A Door-to-Door Multimodal Simulation-Based Framework for the Integration of Advanced Air Mobility Design and Operations

A Master of Science Thesis

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Technische Universiteit Delft

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by

Menno Berger

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Source cover image: [**?**]

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Menno Berger
Delft, September 2023

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Nomenclature

AAM	Advanced Air Mobility
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EUR	Euro
eVTOL	Electric vertical takeoff and landing
GHS	Global Human Settlement
ICE	Inter City Express
KPI	Key Performance Indicator
MoE	Measure of Effectiveness
NASA	National Aeronautics and Space Administration
NJ	NightJet
OD	Origin Destination
OSM	OpenStreetMaps
SoS	System of Systems
SoSID	System of Systems Inverse Design
SUMO	Simulation of Urban MObility
VTOL-AD	Vertical Takeoff and Landing Aircraft Design

List of Symbols

$a_{1...4}$	Tuning parameters population prediction
$b_{1...8}$	Tuning parameters workplace prediction
$C_{mode_{km}}$	Cost per mode-km
$distance_{mode}$	Distance using transport mode 'mode'
$duration$	Trip duration
J	Jaccard Similarity
$NRes_{1...4}$	Counts of non-residential building types
$Pop_{pred.}$	Predicted population in an area
$Res_{1...4}$	Counts of non-residential building types
VoT	Value of time
$w_{1..3}$	Bidding weight agent-based model
$Work_{pred.}$	Predicted workplaces in an area

Introduction

This thesis project started well over a year ago (at the time of writing), when I took the opportunity to start an internship at the DLR institute of System Architectures in Aeronautics in Hamburg, Germany. Here, I joined the group specializing in System of Systems (SoS) Engineering. Within this group I gained valuable experience in the SoS approach, and how this was already applied to investigations in Advanced Air Mobility. After completing an internship here, I was offered to extend my stay with a thesis project, which would start more or less simultaneously with a European project, COLOSSUS.

COLOSSUS is a European collaborative project between DLR, TU Delft, and various other research partners. One of the main objectives in the COLOSSUS project is the development of a Transformative Digital Collaborative framework for the holistic system of systems assessment of complex problems. One of the use cases to which this will be applied is that of intermodal (or multimodal) transport, where the impact of Advanced Air Mobility can be assessed [**?**]. This ties in directly with the overall goals of this thesis, which is to develop a preliminary framework capable of performing this analysis. This framework can then be used for exploratory analysis of the problem, identifying 'big hitters' where a multimodal SoS framework is powerful, and at the same time where further improvements can be made throughout the COLOSSUS project.

This thesis is organized in 3 parts. In Part I, a scientific paper is presented on the development of this framework and some key results. In Part II, the most relevant literature in this field is analysed, supporting the research. In part III additional results and supporting material can be found, explaining in more detail the developments done and further results obtained.

I

Scientific Paper

A Door-to-Door Multimodal Simulation-Based Framework for the Integration of Advanced Air Mobility Design and Operations

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Abstract

This study presents the development of a multimodal System of Systems (SoS) framework, to assess the impact of top-level aircraft requirements in providing advanced air door-to-door mobility. The field of Advanced Air Mobility (AAM) is rapidly evolving, and while current research assesses these vehicles from both aircraft design and operational perspectives, a system of systems perspective combining both domains is required to find the best overall vehicle design and operational concepts. In this work, aircraft design is assessed by its effectiveness in the operating environment, considering the perspective of the stakeholders of passengers, operators and European policy makers. This is done through combining aircraft design in an agent-based multimodal simulation framework, covering both surface and air transport. Doing so allows us to analyse the impact of top-level aircraft requirements on door-to-door travel time, AAM mode share and energy consumption per passenger. Using this framework, it was found that the most impactful parameter on AAM utilization is the passenger's mean value of time. Additionally, several SoS effects could be traced to changes at the agent level, where giving passengers more travel options leads to 16% higher AAM adoption, but at shorter (-8.2 %) average trip distances due to preferences for shorter and cheaper flights. Lastly, the relevance of considering operations for aircraft design was seen, where the best theoretical design for energy efficiency performed 10% worse than the best design considering operations, as the average mission profile in operation is different to the designed profile. In conclusion, the developed framework demonstrates the need for combining operations and aircraft design, and can be used to explore the best concepts in both fields.

1 Introduction

One of the key focus topics in improving air mobility in the next decades is defined by Flightpath 2050, and pertains to door-to-door mobility. It specifies that "90% of travellers within Europe are able to complete their journey, door-to-door within 4 hours" [1]. In an analysis of this goal, Grimme & Maertens identify that access and egress times are the most influential parameter in the feasibility of this goal [2]. This is reinforced by the authors of the X-Team D2D project, who advocate for integrating air transport into an intermodal transport system with other modes of transport [3]. Notably, they identify that one of the biggest positive impacts could come from Advanced Air Mobility (AAM). NASA describes AAM as "safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions" [4]. As such, AAM has the potential of providing accessible aviation on local and intraregional scales, improving door-to-door mobility.

The door-to-door market for AAM from a perspective of aircraft designers has been considered by various authors. From these analyses, top level aircraft requirements are determined on key parameters like the aircraft range [5, 6, 7, 8], battery energy density [9] and speed [7, 8, 10]. At the same time, various other authors consider the impact of operational parameters on the use of Advanced Air Mobility, like the fleet size [11], the number of vertiports [10], and vertiport internal operations [12, 13].

The effectiveness of Advanced Air Mobility is better described as a complex System of Systems (SoS) problem [14], where design and operations are analysed in an interlinked way to generate better insights. This has also been analysed by Kohlman et al. [15], where the impact of the system of system behaviour has been shown on energy related constraints. Even though both authors consider a combination of aircraft design and operations in a system of systems environment, still neither links them to door-to-door mobility, as both studies only consider the air transport leg. Therefore, the objective of this work is to combine the elements of aircraft design, operations and door-to-door mobility in a System of Systems framework. This provides insights on aircraft design at a holistic level and evaluates air mobility in light of the Flightpath 2050 goals. This can be formalized in the following research question:

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In the context of advanced air door-to-door mobility, how can a framework be developed to assess the impact of top-level aircraft requirements on the multimodal transport operational performance, in terms of door-to-door travel time, AAM mode share, and energy consumption per passenger?

As the research question is related to how a framework should be developed, some requirements for the final framework should be set:

1. Traceability - It allows tracing of SoS-level impacts (on key performance indicators) to agent-level choices through individual passenger and vehicle analysis.
2. Sensitivity - It allows simulation driven analysis of the sensitivity of input parameters, which can give great insight on the impact of assumptions.
3. Integration - A framework that encapsulates the all key components of the relevant field can easily be improved with higher fidelity models for any sub component once available.
4. Exploration - It allows for the large-scale evaluation of the whole system of systems design space.
5. Insights - It can help obtain better insights for many different stakeholders that are interested in a contained subdomain, whether it is vehicle design, passenger mobility or energy consumption.

This paper comprises of the following sections: In section 2, the methodology is explained. Starting with an overview of the framework, it is broken down into first the scenario definition, followed by the inputs for the solution space, then the simulation model, concluding with the approach for result exploration. This is followed up by the setup and description of the case study in section 3. Then, section 4 discusses the results for a baseline study, various sensitivity analyses and the final aircraft design study. After this, the effectiveness of the framework is reflected on in section 5, concluding with the key results and recommendations for future work in section 6.

2 Methodology

The developed framework is introduced, as seen in Figure 1. This framework is composed out of several key blocks, and each block in the framework combines different domains. Each of the constituent blocks are elaborated on, starting with the scenario definition in section 2.1, where the methodology to define a case study is specified. After scenario definition, a solution space is set up (2.2), containing the additional inputs going into the framework that can be varied to assess the overall impact on results. The preceding blocks define the necessary inputs which are needed for the multimodal simulation, which itself is detailed in section 2.3. This block also describes the different types of agents and their interactions while running the simulation. Finally, some notions on the different types of results and how their interactions can be identified, is shown in section 2.4.

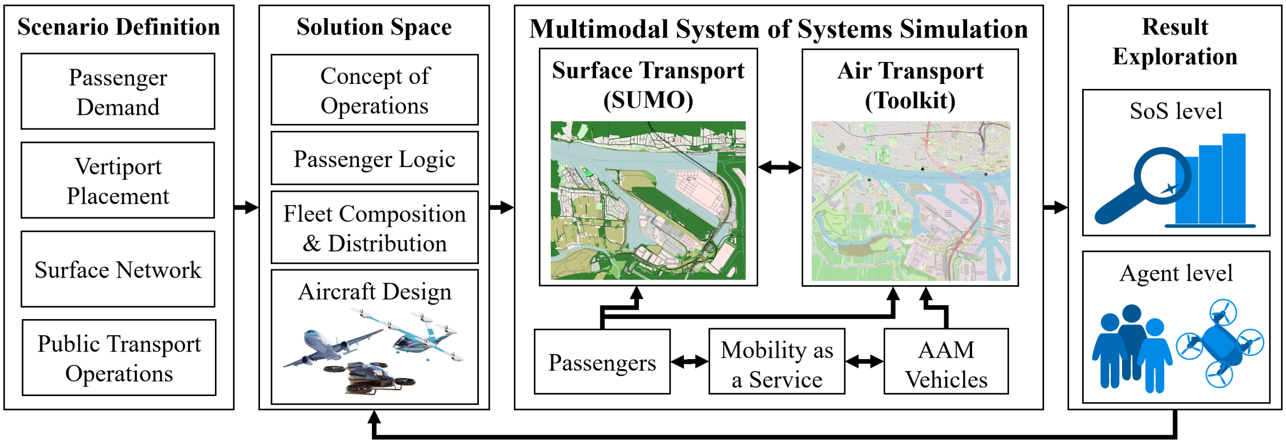


Figure 1: Framework for multimodal system of systems simulations

2.1 Scenario Definition

The first step of the framework is the definition of a scenario. The full approach is detailed in Appendix 1, but is briefly summarized in this section.

2.1.1 Passenger Demand

To ensure the repeatability of results from the framework, passenger demand is defined through a set of specific passengers, with predetermined origin and destination, as well as departure time and a value of time. 3 types of passengers are established. The first are commuters, travelling to and from residential areas to areas with high workplace densities. Second are tourists, travelling at to and from residential areas to tourist destinations at the beginning and end of the day, and between tourist destinations between those times. Third are intercity passengers, travelling between areas with high population density in their origin and destination cities.

2.1.2 Vertiport Placement

For the placement of vertiports, 2 considerations are made. Firstly, as the objective is to provide multimodal mobility, it is important that vertiport locations are complementary to existing public transport. For this reason, vertiports are placed at key public transport infrastructure. In most cases these are train and metro stations, but where suitable also ferry docks and bus stations are considered. Secondly, as one of the demand groups considered is that of tourists, vertiports are placed at key tourist destinations as well.

2.1.3 Surface Network

The OSMWebWizard tool, one of the tools provided in the SUMO package [16], is used to obtain a surface network for multimodal operations. This tool retrieves road networks from OpenStreetMap and performs network processing on this to accurately represent junctions, roads, railroads, and many more geographical features. This interpretation is then translated to a network file that SUMO can use (which will be described in section 2.3). After this, it is processed to reduce the number of unnecessary edges by keeping only the most relevant infrastructure around the vertiports, improving simulation run time.

2.1.4 Public Transport Operations

The OSMWebWizard tool is also used to obtain public transport operations schedules. In addition to processing geographical networks, this tool retrieves information on which public transport modes operate in the area of interest. These operating vehicles are then assigned to a schedule with a fixed period operation. To ensure connectivity, all intercity trains are modelled using a 2-hour period throughout day and night.

2.2 Solution Space

The solution space describes various more complex inputs into the multimodal simulation. In addition to a higher complexity, these inputs are also linked to the results, as varying these parameters is what drives the best overall system behaviour. The first part of the solution space is the concept of operations (section 2.2.1), detailing the assumed concept of a Mobility as a Service provider. Then, the AAM fleet composition and distribution is detailed (section 2.2.2), as well as the method used for aircraft design in section 2.2.3.

2.2.1 Concept of operations

As a general concept of operations, it is assumed that there is a Mobility as a Service (MaaS) provider that manages all passengers and AAM vehicles. The workflow from a passenger perspective is detailed in Figure 2. Here, the passenger makes requests to the service and gets as a return N routes using AAM and the fastest route using public transport. This N is one of the parameters that can be altered to explore the solution space. How a passenger then makes a choice, as well as how the AAM vehicles handle these requests are detailed in section 2.3.4 and section 2.3.3.

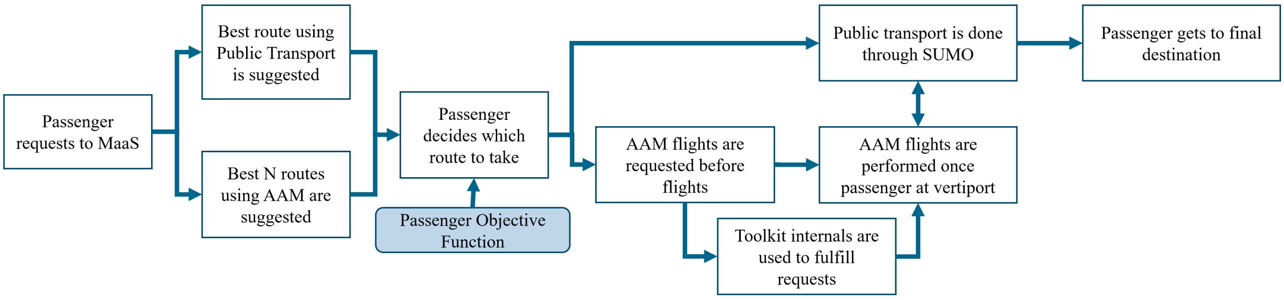


Figure 2: Passenger logic flow through framework

2.2.2 Fleet Composition & Distribution

To ensure comparable results over all experiments, fleet initialization is done in the same way. For any experiment the fleet is distributed evenly over all vertiports initially, and the agents are free to reposition using autonomous deadhead flights to complete requests. As the baseline is set up with a homogeneous fleet of 52 vehicles, this means that every other vertiport has a vehicle initially.

2.2.3 Aircraft Design

For the conceptual design of aircraft, a DLR in-house tool called VTOL-AD is used. Developed by P. Ratei [17], VTOL-AD is a conceptual level aircraft design tool, capable of sizing VTOL multirotor and tiltrotor vehicles with a 2-6 passenger capacity and electric, hydrogen or hybrid architectures.

The design tool VTOL-AD is validated by comparing it to the paper of Ugwueze et al. [18]. In this paper, a similar conceptual aircraft design tool was developed, which has also been compared to prototypes of real eVTOL vehicles. This therefore serves as a suitable baseline to assess the accuracy of VTOL-AD. The model has been calibrated using several technology factors, and the powertrain efficiency has been adjusted. Additionally, the cruise speed for the multirotor configuration is reduced to 40 m/s, as VTOL-AD does not converge to feasible solutions at the high reference cruise speed of 66 m/s.

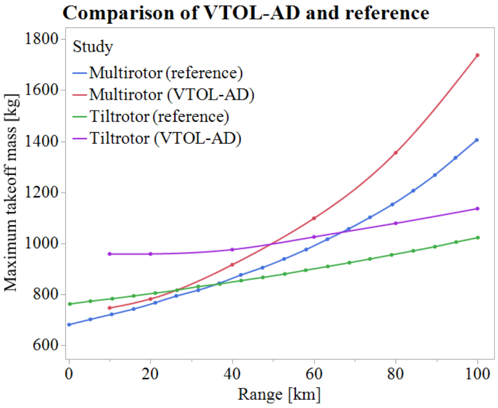


Figure 3: Multirotor and Tiltrotor Architecture Validation for 400kg payload, battery of 275 Wh/kg. Reference data from [18]

Both VTOL-AD and the reference tool converge to similar aircraft masses over the entire range sweep performed (Figure 3). VTOL-AD provides a slightly conservative estimate at any point, with a higher increased aircraft mass. Interestingly, both tools have a crossover point between the multirotor and tiltrotor architecture at which the latter has the lowest takeoff mass, and this crossover point is at a very similar range at around 40 km.

2.3 Multimodal System of Systems Simulation

The multimodal system of systems simulation is the core of the framework, and this is where all the processes act at run time. It consists of 2 simulation tools running in parallel, being the surface transport through SUMO as described in section 2.3.1, and the air transport through the Toolkit in section 2.3.2.

2.3.1 Surface Transport (SUMO)

SUMO, short for Simulation of Urban MObility, is a simulation tool developed by DLR hosted by the Eclipse Foundation [19]. SUMO is a microscopic traffic simulator, which means that each vehicle and its dynamics are modelled individually. The main benefit of a microscopic model is its accuracy on this small level, which can be used to estimate emissions as well as interactions between different vehicles in a network. SUMO has various additional features, like simulating traffic lights that can be activated based on the queue length in front of them, and detailed car following and overtake models are implemented amongst other things. This is useful in various research domains, like for autonomous vehicle modelling [20, 21] and traffic light control systems [22, 23]. However, it comes at the price of requiring the simulations to be set up accurately at this high resolution. Small network issues can have large impacts, and a lot of preparation must be done to ensure accurate results.

In the current framework the mesoscopic model within SUMO is used. This model uses the same inputs as SUMO's default microscopic model, but models them to a lower resolution [24]. This means that intersections and lane changes are simplified, which though less accurate, makes the model more tolerant for errors. More importantly, because the model is at a lower resolution, simulations are significantly faster, up to 100 times [24]. Largely for this latter reason SUMO is used in its mesoscopic simulation setting in this work. This means that not all inter vehicular interactions are captured, but as we are modelling public transport in an uncongested scenario, this is reasonably realistic.

2.3.2 Air Transport (Toolkit)

The final key block in the framework is determined by an agent-based simulation model, here referred to as the Toolkit, developed by DLR. This Toolkit, in other papers also referred to as the SOSID Toolkit, is used to simulate aerial wildfire fighting [25, 26] and Urban- or Advanced Air Mobility [14, 27]. For the current work, use is made of the already existing Advanced Air Mobility example, as explained recently by Naeem et al. [28]. In addition, some assumptions with regards to infrastructure need to be discussed. First, vertiports are assumed to have unconstrained capacity. This means that there is no minimum time between departures and arrivals, and that any number of agents fit on a vertiport. Second, AAM vehicles are assumed to swap batteries if they have sufficient time between missions or need to do so to complete the next mission, taking 10 minutes, and this is possible at all vertiports. Third, airspace in the simulation is assumed to be unconstrained. All aircraft by default route on the shortest path, and do not consider potential keep out zones or collision management. These assumptions are a notable simplification of reality, which could be improved on in future work.

2.3.3 Mobility as a Service

The concept of operations used here is that of on-demand advanced air mobility, where passengers make their request a specified time before departure to a Mobility as a Service (MaaS) provider. Once the request is made, all air vehicles perform a bid on whether they can perform the mission. All bids are done according to Equation 1, and the highest bid is selected.

$$bid = w_1 * \frac{\text{Time delay departure}}{\text{Maximum scheduling horizon}} + w_2 * \frac{\text{Mission energy required}}{\text{Vehicle energy}} + w_3 * \text{Estimated passenger value} \quad (1)$$

Where w_1, w_2, w_3 are -10, -1 and 100 respectively, and the 'Estimated passenger value' is a value function based on the estimated number of passengers that would be taking this flight as well. To calculate the required time delay and mission energy required, the vehicles consider the missions they are already assigned to, whether they would have to fly a deadhead mission to start the mission, and whether they can do so with their current battery state. The overall weights of -10, -1 and 100 are chosen such that they are treated as priorities: all objective values are ranging from 1-0, so that the best Estimated Passenger Value will always be the first choice criteria, then the minimum time delay, and lastly the minimum energy required. An overall dispatcher then determines the best bid and allocates the mission to this vehicle if the passenger also decides to use this option. This passenger choice is discussed in section 2.3.4.

2.3.4 Passengers

Before a passenger departs from their origin, here assumed 1 hour prior, they decide how to get to their destination. For this, the passenger makes a request to the MaaS operator, which returns travel options without AAM, and options involving AAM in combination with other modes of transport. To be able to make the choice between these different modes, a passenger objective function is defined:

$$\text{Obj} \; = \text{Min}\left(duration * VoT + \sum C_{mode_{km}} * distance_{mode}\right) \quad (2)$$

Where $duration$ is the trip duration in hours, VoT is the passengers Value of Time [EUR/hr], $distance_{mode}$ is the distance travelled per mode of transport, and $C_{mode_{km}}$ is the price of a transport mode per km, which is free for walking, 0.10 [EUR/km] for public transport, and 3 [EUR/km] for AAM. This cost originates from the cost analysis of Brown et al. [9], who estimate costs between 2-3 [USD/km]. This is similar to Wu et al. [29], who consider 2 USD/unit distance with a fixed base cost of 30.

Similar passenger choice models have been used by for example Schuh et al. [6], Sells et al. [30], and Wu & Zhang [29]. This model is a simplification of reality, which can be better described by more extensive logit mode choice models also used in literature [31, 32], but these kinds of models require extensive passenger choice characteristics, which are not readily available and outside of the scope of this research.

2.3.5 AAM Vehicles

In the multimodal system of systems simulation, AAM Vehicles are represented as agents, acting in the SOSID Toolkit. Several further assumptions on the vehicle operations should be noted:

- Vehicles are assumed to fly deadhead flights autonomously, and use a pilot whenever operating passenger-carrying flights.
- The mission profile they operate on is one where the vehicle waits until the specified departure time, then vertically takes off, flies to its destination, vertically descends, and allows passengers to deboard. If time allows between missions, or if it is required, the vehicle re-energizes.
- AAM vehicle energy consumption are modelled using a simplified energy model, where power budgets are calculated for each flight stage depending on the payload. In addition, a reserve energy budget is maintained of 20 minutes.

A more complete explanation can also be found in Appendix 2, and in the work by P. Ratei on the development of VTOL-AD [17].

2.4 Result Exploration

As the last component of the framework, and after running a simulation, the results can be analysed. This is done at two levels: the SoS level and the agent level. At the SoS level, the investigations are done with regards to key performance indicators. At this level different operating environments can easily be compared, as well as the impact of solution space changes (like aircraft design changes). At the agent level, the behaviour of any agent can be investigated. In these cases, the driving changes are often found on the small scale, which translate to changes on the big scale. By analysing the results at both these levels, the large-scale changes but also the small-scale drivers for these changes are captured.

3 Description of case study

As the objective of the research is to assess the effect of an integrated framework connecting aircraft design and multimodal transport operations in providing door to door mobility, a case study needs to be set up. First, the scenario is defined in section 3.1, followed by the key performance indicators to assess the outputs (3.2), how they are combined into one measure of effectiveness (3.3), and how the demand for this use case is generated (3.4).

3.1 Description of scenario

A combination of locations needs to be selected that can both test the capabilities of the framework, and make for a realistic use case. This results in the following requirements for different locations:

1. The locations need to be well connected by trains. This is to ensure that multimodal and sustainable mobility can be analysed.
2. The locations need to be significantly different from each other: Different majority of passenger types, different trip distances and different types of public transport all tie into making an interesting use case where contrasting design requirements can be found.
3. The locations need to be attractive for both public transport and AAM, as current alternatives are unsuitable. In this case, we consider the traffic index as a benchmark for congestion, where highly congested cities are attractive for AAM as well as public transport.

After some consideration, it is decided to connect the cities of Hamburg, Munich and Rome in the case study. Within each of these cities commuters as well as tourists are present and can be analysed. Additionally, intercity travellers are created using trains between these cities. All three cities score high on the global TrafficIndex, being 29th, 28th and 26th respectively [33]. The entire scenario can be seen notionally in Figure 4.

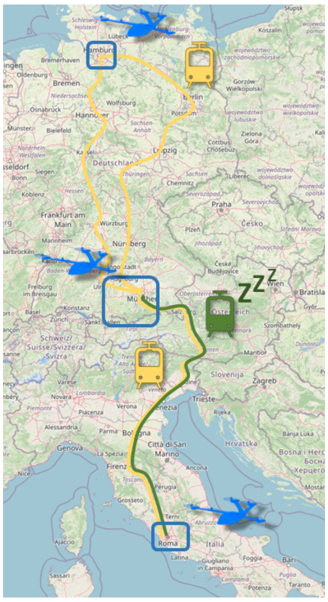


Figure 4: Multimodal framework

3.1.1 Hamburg

In the city of Hamburg 29 points of interest are identified to serve as vertiports (Figure 5). It should be noted that in the central area of the city more points of interest can be found which are not labelled on this map. Hamburg is found to be interesting to consider in the framework, as aside from conventional public transport modes, ferries are also operated. To check whether the travel times found in the SUMO network are realistic, a test is done comparing 100 trips by public transport with the journey time for the same trips using Google Maps. The results can be seen in Figure 6, where the trip times in SUMO have a good correlation with those using Google Maps.

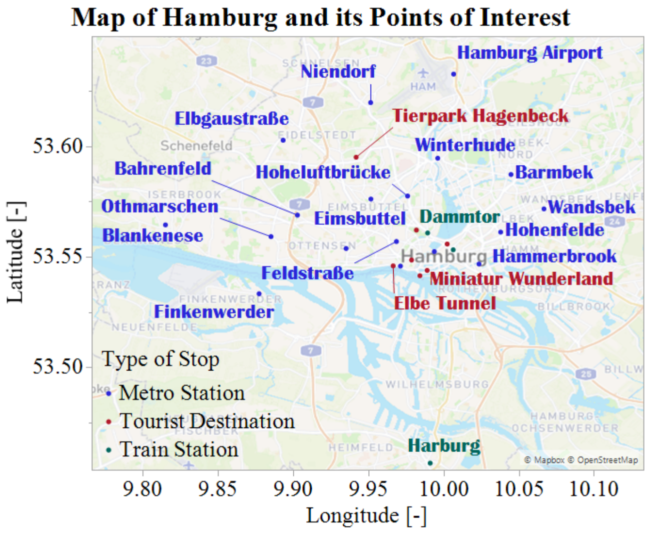


Figure 5: Map of Hamburg and its points of interest

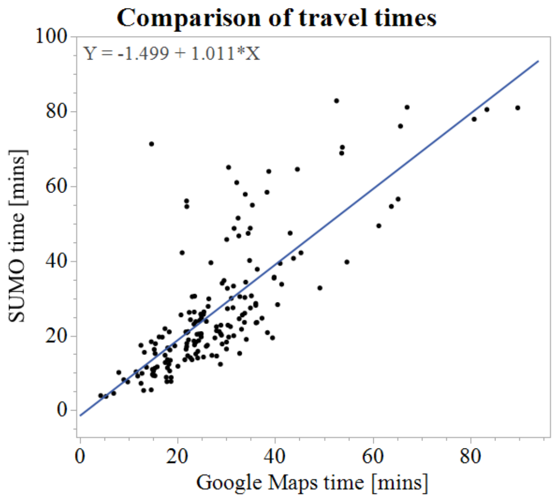


Figure 6: Comparison of Google Maps and SUMO travel times for Hamburg (Maps data retrieved for 22nd of June, 2023)

3.1.2 Munich

In a similar fashion, 34 vertiports are determined in Figure 7 for Munich. One of the major tourist attractions in the proximity of Munich is the Neuschwanstein Castle, but this castle is about 80 km removed from the city, presenting an interesting difference with Hamburg. As a result, the operating area in Munich is much larger, and again many of the vertiports are in the centre of Munich. Travel times can be validated as shown in Figure 8, showing that the SUMO travel time prediction is fairly accurate.

