section 4, which gives a more detailed explanation of the model. Section 5 describes the application of the model to the case study of the Milan metropolitan area. Results of the sensitivity analysis and pricing strategies are presented in Section 6. The paper's conclusions and recommendations can be found in Section 7.

2 Literature Review

In order to find relevant literature that can be applied to an optimization model of an air taxi service, it is necessary to look at papers of comparable operations relying on methods that can be applied to the ATS scheduling model. As the ATS is in many ways similar to the aviation industry, much of the literature used derives from commercial aviation operations.

Flight scheduling
Flight scheduling has been investigated by various papers, with [Levin, 1971] pioneering the integrated flight scheduling and fleet assignment problem. The work focuses on minimising the fleet size used in the model. Papers based on this work, such as [Mezentsev and Estraykh, 2018] and [Zhang et al., 2016], are also interested in the combination of creating an optimal flight schedule, while minimizing costs by assigning the right types of aircraft to each route. However, in the model presented later in this paper, the fleet is considered homogeneous, meaning there is only one type of eVTOL aircraft in the fleet. The papers use mixed-integer linear programming (MILP) as the optimization technique to deal with their linear problems. This involves defining an objective function and a set of constraints with proper variables.

Spill & Recapture
The demand for flights will not always meet the supply. Some aircraft are spoiled if there are not enough passengers to fill the seats, and spillage occurs when the capacity provided is too small for the amount of potential passengers. Recapturing spilled passengers is an important issue in flight scheduling models, as the model loses revenue when paying customers, that want to travel with the aircraft, can't be transported. The paper of [Barnhart et al., 2002] proposed to add spill and recapture in the Passenger Mix Model for the fleet assignment problem. This paper, however, brings the limitation that the market share of the airline is assumed to be constant. An alternative is given by the paper of [Ferguson et al., 2012] to look at passenger discrete choice models, where each possible route is considered a discrete commodity in the market. For every possible route a utility value is calculated which is used to determine the level of attractiveness compared to other travel options. The utility is often calculated with fares, level of service, and/or travel time. The higher the attractiveness value, the higher the probability is that the commuter will choose that option. [Ben-Akiva et al., 1985] uses a multinomial logit (MNL) formulation to divide people over the travel options according to their attractiveness value relative to the attractiveness of the other options. However, as it is not known beforehand what potential flight will be flown, this approach is considered non-linear in the proposed research. The papers of [Birolini et al., 2022], [Zhang et al., 2016], and [Wang et al., 2014] use an approach to avoid this non-linearity. [Wang et al., 2014], for instance, uses constraints that give room for passengers to travel with another option when the proposed flight is not flown or the seat capacity is reached. Therefore, passenger will never be lost.

Time-Space Network
A method used by [Zhang et al., 2016] and [Sherali et al., 2006] to model fleet allocation alternatives and to optimize the movement of flights over space and time is the TSN. With the TSN all potential routes can be constructed that lay the foundation of a flight schedule. The TSN uses nodes, which are (location, time)-pairs, that allow the change of allocation of an aircraft from a flight to a ground arc or wrap-around arc. A flight arc represents all potential flights that can be flown in the model, while ground arcs are the ground times of aircraft at the airport. Wrap-around arcs guarantee continuity between aircraft at the end of the time horizon to the beginning, in order to start this cycle again. Constraints often used in flight scheduling models are the flow balance constraint, balancing the aircraft flow throughout the network, and the count line constraint, which is needed to guarantee the size of the fleet stays the same at any time within the time horizon.

The aforementioned topics of literature on flight scheduling, spill and recapture methods, and TSN representations could be merged to create an eVTOL flight schedule, which has never been performed in research. Especially, pairing eVTOL flight scheduling to vertiport sizing decision variables to determine the appropriate vertiport type per location, brings the proposed model to a higher level. With all these components a representation of a full functioning ATS can be designed, and analyses can be performed to understand the behaviour of the network.

3 Problem Statement

The purpose of the research proposed in this paper is to explore how a flight scheduling model can be integrated with a vertiport design choice to assess profitability of a future ATS. The input of the model is the commuting data of people travelling with cars or public transport in the Milan metropolitan area in 2020. With a passenger discrete choice model a part of this demand will be captured by the new ATS travel mode. This is achieved with utility functions that determines the level of attractiveness for potential passengers to fly with an eVTOL aircraft instead of travelling with other options. This data represents all people commuting from one location to another at specific time steps, also referred to as routes in this paper. As the eVTOL is capacity constrained, the people that want to travel with the ATS are bounded by the aircraft's seats when demand is high. Potential passengers are therefore forced to travel with the other alternatives which aren't constrained by a certain capacity in the model, and are therefore always available. However, to capture more passengers with the ATS, commuters also have the choice to be served by neighbouring routes. Section 4.2 will elaborate more in-depth about the mathematical formulations used in the model.

The objective function of the MILP model is a profit maximization of the total eVTOL network, also including vertiports. The revenue is obtained from transporting people from their origin to their destination. There are of course costs involved to operate the ATS. The eVTOL operating costs are based on the distance flown by the aircraft. Adding this with the purchase costs of the eVTOL to the objective function, the optimal size of the fleet can be determined. Besides buying the fleet, also a whole new infrastructure must be built and operated. Vertiports serve as the take-off and landing places for eVTOLs. The model considers three vertiport types (or designs), being the *vertihub*, *vertibase*, and *vertipad*, with take-off and landing pads of 10, 3, and 1, respectively. Each location in the area is assigned one of the vertiport types. The modelling of this part will be discussed further in Section 4.2, and the costs structure in Appendix C.

With the MILP model the profit of the entire network is optimized, and the vertiport types, eVTOL fleet size and the passenger flow data in the network can be computed as relevant Key Performance Indicators (KPIs). As the ATS is based on many assumptions given its current implementation stage, a sensitivity analysis will be performed to find the results for a range of values of fares. Thereafter, two strategies will be applied to improve the overall profits of the network, of which the results can be found in Section 6.

4 Methodology

This section describes the integrated vertiport design and flight scheduling model, which has the objective to find maximum profits for the network for one operating day. In Section 4.1 the time-space network is formulated, which is used to determine the potential flights that the ATS can take. Thereafter, in Section 4.2, the mathematical formulation of the MILP is described, with the network profitability being the objective of the model.

4.1 Time-Space Network model

A TSN acts as a backbone for the flight scheduling model. It represents the movements of eVTOL aircraft over space - origin to destination vertiport - and time. In the TSN representation the time is divided into discrete intervals Δt which helps to visualize and understand the flow of aircraft through the network. The time horizon is defined between the beginning 0 and end of the time horizon T, thus $t = \{0, \Delta t, 2\Delta t, ..., T\}$. For this model one operating day is assumed with a time discretization of 10 minutes. This interval is large enough to achieve a short computational time, and small enough to imitate a real ATS. The main components of a TSN are the *nodes* representing the locations of vertiports at particular times, and three types of *arcs* serving as the connections between two nodes.

The first arcs considered are the *flight arcs* f, which are the connection between two nodes n that are non-identical in space and time, thus having a different origin and destination vertiport v. The length of the flight arc in the TSN depends on the actual flight time between the two vertiports and the *turnaround time* (TAT) of the eVTOL at its destination. The flight time of f is defined by $t_f = d_f/V_{ev} + t_{TAT}$, with the distance d_f differing per flight route, and where the cruise speed V_{ev} of the eVTOL aircraft is used as an average speed of

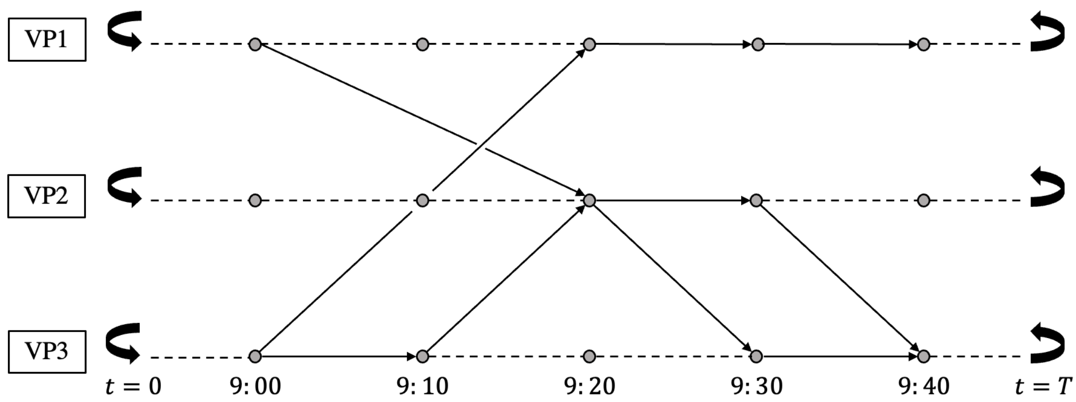


Figure 1: Time-space network representation of an Air Taxi Service.

the trip. The turnaround time is the amount of time it takes for an eVTOL aircraft to be flight-ready again after landing at a vertiport. This includes charging, passenger (de)boarding, and cleaning. In the model a TAT of 51 minutes is considered, based on the paper of [Bruehl and Fricke, 2022]. To conform to the discrete structure of a TSN, flights (including TAT) landing between two consecutive nodes are pushed to the nearest node at the end of the 10-minute time block. However, if they land within the first 10% of that time block, the aircraft is pushed back to the nearest node at the beginning of the time block. Only one aircraft can fly on a flight arc. The second set of arcs are the *ground arcs* g, connecting consecutive nodes in time and sharing the same vertiport. The ground arc represents the ground time of an eVTOL at a vertiport. Lastly, the *wrap-around arcs* w represent the overlay of an eVTOL aircraft at a vertiport at the end of the time horizon ($t = T$) to the beginning of the time horizon ($t = 0$). This arc ensures that there are as many eVTOLs at the start and at the end of the operating day. Prior to the actual modeling phase, all possible flight legs are calculated according to the TSN representation to determine the paths the model can take to create a flight schedule. Flight- and ground arcs are considered not to pass the borders of the time-horizon, which means that these arcs do not move through the end of the time horizon (t=T), or the beginning (t=0). Only wrap-around arcs are considered to link the last node to the first node. Figure 1 gives a schematic view of a time-space network of a completed and running mock model. Here, the small circles represent nodes and the arrows represent the arcs. An example of a flight arcs in the illustration is (VP1, 9:00) → (VP2, 9:20), a ground arc (VP2, 9:20) → (VP2, 9:30), and wrap-around arc (VP3, t=T) → (VP3, t=0).

4.2 Mathematical Formulation

In the TSN in Section 4.1 all possible arcs are built which are used by the model to construct the flight schedule. Table 1 represents the definitions of sets used in the model. Here, the set F of flight arcs is a subset of the set of routes R. In this paper, the term 'route' is used for a direct path from one location to another that can be taken by multiple transportation modes. Routes and flights have the same origin and destination, which means that the distances are identical - only the travel cost and travel time differs per mode of transportation. The set of flights has the same length as the set of routes. However, a flight f can only potentially be flown by an eVTOL, while routes are used for travel by the other modes. A difference is that the model optimizes if a potential flight f will be flown or not, while the routes r of other modes are always used - the car or public transport option remains feasible for every route r. In this section, the objective function is elaborated on and all constraints of the MILP are discussed, and the complete MILP formulation can be found in A. The model makes a choice by assigning specific vertiport types to the locations in the network and optimizing the size of the eVTOL fleet, while creating a flight schedule. The model is performed with Gurobi Optimization which applies advanced algorithms and techniques to find the solution of this complex optimization problem efficiently and quick. The decision variables used to create the constraints and the objective function are described in Table 2.

Objective Function

The objective function of the model is the maximization of profits of the ATS network. This is achieved by optimizing the passenger revenues and associated costs. It is a function that balances the potential revenues earned from transported passengers with the costs that are associated with eVTOL operation, purchasing eVTOL aircraft, and costs for vertiports. In Equation 1a the objective function is depicted with on the left hand side "max $\mathcal{P}$" indicating the maximization of the profitability. The four parts of this function will be explained in detail below, and the parameters used can be found in Table 3.

Table 1: Sets used in the model.

Set	Description	Definition
R	Possible routes, indexed by r	
Rr'	Neighbouring routes of r, indexed by r'	$R_{r'} \subset R$
F	Possible flights, indexed by f	$F \subset R$
$F_{f'}$	Neighbouring flights of f, indexed by f'	$F_{f'} \subset R_{r'}$
G	Ground arcs, indexed by g	
W	Wrap-around arcs, indexed by w	
V	Vertiports, indexed by v	
T	Time steps, indexed by t	
N	Nodes, indexed by n	
N_v	Nodes n belonging to vertiport v	$N_v \subset N$
x_{n^+}	Flight arc f arriving in node n	$x_{n^+} \subset F$
y_{n^+}	Ground arc g arriving in node n	$y_{n^+} \subset G$
z_{n^+}	Wrap-around arc w arriving in node n	$z_{n^+} \subset W$
x_{n^-}	Flight arc f departing from node n	$x_{n^-} \subset F$
y_{n^-}	Ground arc g departing from node n	$y_{n^-} \subset G$
z_{n^-}	Wrap-around arc w departing from node n	$z_{n^-} \subset W$
x_{cl}	Flight arc f crossing count line	$x_{cl} \subset F$
y_{cl}	Ground arc g crossing count line	$y_{cl} \subset G$

Table 2: Decision variables used in the model.

DV	Type	Description
x_f	Binary	Unitary if flight f is flown
y_g	Integer	Flow value ground arc g
z_w	Integer	Flow value wrap-around arc w
E	Integer	Size of eVTOL fleet
$q_{f,r}$	Integer	Pax from desired route r served on flight f
$q_{f',r}$	Integer	Pax from desired route r served on neighbouring flight f'
$q_{f,r'}$	Integer	Pax from desired neighbouring route r' served on flight f
q_r^o	Integer	Pax traveling with other modes on route r
T_v^a	Binary	Unitary if vertiport v is labeled as type a

$$\max \quad \mathcal{P} = \sum_{f \in F} d_f \cdot fare \cdot (q_{f,r} + \sum_{r' \in R_{r'}} q_{f,r'}) - \sum_{f \in F} C_{ops}^{ev} \cdot d_f \cdot x_f - C_{pur}^{ev} \cdot E$$
$$- \sum_{v \in V} T_v^0 \cdot (C_{pur}^{vh} + C_{ops}^{vh}) + T_v^1 \cdot (C_{pur}^{vb} + C_{ops}^{vb}) + T_v^2 \cdot (C_{pur}^{vp} + C_{ops}^{vp}) \tag{1a}$$

Part I: Revenue
The first part of the objective function stated above considers the revenue generated by the ATS. This is the money the company receives from transporting passengers with an eVTOL aircraft from one vertiport to another. The passengers flown can be divided in two types of passengers: the ones that fly on their preferred route r, depicted by decision variable $q_{f,r}$, and the people that prefer to travel on one of the neighbouring routes r' of r, but are served on flight f of route r. More detail on these decision variables is given in the explanation of the "Passenger Allocation" and "Capacity" constraints later on. The revenue per flight is calculated by multiplying the amount of passengers served on f by the distance of the flight d_f times the $fare$, which represents the price per passenger per kilometer flown. Taking the sum over all flights in set F gives the total revenue for one day of operating.

Part II: eVTOL Operating
The second part of the objective function represents the operating costs of all flights flown during one day. The total operating cost do not depend on the amount of passengers on a flight, as the costs stay the same for every kilometer flown. They are dependent on the amount of flights flown and the length of each trip. Per flight the costs are calculated by multiplying the costs associated with one km flown C_{ops}^{ev} times the distance d_f of the flight f times binary variable x_f, which decides if a flight f is flown or not. If x_f is 0, flight f is not flown and

Table 3: Parameters used in the model.

Param.	Description	Value	
$fare$	Fare charged to pax per km	X	[€ /pax·km]
V_{ev}	Cruise speed eVTOL	120	[km/hr]
t_{tat}	Turnaround time	51	[min]
vot	Value of time	20	[€ /hr]
k_{ev}	Capacity eVTOL aircraft	3	[-]
k_{vh}	Capacity vertihub	10	[-]
k_{vb}	Capacity vertibase	3	[-]
k_{vp}	Capacity vertipad	1	[-]
C^{ev}_{pur}	Cost eVTOL purchase	230.14	[€ /day]
C^{ev}_{ops}	Cost operating an eVTOL	0.49	[€ /km]
C^{vh}_{pur}	Cost vertihub purchase	540.18	[€ /day]
C^{vh}_{ops}	Cost operating a vertihub	39890.41	[€ /day]
C^{vb}_{pur}	Cost vertibase purchase	54.02	[€ /day]
C^{vb}_{ops}	Cost operating a vertibase	9972.60	[€ /day]
C^{vp}_{pur}	Cost vertipad purchase	24.93	[€ /day]
C^{vp}_{ops}	Cost operating a vertipad	1869.86	[€ /day]

thus will not be making any operational costs. The sum over all flights in set F gives the total operating costs of the eVTOLs combined during the day. The operational costs are obtained from the white paper of Uber Elevate in [Elevate, 2016]. Appendix C.1 elaborates in more detail about the eVTOL operating costs that are used in this model.

Part III: eVTOL Purchase

The third part of the function above includes the costs for purchasing eVTOL aircraft for the network. Decision variable E considers the number of eVTOL aircraft that are used in the network. The aircraft count line constraint of constraint "Aircraft Count" ensures that the eVTOL fleet remains constant throughout the network. By coupling E to the eVTOL purchase costs C^{ev}_{pur} in the objective function, the model optimizes the amount of aircraft in the network. The amount of eVTOLs are also constrained by the types of vertiports in the model by their eVTOL take-off and landing capacity. The Uber Elevate paper describes that purchasing an eVTOL aircraft is quite expensive initially, and is expected to have an operational lifetime of 13 years. Because the model calculates the profits for one operational day, the purchase costs also have to be brought down to one day. This is done by dividing the purchase costs by 13 years and 365 days.

Part IV: Vertiports

The last part of the objective function includes the operational and purchasing costs for vertiports in the network. As will be stated in the "Vertiport Type" constraint, the number of aircraft entering a node must not exceed the capacity of the vertiport type. By coupling the vertiport type decision variable T^k_v to the purchase and operational costs in the objective function, the model makes a choice to assign one vertiport type per location. A larger vertiport can handle more flights at a time and thus could increase revenues, but is also more expensive to built and operate. Smaller vertiports on the other hand may bring in less earnings, but also cost a lot less. The objective of the model is to calculate profits for one day, which means that (similar to the eVTOL financing) the operational and purchasing costs have to be brought down to one day. The McKinsey & Company article [Johnston et al., 2020] describes all costs per vertiport type. The operational costs are yearly, and are thus divided by the amount of days in a year to calculate the operational costs per day. For the capital expenditures for vertiports the article uses a 30 years useful life. Therefore, the purchase costs for the vertiports are divided by 30 years and 365 days.

Constraint I: Flow Balance

The flow balance constraint restricts the model to have exactly the same amount of eVTOL aircraft going into a certain node as going out of that node. In the model this means that the sum of all flight-, ground-, and wrap-around arcs must be the same at entrance of a node as at the exit of that same node. In Equation 2 the flow balance constraint can be found, which is created with three decision variables. Here x_f is a binary decision variable which gives output 1 if the potential flight f is flown, and 0 otherwise. The flow value of the ground arcs is y_g, and the flow of wrap-around arc z_w - both are integer values that represent the amount of eVTOL aircraft using this arc.

$$\sum_{f\in x_n^+} x_f + \sum_{g\in y_n^+} y_g + \sum_{w\in z_n^+} z_w = \sum_{f\in x_n^-} x_f \sum_{g\in y_n^-} y_g \sum_{w\in z_n^-} z_w, \quad \forall n \in \mathbf{N} \tag{2}$$

On the left-hand side of the formula are the summations of all flows going into each node n for every arc in a subset of incoming arcs, and the right-hand side are all flows going out of each node n for every arc in a subset of outgoing arcs. This equation thus balances the total flow of eVTOL aircraft in the model. A visual example of a flow balance can be seen in Figure 1 where at (VP2, 9:20) two flight arcs enter this node, and one flight- and ground arc leave this node.

Constraint II: Aircraft Count
The idea of an aircraft count constraint is to keep the eVTOL fleet the same size throughout the model and to ensure that the solution uses a limited number of aircraft based on the purchasing cost. This is done by taking a snapshot in time and then calculate how many aircraft cross that fictitious line. Equation 3 shows the aircraft count constraint used in the model. Here the sum of all flight- and ground arcs crossing a *count line* in the time-space network is equal to the size of the eVTOL fleet E. This number must be the same on every time stamp where the line is drawn within the boundaries of the network.

$$\sum_{f\in x_{cl}} x_f + \sum_{g\in y_{cl}} y_g = E \tag{3}$$

Looking again at the example in Figure 1 it can be noticed that it does not matter at what time the line is drawn - at all time steps there are three eVTOL aircraft in the network. This means that this representation of a TSN satisfies the aircraft count constraint. The size of the fleet E is a decision variable that is coupled in the objective function to the purchasing cost of an eVTOL. The model calculates if more profit can be made if an extra aircraft is added to the fleet.

Constraint III: Vertiport Type
An article published by McKinsey & Company in [Johnston et al., 2020] defines three potential infrastructure archetypes for vertiports that could emerge in the future, and gives estimations for building and yearly operating costs: *vertihubs* are the largest with ten active takeoff and landing areas, *vertibases* are medium-sized and have three spaces, and *vertipads* are the smallest with only one place for the eVTOLs to use. The model optimizes the choice in assigning a vertiport type to a vertiport location in the network, which is ultimately a consideration between investment costs en potential revenues. In Equation 4 the constraint is depicted that is used for making this choice. The constraint makes use of decision variable T_v^a which, as seen in Equation 5, has value 1 if a vertiport type a is chosen for vertiport v, and is 0 for the remainder types that are not chosen for that vertiport. It is a capacity constraint where for every vertiport v the flow of flight, ground arc, and wrap-around arcs going into a node belonging to a vertiport, must always be smaller or equal to the capacity of the vertiport. The subset for a group of nodes that belong to a mutual vertiport is denoted by N_v.

$$\sum_{f\in x_n^+} x_f + \sum_{g\in y_n^+} y_g + \sum_{w\in z_n^+} z_w \leq T_v^0 \cdot k_{vh} + T_v^1 \cdot k_{vb} + T_v^2 \cdot k_{vp}, \quad \forall v \in \mathbf{V}, \forall n \in \mathbf{N_v} \tag{4}$$

$$\sum_{a=0}^{3} T_v^a = 1, \qquad \forall v \in \mathbf{V} \tag{5}$$

Equally to the choice for size of the eVTOL fleet, the choice for a certain vertiport type is dependent on the costs of that type. The model makes a consideration between purchasing a larger vertiport type that potentially handles a lot more eVTOL flights and thus creating more revenue on one hand, but having to deal with a lot more building and operating costs. Or choosing a smaller type of vertiport that makes less revenue but is significantly cheaper to built and operate.

Constraint IV: Passenger Allocation
The commuting demand in the network is handled by three travel modes: the eVTOL aircraft, a car, and public transport. Demand D_r represents the number of commuters that want to travel on route r, which is the direct travel path from one specific location to another on a time stamp with a certain travel mode. The eVTOL network wants to transport as many people as possible from the total demand of each route r. Therefore, besides serving the passengers on their preferred time stamp with one of the aforementioned travel modes, commuters also have the chance to be served on neighbouring flights f' of route r. This is a way of serving more people with eVTOLs when capacities of flights are exceeded, creating additional revenue for the ATS network. This can only be done by flights that have the same origin and destination as the desired route r at one and two time stamps later and earlier than r. For each route r in R, there is a list created of neighbouring routes r' ($R_{r'} \subset R$). On

a neighbouring route r' only neighbouring flights f' ($F_{f'} \subset R_{r'}$) are considered to serve passengers originating from their preferred route r, as the other modes option is always present on r and is not capacity constrained. The amount of neighbouring flights f' per route r depends on the locations of the O-D nodes of r within the time horizon. Routes departing at $t = 0$ for instance, only have f_{t+1} and f_{t+2} as neighbours, while flights at the end of the time horizon have f_{t-1} and f_{t-2}. The Figure 2 gives a schematic representation of all possible travel alternatives. The amount of passengers that travel on their preferred route r with an eVTOL aircraft is denoted by the decision variable $q_{f,r}$. Passengers that are served by a neighbouring flight are represented by $q_{f',r}$, where f' can be $f_{t\pm1}$ and $f_{t\pm2}$ based on the location of r in the time horizon. Variable q_r^o are the number of people that travel with other modes on route r - in this case a car or public transport.

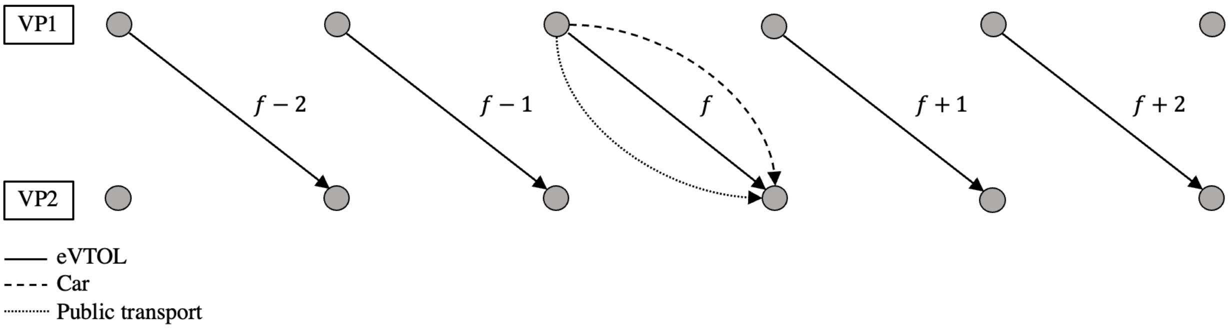


Figure 2: Representation of a flight f and its potential recapture flights in the case of spillage.

