



A city-centric approach to estimate and evaluate global Urban Air Mobility demand

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Abstract

Urban Air Mobility is expected to effectively complement the existing transportation system by providing fast and safe travel options, contributing to decarbonization, and providing benefits to citizens and communities. A preliminary estimate of the potential global demand for UAM, the associated aircraft movements, and the required vehicles is essential for the UAM industry for their long-term planning, but also of interest to other stakeholders, such as governments and transportation planners, to develop appropriate strategies and actions to implement UAM. This paper proposes a city-centric forecasting methodology that provides preliminary estimates of the potential global UAM demand for intra-city air taxi services for 990 cities worldwide. By summing all city-specific results, an estimate of the global UAM demand is obtained. By varying the parameters of the UAM system, the impact of ticket price and vertiport density on UAM demand is shown. Considering low ticket prices and high vertiport densities, possible market development scenarios show that there is a market potential for UAM in over 200 cities worldwide by 2050. The study highlights the significant impact of low ticket prices and the need for high vertiport densities to drive UAM demand. This emphasises the need for careful optimization of system components to minimise costs and increase the quality of UAM services.

Keywords Urban air mobility · Global UAM demand · Market potential · Market development

Abbreviations

AMT	Alternate mode of transportation
EASA	European aviation safety agency
EU	European union
eVTOL	Electric vertical take off and landing
GC	Generalised cost
GDP	Gross domestic product
Km	Kilometre
KPI	Key performance indicator
NASA	National aeronautics and space administration
OD	Origin-destination
OEM	Original equipment manufacturer
PKM	Passenger kilometres
SF	Scaling factor
SLF	Seat load factor
Sk	Square kilometre
UAM	Urban air mobility
USA	United States of America

U.S	United States
VD	Vertiport density
VTT	Value of travel time
WTP	Willingness to pay

1 Introduction

Due to the increasing advances in new vehicle concepts and technologies, Urban Air Mobility (UAM) is expected to effectively complement the existing transportation system by providing fast and safe travel options, contributing to decarbonization, and providing benefits to citizens and communities. The concept of UAM is not entirely new. A first wave of urban air mobility took place between the 1950s and the 1980s, mainly enabled by the emergence of turbine-powered helicopters. But the use of helicopters as an urban transportation mode failed to take off due to a lack of profitability and social acceptance [1–3]. Currently, however, the integration of UAM into existing urban transportation systems as a complementary component is becoming more and more conceivable.

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The term UAM covers several use cases that meet different transport needs, such as intra-city, airport shuttle or suburban commuter [4]. In general, the term UAM is associated with an air transportation system based on a high-density vertiport network and air taxi services within an urban environment, enabled by new technologies and integrated into multimodal transportation systems. The transportation is performed by electric aircraft taking off and landing vertically, remotely piloted or with a pilot on board [5]. UAM has the potential to offer various advantages and benefits for different stakeholders. In this respect, UAM is expected to enable safer, cleaner and faster mobility within urban agglomerations. Studies have shown that the use of air taxis can save 15–40 min on an average standard urban travel time [5]. However, the introduction of UAM is associated with technological, regulatory, infrastructural, social and economic challenges, which require a holistic approach as well as close cooperation between the various stakeholders in order to unlock the full potential of this new mode of transportation. In this process, the UAM system components must be designed to ensure that the system is accessible, affordable, safe, secure and sustainable for users as well as profitable for operators [6].

Whilst initial eVTOL manufacturers are working on certification and plan to start first operations in 2024 [7–9], the global market potential of UAM is still unclear. A preliminary estimate of the potential UAM demand, the associated number of flight movements and the required number of vehicles would be helpful for e.g. manufacturers to plan upcoming production in advance. At the same time, the estimates can be useful for authorities, service providers or research institutions to assess the impact and effects of a potential UAM development from an overall system perspective at an early stage.

The fact that cities and metropolitan areas differ in several ways (area, population, geographic characteristics, wealth level, cultural background, etc.) is one of the main challenges in estimating the potential demand for UAM. From a global perspective, the development of specific transport models for each city, taking into account all transport-related parameters (e.g. mobility patterns, existing transportation infrastructure or transportation policies), is not feasible due to time and cost constraints.

This paper proposes a city-centric forecasting methodology based on a limited set of input parameters relevant for UAM to provide first estimates of the potential global UAM demand, aircraft movements and fleet size for intra-city air taxi services. In addition, UAM market shares for different regions of the world are given. This model is part of a holistic view of UAM, and amongst a set of forecasting models for each of the above use cases.

The remainder of the paper is structured as follows:

Section 2 provides a review of the research project's background. The importance of forecasting methods for estimating the global UAM demand is explored, along with an overview of existing literature in the field. Section 3 outlines the methodology and underlying assumptions of the study, to ensure transparency and replicability. The steps taken to estimate the global UAM demand for intra-city air taxi services are described in detail. The results of the research are presented in Sect. 4. 990 cities worldwide were analysed using the methodology. This section presents the effects of ticket price and vertiport density, as these factors are assumed to be main drivers of the demand for UAM. Also, different market development scenarios are examined. In Sect. 5, the main research findings are summarised, the limitations of the approach are highlighted, and potential future research is discussed. This section emphasises the significance of the present work and its potential impact on further UAM development.

2 Background

Demand forecasting is an essential component in designing the efficiency, the sustainability, and the profitability of new transportation systems. In particular, when evaluating new modes of transportation, the ability to accurately predict future demand enables various stakeholders to make informed decisions, optimise operations, reduce environmental impacts, and increase customer satisfaction. Forecasting capability is also critical for the evaluation and impact assessment of UAM as a novel urban transportation system. A preliminary estimate of the potential demand for UAM, the associated number of aircraft movements, and the number of vehicles required is fundamental to the further design of UAM. This will help stakeholders to develop appropriate strategies and actions to maximise the benefits of UAM whilst addressing potential challenges. Thus, a global UAM forecast can help plan vehicle production according to demand, use resources efficiently, coordinate transportation effectively, integrate ground infrastructure according to demand in cities, better support environmental goals, and set appropriate frameworks and safety standards.

However, forecasting the global UAM demand involves a number of challenges. As long as there are no UAM systems, it is not possible to base estimates of future development on historical data. Uncertainties also remain in connexion with technological development and market launch, which makes it difficult to make reliable long-term forecasts.

Urban transportation systems are extremely complex, multi-faceted and individual, as cities have different characteristics, such as population size, built-up area or wealth level, which have a direct impact on the people's mobility behaviour in each city and ultimately on the potential

demand for UAM. To address all these heterogeneous market conditions in one approach, a method is needed that is as simple and transferable as possible for all cities without the need to create individual, city-specific transport models.

Currently, many international research groups are working on different aspects of UAM in order to find optimal solutions for the implementation of UAM. However, regarding the preliminary estimation of global UAM demand, there is currently little research available. Initial market studies were carried out several years ago by consulting companies, such as Roland Berger [10], Horvath and Partner [11], Porsche Consulting [12] and KPMG [13]. These studies primarily provide an overview of the potential opportunities and economic benefits that could result from the introduction of UAM. However, they tend to provide less insight into the underlying methodologies and assumptions, making it difficult to transfer the methodologies and results.

On the other hand, there are a few publications in the scientific literature that present concrete methodological approaches to determine (global) UAM demand more precisely. These papers provide insights into the models, assumptions and data base used. They enable in-depth analysis and a better understanding of the factors influencing UAM demand.