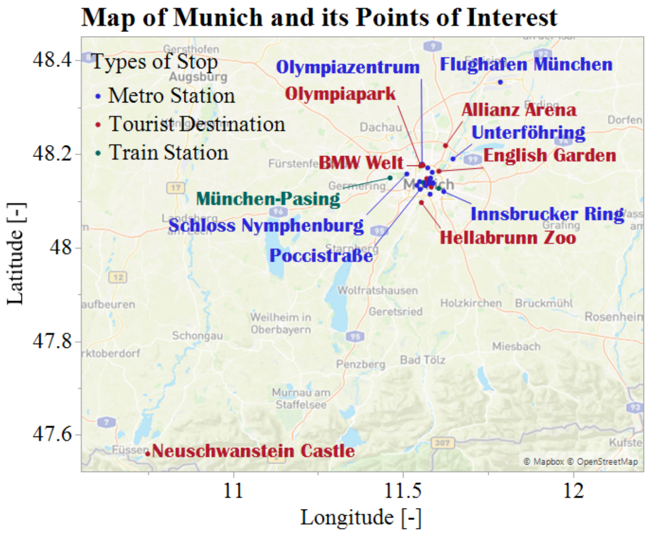


Figure 7: Map of Munich and its points of interest

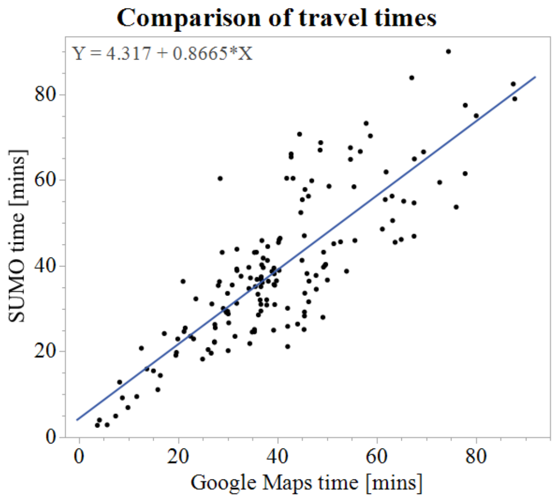


Figure 8: Comparison of Google Maps and SUMO travel times for Munich (Maps data retrieved for 19th of June, 2023)

3.1.3 Rome

As the third and last city to be considered, a total of 40 points of interest are determined as vertiports (Figure 9) in Rome. Here, there are some touristic villa locations at a relatively large distance from the city centre, but the city is still more dense than Munich. Validation of travel times are also performed for Rome, as seen in Figure 10, where a slightly worse (in terms of the linear X coefficient, compared to Hamburg and Munich) agreement between SUMO and Google Maps travel times is seen, but which is still deemed close enough.

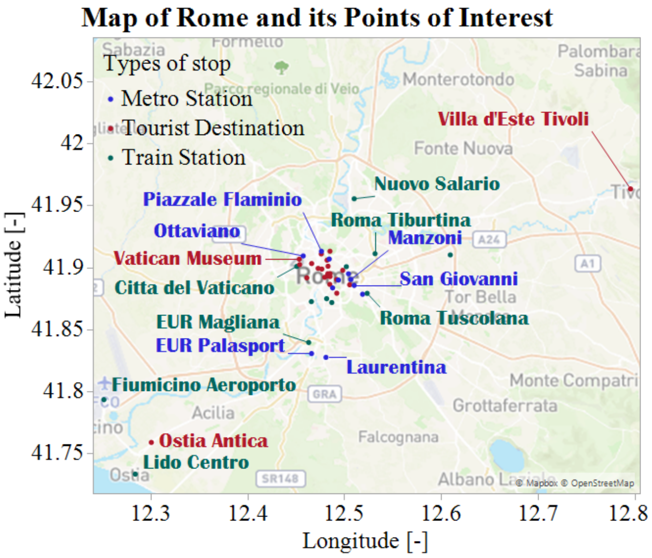


Figure 9: Map of Rome and its points of interest

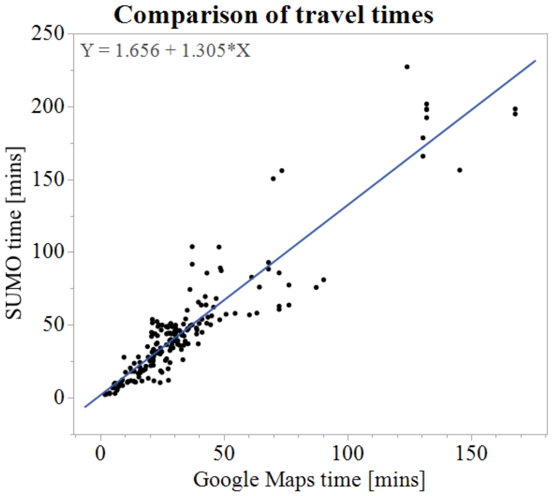


Figure 10: Comparison of Google Maps and SUMO travel times for Rome (Maps data retrieved for 15th of June, 2023)

3.2 Key performance indicators

Top level performance indicators need to be specified to assess the performance of the overall framework at different design points. The benefit of system of system analysis is that multiple stakeholders can be considered at the same time, who all bring different priorities to the table. In this case, 3 stakeholders are identified, which are the passengers, the AAM vehicle operators, and an overarching European policy maker (like the European Commission), who might care the most about the environmental impact of AAM. For these stakeholders many different key performance indicators (KPI(s)) could be considered, but for each one KPI is selected:

- **Total time saved** - This passenger-centric metric is the sum of all the time that passengers in the simulation save by using AAM over using public transport. Importantly, all time saved is taken, which sometimes includes time saved in legs after AAM has been taken. By taking the total time, we can find the maximum benefit for all passengers.
- **AAM Mode Share** - This operator-centric metric is the percentage of all passengers that use AAM. This is of major importance for the operator, as they would like to maximize this percentage.
- **Energy per passenger km** - This environment-centric metric is the energy used for all flights, divided by the passenger kilometres flown. As such, it is influenced by the aircraft's efficiency, but also by the load factor, deadhead trip ratio, and average trip distance.

3.3 Measure of effectiveness

To compare different design points over the design space and combine the different KPIs, they need to be normalized first. This is done using the following equation:

$$\mathrm{KPI}_{norm} = \frac{\mathrm{Value} - \mathrm{Min(Values)}}{\mathrm{Max(Values)} - \mathrm{Min(Values)}} \tag{3}$$

The different designs in the design space are evaluated based on their position between the bounds of their minimum and maximum, resulting in values between 0 and 1. For the 3 determined KPIs, a measure of effectiveness (MoE) is made by combining the normalized values, here with an equal weighting:

$$\mathrm{MoE} = \frac{1}{3} * \mathrm{Time\ Saved}_{norm} + \frac{1}{3} * \mathrm{AAM\ Mode\ Share}_{norm} + \frac{1}{3} * \mathrm{Energy\ Per\ Pax}_{norm} \tag{4}$$

3.4 Demand Generation Use Case

A representative demand case is generated to compete the case study definition. As mentioned in section 2.1.1, the passenger demand is generated for three different sources. The first demand source is commuters. Commuters are assumed here to be half of the city's population, of which a sample of 0.2 % is taken. For tourists, an average stay of 2 days is assumed, which translates the number of tourists in a year, divided equally over the year, to get to the number of tourists travelling per day. Again, only a small fraction of this is taken, in this case 5%. Then, for intercity passengers it is assumed that these are tourists travelling into the city. Therefore, first a fraction of the total tourists is assumed to be coming from a different city (for example, 5% of the tourists in Munich come from Hamburg). Then, again a fraction of this is taken as the considered demand, at 40%. The resulting demand can be seen in Table 1.

Table 1: The generated demands for this use case. Sources from [34, 35, 36, 37]

Commuters:	**People [M]**	**Fraction**	**Travellers / day**	**Subsample**	**Demand**	**Percentage**
Hamburg inhabitants:	1.841	0.5	920500	0.002	1840	11.6%
Munich inhabitants:	1.472	0.5	736000	0.002	1472	9.3%
Rome inhabitants:	2.873	0.5	1436500	0.002	2872	18.2%
Tourists:		**Assumed stay**				
Hamburg tourists:	7.619	2	41748	0.05	2086	13.2%
Munich Tourists:	8.75	2	47945	0.05	2396	15.1%
Rome Tourists:	10.32	2	56548	0.05	2826	17.9 %
Intercity:		**Fraction of tourists**				
Hamburg - Munich		0.05	1199	0.4	478	3.0%
Hamburg - Rome		0.02	565	0.4	226	1.4%
Munich - Rome		0.05	1414	0.4	564	3.6%
Rome - Munich		0.05	1199	0.4	478	3.0%
Rome - Hamburg		0.02	417	0.4	166	1.0 %
Munich - Hamburg		0.05	1044	0.4	416	2.6 %

The last parameter that is set is the value of time. Previous studies by Kreimeier calculated the opportunity costs for private trips, as seen in Figure 11. The fraction of passengers taken for tourists and commuters is between 5 and 0.2 %, which is assumed here to be the richest percentage translating to a mean opportunity cost of 30 [EUR/hr]. This value has also been used in other studies on tourists, by for example Franca et al. [39]. This may be an overestimation for intercity passengers, but a portion of these travellers are business travellers, who typically have a 2-3x higher mean opportunity cost [40]. Therefore, the overall mean value of time for all the passengers is set at 30 [EUR/hr], and the impact of this assumption is evaluated.

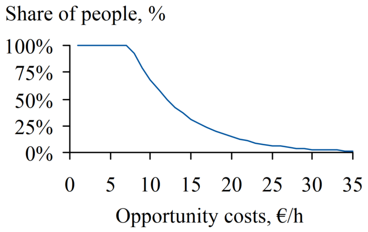


Figure 11: Assumed opportunity cost distribution for a trip [38]

4 Results

This section describes the simulations performed and the insights gained by using the framework. To start this, a baseline experiment is set up and analysed in detail in section 4.1. Then, sensitivity analyses of the key parameters used in the approach are presented in section 4.2 to quantify their impact. With those steps taken, the focus area of the research is tackled through linking the aircraft design to the impact on KPIs, as done in section 4.3.

4.1 Baseline Experiment

A baseline experiment is set up to get an idea of the behaviour of the system, with the following parameters:

- Passenger Capacity 3 (+1 pilot)
- Cruise Speed 30 [m/s]
- Designed range 60 [km]

The goal of the baseline study is to demonstrate the capabilities of the framework with regards to 2 of the requirements: Exploration and Insights.

With the baseline defined, the simulation is run and results can be analysed. First, the different departure times and mode shares for the three types of passengers can be identified (Figure 12). Here, the overall fraction of passengers utilizing AAM is similar over the 3 passenger types at about 15 %. Furthermore, commuters and tourists are similar, except tourists generate a large demand peak in the morning hours. Intercity passengers depart much later and are distributed uniformly.

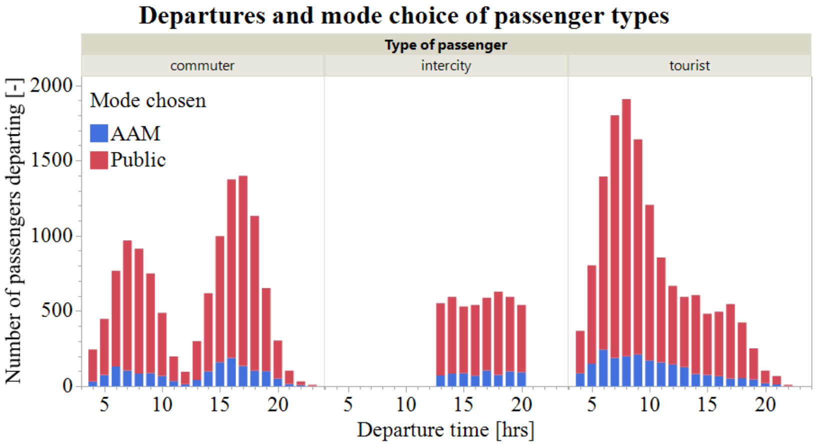


Figure 12: Departure times and mode choice for different passenger types

4.1.1 Commuters & tourists

To get a better understanding of the different city environments, the commuters & tourists are grouped together in one demand source. These can then be shown over the 3 different city environments, as seen in Figure 13. It should be noted that the overall demand for AAM is similar in all 3 city environments. However, the speed using public transport is different: Where the median speed in Hamburg is close to 3 [m/s], in Rome it is just over 1.5 [m/s]. It would therefore be expected that there is a higher demand for AAM in Rome than there is in Hamburg. The reason this is not the case is because the fleet is capacity constrained in Rome (see Figure 14), and so utilisation cannot increase further on account of lacking vehicles to perform those missions. The fleet is also capacity constrained in Hamburg, but is not in Munich, which has an impact all of the results.

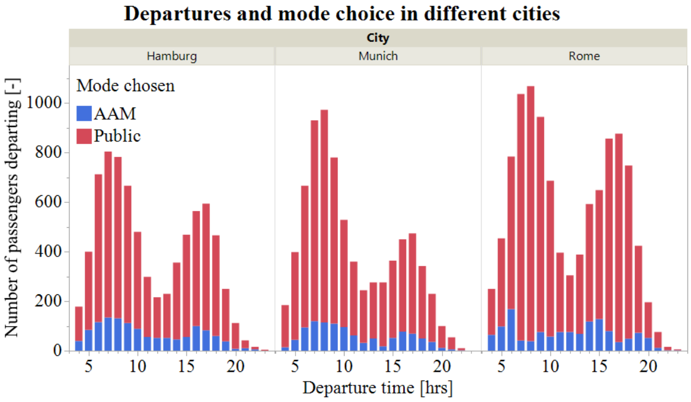


Figure 13: Departure times and mode choice for commuters & tourists in different cities

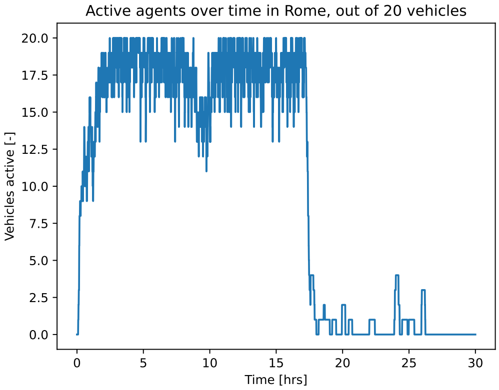


Figure 14: Active agents in Rome, 3 Passenger Capacity

As the AAM operations considers boarding and deboarding times it should be noted that for some routes AAM will always be slower than public transport, which means that no passenger would take AAM. For this baseline study in Hamburg the comparison between routes where AAM is slower or faster can be seen in Figure 15. Using this figure, it becomes evident that most of the locations in the city centre are unlikely to generate any AAM demand, and instead AAM serves as a good method of transport for more remote regions like Finkenwerder, Hamburg Airport and Pinneberg. This effect can also be seen looking at which trips are actually taken using AAM. It is found that AAM has only very light use at very short ranges, the most at 5 [km] range, after which the overall utilization goes down again due to the high cost of this mode of travel.

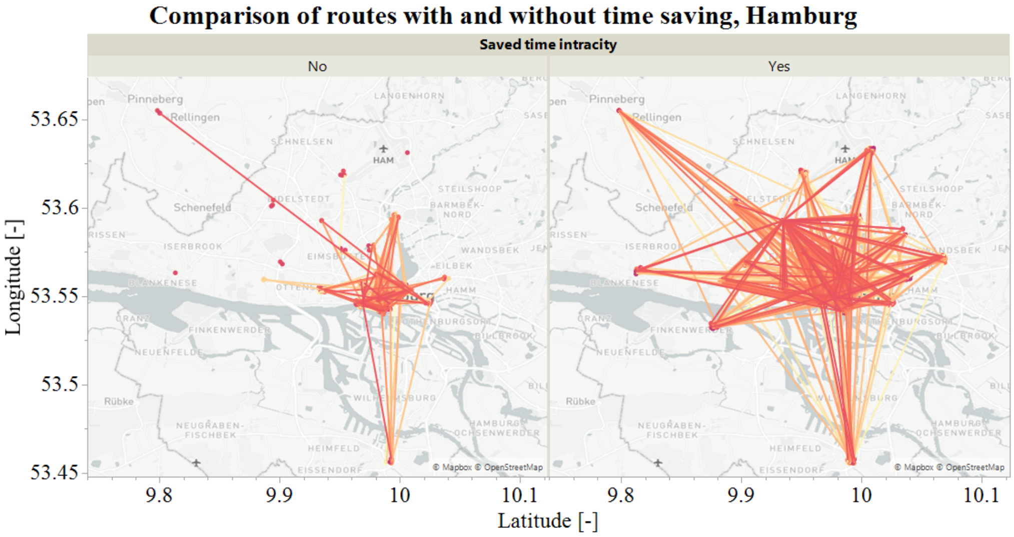


Figure 15: Comparison of which routes have an AAM time saving potential

4.1.2 Intercity Passengers

For intercity passengers, different effects can be observed in the baseline. For example, when comparing their times travelling by public transport and by AAM, as seen in Figure 16, most passengers do not save time by taking AAM. Some passengers save significant time however, and most of these also choose AAM as indicated by the mode choice labels. A different way to compare these passengers with the intracity (commuter and tourist) passengers can be seen in Figure 17. Here, intracity passengers typically show a linear pattern between time savings and their travel time, as the overall travel time if taken by AAM becomes nearly independent of the distance as AAM is a much faster mode of transport. This does not seem to be the case for the intercity passengers. Most passengers seem to save little time (less than 1 hour), but others save significant time, seemingly independent of distance.

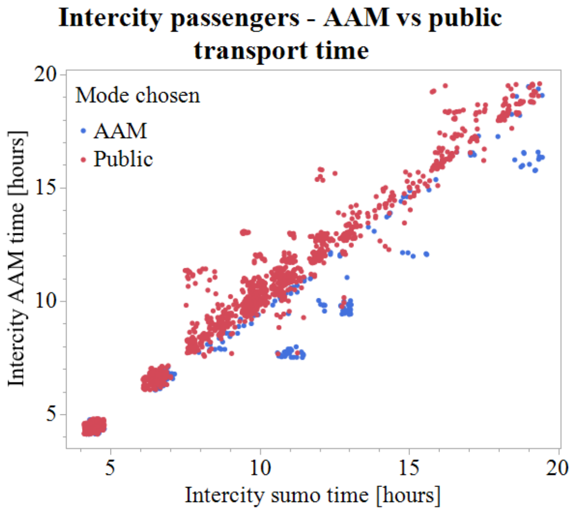


Figure 16: Comparison of AAM and public transport times for intercity passengers

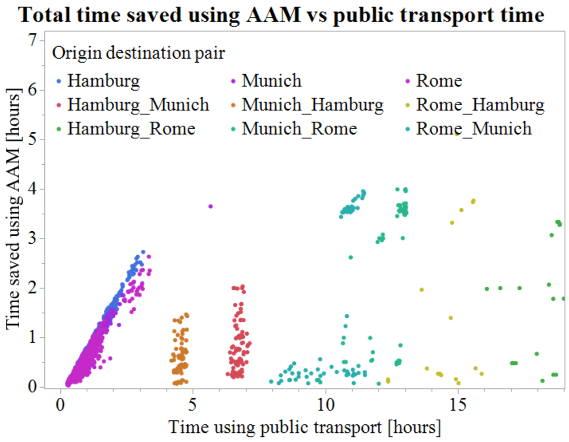
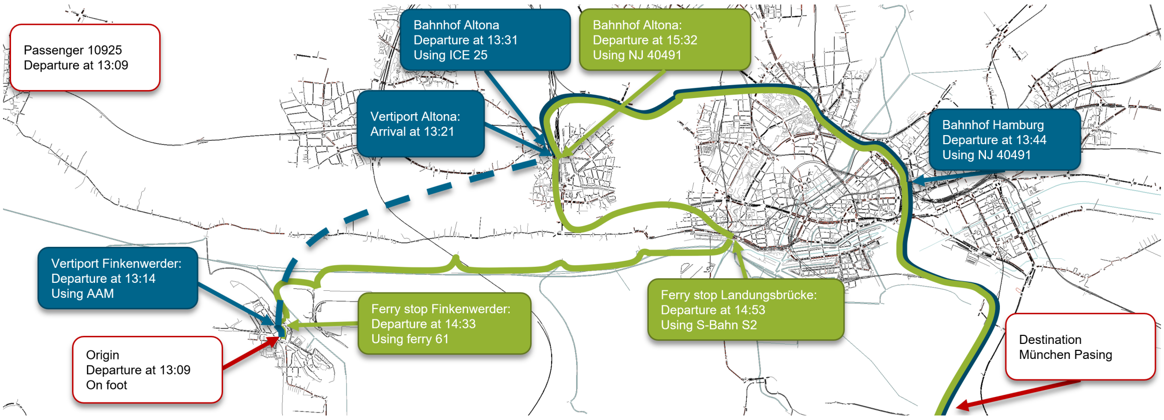


Figure 17: Time saved per city pair for intercity passengers

To understand why some intercity passengers can save more than 2 hours of travel time, a closer look is taken at some of the individual passengers. One of these can be seen in Figure 18, which highlights the route options for a passenger travelling to Munich. The green route here highlights the best public transport route, where because this passenger takes very long to get on to a ferry, they only embark on the intercity train (NJ40491) at 15:32. If this passenger instead takes AAM as shown in blue, they embark on an intercity train at 13:44, saving them almost 2 hours of time.


Passenger 10925
Departure at 13:09

Bahnhof Altona
Departure at 13:31
Using ICE 25

Bahnhof Altona:
Departure at 15:32
Using NJ 40491

Vertiport Altona:
Arrival at 13:21

Bahnhof Hamburg
Departure at 13:44
Using NJ 40491

Vertiport Finkenwerder:
Departure at 13:14
Using AAM

Ferry stop Finkenwerder:
Departure at 14:33
Using ferry 61

Ferry stop Landungsbrücke:
Departure at 14:53
Using S-Bahn S2

Origin
Departure at 13:09
On foot

Destination
München Pasing

Figure 18: Single route options for passenger 10925

Although there are many similarities between intercity and intracity passengers, one of the key differences is that all the AAM flights being used by them are to and from one point, as indicated by Figure 19 and 20. This highlights a potential impact that intercity passengers have, as this could result in higher load capacity flights, but also shows the potential risk of this one vertiport becoming a choke point.

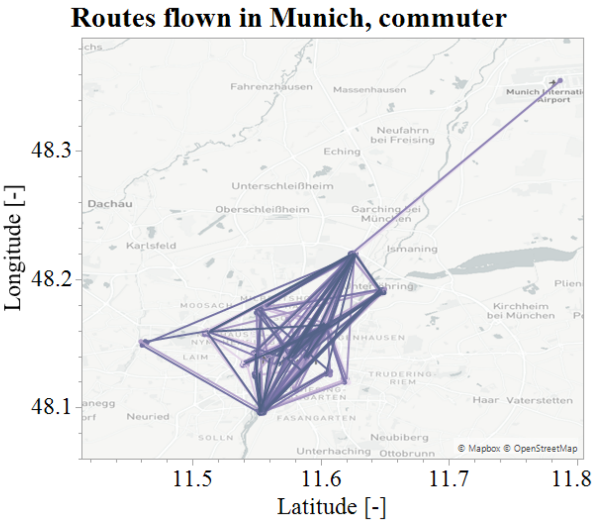

Routes flown in Munich, commuter

Figure 19: Routes flown using AAM in Munich for commuters

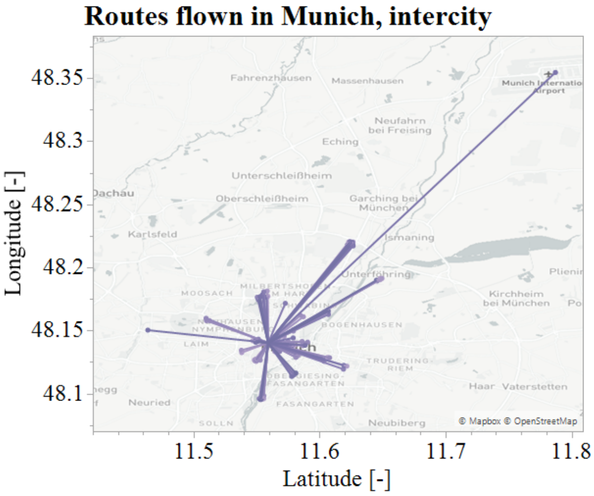

Routes flown in Munich, intercity

Figure 20: Routes flown for AAM in Munich for intercity passengers

4.1.3 Baseline Conclusions

In the baseline study the objective was to demonstrate the capability of the framework with regards to 2 of the requirements: Exploration and Insights. With regards to exploration, results like Figure 12 show the system behaviour, and results like Figure 18 show this capability on an agent-level. At the same time, insights for different stakeholders are shown, like the feasible routes for AAM in Figure 15.

4.2 Sensitivity Analysis

Several sensitivity studies on various parameters are performed from section 4.2.1 to 4.2.3 to get a better idea of the behaviour of the system, and to demonstrate the framework's capabilities with regards to the 3 remaining requirements: Traceability, Sensitivity and Integration. This, as well as the key influential parameters, is reflected on in section 4.2.4.

4.2.1 Sensitivity Analysis - Demand OD pairs

To analyse the sensitivity of the definition of the exact OD pairs, the original pair definition is used to regenerate the demand 3 times. This means that the absolute number of trips of one passenger type stays the same, but the OD pairs differ. This difference can be visually represented as seen in Figure 21 for a subset of the vertiports in Rome, where there are many repeated OD pairs, but the exact numbers are quite different.

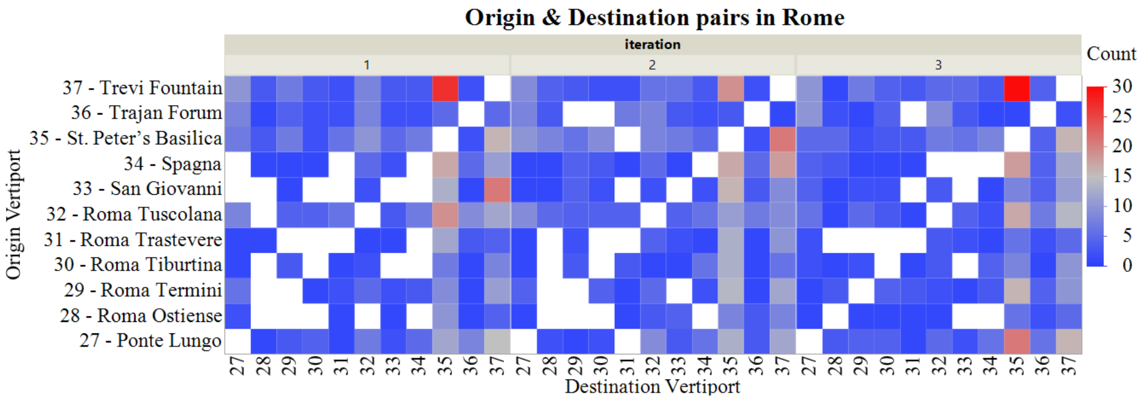


Figure 21: Comparison of subset of origin - destination pairs across 3 iterations in Rome

The weighted Jaccard similarity coefficient for 2 sets can be used to compare the difference and similarity as well, as defined in Equation 5 [41].

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|} \tag{5}$$

Where $|A \cap B|$ represents the intersection of the 2 sets, being the minimum (if any) recurring counts of the same OD pairs. Additionally, $|A \cup B|$ defines the union of the 2 sets, being the maximum number of OD pairs existing in both sets combined. The Jaccard similarity coefficient for iteration 1 and 2 is 0.52, between iteration 1 and 3 is 0.51, and between 2 and 3 is 0.52. This therefore means that slightly over half the OD pairs are reoccurring between any 2 sets, and just under half does not.

As can be seen in Table 2, the overall impact of the changes made in iteration 2 and 3 are negligible, as they are less than 3%. Breakdowns in more detail also reveal no further crucial differences. As a result, it can be concluded that the exact definition of the origin destination pairs does not have a significant influence on the simulation results.

