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Scenario-based Demand Assessment of Urban Air Mobility in the Greater Munich Area

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As traffic levels increase in urban agglomerations, opinions are voiced that wish to elevate urban transport into the third dimension, the air. In this work, we project the idea of aerial passenger transport into the near future: on-demand urban air mobility (UAM) for the greater Munich area in the year 2030. To date, most research is focusing on independent factors regarding the supply and demand of UAM, such as vehicle types and infrastructure capacity. We propose a simulation framework that facilitates analyzing the potential demand of UAM, using a combination of interacting factors. We define five scenarios, ranging from representations of niche application up to mass transport options, by varying fleet size, available technologies, infrastructure placement and pricing strategies. These scenarios are fed into an extended version of the agent-based transport simulation platform MATSim, chained with the microscopic transportation orchestrator (MITO). The simulation results show that the system configuration has a big impact on UAM demand, infrastructure capacity and fleet size were identified as main bottlenecks. We see high levels of demand during peak hours and for trips up to 20 km, however, none of the scenarios results in a sufficiently high modal share of UAM that manages to reduce traffic volumes substantially, and with that congestion, of ground-based modes. When aiming for an effective and sustainable UAM service, our recommendation is to, firstly, use it to support and improve, rather than cannibalize, existing public transport options; and second, minimize negative impacts on environment and society to maximize public acceptance.

I. Introduction

As traffic levels increase in urban agglomerations, opinions have voiced that wish to elevate urban transport into the third dimension, the air. More than 100 companies around the globe are working on vehicle demonstrators to enable aerial mobility within urban settlements [1]. In this work, we project the idea of aerial passenger transport into the near future: on-demand urban air mobility (UAM) for the greater Munich area in the year 2030. We define the greater Munich area as the labor market region of Munich (Germany) consisting of all administrative districts with a rate of out-commuters higher than 25%.

To date, most research on UAM as a transport option focuses on independent factors regarding the supply and demand of UAM. On the supply side, these factors include aspects of the vehicle, such as speed, capacity, energy source; aspects of the infrastructure, such as vertiport (UAM station) location and capacity; and aspects of the service such as price, travel time and safety. On the demand side, we find socio-demographic factors and aspects of travel behavior, like mode choice and acceptance of UAM.

The aim of this research is to bring these independent factors together, so that they are able to interact with each other and form an integral picture of UAM as a future transport option. To this end, we propose a simulation framework that facilitates analyzing the potential demand of UAM. This framework interleaves a version of the agent-based simulation platform MATSim (Multi-Agent Transport Simulation, [2]) for trip realization, extended to include UAM [3], and the agent-based demand model MITO (Microscopic Transportation Orchestrator, [4]).

As inputs for the simulation, we use a synthetic population of the study area in 2030, created by the land-use model SILO (Simple Land Use Orchestrator, [5]). Due to the relative importance of the airport located within the study area, we add a share of airport passengers to the commuter population. We furthermore create three types of infrastructure network, with a low, medium and high density of vertiports in the study area. Routes between vertiports follow ground-based transport infrastructure to avoid flying above populated areas. Moreover, we consider a range of operational and technical parameters, such as vehicle speed and capacity, price, fleet size, processing time and

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infrastructure, as these parameters have proven to have a high impact on demand [6]. All technological advances, such as vehicle autonomy and communication or range extensions, are assumed to be available by 2030. Using these inputs, we parameterize five scenarios, from a representation of a niche application up to mass transport options. These scenarios are then fed into the simulation framework mentioned above and the results on UAM demand are analyzed.

The simulation results contain a detailed analysis on general demand, vertiport throughput, route popularity, trip distribution and airport passengers. They show that the scenario configuration has a big impact on UAM demand, and infrastructure capacity and fleet size are the main bottlenecks when answering passenger demand. In the greater Munich area, we see high levels of demand during peak hours and for trips up to 20 km, and UAM modal shares that range from 0.05% to 1.60%. Even in cases where price levels are comparable to taxi services, UAM remains a niche transportation option and is not able to reduce the traffic volumes of ground-based modes to an extend that eases congestion levels. Further results show that infrastructure capacity and fleet sizes need to be carefully balanced to ensure maximum efficiency.

We see UAM not as a disruption to the mobility system, but rather as a means of supplementing current services by fast and flexible options. More detailed analysis of our results shows that many routes with high demand are well served by public transport or that they are particularly short. Taking travelers away from public transport can be adverse for several reasons, hence we recommend using UAM to support and improve, rather than cannibalize, existing public transport options.

Our choice of vehicle routing means that people can fly longer routes as opposed to direct connections between vertiports, to enhance safety and reduce noise and visual annoyance for third parties. Policymakers need to be aware of the trade-offs to be made here: Ensuring flight routes that enable UAM operation in line with overall environmental goals, while at the same time minimizing risks and negative impacts on third parties is one of the core questions when introducing UAM.

This paper is organized as follows: To give the reader an overview of existing research in the field of UAM demand and supply modelling the paper will start with a literature review (section II). This will be followed by an explanation of the modelling framework's methodological basis and the foundations necessary to simulate the greater Munich region including UAM (section III). Together with the definition of the five UAM scenarios (section IV) this will give an overview over the assumptions made in the context of this research and will help interpret the results described in section V. The discussion of results will focus on potential passenger demand at vertiports, on routes, the distribution of demand over the time of day and different ranges as well as the demand for airport access and egress via UAM. The results from the simulation of an unregulated system allow deriving policy recommendations (section VI). Section VII concludes the paper and gives an outlook on further work.

II. Literature Review

The aim of this literature review is to provide a general picture of the factors that may affect UAM demand, from UAM operational and user behavior aspects. In terms of UAM operations, current studies investigate the impact of UAM operations, including vehicle types, infrastructure requirements, environmental impact, and other potential aspects [7, 8]. Concerning user behavior, current studies attempt to identify the characteristics of potential user groups of UAM and which factors may affect user adoption.

Focusing on speed and capacity concepts for UAM, Baur et al. [9] and Shamiyeh et al. [10] provide overviews on UAM vertical take-off and landing (VTOL) aircraft configurations that are currently under development. There are several types of air vehicles which can accommodate two to four passengers with various ranges of speed. For instance, multicopters with multiple fixed propellers can cruise at speeds between 80 and 100 km/h and might be well-suited for an air taxi use case; a hybrid type of vehicles can cruise at speeds between 150 and 200 km/h and was suggested to be well-suited for the use cases of air taxi, airport shuttles, and intercity flights [9]; a tilt-wing type of vehicle is expected to reach cruising speeds between 180 and 250 km/h and might be suitable for all use cases; a fixed-wing type of vehicle may be expected to reach speeds between 200 and 300 km/h and might be applicable for airport shuttle and intercity use cases.