The probability for people on r choosing a travel mode or different departure time is modeled with a MNL formulation [Ben-Akiva et al., 1985]. This formulation is based on *utility* values, which are a measure of preference for each alternative for a passenger. A utility function quantifies the preference of an individual based on several attributes. We make a distinction between observed attributes such as the travel time tt and travel costs tc, and unobserved variables such as reliability, comfort, perception of safety, or environmental impact. These unobserved factors form the *alternative specific constant* (ASC) which is the part of the utility that cannot be captured by the other attributes. The ASC differs per travel mode, but is the same for every route per mode. The equations below are the utility function formulations for eVTOL flights, cars, public transport, and neighbouring flights respectively. In the equations the travel time tt is multiplied with parameter vot which represents the *value of time*, referring to the amount of money a commuter's time is worth on average. Transport models often use the value of time to monetize the commuter's travel time related to their socioeconomic background. The paper of [Roy et al., 2022] stated that for a business trip, typically 80-120% of the hourly household income of an individual is taken as the value of time. Because the input is the passenger stream during a typical day of the week, we can assume that most of the people travel for business. In the model the middle of this range is taken, the value of time in the model therefore corresponds to 100% of the average hourly income of the commuters. In addition, the utility of f' in Equation 9 also includes the departing time difference $\Delta t_{f',r}$ between the served flight f' and original route r. The travel costs tc are pre-computed for cars and public transport as there is present data to make an assumption on travel expenses in the future[1]. ATS does however not exist yet, and thus no accurate travel costs can be obtained. Therefore the following equation is used to determine the travel costs for a flight f: $tc_f^{ev} = fare \cdot d_f$. The fare is the price a customer has to pay to the eVTOL network per km flown - this fare is tweaked to perform sensitivity analyses later on. The total costs in the functions are multiplied by a negative weight factor γ [2].

$$u_{f,r}^{ev} = (tt_f^{ev} \cdot vot + tc_f^{ev}) \cdot \gamma + ASC_{ev} \tag{6}$$
$$u_r^{car} = (tt_r^{car} \cdot vot + tc_r^{car}) \cdot \gamma + ASC_{car} \tag{7}$$
$$u_r^{pt} = (tt_r^{pt} \cdot vot + tc_r^{pt}) \cdot \gamma + ASC_{pt} \tag{8}$$
$$u_{f',r}^{ev} = ((tt_f^{ev} + |\Delta t_{f',r}|) \cdot vot + tt_f^{ev}) \cdot \gamma + ASC_{ev} \tag{9}$$

With the MNL an estimation can be made on how many people of the total commuting population will choose to travel with the ATS. The amount of passengers that travel on flight f depends on the utility values and their corresponding attractiveness values. The attractiveness of a flight f is defined by $\theta_{f,r}$, calculated as $\theta_{f,r}$ =exp($u_{f,r}^{ev}$), and $\theta_{f',r}$ = exp($u_{f',r}^{ev}$) for a neighbouring flight f'. We further define θ_r^o as the compound

[1]The travel times and travel costs are obtained from the research of S. Birolini at the University of Bergamo
[2]The value of weight factor gamma is -0.048, which is obtained from the research of S. Birolini at the University of Bergamo

attractiveness of cars and public transport on a route r, thus the other modes: θ_r^o =exp(u_r^{car}) + exp(u_r^{pt}). According to the MNL, the expected market share of f with regards to the other alternatives is:

$$ms_{f,r} = \frac{\theta_{f,r}}{\sum_{f' \in F_{f'}} \theta_{f',r} + \theta_r^o} \tag{10}$$

The probability of a passenger choosing flight f is equal to the ratio of the attractiveness of that flight to the total attractiveness of the other options. Hence, multiplying $ms_{f,r}$ with route demand D_r gives an estimate of the passenger demand on f. The total demand is split strictly according to the attractiveness of all alternatives. The higher the travel costs or travel time of the mode of transport, the more negative the outcome will be due to the negative value of γ. This subsequently results in a lower attraction level. The attractiveness for a potential ATS passenger deviating from its original route r is smaller than the attractiveness of travelling on r due to the addition of $|\Delta t_{f',r}|$ to the travel time in the function.

Constraint V: Capacity

The eVTOL aircraft are seat capacity constrained, meaning there is a maximum amount of passengers that can travel with an eVTOL on a potential flight f. This capacity limitation is captured in Equation 11, which ensures that all passengers flown with an eVTOL aircraft on f must be smaller or equal than the capacity of the aircraft. When f is not flown ($x_f = 0$), the right-hand side of the equation becomes 0, which subsequently forces the amount of passengers on f to be 0. The total passengers on board of a flight can be divided in two segments: the passengers $q_{f,r}$ that originate from r and are actually served on f, and the sum of passengers $q_{f,r'}$ that originate from neighbouring route r' of r, but are served on f.

$$\sum_{r' \in R_{r'}} q_{f,r'} + q_{f,r} \leq k_{ev} \cdot x_f \quad \forall r \in R, \forall f \in F \tag{11}$$

In the formulation of the market share constraint, the demand of route r is split according to the attractiveness of all travel options. However, due to the capacity constraint presented above, some passengers on f might be lost. Also, it is not known beforehand if f will be flown or not - making the MNL nonlinear. To linearize it we replace Constraint 10 with Constraints 12,13, and 14, which are based on the papers of [Birolini et al., 2022], [Zhang et al., 2016], and [Wang et al., 2014]. The first two constraints below represent the passenger distribution of the total demand on route f. They ensure that this demand is served in such a way that the probability of serving is proportional to the attractiveness of the flight. The inequality in the constraints gives room for the passengers to move to other modes, which are not capacity constrained. These constraints remain also feasible when a flight is not flown (e.g., $q_{f,r} = 0$ and $0 \leq (\theta_{f,r}/\theta_r^o) \cdot q_r^o$). Since the other modes option is always present in the model, the passenger demand on a flight is upper bounded based on its size relative to the other modes alternative. The passengers on a flight are automatically adjusted if the flight is flown or not.

$$q_{f,r} \leq \frac{\theta_{f,r}}{\theta_r^o} \cdot q_r^o \quad \forall r \in R, \forall f \in F \tag{12}$$

$$q_{f',r} \leq \frac{\theta_{f',r}}{\theta_r^o} \cdot q_r^o \quad \forall r \in R, \forall f' \in F_{f'} \tag{13}$$

$$\sum_{f' \in F_{f'}} q_{f',r} + q_{f,r} + q_r^o = D_r \quad \forall r \in R \tag{14}$$

Demand Constraint 14 imposes that the passengers originating from route r that are served by all travel alternatives presented in Figure 2 must be equal to the total demand D_r of that route. These passengers are subdivided in the sum of commuters $q_{f',r}$ originating from r but served on neighbouring flights f', the people $q_{f,r}$ that fly on their preferred route, and the passengers q_r^o of the other modes on r.

5 Description of the Case Studies

The model is applied to a real-world case study of the Milan metropolitan area, also known as "Grande Milano". It is an area of around 13,000 km^2 containing a population of about 9 million, with Milan as its largest city. The goal of this case is to investigate eVTOL operations in the area by assigning a vertiport type to each vertiport location, and scheduling passenger flows to get an estimation of future revenue streams and the cost structure. The model uses the commuting flow during an average weekday in the year 2020 to create a flight schedule. This section elaborates on the the locations used in the model, the vertiport types placed on these locations, the commuting flow, and the type of eVTOL assigned to the operations.

Location of Commuting

The model uses locations that represent the origins and destinations for commuting in Milan and its surroundings. The research, that acts as a foundation for the case study, has obtained the OD's by narrowing dense commuting areas down to clusters using K-means clustering [3]. This algorithm aims to divide a given set of data points, here the commuting areas of the Milan Metropolitan area, into K clusters. By taking the mean of every location within a cluster the centroid of this cluster is calculated, which corresponds to the optimal location for commuting within a region. Because of this approximation, the locations used in the model differ from the commuter's actual origin and destination. For sake of simplicity ten locations are chosen, which are shown on the map in Figure 3. These form the starting or ending points for commuters, hence also the vertiport locations for the air taxi service. The shortest distance between two vertiports is 6,7 km and the longest is 56,9 km.

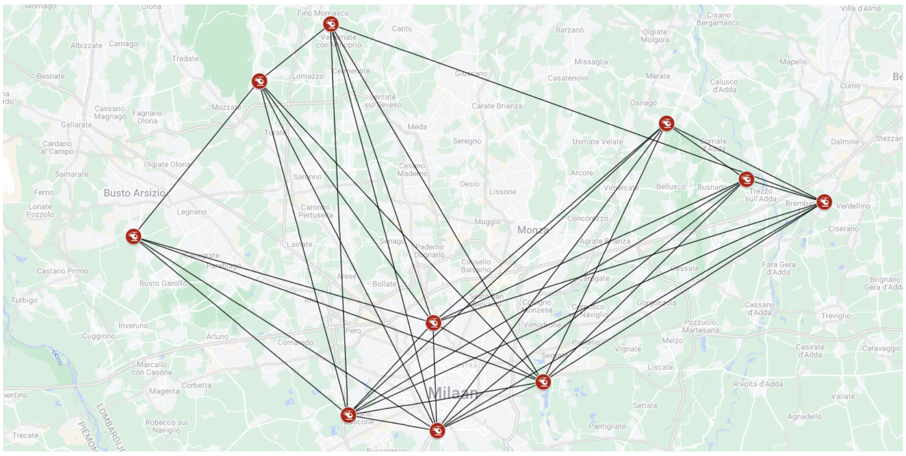


Figure 3: Schematic representation of Milan metropolitan area with all vertiports and available routes.

Vertiport Types

The model described in this research optimizes what vertiport type suits the locations best. The idea to assign a type of vertiport to a location in the network came after reading the McKinsey & Company article 'To take off, flying vehicles first need places to land'. In the article, the consulting company envisions three potential infrastructure archetypes for urban air mobility that could emerge: *vertihubs*, *vertibases*, and *vertipads*. The specifications of the vertiport types are as follows:

- Vertihubs are the largest structures, having ten takeoff and landing areas, plus 20 additional spaces that can be used for maintenance or parking the eVTOL. According to the article, vertihubs will be stand-alone buildings situated in central areas with high levels of traffic.
- Vertibases are medium-sized structures, and will have three takeoff spaces and six parking and maintenance spots. Vertibases will be newly built or placed on existing structures such as parking garages, and will be located in suburbs or retail locations with medium-high levels of traffic.
- Vertipads are the smallest structures, which can handle only one vehicle landing or taking off at a time, while having two areas for parking or maintenance. Vertipads will also be newly built or retrofitted on existing buildings, located in suburbs.

Each location in the area is assigned one the three aforementioned vertiport types.

Commuting Flow

According to the study, the total commuting flow in 2020 was around 4.88 million per day. The ten locations used for the case study encompass almost a quarter of the total commuting population. The people in the network travel point-to-point and in straight lines, thus no buildings, bridges or other vehicles interfere with the trip. Travel from a location to another happens in both directions, without interfering one another. In the map some locations are not connected, which means there is no commuting flow between these areas. As explained in Section 4.2, a commuter has three transport options: travel by car, public transport, or ATS. The willingness to travel with one of the modes on a certain timestamp depends on utility values calculated with the Equations 6, 8, 7, and 9. The value of time used in the equations is equal to the average hourly household income in Milan, which corresponds to €20/hr. As the air taxi business is not existing yet, there is no information on how to give ASC_{ev} a value with regards to the others modes. Therefore, all alternative specific constants are set to 0. In Appendix B an explanation can be found on what the input data of passenger flow looks and how it is

[3] The locations used in this paper are obtained from the research of S. Birolini at the University of Bergamo

handled in the model. Also the data for other modes is depicted in the same appendix.

eVTOL Type
This model uses the parameters of the CityAirbus Nextgen eVTOL aircraft, flying at a cruise speed of 120 km/hr and operating on an 80-km range. This eVTOL is based on a lift-plus-cruise concept, which is suited for operations in the Milan metropolitan area. It is a compromise between the multirotor concept that excels in hovering, but flying short ranges (<10 km), and the vectored thrust configuration that is efficient in cruise flight and therefore flies long ranges (>100 km). The Nextgen has a seat capacity of four - three for revenue passengers and one for the pilot controlling the aircraft. It is believed that eventually pilots will be replaced by autonomous kits, which gives room for one more revenue passenger in the future. It is designed for quiet flights, allowing for a smooth integration in the urban area.

6 Results

In this section the outcome of the MILP is presented, with network profits of the Milan metropolitan area as objective. A sensitivity analysis is performed that addresses the charged fare to passengers, as this is one of the largest uncertainties in the model. Sensitivity analysis allows to quantify the impact of the fare on the model's output, and thus provide insight in the model's behaviour. By varying this parameter in a specific range we can observe how it affects the ATS network, and what commuters are willing to pay. In addition, pricing strategies are applied to achieve a higher profitability for the network.

6.1 Sensitivity Analysis

One of the most important aspect for investors or entrepreneurs before engaging in a new business is to investigate whether it is going to be worth it or not. In other words, will the ATS network be profitable? In the following analyses the fare is used as a variable input to measure the impact to the model, while the rest of the parameters are fixed. The fare is the amount of money a customer has to pay the eVTOL network per kilometer to travel with the ATS, and is written as € /pax·km. Changing the fare gives an idea of how the model behaves and what the optimal price is in terms of highest network profit. Table 3 shows all parameters used for these sensitivity analyses.

Financials & GPM
Figure 4 is a plot of the revenue, costs and profit for multiple fares range € 2 to € 16/pax·km, with € 0,50 intervals. The profit is the difference between the revenues obtained from flying eVTOL pax to their destination during the day, and the costs for operating and purchasing the eVTOLs and vertiports. The profit plot shows that the optimal fare which achieves the most amount of profit per day is € 11/pax·km. The profit reached with this fare is € 72,265 per day which is obtained with a revenue of € 239,015 and costs of € 166,750. The graph in the plot climbs to this peak-profit and from there on declines again - the figures below support this trend. Figure 5 provides a graph of the gross profit margins (GPM) per fare. It is a financial metric to measure the profitability of the eVTOL network operations, and is used as an indicator to value the networks efficiency in generating this profit. It is calculated as follows: gross profit margin = (revenue - COGS)/revenue*100%. COGS refers to the cost of goods sold, which embeds all costs directly associated with the air taxi service, thus in this case all vertiport and eVTOL related costs. In this graph can be seen that the highest profit margin of ~51% is obtained when introducing a fare of € 6/pax·km. At the peak profit at a € 11/pax·km, the gross profit margin is around 30%.

Costs & Pax
In Figure 6 the four cost segments are shown that add up to the total costs in Figure 4. These are the daily costs for vertiport operations, eVTOL operations costs, purchasing vertiports, and purchasing the eVTOL fleet. What immediately stands out is the vertiport operating costs that are significantly higher than all other costs. All cost components grow with a larger fare until the peak at € 11/pax·km is reached, and drop again after this price. However, the vertiport operational costs grow a lot faster than the other costs segments. Where at a lower fare of € 2/pax·km the vertiport operational costs make up for 79% of the total costs, at peak fare € 11/pax·km this is almost 91%. A thorough explanation about the vertiport operational costs is given in C. Figure 7 shows the number of passengers that are transported by eVTOL aircraft during a day per change in fare. The higher the fare, the more pax are served, a peak at € 9.5/pax·km. After fare € 11/pax·km the graph drops significantly. It takes somewhat the same shape as the revenue curve in Figure 4, which makes sense as the transported passengers are the only revenue stream in the network.

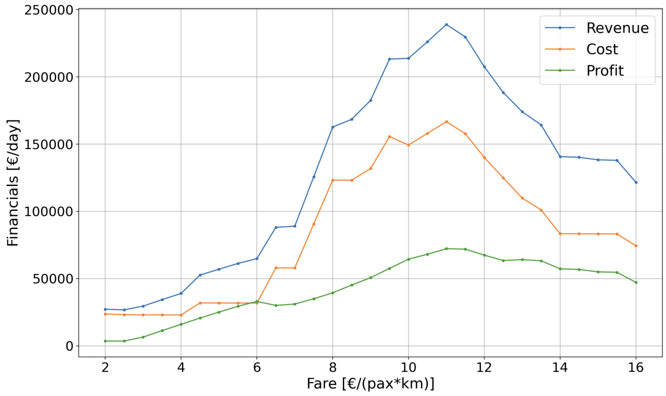


Figure 4: Profit, revenue and costs per day per fare.

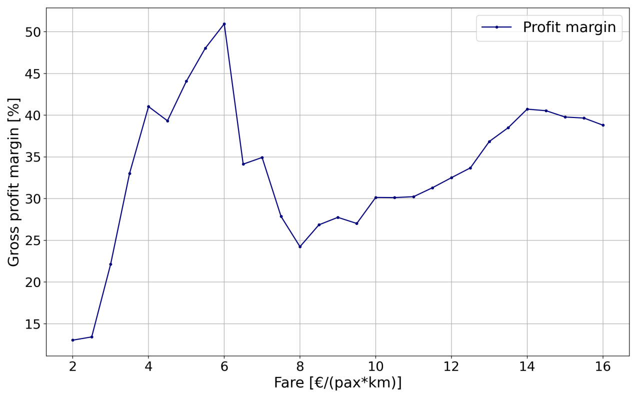


Figure 5: Gross profit margin per fare.

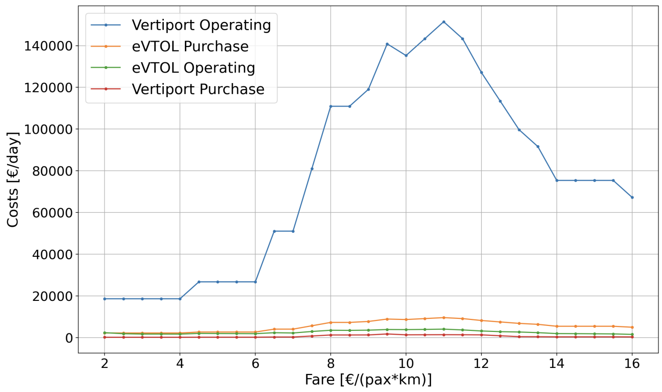


Figure 6: Costs for eVTOLs and vertiports per fare.

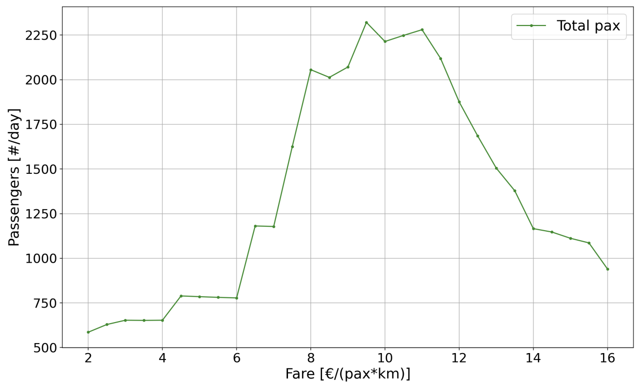


Figure 7: Number of passengers per day per fare.

Vertiports & Fleet size

Figure 8 gives insight in the composition of vertiport types of all vertiports in the network. For fares €2 to €4/pax·km the network consists of only *vertipads* with a maximum handling of 1 eVTOL aircraft at a time. At fare €5/pax·km the first *vertibase* is 'built' in the city which has space for 3 eVTOLs. At €8/pax·km a *vertihub* is introduced to the network, which handles a maximum of 10 eVTOLs at a time. This correlates with the vertiport costs in Figure 6 - the larger vertiport types are significantly more expensive to operate than smaller vertiports. After a fare of €12/pax·km the vertihubs are becoming too expensive and make room for vertibases and thereafter vertipads. Figure 9 depicts the size of the fleet of eVTOL aircraft in the network. The fleet grows with each fare until the peak at €11/pax·km is reached with a fleet size of 42 aircraft. The fleet size follows a similar trend as the vertiport types plot. When fares give the same vertiport type output, the fleet size also stays the same. This is the case for fares €2, €3, and €4/pax·km where the vertiport types stay the same and the eVTOL fleet remains constant, but also for fares €14 and €15/pax·km. Thus the size of the fleet is very dependent on the composition of the vertiports in the network and vice versa. This can also be noticed by the considerable fleet increase of 14 eVTOLs between fares €7 and €8/pax·km, which is the moment a vertihub is introduced which has more space for eVTOL operations. The more people are willing to pay per kilometer, the larger, thus more expensive, vertiport types the model can place on the given locations, and the larger the eVTOL fleet can be. This results in handling more passengers per day and earning more profit for the network. When fares increase, the travel costs tc_f^{ev} for people travelling with an eVTOL also rise. This causes the values of utility functions Equations 6 and 9 to become more negative and subsequently the attractiveness values $\theta_{f,r}$ and $\theta_{f',r}$ to become smaller, while the attractiveness of other modes θ_r^o stays the same. Until the fare of €11/pax·km the benefits of a higher fare outweigh the downside of a lower attractiveness value. However, above this price the attractiveness value for travelling with the eVTOL aircraft becomes to small and people start to prefer the other modes option over the eVTOL. This results in transporting less passengers, thus less potential revenue. To cope with this the model switches back to smaller vertiports and a compacter fleet to keep the profits as high as possible.

Distances & Flights

Figure 10 depicts the total and average distances that are flown in the network during one operational day per fare. The blue graph in the plot depicts the total distance flown, which is the combined travel distances flown by the eVTOLs. Just like the aforementioned figures, also this one peaks at a fare of €11/pax·km. The

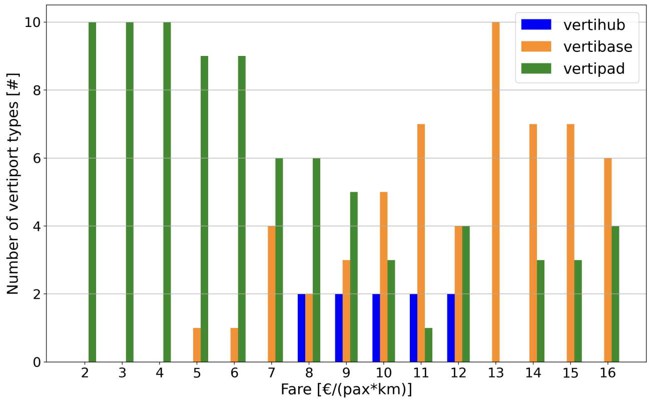


Figure 8: Composition of vertiport types per fare.

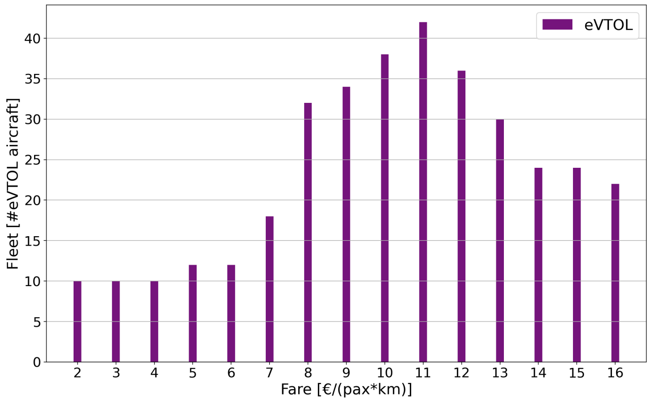


Figure 9: Fleet size per fare.

network at this fare has 2 vertihubs and 7 vertibases, and also the largest eVTOL fleet of all fares. Therefore more flights can be flown and subsequently more distance can be covered in total by the eVTOLs. The orange graph in this figure is the average distance that is flown by eVTOLs in the network. Interesting to see is that the average distance flown is much lower than the average distance (28 km) between all locations in the network. This means that the shorter routes are flown significantly more than the longer routes. It even becomes more significant when the fare increases - the higher the fare, the less distance is covered by the aircraft. Figure 11 shows the number of flights that are flown during a total day of operations per fare. This purple line represents all flight flown which coincides with the revenue and total pax graph in Figures 4 and 7 respectively. The most flights are flown at fare €11/pax·km when the size eVTOL fleet is the largest of all fares.

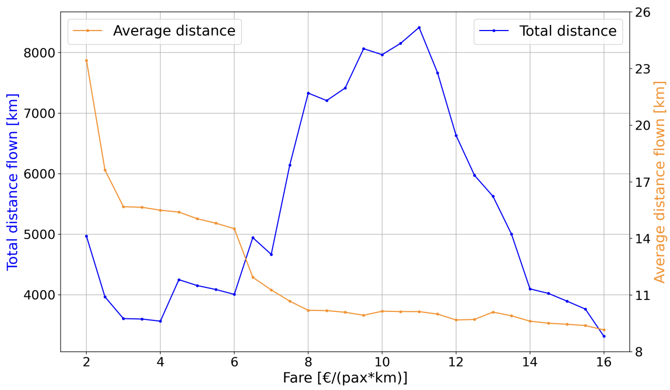


Figure 10: The total and average distance flown per fare.

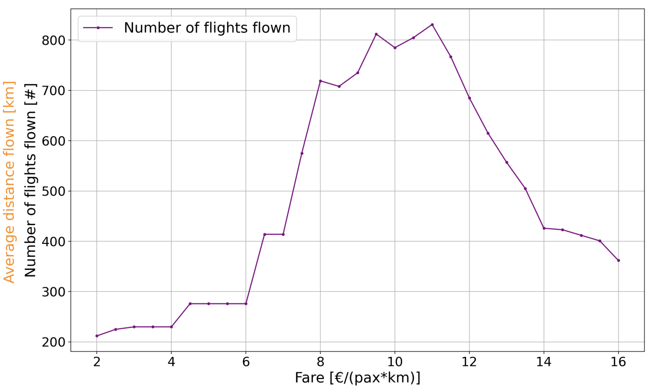


Figure 11: Number of flights flown per fare.