Mayakonda et al. [14] developed a top-down methodology to estimate the UAM demand of individual cities based on a limited number of input variables. For each city, total transport demand, expressed as total passenger kilometres (PKM), is determined based on population and a regression between GDP/capita (independent variable) and PKM/capita (dependent variable). The resulting transport volume is disaggregated into classes by trip distance, trip purpose, ground mode used and income. For each class of transport volume, mode choice is modelled based on the willingness to pay (WTP) for UAM. WTP is estimated as the total value of time saved when using UAM plus the cost of the alternative mode of transport, taking into account a value of travel time savings (VTTS). VTTS depends on income and trip purpose. If the travel cost of the UAM trip is lower than the WTP, then the whole transport volume of the class considered will be allocated to UAM. Travel times are calculated taking into account the speeds of ground mode vehicles and UAM vehicles, access and egress to vertiports depending on vertiport density, and boarding and deboarding. By evaluating WTP and cost of a UAM trip across the entire range of values for trip distance, trip purpose, previous mode and income, transport figures, such as UAM passenger kilometres (PKM), UAM share of total ground PKM, UAM trips and utilisation of vehicles, can be identified.

Mayakonda et al. [14] used this method to estimate the UAM demand for 31 cities for the year 2035 for which UAM operations are expected in the near-term. Aggregated figures of UAM passenger kilometres (PKM), UAM share of total

ground PKM, UAM trips and vehicle utilisation are provided depending on the UAM ticket price and vertiport density.

The results indicate that UAM demand decreases dramatically as the UAM ticket price increases. Similarly, the demand for UAM decreases as network density decreases. The detailed results show that, depending on vertiport density, ticket prices below \$1 per kilometre are required for the aggregate UAM share to exceed 1 per cent in 2035.

Based on the approach of Mayakonda et al., Anand et al. [15] provide a low and a high demand scenario of global UAM market demand for the 2035–2050 timeframe. The methodology is applied to cities considered as viable for UAM operations, i.e. cities with more than one million inhabitants and a GDP greater than five billion USD for the year 2019 and 100 billion USD for 2050, resulting in 542 cities. Scenario variables are vertiport density, average speed and range of UAM vehicle, and VTTS, and are consistently chosen to result in high or low UAM demand. The authors provide aggregated figures of UAM trips, UAM passenger kilometres (PKM), UAM vehicle utilisation and UAM vehicle trips depending on the UAM ticket price. Anand et al. identify a ticket price of \$3.00 per passenger kilometre as the threshold below which significant UAM demand is likely to be generated. For this ticket price, the number of UAM passenger trips is between 20 billion per year (55 million per day) in the low scenario and 110 billion per year (300 million per day) in the high scenario.

Straubinger et al. [16] also conduct a scenario-based estimation of the global UAM demand. The analysis covers three UAM use cases, different urban archetypes, and three market development scenarios for the period 2020–2050. UAM use cases are inner-city transport, airport shuttle, and regional transport. Market development scenarios are “UAM as a niche”, “UAM complements high speed transport”, and “UAM as integral part of future intermodal travel”. 575 agglomerations with a population exceeding one million inhabitants in 2020 were considered as relevant for UAM applications. The agglomerations were grouped by a heuristic clustering approach, taking into account the population of the agglomeration, income, inequality of income and international trade and commerce. Six clusters of cities and their associated city archetypes were identified. For each cluster the average number of motorised trips per inhabitant and day with trip length less than 10 km is derived from the database of the Union Internationale des Transports Publics (UITP). Average distances of motorised trips per cluster are derived in reference to the average number of motorised trips. Based on US mobility data, the average number of motorised daily trips within the range of 10–300 km is set to 1.54 per inhabitant and day. In addition, the data allow to derive a distribution of trips over distance resp. the weighted average distance.

For each city, inner-city and regional total transport demand is calculated by multiplying the agglomeration's population with the associated trip rate. For the airport shuttle case, the premium passengers are considered as potential UAM users. Based on this, the UAM demand is determined by multiplying the total demand of each city and use case by market penetration rates. Market penetration rates are designed to capture all the uncertainties regarding prices, speed of travel, network density, access times and choice behaviour in a single number. These market penetration rates were determined by the authors to the best of their knowledge for each city cluster, each use case, and each market development scenario. Furthermore, the market penetration rates vary over time for the period 2020–2050.

Finally, the UAM fleet size is calculated for each agglomeration based on the average trip length (inner-city use case), resp. distance between the airport and the city centre (airport shuttle), and the distribution of trip distances (regional use case), taking into account the number of seats per aircraft, load factor and process times.

Market penetration rates are set in the range of 0–2 per cent (inner-city use case), 15 per cent (airport shuttle), and 7 per cent (regional use case). Tokyo and the clusters represented by the cities of Johannesburg and Mumbai receive the highest market penetration rates for the “UAM as integral part of future intermodal travel” scenario in 2050.

Straubinger et al. provide aggregated numbers of UAM vehicles required during the peak hour. Depending on the scenario, the total fleet size in 2050 will be between 0.68 and 5.5 million UAM vehicles. The majority of the fleet is used for inner-city transportation up to 10 km and varies between 0.5 and 4.2 million UAM vehicles.

In addition, there are several studies that have been conducted for smaller geographic areas and can be used as a guide both in terms of methodology and results. They are based on the four-step transportation model and make use of detailed travel behaviour surveys, high-resolution geographic and network data and calibrated models for trip generation, trip distribution and mode choice.

The study by Booz Allen Hamilton [17], commissioned by NASA, examined the air taxi demand for 10 U.S. cities at a very detailed level, taking into account not only potential demand but also possible systemic constraints, such as willingness to pay, infrastructure capacity, time of day and weather constraints. The results were then extrapolated to 484 urbanised areas in the U.S. In the near term. The combined potential demand for the air taxi and airport shuttle market is about 0.1% of total daily work trips (55,000 trips), which could be served by 4000 aircraft. The ticket price is estimated to be at least \$6.25 per passenger mile (\$3.88 or €3.61 per passenger kilometre).

Another study commissioned by NASA [18] investigated the market potential of air metro services, resembling

current public transit and on-demand air taxi services for different U.S. cities. Taking into account the target markets, consumers' willingness to pay and the availability of the technology, demand was determined. By multiplying the total number of expected trips in each city by the percentage of trips eligible for UAM, the market size was calculated. The results indicate, that air metro services may have a viable market in the near future, but not the air taxi, as the cost of ubiquitous vertistops may be too high.

Ploetner et al. [19] investigated the market potential of UAM for public transport in the Munich metropolitan area. An existing agent-based transport model was extended by socio-demographic changes until 2030 and the integration of intermodal UAM services. To simulate the demand for UAM, an incremental logit model was used. The study defines three UAM networks with different numbers of vertiports and performs sensitivity analyses on factors, such as fare, vehicle speed, passenger check-in times at transfer stations and network size. For the reference case, the total modal share of UAM is about 0.5% of the total transport volume.

Rihmja et al. [20] conducted a demand estimation and feasibility assessment for UAM in Northern California Area with focus on commuting trips. A sensitivity analysis was conducted to examine the impact of cost per passenger mile and number of vertiports on UAM demand. The spatial distribution of UAM demand in the region is also analysed, with the San Francisco Financial District identified as a major attraction for commuter trips. The results show that low UAM fares and UAM reliability comparable to car travel are necessary to achieve sufficient demand and reduce empty flights. Furthermore, high-income households account for the majority of demand.