The UAM infrastructure locations and capacities were found to be influential to UAM demand. Current studies attempt to identify vertiport locations applying various strategies. Antcliff et al. [11] propose to utilize existing infrastructure such as highway cloverleaf areas in Silicon Valley in order to minimize required land and impacts on surrounding private land through operations. With the goal to minimize travel time, several studies try to allocate stations across cities in the US. Syed et al. [12] employ a k-means clustering algorithm considering the distribution of population and income in the Northern California and Washington D.C. Baltimore regions. Applying a similar algorithm, Wei et al. [13] prove the facilities converge to areas of low and high station throughput in South Florida. The study of Daskilewicz et al. [14] takes into account the spatial distribution of jobs in the San Francisco Bay Area and Los Angeles region, placing stations with the objective to maximize travel-time savings compared to ground transportation, including car and public transport. Following the same strategy, Rath and Chow [15] try to find a suitable number of UAM stations providing access to the three major airports in New York City. Other studies identifies the station locations intending to maximize station coverage. For instance, Holden and Goel [7] tackle the problem in Los Angeles and London by combining both k-means clustering algorithm and network optimization that maximize trip coverage. Considering influential factors (e.g. major transport hub, points of interest, median income, etc.) that have been identified in Fadhil's [16] geographic information system (GIS)-based analysis for UAM ground-based infrastructure in Los Angeles and Munich, Arellano [17] develops a semi-automated the procedure to maximize coverage for all demand points. The result indicates that spatial distribution and appropriate placement of vertiports can be influential for both demand and travel-time savings.

Fleet size is another crucial aspect as it can directly affect waiting time. According to Rath and Chow [15], the hub facilities can be further categorized as with or without capacity restrictions, i.e. with or without limit to the maximum flow passing through a hub [18]. The fleet size of stations was found to be of great importance. Rath and Chow [15], Daskilewicz et al. [14], and Rothfeld et al. [19] state that setting limits on fleet size increases UAM travel times significantly and reduces UAM demand.

Meanwhile, some transport-service attributes, socio-demographic factors, and travel-behavior variables were found to be influential to the preference and acceptance of UAM. Straubinger et al. [1] conduct a meta-study and identify factors affecting the general transport mode choice and UAM acceptance. Elements such as travel time, travel cost, access time, waiting time, value of time, and safety have been highlighted to have high relevance, followed by aspects that are of medium relevance, such as trip distance, trip purpose, comfort, or flexibility. Some socio-demographic variables such as age, educational attainment, and income are proved to be significant in forming future passenger profiles [1]. Other travel-behavior factors like trip purpose, frequency of air travel, and the presence of congestion, are highlighted to affect the traveler's behavioral choice regarding UAM [20, 21].

Recently, a handful of studies based on agent-based simulation further proved the impact of above-mentioned operational and user-centric factors on potential UAM demand. One of the earliest use cases for the MATSim-UAM extension [3] is a study based on Sioux Falls, South Dakota [19]. With the assumption of shared and on-demand UAM service, the authors tested several UAM operational parameters including cruise speed, VTOL speed, processing time, vehicle capacity, fleet size and networks (i.e. different number of stations). The simulation outcome shows that travel-time savings was one of the leading factors for UAM acceptance from passengers. Any decrease in UAM travel time resulted in a higher UAM modal share. Processing time, which corresponds to the time segment between arriving at a UAM station and vertical take-off, was found to be influential as well. The number of UAM stations is another aspect that significantly influenced UAM usage. For instance, decreasing the number of stations by 60% lead to a 55% reduction in UAM demand. Similar findings are highlighted in the work of Ploetner et al. [6]: The fleet size has a significant influence on agents' waiting times and therefore has strongest influence on the overall UAM demand. Applying the MATSim-UAM extension, Balac et al. [22] implemented another case study estimating potential demand for UAM in Zurich. The simulation results indicate that higher UAM cruising speeds could attract more users but cannot compensate for additional processing time. Another finding is that doubling the base fare has a smaller negative influence than doubling the distance-based cost [22]. Ploetner et al. [6] also state that kilometer-dependent prices play a significant role, whereas vehicle speed only has a minor impact on UAM demand.

The literature review reveals that most research addresses how general UAM potentials can be affected by independent factors from the supply side, such as fleet, infrastructure, ticket price, and travel time. Using a scenario-based assessment approach, we intend to foresee the potential UAM demand of the greater Munich area for a range of future scenarios considering the combined impacts of influential factors from vehicle supply, infrastructure supply, and consumer behavior perspectives. To realize the demand estimation, previous studies have deployed agent-based modelling methods to model and simulate UAM, we apply agent-based modelling with an embedded feedback loop to avoid unreasonably long waiting times for a UAM ride [6].

III. Modelling Framework and Setup

The study area is composed of five core cities (Munich, Augsburg, Ingolstadt, Landshut and Rosenheim) and their commuting catchment areas. The area includes a total of 444 municipalities and 4.5 million inhabitants living in 2.1 million households. The greater Munich area has an extensive public transportation and highway system, even though some new highways construction and road widening projects are planned for 2030 [23], the road congestion will still occur especially within cities, due to population growth, according to the result of ground-based travel demand estimation by MITO.

To estimate the potential UAM travel demand of the greater Munich area in the year 2030, Ploetner et al. [6] set up a simulation framework by integrating the agent-based and trip-based model, MITO [4] and the multi-agent travel-based model, MATSim [2]. MITO simulates and generates travel demand individually for every household given by the synthetic population of SILO [5]. MATSim realizes trip assignment using a microscopic description of demand by tracing the daily schedule and the synthetic travelers' decisions [2]. The results of an initial travel demand generation via MITO were fed into MATSim, which has been extended to enable the simultaneous simulation of ground- and aerial-based transportation modes [6].

To enable the functionality of the MITO model and the MATSim simulation, we used a synthetic population of 2030, generated by the land-use model SILO, in order to represent the commuters of the study area. SILO simulated the change of the synthetic population in the study area from 2011 to 2030 based on the input including population and employment forecasts for 2030 [24]. Given the importance of the Munich international airport located in the study area, and the potential of UAM for trips that connect the airport with the rest of the study area, airport passengers were generated and an airport model was developed to include this demand.

Using the MITO model, firstly the number of trips was generated for each household and destinations were selected by taking into account the travel time budget [6, 25]. As the following step, a mode-choice model was implemented incorporating the results of a stated preference survey [20] which was designed to explore the transport mode-choice preference and UAM adoption potentials. The potential modal share of UAM was then estimated based on the survey results and a nested logit model. Within the model, we grouped private (private autonomous vehicle, private car driver, private car passenger) and public transport modes (shared autonomous vehicle, bus, tram/metro, train, UAM) in the corresponding nests, while leaving walking and cycling as independent modes.