Load factor & Demand served by ATS

The top line of Figure 12 represents the average load factor (LF) of flights in the network per day per fare. The LF is calculated with $LF = \sum_{f \in F} pax_f / (\sum_{f \in F} x_f \cdot k_{ev}) \cdot 100\%$, where $\sum_{f \in F} pax_f$ represents the total amount of pax on served by the ATS, $\sum_{f \in F} x_f$ the total number of flights flown, and k_{ev} the seat capacity of the eVTOL. Thus, dividing the total pax by the number of seats available of all flights flown. In the analysis, the LF stays above 85% for each fare, meaning that on average more than 85% of the available eVTOL capacity of 3 passengers is being utilized, which corresponds to an occupancy rate of around 2.55 pax per eVTOL. Thus, the air taxis are carrying a substantial number of passenger relative to their capacity. Between fares €3 and €10/pax·km the LF stays relatively constant at 94%, which means that there are on average 2.82 pax per air taxi at these fares. In a real-time case a LF approaching 100% utilization could lead to challenges, such as longer waiting times or unmet demand at peak hours. There should be a balance between the fluctuating demand with the available supply. The other line in Figure 12 is the passenger load factor that is required for each fare to reach its break-even point, thus the minimal amount of people that need to be transported per eVTOL to make the network profitable. To calculate this, the costs are set equal to the revenues obtained, thus at a profit of €0. The break-even load factor is defined by $BE_{LF} = C_{tot} / (fare \cdot d_{avg} \cdot \sum_{f \in F} x_f \cdot k_{ev}) \cdot 100\%$, where C_{tot} represents the total costs made throughout one operating day - including all eVTOL and vertiport costs - and d_{avg} the average distance flown by the ATS. By doing this calculation for each fare, we know what the minimal occupancy rate must be to break-even with the costs made in the network. If the average LF in the network is higher than the break-even LF, the network makes profit. The BE_{LF} at €6/pax·km is around

44%, which is the lowest result of all fares, and corresponds to an occupancy rate of 1.32 pax for every 3 seats available. Most fares have a break-even load factor between 50 and 70%. The peak fare €11/pax·km has a BE_{LF} of 60%, which are 1.80 pax per eVTOL flown. The greater the difference between the break-even load factor and the actual load factor, the more room there is to deal with unexpected changes in demand. The largest gap between the two can be found again at fare €6/pax·km, which is almost 50%. Figure 13 depicts what percentage of the total commuting demand is covered by the ATS. The shape once more corresponds with other plots, such as Figure 7 and 11. This makes sense, as the more passengers are flown, the higher the ATS percentage is of the total demand. This plot is especially made to give an insight in how small the passenger flow for the air taxi service is compared with the other transport modes. At highest, only 0.19% of the total population is flown. The impact on traffic congestions is thus assumed to be very small, and therefore limiting the effect on greenhouse gasses.

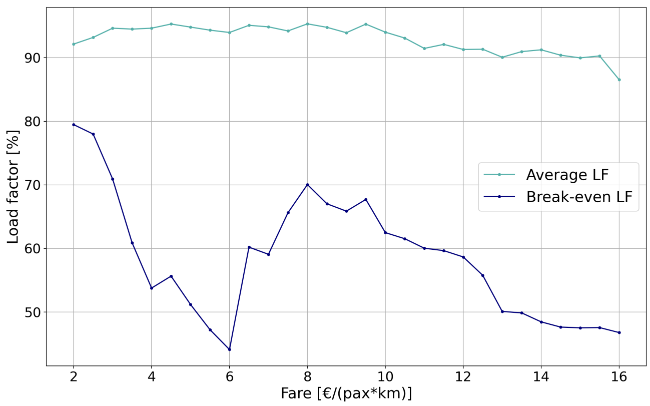


Figure 12: The average and break-even LF per fare.

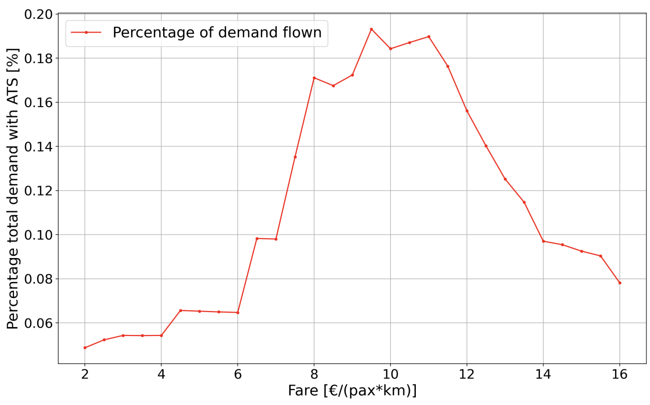


Figure 13: Percentage total demand flying with ATS.

Travel times & Travel costs

The last two plots are created to compare the three travel modes. Figure 14 shows three graphs of the average travel time for each travel mode per fare. For the ATS this is calculated by taking the average of the sum of the distances of all flights flown and dividing it by the cruise speed. For the other modes the travel time considered is pre-computed. Only the values are used of the routes r that match the flights flown f, thus having the same origin, destination and departure time. This is done to better compare the three modes. In the figure can be noticed that the travel time for public transport is the highest, then the car, and the lowest travel time is achieved by eVTOL flights. The decrease in travel time at higher fares coincides with the shorter routes that flown on average at higher fares, as can be seen in Figure 10. Figure 15, which depicts the average travel costs for a commuter for each transport mode per fare. As the car and public transport are not dependent on a variable fare, the costs stay relatively the same for each fare. Taking the average over all fares, a trip with the car costs €2.91, and for public transport this is €4.78. An average trip with the eVTOL is significantly more expensive than with other modes. For a fare of €2/pax·km, an average trip with the ATS would cost a passenger €46.88. At fare €9/pax·km the costs are more than doubled to €94.36 per flight. What can be concluded from these two figures is that the travel duration with the ATS will on average be shorter than for other modes, but the costs are significantly higher for a trip with the eVTOL.

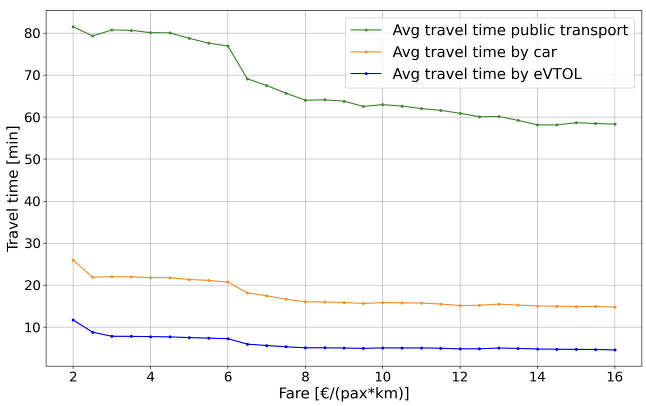


Figure 14: Average travel time of transport modes.

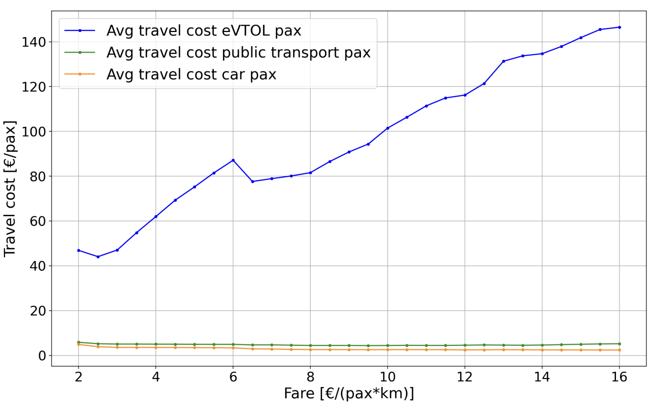
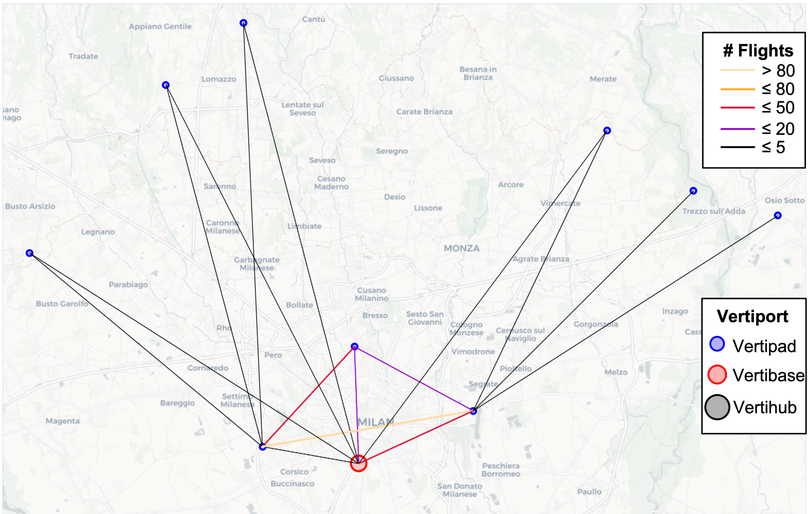


Figure 15: Average travel costs of transport modes.

Main Outcomes of the Sensitivity Analysis
From all plots in this sensitivity analysis can be concluded that for maximum profits the network should handle a fare of €11/pax·km. This also results is the most amount of flights flown, and almost the highest number of pax transported. Apart from these results obtained, there are a couple of risks that fare €11/pax·km brings along. At this fare, 2 vertihubs and 8 vertibases must be built and operated, which is a very large and expensive infrastructure project. Additionally, a fleet of 42 eVTOL aircraft must be bought to transport pax. A lot of cost have to be made in order to make profits and maintain a gross profit margin of 30%. With still a lot of uncertainties in this subject, it could be a large risk to invest in such a large network. This risk can be mitigated by creating a network where the charged fare is €6/pax·km. For this fare only 1 vertibase must be built, and a fleet of 12 eVTOLs is needed. In addition, it has the highest gross profit margin of 51% and the lowest break-even load factor 44% of all fares in the analysis. With the large difference between the LF and the break-even LF at this fare, the network can cope better when at times demand is lower than expected. And with a price of €6/pax·km it is easier to compete with prices of normal taxis. Also can be concluded that the impact on traffic is expected to be low as only a small fraction of the total commuting demand is served by eVTOL aircraft. The industry will be a luxury travel opportunity, as the travel costs are significantly higher for the ATS than for other modes.

6.2 Pricing Strategies

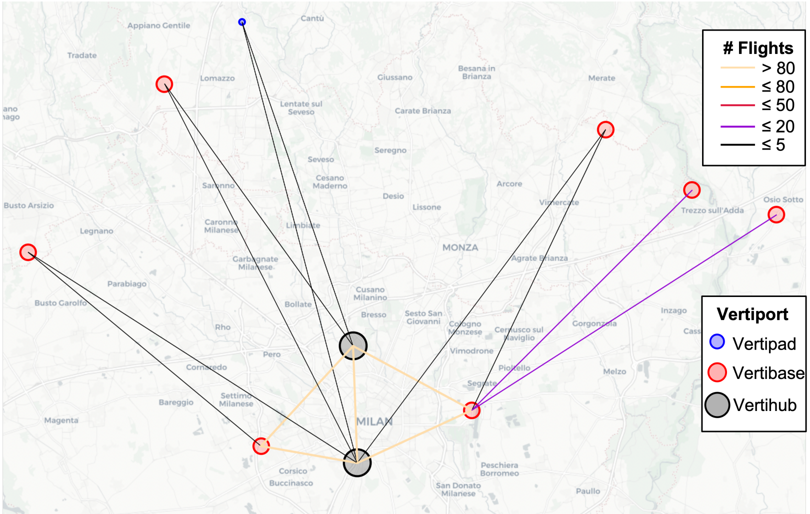
To gain more profit from passengers travelling through the network with the ATS, ad-hoc strategies could be exploited that target specific OD pairs (spatial component) and/or specific times of the day (temporal component) by applying changes to reference fares €6 and €11/pax·km. For the analyses, the vertiport configuration at each of the two fares are fixed. This way we can see more accurate if the strategy applied improves the profits in the network, without changing the types of vertiports at the locations. The eVTOL fleet is not fixed, which means that the size can be adjusted if it happens to be favourable for the network. Before applying the strategies to the reference fares, it is important to understand the outcome of these fares in the network. The eVTOL flow of the optimized flight schedule and other results for reference fares €6 and €11/pax·km are visualized in Figures 16 and 17.



Description	Result	
Fleet size	12	[-]
Vertihubs	0	[-]
Vertibases	1	[-]
Vertipads	9	[-]
Revenue	64,859.66	[€/day]
eVTOL operate	1,971.38	[€/km]
eVTOL purchase	2,761.64	[€/day]
Vertiport operate	26,801.37	[€/day]
Vertiport purchase	278.40	[€/day]
Network profit	33,046.86	[€/day]
Total pax	778	[-]
%Pax total demand	0.065	[%]
Total flights	276	[-]
Average LF	93.96	[%]
Total distance	4,007.37	[km]
Average distance	14.52	[km]
GPM	50.95	[%]

Figure 16: Results of applying fare €6/pax·km to the network.

The figure above displays the map of the Milan metropolitan area with the ten fixed vertiport locations throughout the network. On each location one of the three vertiport sizes is placed, where a blue dot represents a vertipad, a red dot the vertibase, and a larger black dot the vertihub. Each line depicts a flown route between two vertiports - a route without any flown flight on it is not shown on the map. The amount of the flights travelling on a route in both directions is connected to a color, which can be seen in the legend of the figures. This way we visualize what the flight density is between vertiports. In Figure 16 the outcome of the ATS network is shown when a fare of €6/pax·km is used. The model places 9 vertipads and 1 vertibase on the locations. The most amount of flow is around the city of Milan, where also the vertibase is located. Routes to vertiports further away from the center have less flow on them. The map of the optimal fare of €11/pax·km can be seen in Figure 17. For this fare the model now places 7 vertibases, 2 large vertihubs, and only 1 vertipad. Both vertihubs are located near the Milan city center, where there's even more flow than at fare €6/pax·km. Again, there are only a few flights going to locations outside the center of the area.



Description	Result	
Fleet size	42	[-]
Vertihubs	2	[-]
Vertibases	7	[-]
Vertipads	1	[-]
Revenue	239,015.36	[€ /day]
eVTOL operate	4,140.10	[€ /km]
eVTOL purchase	9,665.75	[€ /day]
Vertiport operate	115,458.90	[€ /day]
Vertiport purchase	1,483.42	[€ /day]
Network profit	72,267.17	[€ /day]
Total pax	2,280	[-]
%Pax from demand	0.19	[%]
Total flights	831	[-]
Average LF	91.46	[%]
Total distance	8,415.88	[km]
Average distance	10.13	[km]
GPM	30.24	[%]

Figure 17: Results of applying fare €11/pax·km to the network

The high demand for shorter flights can be noticed by the larger flow between the four vertiports located near the city of Milan. This correlates to the low average distance covered in the network per eVTOL, and the decline of the plot for higher fares in Figure 10. A probable reason for a lower demand for longer distances is that there is not a lot of initial travel from the places located further from the center of the Milan metropolitan area. The four locations near the center act for more than 93% of all routes as the origin of a commuter's trip.

6.2.1 Strategy 1: Short Routes

The network could take advantage of the higher demand on short routes. In this analysis the fare is varied for routes that are shorter than 20 km, which included the four locations closest to the city of Milan. The longer routes use the reference values of €6 and €11/pax·km as their fare, depending on which fare the analysis is performed. We will explore what happens if people are charged more than the reference value for shorter routes. As stated above, the vertiport configurations stay the same for the network per reference fare, but the eVTOL fleet size is adjustable. The other modes option is still always available per route, and is not adjusted in terms of costs. Figures 18 and 19 show the results for applying higher fares for short routes for reference fares €6 and €11/pax·km respectively. In the profit analysis for reference fare €6/pax·km, the fare for commuters travelling on short routes is varied between €7 and €20/pax·km with €1 intervals. In the plot can be seen that the profit increases when this strategy is applied to reference fare €6/pax·km, with a maximum of 40.5% if shorter routes pay €13/pax·km. In the analysis for reference fare €11/pax·km people pay a varied fare between €12 and €19/pax·km with intervals of €1. The profit declines when people have to pay a larger fare for shorter routes. This means that a fare of €11/pax·km is still the optimal price to be paid for a maximum profit.

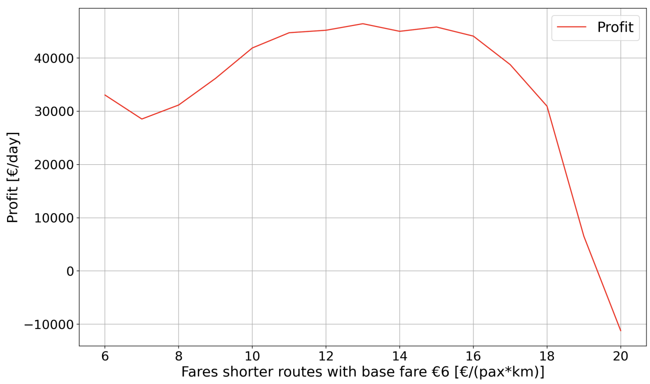


Figure 18: Short route strategy fare €6/pax·km.

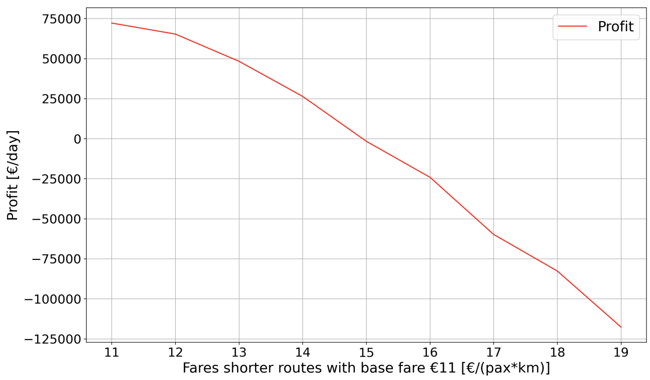


Figure 19: Short route strategy fare €11/pax·km.

6.2.2 Strategy 2: Rush Hours

A different strategy often applied by taxi companies like Uber to earn more profit is to raise the prices at certain times when demand is higher. In the case of an air taxi service this could be applicable to rush hours at which more people want to travel than outside of these hours. The demand used in the model is ∼3.3 times higher during the rush hours than during the rest of the day. The profit generated by the network is for one operating weekday, therefore the average rush hours correspond to a typical workday in the Milan metropolitan area, which is between 7:30 and 9:30 AM, and 5:00 to 7:00 PM. In this analysis the fares are increased for people that have their time of departure within one of the rush hour time blocks. The increased fare is applied to both rush hour blocks, and outside these hours the reference fare is maintained. Figures 20 and 21 show the results for applying this strategy to each of the reference fares €6 and €11/pax·km respectively. In the first figure the rush hour strategy is applied to reference fare €6/pax·km with a variable fare for the rush hours between €7 and €20/pax·km with intervals of €1. Applying this strategy to €6/pax·km generates more profit in many cases. Fare €15/pax·km achieves the highest amount, resulting in a maximum increase in profits of 11% compared to the profits of the reference fare. Hereafter, the profit starts to decline again, meaning that the fare is getting high for potential passengers. In the second figure the profit graph of reference fare €11/pax·km is depicted when the rush hour strategy is applied. The fare for rush hours is varied between €12 and €19/pax·km. Also here an increase in profits is achieved. When people have to pay the ATS a fare of €13/pax·km, the profits increase with 7% compared to the reference fare results without strategy applied. After this fare the graph starts to decline.

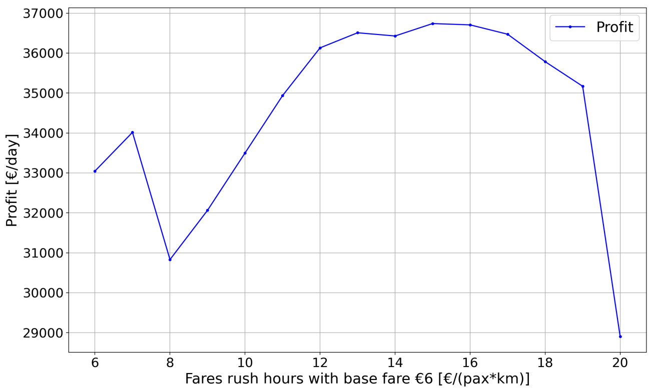


Figure 20: Rush hour strategy fare €6/pax·km.

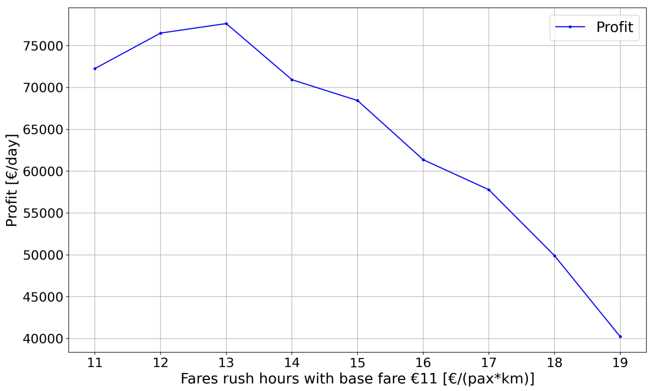


Figure 21: Rush hour strategy fare €11/pax·km.

7 Conclusion and Recommendations

In this paper a model is proposed to assess profitability of a future air taxi service for eVTOL aircraft in Milan metropolitan area for one operating day. A flight schedule is created with commuting demand data of 2020, while also integrating the choice for assigning a suitable vertiport type to each of the ten given commuting locations. In the flight scheduling model a passenger discrete choice is embedded, which uses passenger preferences to determine the level of attractiveness of a travel option. The commuter will travel with the ATS or with the other modes option (car or public transport) based on the attractiveness of the modes. The optimal schedule, size of the fleet, and the vertiport type configuration throughout the network is obtained by the constructed MILP model with a time-space network as backbone. The objective of the MILP is network profitability, which is an interplay between revenues collected from transporting as much commuters as possible, and vertiport and eVTOL costs on the other hand.

Due to the novelty of the subject, the model is based on many assumptions. How much people actually will be paying for travelling with the air taxi service is one of the biggest issues. Therefore, a sensitivity analysis is performed on the fare, which is the price a person has to pay the ATS per kilometer flown. The higher the fare, the larger vertiport types and eVTOL fleet can be bought to create more revenue by the increase in number of pax transported. This analysis resulted in finding a maximum network profit at a fare of €11/pax·km with a load factor of 92%. At this fare, the vertiport configuration would be: 2 vertihubs, 7 vertibases, and 1 vertipad. The operations are handled by a fleet of 42 eVTOL aircraft. Up to this fare, people are still willing to pay, but after this tipping point the profits start to drop. Besides resulting in the highest profit for the network, maintaining a fare of €11/pax·km could also be risky due to large investment costs and uncertain demand fluctuation. In addition, with a large average travel cost of almost €115 per trip, it is harder to compete with the other modes. With a gross profit margin of only 30% there is not a lot of room to move. It could be an option to create a network based on a fare of €6/pax·km. Smaller investment costs are needed and the high profit margin of 51% and smallest break-even load factor of all fares analyzed contribute to the resilience of the network when demand is lower than expected. Compared to other transport modes, the travel time for an eVTOL in the network is much smaller. At a fare of €6/pax·km for instance, the travel time for an average eVTOL flight is 6 minutes, while it takes the car 18 minutes and public transport almost 70 minutes. The costs are on the other hand significantly larger. Where at fare €6/pax·km the car and public transport costs are €2.94 and €4.69 on average per trip, a flight with an eVTOL costs €77.63.

Two pricing strategies are applied to reference fares €6 and €11/pax·km. The first one is based on the output of average distance flown. The strategy is to apply a higher fares for people that take short flight, as we have seen that the demand for these flights is high. When this is applied to the reference fare €6/pax·km, profits can be improved by 40.5%. For fare €11/pax·km the strategy does not cause any improvement. The second pricing strategy focuses on the rush hours in the city, when overall demand is more than 3 times higher than during the rest of the day. Applying a higher fare to these rush hours can increase the profits of reference fare €6/pax·km with 11%, and for fare €11/pax·km around 7%. Besides these two strategies, a next strategy could be to add certain premiums to customers, such as integrated taxi rides from their doorstep to the vertiport.

Besides applying different strategies, several extensions to the model are possible. In future research, the TSN could be further improved upon. In the TSN the turnaround time is now embedded in the flight time. This means that the total length of a flight leg in the TSN is the flight time plus TAT. To make the model more accurate, a second set of ground arcs could be created that are explicitly for the TAT, while the original ground arcs only serve as the moments before landing and take-off. Also the TAT itself could be improved upon. In the model an average of 51 minutes is taken for the TAT, which is applied to every flight flown. The most time-consuming part of the TAT is the refueling of the aircraft. In a real situation, the battery of the eVTOL will not be 100% charged at the origin and 0% at the destination. The refueling should be dependent on the battery level before the flight, the amount of pax on board, and the distances of the upcoming flights. Another approach could also be to look at the impact of battery swapping to the model. A comprehensive research on the energy topic is to add power grid considerations. The focus will be on determining if the current grid is sufficient to provide the required energy level for eVTOL aircraft in the network, and if it is possible to charge multiple eVTOLs at a time per vertiport.