Table 2: Comparison of KPIs over all 3 iterations

Demand study	**Overall energy per pax [kWh/km]**	**Overall time saved [hours]**	**AAM mode share [%]**
Baseline	2.71 (–)	1444 (–)	12.5 (–)
Iteration 2	2.75 (1.42 %)	1485 (2.84 %)	12.1 (-2.82 %)
Iteration 3	2.73 (0.43 %)	1462 (1.27 %)	12.4 (-0.1 %)

4.2.2 Sensitivity Analysis - Passenger Choice Options

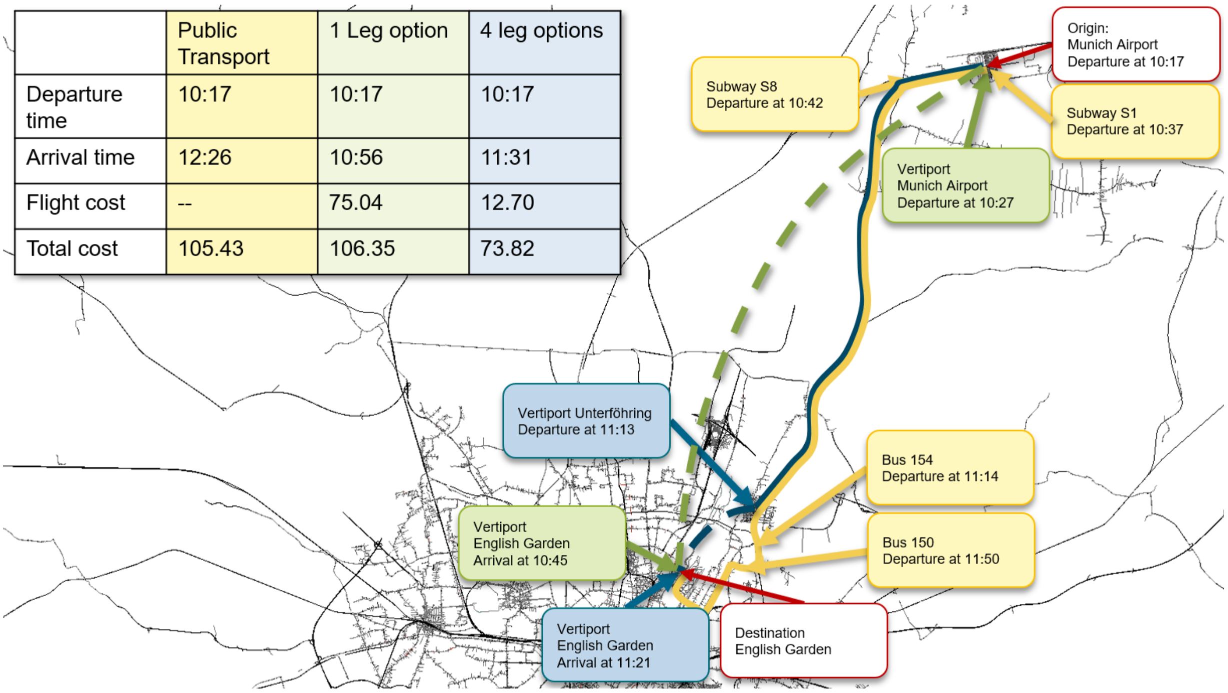
By default, all passengers consider the shortest route by public transport compared to the route using AAM to and from the closest vertiport to their origin and destination. However, this behaviour can be adjusted to where the N nearest vertiports are considered, resulting in N^2 route options by AAM per passenger. The impact of changing this parameter N can be seen in Table 3, where it is shown to have a negligible impact on energy per passenger, a small impact on time saved, and a significant impact on AAM mode share.

Table 3: Comparison of KPIs over passenger leg option sensitivity analysis

Passenger leg options	**Overall energy per pax [kWh/km]**	**Overall time saved [hours]**	**AAM mode share [%]**
1 (base)	2.86 (–)	1474 (–)	12.5 (–)
2	2.86 (-0.11 %)	1518 (3.01 %)	13.8 (9.16 %)
3	2.87 (0.43 %)	1560 (5.85 %)	14.4 (13.81 %)
4	2.89 (0.94 %)	1558 (5.68 %)	14.6 (16.07 %)

To get a better understanding of why the AAM mode share goes up, it is best to look at an individual passenger (Figure 22). Here, the route by public transport is highlighted in yellow. If the passenger only considers the nearest one vertiport, their alternative is the route highlighted in green, consisting mainly out of the AAM flight leg. As shown in the table however, the total cost of this route option is higher than that of the route by public transport due to the flight cost, which means the passenger would not opt for this. If the passenger instead is given the option to pick out of the nearest 4 vertiports, this changes the best AAM route option to the one highlighted in blue. Using this route, the passenger still utilizes public transport for the first leg and only use AAM for a short trip from Unterföhring to English Garden. As a result, the ticket price for AAM is much reduced, but as time saving is still significant this passenger chooses this route. On a large scale, this translates to an increase in AAM mode share by 16 %, but at the same time causes the average revenue trip distance to go down by 8.2 %.

This chosen example highlights some of the strengths of this simulation model, as it gives great traceability into the reasoning of individual passengers. At the same time, it shows some of the risks involved, as it is debatable which of these route options is the most realistic. Therefore, the exact mode choice of a single passenger should not be taken at face value, but rather this insight shows how agent-level choices can translate to SoS level effects.



	Public Transport	1 Leg option	4 leg options
Departure time	10:17	10:17	10:17
Arrival time	12:26	10:56	11:31
Flight cost	--	75.04	12.70
Total cost	105.43	106.35	73.82

Figure 22: Comparison of best route options for a passenger in Munich

4.2.3 Sensitivity Analysis - Value of Time

One of the other major assumptions in the passenger choice model is the value of time parameter. This parameter has been observed in literature to not only vary significantly, but also to depend on travel mode [42]. Therefore, it is important to perform a sensitivity study on this parameter. For this, a study is done where the mean value of time is reduced, resulting in the values shown in Table 4.

Table 4: Comparison of KPIs over value of time sensitivity analysis

Mean value of time	Overall energy per pax [kWh/km]	Overall time saved [hours]	AAM mode share [%]
15	2.75 (1.3 %)	794 (-45 %)	5 (-60.04 %)
18	2.8 (3.16 %)	972 (-32.69 %)	6.7 (-45.86 %)
21	2.83 (4.28 %)	1106 (-23.41 %)	8.5 (-31.82 %)
24	2.87 (5.6 %)	1253 (-13.21 %)	10.1 (-19.25 %)
27	2.87 (5.7 %)	1375 (-4.77 %)	11.4 (-8.28 %)
30 (base)	2.71 (–)	1444 (–)	12.5 (–)

Energy per passenger KPI is not strongly affected by this change, but time saved and mode share are. The reason for this is that with lower value of time, fewer passengers are tempted by the time savings provided through AAM, reducing the mode share. The same impact is seen on overall time saved, as fewer passengers using AAM logically reduces the sum of time saved.

4.2.4 Sensitivity Analysis - Conclusions

Throughout the sensitivity analyses, several sensitivities of the framework have been found:

- Exact OD Pairs - Changes trips taken, but not overall KPIs significantly.
- Passenger choice options - Changes AAM mode share modestly.
- Value of time - Changes AAM mode share and overall time saved significantly.

Overall, the conclusion should be that some of the modelling assumptions have a significant impact on the time saving and AAM mode share KPIs, and therefore any conclusions drawn with regards to aircraft design are not free of the impact of these assumptions. The energy per passenger KPI has shown to be largely consistent independent of the assumptions.

Additionally, the aim of the sensitivity studies was to highlight the framework's capabilities in the fields of Traceability, Sensitivity and Integration. Traceability has been shown to great effect in the example in Figure 22, where clearly agent-level decisions have an SoS-level impact. Integration is shown in the same example, as the passenger behaviour shown also highlights some of the framework's limitations, where a more realistic passenger choice model could enhance the results. Finally, Sensitivity is shown throughout the sensitivity studies.

4.3 Aircraft Design Experiment

With all the sensitivity analyses performed and the framework's capabilities with regards to the requirements demonstrated, it is now time to return to the research question. As the main objective is to analyse the impact of top-level aircraft requirements on the multimodal transport performance, a study is now set up varying 3 of the top-level aircraft requirements:

- Passenger Capacity (1, 3, 5)
- Cruise Speed (20, 25, 30, 35, 40 [m/s])
- Designed range (40, 50, 60, 70, 80 [km])

4.3.1 Effect of Passenger Capacity

The first effect to be analysed is that of the passenger capacity. This can be done in great detail, but as Figure 23 shows, the impact of passenger capacity on the results is of importance, but the pattern is very similar between the 3 different capacities. This is indeed the case not just for time saved, but also for AAM mode share and energy per passenger. As the impact of passenger capacity is notable, but the results between all 3 capacities follow the same pattern, in the next sections, all results are analysed in terms of cruise speed and design range, and passenger capacity is 3 for all of these analyses. For completeness, the full results for the passenger capacity of 1 and 5 can be found in Appendix 5.

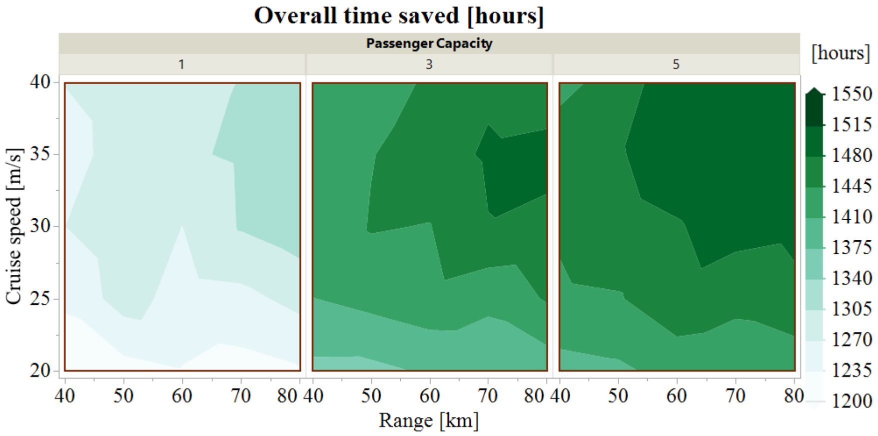


Figure 23: Overall time saved over 3 passenger capacities and variations of range & cruise speed

4.3.2 Effect of Cruise Speed & Designed Range

In Figure 24 to 26, a comparison is made between the time saved with different aircraft configurations, considering the passengers in the different operating environments. Aircraft with increased cruise speed typically perform better in terms of time saved in all environments, though there seems to be an optimum at around 35 m/s. At the same time, range seems to have a smaller impact, but higher range seems to be preferred.

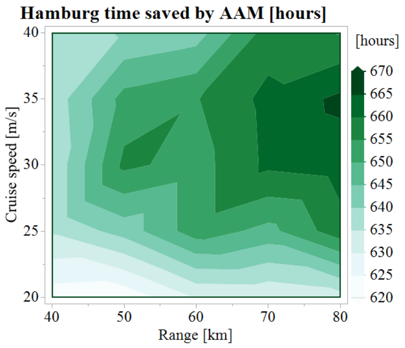


Figure 24: Total time saved in Hamburg, 3 Passenger Capacity

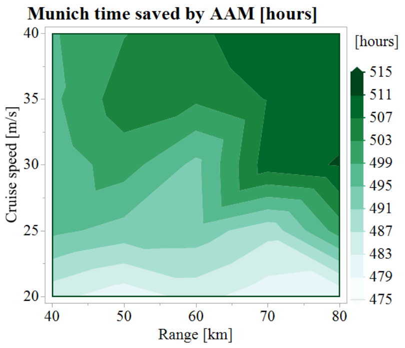


Figure 25: Total time saved in Munich, 3 Passenger Capacity

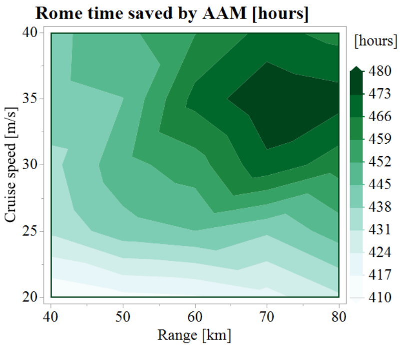


Figure 26: Total time saved in Rome, 3 Passenger Capacity

In Figure 27 to 29, one can see the overall mode share that AAM has for the different scenarios. In most cases, there is an optimum at around 30-35 [m/s], and with a range of 80 km. Hamburg and Rome show similar results, but Munich seems to show two optima. It should be noted however that in Munich the change in mode share is relatively minor, at about 0.5%. This still translates to about 30 passengers, but this is smaller than the changes in passengers in Hamburg (60) or Rome (100).

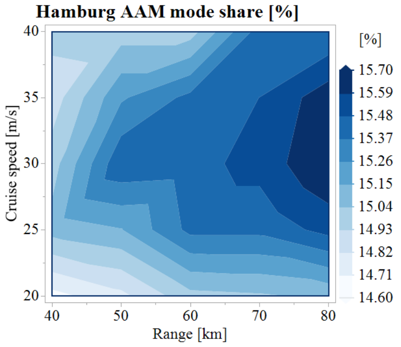


Figure 27: AAM Mode share in Hamburg, 3 Passenger Capacity

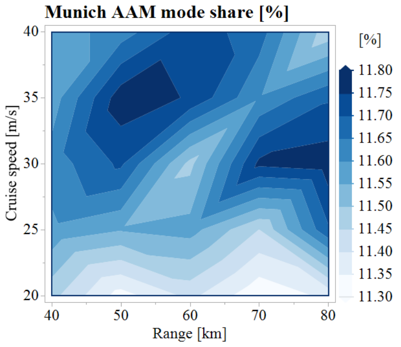


Figure 28: AAM Mode share in Munich, 3 Passenger Capacity

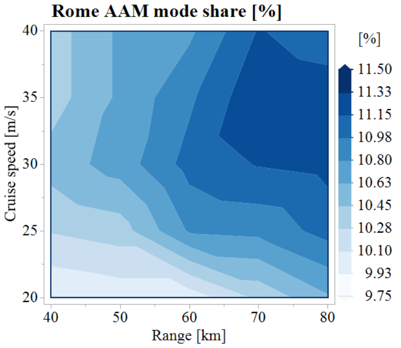


Figure 29: AAM Mode share in Rome, 3 Passenger Capacity

One of the reasons why there is a smaller change in mode share in Munich than in Rome is likely because the fleet is not capacity constrained. To illustrate why this is of importance, one can see in Figure 30 that during peak utilization hours (around 10:00 and 17:00) fewer vehicles are recharging if vehicles have 80 km range. This therefore results in more vehicles being active, which enables capturing slightly more of the demand. If the simulation is not capacity constrained like in Munich, this effect is not so significant, which reduces the impact that range has on mode share.

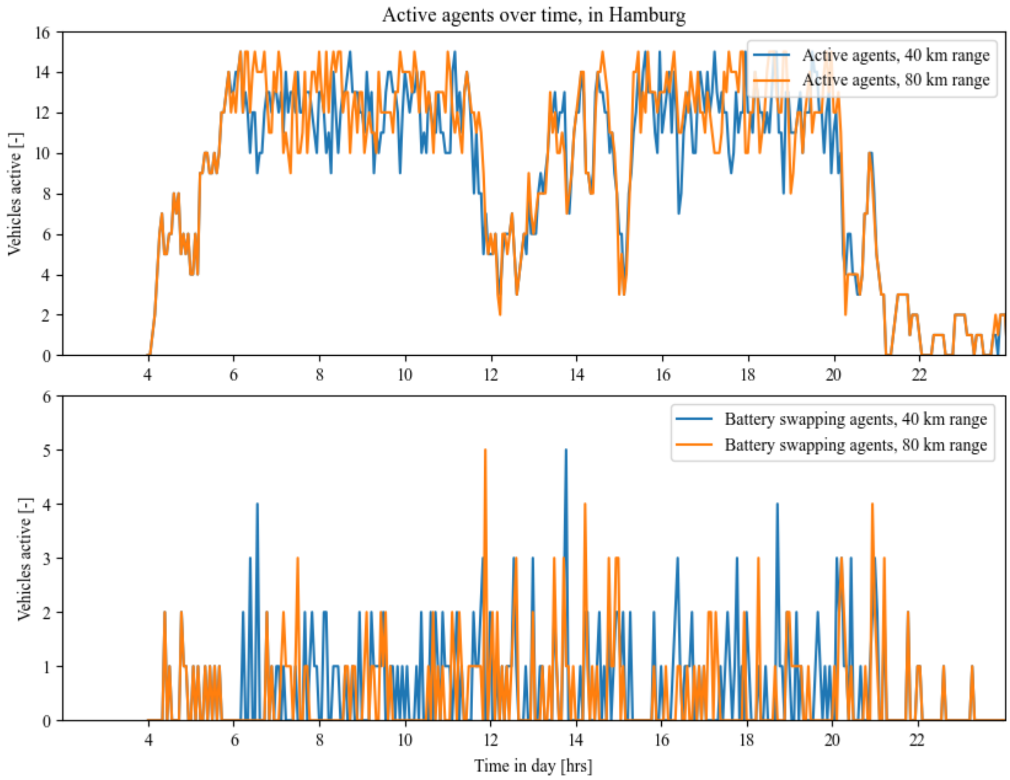


Figure 30: Comparison of number of battery-swapping and mission performing agents in Hamburg, cruise speed of 30

The final key performance indicator analysed is that of energy per passenger. This can also be compared in the different city environments, as seen in Figure 31 to 33. Here it becomes clear that both higher cruise speed and higher range results in a higher energy per passenger. Overall, the energy per passenger is at its lowest at about 1.5 [kWh/km], which is comparable to one of the least fuel-efficient road cars: a Bugatti Chiron [43] with average occupancy of 1.5 [44] comes in at 1.55 [kWh/km].

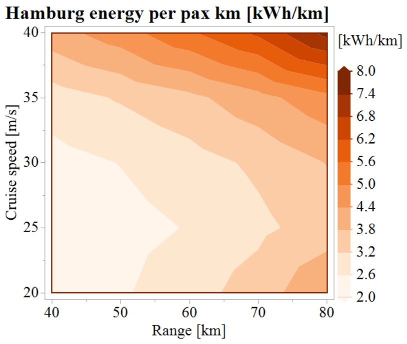


Figure 31: Energy per passenger in Hamburg, 3 Passenger Capacity

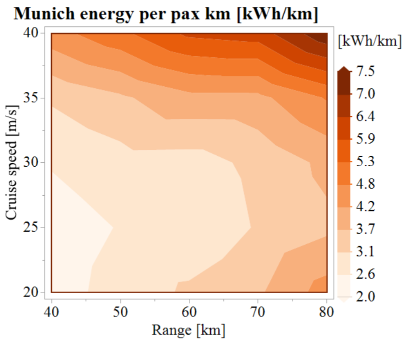


Figure 32: Energy per passenger in Munich, 3 Passenger Capacity

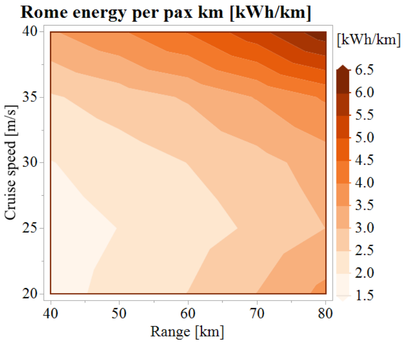


Figure 33: Energy per passenger in Rome, 3 Passenger Capacity

In addition, the energy per passenger parameter can also be compared to the designed energy per passenger coming out of the aircraft sizing tool. This comparison can be seen in Figure 34 and 35. Here, it should be noted that the total energy per passenger at the best case is 5 times worse in operations. A big aspect of this is the fact that the average payload in operation is hovering at around 1.1 passenger per revenue flight and additionally 42% of the flights is a deadhead flight. In the design case, no deadheads are assumed, combined with a full occupation of 3 passengers. In the results, we see that the penalty of increased range is much higher in operation, and that lower speeds are more beneficial. This is due to the fact that in operation most actually performed missions are of a much smaller distance than the designed range, resulting in a lot of spare battery capacity being carried around. Overall, if the optimum design point from an aircraft design was taken at 30 [m/s] and 40 [km] range, the total energy per passenger in operations would be 10 % worse than at the optimal design point derived from this scenario.

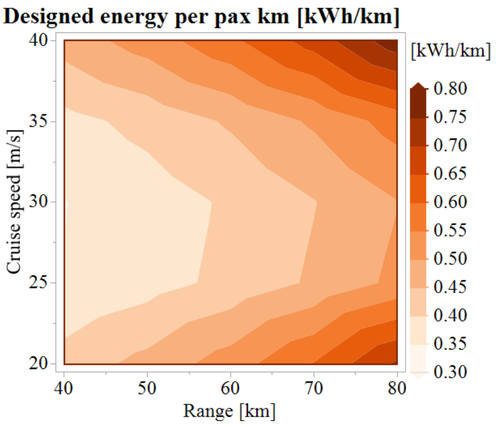


Figure 34: Energy per passenger in aircraft design

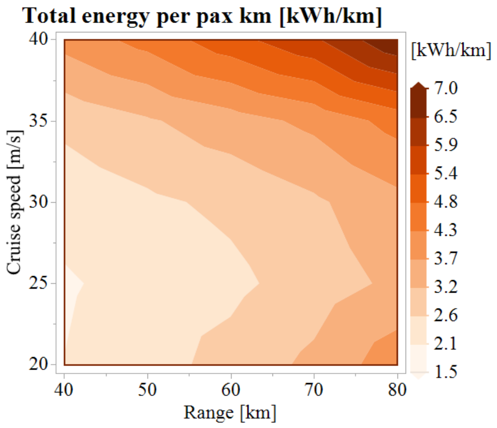


Figure 35: Energy per passenger in actual operations

4.3.3 Overall Measure of Effectiveness

After the individual KPIs have been analysed, their combination into an overall objective, the MoE as defined in section 3.3, can be explored. This is done for all 3 city environments, as shown in Figure 36 to 38. The optimum seems to shift slightly in the different environments, where Munich is the most indeterminate. Overall, there is a reoccurring best design point at around 70-80 [km] range, and 30 [m/s] cruise speed.

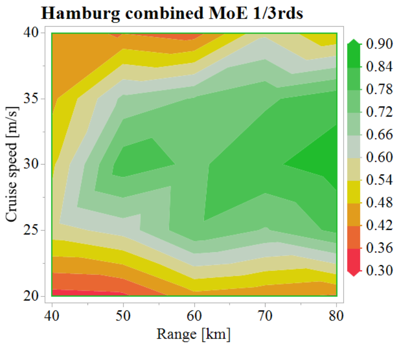


Figure 36: Best MoE design point in Hamburg, 3 Passenger Capacity

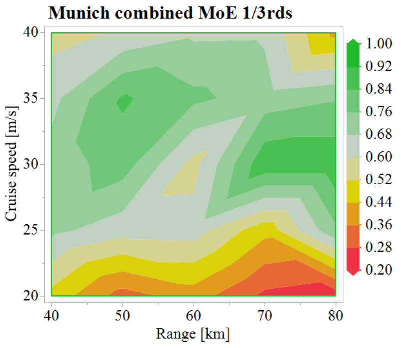


Figure 37: Best MoE design point in Munich, 3 Passenger Capacity

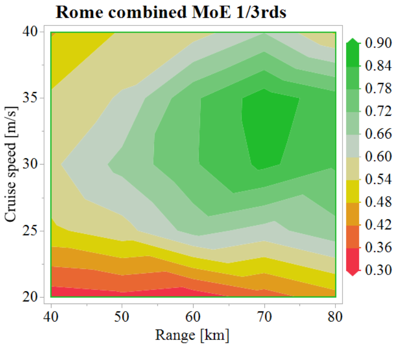


Figure 38: Best MoE design point in Rome, 3 Passenger Capacity

Then, all results are evaluated again on the overall level, also considering the passenger capacity, which is depicted in Figure 39. Here, the combined 3-passenger capacity result aligns well with the separate three city environments, with an optimum being at about 30 [m/s] cruise speed and 70 [km] range. However, it also shows the importance of looking at the bigger picture. The passenger capacity constraint is clearly a much stronger driver of the overall most effective aircraft, and changing this parameter seems to shift where the best aircraft lies as well, as at the highest passenger capacity, the best vehicle range cannot be clearly determined.

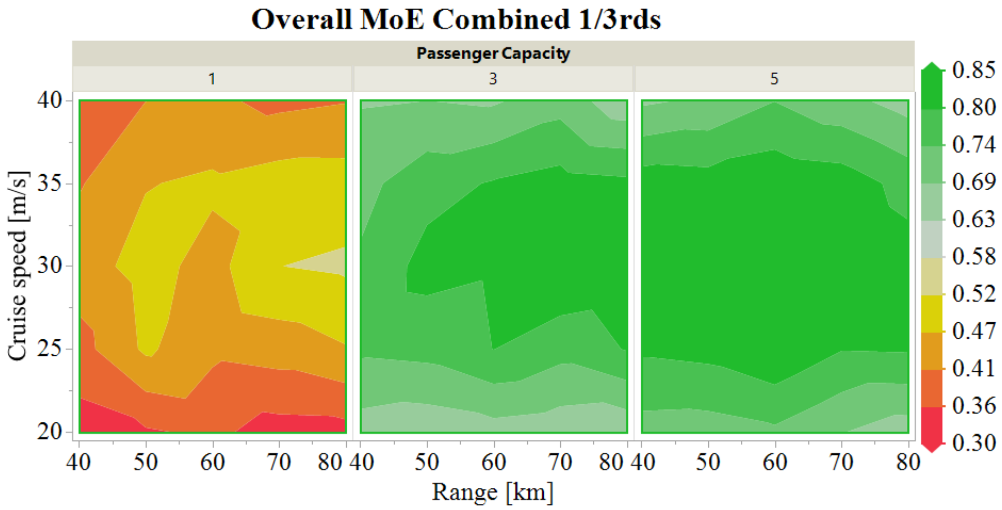


Figure 39: Overall MoE for all combined in Baseline study

5 Discussion

The main aim of the performed work was to develop a framework to assess the impact of aircraft design on multimodal mobility. This framework has shown to meet the requirements set for it:

1. **Traceability** - A good example of traceability, highlighting the ability to show an agent-level change resulting in a SoS-level impact, has been shown in section 4.2.2. Here, it was seen that by increasing the number of route options a passenger has using AAM, they might consider it for a shorter part of their journey, resulting in higher average AAM mode share, but at shorter distances.
2. **Sensitivity** - All the performed sensitivity analyses demonstrate the framework's ability to show simulation-driven analysis of the sensitivity of input parameters. Take for example the sensitivity analysis on the value of time parameter (section 4.2.3), where the AAM mode share KPI is almost linearly dependent on value of time, but energy per passenger is almost independent.
3. **Integration** - The final aircraft design experiments (section 4.3) show how a low fidelity aircraft design tool like VTOL-AD can already predict trends on aircraft energy consumption, which could be validated and extended using high-fidelity modelling techniques.
4. **Exploration** - The assessment of the overall SoS has been captured in section 4.3.3, demonstrating how different stakeholder interests can be evaluated by combining aircraft design and operations.
5. **Insights** - Aside from the representation of the stakeholders through the KPIs, we also saw how the framework can generate stakeholder insights in for example Figure 15, where the framework can identify which routes do and do not make sense to operate AAM on. Insights like this can be extended to assess the business case of AAM, and pricing strategies and vertiport placement can easily be explored further.

While the capabilities of the framework can be demonstrated, the results are also exposed to some limitations.

Throughout the performed studies the results have been presented in terms of KPIs of the overall system of systems. This has been done because it makes comparison between design points clear and objective. However, as many of the methods applied are fairly low-fidelity, it raises concerns about the accuracy of results. A good example of this is the impact of route options on passenger choice (section 4.2.2), where it is seen that passengers can opt for taking shorter routes using AAM to save on overall cost. While the framework aptly captures this trend, it might not be realistic that passengers would choose to use a metro with AAM to reduce trip cost instead of flying the full journey.

In addition, as the sensitivity analyses have shown, many of the assumptions have a large impact on the final results, in some cases to a larger extent than the changes caused by the considered design study. For example, the change in AAM mode share due to the assumed value of time (60 %), is larger than the change due to aircraft cruise speed (less than 20%).

Furthermore, it is shown that there is an important interaction between operations and aircraft design. This was shown for example in the final energy per passenger comparison between theoretical and practical results in Figure 34 and 35, where the overall efficiencies change with almost 10x, based on largely the fleet average load factor and deadhead ratio. As these changes are much larger than the actual changes induced through design, it shows the importance of combining both fields of research.

In conclusion, the developed framework meets the requirements set for it, and can be used for the overall system of systems assessment of door-to-door mobility. It successfully highlights the intricacies in linking aircraft design and operations, and that one cannot be done disregarding the other, especially in the field of Advanced Air Mobility. As a result, a question like 'What is the best AAM vehicle design?' cannot easily be answered, and the current results of the studies performed should be considered merely as exploration of the solution space. The approach here developed does show a process to try to answer questions about design whilst considering operations, and as such enables future research that could eventually get closer to the best vehicle design and operations concept.

6 Conclusions and future work

Throughout this study, an answer has been sought to the following question: In the context of advanced air door to door mobility, how can a framework be developed to assess the impact of top-level aircraft requirements on the multimodal transport operational performance, in terms of door to door travel time, AAM mode share, and energy consumption per passenger?

In the methodology, an approach to develop a framework for this purpose has been described. An agent-based model is used to simulate both aircraft and passengers in combination with a microscopic simulation of surface transport modes. This combined framework has been shown to be able to translate the complex inputs into System of Systems level performance indicators.

In doing so, the impact of changes to passenger behaviour, operational aspects and aircraft design can be assessed in a combined fashion, and their links can be explored. For example, it was found that the passenger-centric parameter of mean value of time was the most impactful on the AAM utilization, where a 50% change in input resulted in a 60% change in AAM mode share.

In addition, the developed framework allows traceability of the problem over different scales and shows how changes in SoS outputs can be caused by agent-level choices. This was seen through increasing the passenger choice options, which induced an additional 16% AAM demand, but reduced the mean trip distance by 8.2 % as passengers chose to use AAM more frequently, but for shorter trips.