In terms of the networks which are required as one of the other inputs for MATSim simulation, both ground-based and flight networks were formed. We formed the ground-based network based on the current existing road networks of the study area, taking into account the planned project for 2030 to construct new roads and to widen the existing roads [23]. To determine the flight network, we conducted four workshops with representatives from Munich Airport, Chamber of Industry and Commerce of Upper Bavaria and the Cities of Munich and Ingolstadt. Based on the discussion results, three levels of network archetypes were formed. Four potential trip purposes relevant to UAM usage have been taken into account, they are commuting, business, tourism and leisure, and traveling to or from less connected regions.

The selected vertiport locations and three archetypes of networks are shown in Fig. 1. The low-density network includes 24 vertiports and covers larger agglomerations, employment centers, transportation hubs and densely populated areas with a large share of high incomes. The medium-density network with 74 vertiports includes all vertiports of the low-density network. Other than that, the terminus of main subway lines and suburban trains, as well as major employment centers were added. Finally, the high-density network with 130 vertiports takes into account the medium-density network plus vertiport locations that serve various target groups based on different trip purposes [6]. The flight connections were enabled within the cities as well as between rural regions. All connections were routed along existing infrastructure, e.g. highways and train tracks, in order to minimize additional noise, the risk in case of vehicle malfunctions and visual impacts, for third parties.

Simulating UAM via the MATSim-UAM extension allows detailed analyzes concerning the impact of UAM operational properties such as vehicle speed, availability, as well as infrastructure accessibility and capacity. Those aspects were then be incorporated into the agents' mode-choice process using MITO through a feedback loop. For instance, if a certain plan for using a specific transport mode was not attractive (e.g. the waiting time is too long), the agents would dynamically decide to switch another mode with a more efficient plan in the next iteration. The mode-choice model generates UAM demand based on utilities that reflect travel time, price and other attributes of UAM services. A flowchart of this feedback loop is shown in Fig. 2. A more detailed description regarding further features of the simulation model can be found in [6].

IV. Scenario Setup

To cover a board range of possibilities for future UAM operations in the study area, we defined five scenarios representing the cases from UAM being a niche transport service to UAM being an affordable mode for daily transportation. Using the above-mentioned modelling and simulation framework, we simulated each scenario that was formulated according to the potential influential factors.

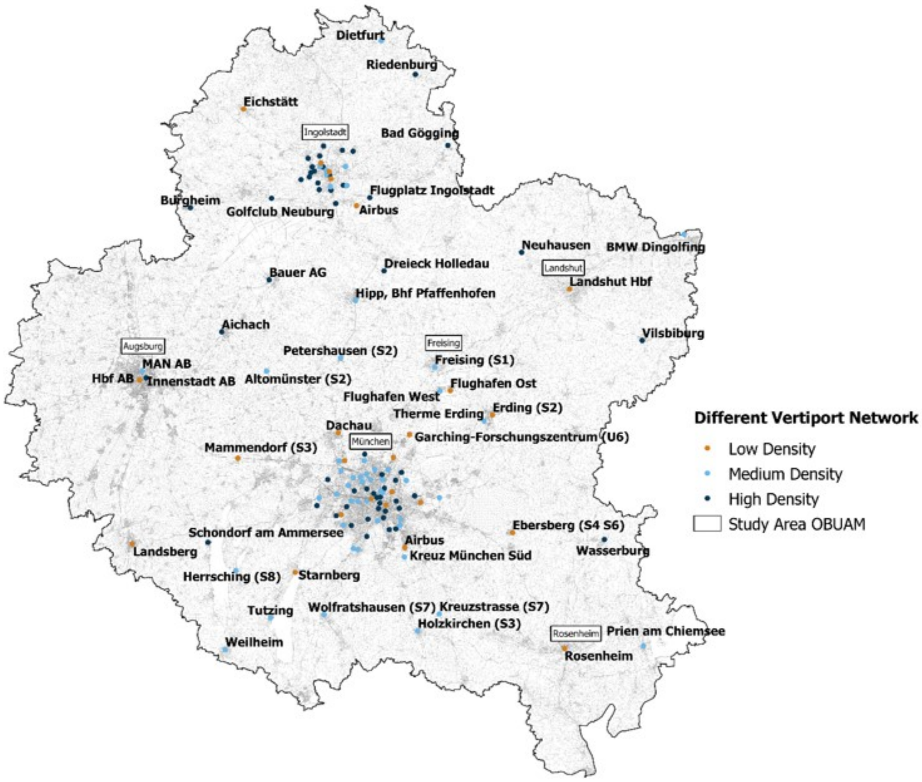


Fig. 1 Low, medium and high-density networks for the Study Area with 24, 74 and 130 vertiports respectively
(Image source [6])

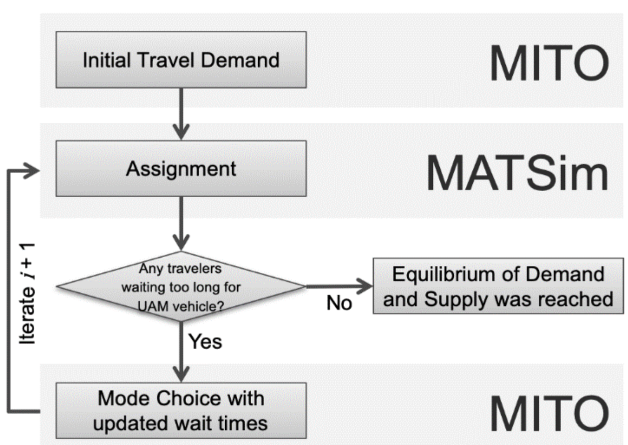


Fig. 2 MITO-MATSim feedback loop
(Image source [6])

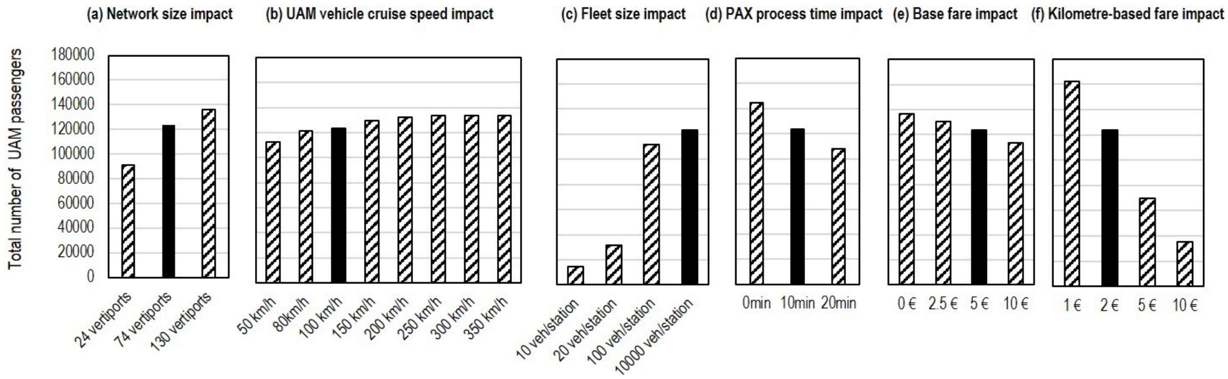


Fig. 3 Sensitivity analysis result
(Image source [6])