In addition, future research should look in to applying more accurate travel times times to the ATS pax. The ten locations given are formed by clustering regions of commuting within the Milan area and taking the middle of each cluster as an origin or destination of the commuters. For people traveling with the car or, to some extend, public transport, this is a correct method as these modes are close to houses. However, for vertiports this likely is not the case - people have to travel a certain amount of time to a vertiport, undergo a check-in and briefing before the flight starts. Adding the average travel time to the vertiport location will certainly be a good extension of the model. Furthermore, increasing the temporal scale of the model is also recommended. The model takes only one one operational day into account. To get a better indication of the real-life feasibility of such a network, it is paramount to know what the predicted flow will be during the weekend, different months or seasons of the year, and if the acceptance for ATS grows over the years. Future work can more accurately determine passenger flows as a function of the day of the week and/or season, together with more accurate prices for building vertiports and purchasing eVTOLs as well as operating costs (such as energy prices), to investigate the optimal network composition.

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Appendices

A MILP Formulation

$$\max \quad \mathcal{P} = \sum_{f\in F} d_f \cdot fare \cdot (q_{f,r} + \sum_{f'\in R_{r'}} q_{f,r'}) - \sum_{f\in F} C^{ev}_{ops} \cdot d_f \cdot x_f - C^{ev}_{pur} \cdot E$$

$$- \sum_{v\in V} T^0_v \cdot (C^{vh}_{pur} + C^{vh}_{ops}) + T^1_v \cdot (C^{vb}_{pur} + C^{vb}_{ops}) + T^2_v \cdot (C^{vp}_{pur} + C^{vp}_{ops})$$

s.t.

$$\sum_{f\in x_{n^+}} x_f + \sum_{g\in y_{n^+}} y_g + \sum_{w\in z_{n^+}} z_w = \sum_{f\in x_{n^-}} x_f + \sum_{g\in y_{n^-}} y_g + \sum_{w\in z_{n^-}} z_w \qquad \forall n \in N$$

$$\sum_{f\in x_{cl}} x_f + \sum_{g\in y_{cl}} y_g = E$$

$$\sum_{f\in x_{n^+}} x_f + \sum_{g\in y_{n^+}} y_g + \sum_{w\in z_{n^+}} z_w \leq T^0_v \cdot k_{vh} + T^1_v \cdot k_{vb} + T^2_v \cdot k_{vp} \qquad \forall v \in V, \forall n \in N_v$$

$$\sum_{a=0}^{3} T^a_v = 1, \qquad \forall v \in V$$

$$q_{f,r} \leq \frac{\theta_{f,r}}{\theta^o_r} \cdot q^o_r \qquad \forall r \in R, \forall f \in F$$

$$q_{f',r} \leq \frac{\theta_{f',r}}{\theta^o_r} \cdot q^o_r \qquad \forall r \in R, \forall f' \in F_{f'}$$

$$\sum_{f'\in F_{f'}} q_{f',r} + q_{f,r} + q^o_r = D_r \qquad \forall r \in R, \forall f \in F$$

$$\sum_{r'\in R_{r'}} q_{f,r'} + q_{f,r} \leq k_{ev} \cdot x_f \qquad \forall r \in R, \forall f \in F$$

$$x_f \in \{0,1\}, \quad y_g \geq 0, \quad z_w \geq 0, \quad T^a_v \in \{0,1\}, \quad q_{f',r} \geq 0, \quad q_{f,r'} \geq 0, \quad q_{f,r} \geq 0, \quad q^0_r \geq 0$$

B Data Handling

In this appendix an explanation is given on what the data input for this model looks like and how it is handled. In Figure 23 a small part of the demand data for traveling in the Milan area is depicted. This Excel sheet includes only the demand between the ten regions chosen for this model. As said earlier in the paper, these ten locations make up for almost a quarter of the entire commuting population through the Milan metropolitan area. The first two columns represent the origin and destination clusters numbers respectively, thus the origin and destination locations for a route in the network. The following four columns are the origin and destination latitude and longitude, which are used to calculate the next column, the distance of the route. The locations of departure and arrival are the same for every mode of transport. The 'pax_daily' column is the sum of all people travelling on that specific route during the day. In the last set of columns all the passengers can be found that travel on a certain route per hour. The time line of operating is one day, thus 24 one-hour blocks of passenger data is given per route. However, in this research time steps of 10 minutes are used for the time-space network. The hours are divided in 10 minutes intervals, and the passengers that travel from one point to another within an hour are divided proportionally over these six time blocks.

cl_x	cl_y	cl_x_lat	cl_x_lng	cl_y_lat	cl_y_lng	distance	pax_daily	00:00-00:59	01:00-01:59	...	22:00-22:59	23:00-23:59
5	13	45,7368316	9,060344851	45,5160821	9,16888795	26,516	324,52	2,96	0,39	...	0,59	0,27
5	30	45,7368316	9,060344851	45,4475276	9,0790968	28,722	118,37	1,06	0,16	...	0,19	0,06
...	...	...	...	...	...	...	...	...	...	...	...	...
13	5	45,5160821	9,168887946	45,7368316	9,06034485	25,708	243,75	0,25	0	...	5,25	6,27
13	30	45,5160821	9,168887946	45,4475276	9,0790968	11,174	46657,3	242,61	49,56	...	631,5	715,12
...	...	...	...	...	...	...	...	...	...	...	...	...
30	52	45,4475276	9,079096803	45,6945071	8,9844441	26,641	403,88	0,66	0,09	...	8,34	9,96
30	58	45,4475276	9,079096803	45,6635243	9,41547709	33,183	695,1	0,97	0,14	...	14,57	17,3
...	...	...	...	...	...	...	...	...	...	...	...	...
91	70	45,6056219	9,582115686	45,4361725	9,17286075	36,171	1121,29	10,83	1,91	...	2,94	1,91
91	87	45,6056219	9,582115686	45,4719874	9,28469489	30,419	205,09	2	0,31	...	0,49	0,3

Figure 22: Input data commuting demand Milan metropolitan area.

Figure 23 shows a part of the data input for the other mode options outside the eVTOL, which are travel by car and public transport. The first two columns again represent the origin and destination locations numbers. The following two columns are the travel times in minutes between the locations for the car and for public transport, respectively. The last two columns are the costs of travelling the distance between the two locations in € for both the car and public transport.

cl_x	cl_y	time car	time public	cost car	cost public
5	13	29,259	78,934	6,492	6,146
5	30	29,667	109,000	6,667	5,833
...	...	...	...	...	...
13	5	27,395	84,125	6,197	5,616
13	30	17,976	74,463	2,824	6,363
...	...	...	...	...	...
30	52	27,000	109,571	6,000	5,857
30	58	41,308	103,030	7,769	7,085
...	...	...	...	...	...
91	70	37,480	82,320	7,720	8,500
91	87	28,000	64,000	6,375	5,500

Figure 23: Travel data for car and public transport between locations.

C Costs Explanation

In this appendix will be explained where the costs that are used in the network are based on. The model uses four cost components, which are the purchase and operational costs for an eVTOL aircraft as well as for the vertiports.

C.1 eVTOL

In this part the eVTOL cost components are elaborated on.

Operational Costs
The operational expenses are all direct and indirect costs that are needed to operate the eVTOL aircraft. For the operational costs the cost analysis of the Uber Elevate white paper is used. In the paper it is assumed that the initial operating costs will be \$1.19 per mile, which is €0.67 per kilometer [4]. The expenses include the following:

- Vehicle utilization, the financing costs of the vehicle.
- Energy use, based on a price of \$0.12 per kWh.
- Infrastructure costs, including lease fees, security, personnel, and support.
- Pilot, the wages of the aircraft pilots
- Maintenance, vehicle maintenance.
- Indirect costs, includes credit card processing fees, and insurance.

In the white paper the vertiport and eVTOL are seen as separate entities - the eVTOL operator has to pay the vertiport operator for using the constructed infrastructure and support. However, in this research, we look at the profitability of the total network, thus the vertiports and eVTOLs combined. Therefore, the eVTOL provider does not have to pay the the vertiport provider. This means that the infrastructure cost is not included in the operating costs for eVTOLs. Vertiport operating costs are covered separate in the model to optimize the vertiport type choice per location. The other cost that is not included in the eVTOL operations in this research is the vehicle utilization cost. A separate financing cost is used to optimize the size of the fleet in the model. Concluding, without the vehicle utilization and infrastructure costs in the vehicle operating costs, the total eVTOL operating expenses C^{ev}_{ops} come down to €0.49 per kilometer. For this research the predicted initial operating costs are used, however the white paper assumes that these costs will drop in the future.

Purchase Costs
In the model the size of the eVTOL fleet is optimized, which is a consideration between transporting more people for more revenue on one hand, and purchase costs for the eVTOL aircraft on the other hand. As the research focuses on one day of operating, the eVTOL purchase costs also must be brought down to one day. The Uber Elevate white paper estimates the purchasing an eVTOL aircraft initially will be around \$1.2 million. The paper states that on average an eVTOL will have a 13 years operational lifespan. To comply with the single operational day, the costs are divided linearly over 13 years and 365 days per year, which comes down to an eVTOL purchase cost C^{ev}_{pur} of €230.14 per day.

C.2 Vertiport

In this part the vertiport cost components are elaborated on.

Operational Costs
The annual costs for operating one of the three vertiport archetypes consists of the following segments:

- Labor, which includes vertiport security, customer service, maintenance, and management. Labor makes up for ∼40% of the total operating costs.
- Depreciation, a reduction of the value of the vertiport over time based on a 30-year useful life. This makes up for ∼6% of the costs.
- Rent, depending on the dimensions of the type of vertiport, but in the whole network making up for ∼40% of operating costs.
- Other, this is all other cost, such as connectivity costs and regulatory fees.

[4]Based on the price of a dollar on May 11, 2023

For a vertihub the expected operating costs will be \$16 million per year on average. Therefore, the vertihub operating cost C_{ops}^{vh} comes down to €39,890.41 per day. The operating cost for a vertibase is around \$4 million per year, which leads to a vertibase operating cost C_{ops}^{vb} of €9,972.60 per day. In order to operate a vertipad, the network is expected to pay around \$750,000, which gives a vertipad operating cost C_{ops}^{vp} of €1,869.86 per day.

Purchase Costs

As the largest structure in the network, the vertihub is also the most expensive to build. The article of McKinsey & Company estimates the infrastructure costs to be around \$6.5 million. As the model looks only at one operating day, and the useful life of the building is 30 years, the costs are linearly divided over the 30-year lifespan, which gives a vertihub purchasing cost C_{pur}^{vh} of €540.18 per day. The vertibase is less expensive, estimated to be around \$650,000. Dividing the purchase cost C_{pur}^{vb} over 30 years comes down to €54.02 per day. The article expects a vertipad to cost \$300,000. If the costs are divided over the lifespan of the vertiport, the vertipad purchase cost C_{pur}^{vp} will be only €24.93 per day.

II

Literature Study
previously graded under AE4020

Literature Study

Safety of Air Taxi Services in the Urban Airspace

Thomas Hermans

Technische Universiteit Delft

Literature Study

Safety of Air Taxi Services in the Urban Airspace

by

Thomas Hermans

in partial fulfilment of the requirements for the degree of

Master of Science
in Aerospace Engineering

at the Delft University of Technology,
Control and Operations - Air Transport Operations

Student Number: 4480651
Date of publishment: September 2, 2022
Thesis supervisor: Dr. A. Bombelli

The cover photo is the Embraer Eve eVTOL flying over New York / ©Eve

Delft University of Technology

Contents

List of Figures

List of Tables

List of Abbreviations

ADARTW	Advanced Dial-a-Ride with Time Windows
ATC	air traffic control
ATM	Air Traffic Management
ATS	air taxi service
BEV	battery electric vehicle
ConOps	Concept of Operations
DARP	Dial-a-Ride Problem
DEP	distributed electric propulsion
EASA	European Union Aviation Safety Agency
eVTOL	electric vertical take-off and landing
FAA	Federal Aviation Administration
FAP	Fleet Assignment Problem
ICAO	International Civil Aviation Organisation
ICEV	internal combustion engine vehicle
IFR	instrument flight rules
MILP	mixed-integer linear programming
TAT	turnaround time
TSN	Time-Space Network
UAM	urban air mobility
UTM	Unmanned Aircraft System Traffic Management
VFR	visual flight rules
VRP	Vehicle Routing Problem

1 Introduction

The Future of Flying

With the rapidly changing world, a futuristic concept awaits to be introduced in many metropolitan cities across the globe – the idea of aerial ridesharing with on-demand electric vertical take-off and landing (eVTOL) aircraft in the urban airspace. Aerial ridesharing is a subset of the broader concept of urban air mobility (UAM), and represents an exciting and complex way of providing aerial transport to the public over urban areas and seeking to transform the way of travel [48]. The eVTOL is a transportation aircraft that uses electrical power to hover, land, and take-off vertically, which is ideal for flights in densely populated areas [80, 61]. One of the first companies that envisioned this concept was NASA, who noticed that the advancing technology of electric propulsion is a potential game-changer for the aircraft industry, creating new markets [48, 69]:

> *"The convergence of technologies, and new business models enabled by the digital revolution, is making it possible to explore this new way for people and cargo to move within our cities"* said Jaiwon Shin, NASA Associate Administrator for Aeronautics Research Mission Directorate [102].

And a new way of travelling in cities is needed, since traffic congestion in urban areas has become a ubiquitous problem over the past decades. In a large city as New York, a person driving the car to work has a loss of over 102 hours per year due to traffic congestion [54]. The fast-growing human population and increasing urbanization causes a growth in demand for travel in metropolitan cities worldwide. In addition, the commuters traveling from low-density areas often face the issue that public transport does not serve the passengers effectively, which increases the number of privately-owned cars [14, 35, 62]. The travel restrictions during the COVID-19 pandemic resulted in a sharp reduction in traffic throughout the US, however with people travelling to work again and with an increase in single-occupancy vehicles the congestion is predicted to grow even further than before the pandemic [52].
Vehicles in places like Manhattan emit 330 grams of CO_2 per mile into the atmosphere during traffic jams. The growth of the congestions in Manhattan contribute to an annual loss of $20 billion and increases the chance of road accidents [72, 74, 13, 34]. Thus, exploring new solutions for urban transport beyond ground transportation is crucial to meet future demand and alleviate road congestion along with the external problems it causes.

UAM complemented with an on-demand air taxi service (ATS) of eVTOLs could be an answer for the problems aforementioned. However, before the concept of air taxis flying through 3D-space can be implemented, first a whole new infrastructure must be built and the new eVTOL aircraft need to be designed according to the regulations set by organizations as the FAA and EASA [37]. If all is set, the focus can be laid on developing efficient and safe routing through and over the metropolitan cities - one of the most important instruments to make ATS a profitable and sustainable business. To gain better understanding of the capabilities of eVTOLs, and how to implement their routes for aerial ridesharing in existing urban areas, a literature study is conducted.

Report Structure

In the Table 1.1, an overview is created for all chapters and their contents described in this Literature Study. After this introduction, chapter 2 will describe ridesharing on ground-level and compare it to aerial ridesharing. Subsequently, chapter 3 gives an overview of urban air mobility and eVTOL aircraft. Thereafter, the infrastructure is discussed in chapter 4. In chapter 5 the relevant models from the literature are elaborated on. The conclusion of all the important findings throughout the Literature Study is written down in chapter 6. And lastly, the research plan is proposed in chapter 7.

#	**Title**	**Content**
2	Ridesharing	Discusses ridesharing as transportation mode on the ground
3	Urban Air Mobility	Gives an insight in Urban Air Mobility and eVTOL aircraft
4	UAM Infrastructure	Discusses the infrastructure needed for Air Taxi Services
5	Routing Models	Presents models for eVTOL routing problem and en-route safety
6	Conclusion	Giving a conclusion based on the findings in chapters 2-5
7	Research Framework	Presenting the Master Thesis research plan

Table 1.1: Overview of the chapters in this Literature Study.

2 Ridesharing

The implementation of an air taxi service in urban areas is not only a very complex problem, but also a brand new concept. Due to this early stage of the ATS, it is important to first take a look at existing transportation methods on ground-level that resemble ATS to some extend. In section 2.1 a couple of travel modes for commuters are discussed and compared based on different criteria. Here will also be explained why ridesharing is an important transportation method for the future. Hereafter, in section 2.2, the working-principle of rideshare is further elaborated, and the difference between ridesharing and ridehailing is described. Furthermore, section 2.3 gives some depth about the ridesharing models used in literature. And section 2.4 concludes what differences and similarities there are between ground transportation and aerial ridesharing, and why ridesharing can be useful for the implementation of eVTOLs in the urban skies.

2.1. Transportation Varieties

This section gives an insight in travel modes used by commuters, and compares them on the basis of travel criteria. Commuters nowadays have the choice from a variety of travel options for transportation to their work. All options have their advantages and disadvantages which are taken into consideration by the commuters when choosing a transportation mode that suits them best.
Their choice can depend on multiple criteria, such as [39]:

- Travel time between point A and point B;
- Cost of travel with transport option;
- Flexibility of adapting changes in the schedule;
- Convenience of choosing a pick-up and a drop-off point;
- The amount of privacy one perceives during travel;
- Reliability of the transportation mode;
- (Perception of) security.

In Table 2.1 some ways of transportation for people travelling to work in a metropolitan city are compared by giving each of them a rating per criterion. Here, for instance, can be seen that by taking the bus or subway the passenger benefits from low costs in the form of a ticket. This, however, comes at the expense of the convenience and flexibility of travel due to fixed routes, and the commuter's privacy. A private car or taxi allows for a more flexible, convenient, and (often) faster option than the train or bus, but is a lot more expensive [39].
In addition to the traditional transportation modes aforementioned, the concept of *ridesharing* is taken into account. This mode refers to the idea of individuals, with a similar destination and schedule, sharing a vehicle. The passengers therefore can split the costs of travel, such as fuel, insurance, parking fees, and toll. Ridesharing has the same flexibility and a somewhat same travel time as a privately owned car, yet without the high travel costs. On the other hand, ridesharing decreases the amount of privacy and convenience relative to private cars.

	Travel time	Costs	Flexibility	Convenience	Privacy	Reliability	Security
Bus	±	±	-	-	-	+	-
Subway	±	±	-	-	-	+	-
Private car	+	-	+	+	+	±	+
Taxi	+	-	+	±	±	±	±
Ridesharing	±	±	+	-	-	±	-
Cycling	-	±	+	+	±	+	-
Walking	-	+	+	+	±	+	-

Table 2.1: Criterion ratings of transportation modes for commuters.

Thus, equally to the other transportation modes, ridesharing has its advantages and disadvantages. But if this concept does not have a high rating for every criterion mentioned in Table 2.1, then why should we dedicate a whole chapter to it? This is because of the overall contribution that ridesharing makes to the society and the environment. With a low average commuter car occupancy of 1.1 per private car in Europe and a high demand for automotive transportation during peak-hours, traffic congestion grows [57, 39]. Usage of private cars is the dominant mode of transportation in producing CO_2 emissions, which has a local and even global impact [46]. Locally, the health problems arise due to the rising emissions, and globally, air pollution is associated with climate change and global warming [23, 93]. Implementing effective ridesharing to our metropolitan cities could help mitigate congestion, because the more people travelling per single car, the less cars will be driving on the road. The use of less vehicles in the cities helps lowering the extreme emissions of CO_2, causing a less negative local and global effect on human health and climate.

2.2. Ridesharing Overview

Ridesharing is defined as a joint-trip arrangement of at least two people sharing a vehicle. All passengers have their own origin and a destination for the trip, which requires good coordination to manage all location specifications set by the passengers [39]. Advanced mobile technology and extremely accurate GPS makes the introduction of ridesharing be closer than ever [24, 87]. This section gives an overview of the whole ridesharing concept.

2.2.1. Concept of Ridesharing

Ridesharing is often called *dynamic* ridesharing, where 'dynamic' refers to the automation of the real-time process of ride-matching between passengers, which is a process that takes mostly place before the trip, but can also be optimized en-route. In Figure 2.1 an overview is created to make the concept more clear and show the sub-forms it exists of. *Unorganized ridesharing* is a form of ridesharing without any third party involved in the joint-trip. This can be a shared ride where the driver has a personal relationship with the people sharing the car with (e.g. family, friends, colleagues or neighbours), or 'ad hoc' (immediate) ridesharing, such as picking up hitchhikers on the side of the road. Commuters make use of *organized ridesharing*, a prearranged rideshare controlled and operated by a third party providing the rideshare service. In organized ridesharing, the potential passengers link the locations of their origin and destinations to the agency via GPS, whereafter the demand and the supply are matched.

The agency is a service provider, which is a broader concept that can be distinguished into *service operators* and *matching agencies* [39]. A service operator handles its ridesharing services while using its own vehicles and drivers. An airport shuttle service, for instance, has a car and a driver to transport passengers from or to the airport. The requests of potential passengers are accepted, whereafter the passengers will be assigned to available shuttles and drivers that successfully operate the rides. This service is also defined as 'one-sided matching' - matching an agent (passenger) to its preference (location & time). One disadvantage of this service is the limited service area, a place can be too far out of range or in an area with lack of potential passengers. Secondly, most decisions are made by the service operator, passengers just have to decide whether or not to participate. This can result in inaccurate pick-up or drop-off times. Thirdly, additional requests have to be communicated in advance and, consequently, can't be solved en-route.

The focus of matching agencies lies in matching passengers to individual drivers. Unlike service operators, the drivers have their own car and their own preferred destination. The driver uses an automated matching application, like UberX Share and Lyft Shared, to get in contact with a potential passenger (or multiple passengers) and vice versa, that are willing to share a trip and therefore save travel expenses. The app guides the driver to the pick-up point of the passenger and from thereon to the passenger's destination via an incorporated navigation system. After the trip, the driver receives a fee from the costumer, and the agency receives a fixed percentage [91]. The application, acting a matching agency, searches for ridesharing matches between two agents willing to travel together: the passenger & car driver. It is therefore defined as 'two-sided matching' - both the driver and passenger have a time and location preference that they want to attain [39].

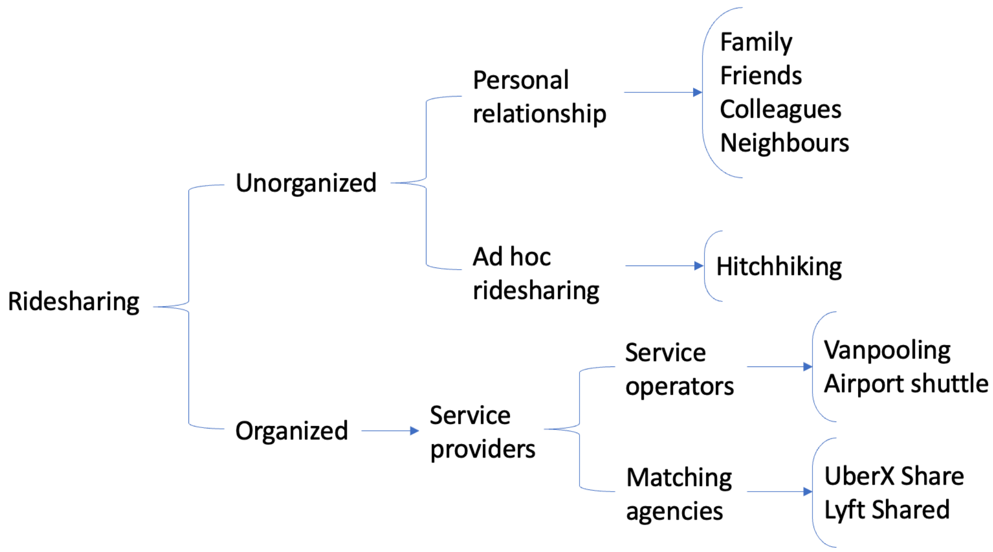


Figure 2.1: Diagram with all possible forms of ridesharing.

2.2.2. Ridehailing

The agencies of UberX Share an Lyft Shared aforementioned are companies that provide ridesharing, where the owner of the vehicle and one or more passengers are matched with each other to save money on the trip. The definition of ridesharing must not be confused with the procedure of companies like Uber, Didi Chuxing, and Ola Cabs, which all provide 'ridehailing' (or ridesourcing) instead of ridesharing. A ridehailing company or is a company providing a platform for on-demand private rides with a licensed driver. The driver does not have a origin or destination preference and thus acts as a taxi driver while using one's own car [90]. Although the commuter shares a ride with the driver, it is not possible not share a ride with another passenger, therefore it is not defined as ridesharing. In daily commute, ridesourcing has the same principle as a taxi with only one costumer per vehicle.

2.3. Basics of Ridesharing Models

Ridesharing provided by matching agencies is a difficult activity to fully implement as an efficient transportation alternative in cities. Unlike taxi-drivers, the driver providing the ride for ridesharing has its own origin and destination. Thus, prearrangement is necessary as the driver also has a time schedule. In this section, the basic objectives, constraints, and patterns of ridesharing will be explained to get a better understanding of the working principles.

2.3.1. Objectives Ridesharing

Drivers owning a car plus its passenger(s) use ridesharing to save expenses on their trip. Through the medium of matching agencies, a match is established for the passenger(s) and driver, based on the locations of origin and destinations of both parties. The platform (or app) of the agency matches them automatically and generates revenues by earning a fixed or proportional fee, or through advertisements when a rideshare is executed. The objectives of the passengers and the driver are in line as they both want to maintain a short travel time, while attaining low costs and keeping emissions low. This is achieved by minimizing or maximizing the following objectives [3]:

- *Minimize the system-wide travel distance*. This represents the total distance traveled by the vehicle operating the rideshare. It contains the distance driven to the origins and destinations of all participants, either with or without any passenger in the car. In addition to the minimized travel distance, the costs of driving (e.g. fuel) are kept low. And from a societal point of view, the objective contributes to the reduce of greenhouse gases and traffic congestions.
- *Minimize the system-wide travel time*. It is the time spent in the vehicle driving from its origin to the destination. The lower the time of travel, the more convenient for the participants (i.e., drivers and passengers). Besides, the shorter travel time also corresponds to lower emissions.
- *Maximize the number of participants*. This objective maximizes the number of satisfied participants of the vehicles' rideshare. The more people participating in the ride, the less money the trip will cost. This can have a positive impact on the traffic congestion problem in cities and, again, results in the CO_2 reduction.