Pertz et al. [21] developed an approach for modelling the UAM commuter demand in Hamburg, Germany. The approach is based on a discrete choice model that predicts commuters' mode choice. For this purpose, predefined traffic cells are used to generate and distribute a door-to-door commuter traffic. By combining the modal split and the market volume for commuting, the market share for commuter UAM traffic in Hamburg is determined. The model offers the possibility to evaluate individual passenger routes and catchment areas as well as to analyse characteristics of travellers and routes with high and low demand. The UAM market share of the commuter market in Hamburg is estimated to be 0.24%.

In summary, the approaches used to estimate UAM demand differ significantly at the local and global levels.

Studies conducted for a single geographic area use an approach using detailed models of trip generation, trip distribution and mode choice. This approach to transportation modelling and forecasting requires high-resolution, spatially distributed and data-intensive information, with

both socio-demographic and trip purpose data serving as the basis for the modelling.

However, at the global level, comparable data are not available for each individual city to model total demand and mobility behaviour with the same quality as on the local level. Therefore, global approaches attempt to simplify modelling using high-level socio-economic and geographic data. The work of Straubinger et al., Mayakonda et al., and Anand et al. show different ways to estimate total transport demand and UAM demand, but other approaches seem to be possible.

Global approaches tend to group cities with similar characteristics into clusters, perform analyses for one representative city per cluster, and apply the results to all other cities in the cluster. For example, Mayakonda et al. and Anand et al. use the same representative distance distribution and Straubinger et al. use the same market penetration rate for each individual city in the cluster. However, clustering can significantly distort the results.

The UAM share is determined in various ways. Mayakonda et al. and Anand et al. use a mode choice model with the willingness to pay (WTP) approach. The WTP approach allows a direct correlation with the income distribution, but only allows for the consideration of two competing modes. Straubinger et al., on the other hand, use predefined UAM shares that are identical for cities within a cluster. Since determining the UAM share is essential, it seems appropriate to test whether other approaches to model mode choice are suitable and applicable.

This study proposes a methodology that focuses on individual cities by avoiding clustering and is able to account for a spatial distribution of transportation demand, but is still based on a limited set of input parameters. The spatial distribution may enable a more precise representation of the entire air taxi travel chain, considering both the location of the vertiport locations and pre- and onward-carriage. Furthermore, a simplified logit model is used for mode choice. In addition, the cities suitable for UAM are selected based on the number of vertiports, which depends on the area and wealth of a city.

The methodology is designed to be expanded further. The flexible design of the forecasting methodology allows for the individual specification of parameters, taking into account new insights and data to improve the long-term estimation of UAM demand and the analysis of market potential in global urban areas. Our methodology seeks to combine the benefits of high local resolution with global generalisation to provide a comprehensive analysis of UAM demand.

3 Methodology

This paper proposes a different forecasting methodology to provide initial estimates of the potential global UAM demand for intra-city air taxi services following the ideas of the traditional four-step transportation model. The four-step model [22] is a widely used approach for the determination of total and mode-specific transport demand, amongst others. It requires a detailed database including information on population, household size and income, activity patterns, on existing and future transportation infrastructure, supply, pricing etc. At a global stage, these data are not available at a sufficient level of detail. Therefore, a city-centric approach (Fig. 1) was developed that uses a limited number of parameters to estimate the UAM demand for a city or an urban agglomeration. The characteristics of the city that serve as the main input parameters of the city-centric approach are the number of inhabitants, the urban area and the country-specific GDP per capita as a proxy for the level of wealth. These data are available for the present and for the future, some of them publicly and some of them commercially. The model approach focuses on intra-city passenger transport. Thus, only trips that start and end within the city boundaries are included in the analysis. Passenger demand, that exists between cities is not calculated in this approach and would require an extended forecast method. Demographia's World Urban Areas Data-base [23] serves as database that covers 990 urban agglomerations with more than 500,000 inhabitants and provides the number of inhabitants, the population density and the built-up urban area of each agglomeration in the year 2022. GDP per capita (real, harmonised) is taken from [24]. The number of inhabitants and GDP per capita in the future is determined

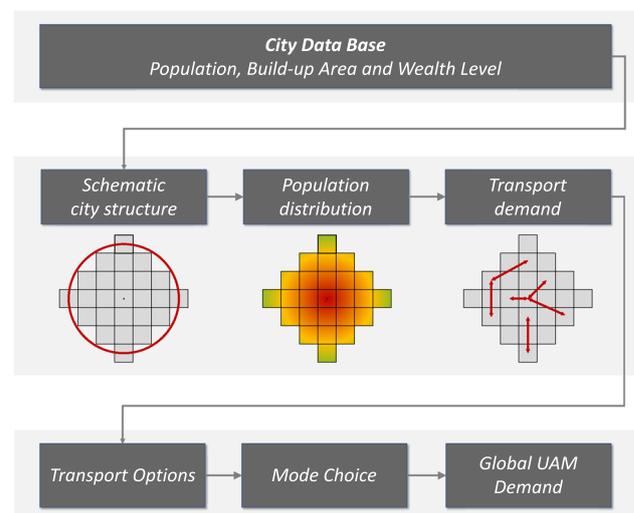


Fig. 1 Concept of the city-centric forecasting approach

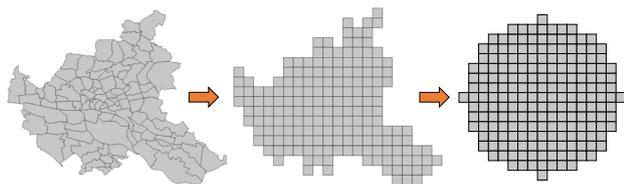


Fig. 2 From original city shape to generic shape - example of the City of Hamburg, Germany

by applying country-specific growth rates of population [24] and of GDP per capita by [24].

By applying this method to a set of worldwide cities and summing up all city-specific results, an estimate of global UAM demand for intra-city air taxi services is provided. Variation of major characteristics of the UAM transportation system allows different scenarios to be developed and analysed.

UAM transport demand is derived in five main steps:

Schematic city structure

First, each city is mapped onto a circular structure consisting of square grid cells. Using Hamburg in Germany as an example, Fig. 2 shows how the generic circular city shape is generated from the real extension of the city by transforming it into a grid cell structure. The actual shape of the city is omitted due to the lack of data on the city shapes of all the 990 cities considered. Instead, the shape is approximated to a circle using the city area and a predefined grid cell size which is the same for all cities. The smaller the edge length of each cell is chosen, the more detailed the city structure can be described. Here, each cell has an edge length of 2 km, which has been found to be suitable with regard to the calculation performance and level of detail.

Population distribution

Second, the population is distributed amongst the grid cells with the highest population density in the centre grid cell. The population density decreases from the centre grid cell with increasing distance to the city outskirts. The distribution of the population is based on two universal patterns which can be observed worldwide: the greater the distance from the city centre, the lower the density and the larger the city, the more distance is needed for the population density to decrease [25]. The population distribution is achieved using Eq. (1). It determines a population density factor p for each grid cell based on its distance d from the centre grid cell in relation to the maximum distance d_{\max} between the centre and the outer grid cell. The factor x indicates the ratio between the population density in the city centre and in the outer grid cell, whilst the value k is a reference for the

population density in the outer grid cell of the city and is used to shape the progression of the equation.

$$p(d) = e^{(\ln(x*k) - \ln(k)) * \frac{d_{\max} - d}{d} + \ln(k)} \quad (1)$$

To determine the population density for each grid cell, the total population of the city is distributed amongst the grid cells in proportion to the size of the individual density factor p .