In order to gain an in-depth understanding of how each aspect impacts UAM demand, a comprehensive literature review and a sensitivity analysis were performed in earlier work [6]. Several noteworthy aspects include vehicle cruise speed, ticket fare, vertiport number and capacity, fleet size (veh/station), processing time, and seat capacity (PAX/veh) [6]. According to Ploetner et al. [6], among these factors, the fleet size and the km-based fare have the greatest influence. Additionally, the passenger processing time mainly affects demand on shorter routes. However, the impacts of the network, the cruise speed, and the base fare are rather small. It is worth-noting that passengers were allowed to share rides with their travel groups (families or friends), passenger pooling with strangers, however, was not considered or simulated in this case study. Hence, the seat capacity was defined for describing the scenario and the impact of it was not investigated. The sensitivity analysis result is displayed in Fig. 3.

In terms of the specific value settings of the measured parameters, three levels of vertiport locations and network densities were determined qualitatively based on conducted workshops [6]. Based on an overview of design concepts regarding vehicle configurations [9, 10], We defined the cruise speed ranging from 50 km/h to 300 km/h and the seat capacity ranging from two to four passengers per vehicle. Referring to the existing UAM modelling and simulation works [6, 19, 22], we defined the base fare varying from 0 €/trip to 10 €/trip, the km-based fare varying from 1 €/km to 5 €/km, the fleet size varying from 10 to 100 vehicles per station, and processing time (combined times before and after the flight) varying from 10 to 30 minutes. The parameter setting of each scenario is summarized in Table 1.

In terms of the defined scenarios:

- *Scenario A* represents a UAM use case which is comparable to today's luxurious transport offer, with a high base price of 10 € and high km-based price of 5 €/km, yet with a low vehicle speed of 50 km/h. Dedicated take-off and landing infrastructures are distributed at a low-density and with very limited fleet size of 10 vehicles per station. A relatively long processing time of 30 minutes is included in the journey.
- *Scenario C* represents how UAM might be deployed in the way similar to current taxi services. Ticket fares are set to be about the level of taxi services: 5 € as the base price and 2 €/km as the km-based price. The on-demand service is expected to be provided with an improved vehicle cruise speed of 100 km/h within a medium-density network. Dedicated take-off and landing vertiports with fleet size of 50 vehicles per station are required. And 20-minutes processing time is added.
- *Scenario E* represents UAM as an affordable and fast mode for daily transportation for the masses throughout a network covering a whole city/region. The fleet size is expanded to 100 vehicles per station. UAM vehicles can travel up to 300 km/h with no base fare and only 1 €/km km-based fare. The on-demand service may be closely linked to other transport modes. The processing time is shortened to 10 minutes, making seamless inter-modal transport achievable.
- *Scenario B* is set between the scenario A and the scenario C. It shows a conservative case with 80 km/h of vehicle speed, 10 € of ticket base fare and 2 € of km-based fare, and 20 minutes of processing time. A low network density and 50 vehicles per station are set in this case.
- *Scenario D* represents the case between the scenario C and the scenario E. It shows an inferior case with 150 km/h of vehicle speed, 5 € of ticket base fare and 1 € of km-based fare, and 10 minutes of processing time. A medium network density and 50 vehicles per station are set in this case.

Table 1 Scenario description

Scenario	A	B	C	D	E
Network density (no. of vertiports)	low (24)	low (24)	medium (74)	medium (74)	high (130)
Speed [km/h]	50	80	100	150	300
Base price [€/trip]	10	10	5	5	0
Km price [€/km]	5	2	2	1	1
Fleet size [veh/station]	10	50	50	50	100
Process time (pre + post flight) [min]	30	20	20	10	10
Seat capacity [PAX/veh]	2	2	2	4	4

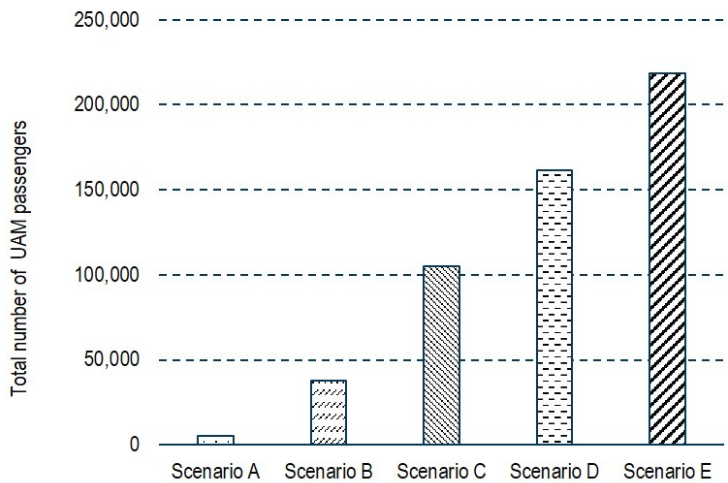


Fig. 4 Total number of daily UAM passengers

V. Results

The conducted simulations are based on the specific geographical situation and travel behavior within the study area. For regions with different income levels, location patterns, transport systems and population mindsets, the results might be different. The following discussion of simulation results and derived policy recommendations are all based on the greater Munich area. Applicability to other regions might be limited.

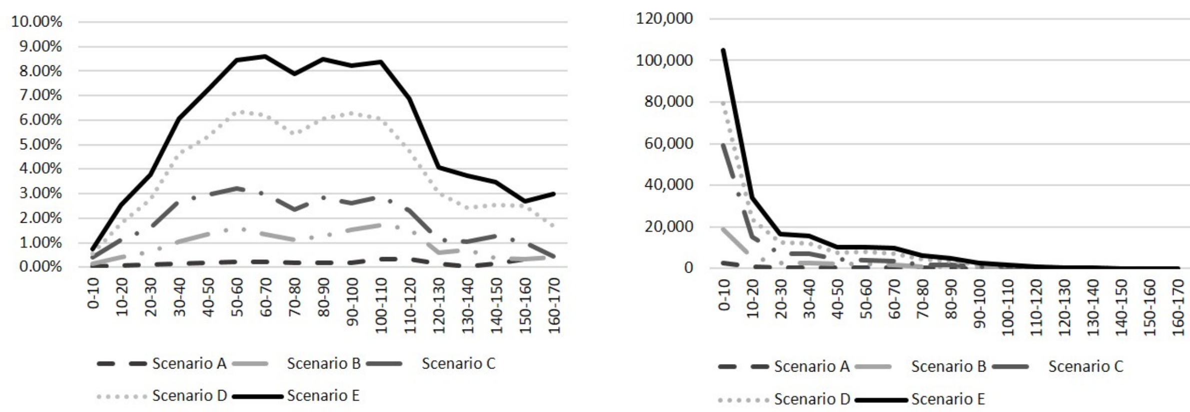
The framework described in section III was applied to simulate five developed scenarios (section IV). The simulation gives insight into UAM usage, amongst others with a focus on overall demand, demand shares, demand patterns with regard to time of day, trip length, dominant routes and highly demanded vertiports. Additionally, a better understanding of trips, their duration, their spatial distribution and the behavior of users can be gained. The following result description first gives an overview of overall UAM demand for the different scenarios and is followed by a discussion on modal shares. This information will be broadened and underpinned by discussions on demand at certain vertiports, along different routes, temporal trip distribution, the demand distribution for different trip lengths and the importance of airport access.