Furthermore, the importance for aircraft designers to consider operations in aircraft design can also be highlighted. When comparing the best theoretical aircraft design to the best design in operations, a further 10% reduction in energy per passenger was found.

Lastly, the relevance of developing a large scale, multimodal framework for door-to-door mobility should be stressed. Throughout the results it is shown how linking different urban environments can give better insights in intercity travellers, and how the best design point for any individual location does not necessarily translate to the best overall design point.

The developed framework opens many new research directions that could directly be explored. Some examples are:

- Ticket pricing study - The impact of different ticket pricing strategies could be assessed. Just by changing the pricing model to a start cost + flat rate, the utilization could already change significantly, and more interesting dynamic pricing schemes could be explored as well.
- Business case study - Extending the ticket pricing to also include (operational) cost, one could try to find the best profitable routes and AAM vehicle designs.
- Vertiport placement study - In this study considered at fixed locations, vertiports could be moved around to see the impact of different locations, as well as the impact of adding and removing vertiports.
- Passenger mobility study - The passenger modelling could be greatly extended to include other sensitivities like comfort and climate impact into the choice modelling. In doing so, one could model passengers more realistically, or even use the framework as a test case for studies on these parameters.
- Other use cases - The developed framework is not limited to AAM use cases. It could be used for air cargo delivery, or other on-demand air mobility like helicopters and seaplanes. In addition, it could be used for studies on for example ground-based taxi operations, or any other mobility concept.

In addition to opening up further research opportunities, it would be beneficial to analyse the accuracy of the modelling techniques of subdomains going into the current framework. The impact of these assumptions has been analysed through several sensitivity studies on the same fidelity level. However, only through improving the level of fidelity (in for example the passenger choice modelling) will we know whether the fidelity currently used was indeed sufficient to draw conclusions from. By exploring the current work in more depth, as well as extending it to new studies, we will get a better understanding of the robustness and utility of System of Systems approaches to aircraft design problems.

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II

Literature Study

previously graded under AE4020

LITERATURE STUDY ON ADVANCED AIR MOBILITY VEHICLES FOR DOOR-TO-DOOR MOBILITY

AE4020 Literature Study

Under Supervision of:
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Table of Contents

1 Introduction

To improve European mobility, goals have been set by the European Union through Flightpath 2050, which includes the goal that 90% of the intra-European travellers should be able to complete their door-to-door (D2D) journey within 4 hours [1]. As of 2019, over 500 million passengers departed on intra-European flights [2]. All of these passengers embarked on a D2D journey, which is estimated to have taken seven and a half hours for 90% of travellers [3]. Clearly, there is much to improve in order to reach the goals set out in Flightpath 2050.

One of the fields where this improvement can be made is by the emerging area of Advanced Air Mobility (AAM). By integrating AAM into Europe's transport systems, improvements can be made in D2D travel time, as well as reductions in environmental impact. The field of future and current mobility is a place of much research, as is the field of AAM. However, the link between these fields is currently not adequately assessed, which is a motivation for future research.

Within this literature study, Chapter 2 discusses the current research on Mobility in Europe. Chapter 3 discusses research in the field of Advanced Air Mobility. The synergy and current gap in research are then discussed in Chapter 4. This is followed up with a proposal for the future research objective in Chapter 5, and a methodology to do this research in Chapter 6, ending with some conclusions in Chapter 7.

2 Mobility in Europe

One of the key elements within the scope of this research project is the current literature that is available on the mobility in Europe. To introduce the topic of Mobility in Europe, it is important to analyse some of the available European projects, which help define the scope of research. These are now detailed in Section 2.1 to 2.3.

2.1 Flightpath 2050

Flightpath 2050, published in 2011, is one of the leading documents defining goals for aviation in Europe in 2050 [1]. It defines goals and challenges in societal & market needs, industrial leadership, environment & energy, safety & security and research & education.

One of the key goals relevant to this research project is on mobility: “90% of travellers within Europe are able to complete their journey, door-to-door within 4 hours” [1]. This goal will be explored and critically analysed for its feasibility.

One of these analyses is done by Grimme & Maertens [4]. Their research starts with providing a refined definition of the Flightpath 2050 goal: “90% of trips involving at least one flight segment and car traffic as airport access/egress mode within and between the EU-28 member states could theoretically be completed door-to-door within 4 hours”

To check the feasibility of this goal, they use an existing dataset of flights. Then, based on assumptions on access and egress times, they find different levels of achievability of the 4-hour goal. It is found that access and egress times is the most important parameter in finding this achievability. In the most optimistic case however, with 30-minute access time and 15 minutes egress time, still only 82.4% of the passengers could reach their destination within the 4 hours. If more realistic access and egress times are assumed combining to 180 minutes, then only 5.9% of passengers reach their destination in 4 hours.

The authors conclude that the feasibility of the 4-hour goal should be reconsidered, and is unlikely to be met. The combination of a critical analysis and a rigid definition of the 4-hour goal are the most important aspects of this paper. At the same time, it should be noted that a severe limitation is that the authors do not actually use data on origin and destinations, which would be an area where this research could be enhanced significantly.

Monmousseau et al. [5] used aggregated Uber data to check the feasibility of the Flightpath 2050 door-to-door mobility goals for the Amsterdam-London and Paris-London trajectories. By using Uber Data, the effects of congestion can clearly be seen throughout different times of the day. This can be seen for example in Figure 1, where the variation of travel time depending on the time of departure is significant. It should also be noted that in these cases the door-to-door within 4 hours, as indicated by the red lines, is not achieved most of the time.

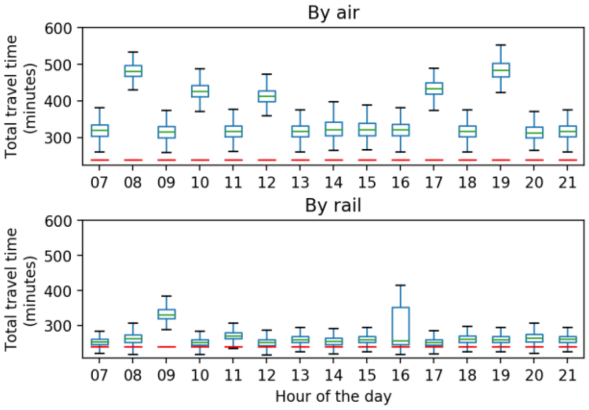


Figure 1: ''Hourly boxplots of door-to-door travel times to London starting from the Eiffel Tower in Paris. The top figure shows the boxplot related to air travel, the bottom figure the ones related to train travel '' [5]

To expand this, Monmousseau et al. [6] did a further study using additional city pairs. The analysis starts by expanding the Amsterdam-Paris analysis, looking at which parts of Paris can best be reached by different modes of transport, depending on time of day. This analysis is then expanded to the US, where a comparison of 6 different US airports is done. This approach is then used to compare these airports for their accessibility. Additionally, an analysis of the impact of a landfall in Boston is shown on the reachability of different parts of the city.

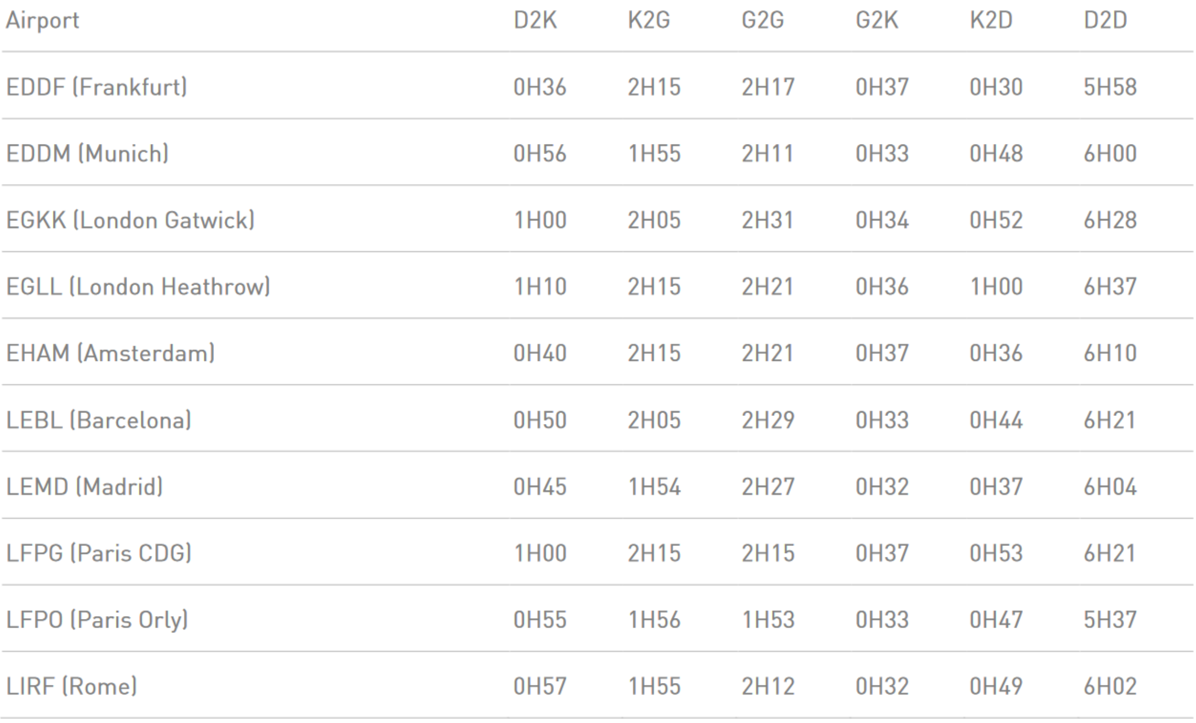
2.2 Modus

One other large-scale research project on European mobility is Modus. It includes the topics of ticketing, interoperability & data, connectivity, intermodal alignment and environmental impact, as defined in D5.1 [7]. Within the topic of multimodal mobility, the integration between air-rail is established in D4.2, which also shows results on current door-to-door travel times within several exemplary areas [8]. The final project results are highlighted in D5.2, including an analysis of modal choice for France, Germany and Spain, as well as future mobility experiments and results on expert interviews [9].

2.3 DATASET2050

Another research project of relevance is the DATASET2050 project. Its main goal is the analysis of door-to-door trips in the EU, with at least 1 air transport segment [10]. It defines in great detail current and future passenger demand profiles, as detailed in Deliverable 3.2 [11]. For the analysis of door-to-door journeys, the following legs are modelled: Door-to-Kerb, Kerb-to-Gate, Gate-to-Gate, Gate-to-Kerb, Kerb-to-Door [3]. Combining detailed future passenger demand profiles with information on all of the stages of door-to-door journeys, results are shown in Deliverable 5.2. One of the key results is the analysis of door-to-door travel times originating and arriving at specific airports, of which some are shown in Figure 2. These results can also be interacted with on a dashboard, providing even greater insights [12].

Overall, DATASET2050 provides a great source of information in future air transport demand, combined with a detailed analysis of door-to-door travel times all over the EU. As shown in Figure 2, it could also provide motivation for specific locations in the EU where great improvements in door-to-door mobility could be achieved.



Airport	D2K	K2G	G2G	G2K	K2D	D2D
EDDF (Frankfurt)	0H36	2H15	2H17	0H37	0H30	5H58
EDDM (Munich)	0H56	1H55	2H11	0H33	0H48	6H00
EGKK (London Gatwick)	1H00	2H05	2H31	0H34	0H52	6H28
EGLL (London Heathrow)	1H10	2H15	2H21	0H36	1H00	6H37
EHAM (Amsterdam)	0H40	2H15	2H21	0H37	0H36	6H10
LEBL (Barcelona)	0H50	2H05	2H29	0H33	0H44	6H21
LEMD (Madrid)	0H45	1H54	2H27	0H32	0H37	6H04
LFPG (Paris CDG)	1H00	2H15	2H15	0H37	0H53	6H21
LFPO (Paris Orly)	0H55	1H56	1H53	0H33	0H47	5H37
LIRF (Rome)	0H57	1H55	2H12	0H32	0H49	6H02

Figure 2: Door-to-door travel times in 2050 from DATASET2050 [3]

3 Advanced Air Mobility

The topic of advanced air mobility is an area where much research is already done. By focussing on the 3 key relevant topics, existing literature can be analysed and gaps in research can be defined. Starting with research on AAM in door-to-door applications in Section 3.1, literature on AAM vehicle design is then considered in Section 3.2, which is followed up with some literature on the integration of AAM with its infrastructure in Section 3.3.

3.1 Door-to-door

The field of door-to-door mobility has been investigated in the application of advanced air mobility. One often cited paper, analyzing AAM on European scale for door to door mobility is that of Sun et al. [13]. The authors build a grid cell based network of Europe. Using this network, they estimated lower bounds of door-to-door travel time using different modes of transport. For car transport and train transport use was made of OpenStreetMap. For air transport both using AAM and regular flights, use was made of existing airports, and routing through all non-restricted airspace at FL100 and FL300, respectively. For all non-car transport methods, a car was still used as transport method to and from connecting stations. Because assumptions are made on flight speeds and onboarding and deboarding times, this then allows the authors to find feasible windows for AAM to be competitive based on minimum travel time. This is then shown for various different cities in the network. It can be summarized also, like seen in Figure 3. This shows a nice approximation of where AAM could be a competitive mode of transport.

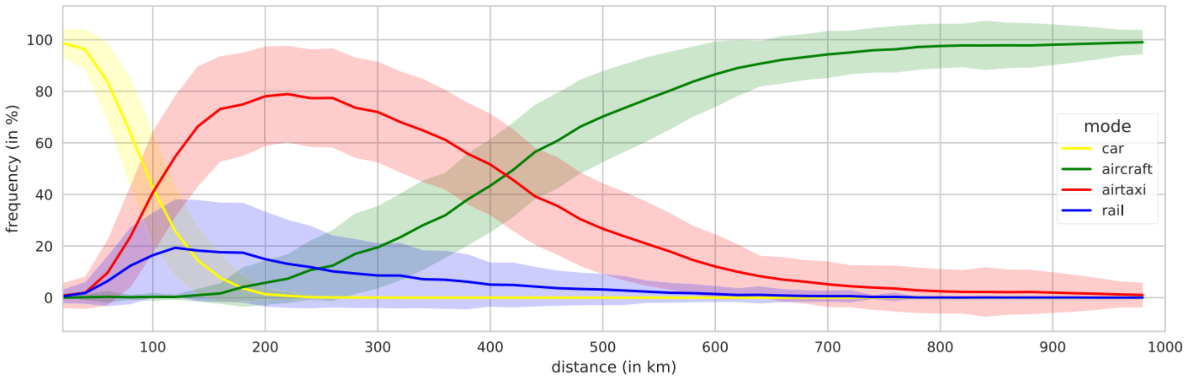


Figure 3: Relative competitiveness of different modes of transport for the top 100 considered cities [14]

The authors then go on and do another interesting analysis. The competitiveness of AAM can also be shown spatially by connecting the grid cells based on density-based demand, and finding at which links AAM would allow the biggest respective travel time reduction. This can be seen in Figure 4.

Figure 4: "Visualization of the top 1000 links when considering travel time reduction and travel demand between grid cell pairs in Europe. The red coloured grid cells indicate the population density of the grid cells is above the median values of all grid cells." [13]

Overall, this paper provides a really interesting baseline for estimating door-to-door mobility on a large scale, as well as the impact AAM could have on this. There are however some limitations still: Traffic is considered to be free flow, significant approximations are made in air-travel time, mode choice is only based on travel time, and AAM vehicles are assumed to have a certain performance which is not analysed thoroughly. Nevertheless, this paper will serve as a certain inspiration for future research in this area.

One of the papers following in the footsteps of Sun et al. is that of Schuh et al. [15]. Applying a similar methodology of comparing car, train, regular flights (on CS25 airfields) and on demand advanced air mobility, the competitiveness of AAM is modelled. This is applied to a model of Germany, where demand is based on business travellers. Crucially, the authors include the notion of value of time. By modelling mode choice as not just the fastest route but also the most affordable, demand can be shown for all routes. The result is shown in Figure 5, which is clearly different to Figure 3. This therefore shows the potential importance of considering value of time as a choice parameter. Even with this factor considered, a market share potential of 2.7% of all business travellers is found, which is not insignificant.

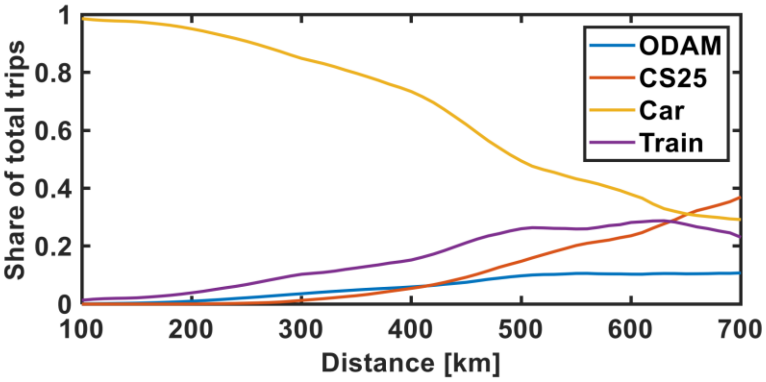


Figure 5: Advanced Air Mobility in Germany, considering time and travel cost for mode choice [15]

A similar approach is used by Wu & Zhang [16] in the modelling of Urban Air Mobility in the Tampa Bay area. Starting with identifying potential locations for vertiports based on criteria like land use, large enough (rooftop) space and proximity to other potential nodes, a selection is made on potential locations. Then the most competitive vertiports were selected based on a hub-and-spoke network.

Other transport mode usage data was obtained from existing demand data, as well as information relating to value of time of prospective UAM users. Then using this, a demand was found for the UAM service. Additionally, in this paper, extensive sensitivity analyses are done to see which parameters would influence potential service usage the most. This is shown for the number of hubs, number of vertiports, transfer time, and air trip cost.

The usage of a sensitivity analysis to see which of these parameters are important in the behavior of the system is crucial, and this is one of the key aspects of this study that has not been discussed extensively yet.

Adding on to this paper on the demand for UAM in the Tampa Bay Area, a study by Zhao et al. [17] looks at the environmental impact of this service. Based on the energy consumption of UAM vehicles, the Tampa Bay area electric energy source composition, and existing ground transport emissions, they find the changes due to UAM inclusion. Additionally, the impact of different energy source compositions is considered. It is found that in the current state, UAM will increase greenhouse gas, SO_2 and $PM_{2.5}$ emissions, while reducing NO_x emissions.

Another leading paper on UAM is the paper by Rothfeld et al. [18]. Combining a ground-based car transport network using MATSim with an UAM simulation, they analysed potential time savings in 3 metropolitan areas: Munich, Paris and San Francisco Bay Area.

For these areas the authors build on previously built models by different researchers for the ground transportation data. This ensures that this data is already calibrated correctly. Then, vertiport placement is done based on expert judgement combined with a minimum impedance method for the different regions. Importantly in this paper, UAM vehicle routing is done through overflight over primary infrastructure (like high density roads), instead of shortest Euclidean flight paths. UAM trips are assumed to be eligible if the trip would otherwise be made by car, and UAM can accommodate at least two thirds of the total trip length. Congestion is considered, and a baseline UAM design is established.

Then, a sensitivity analysis is performed for various parameters in all 3 metropolitan areas. This can for example be seen in Figure 6, where the impact of both cruise speed and number of UAM stations is considered. Such a sensitivity analysis is shown to provide great insight in the problem, as all 3 situations are affected differently, and nonlinear relationships between the different parameters seem to exist.

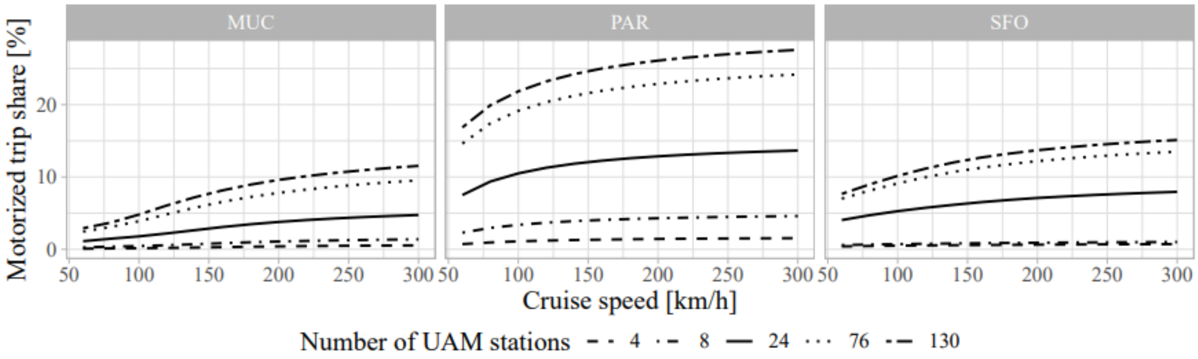


Figure 6: Variation of Cruise Speed and Number of UAM Stations versus trip share [18]

This paper then concludes with several remarks on the utility of UAM. It is found that UAM in this case study is useful to reduce travel time by 3-13%. It is found to be less affected by congestion, and effective at a range beyond about 50 minutes by car. It is noted however that the results are highly dependent on the placement and accessibility of vertiports as well as service times. Costs and environmental impacts are also not considered, which are future recommendations as well.

Another study on the door-to-door mobility benefits provided by regional air mobility is done by Roy et al. [19]. Applied to a use case of the Midwest United States, a comparison of regional air mobility to automobile and conventional airline flights for commutes within the area. Passenger choice is assumed based on value of time and economic costs of the mode of travel. Based on an assumed value of time of 100$/hr, a market potential in terms of range for CTOL aircraft (170-260 nmi) and electric eCTOL aircraft (135-200 nmi) is established. The minimum value of time is then determined at which these modes of transport are still competitive, and based on mean incomes of passengers in the Midwest, this allows for a market potential of 2.42% and 8.7% respectively. Then, a sensitivity study is done to see the impact of which future technologies could enable further market potential, which is identified to be largely enabled by autonomy and ride-sharing.

To analyse the global demand for UAM, Anand et al. [20] make various assumptions. The demand is forecasted based on a willingness to pay dependent on value of time saved and ticket pricing. 542 global cities are considered, which are approximated by a subset within them. It is found that UAM demand is highly dependent on ticket pricing.

3.2 Vehicle Design

One of the most interesting research papers on the design of AAM vehicles is that by Ratei et al. [21]. By using a system of systems approach, the fleet design is performed at a large scale, and interlinked with operations, vertiport placement and other effects. This framework can be seen in Figure 7. Within this simulation, different aircraft architectures (multirotor and tiltrotor) are considered, with varying fleet size, passenger capacity, cruise range and cruise speed.

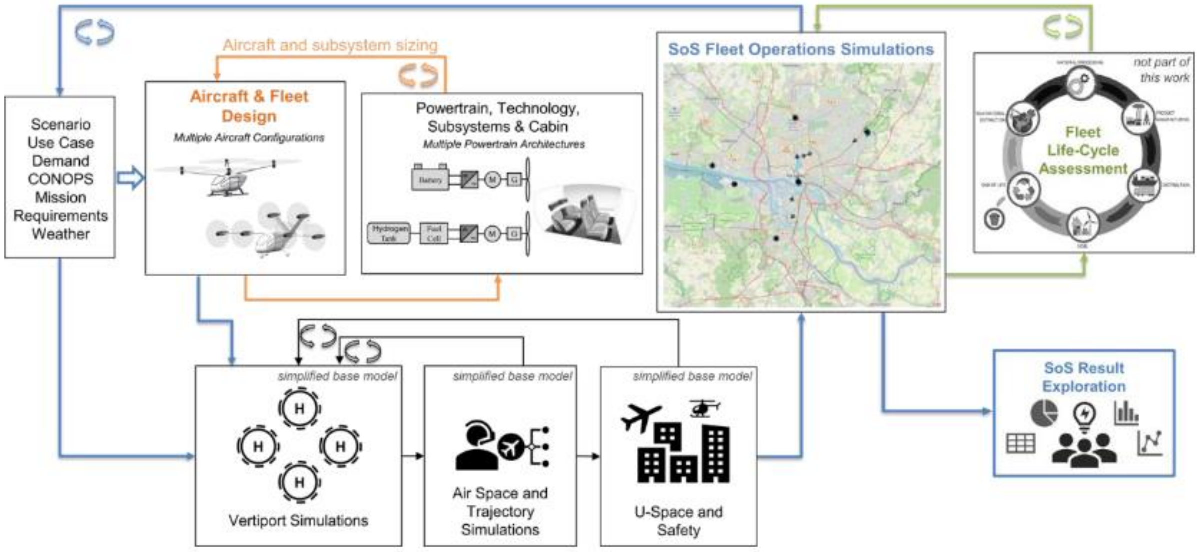


Figure 7: "System of systems simulation framework for vehicle and fleet design" [21]

To analyse the effectiveness of these vehicles, a measure of effectiveness is developed, considering converted requests, fleet energy usage and load factor.

Then, extensive sensitivity analysis is performed, which are summarized in figures like Figure 8, showing the optimal design of the tiltrotor design, averaged over all fleet sizes. The authors then analyse this for different fleet sizes as well, and find that for the use case of UAM in Hamburg, the best tiltrotor design would fly at 60 m/s, seat 4 people, and have a range of 60-110 km. The optimal multirotor design would fly at 45 m/s, with 4 people, and a range of 60 km.

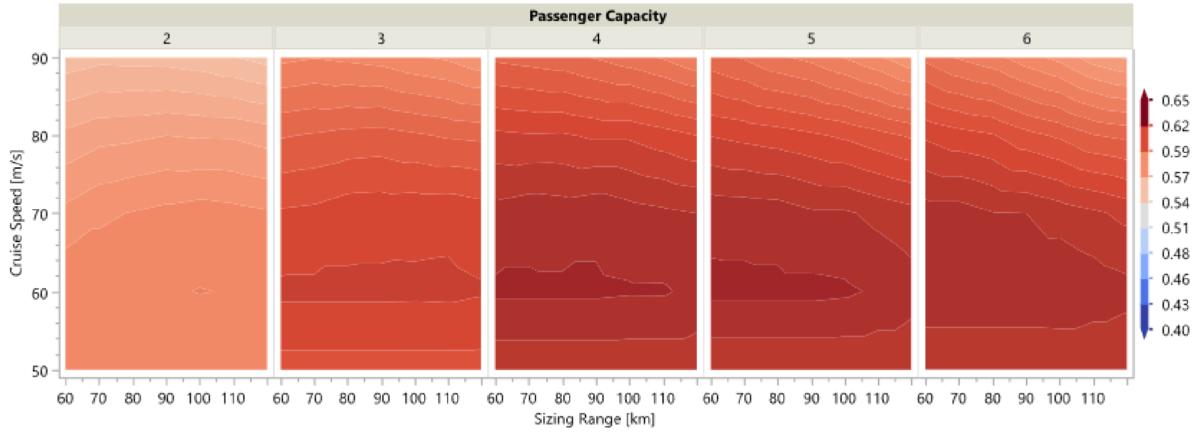


Figure 8: "Derivation of top level aircraft requirements for the tiltrotor architecture" [21]

Another interesting paper treating different aspects of regional air mobility vehicle design is that of Justin et al. [22]. Applied to the American Northeast Corridor, an analysis is done on different size vehicles (9 pax, 19 pax, 48 pax), hybrid vs electric, and different battery density studies.

A different modelling approach is used, as use is made of a mixed-integer linear program formulation with a multi-objective optimization for profitability and emissions. To account for emissions, an analysis is done of the different energy sources and their carbon intensity in 2019, linearly propagated to 2040 based on the assumption that electric grid production will be without emissions by 2050.

One of the particularly interesting initial analyses is on the comparison of a hub-and-spoke (HS) network and a point-to-point (PTP) network. This can be seen in Figure 9, where it becomes apparent that the HS network has higher utilization rates, serves more passengers, and has higher operating profits and emissions. One interesting change is that the 48-pax aircraft are completely eliminated in the PTP network, as there is not enough demand to fill them sufficiently.