For all cities examined, it is assumed that the population decreases by a factor $x=10$ and the reference value $k=2$, from the centre to the edges of the city (Fig. 3). Very similar developments can be observed in different cities around the world. In North American, East Asian and Pacific cities with populations larger than 10 million, the size assumption of this factor is best expressed, whilst it varies with population size and world region [25].

Transport demand

Third, a trip table (OD matrix) is constructed, indicating the number of trips between each pair of grid cells. For this purpose, an average daily trip rate per person is used to determine the number of trips originating from a cell. It is assumed that each person makes on average three trips per day, with no distinction made by trip purpose, household income, sex or age. The assumption is based on the “Mobility in Germany” report [26], although this figure may change in relation to socio-demographic characteristics in different countries and cities [27, 28].

Then the resulting trips are distributed to all other cells using an empirical trip length distribution. For now, the trip length distribution is based on GPS car movement data from the U.S. metropolitan region of Dallas, TX [29], shown in FIG 4. The Dallas metropolitan area provides a good basis for the model approach due to its roughly circular structure and covers trips length up to

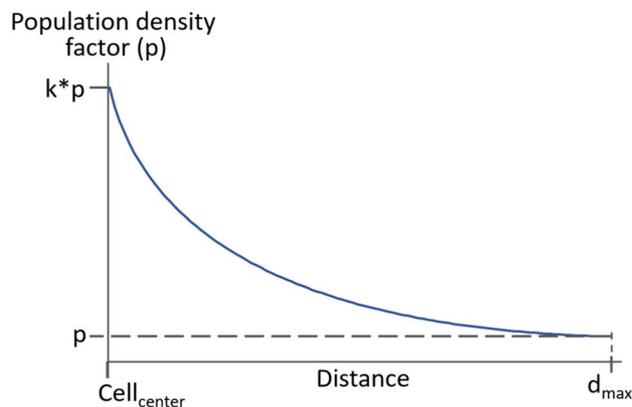


Fig. 3 Population density factor versus distance from the city centre

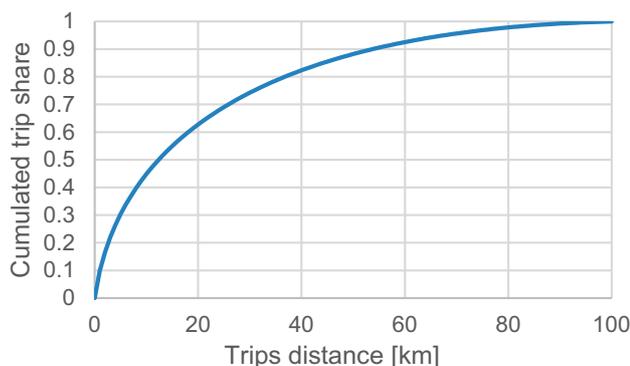


Fig. 4 Empirical trip length distribution of the U.S. metropolitan region of Dallas, TX

100 km, which allows for good transferability between the schematic city structure and the real geographic structure.

Figure 4 reveals that 99% of the total population’s trips are made up to a distance of 100 km. This entails the characteristic that trips in cities with smaller areas are not completely covered within the city boundaries, but additionally go beyond them. For example, in a city with a maximum distance of 40 km within the urban area, almost 82% of trips are made inside the city boundaries and 18% of trips go beyond them.

For use in the model, the empirical trip length distribution of Dallas is approximated by Eq. (2).

$$\text{Cumulated trip share} = 0.2051 * \log(\text{trip distance}) + 0.0592. \tag{2}$$

Due to the symmetric shape of the generic city and the arrangement of grid cells, single discrete distances occur between multiple pairs of grid cells. Therefore, the number of total trips per discrete distance must be divided amongst the corresponding pairs of grid cells. Once this procedure is completed, a predefined percentage of outbound trips is determined for each grid cell. Trips remain within a grid cell for a discrete distance equal to half the length of a grid cell edge. This predefined percentage of outbound trips is then adapted according to the population of the destination grid cell. For equal discrete distances between two or more pairs of cells with the same origin cell, the population size in the destination cell affects how high the trip number is on each pair of cells. In this way, the attractiveness of grid cells is highlighted and considered by grid cell specific characteristics, which in this case is expressed by the size of the population. This allocation represents the final step of the trip distribution calculation that leads to the final OD matrix.

Transport options

The fourth step is to create the transport options. It is assumed that in addition to the air taxi, there is an alternative mode of ground transportation (AMT) that represents the mode that is currently being used (Fig. 5). For now, the alternative mode of ground transportation is represented by the cost and speed parameters of a private car. For each OD pair, travel times and travel cost are determined for both modes of transportation.

The alternate mode trip consists of a direct connexion between origin and destination. The associated travel time is calculated based on the linear distance between origin and destination and assuming a constant average speed of 18 km per hour [30]. The monetary cost of an alternate mode trip is calculated using a price per km and a detour of 20 per cent. The price per km varies from country to country depending on many factors, such as market prices for the vehicle, maintenance and insurance, vehicle age, energy consumption or the structure of charges and taxes [31]. Costs

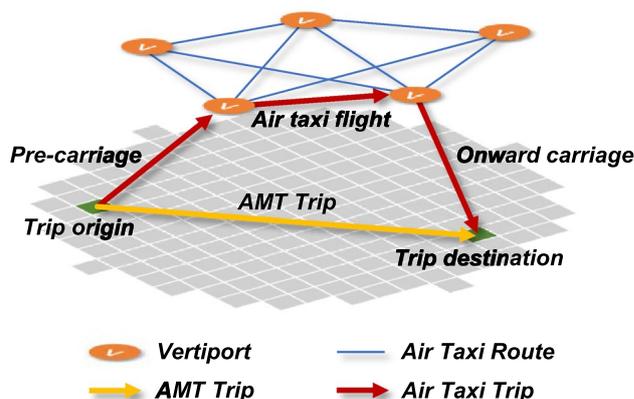


Fig. 5 Itineraries for air taxi and for alternative mode of transportation

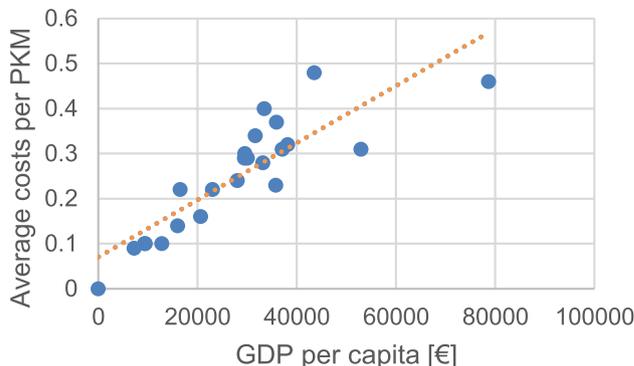


Fig. 6 Average costs per PKM of the car versus GDP per capita in the EU and the US [31]

are determined based on results of the EU-funded project COMPETE (Fig. 6), which analysed the average operating costs per PKM by car in the EU and the USA taking into account key macroeconomic indicators, such as information on national fleet structure, average fuel consumption, GDP per capita adjusted for purchasing power, national interest rates and different degrees of liberalisation [31].

Based on the results of, Eq. (3) was derived using linear regression analysis to determine the average cost per km for the alternative mode. As the analysis was already carried out in 2006, the average operating costs were adjusted by a factor of 1.7 to reflect current market conditions regarding the increased average operation cost per km since 2014 [32].

$$\text{Costs}_{\text{amt}} = (6 * 10^{-6} * (\text{GDP per capita}_{\text{country}}) + 0.0703) * 1.7. \quad (3)$$

The air taxi trip consists of three segments: pre-carriage, air taxi flight and onward carriage. In order to model air taxi trips, first vertiports are evenly distributed by placing them using the sunflower algorithm (Fig. 7) [33].