The overall number of UAM trips (Fig. 4) for the different scenarios already indicates the importance of the general system set up for the success of UAM. While in scenario A inhabitants generate demand 5,358 of UAM trips per day, the UAM system in scenario E is able to create a more than 40 times higher demand of 218,499 daily UAM trips. Overall the study area's inhabitants make nearly 17 million trips per day.

In the following, we analyze further simulation results with focus on modal split, vertiports, routes, trip distribution and airport passengers.

Table 2 Modal split of UAM per scenario

	A	B	C	D	E
Modal split UAM [% of 16.9 million trips]	0.03%	0.22%	0.62%	0.96%	1.29%
Modal split UAM [% of 122.5 million km]	0.05%	0.36%	0.93%	1.13%	1.60%



(a) UAM share per distance bin **(b) Number of UAM trips per distance bin**

Fig. 5 UAM demand in shares and absolute numbers per distance bin

A. Modal Split

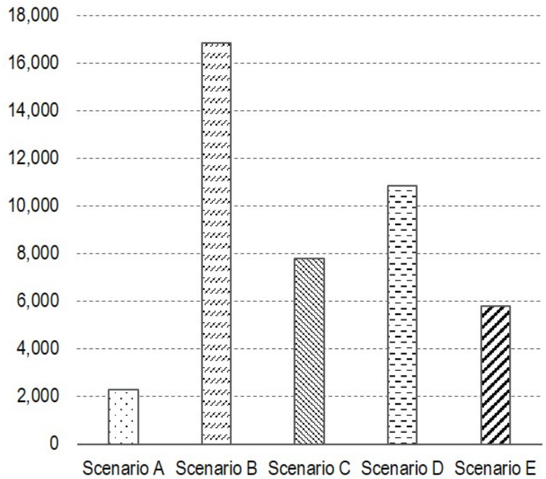
While these numbers appear to be relatively large, we do want to emphasize that even in the most positive scenario (scenario E), UAM trips only account for 1.6% of all passenger kilometers traveled within the greater Munich area during one day. In scenario A, UAM is only used for three out of 10,000 trips within the region. The modal shares per trip and per kilometer traveled for each scenario are given in Table 2. The numbers given in Fig. 4 and Table 2 point towards possible futures of UAM in the greater Munich area. As expected, scenarios do not attract a large number of passengers when: UAM and car travel speeds are similar; processing and waiting times for passengers at vertiports are comparable; and prices are approximately 20 times higher than for private car usage (scenario A). Nevertheless, even when massively decreasing kilometer-dependent fees and increasing travel speed, demand does not exceed 2% of modal split under our assumptions. Previous work using this framework [6] has shown that one of the drawbacks most scenarios face is excess demand, except for scenario E. With the given number of vehicles per station (10 or 50 depending on the scenario), UAM demand exceeds supply for each of the scenarios (see Table 1). Long waiting times are caused for passengers if no vehicle is available when requesting UAM. This result, in turn, makes UAM rather unattractive as a mode of transport. This finding is especially interesting when considering the (large) number of vehicles assigned to each vertiport. Straight forward calculations show that land demand is high when vertiports are required to accommodate 50 UAM vehicles and more. Moreover, this number still leads to capacity restrictions. We conclude that ground infrastructure, together with fleet size, will be crucial bottlenecks for UAM's success.

Comparing the modal shares on a trip and kilometer basis, we see that UAM is especially relevant for longer trips as the modal split is higher for kilometers traveled (Table 2). This finding is supported by Fig. 5 which shows the modal share for UAM on the left and the overall number of UAM trips on the right for the different scenarios over different distance bins.

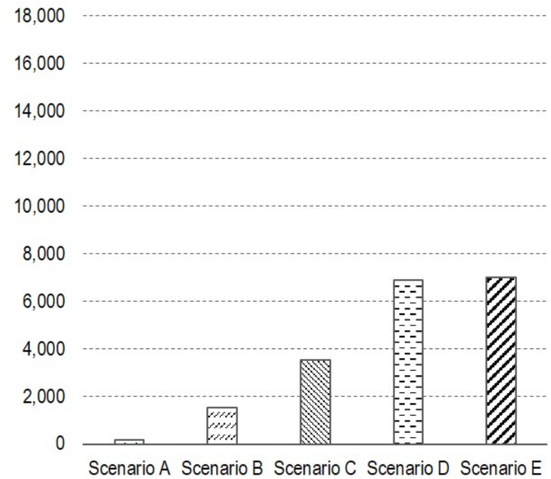
We do see high demand in absolute numbers of trips for short distances in all scenarios. Nevertheless, the modal share of UAM in the short distance bins shows that it is only a small share of people using UAM for short distances. In contrast to that, in scenario E, nearly 9% of trips between 60 and 120km are served by UAM. The trend is similar to scenario D and less visible for the remaining scenarios with higher kilometer-dependent prices. This is in line with results of the sensitivity analysis (Fig.3) which showed that the kilometer-dependent fare is a key driver of demand.

Table 3 Numbers of take-offs and landings at vertiports within and outside of Munich city

	A	B	C	D	E
Network density	low	low	medium	medium	high
Stations outside Munich city	71%	71%	59%	59%	60%
Take-offs and landings inside Munich city	7,979	57,406	162,725	232,482	289,148
	74%	76%	77%	72%	66%
Take-offs and landings outside Munich city	2,737	18,318	47,913	90,709	147,850
	26%	24%	23%	28%	34%



(a) Total daily UAM PAX of Hauptbahnhof



(b) Total daily UAM PAX of Flughafen Ost

Fig. 6 Passenger demand development per station for "Hauptbahnhof" and "Flughafen Ost"

B. Vertiports

As described in the scenario setup in section IV, the used networks vary for the different scenarios. While scenarios A and B use the low-density network with 24 vertiports in the study area, scenarios C and D are built on the medium-density network with 75 vertiports. Scenario E incorporates the high-density network that includes 130 vertiports.

Within these networks, the vertiports are spread over the study area. Table 3 shows that the low density network has the highest share of vertiports outside of Munich (71%) while the medium and high-density networks have approximately 60% of the vertiports outside of the Munich city.