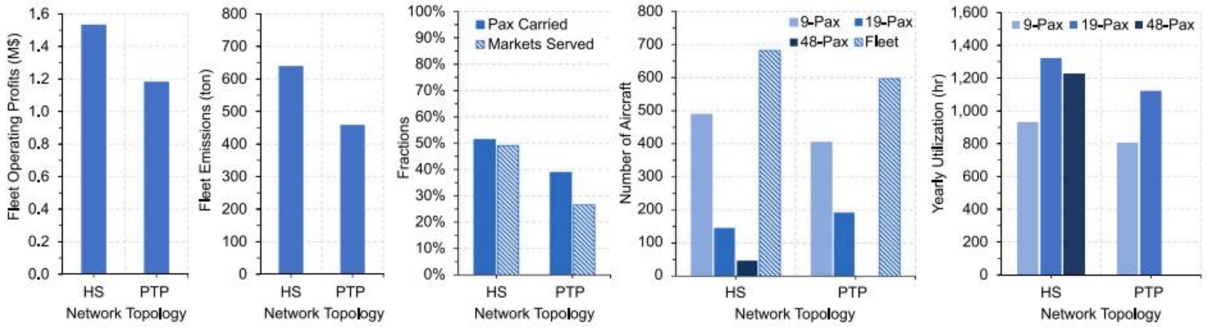


Figure 9: "Metrics comparison between baseline hub-and-spoke and point-to-point network" [22]

One redeeming factor for point-to-point network operations is that it should reduce passenger door-to-door travel times. Because all passengers will travel without unnecessary connections, their door-to-door travel times should be lower. This is confirmed to be the case in the authors' simulation, as seen in Figure 10.

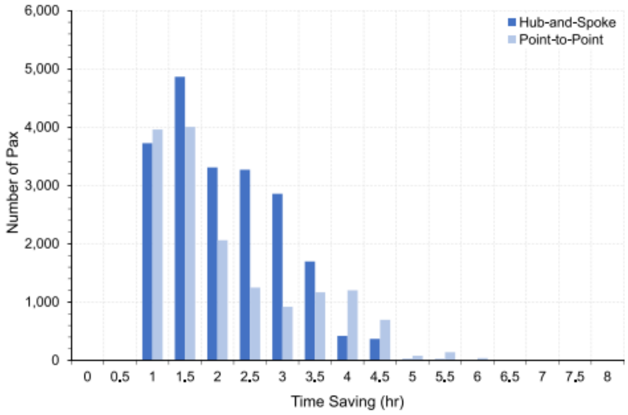


Figure 10: Comparison between door-to-door travel times for PTP and HS networks [22]

With regards to aircraft design, the key design feature considered is that of battery specific energy. This is summarized in the trade-off seen in Figure 11, showing clear trends in favour of higher battery density. The degradation shown is that of profit, which is done to include environmental considerations.

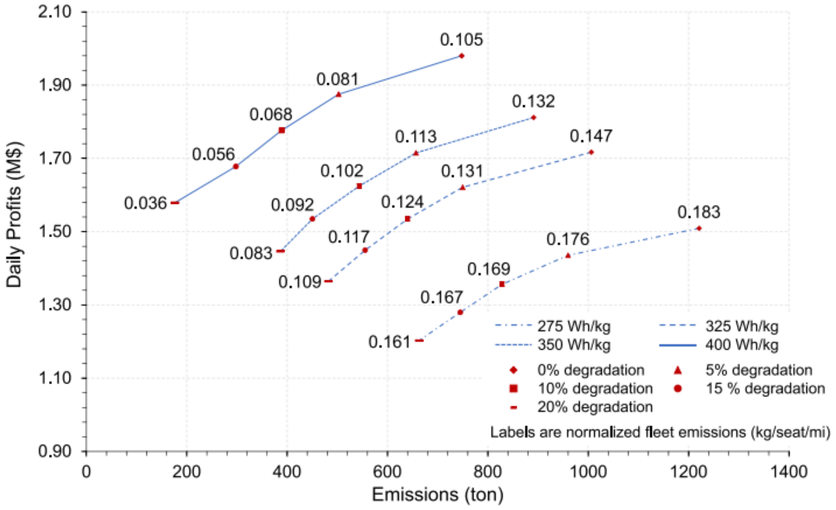


Figure 11: Pareto fronts for daily profits vs emissions for different battery technology levels [22]

Several other authors consider the effect of battery density [23] [24] [25] [26]. Other parameters often considered are that of aircraft speed [27] [15] [28] [21] [24] [26], and range [27] [25] [26]. Another important objective for hybrid architectures is the hybridisation factor, which has been investigated by Cakin et al. [29], though this study included only sizing for specific mission profiles. Additionally, wing area and number of propulsors has been considered by Xiao et al. [30].

In an attempt to combine different aspects of design of UAM vehicles, Brulin et al. [31] looked at using a genetic algorithm to perform evolutionary optimisation to maximize revenue in a multimodal framework applied to Corsica. The best vehicle design was found to have a capacity of 1 passenger, a range of 108 km and a speed of 176 km/h.

In a similar large scale optimization, Ha et al. [32] optimized the design of 2 conceptual UAM vehicles based on a combination of design aspects like speed, range, wing design and propeller design, but also including economics relating to the revenue and cost. They found that including economic aspects simultaneously in the design optimization improved the final solution by 11% with respect to performing design and economics optimization separately.

3.3 Concept of Operations

Another aspect that should be considered is the operational environment in which Advanced Air Mobility vehicles will be used. This has also been investigated extensively in previous literature. One important consideration here is the impact of the amount of vertiports and their placement.

One key article on this topic is by Rath & Chow [33], applied to New York City. Based on demand data from for-hire vehicles, a mathematical optimisation is done on a short-term and long-term use case. Then, a sensitivity analysis is done on the short-term use case, which highlights the effect of additional vertiports on time savings that can be obtained, as seen in Figure 12.

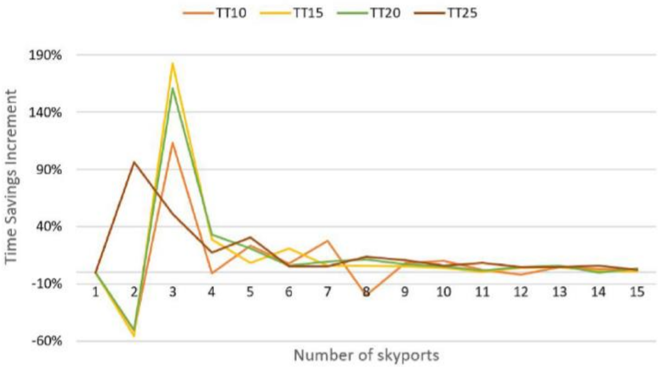


Figure 12: Time savings versus number of skyports for different transfer times TT [33]

Also applied to New York City, Rajendran & Zack [34], have considered the effect of various passenger demand aspects on the number of feasible vertiports to be operated. In a similar fashion, Sells et al. [35] optimize a network of vertiports in Chicago to enhance the demand based on passenger mode choice. Further studies including variation on vertiport placement are in the San Francisco area [36], the Tampa Bay Area [37], Salt Lake City, Dallas & Washington [38] and Seoul [39]. A vertiport placement consideration is made as well by Maheshwari et al. [40], which considered the time saved and its value as well for a chosen journey. They also considered the opportunity for ridesharing, which they found to reduce effective cost.

The internal operations of vertiports can also be investigated, as done for example by Preis & Hornung [41]. Through varying the fleet size, approach and boarding times, as well as the number of pads and gates, it was found that pad operations are the most impactful on passenger travel times, and there are certain threshold capacities within operations that should not be exceeded. This has been investigated as well by Preis & Cheng [42], Preis & Vazquez [43], Rimjha & Trani [44], Guerreiro et al. [45] and Vascik & Hansman [46].

Once UAM vehicles are airborne, the different flight segments that have to be performed also have a large impact on the total energy needed for the vehicle to operate. Different aspects like cruise altitude, climb and descent rates and angles have been investigated by Preis et al. [47], who found that these aspects not only have a big influence, but also vary between tilt-rotor and multirotor concepts.

As multiple vehicles will be airborne at the same time, air traffic management will also have to be considered for advanced air mobility. One consideration here is the number of conflicts between different vehicles in flight, which has been considered by Niklaß et al. [48] in the development of their model. Tactical deconfliction was also investigated by Pelegrin et al [49], who found the level of cooperation to be a key sensitivity in the effectiveness of deconfliction measures. Another deconfliction approach is proposed by Bosson & Lauderdale [50], who found that amongst other things, deconfliction before flights even take place is highly effective in reducing the amount of conflicts that have to be resolved.

Another key operational concept is the choice between charging and battery swap operations for electric fleets. The effect of charging power herein has been investigated for an Air Ambulance service by Goyal & Cohen [51]. It has also been considered in studies on Hamburg by Shiva Prakasha et al. [52].

An important aspect of the environmental friendliness of advanced air mobility is the CO2 emissions that are caused. This has been considered in a case study by Mudumba et al. [53] on Dallas and Chicago. It is found that the CO2 emissions are highly dependent on the sources used for generating the electricity needed for UAM vehicles, as well as to which type of automobile the comparison is made. This is also seen in Figure 13.

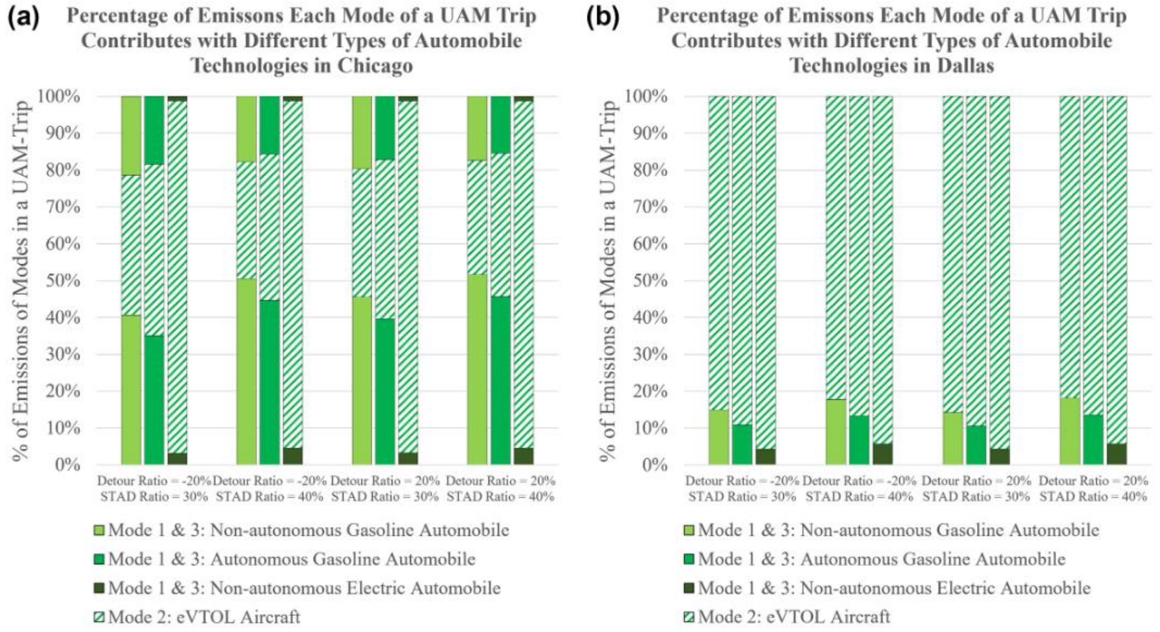


Figure 13: Percentage of CO2 emissions contributed by a UAM trip for Chicago and Dallas [53]

Some other consideration in modelling the operations of UAM vehicles is the occurrence and resilience to disruptions. One of these aspects is that of extreme weather, which has been studied by Wright et al. [54], which found that for an increase in extreme weather cases by 5%, viable UAM trips could go down with up to 14%. In order to find more general impact of the weather over the entirety of the United States on AAM operations, Sharma et al. [55], and they found that there is large variabilities in the percentage of flight time available throughout the year, varying from less than 50% to close to 100% for various regions.

Looking towards the future of operations, autonomous flight has to be considered as well. This has been shown as a factor with great impact on operations by Goyal et al. [56]. It is also considered by Shiva Prakasha et al. applied to Hamburg and San Francisco [57] [58].

4 Gap in Research

As Chapter 2 and 3 went into great detail on the existing literature on European mobility and advanced air mobility, it is now time to synthesise this literature, and identify areas of commonality as well as the existing gap in research.

Starting with the gap in research: It is found that although there is much research in the field of advanced air mobility, the link of the vehicle design to passenger choice, operations and surface transport is often not considered fully. Integrating these aspects in a robust framework would make it possible to draw more general conclusions about advanced air mobility.

Within the field of European mobility, several large-scale projects analysed door-to-door mobility [9] [3]. Door-to-door mobility has been linked to advanced air mobility in several papers [13] [16] [17] [18] [19]. Some of these papers even link advanced air mobility and door to door performance to vehicle design [15] [22], but these only consider parametric variations in vehicle design aspects, not respecting feasibility.

Going into greater vehicle design fidelity has been done in several other papers that investigated different architectures [21] [24] [25] [31] [32]. Additionally, various publications consider variations of key parameters [22] [23] [26] [27] [29] [30] for AAM design.

Operations has additionally been considered in detail, starting with investigations on the number and placement of vertiports [33] [34] [35] [36] [37] [38] [39] [40]. The internal operations of vertiports has also been investigated by various authors [41] [42] [43] [44] [45] [46] [47]. The topic of air traffic management has also been touched upon [48] [49] [50], as well as some other aspects like environmental impact [53] and autonomous operations [56]

To be able to identify more clearly where the existing literature can be expanded, use will be made of a spider plot. In order to build up the spider plot, the axis first have to be defined. On these axes, different levels within each category are then specified. This is done to be able to make fair distinctions between different literature sources. This split is done as follows:

- Setup of air transport network
    - Free choice – Aerodromes are placed based on authors judgement without constraints
    - Existing infrastructure – Aerodromes are placed on existing helipads and airports
    - Single objective – Aerodromes are placed based on optimization for a single objective, like maximum utility for operator, maximum time saved for passengers
    - Constrained multi objective – Aerodromes are placed through consideration of multiple stakeholders, and constrained to realistic locations
- Modeling of alternate transport modes
    - 1 Alternative - 1 Alternative mode considered, typically car
    - 2-4 Alternatives – 2-4 Alternative modes considered, typically car, train and conventional flights
    - 5(+) Alternatives – At least 5 alternative modes considered. Typically, car, train and conventional flight, as well as buses, metros, ferries, bikes.
- Modeling of surface travel time
    - Simple - Travel times estimated based on generalized data within the considered area
    - Specific data – Travel times obtained using real life data for the specific journey
    - Simple simulation – Travel times obtained from simulation for the specific journey, based on uncongested and scheduled operations

    - Detailed simulation – Travel times obtained from simulation for the specific journey, considering congestion and other disruptions
- Modeling of demand forecast
    - Generalized data – Demand forecast is based on general population data randomly distributed over the area
    - Specific data – Demand forecast is based on specific data for the area
    - Trip generation – Demand forecast is based on activity-based trip generation for every individual passenger
- Vehicle Design
    - No vehicle design - One vehicle design is assumed
    - Variation of vehicle design parameters – Variations are done on a base vehicle design, but these disregard the feasibility of these concepts
    - Conceptual vehicle design – Variations of vehicle design are done with conceptual design tools, such that resulting designs are feasible
    - Higher fidelity vehicle design – Vehicle design is done incorporating higher fidelity methods like FEM and CFD
- Modeling of aerodrome operations
    - No operational aspects – Aerodromes just allow passengers to perform a mode change
    - Simple operations – Some parameters are considered, like charging speed, boarding times and turnaround times
    - Detailed operations – More detailed considerations are done, like capacity constrained vertiports, air traffic management, and internal vertiport operations
- Passenger Choice
    - Travel time – Passenger choice based on which mode has lowest travel time
    - Effective cost – Passenger choice based on combination of mode cost and value of time
    - Complex choice – Passenger choice based on more than cost and value of time, considering for example convenience, reliability or mode preference
- Modeling of fleet allocation & dispatching
    - Unlimited fleet – No fleet size constraints, for every passenger there is a vehicle to fulfil transport demand
    - Limited fleet - Limited homogeneous fleet is dispatched on demand with the inclusion of deadhead flights
    - Mixed limited fleet - Heterogeneous fleet is dispatched on demand including deadhead flights
    - Optimized limited fleet – Predictive dispatching is performed to reallocate aircraft to improve overall effectiveness
- Modeling of air traffic management
    - Free routing – A point-to-point network is maintained where all aircraft fly the shortest path to their destination
    - Constrained routing – Static no-fly areas are established to reduce the areas where flights are performed, or static routes are designed for OD pairs
    - Dynamic routing – Dynamic no-fly areas are established to deconflict routing such that aircraft maintain appropriate distance

With the axes defined, some of the most exemplary literature previously described is added to these axes, as seen in Figure 14. The literature represented is focused on literature that has aspects in all categories.

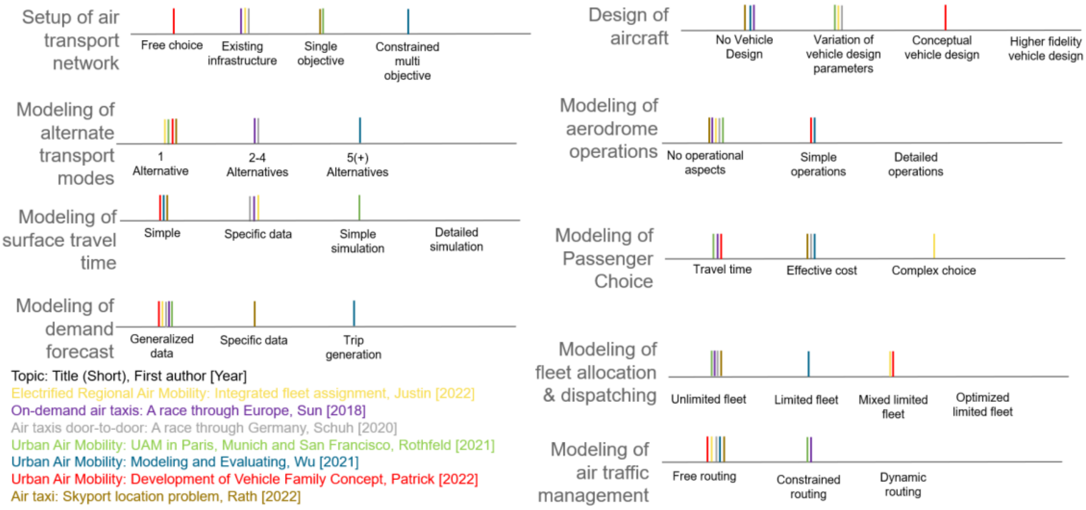


Figure 14: Spider plot axis including most relevant literature (own work)

With the axis of the spider plot defined and literature added to these axes, they can now be graphically represented, as done in Figure 15. It can be seen that much of the literature is on a similar level in certain aspects (design of aircraft, modeling of passenger choice, modeling of air traffic management), with only a few exceptions pushing the boundaries of a field of knowledge. Notably, these pushes of the boundaries only focus on 1 topic, meaning that there are no papers strong in delivering an overall framework that is capable of pushing a combination of boundaries.

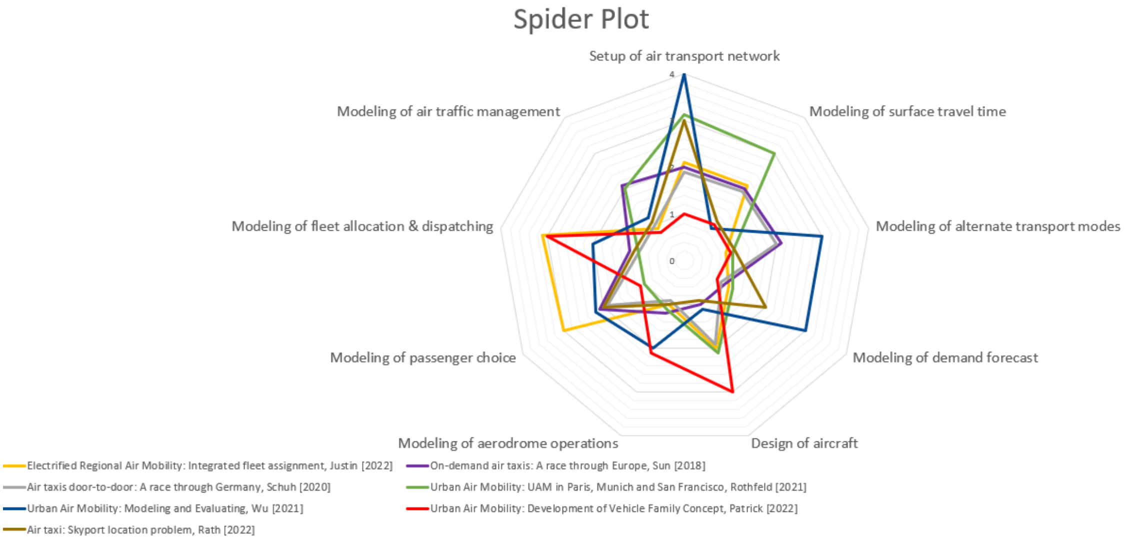


Figure 15: Spider plot existing literature (own work)

However, as identified in Flightpath 2050, one of the goals for aviation should be: “coherent ground infrastructure is developed including: airports, vertiports and heliports with the relevant servicing and connecting facilities, also to other modes” [1]. Only by integrating the ground infrastructure and operations into vehicle design will we be able to achieve the Flightpath 2050 goals. To this end, it therefore makes sense for future research to focus on integrating the different aspects of operations, air vehicle design and surface transport into one framework.

5 Research Proposal

With the gap in research identified, it is now time to establish the key research question that is to be answered to fill this gap. This is specified as the following main question:

How effectively can on-demand Advanced Air Mobility improve door-to-door travel times in a simulation-based framework, through vertiport placement, dispatch strategies and vehicle design for an exemplary urban environment?

As the key focus of this work should be developing an integrated framework, it will be tested through the 3 aspects were variations will occur, being vertiport placement, dispatch strategies and vehicle design. This main question will now be broken down in some sub-questions that are easier to answer:

1. What is the impact of the location of vertiports on reducing door-to-door travel times?
    a. At what locations should vertiports be considered?
    b. How many vertiports are considered?
    c. Which internal processes within the vertiports are considered?
2. What is the impact of dispatch strategy on reducing door-to-door travel times?
    a. What dispatch strategies are considered?
3. What is the impact of conceptual aircraft design on reducing door-to-door travel times?
    a. What existing tools can be used for this?
    b. What aircraft architectures should be considered?
    c. What technology levels should be considered?
4. How can door to door travel times of passengers be simulated?
    a. What tools are already existing that can simulate surface transport?
        i. How can existing tools be linked to Advanced Air Mobility?
    b. How are individual passengers and their choices modelled?
        i. What choice parameters are considered for passenger choice?
5. What exemplary urban environment is considered?
6. What passenger demand is considered?
    a. How are passengers modelled?
    b. What choice parameters are considered for passenger choice?

6 Research Methodology

In order to be able to answer the research questions posed in Chapter 5, the scope of the problem has to be clearly specified. This will be done in Section 6.1, which will go over all arms of the considered spider plot in Chapter 4. Then, a framework will be described that combines all considered aspects in Section 6.2. Finally, the proposed literature will be represented within the existing spider plot in Section 6.3.

6.1 Scope of research project

In order to limit the scope of the research project, the research will be determined along the arms of the spider plot of Chapter 4.

6.1.1 Setup of air transport network

For the modelling of the air transport network, use will be made of the SoSID toolkit, developed by DLR [59]. Its internal methodology has recently been explained by Naeem et al. [60].

This toolkit currently has 2 applications on which research has been performed. These are the topics of wildfire fighting [61] [62] and of Urban Air Mobility [21] [52] [58] [63]. Research in UAM has also already been expanded to include aircraft design in the work of P. Ratei [64]. Because the research to be completed will be done at DLR with many of the original developers still present, this is an excellent choice of a tool for this modelling aspect.

To determine the vertiport locations, a constrained single objective approach will be used. Vertiport locations will be selected based on some existing infrastructure like helipads and airports, but major train stations and other key locations will be included. Then, a selection will be made based on the most utilized vertiports in a baseline scenario.

6.1.2 Modeling of surface travel time

In order to be able to model the surface mobility considered, use will be made of SUMO. SUMO, short for Simulation of Urban MObility, is developed by DLR, and hosted by the Eclipse Foundation [65]. It is a microscopic simulator, meaning that the interactions between individual vehicles in a transport network can be modelled. As such, it allows for high resolution modelling of large-scale systems, while at the same time keeping fast runtimes.

SUMO has already been used for the modelling of various transport systems, like for autonomous vehicles [66] [67], traffic light control systems [68] [69], and for the setup of some large scale networks [70] [71], to name just a few applications.

As it allows the modelling of large-scale networks, combined with the modelling of individual vehicles, it is a good match to extend the agent-based air transport network described in Section 6.1.1. To reduce the complexity, congestion will not be considered, which places the research in the category of simple simulation.

6.1.3 Modeling of alternate transport modes

As SUMO is a microscopic model that uses OpenStreetMap for its data, it is easy to integrate all available sources of transport within an urban environment. This means that 5(+) alternatives will be modeled, including buses, trains, metros, personal cars, walking, and any others that might be available in the selected urban environment.

6.1.4 Modeling of demand forecast

Demand generation will be done based on specific data for the chosen environment. For this it is important to consider also which passenger choice parameters (see also Subsection 6.1.7) are considered, but at least the number of trips within the urban environment will be considered to generate origin-demand combinations, as well as passenger specific information like their perceived value of time, which will influence the passenger choice model.

6.1.5 Design of aircraft

For the design of Advanced Air Mobility vehicles, use will be made of existing tools for this purpose. The design level considered will be that of conceptual vehicle design.

One of the design tools available for this is openAD, a DLR-internal multidisciplinary aircraft design tool [72]. This tool has the objective of establishing consistent aircraft design in multiple disciplines, based on high level requirements. This allows overall aircraft design, linked to different modules for analysis within other disciplines. This tool has been applied in the analysis of mid-range aircraft using hydrogen and synthetic kerosene [73], to do the mass breakdown of a long-range aircraft [74], a family of business jets [75], an optimized airliner for aeroelastic loading [76], an electrified small regional turboprop aircraft [77], preliminary blended wing body designs [78], and many more.

A more simplified DLR-based tool that can be used for the design of VTOL aircraft is VTOL-AD. Developed by P. Ratei [64], it is based on the work by Kadhiresan & Duffy [26], which provides a basis for conceptual design of different VTOL architectures. The model has been validated with respect to some baseline designs, and as such serves as an excellent basis for the rapid development of new VTOL designs. It is fairly limited in its resolution, but it will provide feasible conceptual designs for different parameter variations.

There are other design tools that could be considered, like the Open Source tool SUAVE [79], CEASIOMpy [80], and the more historical FLOPS [81], but as VTOL-AD is already frequently used for AAM design at DLR, this software will be used. As VTOL-AD imposes some constraints on the vehicle architectures, the vehicle design space will therefore also be limited to eVTOL vehicles with multirotor and tiltrotor architectures.

6.1.6 Modeling of aerodrome operations

For the modeling of aerodrome operations, simple operations will be considered. Capacity constraints will not be enforced, but operational aspects will be considered through boarding and deboarding times. Charging time will also be considered.

6.1.7 Modeling of passenger choice

Passenger choice modeling will be done through an effective cost model. Door-to-door travel times will be determined through SUMO, where the expected travel time can easily be obtained. Additionally, for all the modes that can be used the associated travel cost is obtained from literature.

Lastly, value of time will be determined for every passenger. With this in mind, a simple objective function for the passengers can be set up:

$$\text{Obj} = \mathrm{Min}\left(\text{Time} * \text{VOT} + \sum \text{Cost per mode } km * \text{Used mode distance}\right)$$

6.1.8 Modeling of fleet allocation & dispatching

The modeling of fleet allocation & dispatching will be one of the more in-depth topics for this thesis, and will be done through optimized limited fleet dispatching.

To enable this, use will be made of the existing dispatch model enabled in the SoSID toolkit. The current dispatch model is based on an agent-based bidding model, where every AAM agent provides a bid for the created demand. The winning bid is selected based on a multi-objective selection, including travel time and energy cost.

This existent bidding model has the limitation that once new demand is created, the bids will not be recomputed. This means that for a large time horizon, it is unlikely that the optimal aircraft assignment is achieved.

This limitation will have to be addressed, and the bids will have to be recomputed for a larger time horizon in a more general way. Once this is done, predictive dispatching can be performed and its impact assessed.

6.1.9 Modeling of air traffic management

The modeling of air traffic management is outside of the scope of this work, and will be done through free routing.

6.2 Framework

As all the previously described components have to collaborate, a framework has to be established that highlights how the different disciplines collaborate. This framework is shown in Figure 16, where it can be seen that the Vehicle Design module feeds into the Air Transport module. Air Transport and Surface Transport will run in a synchronized multimodal simulation, where the dispatching is done through the Fleet Operational Tactics block. The results of this overall simulation will be explored through the system-of-systems exploration.