2.3.2. Constraints Ridesharing

When the matching agent wants to establish a route between a passenger and driver, there are a number of constraints that need to be taken into account. Constraints for rideshare can be divided into two segments: hard and soft constraints [60]. Time, a hard constraint, is probably the most important when searching for matches. The rider and the driver both have a time schedule preference, thus the agency tries to find a potential departure time that is as close as possible to the desired departure time. This schedule preference provides too little information about the participants' flexibility. The study of Agatz et al. (2011) captures the time preference in a time window representation by specifying the earliest and latest possible time of departure [2, 3]. Other papers like Baldacci et al. (2004) and Amey (2011) limit the participants' total travel time during the rideshare. The driver and passenger(s) have to specify how much time they are willing to wait or detour [12, 6].
In addition to time, location is a crucial limitation for providing matches. An example for this constraint is the amount of distance the driver is willing to drive to pick-up or drop-off the passenger(s), which again depends on the origin and destination of the driver. It also works the other way around, where the passenger has a maximum distance it wants to travel to the pick-up or from the drop-off point.
One of the objectives stated above is to maximize the number of participants in the vehicle. The capacity of the vehicle is limited by the amount of seats in the car - the more seats there are, the more people can travel along - or by the driver's preference. Thus, capacity can be seen as a hard constraint.

Soft constraints are also very important to consider when dealing with a ridesharing problem. Soft constraints are certain preferences set by passengers or the matching agency in order to accommodate a safe and pleasant travel experience [60]. An example for passenger preference is about women not feeling comfortable joining a ride late at night with male strangers. It could also be that someone only wants to join rideshares with people they know, like friends or colleagues. Matching agencies can set rules which can be used as constraints. They can prohibit the use of cigarettes in the vehicles driving (smokers are not allowed), the agency can set a minimum age for the any participant to make use of ridesharing, and the amount of space in the car between people can be set. The more restrictions the agency and its users place on the pool of potential rideshare participants, the more difficult it will be to create successful matches [30, 3].

2.3.3. Positional Elements of Ridesharing

The positions of the origin and destination of the driver and its passengers is important information when the matching agent sets up the trip. Furuhata et al. (2013) published a paper where a distinction is made between the different types of ridesharing trips, or patterns, that one can make [39]. All patterns that are described in the paper are illustrated in Figure 2.2.
Before setting out the patterns, the notations of the positional elements must be first explained. In the illustration above, a is the symbol for the driver of the vehicle, b is the passenger, and b' is a second (or third, or fourth, etc.) passenger within the set of passengers B. The origin is denoted as o, the

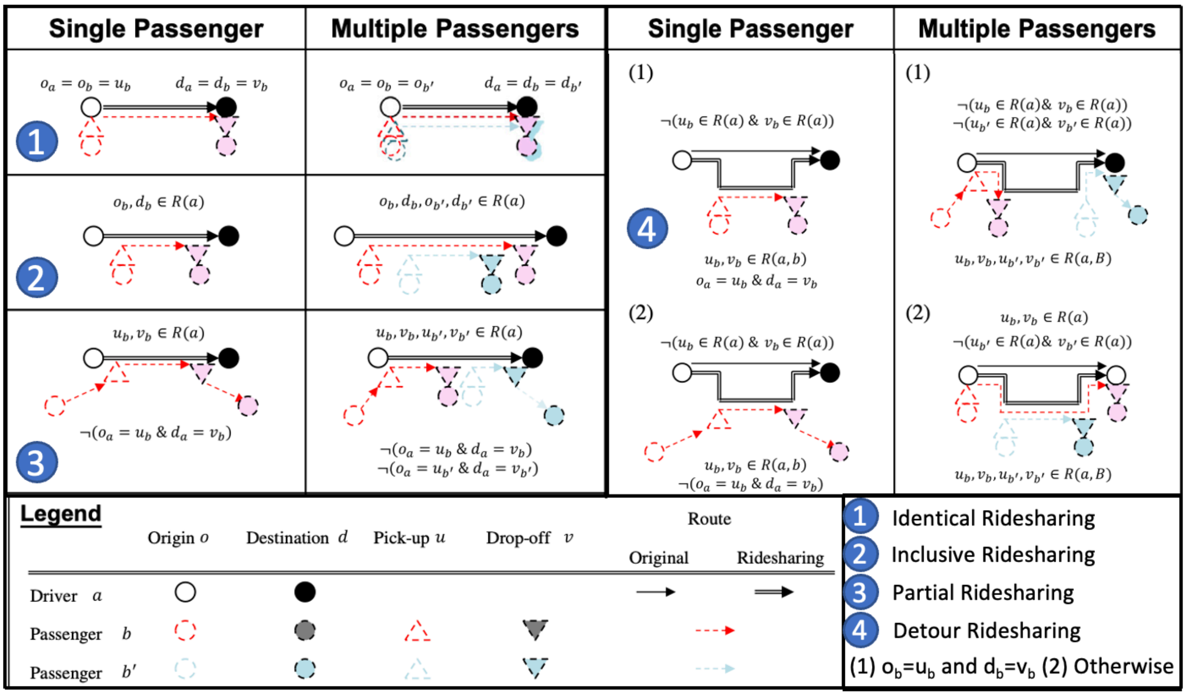


Figure 2.2: Positional elements of ridesharing for one or more passengers from [39].

destination as d, the pick-up as u, and the drop-off location as v. The original route of driver a is $R(a)$, and the route formed by driver a and a set of passengers B is marked as $R(a, B)$. There are four patterns described in the paper, each for a single passenger and for multiple passengers, which are:

1. **Identical Ridesharing**
   The origin and destination of the driver a and passenger b are exactly the same, i.e., $o_a =_b = u_b$ and $d_a = d_b = v_b$. Therefore, the ridesharing trip of the driver and passenger is identical.

2. **Inclusive Ridesharing**
   The origin and destination of passenger b is on the way of the original route of the driver $R(a)$, however their origin and destination are not exactly the same, thus, $o_b, d_b \in R(a)$. The shared trip is only a section of the whole ride of the driver a.

3. **Partial Ridesharing**
   The pick-up and drop-off locations of passenger b, u_b and v_b, are on the the original route $R(a)$ of the driver, however either the origin and destination of the passenger is not located on this route. This means that the passenger has to travel from its origin to a pick-up location and from the drop-off location to its destination, therefore $u_b, v_b \in R(a)$ and $\neg(o_b = u_b$ and $d_b = v_b)$.

4. **Detour Ridesharing**
   The pick-up location u_b or drop-off location v_b of passenger b, or both, are not on the original route $R(a)$ of driver a. The driver takes a detour $R(a, B)$ to drive to the pick-up and drop-off locations of the passenger. In detour ridesharing, a distinction can be made between two sub-patterns: (1) The pick-up and drop-off locations of the passenger is at the same location as its origin and destination, so, $o_b = u_b$ and $d_b = v_b$. (2) Otherwise.

When considering multiple passengers willing to participate in the rideshare, the patterns for identical, inclusive, and partial ridesharing are similar to single passenger rideshare. The difference lies in detour ridesharing, which is a lot more complicated with multiple passengers. For instance, suppose the trip with driver a and passenger b is identical. When passenger b' joins, it is required to detour from the original route $R(a)$ to pick-up b' from its location. Therefore, this trip is suddenly changed to detour ridesharing [39].

2.4. Ground vs. Aerial Ridesharing

Air taxi service has overlap with both ridesharing and ridehailing. However, for the reason that it is a transportation mode where different passengers share the same vehicle that carries them through the air between point A and point B, it is called *aerial ridesharing*. In contemporary literature the amount of publications related to this new concept of aerial ridesharing is growing. There is, however, significantly more literature to be found about transportation on the ground. Therefore, it is helpful to dig into this existing ground-based ridesharing and ridehailing literature, which has overlap with this subject to some extend. To understand what further literature research is needed for the implementation of eVTOLs as a new mode of transportation, it is important to know what the differences and similarities are between this transportation on the ground and in the air.

ATS will be an organized way of ridesharing in the skies. The eVTOLs used for this operation are stationed at so-called *vertiports*, which are landing and take-off areas designed for UAM, similar to a helipad. These can be situated on multiple spots in the area, from high office buildings to local parks. To initiate a flight with the eVTOL, a matching agency is informed about the location of the passenger and its preferred destination. The agency searches for a ride that limits the amount of travel distance and time. It looks for the nearest vertiport and available eVTOL, and matches the passenger to this ride along with other participants heading the same way at the same time. The eVTOL is then flown by a licensed pilot across the city via efficient, predestined routes to limit battery consumption and flight time.

As well as on the ground, aerial ridesharing is also considered to be a shared travel with multiple passengers. Both make use of a matching agency that regulates the service and creates routes and trips. A big difference is that the pick-up and drop-off locations are fixed due to vertiports. The potential passengers must travel to a vertiport to get board an eVTOL - it is not capable of picking someone up wherever and whenever they want. A basic travel path for aerial ridesharing can be seen in Figure 2.3 - the passenger begins at the starting point (its origin), travels to the vertiport location via other transportation modes, then gets transported with an eVTOL to the arrival vertiport, and travels further to its destination. Comparing it with the ground, aerial ridesharing corresponds to *identical ridesharing*, portrayed in Figure 2.2. The eVTOL has fixed routes and therefore can not change destination mid-air or detour. In addition, aerial ridesharing is on-demand which means that a ride can be arranged on very short notice. This differs from ground-based ridesharing, where the rides are usually arranged longer before. The fact that the rideshare is on-demand and that the pilots do not have a preferred destination themselves, corresponds with ridehailing.

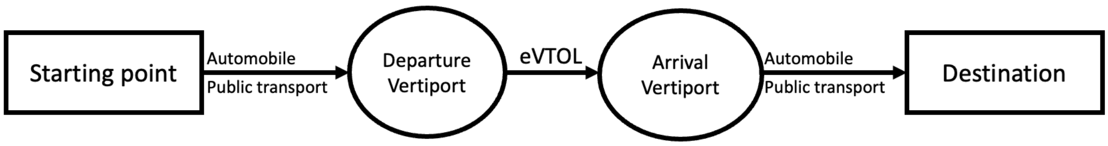


Figure 2.3: Simplified travel path for eVTOL transportation.

Aerial ridesharing thus has some of the same traits as ridesharing and hailing on ground-level. It transfers multiple people on-demand from one part of the city to another in no time. ATS could reduce the traffic congestions by lowering the use of cars on the road and limit emissions by flying electric. The next chapter dives deeper into urban air mobility, eVTOLs, and the air taxi service to get a better understanding about the new way of travelling in urban areas.

3
Urban Air Mobility

On July 8, 1953, one company in New York started with exploring the possibilities for air taxi services in urban areas: New York Airways. The company began a helicopter service between three major airports, while flying on scenic routes over Manhattan and the Liberty Statue. The concept became immensely popular and found its way to cities like Los Angeles and Chicago. At one point, New York Airways carried more than 250,000 passengers per years, providing a fast and relatively cheap alternative to taxi cabs. Unfortunately, a fatal crash and the oil crisis in the late 1970's resulted in the company being shut down. Apart from the accidents at the company, the helicopter service did show that there was a demand for air taxi service, however perhaps a little too early [17].

Helicopters are the current solution to air mobility. It has proven to effectively transport passengers and goods for short to medium distances, taking-off and landing vertically at a small area. But given the depth of knowledge about helicopters that has been built up over the years, why are companies seeking to replace them with an entirely new device? This is because of some aspects helicopters have that are not ideal for the air taxi service, such as noise pollution, safety consideration, high manufacturing costs, operational expenses and emissions [100].

In this chapter the concept of UAM will be broadly explained. First discusses section 3.1 the types of applications of eVTOLs in the urban skies. Subsequently, section 3.2 explores the technology of the eVTOL. With the help of useful literature, this section will go into detail about the technical aspects of the eVTOL aircraft, such as the design specifications and the flying capabilities. In section 3.3 the important financial subject will be handled, which presents the industry players, the demand for urban aerial taxis, and the costs specified for the companies and passengers. Then, section 3.4 depicts the challenges for the UAM industry, such as visual intrusions of eVTOLs in the skies, environmental drawbacks, and public acceptance. And lastly, section 3.5 gives a summary of the most important information described in the sections of this chapter that is useful for the Master Thesis project.

3.1. Applications for UAM

Urban air mobility has a variety of interpretations, the eVTOL therefore has many applications. In this section a few of those applications will be discussed, being air taxi service, package delivery, and medical assistance.

Air Taxi Service

A significant amount of companies have already noticed the capabilities of eVTOLs for future travelling within urban areas. This air taxi service (ATS) could be an ideal solution for congested locations in large cities around the world, allowing people to commute between locations in a very short time compared to the ground transportation methods. Air taxis do not require roads, which makes the infrastructure very efficient. In the US alone, traffic congestion causes an extra travel time of seven billions of hours each year, subsequently leading to the waste of eleven billions liters of fuel [98].

Package Delivery

The usage of eVTOLs could also be applied to the ever-expanding E-commerce, which has a total market value of 4.9 trillion *USD* and is expected to grow even further [25]. With eVTOLs, packages can be delivered much quicker than with ground vehicles. This opportunity is as we speak being explored by large e-commerce and transportation giants. Companies like FedEx, UPS, and DHL are partnering with eVTOL manufacturers to eventually deliver packages via the air in cities instead of everything on ground-level [76].

Medical Assistance

In a life-threatening situation it is difficult for ambulances to drive as quickly as possible to the person in need, especially if there are many vehicles on the road. Nowadays, helicopters with medical assistance on-board are sometimes used to help a patient. However, an eVTOL would be much quicker en safer to operate in dense cities compared to a helicopter. The eVTOL, functioning as an air ambulance service, can carry medical goods, such as an AED or blood, and transport the patient to a hospital close by [40].

Reflection on Applications

The above mentioned applications are the main implementations for future UAM. Apart from urban use, the eVTOL aircraft can also be applied to other regions for various implementations. It could have a maritime function for rescues offshore, or for the evacuation of people during earthquakes or fires. The United States Air Force also sees salvation in the use of eVTOL for their missions and made a 25 million *USD* contribution to the development of 30 vehicles [75].

3.2. eVTOL Technology

Over the past decade, a lot of research has been done in investigating the ultimate properties for eVTOLs. Developers have freedom to some degree, however they are mainly limited to the specifications set by government agencies like the Federal Aviation Administration in the US. There are five degrees of freedom in which the aircraft must perform, which are: speed, range, payload, noise, and safety. Each of them is strongly interlinked with the others, causing an improved parameter to sometimes have a negative effect on another [65]. This section will discuss the major aspects of the eVTOL aircraft and elaborate on what solutions different companies came up with for these aspects. This is done by dividing the section into subsections, where subsection 3.2.1 evaluates the design specifications, subsection 3.2.2 discusses the propulsion methods and the four most common designs, subsection 3.2.3 elaborates on the battery usage, subsection 3.2.4 indicates what speeds and ranges the eVTOLs can achieve, subsection 3.2.5 will be about noise created by the aircraft, and subsection 3.2.6 focuses on the automation of aerial ridesharing.

3.2.1. Design Specifications

Since the introduction of the Puffin electric tailsitter by NASA in 2010, more than 130 electric VTOL concepts have been proposed, each one having different configurations and dimensions [69, 50]. To satisfy aerospace regulators both the Design Organization and the Production Organization have to be certified by the authorities such as, respectively, the FAA in the USA or EASA for Europe. Only a certified design organization according to EASA / FAA Part 21.J may design an aircraft [97].

In a draft version of the Engineering Brief #No.105, the FAA sets criteria for the composition of the aircraft, which can be found in Table 3.1[68]. Here, the design characteristics are specified, such as the maximum aircraft length and width, as well as the maximum take-off weight and the propulsion. But also the operating conditions are indicated, such as a criterion for the aircraft to be land-based, and that it must fly under the regulations of visual flight rules (VFR). The performance criteria state that the eVTOL must take-off and land vertically, and that it must comply with the hover out of ground effect (HOGE), which includes the potential for an aircraft to fly at high altitudes. The aircraft also must ensure safe downwash/outwash, which is the amount of air that the rotors blow downwards. All these criteria have to be taken into account when designing an eVTOL aircraft in the United States.

3.2.2. Propulsion

Helicopters use internal combustion engines and mechanical transmissions to drive their large rotors in order to fly. An eVTOL, on the other hand, makes use of smaller propulsion units which are operated by

Design Characteristics	**Criteria**
Propulsion	Electric battery driven
Propulsive units	2 or more
Battery packs	2 or more
Maximum take-off weight	7,000 pounds (3,175 kg) or less
Aircraft length	50 feet (15.2 m) or less
Aircraft width	50 feet (15.2 m) or less
Operating Conditions	**Criteria**
Operation location	Land-based (ground or elevated)
Pilot	On board
Flight conditions	VFR
Performance	**Criteria**
Hover	HOGE in normal operations
Takeoff	Vertical
Landing	Vertical
Downwash/Outwash	Ensure no impact to overall safety

Table 3.1: Criteria for design characteristics, operating condition, and performance for eVTOL aircraft [68].

an electric motor. Most companies designing an eVTOL make use of the concept of distributed electric propulsion (DEP), which enables new capabilities in the overall efficiency of the aircraft. Because of DEP, propellers only have to be connected electrically to an energy source ("power-by-wire"). The propulsion units can be placed almost anywhere on the aircraft, which results in enormous design flexibility to improve the performance of the eVTOL over the traditional helicopter designs [59].
Another important design specification is the disk loading factor, which is defined as the ratio of the gross weight of the vehicle to its rotor system's disk area. What a rotor does is pushing the air downwards to lift the eVTOL up. When producing the same force upwards, for comparison, it is more efficient to move a large volume of air downwards slowly, than to move a smaller volume of air more quickly. This means that the higher the disk loading, the more efficient the hovering is of the eVTOL. In addition, the high disk loading also causes more severe downwash, and more noise is created due to the faster moving blades [31].
Then why not create eVTOLs with enormous disk areas to create upward force with very little downward power? First of all, the large blades can be very heavy, which costs a lot and are harder to build. Also, the blades will be more sensitive to wind, making the aircraft less stable. Besides that, the slow moving rotor limits the forward speed. And lastly, the larger disk area subsequently requires more space, which is not unlimited available in urban areas.

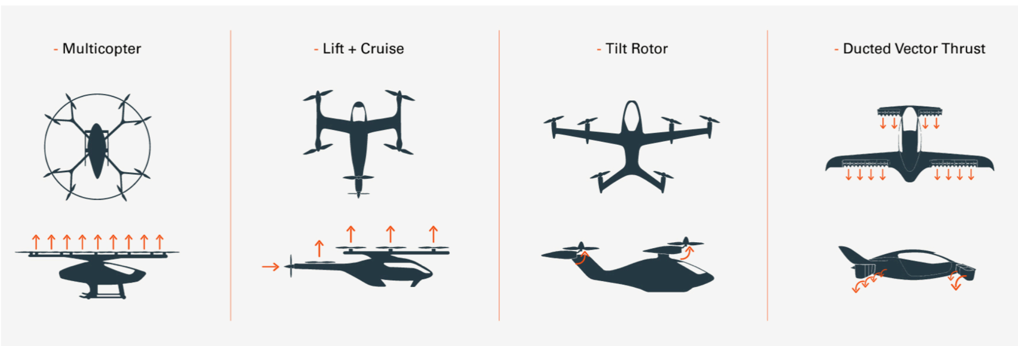


Figure 3.1: Various eVTOL architecture standards, with the arrows indicating the direction of thrust generated from [65].

A well thought out design is needed in order to make the eVTOL aircraft an airworthy concept. And with the design specifications set in Table 3.1, the companies designing the aircraft are left with some room for own interpretation. This freedom has led to multiple designs of eVTOLs, with a few of them now forming the architecture standards. The four most common standard designs, which are schematically depicted in Figure 3.1, consist of (from left to right) a *multicopter*, *lift + cruise*, *tilt rotor*, and a *ducted vector thrust* concept. All designs have their pros and cons, and will be discussed below [65].

Multicopter

The configurations of the multicopter are fairly simple and, due to a low disk load, this concept is very efficient during its (vertical) take-off, landing, and hovering. It has a large disk actuator surface which makes it efficient at hovering, but without a wing it causes the aircraft to lack in cruise flight. This inefficiency during the cruise must be compensated with a larger battery, which adds to the overall weight and thus makes the eVTOL heavier. Without a wing for efficient forward flight, the multicopters are limited in speed and range [79, 11].

Lift + Cruise

The lift-plus-cruise design merges the multicopter, enabling the vertical take-off and landing operation, with a standard aircraft wing design for cruise flight. Combining the two propulsion systems, allows the eVTOL to achieve efficient vertical motion and cruise. In order to maximize its range, the propellers are designed with fewer blades and shorter chords. This adjustment ensures a reduced drag during cruise flight. The downside of the smaller propellers is that the blade tips have to rotate faster and the resulting higher disk load, creating more noise when operating.

Tilt Rotor

A tilt rotor design involves two tilting concepts, one with a wing and propellers, and the other one with only the propellers. This tilting allows the axis of the propeller to rotate 90°, enabling the eVTOL to transition from vertical to a horizontal movement. This concepts aims for high range and low noise emission which, however, comes at the price of high technological complexity. In addition, due to the tilt mechanisms and big propulsion systems, the weight of the aircraft increases.

Ducted Vector Thrust

All three categories aforementioned rely on a propulsion system with propellers. The ducted vector thrust concept uses ducted fans over unducted propellers. The vectored thrust eVTOLs have a wing for an efficient cruise and use the same propulsion system for both hover and cruise.
The ducts help to significantly mitigate the noise due to the shape of the ducts and its acoustic liners. In order to keep the level of noise at a constant level when the payload of the aircraft increases, the designs of the propeller aircraft and of the ducted fan aircraft need to be adjusted. For instance, the propeller aircraft needs to keep the disk load constant and increase the size of its blades. However, at the ducted design, the disk loading can rise and the acoustics in the ducts limit the increase in noise. This results in a ducted fan aircraft to have a 40% higher payload than a propeller aircraft. As a downside, the system is very complex to design and build [71, 11].

3.2.3. Batteries

Large traffic congestions in metropolitan cities causes pollution levels to rise dramatically, creating global environmental problems. To make aerial ridesharing concept attractable for governments to implement in the urban areas, the eVTOL must be designed to emit less than other transportation methods such as cars and helicopters. Companies producing eVTOLs therefore aim for electric zero-emission aircraft, powered by large batteries, giving the VTOL its letter ”e”.

Implementing the right batteries to the system, however, is a much more complicated problem than it seems. ”The main hurdle for a completely electric plane is battery technology” says Nikhil Sachdeva, who leads the electric propulsion team at Roland Berger [63]. As of today, no eVTOL has entered the commercial application phase. The reason for this is a lack of technological advancements in battery technology, causing insufficient battery capacity for this market. The higher the energy density of the battery, the longer the battery can emit a charge in relation to its size. Multiple studies portray the drawbacks of current eVTOL battery technology, such as its poor range and endurance with practical payloads [78, 79, 81]. The eVTOL companies thus aim for further development of the energy storage of batteries in eVTOLs, which is driven by three business requirements:

1. An eVTOL operation benefits from long flight times, which requires the battery’s weight to be as low as possible and to have a high energy density.

2. Safety is a very important requirement, because poor safety measurements in aviation can lead to dangerous situations. This can subsequently result in the downfall of an eVTOL company, especially in this brand new industry. Additional safety measures typically increase the system's weight.

3. The flight can be divided into different flight phases, such as the vertical take-off and the horizontal flight. These phases require their own energy consumption, which translates to high peaks and low average power.

The overall goal of the companies is to create safe and reliable batteries that have a high energy density and are as light as possible to perform flights in aerial travel. The currently used Lithium Ion batteries have a theoretical capacity limit of around 250 Wh/kg, which is insignificant when compared to jet fuel with a density of 12,000 Wh/kg. The applications of the Lithium Ion battery is for now limited to small one or two passenger aircraft, because it does not generate enough power to manage more weight [78, 63].
The flight duration also depends on the disk loading, which can be explained through the following example: an eVTOL with a low disk loading of 20 lbs/ft^2 completely empties its batteries after hovering for 15 minutes. If the aircraft has a somewhat higher disk load of 30 lbs/ft^2, the hovering time drops to 12 minutes. A high disk loading of 50 lbs/ft^2 brings the endurance of hovering even lower to only 10 minutes. This underlines the efficiency of a low disk loading when flying with an eVTOL.

The idea of implementing more batteries is not an option, as the current batteries per aircraft already have a weight fraction of 30% to 40% relative to the eVTOL weight [49]. Engineers thus have to seek for breakthroughs in battery research, and even look at different (hybrid) alternatives.

3.2.4. Range & Speed

The range and speed of the eVTOL depend heavily on the capacity of the aircraft's battery - the higher the capacity, the more kilometers it can travel at once and the faster it can fly. The full range and velocity are based on a fully charged battery at the beginning of a flight. After a number of consecutive flights, the battery level is decreased, which results in reduction of the range and speed for the next ride. The amount of energy the eVTOL uses during flight is not constant, different segments have different energy needs. These flight phases of the eVTOL, portrayed in Figure 3.2, are defined as follows [71]:

- **Hovering** after take-off (1) and landing (7) is the period of flight where the eVTOL remains in one place in the air. The energy consumption during this phase is constant.
- **Transition** (2) is the phase where the aircraft transitions from hover into forward flight, thus **re-transition** (6) is the conversion from forward flight to hovering. The consumption of energy drops when the lift is generated by the wings instead of the propellers.
- **Climb** (3) is the stage of the flight where the eVTOL climbs to cruise altitude and accelerates to cruise speed. During **descend** (5) the aircraft descends from cruise altitude and decelerates its speed.
- **Cruise** (5) is the period of flight where the aircraft has a constant velocity and altitude. The cruise segment is generally about 90-95% of the total flight length, and demands a constant power of the battery.