Although most vertiports are located outside the city, most take-offs and landings take place within the city. Table 3 shows that this effect is rather stable over all scenarios, except for scenario E. Here, a third of all take-offs and landings are taking place outside of Munich city.

These findings are in line with the top vertiports for take-off and landing. In all scenarios, the ten vertiports with the highest demand are inside Munich. While the main station (Hauptbahnhof) is the most frequented vertiport in scenarios A and B, it loses importance with the increased number of vertiports, since demand spreads more evenly across different vertiports in the vicinity.

This trend can also be seen in Fig. 6. Fig. 6a shows passenger movements at the main station (Hauptbahnhof). At first sight, this development seems to be counter-intuitive. Yet, as described above, scenarios A and B use the same network where most demand focuses on the main station vertiport. When adding more vertiports in close proximity (medium and high-density network; scenarios C–E), demand is spread across more vertiports. This action also leads to a drop in demand at the main station vertiport from scenario B to scenario C even though demand overall is increasing. The same holds for changes from scenario D to E.

As shown in Fig. 6b, overall passenger numbers at the principle airport vertiport (Flughafen Ost) are lower than that at the main station. The figure shows absolute values, and therefore, it is hard to see that the above-described effect

Table 4 Demand on routes within and outside of the City of Munich

	A	B	C	D	E
demand on routes within Munich	3,056	22,471	72,411	98,340	118,404
	57%	59%	69%	61%	54%
demand on routes crossing Munich city's border	1,867	12,464	17,903	35,802	52,340
	35%	33%	17%	22%	24%
demand on routes outside Munich	435	2,927	15,005	27,454	47,755
	8%	8%	14%	17%	22%

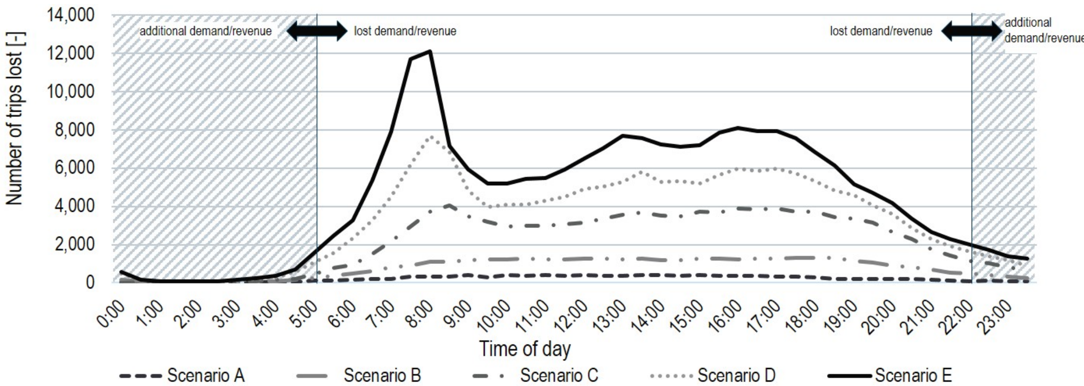


Fig. 7 Trip distribution by time of day

is also relevant to the airport. In the medium and high-density networks, the airport is served by a second vertiport (Flughafen West). Even though it is less attractive, it takes some of the demand away from the first airport vertiport (Flughafen Ost).

C. Routes

In addition to looking at demand per vertiport, it is also important to understand where people come from and where they travel to. Table 4 gives absolute numbers and shares for trips inside the city of Munich, trips crossing the city border and trips outside the city. These numbers show the relevance of Munich in the given study area even better. For scenarios A and B only 8% of trips start and end outside Munich, while nearly 60% take-off and land within Munich. For scenario C, the trips inside the city of Munich even account for 69%. When decreasing kilometer-dependent prices in scenarios D and E (1€/km), the demand on longer routes, especially routes starting or ending outside Munich, gain importance. It is especially noticeable when considering that only 16% of routes lie within the city of Munich for the full density network and nearly half of all routes cross the city border. However, Table 4 only shows shares of all UAM trips and does not put this in the context of all trips within the study area. As concluded from Fig. 5, in absolute numbers, most trips take place on rather short distances, which explains the emphasis on routes within Munich. The top routes for scenarios A to C mainly cover short distances and routes that are well served by public transport within Munich. For scenarios D and E, top routes are longer and are competing less with public transport services. This finding is in line with the results of the sensitivity analysis that show higher demand for lower kilometer-dependent fees (see Fig. 3).

D. Trip Distribution

Besides the spatial distribution of demand (over vertiports and routes), the distribution over time can also give valuable insight into demand patterns and can guide service design. Especially in Germany, where night curfews exist for conventional airports, it is essential to understand what impact night curfews could have for UAM.

Fig. 7 gives the absolute number of UAM trips for every hour of the day for each scenario. Cut-offs in the early morning and the late-night indicate potential demand losses if service operation is not possible during the night. Only minor losses would occur in all scenarios if night curfews were in place between 10:00 pm and 5:00 am.

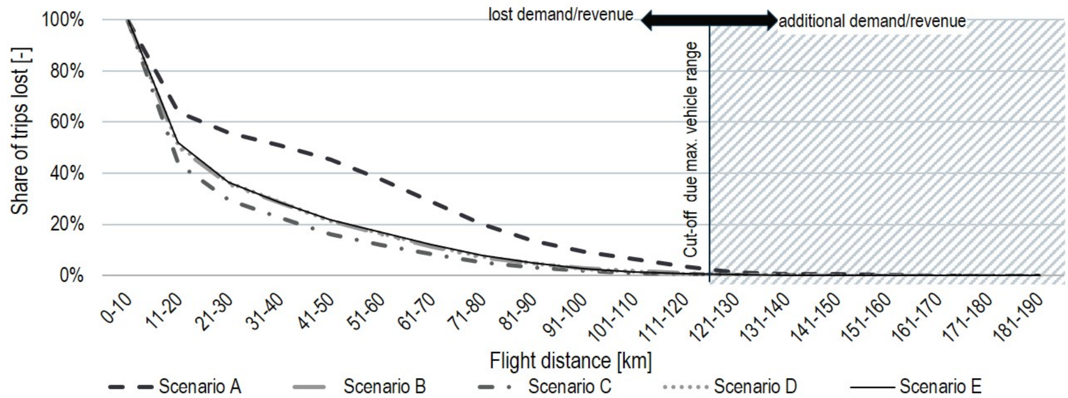


Fig. 8 Trip distribution by travel distance

Additionally, Fig. 7 gives insight into the trip distribution over the day. For scenarios D and E, a strong morning and a minor evening peak can be seen. Scenario C only has a small morning peak and in scenarios A and B no peaks can be seen. This effect was already visible in earlier work [6], where the authors were able to show, that small fleets do not allow for sufficient service offers to answer the demand. Even though UAM demand during peak hours would be higher in scenarios A and B, the small fleet size does not enable this demand to be served and limits the number of flights.