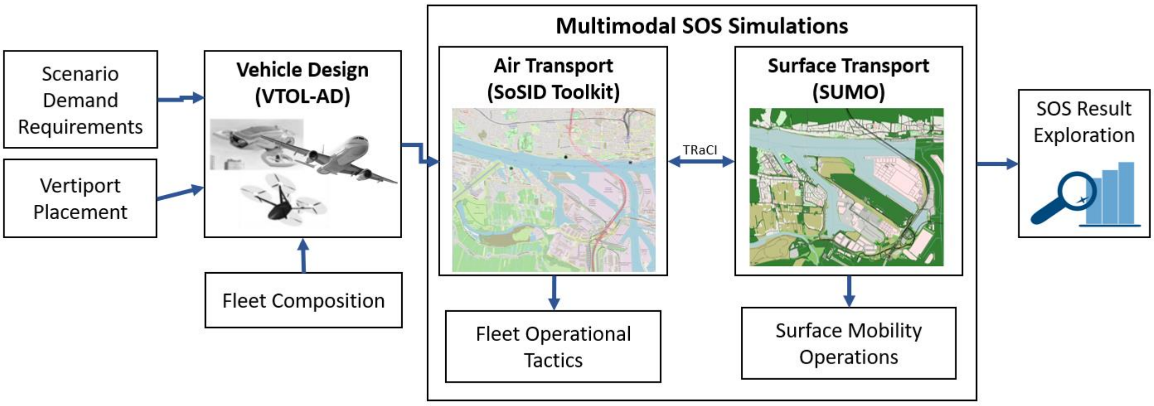


Figure 16: System of Systems Framework for Advanced Air Mobility Vehicle Design (own work)

6.3 Spider Plot Future Work

To conclude the analysis of where the future research will position itself, it can be placed on the previously made spider plot. This can be seen in Figure 17, where it is clear that the proposed future work provides a significant knowledge gain through combining key disciplines. Additionally, it pushes the boundary in the modeling of fleet allocation & dispatching, where the field of current knowledge is expanded.

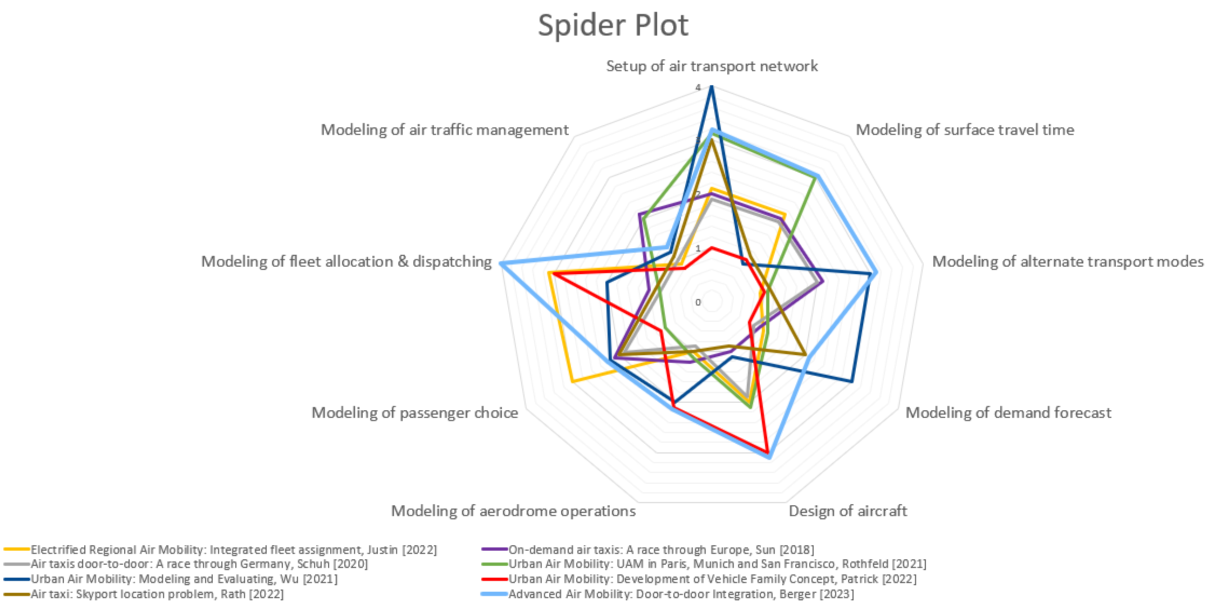


Figure 17: Spider Plot with future research (own work)

7 Conclusions & Recommendations

As the aviation sector continues to evolve, it is important that large scale goals will be set that can be aimed for. Some of these goals have been described in Flightpath 2050, which serves as a guideline for this sector until 2050. Within these goals a key focus is on the improvement of the mobility provided by the aviation sector to its end users. Some approaches to aid in this call have already been proposed, like the introduction of advanced air mobility vehicles. In order to guide the development of advanced air mobility vehicles for door-to-door mobility, future research is key.

This report has started out with an analysis of some key papers within the field of door-to-door mobility in Chapter 2. Additionally, research on the field of advanced air mobility is summarized in Chapter 3. It is found that there is significant research spanning both sectors, but the research is not well integrated within all aspects. This is highlighted in Chapter 4, which proposes that the integration of operations, air vehicle design and surface transport should be tackled in a combined manner. To answer this call, a research question is identified in Chapter 5, with further sub-questions allowing the problem to be unpacked. In an attempt to answer the proposed research question, a scope is defined in Chapter 6, as well as a summary of tools that could be utilized to answer the research question.

Ultimately, this document serves as an analysis of existing literature. An attempt has been made to summarize the most important literature in the field, but as this field is ever growing and vast, it should be updated at future moments to incorporate any further research past and present. Additionally, the proposed research question and methodology will likely serve as a good starting point, but should also be revisited to optimally answer to the gap in research presented.

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III

Supporting work

1

Appendix - Scenario Definition

This chapter describes in some more detail some of the methodology for scenario definition. First, the vertiport placement is described in section 1.1, followed by the surface network generation in section 1.2, public transport operations in section 1.3, and finally passenger demand defintion is done in section 1.4.

1.1. Vertiport Placement

One of the most important aspects in AAM adoption that has been identified is the accessibility of vertiports, with access and egress time being a key determinant in the adoption of the service [**?**]. Therefore, various authors consider easily accessible infrastructure as a logical location for vertiports, like already existing helipads [**?**], possibly combined with existing airport [**?**]. Combining the importance of accessibility and existing infrastructure, vertiports are placed at considered points of interest. Of this, there are of 3 types: Popular tourist spots (>1000 visitors/day), major public transport nodes (train & metro stations), and international transport hubs (airports & major train stations).

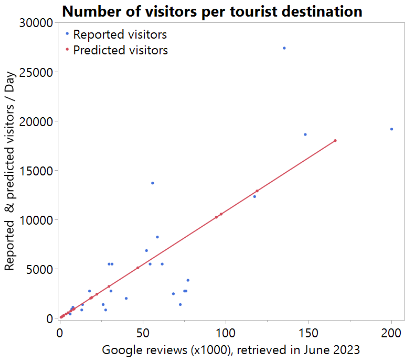


Figure 1.1: Number of tourists predicted based on Google Maps reviews, compared to known datapoints

For this, first the number of relevant tourist spots have to be determined. An internet search was used to find the highest rated spots, for which then different online sources were used to get the number of visitors per year. The number of visitors is assumed to be distributed uniformly, and a resulting number of visitors per day is obtained. For the locations where this information was unavailable, use was made of a linear regression between Google Maps reviews and number of reported or predicted visitors. The datapoints for the Colosseum and Trevi Fountains were excluded, as these seem to have a higher proportional number of ratings, for these the reported number of visitors were used. Then, the predictions of number of tourists, as well as the datapoints where they are known can be seen in Figure 1.1, which shows that the prediction works adequately as a first estimate.

1.2. Surface Network

The OSMWebWizard tool, one of the tools provided in the SUMO package [**?**], is used to obtain a surface network for intermodal operations. This tool retrieves road networks from OpenStreetMap and performs network processing on this to accurately represent junctions, roads, railroads, and many more geographical features. This interpretation is then translated to a network file that SUMO can use.

Because the network as retrieved from the OSMWebWizard is rather large, it is desirable to reduce the network size while maintaining the relevant infrastructure. A custom processing algorithm is developed to perform this task. The algorithm is designed to keep infrastructure that meets the following criteria:

- Edges or junctions (partially) within proximity of 500 m to a point of interest
- Edges or junctions used by public transport modes, or used as access to public transport modes
- Edges of a major road type that is to be kept

As it is important that the junctions that are kept are represented accurately, for these, also the adjacent edges are kept.

Using this algorithm with an exemplary 20 vertiports in Hamburg, all public transport modes considered, and highways as roads to keep, the network can be significantly reduced. The resulting network (shown in Figure 1.2) consists of 44000 edges, down from an original over 250000 edges.

Figure 1.2: Processed network of Hamburg

Because OSMWebWizard does not always maintain pedestrian walkways, some resulting accessibility issues were observed. To mitigate this, sidewalks have been added to all roads with a travel speed below 20 [m/s].

1.3. Public Transport Operations

The OSMWebWizard tool was also used to obtain public transport operations schedules. Combined with retrieving all geographic data, this tool retrieves information on which public transport modes operate in the area of interest. These operating vehicles are then assigned to a schedule with a fixed period operation. Several adjustments to the public transport operations are made with respect to the imported transport modes from OSM:

- All ICE trains and interregional trains are modelled using a 2-hour period.
- A day train from Munich to Rome is added, using the route of the night train NJ 295 [**?**].

1.4. Passenger Demand

The passenger demand in this use case is assumed to come from 3 sources, here briefly described:

- **Commuters -** Commuters are assumed to travel from an area of high residential population to one with high workplace availability at mean time of 08:00 and standard deviation of 2 hours, and make the inverse trip at mean time 17:00.
- **Tourists -** Tourists are assumed to travel from an area of high population to a tourist destination at mean time of 09:00, throughout the day between tourist locations, and return to an area of high population at 17:00.
- **Intercity -** Intercity travellers are assumed to depart between 9:00 and 17:00 from a location with high population to density to a destination in their location city with high population density.

For these three demand sources, to generate origin-destination (OD) pairs, inflow and outflows are created at any given point of interest. For example, for commuters within Hamburg, inflows are created in the morning with respect to the number of workplaces at the point of interest, and outflows are created at the same time with respect to the number of houses in an area.

Then using this in- and outflow data, the trips are generated as shown in Figure 1.3. More detailed information on this model is described by Prakasha et al. [**?**], but what should be noted here is that the OD pairing is random, and only respecting the in- and outflows. It is therefore possible that certain distance trips are over- or underrepresented.

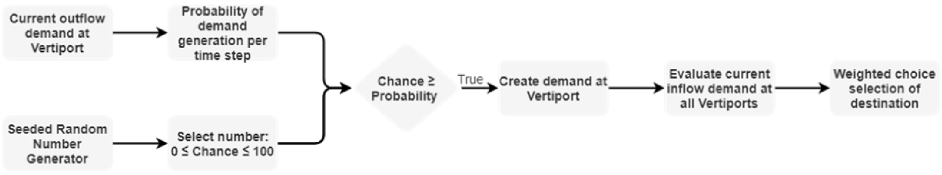


Figure 1.3: Demand generation logic [**?**]

These generated OD pairs can then be visualized as individual trips, but also as the inflow and outflows of the vertiports. An example of this can be seen in Figure 1.4, where this is demonstrated for 3 of the vertiports in Hamburg.

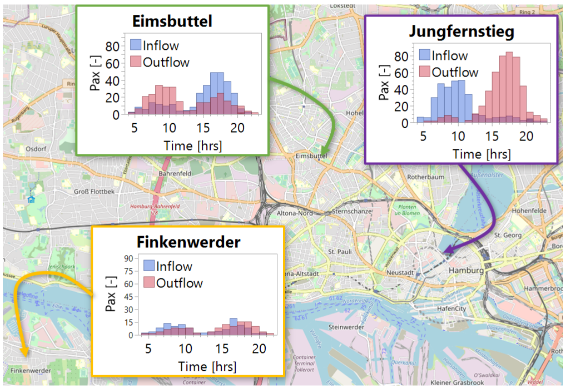


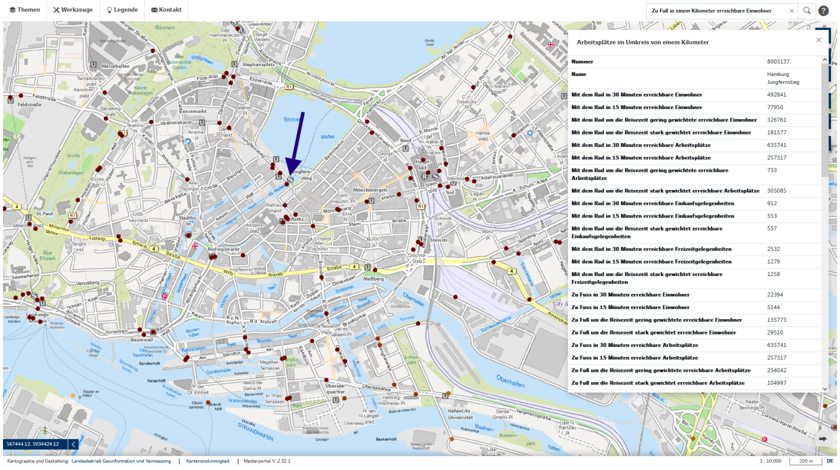
Figure 1.4: Exemplary in and outflows at 3 vertiports in Hamburg

Identification of population and workplace densities

To determine the number of houses and workplaces available in an area, use will be made of the Global Human Settlement (GHS) dataset, published by the European Commission [**?**]. This is a global dataset which identifies building types at a 10 m resolution, and indexes in different building heights and whether the building is residential or non-residential. To be able to translate this to the number of residents and workplaces, a calibration is performed.

The first step of this calibration is obtaining some real-world data on number of workplaces and residents. One of the regions of interest, Hamburg, provides an online portal with this information. As can be seen in

Figure 1.5, the number of residents (Einwohner) and working places (Arbeitsplätze) surrounding a location can be obtained. The considered category for collecting data is that of 'By foot reachable residents/working places in 1 kilometer' (Zu Fuß in einem Kilometer erreichbare Einwohner/Arbeitsplätze), which is not shown in Figure 1.5.



Arbeitsplätze im Umkreis von einem Kilometer

Nummer	8003137
Name	Hamburg Jungfernstieg
Mit dem Rad in 30 Minuten erreichbare Einwohner	492841
Mit dem Rad in 15 Minuten erreichbare Einwohner	77950
Mit dem Rad um die Reisezeit gering gewichtete erreichbare Einwohner	326761
Mit dem Rad um die Reisezeit stark gewichtet erreichbare Einwohner	181577
Mit dem Rad in 30 Minuten erreichbare Arbeitsplätze	635741
Mit dem Rad in 15 Minuten erreichbare Arbeitsplätze	257317
Mit dem Rad um die Reisezeit gering gewichtete erreichbare Arbeitsplätze	733
Mit dem Rad um die Reisezeit stark gewichtet erreichbare Arbeitsplätze	305085
Mit dem Rad in 30 Minuten erreichbare Einkaufsgelegenheiten	912
Mit dem Rad in 15 Minuten erreichbare Einkaufsgelegenheiten	553
Mit dem Rad um die Reisezeit stark gewichtet erreichbare Einkaufsgelegenheiten	557
Mit dem Rad in 30 Minuten erreichbare Freizeitgelegenheiten	2532
Mit dem Rad in 15 Minuten erreichbare Freizeitgelegenheiten	1279
Mit dem Rad um die Reisezeit stark gewichtet erreichbare Freizeitgelegenheiten	1258
Zu Fuss in 30 Minuten erreichbare Einwohner	22394
Zu Fuss in 15 Minuten erreichbare Einwohner	5144
Zu Fuß um die Reisezeit gering gewichtete erreichbare Einwohner	135773
Zu Fuß um die Reisezeit stark gewichtet erreichbare Einwohner	29510
Zu Fuss in 30 Minuten erreichbare Arbeitsplätze	635741
Zu Fuss in 15 Minuten erreichbare Arbeitsplätze	257317
Zu Fuß um die Reisezeit gering gewichtete erreichbare Arbeitsplätze	254042
Zu Fuß um die Reisezeit stark gewichtet erreichbare Arbeitsplätze	104997

Figure 1.5: Screenshot from Geoportal Hamburg centred on Jungfernstieg [**?**]

This data has been sampled at 50 locations, at which also the settlement data is sampled to get the number of residential and non-residential building types in a range of 1 km. Then, a prediction for the number of residents and workplaces is made from the GHS data as follows:

$$\text{Pop}_{\text{pred.}} = a_1 * Res_1 + a_2 * Res_2 + a_3 * Res_3 + a_4 * Res_4 \tag{1.1}$$

$$\text{Work}_{\text{pred.}} = b_1 * Res_1 + b_2 * Res_2 + b_3 * Res_3 + b_4 * Res_4 + b_5 * NRes_1 + b_6 * NRes_2 + b_7 * NRes_3 + b_8 * NRes_4 \tag{1.2}$$

Where Res_{1-4} and $NRes_{1-4}$ are the counts of in GHS data identified buildings of residential and non-residential types, and a_{1-4} and b_{1-8} are tuning parameters. These parameters are then tuned on the 50 data points available to reduce the minimum squared error of the prediction. Then, the behaviour of these tweaked parameters is tested at 10 independent data points, of which the results can be seen in Figure 1.6 and 1.7. The prediction of population is fairly accurate, with a slope of 1.2 between predicted and actual, but workplace estimations are less accurate, with a slope of 0.5. The implication of this is that the predicted residential areas and their densities should be representative, but the densities of working areas are less so, meaning that the resulting OD pairs might be focused on locations that differ from real life.

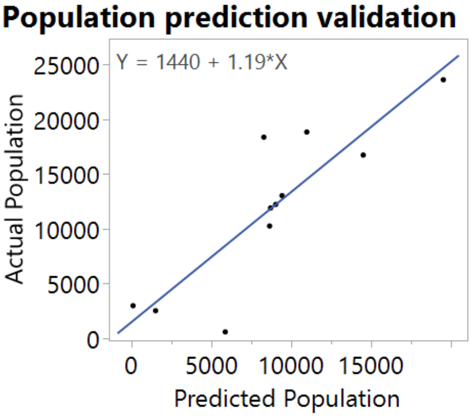


Figure 1.6: Population prediction in Hamburg - Predicted versus Actual

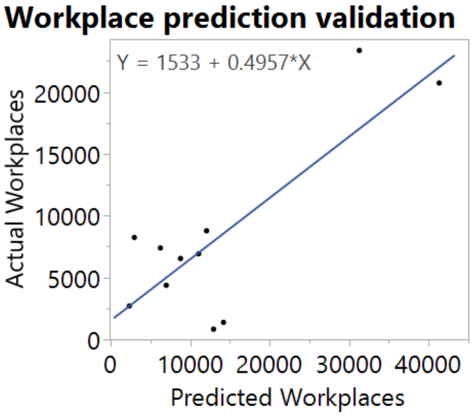


Figure 1.7: Workplaces prediction in Hamburg - Predicted versus Actual

2

Appendix - VTOL-AD Validation

2.1. Full input parameters VTOL-AD

Table 2.1 provides the full set of input parameters to VTOL-AD for the generation of the aircraft designs as used in the report. It contains information on a Tiltrotor vehicle as well, which has been analysed too, but is not reported on. This therefore serves merely as our suggestion for a more or less realistic planform based on the validation data from [**?**]. During the design sweeps performed, the following parameters were varied in addition:

- Range - vehicle revenue range was changed from 40 to 20-80 [km]
- Cruise speed - vehicle cruise speed was changed from 66 to 20-40 [m/s]
- Passenger Capacity - 2 things were changed. Payload mass was changed by 200 kg per 2 passengers. Additionally, fuselage cabin length was increased by 1.1 [m] for an additional 2 pax, and reduced by the same for only 2 pax. This is based on previous work by the developers of VTOL-AD [**?**].

Table 2.1: Complete VTOL-AD input file for baseline runs

Parameter	Unit	Tiltrotor	Multirotor
Run sizing	dimensionless	TRUE	TRUE
Run sosid	dimensionless	FALSE	FALSE
Study	dimensionless	EASN refined	EASN
Conobs	dimensionless	Study 0	Study 0
Config	dimensionless	tiltrotor	multirotor
Is winged	dimensionless	TRUE	FALSE
Is autonomous	dimensionless	FALSE	FALSE
Footprint	m	15	15
Wing max aspect ratio	dimensionless	15	15
Wing aspect ratio	dimensionless	7	0
Wing area	m**2	12.8	0
Wing span	m	6	0
Wing chord	m	0.7	0
Wing loading	N/m**2	500	0
Stall speed	m/s	33	10
Max lift coefficient	dimensionless	2	2
Flat plate drag area	m**2	0.55	1.79
Ultimate load factor	dimensionless	5.7	5.7
Fuselage cockpit length	m	1	1.7
Fuselage cabin length	m	0.9	1.7
Fuselage empennage length	m	3.1	1.6
Fuselage length	m	5	5
Fuselage max diameter	m	1.49	1.49

Parameter	Unit	Tiltrotor	Multirotor
Fuselage empennage radius	m	0.25	0
Fuselage wetted area	m**2	22	10
Horizontal stabilizer aspect ratio	dimensionless	2	2
Horizontal stabilizer area	m**2	2	0
Vertical stabilizer aspect ratio	dimensionless	1.3	1.3
Vertical stabilizer area	m**2	2	0
Number of wheels	dimensionless	2	2
Persons on board	dimensionless	4	4
Wing technology factor	dimensionless	1.9	1.9
Empennage technology factor	dimensionless	1.9	1.9
Fuselage technology factor	dimensionless	0.3	0.3
Landing gear technology factor	dimensionless	0.2	0.2
Maximum takeoff mass	kg	5000	5000
Payload mass	kg	400	400
Max disk loading	N/m**2	200	200
N rotors	dimensionless	4	4
N rotors wing	dimensionless	2	0
Rotor is speed controlled	dimensionless	FALSE	FALSE
Rotor n blades	dimensionless	3	3
Rotor solidity	dimensionless	0.2	0.08
Rotor relative thickness	dimensionless	0.12	0.12
Rotor induced power factor	dimensionless	1.26	1.23
Rotor parasite drag	dimensionless	0.01	0.01
Rotor max tip Mach number	dimensionless	0.9	0.9
Rotor max cl mean	dimensionless	0.9	0.9
Rotor max diameter	m	2	2
Battery specific energy	Wh/kg	275	275
Battery specific power	kW/kg	2	2
Fuel cell specific power	kW/kg	0	0
Powertrain architecture	dimensionless	FullElectric1	FullElectric1
Powertrain efficiency	dimensionless	0.912375	0.912375
Powertrain reliability	dimensionless	0	0
Powertrain supplied power ratio	dimensionless	1	1
Propeller efficiency	dimensionless	0.85	0.85
Best range speed	m/s	999	999
Best endurance speed	m/s	999	999
Charging c rate	1/hr	2	2
Performance vertical climb altitude	m	1.5	1.5
Performance cruise altitude	m	300	300
Performance aerodrome density	kg/m**3	1.225	1.225
Performance cruise density	kg/m**3	1.19011	1.19011
Performance cruise speed	m/s	66	40
Cruise speed	m/s	66	40
Revenue range	km	40	40
N legs	dimensionless	1	1

2.1.1. Subdisciplines

Adding to the validation studies in the paper, we can compare VTOL-AD and the reference paper by evaluating subdisciplines within both tools, which can highlight similarities and differences in results. As both tools are conceptual design, the main focus here is to assess whether the results are consistent.

For the tiltrotor architecture, this can be done by looking at the impact of wing aspect ratio and disk loading on aircraft mass. As can be seen by comparing Figure 2.1 to Figure 2.2, both tools find a very comparable lowest aircraft mass at an aspect ratio of 5-7, and the lowest wing loading. Also, the aircraft masses are fairly consistent throughout the design space.

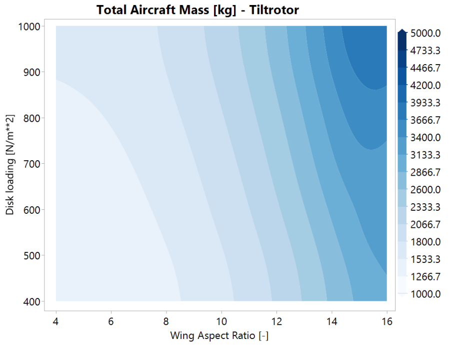


Figure 2.1: Relation between wing aspect ratio, disk loading and aircraft mass from VTOL-AD for 400 kg payload, 100 km range mission

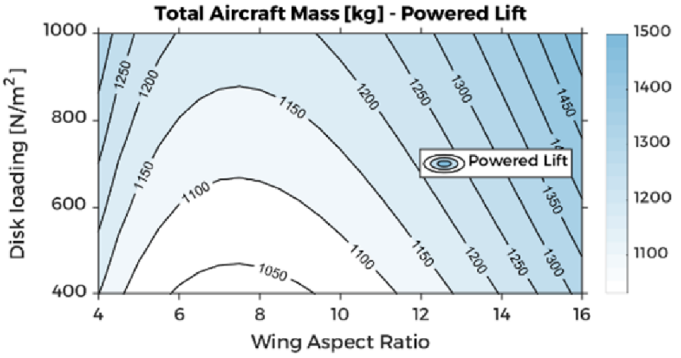


Figure 2.2: Relation between wing aspect ratio, disk loading and aircraft mass from reference [?] for 400 kg payload, 100 km range mission

For the multirotor architecture, a similar comparison is done in Figure 2.3 and Figure 2.4. Here, it must be noted that the mission range for VTOL-AD is reduced to 60 km, as opposed to the 100 km of the reference mission. This is done because VTOL-AD seems to converge to high aircraft masses at high disk loading for the multirotor architecture. This can also be seen in the figures, as the aircraft masses are comparable for disk loadings of 400-600 [N/m^2], but rather different at the disk loading of 1000 [N/m^2], where the plot exceeds the maximum mass of 7000 kg. This inconsistency is deemed acceptable, as several authors suggest lower disk loadings of 100-300 [N/m^2] to mitigate aircraft noise [?] [?], and the reference paper VTOL-AD is based on finds an optimal solution for multirotor architectures at 163 [N/m^2] [?], indicating that the 100-300 [N/m^2] range is a more realistic design space for multirotor architectures.

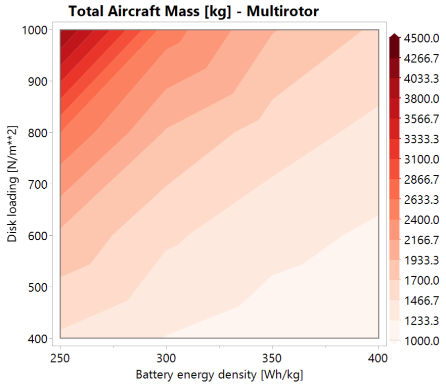


Figure 2.3: Relation between battery energy density, disk loading and aircraft mass from VTOL-AD for 400 kg payload, 60 km range mission

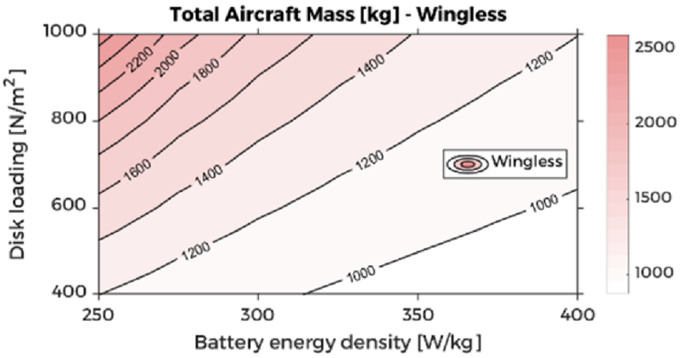


Figure 2.4: Relation between battery energy density, disk loading and aircraft mass from reference [?] for 400 kg payload, 100 km range mission

2.1.2. Comparison to prototypes

Finally, a comparison can be done between VTOL-AD, the reference solver and existing prototypes. For the tiltrotor architecture this is done in Figure 2.5, where it can be seen that both tools find comparable solutions, in line with the existing prototypes for a range up to 250 km. A similar comparison is done in Figure 2.6, where it can be seen that VTOL-AD gives more conservative weight estimates over the entire range, but is still consistent with data from the prototypes.