The number of vertiports to be placed depends on the city area and a prescribed vertiport density vd_{city} . Vertiport density varies from city to city, dependent on the city area and GDP per capita, and is determined for each city individually. It can be expected that cities with lower levels of wealth will have more difficulty building high-quality transportation systems, resulting in lower vertiport density. Additionally, smaller cities typically have shorter distances to be covered, so lower vertiport densities are expected.

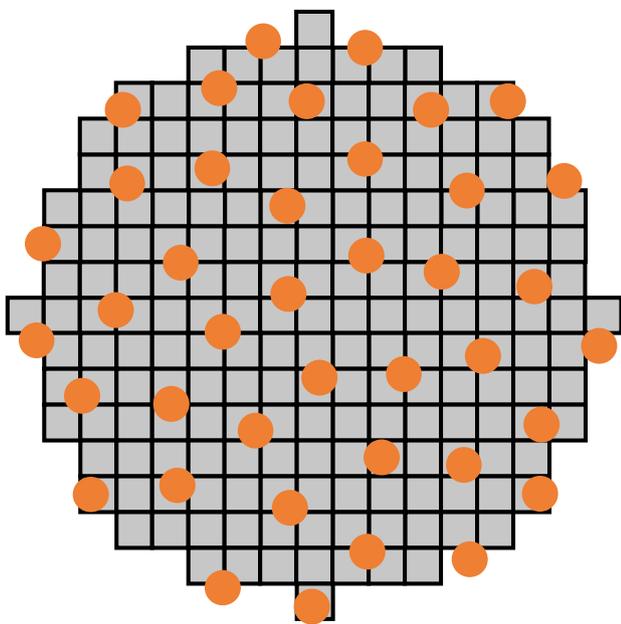


Fig. 7 Schematic city with 253 grid cells and 40 vertiports

For this purpose, a vertiport density vd_{ref} is assumed, which can be understood as a target value and is valid for cities with an area larger than 3000 km² and a GDP per capita equal to or larger than that of the United States. Cities with area and GDP per capita greater than or equal to the reference values are assigned the vertiport density of the reference city. For all other cities, the vertiport density is scaled down using a scaling factor for the area (SF_{area} , Fig. 8) and for the GDP per capita (SF_{GDP} , Fig. 9), considering the different city characteristics. The scaling functions are designed in a way that a small deviation in GDP per capita has a significantly larger impact on the scaling factor than the area of the city, which only has an influence when the city has only around 1/5 of the area of the reference city. Depending on how the urban area and GDP per capita of the city under consideration differ from the values for the reference city, the reference vertiport density is adjusted resulting in a city-specific vertiport density vd_{city} :

$$vd_{\text{city}} = vd_{\text{ref}} \cdot SF_{\text{area}} \cdot SF_{\text{GDP}}, \quad (4)$$

where SF_{area} and SF_{GDP} are the scaling factors, and vd_{ref} is the reference vertiport density.

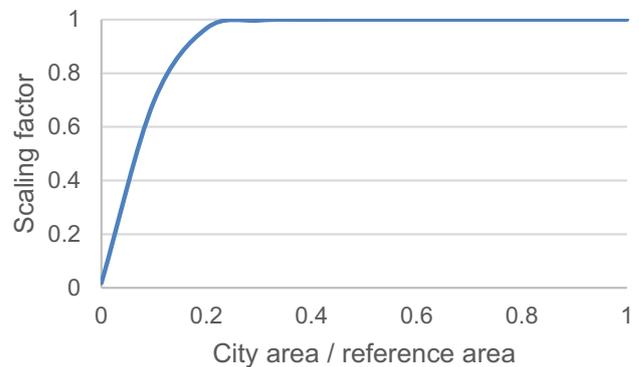


Fig. 8 Function for determining the scaling factors for the area

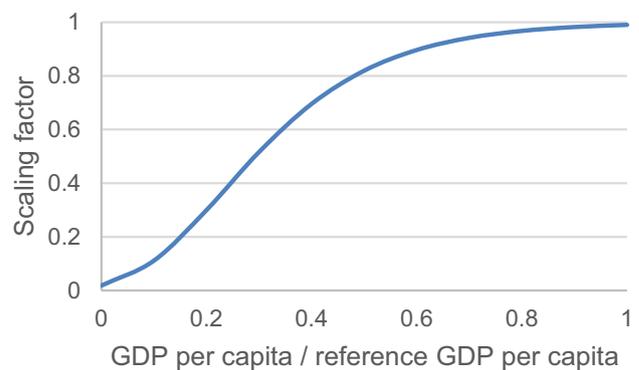


Fig. 9 Function for determining the scaling factors for the GDP

Furthermore, it is required that the number of vertiports of a city is at least five. The reference value of the vertiport density can be varied to investigate the impact on the air taxi demand.

The pre-carriage from the origin to the next vertiport and the onward carriage from the arrival vertiport to the destination are performed by car. The monetary cost and time of travel by air taxi are composed of the cost and time of the flight and of the ground transportation to and from the vertiport. The cost and time for the flight are calculated based on the linear distance between the departure and the arrival vertiport and considering a detour of 5 per cent. Cruise speed is set to 100 km/h. Time for take-off and landing is set to 2 min each. In addition, 3 min each are added for boarding and deboarding. Further, it is assumed that the itinerary is seamless, so there is no additional waiting time at the vertiport. Travel costs for the flight are determined using an air taxi ticket price per km, which is constant for all countries and can be varied to study its effect on air taxi demand. The cost and time for the first and last mile are determined based on the linear distance between origin and departure vertiport resp. between arrival vertiport and destination, using the ticket price per km, the speed and the detour factor of the alternate mode.

Mode Choice

In the last step, a simplified multinomial logit model is applied to determine the mode choice between the car as alternate mode of transportation and the air taxi. It is assumed, that the mode choice depends primarily on cost and time. Considering the characteristics of transport options between each pair of grid cells, the air taxi share of each OD pair i - j is calculated by (i and j omitted for simplicity):

$$P_{\text{air taxi}} = \frac{e^{U_{\text{air taxi}}}}{e^{U_{\text{air taxi}}} + e^{U_{\text{amt}}}}, \tag{5}$$

where $U_{\text{air taxi}}$ and U_{amt} are the utilities of the air taxi and the alternate mode. The utilities are calculated as:

$$U_m = \beta_m + \beta_{GC} \cdot GC_m, \tag{6}$$

where U_m is the utility of mode m , β_m is the mode-specific constant, and β_{GC} is the parameter associated with the generalised cost of travel GC_m of mode m .

The mode-specific constant can be interpreted as the average effect of un-included factors on the utility of an option relative to the other alternatives [34]. Since there is currently no reliable information on whether users tend to prefer the air taxi over the car or not, it is first assumed that $\beta_{\text{amt}} = \beta_{\text{air taxi}} = 0$. This assumes that mode choice depends only on travel time and cost. β_{GC} generally varies depending on factors, such as trip purpose and car availability

[35]. In the context of this work, which refrains from further differentiation of trips and travellers, we obtained reasonable results with values of β_{GC} between -0.2 and -0.3.