In order to define vehicle requirements, it is essential to also understand the distribution of demand across different trip lengths. In this context, it is especially important to keep in mind that the assessment only holds for the given study area. The maximum UAM trip length within the study area is 180 km.

Fig. 8 shows the cumulative share of UAM trips over flight distance. The cut-off at the right indicates trips that could not be served if vehicle ranges are not sufficient to serve all routes within the study area.

The figure (Fig. 8) shows that vehicles with a maximum range of 120 km would be sufficient to cover more than 95% of demand in all scenarios. The demand that would be cut off by using vehicles with this short range is marginal.

E. Airport Passengers

Airport access is one of the trip purposes often mentioned in the context of UAM. The study area in this research includes a major European airport. Travel to and from Munich airport, therefore, is relevant. The airport is served by up to two vertiports. Airport East (Flughafen Ost) is part of all networks, the medium- and high-density networks additionally include Airport West (Flughafen West).

To appropriately model airport access, airport passengers were included in the basic model setup, as described in section III. However, as MATSim and MITO have a strong focus on local inhabitants, we do expect that the share of airport passengers is still underestimated, since the model is not able to depict tourists that might use UAM service as part of their holiday experience.

Fig. 9 shows the share of all UAM trips per scenario that end or start at one of the airport stations (Flughafen Ost and Flughafen West). We can see that trips to and from the airport account for 3.21% to 6.11% of all UAM trips. The attractiveness of UAM for airport access increases with increasing geographical coverage of the UAM network. An exception is scenario E, where a decrease in comparison to scenario D can be seen. Nevertheless, in absolute numbers, demand increases from scenario D (9,874) to E (10,641). The second airport vertiport appears not to add additional demand but rather spreads demand across both vertiports.

VI. Policy Recommendations

The above-described simulation results for the different scenarios allow deriving first policy recommendations to enable a sustainable, efficient and socially accepted UAM service. Despite the scenarios show an unregulated situation, the results point towards possible drawbacks.

As described in [26], there are various reasons for political intervention regarding UAM introduction. The need for infrastructure could give rise to natural monopolies, in addition to that, negative externalities, such as noise or visual disturbance, demand for decision-makers to take action. A comparison with other modes of transport show, that

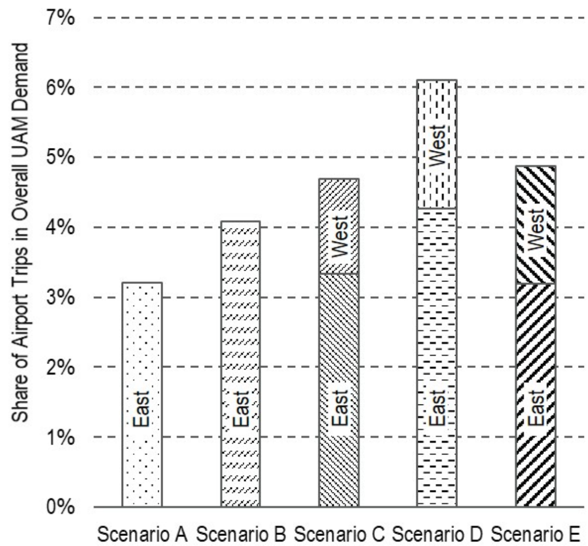


Fig. 9 Share of airport trips in overall UAM demand; consisting of demand at vertiports Flughafen Ost (east) and Flughafen West (west)

regulation can be strict, especially for transportation in urban settlements that have an impact on the population through negative externalities.

Policy measures that tackle these aspects can be divided into three categories [27]: quantity regulation (e.g. concessions), quality regulation (e.g. tender for the market) and price regulation (e.g. Ramsey pricing, peak-load pricing, subsidies). Transferring these measures to UAM could lead to the following measures and related aims:

- regulation on prices (price structure, level of prices):
  - limit market power
  - make UAM affordable for society access
- restriction of fleet size (concessions, tender for the market):
  - limit market power
  - limit negative externalities
  - ensure quality standards
- specification of network design (routes, vertiport location, no-fly zones):
  - limit negative externalities
  - prevent direct competition with PT
  - prevent short trips that are not in line with overall environmental goals
- limitation of operating hours (night curfew):
  - limit negative externalities

The simulation results show that an unregulated development can lead to situations that are not in line with overall development strategies regarding the environment, equity and multi-modality. Therefore, policymakers need to understand how efficient UAM systems could look like, in order to find common ground between different stakeholders and society. The following policy aims have been derived from our simulation results:

1) **Prevent cannibalization of publicly funded transport connections.** The simulation results show that many routes of high demand are well served by public transport. Taking travelers away from public transport can be adverse for several reasons. Firstly, energy consumption in mass transport can be expected to be lower than it would be when using UAM on the same trip in most cases. Thus, modal shifts from public transport to UAM would not be favorable from an environmental perspective. Secondly, there is a risk of cherry-picking, especially when assuming UAM operation through a private actor. UAM service offers on routes that so far have been profitable for the public transport provider could take demand from the public transport provider, increasing the public transport provider's need for subsidies. UAM introduction could, therefore, initiate a higher demand for fiscal revenues due to the public service character of public transport.
2) **Minimize negative impact on environment and society.** The simulations were conducted based on a vertiport

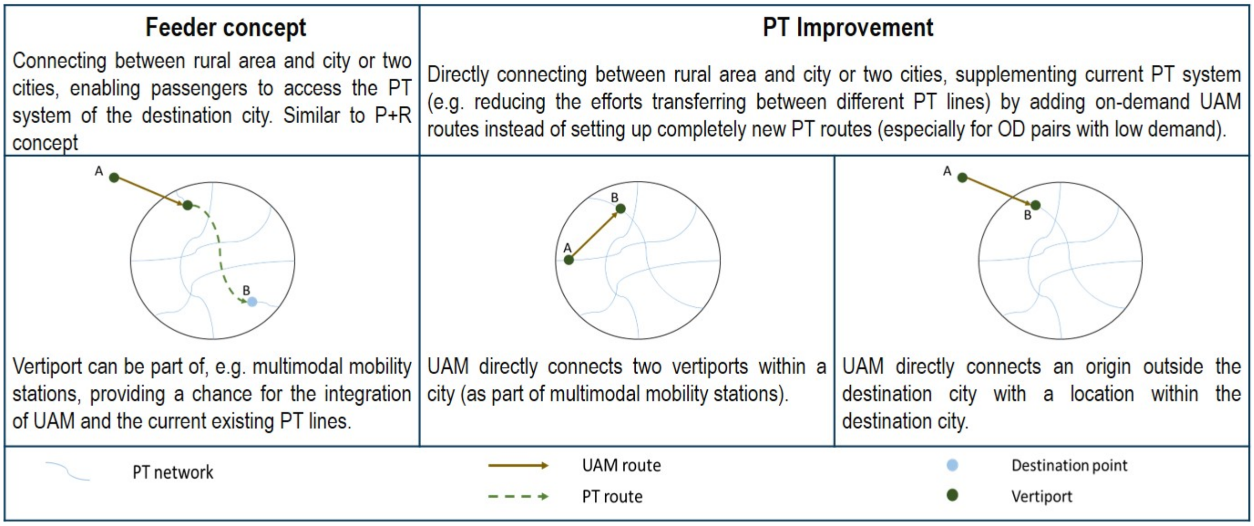


Fig. 10 Integration with public transport (Image source [28])