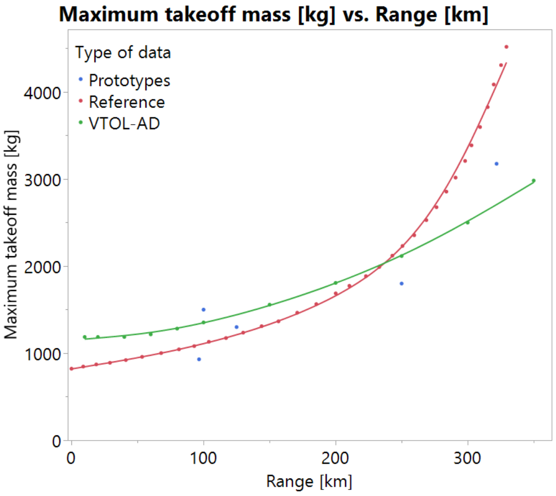


Figure 2.5: Comparison of VTOL-AD, reference solver and existing prototypes for mission with 450 kg payload and 275 Wh/kg battery energy density. Reference data from Ugwueze et al. [**?**]

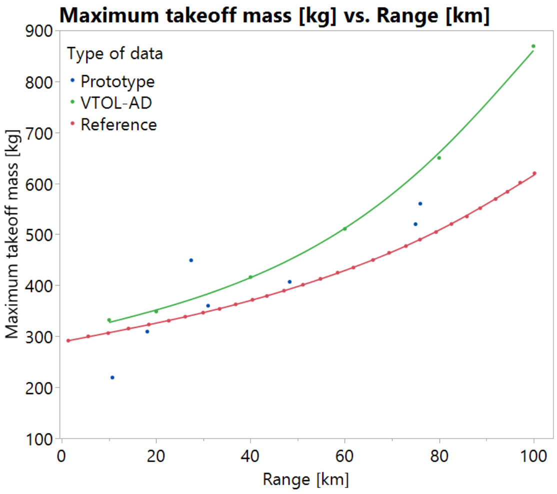


Figure 2.6: Comparison of VTOL-AD, reference solver and existing prototypes for mission with 100 kg payload and 275 Wh/kg battery energy density. Reference data from Ugwueze et al. [**?**]

3

Appendix - Multimodal Simulation

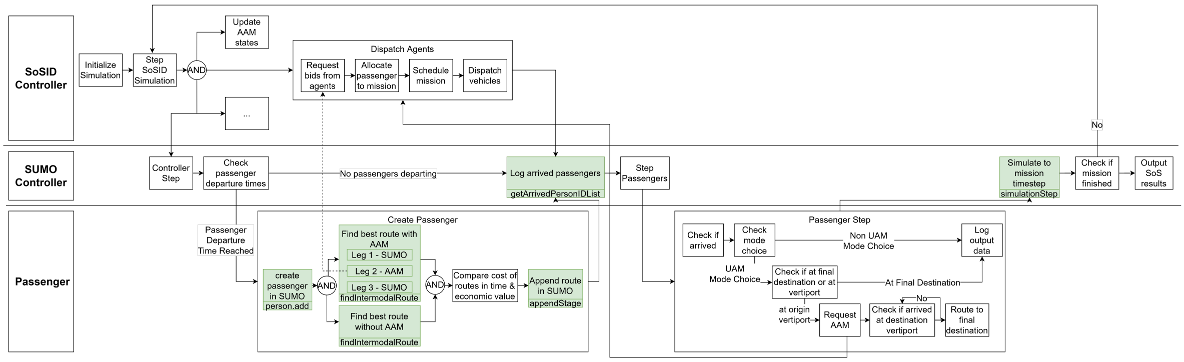


Figure 3.1: Internal logic of the multimodal framework

3.1. SoSID Controller

The SoSID Controller is at the heart of the agent-based model. It is the core of the simulation, and it's what everything else is building upon. It serves several purposes, which will now be broken down in some detail.

3.1.1. Initialize Simulation

At the simulation initiation, the SoSID controller instantiates the simulation environment, and creates the 3 different types of agents: One DispatchAgent is created, which is the brains of the internal model, as it handles and dispatches flights. Additionally, VertiportManagers are created which serve as the vertiports in this simulation, and track the number of agents present at each vertiport. Lastly, TransportAgents are created, which in this simulation are the advanced air mobility vehicles.

3.1.2. DispatchAgents

If at a certain time step a request for use of AAM comes in at a vertiport, the DispatchAgent will try and fulfil this request. In order to do this, all TransportAgents are requested to make a bid in order to try to find the best vehicle to handle this demand request. All bids are done according to Equation 3.1, where the best bid is selected.

$$bid = w_1 * \frac{\text{Time delay departure}}{\text{Maximum scheduling horizon}} + w_2 * \frac{\text{Mission energy required}}{\text{Vehicle energy}} + w_3 * \text{Estimated passenger value} \tag{3.1}$$

Where w_1, w_2, w_3 are -10, -1 and 100 respectively, and the 'Estimated passenger value' is a value function based on the estimated number of passengers that would be taking this flight as well. To calculate the required time delay and mission energy required, the vehicles consider the mission they are already assigned, whether they would have to fly a deadhead mission to start the mission, and whether they can do so with their battery state.

Once the most suitable bid is found, the demand would typically be allocated according to the logic described in Figure 3.2, after which the mission will be handled by the transport agent. However, in the multimodal simulation the passenger also has a choice. The request will therefore only be allocated for the final mission requests, but not for mock requests, which we will see later on.

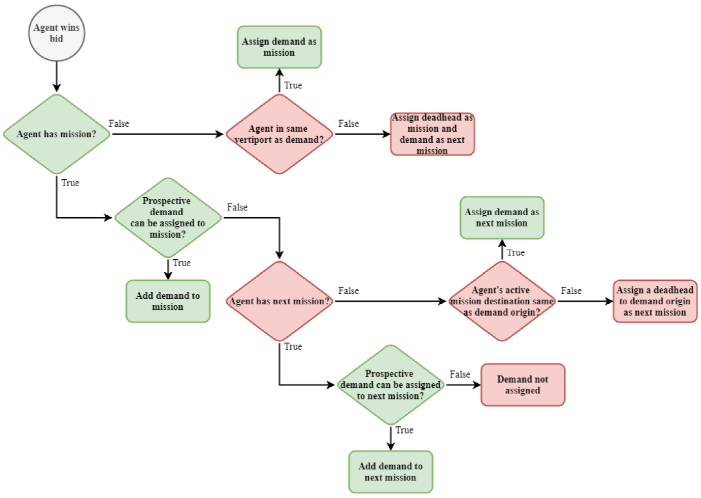


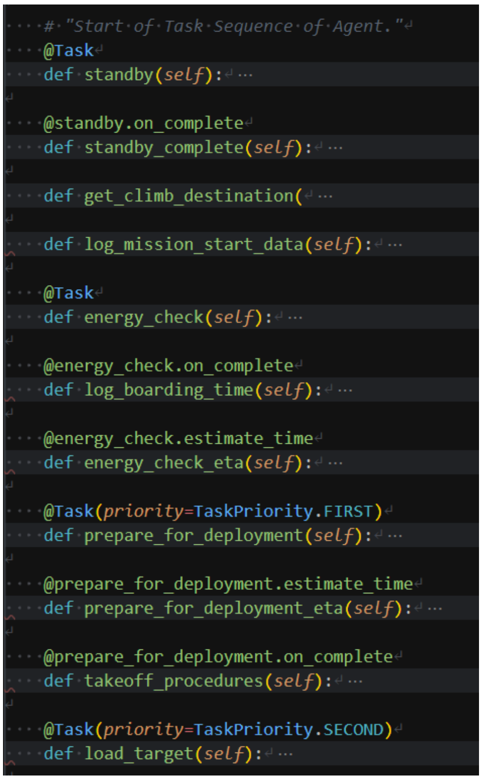
Figure 3.2: Logic for demand allocation agent [**?**]

3.1.3. VertiportManager

The VertiportManager, as the name suggests, manages a vertiport. It has a graphical representation if the GUI is enabled, and its main function is tracking the AAM agents present at its location. In doing so, it registers arrivals and departures, and it gives takeoff clearances to agents that request this. In the current implementation the takeoff clearances are unrestricted, meaning that there is no minimum time between departures. Additionally, the vertiport is not considered to be capacity constrained, which is also a capability that is not utilized in this scenario.

3.1.4. TransportAgent

The TransportAgents in this simulation represent the Advanced Air Mobility vehicles, which transport passengers between different locations. In the SoSID Toolkit, they operate based on a task-based logic, as seen in Figure 3.3. Here, the entire sequence of tasks from standby to departure is shown, but this continues through the different phases of flight, ending with the landing, deboarding and potential re-energization.



```python
    # "Start of Task Sequence of Agent."
    @Task
    def standby(self): …

    @standby.on_complete
    def standby_complete(self): …

    def get_climb_destination( …

    def log_mission_start_data(self): …

    @Task
    def energy_check(self): …

    @energy_check.on_complete
    def log_boarding_time(self): …

    @energy_check.estimate_time
    def energy_check_eta(self): …

    @Task(priority=TaskPriority.FIRST)
    def prepare_for_deployment(self): …

    @prepare_for_deployment.estimate_time
    def prepare_for_deployment_eta(self): …

    @prepare_for_deployment.on_complete
    def takeoff_procedures(self): …

    @Task(priority=TaskPriority.SECOND)
    def load_target(self): …
```

Figure 3.3: Task sequence in the SoSID Toolkit

Additionally, transport agents hold their mission queue with sequential missions to perform. As already mentioned, agents also compute bids for new missions, and will have their mission queue populated by the DispatchAgent with won bids.

Some additional assumptions on the vehicles in the AAM model should be documented and clarified:

- Autonomous revenue flights are not considered. All revenue flights will in this simulation use a pilot.
- Autonomous deadhead flights are enabled. It is expected that in the near future, partially autonomous flight will be possible, which is incorporated here in the form of the deadhead flights.
- The maximum scheduling horizon, both for AAM vehicles and passengers, is one hour. This means that agents will not be planning further than one hour ahead, resulting in an on-demand AAM use case.

3.2. SUMO Controller

The next cornerstone of the multimodal framework is the SUMO Controller. As suggested by the name, the SUMO Controller maintains the SUMO simulation, which models all ground-based transport modes. It keeps the SUMO simulation in sync through using the Python package libsumo. Aside from this, the SUMO Controller has 2 functions: Instantiating SUMO Passengers, and tracking where they are and when they arrive at vertiports.

3.3. SUMO Passenger

The next key element of the multimodal framework, and the biggest addition by this work to the SoSID Toolkit is that of (SUMO) Passengers. Previously passengers only existed at vertiports, and only chose their best routes based on travel time compared to transport by car (based on shortest distance). Now, passengers will actually depart from an origin spread out over the catchment area of a vertiport, and will see multiple alternate modes of transport based on a realistic simulated schedule. In addition, the mode choice is extended, as already described in the research paper. To make all of this possible, first, a custom route selection method will be explained, followed by the 2 passenger types that have been created.

3.3.1. Passenger Route Selection

One of the additions to the current model is the passenger route selection logic. This will now be explained in some more detail than can be captured in Figure 3.1, starting with intracity passengers. An intracity passenger has 2 route options:

1. First, the SUMO route is requested from origin to destination using the findIntermodalRoute operation embedded in libsumo. This function requests SUMO at the desired departure time what the optimal route is from origin to destination. SUMO in this case considers the fastest route the most optimal. For this route selection, public transport as well as walking are enabled as transport modes.
2. For the public transport route, the total cost is assessed. Here, there is the time component, which simply is the total time between departure and arrival. Additionally, the cost of using public transport is obtained by taking the summed distance of all of the public transport legs, and multiplying by the cost per km set for this.
3. Then, for the AAM legs: Depending on the input parameter on number N of passenger leg options, an N number of origins are considered, starting with the vertiport closest to the departure location and building outwards. At the same time, an N number of destinations are considered. For all of these, the following procedure is applied:
    (a) Just like in step 1 and 2, the route from the passenger's origin to the vertiport is established using SUMO. Here, the total costs are calculated using the same metric.
    (b) Then, the required AAM leg is requested as a dummy request, with a departure time at the arrival time obtained from SUMO at this vertiport. This calls to the SOSID Toolkit, and the best agent bid is calculated according to the toolkit's internal logic as already described in subsection 3.1.2.
    (c) For this AAM request, the travel time is calculated as the time between the AAM arrival and the SUMO arrival at the vertiport. In addition, the flight distance is taken to calculate the economic cost, which is added to the previously calculated SUMO cost of the vertiport.
    (d) Finally, another call to SUMO is made to find the best route from the destination vertiport to the final destination. For this, total cost is again calculated like in step 1 and 2, and added to the previous components.
4. Once all different routes and their costs have been calculated, a comparison between them is made using Equation 3.2. Note that this is therefore between 1 SUMO route, and N^2 routes using AAM. The route with the lowest total cost is taken, which gives two further options:
    (a) If the passenger does not use AAM, these route stages are loaded into his itinerary, and he goes on to perform them. This requires no further interactions, and only when the passenger arrives at his destination will his route be logged.
    (b) If the passenger however does use AAM, only the first route to the vertiport and the AAM leg from there are loaded into their itinerary. The passenger will in this case also actually request the AAM flight, and update the AAM leg according to the actual flight they will be taking. Then, once the passenger has taken his AAM flight and their arrival at the destination vertiport is logged, they will re-request the route from destination vertiport to final destination. Note that this route might be different than the original request, as the passenger might have incurred delays or speedups in the previous legs. Then, the passenger routes to their destination, and their arrival is logged once they get there.

For intercity passengers, the logic is slightly more complicated. Instead of routing from their origin to destination right away, the same logic as described above is applied from the passenger's origin to the closest intercity train station, which is then combined with a routing using SUMO from the closest intercity station at their origin to the closest station at their destination. This is done such that all AAM legs in the origin city can be compared to the SUMO route to the train station, and that the time saving potential from catching an earlier train can be included. Then, once the passenger arrives at his destination train station, the same logic as above is applied to get from this train station to his final destination. Therefore, an intercity passenger will always have the option to use AAM twice, both in the origin city and the destination city. Their mode choice in the destination city is assumed here to be independent of the choice in the origin city, which is why the latter is calculated only once they get to the destination city.

$$\text{Obj} = \text{Min}\left(\text{Time} * \text{VoT} + \sum \text{Cost per mode km} * \text{Used mode distance}\right) \tag{3.2}$$

Finally, one more note should be made here. As the SUMO legs requested can be between the same origin and destination at the same departure time (especially over multiple simulations), these requests have been stored into a dictionary. This allows a reduction in calls to the findIntermodalRoutes function, which at some points was the bottleneck in simulation speed.

3.3.2. Microscopic Passenger

The first type of passenger created is the most detailed one, and it's the microscopic passenger. The microscopic passenger utilizes the full capabilities of SUMO in simulating microscopic traffic interactions, and initializes microscopic passengers as pedestrians in the SUMO Simulation. As such, it utilizes the pedestrian model for legs by foot. This pedestrian model considers various high-resolution interactions. For example, in this model pedestrians will wait for traffic lights, where traffic lights could even be activated based on their presence. Additionally, they will be subject to capacity constraints when travelling by public transport, such that if a bus is full, they will wait for the next one. Pedestrians will even have interactions on sidewalks with other pedestrians where they will prevent collisions and overtake slower pedestrians. All of this is made possible by the existing pedestrian model in SUMO, best described in SUMO's documentation [**?**]. Microscopic passengers in the multimodal framework utilize the mode choice as described in subsection 3.3.1, but if any delays are encountered, they will reroute all following legs. This last behaviour slows down the simulation significantly, but it ensures that passengers will behave realistically and without teleportation.

3.3.3. Mesoscopic Passenger

As an alternative to the microscopic passenger, a mesoscopic passenger is created. The mesoscopic passenger is intended to be used in parallel with the SUMO meso model. The SUMO meso model is a model where the interactions between vehicles are reduced, and the modelling accuracy of various objects, like traffic light, is also reduced. This already provides an alleged speedup of 100x [**?**], which in this use case has been found to be just over 20x. However, as the most significant source of the model slowing down is the passengers, this is where further speed improvements can be found. Mesoscopic passengers make the same mode choice as microscopic passengers as described in subsection 3.3.1. After this however, a key change is made: The passengers are not actually added to the SUMO surface model. Because in the mesoscopic simulation the sources of any passenger delays are disabled, in practice these passengers will always arrive on time. Therefore, there is no need to actually insert them in the simulation, and we can use their route plan as the actual route they would be taking. These passengers therefore use SUMO only to a much smaller extent, as they only calculate the optimal routes using it, and it is assumed that they can follow it without issues. For the AAM legs however they will still perform the rerouting as described at arrival at the destination vertiport, so any delays and changes in AAM operations will still affect them. It should be clear that the mesoscopic passenger model is a significant simplification of reality. The travel times obtained using it however were found to be realistic, as shown in the verification chapter of the scientific paper. For this reason, combined with computational efficiency, this model was utilized for all simulations performed in this thesis.

4

Appendix - Detailed surface network description

This section serves as some extra material on the exact network utilized, and discusses some of the accuracies and inaccuracies. All 3 cities will be discussed separately first, after which conclusions based on the combined network are shown.

4.1. Hamburg

The first city considered is Hamburg. In Hamburg, 29 vertiports are created at the locations in Table 4.1.

Table 4.1: Vertiports placed in Hamburg

#	Vertiport	Longitude	Latitude	Type
1	Pinneberg	53.65503	9.79768	Local Station
2	Niendorf	53.61966	9.95152	Local Station
3	Hamburg Airport	53.63253	10.00668	Local Station
4	Elbgaustraße	53.60268	9.89336	Local Station
5	Winterhude	53.59455	9.99612	Local Station
6	Barmbek	53.58721	10.04482	Local Station
7	Hoheluftbrücke	53.57748	9.97608	Local Station
8	Eimsbuttel	53.57612	9.9517	Local Station
9	Wandsbek	53.57167	10.06673	Local Station
10	Bahrenfeld	53.56886	9.90286	Local Station
11	Jungfernstieg	53.55239	9.99387	Local Station
12	Hohenfelde	53.56119	10.03795	Local Station
13	Feldstraße	53.55694	9.96866	Local Station
14	Hamburg Hauptbahnhof	53.55319	10.00642	Local Station
15	Blankenese	53.56444	9.81514	Local Station
16	Othmarschen	53.55915	9.8853	Local Station
17	Hammerbrook	53.54676	10.02351	Local Station
18	Altona Bahnhof	53.55379	9.93518	Local Station
19	Landungsbrücke	53.54583	9.97132	Local Station
20	Finkenwerder	53.53333	9.87737	Local Station
21	Harburg	53.4567	9.9911	Local Station
22	Dammtor	53.5608	9.9894	Local Station
23	Elbphilharmonie	53.54148365	9.98428899	Tourist
24	Planten un Blomen	53.56210379	9.98192597	Tourist
25	Kunsthalle Hamburg	53.55579968	10.0024055	Tourist
26	Miniatur Wunderland	53.54389188	9.98909917	Tourist
27	Elbe Tunnel	53.54592504	9.966494	Tourist

#	Vertiport	Longitude	Latitude	Type
28	St Michaels Church	53.54858609	9.97871934	Tourist
29	Tierpark Hagenbeck	53.59500681	9.9418816	Tourist

These vertiports can also be displayed graphically, as seen in Figure 4.1 and 4.2.

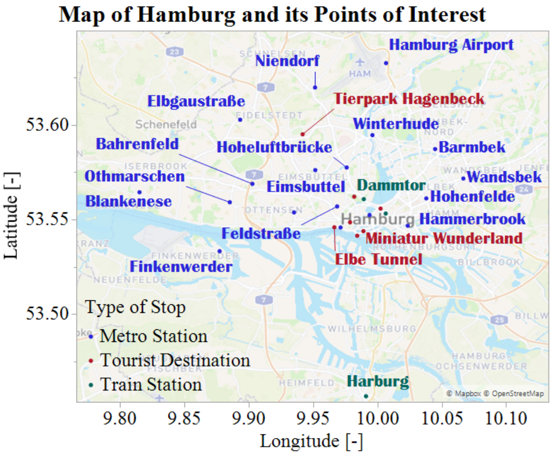


Figure 4.1: View of placement of all vertiports in Hamburg

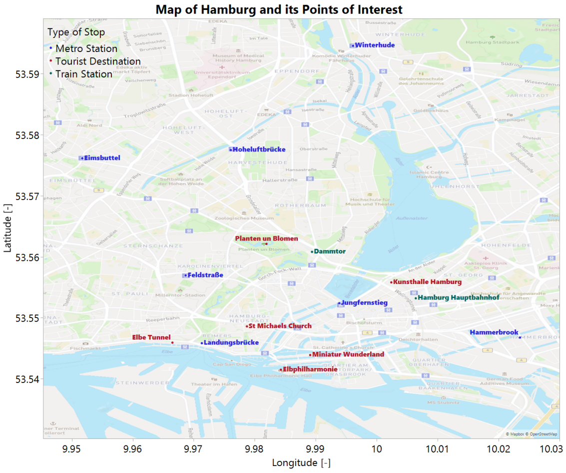


Figure 4.2: View of placement of vertiports in Hamburg centre

With the vertiports placed, the SUMO surface network is reduced to contain only the main roads and the network at full resolution around the vertiports. The resulting network can therefore be seen in Figure 4.3, where the vertiports can also be seen again. For all vertiports there is an access and an egress node, which in most cases cannot be distinguished as they are aligned. At some locations they can be seen to differ slightly. Additionally, it can be seen that not all of the vertiports align well with the network underneath them, but this is still the case in at least 90% of the cases. Both of these factors will have an impact on some of the passengers travelling through the system, but it was not significant enough to be noted during validation.

Figure 4.3: SUMO network of Hamburg, with vertiports as yellow H markers

4.2. Munich

The second city considered is Munich. In Munich, 34 vertiports are created at the locations in Table 4.2.

Table 4.2: Vertiports placed in Munich

#	Vertiport	Longitude	Latitude	Type
1	Marienplatz	48.1371372	11.5756396	Tourist
2	English Garden	48.1642609	11.6054342	Tourist
3	Olympiapark	48.1755006	11.5517989	Tourist
4	BMW Welt	48.1773179	11.5562929	Tourist
5	Allianz Arena	48.2188783	11.6249379	Tourist
6	Hellabrunn Zoo	48.0971557	11.5540502	Tourist
7	BMW Museum	48.176903	11.559018	Tourist
8	Deutsches Museum	48.1303765	11.5830759	Tourist
9	Neuschwanstein Castle	47.5576826	10.7496824	Tourist
10	Frauenkirche	48.1386238	11.5736469	Tourist
11	Alte Pinakothek	48.1483772	11.5699418	Tourist
12	Pinakothek der Moderne	48.1469483	11.5720661	Tourist
13	Flughafen München	48.3541375	11.7861254	Airport
14	Unterföhring	48.1904301	11.646806	Local Station
15	Innsbrucker Ring	48.120758	11.6196845	Local Station
16	Silberhornstraße	48.1150924	11.5795203	Local Station
17	Sendlinger Tor	48.1335368	11.565862	Local Station
18	Poccistraße	48.1258131	11.5503533	Local Station
19	Marienplatz	48.1378205	11.5760785	Local Station
20	Nationaltheater	48.1393778	11.5784503	Local Station
21	Karlsplatz	48.140531	11.5665606	Local Station
22	Maxmonument	48.1377543	11.5879721	Local Station
23	Lehel	48.1397795	11.5877591	Local Station
24	Odeonsplatz	48.1431033	11.577296	Local Station
25	Universität	48.1496657	11.5808918	Local Station
26	Münchner Freiheit	48.1619039	11.5858534	Local Station
27	Scheidplatz	48.1712753	11.5726365	Local Station
28	Olympiazentrum	48.1794835	11.5559268	Local Station
29	Schloss Nymphenburg	48.1582642	11.5111714	Local Station
30	Münchner Hackerbrücke	48.1419925	11.5490165	Local Station
31	Schwanthalerhöhe	48.1339789	11.5408156	Local Station
32	München Ost	48.1275298	11.6050027	International
33	München Hauptbahnhof	48.1402834	11.5597462	International
34	München-Pasing	48.1498658	11.4619195	International

These vertiports can also be displayed graphically, as seen in Figure 4.4 and 4.5.

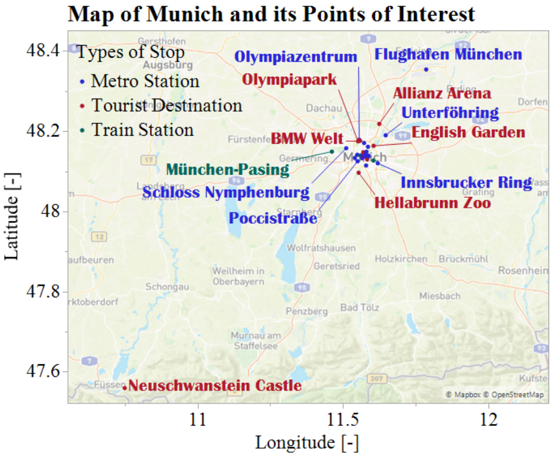


Figure 4.4: View of placement of all vertiports in Munich

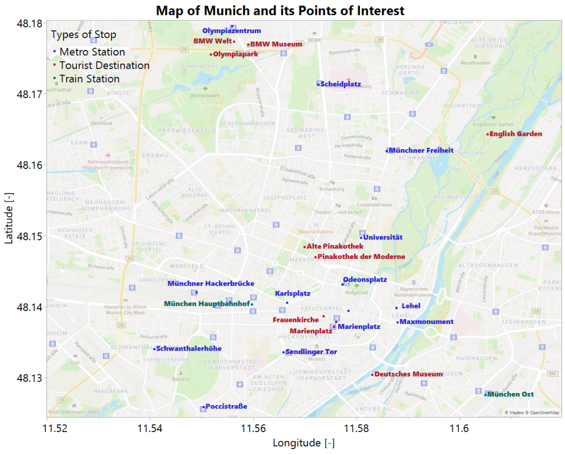


Figure 4.5: View of placement of vertiports in Munich centre

Again, the network can be filtered to a lower resolution everywhere except for around the vertiports, which is seen in Figure 4.6. Because the map of Munich was created differently to account for the location of Neuschwanstein Castle in the bottom left corner, some extraneous roads can be seen in the surroundings. These will not be used in the simulation, but as these are very few nodes it was deemed acceptable to leave them in.

Figure 4.6: SUMO network of Munich, with vertiports as yellow H markers

4.3. Rome

The third city considered is Rome. In Rome, 40 vertiports are created at the locations in Table 4.3.

Table 4.3: Vertiports placed in Rome

#	Vertiport	Longitude	Latitude	Type
1	St. Peter's Basilica	41.902291	12.4540022	Tourist
2	Trevi Fountain	41.9009774	12.4833051	Tourist
3	Piazza Navona	41.8992361	12.4730661	Tourist
4	Colosseum	41.8903055	12.4922433	Tourist
5	Pantheon	41.8986826	12.4768836	Tourist
6	Vatican Museum	41.9066315	12.4535984	Tourist
7	Piazza di Spagna	41.9058511	12.4823046	Tourist
8	Piazza del Popolo	41.9109114	12.4762828	Tourist
9	Forum Romanum	41.8926619	12.4853572	Tourist
10	Circus Maximus	41.8863167	12.4851186	Tourist
11	Monument of Vittorio Emanuele II	41.8948022	12.4831274	Tourist
12	Basilica di Santa Maria Maggiore	41.8976944	12.4984728	Tourist
13	Arcibasilica di San Giovanni in Laterano	41.8860169	12.5056515	Tourist
14	Castel Sant'Angelo	41.9031461	12.4663597	Tourist
15	Belvedere del giancolo	41.8916185	12.4613995	Tourist
16	Baths of Caracalla	41.8792139	12.4923428	Tourist
17	Villa Borghese	41.9130789	12.4853158	Tourist
18	Capitoline Museums	41.8931265	12.4826221	Tourist
19	Villa d'Este Tivoli	41.9633181	12.7958253	Tourist

#	Vertiport	Longitude	Latitude	Type
20	Marcellus Theatre	41.8920586	12.479801	Tourist
21	Trajan Forum	41.8949663	12.4853557	Tourist
22	Fiumicino Aeroporto	41.7932	12.2518	Airport
23	Roma Trastevere	41.8724	12.4661	Local Station
24	Roma Ostiense	41.8717	12.4872	Local Station
25	EUR Magliana	41.8394	12.4633	Local Station
26	Piramide	41.8748	12.48186	Local Station
27	Roma Tuscolana	41.8791	12.5237	Local Station
28	Roma Termini	41.9006	12.5022	Local Station
29	Citta del Vaticano	41.90083	12.45095	Local Station
30	Roma Tiburtina	41.9111	12.5319	Local Station
31	Nuovo Salario	41.9554	12.5103	Local Station
32	Circo Massimo	41.88349	12.48803	Local Station
33	Manzoni	41.8903	12.50686	Local Station
34	Piazzale Flaminio	41.913	12.4765	Local Station
35	Spagna	41.90679	12.48451	Local Station
36	Ottaviano	41.9092656	12.4576322	Local Station
37	San Giovanni	41.8854912	12.5103159	Local Station
38	Ponte Lungo	41.8783707	12.5189879	Local Station
39	EUR Palasport	41.8304571	12.4662654	Local Station
40	Laurentina	41.8274058	12.4811477	Local Station

These vertiports can also be displayed graphically, as seen in Figure 4.7 and 4.8.