Generalized costs involve variable monetary costs of a trip and monetized travel time:

$$GC_m = c_m + VTT \cdot t_m, \tag{7}$$

where GC_m is the generalised cost of travel from origin i to destination j with mode m , c_m and t_m are the costs and the time associated with the trip, and VTT is the value of travel time.

VTT is the monetary value of travel time reduction, in other words: how much it is worth to a user to reduce travel time by a time unit, usually by an hour. Since travel time can be thought of as a disutility, consumers are generally willing to pay to have less of it. VTT can vary significantly depending on many different factors, such as the purpose of the trip, the traveller’s income, the mode of transportation or the weather conditions, and is usually different for each person [36]. On a global scale, it is challenging to determine VTT taking into account these specific factors due to limited data availability. Therefore, VTT_{city} is calculated as a function of the GDP per capita:

$$VTT_{\text{city}} = 0.0003 * (\text{GDP per capita}_{\text{country}}) - 0.3404. \tag{8}$$

Equation (8) is based on an extensive meta-analysis by Wardman et al. [37] that considered 3109 monetary valuations from 389 European studies conducted between 1963 and 2011, shown in Fig. 10.

Finally, the total air taxi demand is obtained by multiplying the air taxi modal split of each OD pair by its respective trip demand and then summing.

In addition to air taxi demand, total air taxi movements and fleet size are estimated based on the total number of air taxi trips of each city. The number of seats per aircraft, the average seat load factor (SLF), and the air taxi utilisation per hour are taken into account, assuming that the

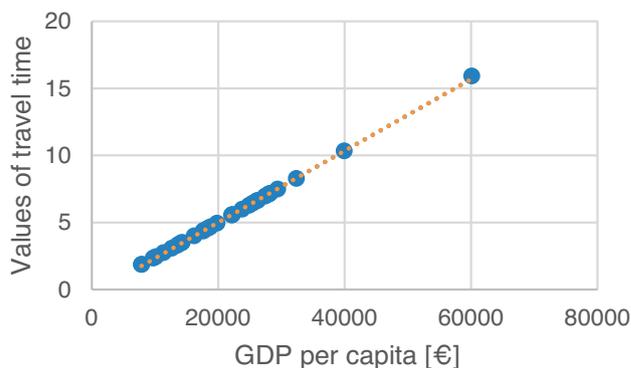


Fig. 10 Value of travel time by GDP per capita

aircraft have four seats, the SLF is 50%, and the vehicle can be utilised 33% of the time.

The total number of air taxi movements per city is calculated by:

$$\text{movements} = \frac{\sum \text{air taxi trips}_{\text{city}}}{(\text{seats per aircraft}) * \text{SLF}} \quad (9)$$

The fleet size per city is calculated by:

$$\text{fleet size} = \frac{\sum \text{air taxi flight time} p.d._{\text{city}}}{(\text{seats per aircraft}) * \text{SLF} * \text{utilization} p.h.} \quad (10)$$

In conclusion, all city-specific results are summed up to estimate the global demand for UAM, the global number of air taxi movements and the global fleet size.

4 Results

The methodology described above was applied to 990 cities worldwide with populations greater than 500,000 inhabitants. In the first step, a parameter study was performed to better understand the dependencies and effects of the UAM specific model parameters ticket price and vertiport density. In a second step, different market scenarios on global UAM demand, aircraft movements and fleet size are outlined.

4.1 Parameter study

In the parameter study, the effects of two crucial factors, the air taxi ticket price per km and the vertiport density per km², are evaluated, which are main drivers for UAM demand [38]. The air taxi price per km is directly related to the customers' willingness to pay and, together with travel time, is a key factor influencing the choice of transportation mode. The density of vertiports affects the time needed for access and egress and therefore has a significant impact on the total travel time.

Figure 11 shows the global demand for UAM as a function of air taxi ticket price at constant vertiport density. Air Taxi price per km is varied between 2.50 and 6.00 €/km. Within this range, demand is the highest for each given vertiport density, at the ticket price of 2.50 € per km. An increase in price leads to a decrease in demand. In this case, demand decreases very steeply at first and then more gradually. This curve progression is similar for all vertiport densities. Whilst at the lower vertiport density, the demand is practically zero at an air taxi ticket price of about 3.50 € per km, at the higher vertiport density there is still demand up to a price of 4.50 € per km. This is due to the fact that at higher vertiport densities the times for pre-carriage and

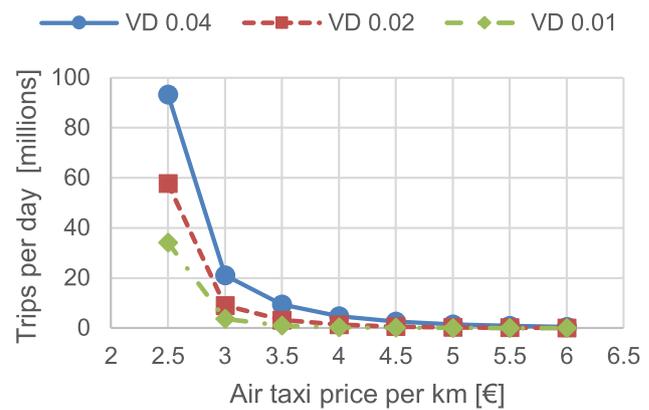


Fig. 11 Global daily UAM demand versus air taxi ticket price per km [€]

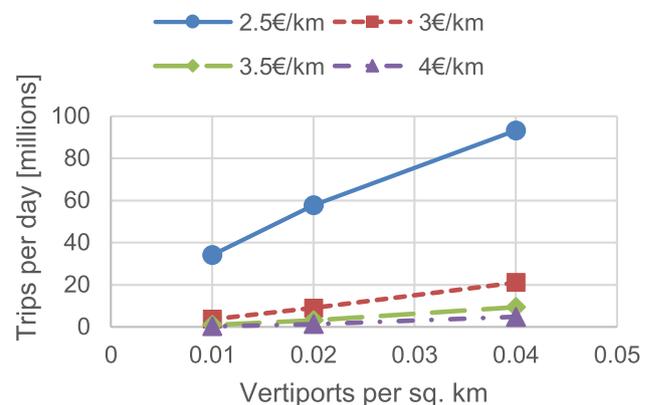


Fig. 12 Global daily UAM demand versus vertiport density

on-carriage are lower, making the air taxi attractive to a larger share of traffic demand even at higher prices.

Figure 12 shows the global UAM demand as a function of vertiport density at constant air taxi ticket prices. At low vertiport densities, demand is small and almost disappears at air taxi prices of 3.00 € per km and above. Only at an air taxi ticket price of 2.50 € per km there is a notable demand, even with a vertiport density of 0.01. This is due to the fact that the low price compensates for the relatively long pre- and post-trip times that apply to much of the demand at low vertiport densities. Thus, at constant price, demand increases when vertiport density is increased.

Table 1 shows the results of the parameter study for the variation of air taxi ticket prices and vertiport densities.

4.2 Market development

The city-centric forecasting approach is used to outline different possible development paths of UAM until the year 2050. Four market development scenarios (S1–S4)

Table 1 Number of daily UAM trips for different air taxi ticket prices and vertiport densities

Number of Daily UAM Trips		Vertiport density /km ²		
		0.01	0.02	0.04
Air taxi ticket price [€] / km	2.50	34,178,038	57,736,491	93,253,541
	3.00	3,669,134	9,020,090	21,070,562
	3.50	988,826	3,193,060	9,392,581
	4.00	318,304	1,327,331	4,791,927
	4.50	108,973	587,926	2,585,372
	5.00	38,912	270,569	1,441,318
	5.50	14,342	127,540	820,061
	6.00	5,415	61,105	473,132

Table 2 Vertiport density and air taxi ticket prices for the four scenarios

	Vertiport density	Air taxi prices
Scenario 1	High	Optimistic
Scenario 2	Low	Conservative
Scenario 3	High	Conservative
Scenario 4	Low	Optimistic

are considered with different assumptions regarding the development of vertiport density and air taxi ticket price per km over time. External market conditions, such as population growth and wealth development, are identical throughout the scenarios.