network with routes following ground-based transport infrastructure, in order to avoid flying above populated areas. However, this leads to longer travel distances compared to direct routes. Policymakers need to be aware of the trade-off between short routes and routes minimizing the negative impact for third parties (noise, visual annoyance). When introducing UAM, one of the core questions is to ensure flight routes that enable UAM operation that is consistent with overall environmental goals, and at the same time, to minimize risks and negative impact on third parties. A similar discussion has to be conducted with regard to vertiport locations. Vertiports that are too close to dwellings, schools and hospitals can have negative health impacts. Locations that are too far away can make the system unattractive for users. Policymakers need to be aware of user groups as well as population groups that are exposed most to the negative impacts: Routes that follow corridors with existing noise pollution are likely to be deprived areas, but due to the expected cost of UAM, we cannot assume that the population living in these areas will be a core user group of UAM.

Some of these high-level suggestions are tackled by network-design approaches aiming at a successful integration with public transport. A possible approach was first presented in an earlier version of this research [28].

The framework (Fig. 10) distinguishes between two aims, firstly, UAM serving as a feeder concept for the public transport system, and second, public transport improvement through UAM. In both cases, direct competition with public transport does not occur.

The feeder concept aims at setting up connections from rural regions or other cities to the public transport system of the considered city. The approach is comparable to the currently existing park-and-ride concepts. UAM can be used to travel to the first public transport stop, which enables passengers to travel everywhere within the city using public transport. This approach opens up several advantages. First of all, the accessibility of rural regions can be enhanced by enabling access to cities nearby. In addition, vertiports are not required inside the city but only at the outskirts close to multi-modal mobility hubs.

The public transport improvement approach aims at supporting the public transport system on routes that are currently not or not well served. On routes with low demand UAM might be advantageous, as en-route infrastructure is not required. Public transport improvement can either take place on intra-city level by connecting two vertiports inside a city, or on inter-city level by connecting two regions or cities. In contrast to the feeder concept, the user does not need to continue the journey using PT but already arrives very close to the final destination.

VII. Summary and Conclusion

Focusing on the greater Munich area, we use an agent-based simulation framework to evaluate the UAM market potential in the year 2030, influenced by a range of individual factors. This framework interloops the multi-agent transport simulator MATSim [2] with the transport orchestrator MITO [4], as shown in Fig. 2. For that same year and area, we furthermore use a synthetic population created by SILO [5], a stated preference survey [20] to define the mode choice using a nested logit model, and a transport network including a variable number of vertiports for UAM, as we described in section III. We then define a set of five scenarios, guided by a sensitivity analysis of individual factors from previous work [6]. Each scenario represents state-of-the-art technology (assumed for 2030) and operational decisions, such as ticket fares, fleet size, vehicle speed and UAM network density. The composition of scenarios, i.e. the specification of individual factors, aims to cover the range of transport offers from luxurious to suitable for the masses.

The simulation results give insight into UAM usage, with focus on overall demand, demand shares, demand patterns throughout a day, trip length, popular routes and highly frequented vertiports. Across all scenarios, the modal share for UAM ranges from 0.03% to 1.29% of total trips in the study area, see Table 2. The average modal share for UAM across the distance bins 60–70 km to 110–120 km increases from 0.2% to 8.1% for scenarios A–E, respectively. analyzing the number of UAM trips in terms of distance traveled shows that a large percentage of total UAM trips per scenario, between 48% and 56%, are short trips of up to 10 km, see Fig. 5. This is also reflected by the fact that most take-offs and landings occur at vertiports within Munich city: between 66% and 77% as shown in Table 3. It is to be noted, however, that a considerable number of trips connect to the airport, between 3.21% and 6.11%, see Fig. 9, and that this number is likely to be underestimated due to the focus on local travel behavior. Figure 7 displays the distribution of UAM trips throughout a 24-hour period. From the high demand during day hours, we conclude that night curfews from 10 pm to 5 am would not result in significant losses in revenue. Neither would a vehicle range limit of 120km as can be seen in Fig. 8. Further observations highlight that the infrastructure and fleet size influence waiting times, and therefore can have a substantial impact on UAM demand. In summary, we can say that we do not see UAM as a disruption to the mobility system, but rather as a means of supplementing current services by fast and flexible options.

The simulation results presented above show an unregulated development of UAM services. In order to maximize the benefits of this new mode of transport, policymakers need to understand how efficient UAM systems could look like. It is important to align the service with the city's overall development strategies regarding the environment, equity and multi-modality. In section VI, we make two policy recommendations. Firstly, use UAM to support and improve, rather than cannibalize, existing public transport options. Many routes with high demand are well served by public transport or they are particularly short. Taking travelers away from public transport risks higher energy demand or cherry-picking of routes by UAM operators. Second, ensure flight routes that enable UAM operation in line with overall environmental goals, while at the same time minimizing risks and negative impacts on third parties, such as noise and visual annoyance.

One limitation of this study is its applicability to other regions. The presented results and conclusions hold for the greater Munich area projected to 2030, but for regions with different income levels, location patterns, transport systems and population behavior, the results may differ. Additionally, the mode choices are susceptible to bias due to the hypothetical nature of the stated preference data regarding the new transport mode. Finally, the demand for UAM is assessed for local commuters and airport passengers only, however, survey results of a UAM market study have pointed out the propensity to use UAM for periodic leisure or recreational trips [29].

In the future, we plan to conduct a large-scale survey to collect both revealed and stated preference data. Using this mixed data for the mode-choice model, we aim to reduce the hypothetical bias which was caused by using stated preference data only. We also plan to apply our framework to other cities and regions, to cover a range of population and transport-network combinations. Furthermore, we would like to investigate the effects of the policy recommendations, for example by constraining UAM routes where they might compete with public transport options, balancing energy consumption with third-party impacts, or considering different types of pricing structures.

Other avenues of research could be extended from the local population to tourists and business visitors to the region, either in general or for special events such as major sporting events or trade fairs. Additional routes could be brought in that connect points of interest, or even the different sites of a company. Given that we consider UAM to be a niche transport option for the commuter market, these applications could open up interesting business avenues.

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