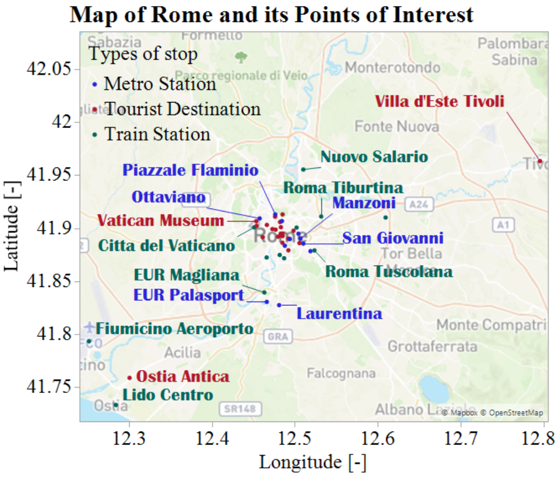


Figure 4.7: View of placement of all vertiports in Rome

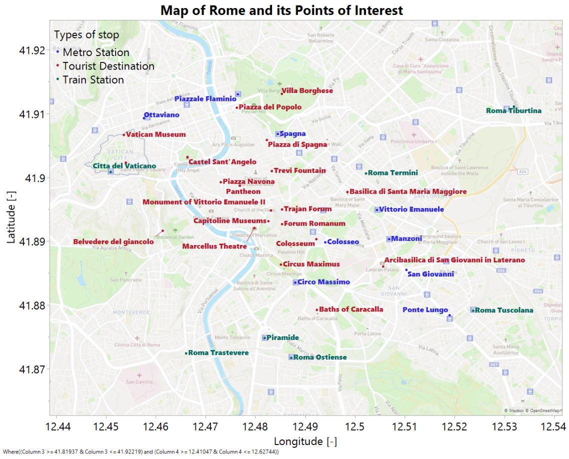


Figure 4.8: View of placement of vertiports in Rome centre

Again, the network can be filtered to a lower resolution everywhere except for around the vertiports, which is seen in Figure 4.9. What can be noted in the case of Rome is that the density of vertiports in the centre is very high, attributable to the many tourist locations found here.

Figure 4.9: SUMO network of Rome, with vertiports as yellow H markers

4.4. Final Network & discussion

With all the separate networks defined, they can be combined into one very tall network. Here, the joining arteries are the main train lines connecting the 3 cities that are used by direct trains. There are some other ways to get from Munich to Rome for example, but as these are indirect or involve non-train legs, the connections for these have been omitted. The resulting final network can be seen in Figure 4.10.

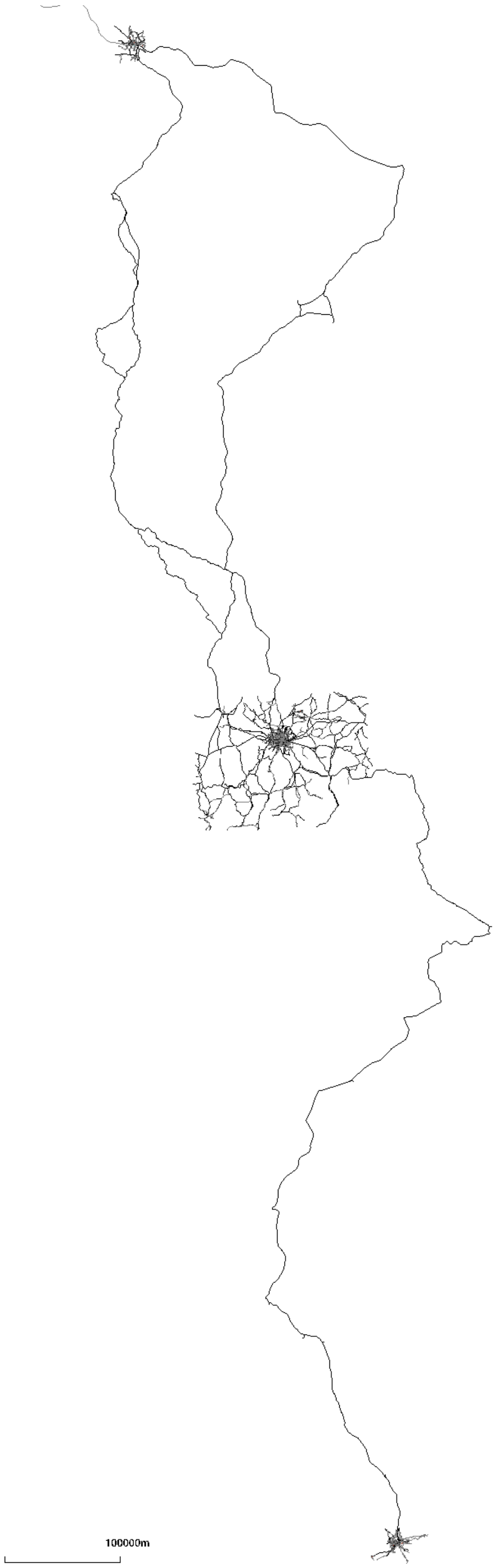


Figure 4.10: SUMO network of full framework

Lastly, one point of discussion should be raised. In most cases the SUMO network and the vertiport locations align very well. A good example of this can be seen in Figure 4.11, where the vertiport for the castle is placed right in front of the star-shaped outline of the castle. In other cases, like for Munich Hauptbahnhof, it can be seen in Figure 4.12 that the vertiport is placed significantly north of the train station. This will result in a travel time penalty for any passenger that wants to take AAM to Munich Hauptbahnhof, as they will have to walk an additional couple hundred meters. This inaccuracy is caused by the vertiports and their access points being placed automatically, which in some cases caused some displacements. Nevertheless, as the validation data suggests the travel times are more or less realistic, and these vertiports are being used in the simulation it can be assumed that this inaccuracy has a reasonably small impact. In any case, the question of where exactly a vertiport is placed is outside of the scope of this research, and it could very well be that these will not be possible to be placed exactly at the desired locations for optimal mobility.

Figure 4.11: View of placement Castel Sant'Angelo Vertiport

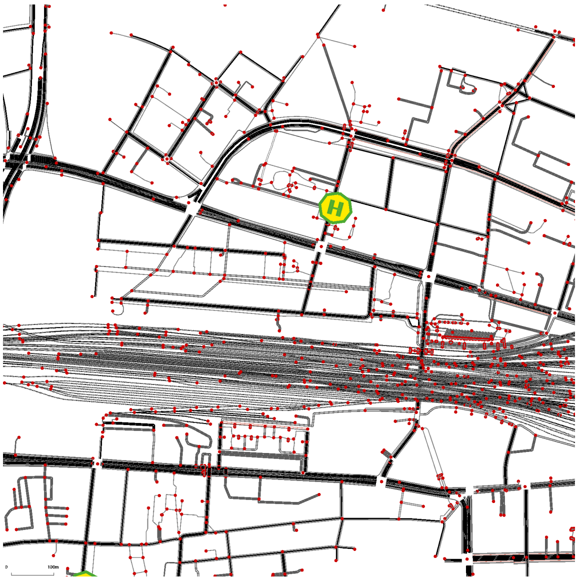


Figure 4.12: View of placement Munich Hauptbahnhof Vertiport

5

Appendix - Additional results

Throughout the generation of the thesis, various additional results have been generated, which might be of interest to the reader, even if not all of them fit in the storyline of the general thesis. These will therefore find a home in this section, where hopefully they can inspire new insights for the reader.

5.1. Baseline

In the baseline analysis, various different results have also been generated and now omitted.

5.1.1. Commuters & Tourists

For the commuters and tourists, it was mentioned that the fleet was capacity constrained in Hamburg and Rome. Confirmation of this can be seen in Figure 5.1 and Figure 5.3. As can be seen as well, this is not the case in Munich.

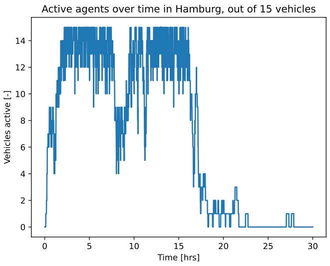


Figure 5.1: Active agents in Hamburg, 3 Passenger Capacity

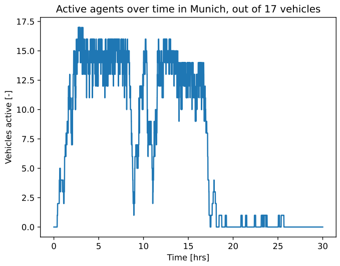


Figure 5.2: Active agents in Munich, 3 Passenger Capacity

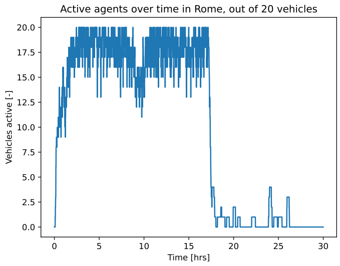


Figure 5.3: Active agents in Rome, 3 Passenger Capacity

5.2. Sensitivity Analysis

As part of the verification of the model several sensitivity analysis have been performed, of which some results were omitted in the final paper

5.2.1. Sensitivity Analysis - Ticket Price

As ticket price is one of the parameters of major importance in the passenger choice model, it is worthwhile to analyse its impact on the results. Therefore, a study is set up where ticket price is varied between 0.5 and 4 [EUR/km]. The resulting impact on the overall KPIs can be seen in Table 5.1. Here, it is clear that the ticket price has a significant impact on all KPIs, and especially on the AAM mode share.

Table 5.1: Comparison of KPIs over ticket price sensitivity analysis

Ticket price [EUR/km]	Overall energy per pax [kWh/km]	Overall time saved [hours]	AAM mode share [%]
0.5	2.23 (-21.1 %)	1749 (21.2 %)	21.4 (71.8 %)
1	2.42 (-14.4 %)	1694 (17.4 %)	19 (52.6 %)
1.5	2.56 (-9.6 %)	1708 (18.4 %)	17.5 (40.2 %)
2	2.65 (-6.3 %)	1691 (17.2 %)	16.1 (28.9 %)
2.5	2.76 (-2.4 %)	1570 (8.8 %)	14.1 (13 %)
3 (base)	2.83 (–)	1443 (–)	12.5 (–)
3.5	2.82 (-0.2 %)	1299 (-10 %)	10.6 (-14.6 %)
4	2.85 (0.8 %)	1175 (-18.6 %)	9.2 (-26.5 %)

To get a better understanding of why ticket price has such an impact, a more detailed look should be taken. When comparing the different urban environments as done in Figure 5.4, it can be seen that mode share goes up in all cases, but especially in Munich, which is likely attributable that Munich was not capacity constrained around the baseline at 3 [EUR/km] as shown previously in Figure 5.2. Additionally, in Figure 5.5, it can be seen that the average passengers per flight goes up, which is directly correlated with the decrease in energy per passenger as seen in Table 5.1.

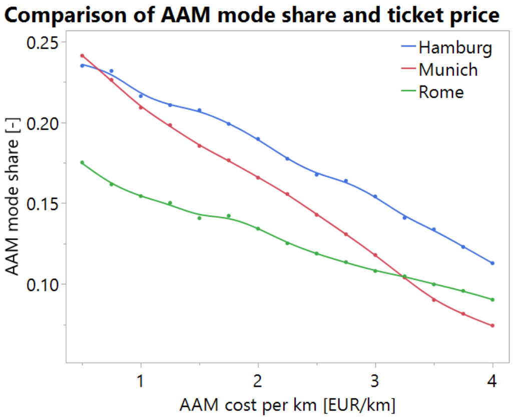


Figure 5.4: Change in AAM mode share with changing ticket price

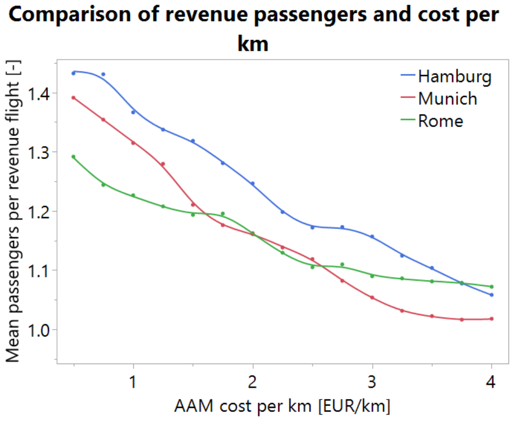


Figure 5.5: Change in passengers per flight with changing ticket price

5.2.2. Sensitivity Analysis - Value of Time

The link between overall time saved and mode share can be explored in some more detail. As shown in the paper, mode share goes down with decreasing value of time. This same relation can be seen in Figure 5.6, highlighting this effect in the different city environments. However, if we look at the time saved per passenger that actually uses AAM, we see that the mean time saving goes up with decreasing value of time in Figure 5.7. This touches on a consequence of the chosen key performance indicator, where the mean time saved per passenger using the service and the total time saved are inversely linked.

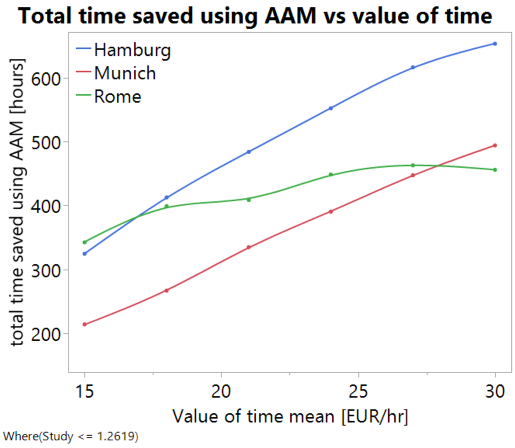


Figure 5.6: Change in total AAM time savings with changing value of time

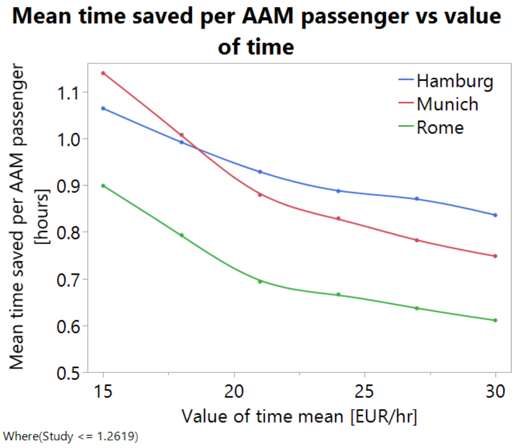


Figure 5.7: Change in mean AAM time savings with changing value of time

5.3. Results - 1 passenger capacity

As discussed in the scientific paper, all results for 1, 3 and 5 passenger capacity look fairly similar when it comes to the best design for the different KPIs. For this reason, only the 3 passenger capacity results were documented in the report. For completeness, this section contains all the same plots, but for the 1 passenger capacity.

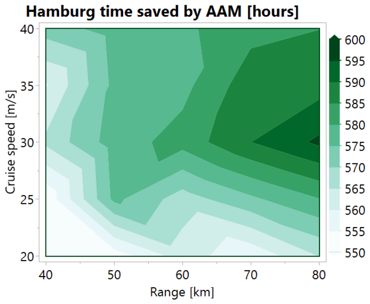


Figure 5.8: Total time saved in Hamburg, 1 Passenger Capacity

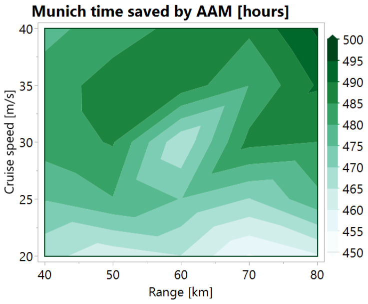


Figure 5.9: Total time saved in Munich, 1 Passenger Capacity

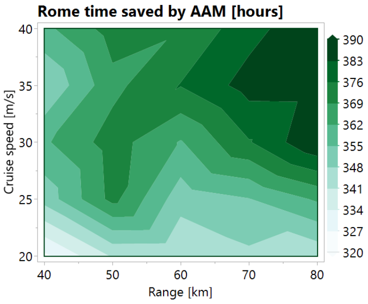


Figure 5.10: Total time saved in Rome, 1 Passenger Capacity

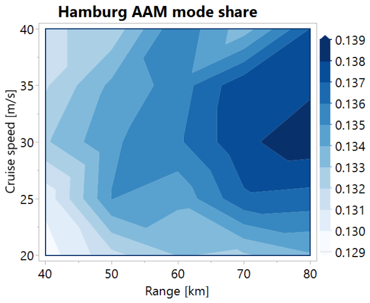


Figure 5.11: AAM Mode share in Hamburg, 1 Passenger Capacity

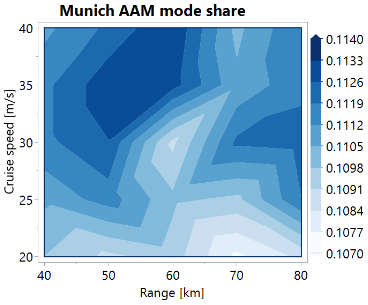


Figure 5.12: AAM Mode share in Munich, 1 Passenger Capacity

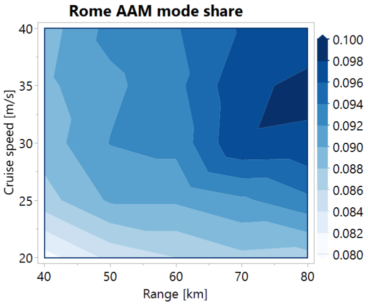


Figure 5.13: AAM Mode share in Rome, 1 Passenger Capacity

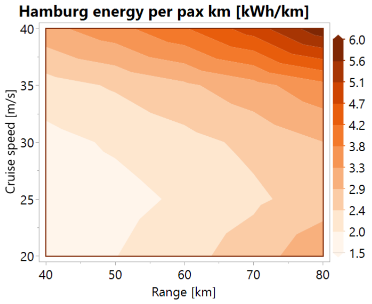


Figure 5.14: Energy per passenger in Hamburg, 1 Passenger Capacity

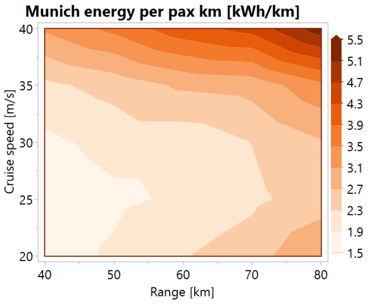


Figure 5.15: Energy per passenger in Munich, 1 Passenger Capacity

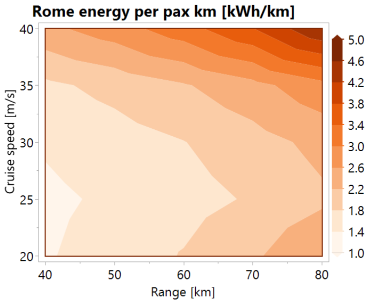


Figure 5.16: Energy per passenger in Rome, 1 Passenger Capacity

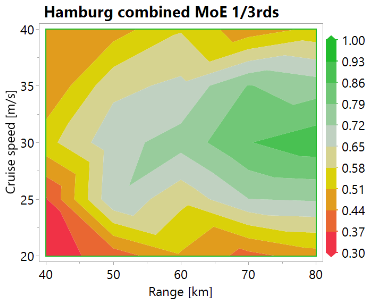


Figure 5.17: Best MoE design point in Hamburg, 1 Passenger Capacity

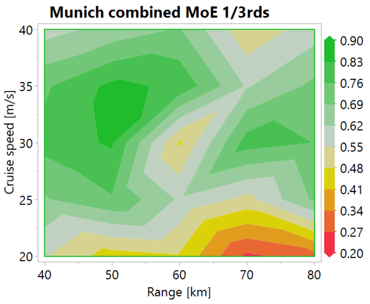


Figure 5.18: Best MoE design point in Munich, 1 Passenger Capacity

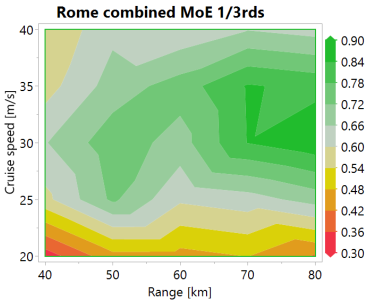


Figure 5.19: Best MoE design point in Rome, 1 Passenger Capacity

5.4. Results - 5 passenger capacity

In the same way as in last section, this section summarizes all results for the 5 passenger capacity vehicles, which still look very similar to the results for 3 passenger capacity.

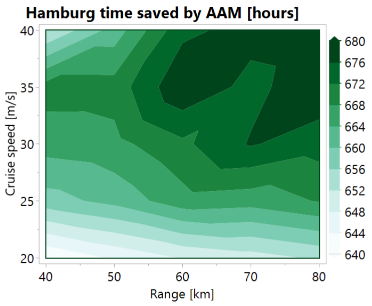


Figure 5.20: Total time saved in Hamburg, 5 Passenger Capacity

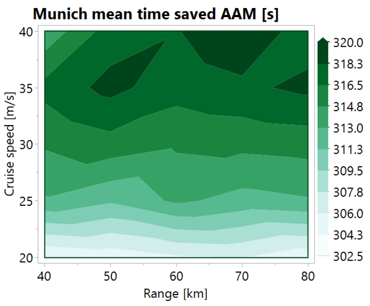


Figure 5.21: Total time saved in Munich, 5 Passenger Capacity

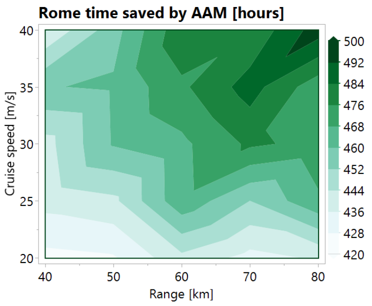


Figure 5.22: Total time saved in Rome, 5 Passenger Capacity

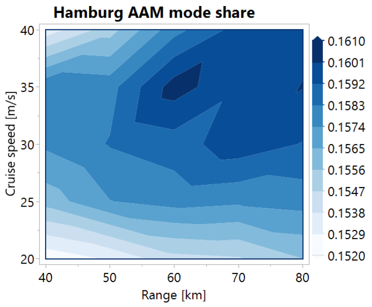


Figure 5.23: AAM Mode share in Hamburg, 5 Passenger Capacity

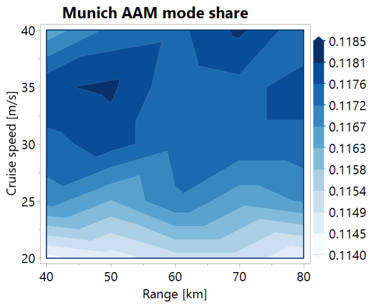


Figure 5.24: AAM Mode share in Munich, 5 Passenger Capacity

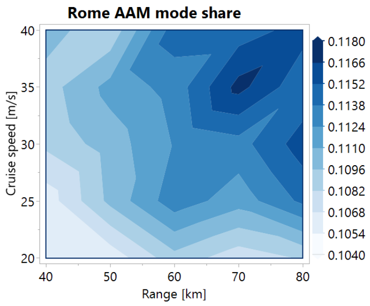


Figure 5.25: AAM Mode share in Rome, 5 Passenger Capacity

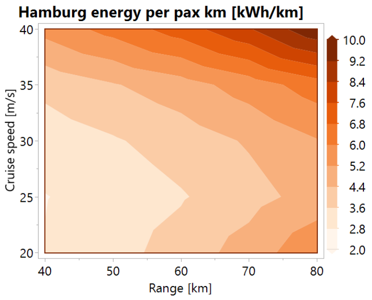


Figure 5.26: Energy per passenger in Hamburg, 5 Passenger Capacity

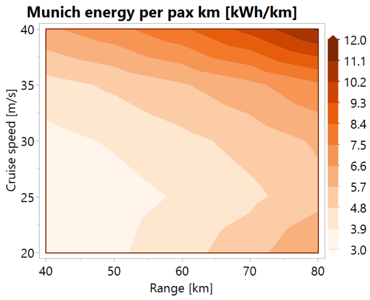


Figure 5.27: Energy per passenger in Munich, 5 Passenger Capacity

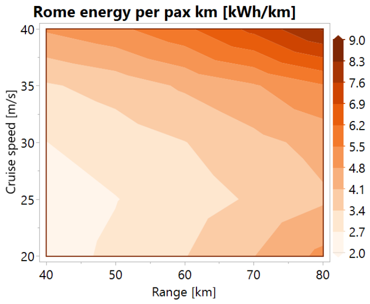


Figure 5.28: Energy per passenger in Rome, 5 Passenger Capacity

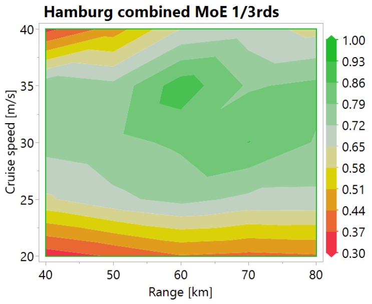


Figure 5.29: Best MoE design point in Hamburg, 5 Passenger Capacity

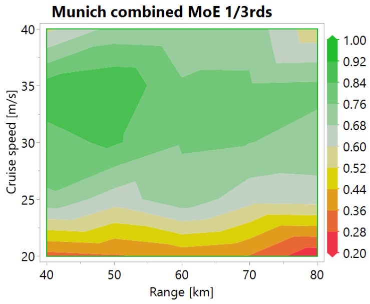


Figure 5.30: Best MoE design point in Munich, 5 Passenger Capacity

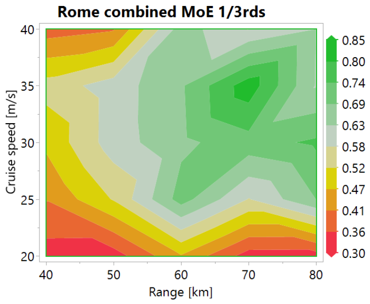


Figure 5.31: Best MoE design point in Rome, 5 Passenger Capacity

5.5. Results - Comparison of 1, 3, 5

For completeness, this section contains a comparison of the best overall MoE locations for the different cities. This is very similar to the overall assessment shown in the report. The only difference is that for these plots, the best design point is determined separately from each other. As a result, all plots contain scores from close to 0 to close to 1. It can be seen however that the overall best design for each passenger capacity is still at 30 [m/s], and at around 70-80 [km] range.

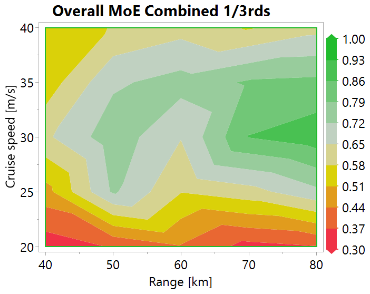


Figure 5.32: Best MoE design point overall, 1 Passenger Capacity

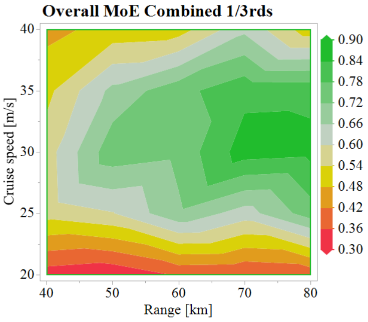


Figure 5.33: Best MoE design point overall, 3 Passenger Capacity

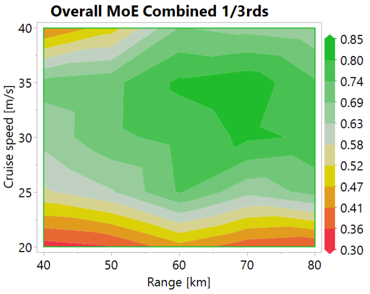


Figure 5.34: Best MoE design point overall, 5 Passenger Capacity

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