The air taxi ticket price per km affects the affordability and the vertiport density determines the accessibility of UAM services, both important aspects of user acceptance. By defining a high and low vertiport density evolution and an optimistic and conservative price evolution, four market scenarios are elaborated (Table 2).

The different scenario characteristics can illustrate different development paths. A low vertiport density in a scenario may reflect the fact that only a few vertiports can be placed for political, environmental or social reasons. Lower ticket prices may be the result of technological advances in vehicle and infrastructure automation.

The assumptions regarding air taxi ticket prices per km are based on studies by Pertz et al. [39]. Using a cost and revenue model for inner-city air taxi services, they found that under favourable conditions, an air taxi fare of 4.10 €/km is required to operate profitably. Under less favourable conditions, an air taxi fare of 5.70 €/km is required to ensure sound profitability. These values are used as a baseline for the year 2030. For further market development it is assumed that these prices decrease linearly by 1/3 until 2050, shown in Fig. 13.

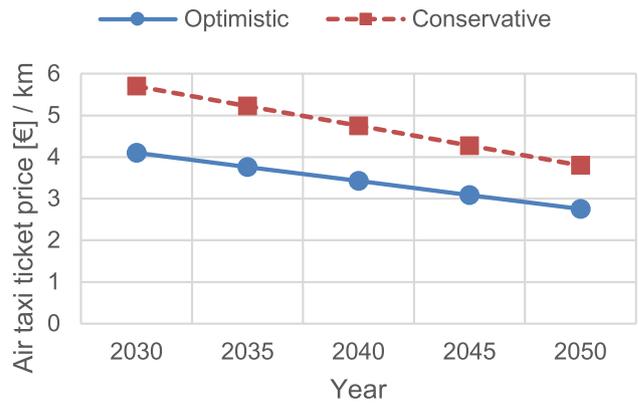


Fig. 13 Development of air taxi ticket prices over time

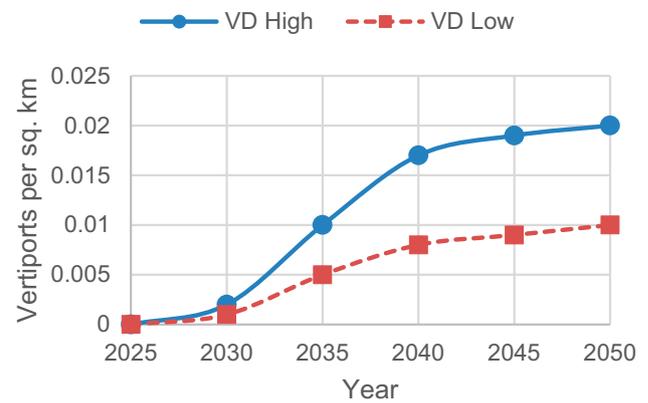


Fig. 14 Development of vertiport density over time

As the vertiport density of a city is linked to the reference vertiport density (Sect. 3), development paths are assumed for the reference vertiport density (Fig. 14). For the scenarios with high vertiport density, it is assumed that the reference density of 0.002 vertiports per km² in 2030 will increase to 0.02 vertiports per km² in 2050. According to Mayakonda et al. [14], this corresponds to an average access and egress distance of 9 and 3 km, respectively. For the scenarios with low vertiport density, the reference vertiport density increases from 0.001 vertiports per km² to 0.01 vertiports per km² in the same period. This is equivalent to an average access and egress distance of 12 and 5 km, respectively. Thus, the potential development of vertiport density is significantly lower in the second development path (Fig. 14).

The evolution of the daily UAM demand, the number of movements and the corresponding fleet size for the scenarios are shown in Figs. 15, 16 and 17. They are similar for all four scenarios, but at different levels. Initially, the market grows very slowly in all scenarios, so that there are hardly any significant differences in the results up to 2035. From 2040 onwards, market growth increases, where scenario 1 stands

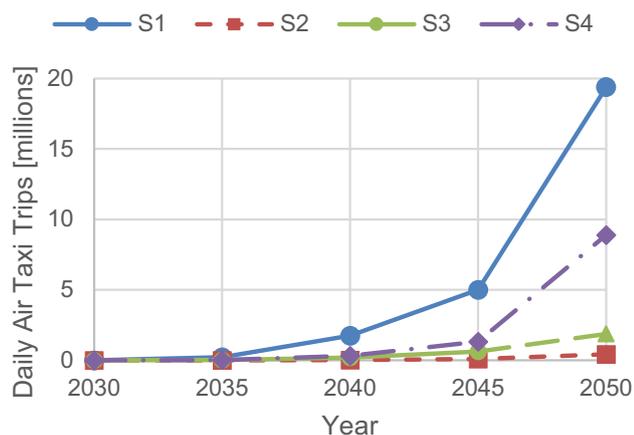


Fig. 15 Global UAM transport demand for the various scenarios

out slightly from the other scenarios. From 2045 onwards, the divergence between the scenarios becomes more pronounced. Market growth is stronger in scenario 1 and 4, which are characterised by optimistic air taxi ticket prices, whereas markets develop only moderately in scenarios 2 and 3 with conservative air taxi ticket prices.

In 2050, the daily UAM demand is about 19 million pas-

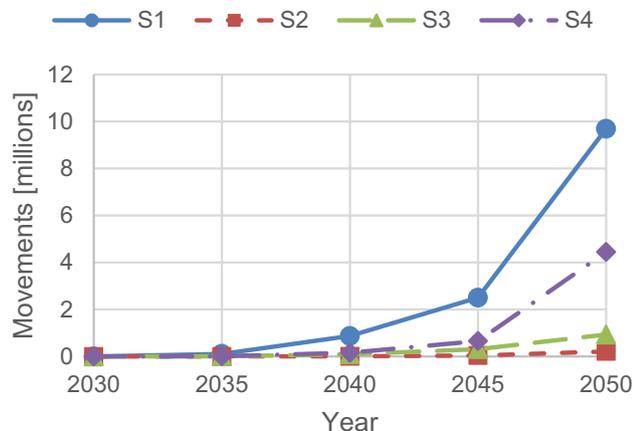


Fig. 16 Global UAM movements for the various scenarios

sengers in Scenario 1. This demand is accompanied by about 9.7 million aircraft movements and a fleet size of about 1 million vehicles. In Scenario 4 daily UAM demand is about 9 million passengers in 2050, accompanied by about 4.5 million aircraft movements and a fleet size of about half a million vehicles.

Scenarios 2 and 3, on the other hand, market size is comparatively low by 2050. For Scenario 2, the daily UAM demand is about 400,000 passengers, with about 200,000 aircraft movements, and a fleet size of about 10,000 vehicles.

By 2050, for Scenario 3, the daily UAM demand is of about 1.9 million passengers, with about 900,000 aircraft movements and a fleet size of about 50,000 vehicles.