A dominant topic in the development of the future air taxi system is the distance that the eVTOL will be flying in the urban areas. The distances covered will be a lot shorter than traditional aircraft, however there are still multiple eVTOL companies that have different lines of thought when it comes to the range their eVTOL will be flying in cities. Volocopter, for instance, aims for a range between 30 and 35km, which enables inner-city taxi and airport shuttle services. This range is chosen by first looking at the spanning of urban areas around the geographic center of the top 100 largest cities in the world, which is around 30km for most cities [53]. In Figure 3.3 nine of these dense cities are portrayed with a circle drawn at 15 and 30km to illustrate the span of the urban areas of each city. Hereafter, the company observed locations of major airports around these metropolitan cities. Of the analyzed cities, 70% have a major airport within 20km of the city center, and even 93% have an airport within 30km.

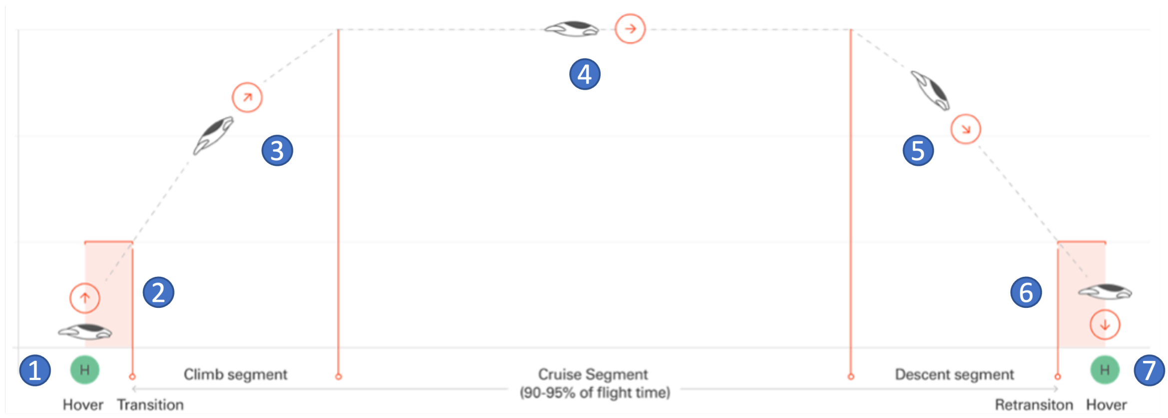


Figure 3.2: A simplified scheme for the different flight phases of eVTOLs from [65].

An example of the future abilities of the Volocopter is an air taxi service between John F. Kennedy International Airport (JFK) and Midtown Manhattan, a 30km long, cumbersome route when travelling with a taxi on the ground. Due to traffic congestions, or lack of efficient routing in busy New York, the route often takes longer than 60 minutes when travelling on the ground, while the eVTOL covers the flight path in 20-25 minutes. This route is taken with an average speed between 80 and 100km/h, which is based on a trade-off between multiple factors. The speed must be high enough to save a significant amount of time, but not too high in order to limit noise levels and have time to avoid collisions with other eVTOLs, drones, buildings, and animal life [21].

Other companies take a different approach on how to define the speed and range of their electric VTOL aircraft. Uber Elevate, the air mobility department of Uber, which is acquired by Joby Aviation in 2020, aimed for mega-commuters who have longer distances to travel compared to ordinary commuters. The eVTOL prototype of Joby Aviation has the ability to fly more than 240km on a single charge while flying almost 200km/h, and is even expecting to transporting passengers in the future with a speed of up to 320km/h [9].

The range and speed of the eVTOL aircraft during urban air taxi services depend on multiple factors. First of all, the company makes a choice for a market and thus focuses on certain ranges of flights - it therefore aims for shorter or longer range aircraft with lower and higher velocities. Moreover, if the battery technology improves in the future, much more can be possible regarding speed and range. And additionally, the design plays an important role, where some designs are better suited for longer flights with a higher velocity and others aim for shorter trips with lower velocity.

3.2.5. Noise

Modern transportation modes all produce a significant amount of noise. When a train or metro arrives at the station, its loud rumbling and screeching sounds can be heard from a mile away. When living near a highway, the horns, breaks and accelerating noises of cars penetrate the houses. Also, the ground crew at the airport has to wear ear protection to counteract the sound of huge aircraft engines. People are conditioned to believe that transportation is loud. The thought of extra noise during their already heavily-noised day could be a fair reason for people to be against urban air mobility. For the eVTOL industry to be publicly accepted, the aircraft must have a significant noise reduction compared to existing transportation modes.

To show the differences between the level of noise creation of known transportation modes and the expected levels for eVTOLs, it is important to understand how sound and decibels work, and how people perceive the different levels. Sound is measured in decibel (dB), with 0dB being the smallest audible sound. It is measured on a logarithmic scale, which causes 10dB to be 10 times a powerful, 20dB to be 100 times as powerful, and 30dB 1,000 times as powerful compared to 0dB. This means that a small change in decibels can increase or decrease the amount of noise significantly. For scale the A-weighted decibel (dBA) levels are used, which is an expression of the relative loudness of sounds

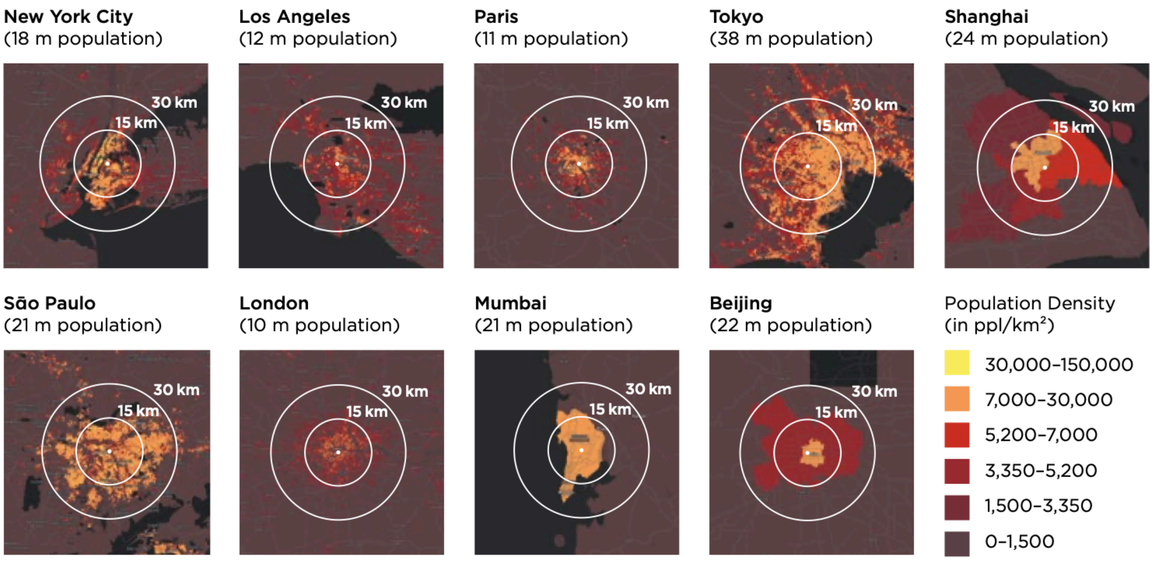


Figure 3.3: Population density of nine metropolitan cities of the top 100 most dense cities, with a circle drawn at a span of 15km and 30km around the geographic center from [21, 53].

in air as perceived by the human ear. Soft, pleasant noises like whispering have a sound of 30dBA, standard household noises are 40dBA, normal conversations around 60dBA, and a vacuum cleaner is around 75dBA at a few meters away [19]. Above 80dBA is considered to be potentially harmful. The higher the level of noise, the shorter time it takes before the human ear is damaged. It takes a couple of hours before the level of 80dBA is harmful, where 115dBA is limited to only a few seconds before it damages the hearing [105, 64].

The objective is to design eVTOL aircraft whose noise levels can effectively blend in with background noises. Medium-sized trucks in urban areas produce a sound level of 75-80dBA at 15 meters distance. Uber Elevate (before acquired by Joby Aviation) set a goal for their eVTOLs to generate 67dBA measured from ground level to the aircraft at 75 meter height, which is the half of the noise level of the truck [37]. Sound of the eVTOL is directly related with the design of the aircraft. It is therefore of great importance for companies to design their eVTOL in such way, that noise can be limited. Noise reduction is a difficult to achieve, as the design process of the eVTOL is a constant tradeoff between other important criteria such as speed, weight, efficiency, and safety.
For example, the amount of noise the rotors make is related to the speed of the tips of the blades. When, for instance, the tip speed is reduced by a third, the level of noise can be reduced by 24. This, however, will subsequently limit the weight that the eVTOL can carry. Another example is the rotor size, which at low revolutions per minute allows the aircraft to hover very efficient, but also generates a low frequency sound which travels further than higher frequencies [37].

The use of distributed electric propulsion is expected to have a significant impact of the vehicle noise levels in terms of low engine and propulsor thrust noise. This change will be an enormous improvement compared to helicopters [59]. Different companies create their own designs and make tradeoffs. It is therefore difficult to say what the average noise level will be of an eVTOL aircraft, but the overall idea is to produce noise 1,000 times less than traditional helicopters.

3.2.6. Autonomy

For now, the air taxi service will be operated by a pilot. The eVTOL is however different from a helicopter and thus requires a whole new pilot training. In addition, within the industry no eVTOL will be the same due to the different designs of companies, which means that pilot training needs to be very specific. Nonetheless, a training center will soon be opened in Ireland to facilitate eVTOL pilot training, which estimates that around 50,000 pilots will be needed by 2030 [5]. A different approach is to make the aerial flights in the cities fully autonomous. This saves a lot of money on pilot training and wages, plus

it creates extra space for a paying costumer.
Even though autonomous flights would be beneficial for companies, the public may not be comfortable with stepping into a self-flying vehicle without any pilot near the steering wheel. A comparison can be made to the automotive industry, where self-driving cars are also difficult to be widely accepted by the public. The higher the level of automation, and thus the less control over the situation, the lower the acceptance is for people to ride autonomous [70]. To make automation in air taxi more public acceptable, the level of safety of the flight and the eVTOL aircraft has to be extremely high. Moreover, it can take some time to get used to eVTOL roaming the urban skies, therefore it could be helpful to first introduce these aircraft with pilots, and at a later stage fully autonomous. Research already sees an increase in the acceptance of self-driving cars, only time will tell if this will also be the case for eVTOLs [103].

3.3. Economics of ATS

In this section, the economics of the eVTOL industry will be discussed through different subsections. The first one, subsection 3.3.1, focuses on the companies designing eVTOLs and shows some of the designs for the air taxi service. Furthermore, subsection 3.3.2 will elaborate on the future demand of aerial ridesharing. Lastly, subsection 3.3.3 gives an inside of the costs the companies make for building and flying the eVTOLs, and what the costumer will pay per trip to make aerial ridesharing an affordable business.

3.3.1. eVTOL Companies

During this chapter a couple of industry players have already been mentioned. These companies try to create a design for eVTOLs that complies with specifications set by governments, that maximizes efficiency through efficient battery consumption and propulsion, and that brings noise level as low as possible. Today, there are already more than 250 companies working towards a revolution in UAM, with some of them having a working prototype, and others only having a design concept [38]. Generally, the companies in the eVTOL business can be divided into independent companies and startups, and commercial aircraft manufacturers. And until recently, even Uber, one of the largest ridesharing and ridehailing companies in the world, took a shot at developing an eVTOL aircraft under their Elevate department.

As mentioned in subsection 3.2.4, Elevate has now become part of Joby Aviation, which is an independent company located in Santa Cruz, California (USA). The showpiece of Joby Aviation, as seen in Figure 3.4a, is their Joby S4, which uses tilt rotors to reach enormous airspeed and has flown further (241 km) and faster (330 km/h) than any eVTOL to date. Joby S4 can carry as much as five people, which is one pilot and four passengers [29, 9].

Lilium GmbH, a German aerospace company, does things differently. This startup is designing an eVTOL propelled by ducted vector thrust in form of distributed electric propulsion in the rear of its four wings. The Lilium Jet in Figure 3.4b is designed to carry up to six passengers, or to serve the zero-emissions logistics market [65].

With 18 rotors and room for two passengers, the VoloCity concept of Volocopter GmbH has put its focus on the multicopter, as can be seen in Figure 3.4c. The German aircraft manufacturer designed its eVTOL to be incredibly quiet, and ensures a quick turnaround time due to the quick battery swap of only 5 minutes [21]. Another company designing a multicopter aircraft is EHang, a Chinese company creating the world's first autonomous aerial vehicle.

The multinational Brazilian aircraft manufacturer Embraer also saw opportunities in UAM. The company founded their independent company Eve, which designs an eponymous eVTOL based on lift-plus-cruise. The Eve, whose design is used as the front cover of this literature studies, has room for four passengers. The simple and reliable design is formed by combining the intellectual properties of years of aircraft development at Embraer with new innovations developed by Eve [45]. Beta Technologies also makes use of the lift-plus-cruise design for transportation, as seen in Figure 3.4d. Besides transporting people, they will also lay their focus on cargo transport, which triggered a large investment of UPS in their electric VTOLs [44].

(a) Joby S4, tilt rotor design by Joby Aviation [9].

(b) Lilium Jet, ducted vector thrust design by Lilium GmbH [65].

(c) VoloCity, multicopter design by Volocopter GmbH [21].

(d) Beta Alia-250, lift-plus-cruis design by Beta Technologies [44].

Figure 3.4: Four UAM companies with the four different eVTOL designs.

3.3.2. Demand for ATS

It is difficult to forecast the demand of air taxi services due to the fact that the market does not exist jet - there is no historical data to be used to forecast future demand. Multiple organisations have performed market studies on the potential of ATS. A study done by McKinsey & Company (2018) on request of NASA concluded that there is a limited potential market for air taxis in urban areas in the coming years. The study stated that ”high investment costs make a widespread air taxi market with ubiquitous vertiports unlikely in 2030” [41]. This does not mean that they don’t see any benefit in the eVTOL development. The research predicts that the full potential will lie in the parcel delivery, where the eVTOLs deliver packages of large e-commerce companies.
Others, however, do see a high potential for the for passenger drones in the near future. Roland Berger (2021) estimates that 12,000 eVTOLs around the world will be carrying passengers in 2030, and even close to 100,000 in 2050 [15]. They foresee that the first few years the passenger drones will be mainly used as an airport shuttle, and later as a point-to-point service. Porsche Consulting (2018) also sees a bright future for air taxi. In their forecast, they estimate that by the year 2035 around 23,000 vertical aircraft will roam the urban skies, creating a market worth 32 billion *USD*[42].

Besides consultancy forecasts, there are also some actual papers that describe demand modelling of aerial ridesharing. Birolini et al. (2021) formulates a demand model as an aggregate nested logit model based on ”the separate grouping of air travel itineraries and the non-air alternative” [18]. In the paper, the total demand is calculated for air travel and the demand for an itinerary, based on the saturated demand - the expected maximum number of trips in a given market. This is decomposed into non-air and air travel, and is further broken down into the different air travel itineraries, and used in a nested logit formulation to calculate the market demand. For the thesis project, the demand for aerial ridesharing is fixed. However, to create a model that is as realistic as possible, such papers can be useful.

3.3.3. Costs of ATS

In order to make ATS attractive to travellers, the price of a ride with an eVTOL should be somewhat comparable to the transportation costs on the ground. The aerial ridesharing business is expected to go from initially an expensive premium product to an affordable way of travel for more people in the

future [42]. This transition can take some time due to the initial expenses of the companies to construct the fleet of aircraft, which are estimated to be somewhere between 1 million and 3 million *USD* per eVTOL aircraft [77].
Joby Aviation shared that the cost of manufacturing its aircraft will be 1.3 million *USD* apiece, and estimates that when in full operation in 2026, the investment will be earned back in less than 1.5 years. This is based on the assumption that the aircraft fly 40 flights a day, seven days a week, with an average of 2.3 passengers on board per flight. The reason that the investments can be earned back on such a short notice, is due to the operating economics of the aircraft and the willingness to pay for a faster transport compared to ground transportation. Bevirt, the founder at Joby, says that “the time they save and the productivity of our aircraft make this a remarkable recurring revenue opportunity” [22]. Joby has set a price of around 3 *USD* per passenger per mile, which is based on an average flight length of 24 miles with 2.3 people. This gives an estimate of 72 *USD* per trip.

To gain profit from these flight, the operational costs should be held as low as possible. Operational costs associated with each flight depend on the different sub-markets and market actors within UAM. Existing literature discusses the following [94]:

- The service provider supplies the air transport service by scheduling trips and managing its fleet, which includes charging batteries, maintenance, repair, and cleaning. These will subsequently have their own sub-markets.
- The company owning the vehicle can be the same company as the service provider, or a separate firm that only leases or sells eVTOL aircraft to the operators.
- Insurance companies are needed to provide security in case of aircraft failures or flight restriction due to difficult weather conditions.
- Pilots operating the aircraft include high costs for the service providers. However, in the future it is also possible that the eVTOLs become fully autonomous, which reduces the cost of training pilots and paying their salary.
- An eVTOL has two possible places to land and take-off: a *vertiport*, which is a large station of multiple landing and takeoff facilities along with charging and maintenance sites, or a *vertistop*, which is a smaller station with only one helipad used only for pick-up and drop-off. These facilities could either be supplied by public authorities, or public or private companies.

At Joby Aviation, the operational costs per available seat mile is the sum of the pilot expenses, the maintenance, vertiport landing fees, battery and charging costs, insurance, and other costs such as leasing or buying the aircraft. The expenses per cost driver, which can be found in Table 3.2, sum up to a cost per available seat-mile of 0.86 *USD* [22].

Cost drivers	Cost per seat-mile
Pilot expenses	22 cents
Maintenance (incl. labor)	19 cents
Vertiport landing fees	11 cents
Battery and charging	13 cents
Aircraft insurance	9 cents
Other expenses	12 cents
Total operational cost	0.86 *USD*

Table 3.2: Operational cost drivers per aircraft with estimated cost per available seat-mile [22]

The costs in the table are estimates since eVTOLs are not yet in operation and multiple aspects of the cost structure still have to be determined. It is possible, for instance, that multiple eVTOL operators share the same vertiports and other (maintenance) facilities. Over the coming years it will become more clear how this cost overview will look like.

3.4. Challenges for UAM

The emerging eVTOL industry has generated a significant amount of enthusiasm amongst engineers, entrepreneurs, and big investment companies. It is for a good reason that the top 10 largest eVTOL

startups have a combined funding of over 6 billion *USD* [1]. Although this transportation mode of passenger drones flying over cities sounds fascinating for some, for others it does not look that attractive. There are many public, environmental and safety constraints that need to be scrutinized before designing a new eVTOL aircraft and eventually implementing it in existing infrastructure.
The EASA, together with the consulting firm McKinsey & Company (2021), carried out a comprehensive study on the societal acceptance of UAM operations in Europe. The EU citizens who participated in this research indicated that they want to limit their own exposure to issues such as safety, environmental impacts, and noise [70]. In this section, these public challenges will be addressed and their solutions, proposed in the literature, will be elaborated on.

Safety

The higher the level of safety is for ATS, the more the public acceptance will increase. Citizens would not be pleased with moving through cities when there is a significant chance of getting injured by a crashing eVTOL - let alone fly in it. The safety of ATS operations can be decomposed into four categories [84]:

1. **Operational Environment**
   The environment in which eVTOLs will be flying will be diverse - weather conditions, locations of vertiports, urban routes, day and night - and needs to be performed by the aircraft at the highest safety standards. Pilots will be able to execute eVTOL flights and handle safety protocols after their UAM pilot training. The greatest safety issues of the flight will be during take-off and landing procedures due to all incoming flights and people walking on the vertiports [84].

2. **Aircraft and Automation Certification**
   The eVTOL aircraft require a robust certification standard to guarantee safety throughout its lifetime. This includes additional enhancements to ensure safe operations when the aircraft is used as an autonomous vehicle. Thereover, it must be equipped with collision avoidance technology on board to ensure safe separation during operations [84].

3. **Aircraft and Fleet Management**
   The aircraft and fleet management standards have to be met within the requirements set by the FAA and EASA. There are strict processes required for landing, charging, and maintenance. Due to the costs associated with these processes the eVTOL companies want to maintain a small turnaround time, which subsequently requires communication with other aircraft or with vertiport operators [84].

4. **Community Integration**
   The main concern of the people living in urban areas is about the safety of the operations of eVTOLs flying at low altitude and navigating next to buildings or other obstacles. These concerns must be addressed through stakeholder engagement and the future plans of urban air mobility should be openly discussed [84]. Only with transparency can the safety concerns of the public be reduced.

Emissions

Despite a small dip due to reduction in human activity during the pandemic, the concentration of greenhouse gasses continued to increase and reached new highs. The goal of meeting the Paris Agreement of limiting emission levels to 1.5°C above pre-industrial levels by 2050 is off track, which encourages the arise of more net-zero carbon emission initiatives [96]. More than 20% of global CO_2 emissions is caused by transport, with road travel accounting for three-quarters [83]. Using eVTOLs as a way of transporting people and freight could be a part of the solution in lowering transportation emissions in urban areas, only if, of course, the emissions of eVTOLs are significantly lower than cars.

In a case study published in the renowned science journal Nature Communications (2019), the greenhouse gas emissions for a car - both an internal combustion engine (ICEV) and a battery electric vehicle (BEV) - were compared with an eVTOL. For the base case, a point-to-point trip of 100km is studied with an occupancy of one passenger/pilot. This resulted in 35% lower emissions of the eVTOL than of the ICEV but 28% higher than the BEV. When comparing fully loaded eVTOLs with cars that have an average occupancy of 1.54, eVTOL emissions per passenger-kilometer are 52% and 6%

lower than ICEVs and BEVs. The aircraft are designed to be very efficient during cruise but consume substantial energy for takeoff and climb - hence, their reduced emissions per passenger-kilometer depend critically on trip distance and the number of passengers. The study states that "VTOLs offer fast, predictable transportation and could have a niche role in sustainable mobility" [58].

Thus, the emissions of eVTOLs are expected to be significantly smaller than internal combustion engine vehicle. However, UAM is expected to be a niche market, which means that it will not have a large contribution to the global greenhouse gas emissions. Nonetheless should further research focus on designing more efficient batteries, and on finding ways to generate greener energy for these batteries - the more green energy is generated, the smaller the carbon footprint will be for the eVTOL industry.

Noise pollution
Another concern which makes the public hesitant for introducing eVTOLs to the urban areas is the amount noise perceived from the new aircraft. In the EASA research, air taxi noise was expressed as the second highest concern (after safety). It was tested by exposing participants to several sounds of different vehicles on top of a typical city background noise at 55dB and rate the annoyance level of the respective sound. It lead to the conclusion that UAM sounds are perceived more negatively than other sounds at the same maximum noise level, presumably for the reason that the sound is yet unfamiliar to people.
The study indicated that the acceptance versus annoyance levels vary a lot due to familiarity with the sound, the distance from the receiver (human) to the originator (eVTOL), the duration of the sound, and the repetition [70]. Although the some companies expect eVTOLs to be almost 1,000 times quieter than traditional helicopters, it will take some time till its noise is publicly accepted and is blended in with the typical city background noise [51].

Bird strike
Apart from issues concerning humans, also animals can be seriously effected with the introduction of eVTOLs to the urban skies. Considering that the electrical aircraft will be spending most of their flight hours below 3,000ft, where over 90% of the bird strikes occur, the probability of an impact with a bird becomes fairly large [86]. The Proposed Special Condition of EASA for small eVTOL aircraft states that passengers must be sufficiently protected from likely bird impacts. For instance, pilots must be able to perform manoeuvres in the case of potential bird strikes [32].
However, the most obvious way to be more resistant to bird strike is to strengthen the structure of the windshield. A downside of this solution is the likelihood of extra weight on the structure, making it the eVTOL less efficient. Therefore, also other options are explored such as on-board LiDAR, which is a method for determining the distance between two objects [86]. The LiDAR targets an object with a laser and by calculating the time for the reflected light to return to the receiver, the distance can be determined. The eVTOL can use this tool to detect birds flying near the aircraft, giving the pilot time to avoid a bird strike.

Conclusion on UAM challenges
As mentioned in this section there are lots of concerns regarding the introduction of UAM, mostly because of the novelty of this way of traveling and transporting. Overarching aviation organisations, such as the EASA an FAA, must make strict regulations regarding all of the concerns in order to enhance public acceptance. Unfortunately, these are not the only concerns of citizens that have to be dealt with. Besides the aforementioned concerns, there are many other challenges, such as security concerns, lack of privacy, fear for job loss, affordability of a flight, and visual pollution of eVTOLs in the skies [86].

3.5. Synthesis on UAM Operations
In this chapter, the applications for urban air mobility, the eVTOL technology, the economics of air taxi services, and the negative sides of UAM have been investigated. This section synthesises these four subjects and findings, and concludes what information is useful for future research for creating the eVTOL Routing Model.

Applications for UAM
An eVTOL aircraft can be useful in many different applications in urban areas. Although all applications

are worth being researched, the focus here will be laid on the use of eVTOLs as passenger drones functioning as an air taxi service (ATS).

eVTOL Technology

Hundreds of concepts of eVTOL aircraft have been proposed over the past years. Companies designing the aircraft want to create the most efficient design possible which satisfies the criteria set by flight agencies such as the FAA and EASA. The use of a battery-driven distributed electric propulsion (DEP) has become the standard in eVTOL propulsion systems, nonetheless, the outer designs still vary significantly from each other. However, this is not in the scope of this research, therefore a homogeneous fleet of eVTOL aircraft will be used with fixed specifications (that comply with the regulations set). This means that all aircraft have identical designs, and thus fly the same range and speed on the same battery capacity, creating the same level of noise. The number of seats per aircraft is also fixed.

Economics of ATS

It was found that the ATS industry will grow significantly is the next decades. In this research, the number of passengers that are willing to fly from an origin to a destination (the demand) is fixed for simplicity reasons. The different companies mentioned have their own vision on the future operation costs and cost per air taxi trip. There will be made use of fixed costs in a simplified environment without competition between companies.

Challenges for UAM

Although it is important to mention the downsides of UAM beside all of the enthusiasm around this newly evolving transportation method, it is not a subject that is significant in the scope of this project. As mentioned, a fixed demand is used throughout the research, and this will not decrease due to the challenges UAM faces due to lower expected public acceptance.

4 ATS Infrastructure

On March 12, 1990, the International Civil Aviation Organisation (ICAO) adopted the airspace classification scheme that is still used on this day. The classes are defined in terms of flight rules and interactions between aircraft in the air and the air traffic control (ATC). Herewith, the ICAO shifts responsibility of collision avoidance to the ATC (if separation is provided) or to the pilot (if not) [7].

For aerial ridesharing to be implemented in large cities, the current airspace structure must be adapted to function within a complex urban environment. The operating eVTOL must avoid flying too close to buildings, and also between different eVTOLs there has to be a minimum amount of separation in order to prevent dangerous situations. The eVTOL aircraft will be flying from point-to-point on predefined routes over the urban areas. The pick-up and drop-off locations, so-called vertiports and vertistops, must be located at a tactical position within the city that is easy to reach for commuters.

Firstly, section 4.1 gives an insight in the urban environment and section 4.2 issues the tactical placing of the vertiports in this area. Subsequently, section 4.3 gives an overview of the current en future airspace structure for ATS operations. Thereafter, section 4.4 discusses the flight safety of eVTOL operations and elaborates on models from papers that describe this issue in the literature. This subject leads to the incentive for the thesis project by mentioning a research gap. Lastly, section 4.5 concludes this chapter regarding the infrastructure of air taxi services.

4.1. Urban Environment

The operations of ATS are heavily influenced by the urban environment of the specific city. Some cities have enormous business districts with skyscrapers, others have lower buildings in the city center. Some cities have lots of green areas such as parks, and others include a lot of water in the form of rivers or canals. That cities around the world are totally different can be be emphasized in Figure 4.1, showing the various types of city structures around the world:

- The top left figure shows Amsterdam with its center surrounded by small canals, almost making a circle around the city centre.
- The top right outlines the structure of New York, which consists of (mostly) straight city blocks throughout the city.
- The bottom left depicts a schematic overview of Paris' famous traffic junction "Place Charles de Gaulle", creating a star-like street network.
- The bottom right portrays the network of Seoul. This is a less structured design than the other cities, with both small and large blocks, set at an angle or straight-lined.

Due to the diverse structures of cities, it is hard to define how the ATS operations will interact with the environment. This makes it difficult to eventually create a model that is suitable for the operations in each city - Amsterdam won't have the same operational challenges as New York, and Paris with Seoul idem.

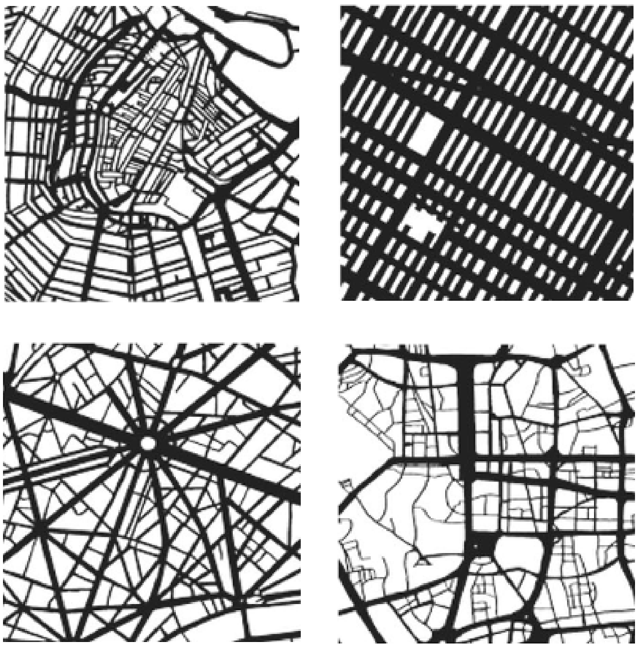


Figure 4.1: Street network of four different cities: Amsterdam (top left), New York (top right), Paris (bottom left), and London (bottom right) from [8].

4.2. Vertiports

Before aerial ridesharing can make an introduction to the metropolitan cities, a whole new infrastructure is needed. ATS will be using so-called *vertiports* and *vertistops* to facilitate the movement of people and goods more rapidly and efficiently than traditional transport infrastructures. A vertiport is a ground station with multiple take-off and landing facilities, along with a charging station and maintenance sites. A vertistop is a smaller station with only helipads without charging possibilities, used entirely for the pickup and drop-off of costumers. In the rest of this section only the term vertiport is used for simplicity. Firstly, in subsection 4.2.1 the vertiport itself will be elaborated on in terms of designs. And thereafter, in subsection 4.2.2, the actual placing of vertiports in urban areas is discussed.

4.2.1. Vertiport Design

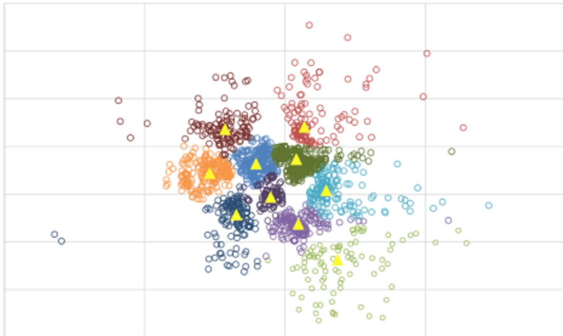
Why aren't heliports sufficient enough for the eVTOL industry? Literature indicates that eVTOLs demonstrate some similar performance characteristics compared to helicopters, such as the use of propellers and the ability to hover. However, despite these similarities there are also some major design differences. As seen in Figure 3.1, the eVTOL aircraft come in various configurations: with or without wings, the amount of propellers, and different landing systems. And besides all of this, the eVTOL is also electric powered which requires a battery charging station at the vertiport. The differences mentioned between a helicopter and eVTOL aircraft calls for a wider touchdown and lift-off area (TLOF) and a load bearing final approach and take-off area (FATO) than currently required at a general heliport [68].

Many companies have an idea on how vertiports should be designed. A common notion is that the vertiports should integrate aesthetically into the existing urban environment. The FAA and EASA created guidance reports on the specifications of the global designs, such as the dimensions for the TLOF, FATO, and Safety Area. The architecture firm Corgan designed a skyport for Uber's future landing and charging facilities. This design, as seen in Figure 4.2a, has two areas for take-off and landings, and can hold up to five eVTOLs [99]. This is just one of many examples, the amount of eVTOLs varies per vertiport design and is based on the demand for ATS.

4.2.2. Vertiport Location

The search for locations of vertiports is an important issue within UAM. Finding the optimal location is essential for the industry to be able to compete with ground transportation methods. Lilium partnered up with Travistock to develop the first urban and regional air mobility network in the US. They created an eVTOL network in Florida to connect entire regions by flying up to 300*km* in one hour on a single charge [66]. This network will consist of 11 vertiports to connect major cities in Florida, with 20 million residents within a 30 minute drive from one of the locations. However, extended research is needed to find the optimal locations of vertiports in or near cities.

(a) Vertiport design by Corgan for Uber from [99].



(b) Location optimization of vertiports in Seoul from [67].

Figure 4.2: Vertiport design and placement.

Research vertiport location

The article of Lim,E. and Hwang,H. (2019) investigates the decrease in commuting time in Seoul by introducing aerial ridesharing to the city [67]. The existing travel times of three routes in the most crowded places in Seoul are compared with the travel time of an air taxi service with vertiports near the routes. The paper proposes a K-mean algorithm that is able to find optimal locations of an X-number of vertiport locations. This research gives more insight in finding suitable vertiport locations in metropolitan cities, which could be helpful for creating a more realistic set-up for the master thesis project.

Experimental setup

First the locations of 14.5 million commuters in Seoul are mapped. Data points are allocated to groups of commuters in districts that were rounded to the thousand, and divided by ten thousand to get a clear visualization of the locations. Hereafter, a K-mean algorithm is used to cluster the data points, based on their x- and y-coordinates. It uses Euclidean distances to find the middle of the clusters - the vertiport locations. The k-value determines the amount of clusters, and thus vertiport locations, formed. Figure 4.2b shows the data points and the 10 clusters formed with the triangles representing each vertiport per cluster. For every value of k (from 2 to 36 in increments of 2), a dissimilarity value is calculated which is closer to one if data points are better clustered. Hereafter, the commuting times for using all possible amounts of vertiports are calculated when using, respectively, a car or public transportation to travel to the vertiports.

Results

Based on average speeds, it took 60 min to travel with a car on Route 1, 51 min for Route 2, and 66 min along Route 3 during weekdays. By public transportation, Routes 1, 2, and 3 took 118 min, 99 min, and 78 min, respectively. Results show that increasing the number of vertiports, gives a decrease in travel time. This trend, however, fades away beyond a certain number of vertiports. The minimum travel time was different at each Route and for each travel mode to and from the vertiports. And if locations were not right, the model did not show a meaningful difference in travel time. Compared to the total travel time, the eVTOL flight time was relatively small - traveling to of from the vertiports dominates the total time.

Discussion

The case study shows a significant impact on the traveling time for commuters with ATS. The amount of time reduction does not depend heavily on the amount of vertiports after a certain number, but mainly on the vertiport locations. The position optimization of vertiports requires the best proximity to the arrival and departure locations of the passenger. The ideal location would be free of large buildings, with enough space to create safe approach and departure flight paths. Another consideration is the access to electricity to recharge dozens of eVTOL aircraft per day. A rooftop is often seen as a perfect location for vertiports, however the high costs of developing passenger and charging facilities far above the ground make rooftops unattractive for vertiport placement [101]. Areas near highways, riversides, and creeksides are expected to be much more sufficient, where the position reflects the geographical conditions of the city while aiming for efficiency and optimality.

4.3. Airspace Structure

As organizations set regulations and policies for the design of eVTOLs and vertiports, governmental authorities such as the FAA suggest that also the airspace needs modifications for the implementation of UAM [16]. But also researchers from the TU Delft and aerospace corporation Airbus proposed concepts for airspace design. The eVTOL aircraft will operate in urban airspace where also aircraft, helicopters, and such as drones (unmanned aerial vehicles) will fly. This substantiates that strict regulations are needed for the urban airspace to enable safe operations for urban air mobility.
This section consists of two subsections, subsection 4.3.1 gives a brief overview of the current airspace adopted by countries, and subsection 4.3.2 discusses the different approaches of implementing UAM operations into the current airspace.

4.3.1. Current Airspace

A short overview will be given of the current airspace structure established by the ICAO, which is divided into three-dimensional segments assigned to a specific class with letters A - G. Each segment has its own specifications in terms of *separation* (minimum distance between two aircraft), *ATC clearance* (permission granted by ATC to proceed under certain conditions within clearance), *traffic information* (information on position and other flights), and *flight rules* (aircraft operate under visual flight rules (VFR) or instrument flight rules (IFR)) [7]. Each national aviation authority determines how the ICAO classification should be used within the country of operation, which leads to some differences between countries. Within the U.S. there exists controlled airspaces (A, B, C, D, and E) and the uncontrolled airspace G. Class F is not used in the U.S., the others are categorized as follows:

- **Class A**: High altitude airspace (between 18,000 - 60,000 feet MSL).
- **Class B**: Airspace surrounding key airport traffic areas.
- **Class C**: Airspace around airports of moderate importance.
- **Class D**: Airspace around small airports.
- **Class E**: Controlled airspace outside of class A - D.
- **Class G**: All uncontrolled airspace outside of class A - E.

Apart from the classes discussed above, there are also areas wherein activities must be confined due to their nature and/or wherein limitations are imposed upon aircraft operations. This special use airspace consists of areas such as Prohibited areas, Restricted areas, and MOAs (military operation areas) [4].

4.3.2. Future Airspace

How will UAM be successfully implemented in an already existing airspace structure? Contemporary literature gives multiple approaches on integrating UAM airspace into the current structure. A number of these solutions will be discussed below - proposed by, respectively, the FAA, TU Delft, and Airbus.

Corridors

The FAA envisions in their Concept of Operations (ConOps) that eVTOL aircraft should operate between aerodromes within a UAM Corridor, which is "an airspace volume defining a three-dimensional route segment with performance requirements to operate within or cross where tactical ATC separation services are not provided" [26].
The corridors, seen on the left in Figure 4.3, function as a separation mechanism between UAM and other operations, such as Unmanned Aircraft System Traffic Management (UTM) and Air Traffic Management (ATM). And within the corridors, the separation is maintained by eVTOL pilots. Also

additional tracks help enabling this safe separation. Initially, the corridors connect two aerodromes via a point-to-point network, however, in later stages the FAA expects a more complex and efficient network [16].

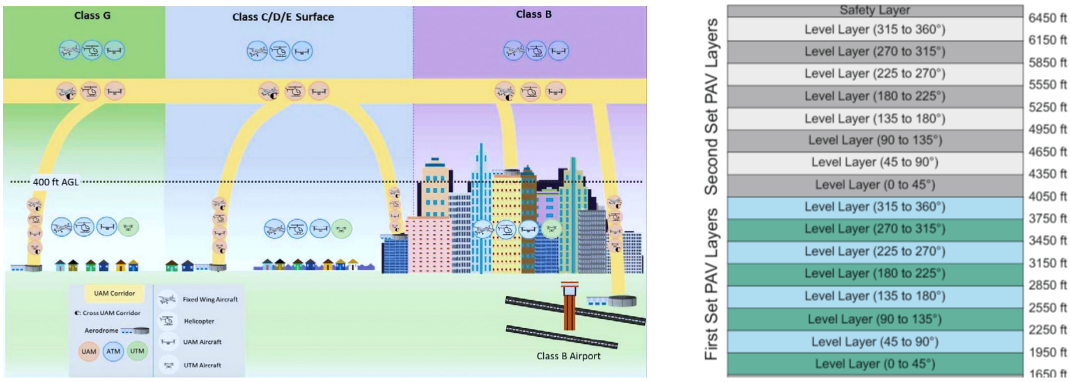


Figure 4.3: Illustrations of operational environment of UAM with corridors and layers from [26, 95].

Layers

The airspace is divided into a system of layers, where each layer (altitude band) corresponds to a heading range. The project Metropolis, conducted by a team of researches at the TU Delft, proposed this method of facilitating separation and increasing safety. It is portioned into a low feeder layer used for climbs and descends, a UAV layer reserved for small, unmanned drones, a separation layer between the UAV and eVTOL layer, and an eVTOL layer for eVTOL operations. The altitude depends on the height of buildings in the city. The minimum cruise altitude for eVTOLs in this concept is 300*ft* above ground and 500*ft* above the highest building [16, 95]. A visualization can be seen on the right in Figure 4.3.

Basic Flight

One of the concepts proposed by Airbus is the method of Basic Flight, which is system wherein both drones and eVTOLs are responsible for self-separation and must maintain it at all times [16]. It reduces distance traveled as the vehicle does not have to climb to specified altitudes, reducing costs.

Conclusion on Future Airspace

In several papers, a considerable amount of future airspace structures are proposed for UAM operations. Choosing one of these visions is not in the scope of this thesis, however, it is important to mention that the project will include a structured airspace with predefined paths. This means that concepts such as Basic Flight are not at all considered.

4.4. Flight Safety

When the vertiports are placed, the airspace is structured, and the ConOps are implemented, the air taxi service is ready to take place. The potential passenger for the flight indicates its origin and destination to a service operator (presumably via an application on a smartphone), which subsequently determines the vertiport locations suited for the trip. The passenger travels to the vertiport where an eVTOL transports the passenger along with others to another vertiport location across the city.
When the demand grows as expected over the years, more vertiports will need to be built to be able to hold more aircraft and cover more flights. This growth causes many flight paths to cross with each other, creating potential hazardous situations. The danger is especially large when the eVTOLs are not fully automated yet, but are flown by trained pilots to keep the aircraft separated from other eVTOLs. In the ConOps of the FAA, the ATC will not provide tactical separation within the corridors - this separation is ensured by the pilots themselves.

The arrival of eVTOLs at a vertiport is the most hazardous segment of the flight. There are aircraft taking off, others are landing and some are at the maintenance or recharging facility of the vertiport.

The arrival approach of eVTOLs is extensively described in the paper of Kleinbekman et al. (2018) - proposing a minimum separation time of 90s, and flying at a predefined speed and altitude profile when in a range of 400m from the vertiport [61]. The separation at vertiports is schematically depicted on the left in Figure 4.4. On the right side, the conflict avoidance during flight, proposed by Jenie, Y. (2017), is shown. The paper discusses the en-route conflict detection of UAV's, which can be applicable to unmanned eVTOLs in the future [56].

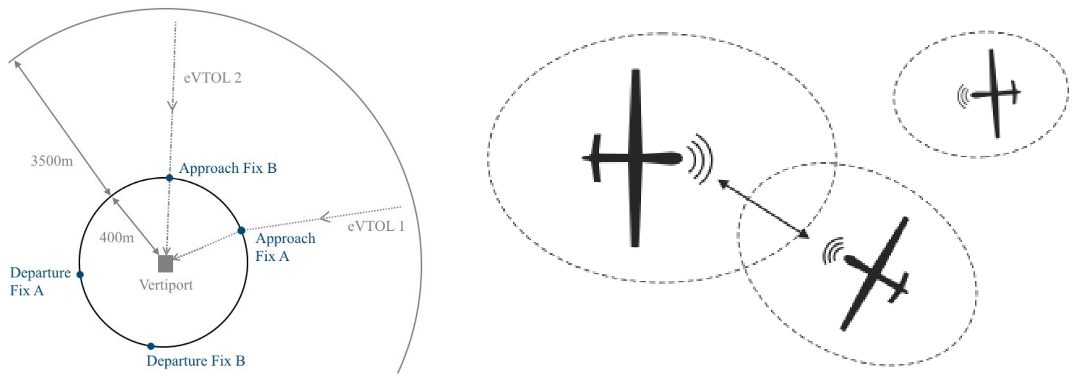


Figure 4.4: The separation of eVTOLs at vertiports and en-route from respectively [61] and [56].

Research Gap

Multiple studies describe the need for eVTOLs to have collision avoidance capabilities [104, 85, 56]. These papers discuss the manoeuvres en-route of eVTOLs or the minimum of separation at vertiports to ensure safety. However, especially because ATS will initially not be fully automated yet, there is a need for a model that avoids en-route losses of separation without the use of automated collision avoidance systems [47]. This research gap gives the opportunity to investigate and create an eVTOL routing model which ensures en-route safety pre-flight.

4.5. Conclusion on ATS Infrastructure

In this chapter, the infrastructure of the future urban air mobility operations has been discussed. The was done by elaborating on the urban environment, the eVTOL vertiports, the airspace structure, the traffic management, and the flight safety. Each subject is important for the development of an eVTOL routing network. The information gained by literature research on the various infrastructure subjects will be used to make decisions on how to construct the network in an efficient way during the Master Thesis project. The research gap will be the base for research into routing models in chapter 5. Here, the models will be discussed for designing eVTOL routes to match the passenger demand with the eVTOL supply. Also, dynamic models are introduced that could be used to enhance the safety of the operations of on-demand eVTOLs in urban areas.

5

Routing Models

The model developed during the Master Thesis project will be created to plan and schedule an eVTOL network, based on a fixed demand per time interval and fixed vertiport locations, in an urban area. The model exists of two parts, where the first phase models the scheduling network of the eVTOL aircraft during one day of operation, and the second phase limits the potential en-route conflicts of eVTOLs. In this chapter, the theoretical foundation is laid for the models used during the thesis. This is done by examining relevant literature on topics that could be applicable to the models. In the first part of this chapter, section 5.1, elaborates on the concept of the Time-Space Network (TSN) and discusses its relevance for the eVTOL model. Subsequently, section 5.2 discusses the Dial-a-Ride Problem (DARP), which is a problem extensively described in the literature for ridesharing models. Thereafter, in section 5.3 the subject 'loss of separation' is explained, which is a measurement for potential in-air conflicts. In section 5.4 the techniques and algorithms used for obtaining solutions from such a large problem are discussed. And lastly, section 5.5 gives a conclusion and remarks on the literature found.

However, firstly, the choices for a routing model and complementing literature are explained, which includes a discussion on how this will be used to satisfy safety requirements for the flight paths of eVTOL aircraft. In addition, the difference between a static and dynamic model are showed, which are fundamental concepts worth mentioning.

Model Explanation

As said previously, the model designed during the thesis is described as an 'eVTOL Routing Model', a modification of the typical Vehicle Routing Problem (VRP) model. The schedule alternatives for the times of arrival and departure of the eVTOL aircraft in the network will be formed using a Time-Space Network model, which is originally the basis of a Fleet Assignment Problem (FAP). In an aircraft network, the fleet assignment investigates what *aircraft type* should operate a specific flight, and aircraft routing determines which *specific aircraft in the fleet* operates each flight in the timetable. The difference between the two model approaches are, however, negligible. The eVTOL fleet is considered homogeneous, which could imitate an aircraft routing model or a single-fleet fleet assignment model. Both approaches are used to develop the structure of the eVTOL Routing Model.

The literature discusses the VRP applied in many ways, e.g., aircraft routing or pick-up and delivery. The model designed during this thesis project will be created for aerial ridesharing, a subject not yet extensively described in the literature. As discussed previously in chapter 2, the concept of aerial ridesharing has some similarities to ground-based ridesharing. Because of the lack of existing eVTOL routing literature, and due to the resemblances with ridesharing on the ground, the literature on the ground-based ridesharing models is researched for potential eVTOL routing model use. A problem that comprises both ridesharing and routing is the DARP. DARP is a generalization of a number of vehicle routing problems, such as the Pickup and Delivery and the VRP with Time Windows. The difference is that the DARP takes the human perspective into account.

The second part of the model will be on flight safety, which is obtained by establishing a model that calculates the losses of separation between all eVTOL flights, and uses this information to reschedule flights in conflict. The output of the dynamic model will be the new input of the first part of the model, thus acting in a feedback loop fashion.

Static vs. Dynamic

Models discussed in this section elaborate on both *static* and *dynamic* operations. Static models focus on the structures of the objects that exist in the problem domain, based on the state at a fixed point in time, therefore making it time-independent. In the research following up this Literature Study, the static part of the eVTOL Routing Model is based on predetermined elements, such as the fixed passenger demand and vertiport locations.
On the other side, dynamic modeling is used to express and model the behaviour of the system over time, thus time-dependent. The model that will be created is dynamic in the sense that it reduces the potential en-route conflicts over time. With the dynamic and static models combined, the goal is to effectively ensure air traffic safety between eVTOLs when en-route while minimising costs or maximising profit.

5.1. Time-Space Network

Given a set of routes to be operated in an eVTOL network, the schedule development begins with the task of creating a timetable design, which investigates how often eVTOLs should operate on the selected route(s) and at what times they depart. It is important to understand that a TSN is different from a static network. In the lectures on Airline Planning & Optimisation of Dr. Bombelli and Dr. Santos in the course AE4423-20 at the Faculty of Aerospace Engineering, the main difference between a Time-Space Network and a static representation is defined as follows [10]:

> ”Time-space networks are used to *model* fleet allocation alternatives, while a schedule map already represents one *solution*.”

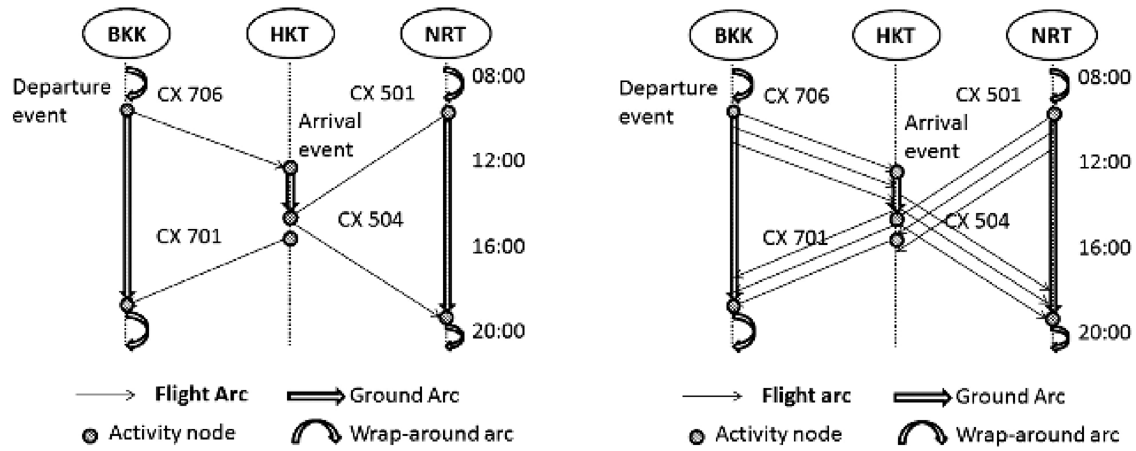
Thus, a TSN eventually is an extension of a static network, with the static network being a representation of a schedule - a solution to the FAP - and the TNS a model of schedule alternatives. This can be seen in Figure 5.1a, which shows a schematic representation of a TSN of airports and aircraft, where the x-axis represent the airports in the model (the space perspective), and the y-axis represent the time from left to right. The network is shaped by multiple nodes and three types of arcs [106, 10]:

- **Nodes** are the elements in the model that allow the change of allocation of an aircraft from a flight arc to a ground arc, or vice versa.
- **Flight arcs** illustrate the flights that have to be covered in the timetable. The arc connects between airports, for instance Airport BKK to HKT. The arcs are diagonal, because they represent flights over time.
- **Ground arcs** display the possibility of an aircraft to stay on the ground over time at a given airport.
- **Wrap-around arcs** guarantee the continuity between the aircraft at the end and start of the scheduling horizon, whereby the cycle can start over again.

In order to keep a balance throughout the network, at each node a flow balance is guaranteed. Each node has input flows from and output flows to a flight arc, ground arc, or wrap-around arc. This gives the following constraint: $flow_{f_1} + flow_{g_1} + flow_{w_1} = flow_{f_2} + flow_{g_2} + flow_{w_2}$. There might be multiple input and output flight arcs per node, as they are balanced. One way to count the amount of aircraft in the network is by looking at a specific time and counting the amount of arcs crossing the *count time-line*. The number indicates the number of aircraft needed, therefore it has to be guaranteed that the flow crossing the line must be smaller or equal to the number of available aircraft [106, 92].

Dong et al. (2016) describes the need for a flight scheduling problem to have different departure options per flight. This is represented by incorporating several flight leg copies for each original flight leg. An example of this can be seen in Figure 5.1b which has two extra flight legs incorporated per leg compared to the original network in Figure 5.1a, each having a slightly different departure time. Additional constraints are needed to guarantee that only one option is chosen. The study of Rexing et al. (2000) uses this approach in their FAM by using time windows or 20 and 40 minutes, in which copies of legs are created for, respectively, 5- and 1-minute intervals [82] - one of these copies has to be covered by a flight, obviously.

The inclusion of these flight leg copies increase the number of decision variables, and hence, the overall problem size. Rexing et al. (2000) applied pre-processing to its model by applying a *node aggregation* and *island formation* technique. Node aggregation is a method where a node is shared by consecutive arrivals and the subsequent consecutive departures, such that each arrival at the aggregated node can be feasibly connected to any departure at this node. By eliminating ground arcs with a zero-flow, islands are created. In addition to aggregation and islands, the study also proposes the method of deleting the *redundant arcs* that stem from the existence of multiple copies of flight legs. Node aggregation reduced over 80% of rows and 56% of columns in the model, islands helped the problem to be solved 10-20% faster, and eliminating the redundant arcs reduced the problem size by respectively 40% and 66% for the aforementioned time windows and intervals [92].



(a) Time-space network of a flight schedule.

(b) Leg copies in a time-space network.

Figure 5.1: Representations of an aircraft time-space network from [106].

Sherali et al. (2006) explains that a ”time–space network representation superimposes a set of networks, one for each fleet type” [92]. Each aircraft type has a different effect on the network. Firstly, because of different cruise speeds of the types, which has an effect on the duration of the flight. Additionally, the end nodes represent the moment that the aircraft is available. The time that passes from landing until take-off for a new flight is the turnaround time (TAT), which differs per type of aircraft. The third reason that the aircraft type has a large influence on the schedule, is because of certain limitations of the aircraft, such as the maximum range, and limitations of the airports, such as lengths of runways. As said previously, however, the types of eVTOL aircraft are not considered during this thesis - there only exists a homogeneous fleet of eVTOLs with a fixed velocity, TAT, and range.

A TSN model will be used as a framework for the eVTOL Routing Model. The objective of the model is to maximize the revenue (or profit), or, equivalently, to minimise costs. However, some adjustments have to be made to make it applicable for an eVTOL network. Generally, the TSN is a base for a scheduling model for different types of aircraft and airports over a period of time, divided into discrete periods of equal length. As seen in subsection 3.3.1, there will be many companies on the market designing different types of eVTOLs. The eVTOLs vary in velocity, capacity, and range, and vertiports differ in size and charging capabilities. Nonetheless, for sake of simplicity, only one type of eVTOL will be used with a fixed seat capacity, which has the ability to land at any vertiport without limitations.
Using the approach of Dong et al. (2016) by incorporating multiple flight departure options could be an interesting approach for this project, as en-route loss of separation could force eVTOL aircraft to depart at a different time. This means that a time window will be set in which the eVTOL must fly, and that this window will be divided into multiple time steps at which the aircraft can depart.

5.2. Dial-a-Ride

The research of Cordeau and Laporte (2007) explains that the "*Dial-a-Ride Problem* (DARP) consists of designing routes and schedules for n users who specify pick-up and delivery requests between origins and destinations" [28]. The transport is provided by a homogeneous fleet m, based at the same depot. However, different situations assume multiple depots. For our research, a homogeneous fleet of eVTOLs is used with a fixed number of seats, and multiple depots (vertiports). The global objective of the DARP is to accommodate as many request as possible while minimizing the costs of the vehicle routes under a set of constraints.
The paper of Jaw et al. (1986) describes a heuristic algorithm for a multi-vehicle DARP with service quality constraints, called Advanced Dial-a-Ride with Time Windows (ADARTW) [55]. This static model considers specified time windows on the arrival of the inbound and departure of the outbound requests. The service quality constraints guarantee that: "(1) customers' ride times will not exceed a prespecified maximum and (2) the time of pick-up or delivery of customers will not deviate from the most-desired pick-up or delivery time of these customers by more than pre-specified amounts ("the time windows")" [55]. The heuristic selects passengers in order of the earliest feasible pickup time and inserts them into the vehicle routes in order to keep the objective function as low as possible. The algorithm is interesting due to its convenience and flexibility, and the low computational cost for a high-quality solution. The ADARTW assumes that costumers specify either a desired pickup or delivery time. The paper describes its computational experiences, including a run with a data set of 2600 costumers and 20 active vehicles at once.

A technique commonly used for such a problem is to define clusters of costumers that will be transported by the same vehicle, prior to the routing phase. This idea is described by Bodin and Sexton (1986) who constructed clusters before applying them to the routing model [20], which came from their previous work describing a single-vehicle algorithm executed on a Baltimore data set containing 85 users [88, 89]. The paper explains the use of a 'swapper algorithm' which attempts to move costumers among the specified clusters in order to find the final set of clusters while keeping costumer inconvenience at a low. Also penalties are introduces for exceeding ride times and delivery time deviation. Dumas et al. (1989) improved upon the approach with the creation of so-called 'mini-clusters', which are groups of costumers to be served within the same area at the same time [36]. This problem is managed by going through four stages. At the first stage, instead of clustering costumers to the working period of a vehicle for one day, mini-clusters are formed corresponding to small work periods of the vehicle. Each mini-cluster travels somewhat the same distance at somewhat the same time. Thus, the focus will be only on local temporal and spatial considerations. The second stage assigns mini-clusters to vehicles in an efficient way. Stage three uses the single vehicle dial-a-ride algorithm of Desrosiers et al. (1986) to construct routes for all vehicles simultaneously [33]. At the fourth stage, the schedule of each vehicle is optimized over a fixed itinerary.

In the papers mentioned above, the DARP focuses on a costumer pick-up and drop-off from homes and special locations such as hospitals or clinics. However, in this research, a passenger has to travel to a vertiport to be able to fly with the eVTOL aircraft. And after landing at the next vertiport location, the passenger will have to travel to its final destination. This means that, looking at the positional elements of ridesharing in Figure 2.2, this problem matches the 'identical ridesharing', because the eVTOL will not detour or pick-up the passenger en-route. The situation can better compared to Uber's new feature 'Express Pool', where "passengers are willing to walk a short distance to be picked up and be dropped off somewhere close to destination in exchange for a reduced fare" [43].

5.3. Loss of Separation

For the second part of the project, a dynamic model is created to avoid conflicts in the routing model. In order to make this, we first want to know where the potential conflicts are in the routes. This is done by calculating the losses of separation of the eVTOLs, which occurs when the positions of two passenger drones are predicted to be closer than a set of separation minima.
Hernández-Romero et al. (2020) explains that "a conflict exists when the protected zones around the aircraft, two cylinders of diameter D and height H centered at the aircraft, are predicted to overlap" [47]. This paper proposes a probabilistic method for the conflict detection and resolution of multiple

en-route aircraft flying at constant speed, following a multi-segment trajectories with wind conditions. For the thesis, wind is not considered, however the paper explains very clear the conflict detection of two aircraft. As seen in their aircraft conflict representation in the left sketch of Figure 5.2, the aircraft have a 'protected zone' around them of a circle with diameter *D*. Time t_1 gives the moment at which the future aircraft positions are predicted. At this time, the distance *d* between the aircraft is larger than the separation minimum of the protected zones ($d(t_1) > D$). However, the zones are predicted to overlap at t_2, which brings the two aircraft in conflict ($d(t_2) < D$).

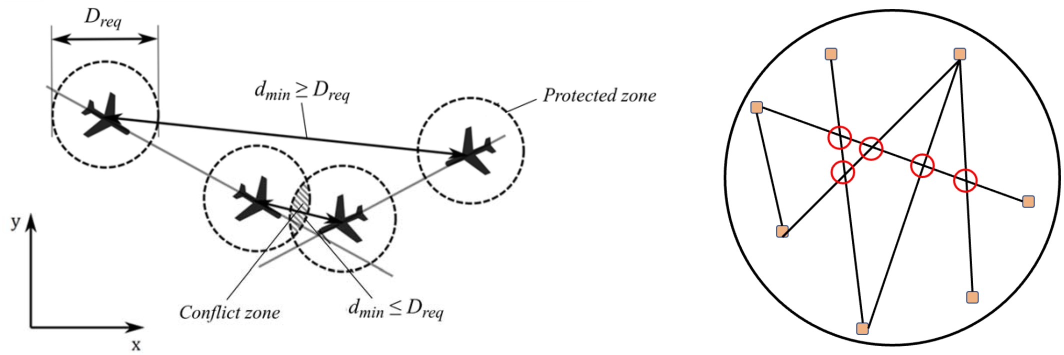


Figure 5.2: Two aircraft with loss of separation from [47] and potential conflict areas in eVTOL routes.

During the simulation, the losses of separation of eVTOL aircraft in the routing model are measured. The right drawing in Figure 5.2 gives a visualisation on where these conflicts may occur in the network. The black circle represents the enclosure of an urban area with orange vertiports. The lines drawn between the vertiports are the routes that are covered by the eVTOLs. The red circles are the potential conflict areas within the network. The model calculates the information of the location and time of the potential conflicts. This information will be used in a feedback-loop fashion to provide information to the routing model, which, subsequently, uses it to reschedule certain flights. This should eventually decrease the number of conflicts, creating a safer airspace.

5.4. Solution Techniques

In the previous section a couple of models that are extensively described in the literature, were elaborated on. With a large amount of vertiports and possible routes and potential conflicts, the eVTOL network problem will become extremely large. To tackle this, various smart techniques that have been presented in the literature are used to solve such a large problem. In this section, a method on how to find an optimal solution to the problem is presented in the least amount of computational time.

Model 1

A solid base for the model should be a *mixed-integer linear programming (MILP)*, which is a mathematical optimization program which is written in a specific structure. It maximizes or minimizes the objective function formed, and provides decision variables, parameters, and constraints in order to find the optimal solution of the problem. Integer programming is 'NP-complete', a computational complexity theory which is short for "nondeterministic polynomial-time complete". A problem is NP-complete if the correctness of the solutions can be verified in polynomial time, and a search algorithm finds a solution by going through all potential solutions. Finding an algorithm for any problem implies that for every other problem a solution can be found. A commercial solver is needed to obtain the nearest solution of the problem. Gurobi is such a solver, which is designed to process large amounts of data efficiently. This solver has become familiar during the Airline Planning & Optimization course, this also counts for the programming language of Python.

For this project the MILP foundation of a FAP in combination with a TSN can be used, which is an excellent way to create a scheduling structure for the network. The objective of the FAP is to minimize costs of the whole fleet, and/or to maximize the profit based on the revenue minus the costs of operation. An example for the revenue of a fleet of eVTOLs could be the fare price for a passenger of a flight, dependent on the range the costumers wants to fly. The costs for each flight can be divided into certain categories, such as fixed operating costs, time-based costs, or fuel costs. Fixed operating costs are associated with each flight leg are landing fees of vertiports, time-based costs are the pilot's wages per hour, and the fuel (battery) costs depend on the distance flown.

Model 2
When the routing model is created, the second step has to be integrated into the network model. As mentioned before, the goal of this literature is to create a routing network with a limited amount of aerial conflicts en-route. The reduction of conflicts is obtained in the second part of the model, which interacts with the first part. The literature often describes the use of *heuristic algorithms*, which are designed to solve problems not only faster, but also more efficient than traditional methods, by sacrificing optimality, accuracy, precision, or completeness for speed [27]. Özkır & Özgür (2021), for instance, apply a *two-phase* heuristic algorithm for an integrated airline fleet assignment and routing problem [73]. The first phase of the algorithm generates a basic, feasible solution. The second phase proposes a mechanism to improve the solution.

Using a heuristic algorithm or not, the goal of the second part is to avoid collisions in the network while obtaining the highest maximum profit for the network possible. Smart solutions need to be found, interacting with the first part of the model. For example, the potential conflicts must be calculated, which subsequently will result in re-timing of flights, which is made possible by the time-space network in the first model.

5.5. Concluding Remarks

In the eVTOL industry, just like for airlines, the nature of competition makes it necessary to find new ways for maximizing profits while decreasing operational costs of regular activities. In this chapter, different models and solution techniques were discussed that could be useful for the creation of the eVTOL Routing Model during the Master Thesis project. This routing model consists of two stages, where the first stage models a network and schedule of eVTOL aircraft during one day of operation, and the second part limits the en-route conflicts within that schedule. Firstly, the time-space network was studied, which gives a foundation for modeling a network with schedule alternatives and time windows. Subsequently, the dial-a-ride problem gives an inside into a ridesharing model that is extensively described in the literature. Some literature of the DARP takes time windows into account, and clustering of costumers is also an important subject to consider. Thirdly, the loss of separation is mentioned, which occurs when the protected zones of two (eVTOL) aircraft cross each other. After creating the routing network for one day of operation, all losses of separation will be determined, which is subsequently used to re-time the previously created schedule to bring the conflicts to a low.

With the conducted literature research in mind, a MILP model will be created with the objective to minimise the operational costs or maximising the obtained profit of transporting passengers to their desired location. A decision variable is brought in the formulation to represent the flow on a flight leg - the eVTOLs flying from one vertiport to another on a timestamp. The constraints will ensure limitations on capacity and flows per node. The exact decision variables, parameters, and constraints will be obtained during the project. Because of the large dimensions of the MILP model, a commercial solver is needed to help solve the whole model in less computational time. Nonetheless, all the methods written likely won't form the final methods used during the thesis. The literature study still continues during the project to eventually find the most suitable and efficient solution technique(s) for the problem.

6
Conclusion

In the chapters 2-5, a literature study was conducted on urban air mobility operations of eVTOL aircraft. The knowledge gained during the literature study gives a strong foundation for the actual project of the Master Thesis. During this chapter, the most important conclusions of the subjects described will be summarized.

Ridesharing

Ridesharing is a transportation method which transports multiple commuters with a (somewhat) similar origin and destination with one vehicle. This method aims for higher vehicle-occupancy for the sake of reducing traffic congestions in metropolitan cities, and lowering CO_2 emissions [57, 39, 46].
Many companies have created platforms where commuters can be matched by an agency to a car driver who is willing to pick-up and drop-off these costumers at or near their desired locations. Ridesharing is often called 'dynamic' which refers to the automation of real-time matching of rides to potential passengers beforehand or en-route. This concept must not be confused with ridehailing, where the company has a platform for on-demand private rides with licensed drivers, who acts as taxi drivers with no origin or destination themselves [91].
For the companies to make any profit and keep emissions low, certain objectives must be optimized, such as the minimization of the travel distance, the minimization of the travel time, and the maximization of the number of passengers [3].
Aerial ridesharing, also referred as 'air taxi service' (ATS), has similarities with ridesharing on ground-level. For instance, both methods use the same principle of transporting different people, who sharing one vehicle with the same heading. ATS corresponds with *identical ridesharing*, where the driver (now: pilot) has the same staring location and destination as the passenger [39]. The commuter has to travel to the starting 'vertiport', the location where the electric vertical take-off and landing (eVTOL) aircraft are based. From there, the eVTOL flies the passenger to the arrival vertiport, which is as close as possible to the passenger's destination. A difference is that the route of the eVTOL is fixed and therefore can not be changed mid-air to pick-up an extra passenger. Due to the novelty of aerial ridesharing, there is not a lot of literature to be found. However, because of the similarities with both ridesharing and ridehailing, the literature for ATS can be partially derived from these ground-transportation methods.

Urban Air Mobility

Air taxi service is one of the application of eVTOLs in the operations of the so-called 'urban air mobility' (UAM). Other applications could be package deliveries or medical assistance, and outside the urban area the eVTOLs could be used for maritime operations or evacuations [76, 40].
The technology of eVTOLs is fast evolving, which is partially a result of the regulations set by the FAA and EASA. These authorities specified the design characteristics of the aircraft and the criteria, such as the weight, length, and propulsion [68]. Most companies designing eVTOL aircraft make use of distributed electric propulsion (DEP), making the aircraft electric [59]. Some degrees of freedom resulted in four main architecture standards: the multicopter, lift-plus-cruise, tilt rotor, and the ducted vector thrust design [65]. The different designs contribute to the various ranges and speeds of eVTOLs,

but also have an impact on the the phases of flights: hovering, (re-)transition, climb, descend, and cruise [71]. An important similarity between design concepts is the reduction of noise compared with traditional helicopters, which is plausibly more than 1,000 times [51].
The demand for ATS is expected to grow significantly in the next 20 years [15, 42]. This is important, as the investments for enabling a aerial ridesharing system is very expensive. The cost drivers per seat-mile comprise the pilot expenses, maintenance, landing fees, battery charging costs, aircraft insurance, lease of buying costs, and other expenses. The revenue comes form the commuters, who pay a fixed price per mil [22].
There awaits some challenges for UAM in order to make it more attractive to the public. The challenges include the level of safety during the flight that is ought to be acceptable, in addition the emissions have to be significantly lower than car rides, the amount of noise from the propellers must be low, and companies also have to take animal life in to account [70, 84, 32, 86].

UAM Infrastructure

The routes for eVTOL operations in urban areas depend heavily on the environment of that area. No city structure is exactly the same and not all areas are suitable because of high buildings or restricted areas - this makes it difficult to determine what the best vertiport locations and network routes should be. Different studies use certain methods to find the best possible location, which often is within highly commuting areas and preferably near highways or riversides [8, 67].
Also the current airspace must be adjusted for UAM operations. The literature proposes multiple solutions to implement the eVTOL aircraft into existing structure, such as separation by flying through *corridors*, in a eVTOL *layer*, or maintain self-separation in *basic flight* [26, 16, 95].
When the airspace is structured and the vertiports are placed, the routes can be designed according to the forecasted demand. The network established must guarantee route safety for eVTOL operations. Some papers propose separation times near vertiports, and others envision en-route separation manoeuvres through conflict avoidance detection. However, no paper in the literature describes the avoidance for potential conflicts by re-timing the flights [61, 56].

Routing Models

During the project of the Master Thesis an eVTOL Routing Model will be created. The model exists of two parts: development of a routing schedule and limit the potential en-route conflicts. The schedule will be designed for one day of ATS operations, and will be based on a fixed demand and pre-determined vertiport locations. A MILP will lay the foundation of the model for the schedule. And to design this timetable, literature on a time-space network (TSN) is investigated, which is a basis for a fleet assignment problem, and used to model fleet allocation alternatives. The basic components of the TSN are the nodes, flight arcs, ground-arcs, and wrap-around arcs. Every node has the same inflow as outflow [10, 106].
An optimization problem often cited for ridesharing is the Dial-a-Ride Problem (DARP), which consists of designing routes and schedules for pick-up and deliveries. The problem could also be extended to a DARP with time windows, which corresponds more with the eVTOL model[28, 55].
The second phase of the model is to calculate the losses of separation in the routing schedule and use this information as an input for the first model to avoid these potential conflicts. A loss of separation occurs when the ’protected zones’ of two eVTOL aircraft overlap. This means that the aircraft are too close to one another, which could lead to dangerous situations [47]. With dozens of eVTOLs flying through the network, the problem can become very large. In order to minimize the overall computational time, a commercial solver is needed to help solve the model.

7

Research Framework

With the Literature Study conducted, a research framework is established to give a structured foundation for the Master Thesis project. The first section describes the problem, and thus the incentive for this project. It is followed up by the research question, which is the main question that is aimed to be answered during the thesis. This main question is divided into multiple core and sub-question. The next section describes the objective for the research and elaborates on what must be done in order to answer the (sub-)questions. Lastly, a project plan is made using a 'Gantt Chart'. This chart visualizes the timeline of the project and gives an indication how much time will be spend on what part of the project.

7.1. Problem Statement

The problem that is considered for the Master Thesis project is a routing model for an eVTOL company for one day of operation in an urban area that minimizes potential en-route conflicts. The difficulty of this project is that the second phase of the model, the mitigation of conflicts, most likely goes against the objective of the first phase, maximizing profits. For the model it is assumed that demand is predetermined and that vertiport locations within the urban area are fixed. Additionally, a homogeneous fleet in considered, meaning that all eVTOLs have the same capacity and flight performance, such as speed and range.

The routing model is focused on maximizing profit of the eVTOL operations, by transporting passengers from one vertiport to another. The profit is obtained by creating as much revenue from the point-to-point flights as possible, and limiting the (operational) costs. The revenue is the money generated from the transportation of a passenger over a certain distance between two vertiports, and the operational costs are the operating expenses for that flight. The other costs include costs for leasing or buying an eVTOL aircraft, which ensures that the amount of eVTOL within the network is optimized according to the demand - making the model more realistic.

When the routing schedule is created, the second phase of the model is created. This part will be a dynamic simulation model that acts in a feedback loop fashion with the first phase. This is done by measuring the potential conflicts within the network at locations and timestamps, and subsequently using this information to re-time the routing schedule to avoid these conflicts. This combination of an eVTOL routing network schedule and reduction of potential conflicts en-route supports further research for the implementation of UAM operations in the near future.

7.2. Research Question

The main research question that is aimed to be answered is stated below:

> ”How can an eVTOL routing model be paired to a simulation environment to assess en-route safety of the computed solution?”

The main question can be divided into four core questions and corresponding sub-question, which are stated below:

1. How should the routing model mathematically be formulated?
    (a) What input data is used for creating the schedule of the routing model?
    (b) What existing mathematical models can be used to create routes?
    (c) What are relevant objective functions, decision variables, and constraints for the routing model?
    (d) What are representative parameter values for air taxi service operations?
2. How should the dynamic simulation be constructed to assess en-route safety?
    (a) What are current models for en-route dynamics?
    (b) At what timestamps and locations in the routing model do losses of separation occur?
    (c) How can the simulation model be paired with the routing model?
3. What is the performance and sensitivity of the model?
    (a) What solving techniques are used for the performance of the model regarding to computational time?
    (b) What is the minimal number of conflicts that occur in the model?
    (c) What is the loss of profit due to re-timing flights?
    (d) What is the effect of different parameter values?
    (e) What is the impact of the implementation of air taxi services on traffic congestions and emissions?

7.3. Research Objective

The main research objective for this thesis is stated below:

> To create an eVTOL routing model for air taxi service operations in an urban area, based on forecasted demand, fixed vertiport locations, and a homogeneous fleet, while incorporating a dynamic simulation model to assess en-route safety and maximize the total profit of the eVTOL operating network for one day.

The objective described above can be split up in multiple, more detailed sub-goals. The first sub-goal is to formulate a routing model based on ridesharing and aviation models, and find out how to match the predetermined demand with flights. This also includes the composition of the objective function, the main decision variable(s), constraints, and the parameter values. Secondly, the dynamic simulation is formulated to assess en-route safety. For this, the losses of separation of the routing model must be determined, which is subsequently used to lower the conflicts in the routing model by re-timing certain flights. The Third sub-goal is to evaluate the performance and sensitivity of the optimization model. The objective stated is not yet described in the literature and would create a basis for further research for on-demand eVTOL air taxi services.

7.4. Project Planning

The nominal duration of the Master Thesis project is approximately 30 weeks. To manage this time properly, an indication for the timeline of the project is visualized in the Gantt Chart in Figure 7.1.

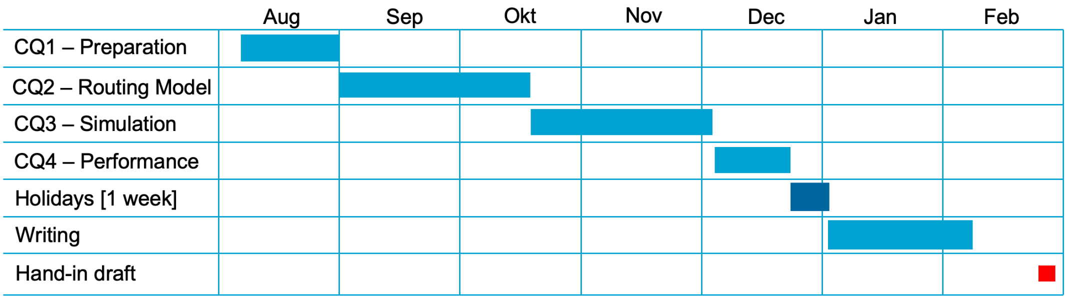


Figure 7.1: Timeline indication of the Master Thesis project visualized in a Gantt Chart.

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