Furthermore, the results show that there is potential for UAM in only a subset of the 990 cities under consideration, where the demand is high enough and a sufficiently large vertiport network can be set up. In 2050, the number of cities where UAM services are conceivable ranges from 135 in scenario 2 to 222 in scenario 1. Amongst these cities are international metropole regions, such as London, Tokyo or New York, but also major German regions like the Rhine-Ruhr region, Berlin, Munich or Hamburg.

The potential market shares for UAM varies considerably between different regions of the world (Fig. 18). For 2050 in Scenario 1, the modelling results show particularly high market shares for air taxis in North America, with over 2% in selected metropolitan areas. Especially large cities in Oceania also projected higher average market shares for air taxis of around 1%. In contrast, the UAM market shares in Europe are estimated to be comparatively low, with an average market share of around 0.5% by 2050 in Scenario 1.

Furthermore, the results show a heterogeneous distribution of air taxi shares for the Asian region: Whilst the model indicates limited UAM shares for large parts of the region,

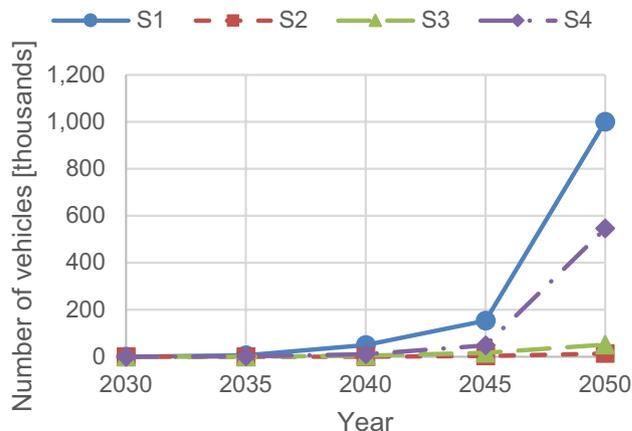


Fig. 17 Global UAM fleet size for the various scenarios

with air taxi shares below than 0.5%, higher UAM shares can be expected in selected cities in this region. Examples include Doha, Qatar in Western Asia or the city-state of Singapore in Southeast Asia.

In contrast, the forecast for South America, South Asia and Africa indicates marginal market shares for air taxis. In these regions, UAM demand for intra-city air taxi services is likely to be possible only under special conditions and at high investment costs by 2050.

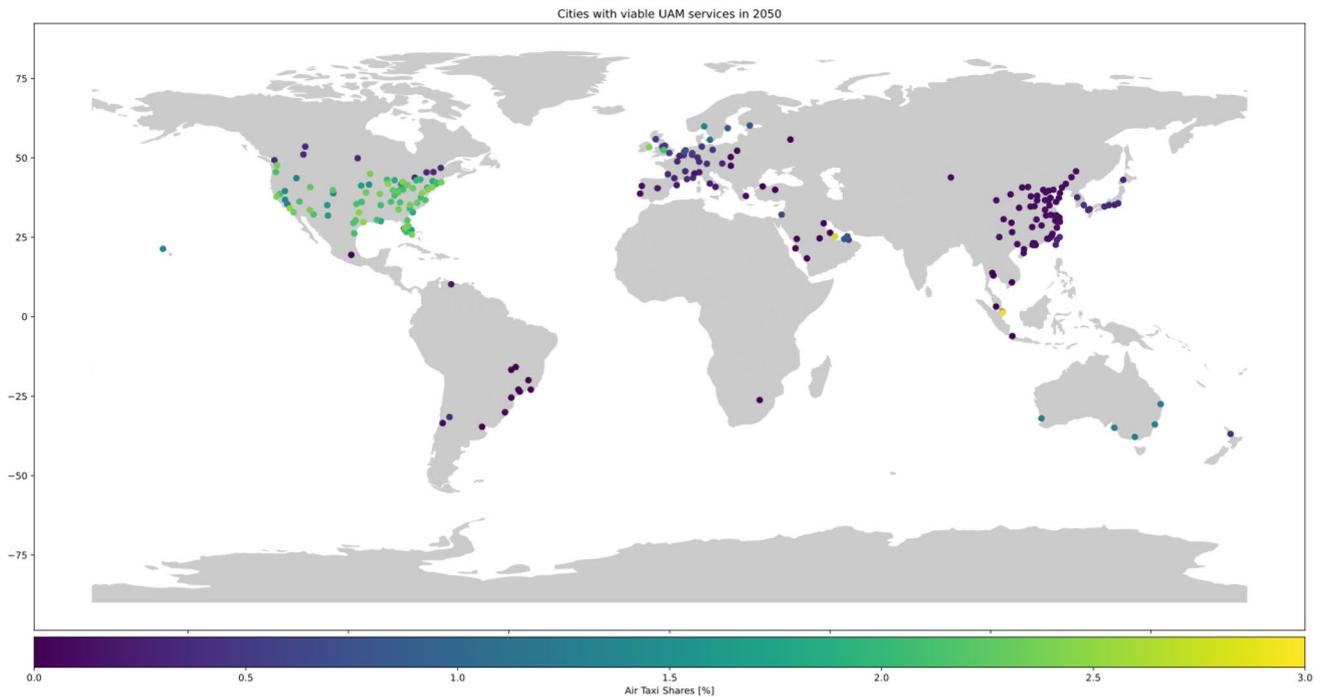


Fig. 18 Air taxi shares for Scenario 1

Overall, the study shows a regional variation in demand for UAM, with high market shares in large cities, particularly in North America, Oceania, Europe and Asia, influenced by local market conditions.

The regional differences in market shares are resulting from the differences in economic power, as the model is based on the assumption that the economic strength of a region influences both the implementation of the UAM system and the willingness of people to use UAM. On the one hand, a high economic power means that UAM systems and especially the necessary ground-based infrastructure can be developed faster and more extensively than in economically weaker regions. This results in a faster pre- and onward-carriage to the UAM system and subsequently in a greater travel time advantage with the air taxi, which increases the attractiveness of this mode of transport. On the other hand, a high economic strength is the basis for the air taxi to be an affordable means of transportation for many people with a positive effect on the UAM share.

It should be noted that the results are highly dependent on the assumptions regarding the development paths for vertiport density and air taxi ticket prices.

Due to the differences in scope, methods, metrics and assumptions used in other studies, the results in terms of passenger numbers, flight movements and fleet size are only comparable to a limited extent to other studies. However, the results emphasise the significant influence of low ticket prices and the need for high vertiport density to increase

demand for UAM, which is in line with other studies [14, 15, 40, 41].

In addition, the results show metropolitan areas with high UAM demand, similar to other studies [11, 42].

Finally, it should be noted that the findings regarding the UAM market share are in line with [16, 19–21].

5 Conclusion

This paper proposes a forecasting methodology that provides initial estimates of potential global UAM demand for intra-city air taxi services. The concept is based on a city-centric approach that uses a limited number of parameters to estimate the total transportation demand for each city. A simplified multinomial logit model is used to determine the probability that travellers will choose the air taxi for their individual trips within a city, using travel time and travel costs of each available mode as input parameters. Based on the resulting UAM demand, cities with potential for UAM services can be identified. By summing all city-specific results, an estimate of the global demand for UAM is obtained. By varying the main characteristics of the UAM transportation system, a parameter study can be conducted as well as market development scenarios can be analysed.

A parameter study was conducted to investigate the impact of vertiport density as well as ticket price on UAM demand. Vertiport density was varied between 0.01 and

0.04 vertiports per km², and ticket price between 2.50 € and 6.00 € per km. As expected, UAM demand is the highest when air taxi ticket prices are low. However, it is remarkable how strongly demand declines as air taxi ticket price increases. UAM demand reaches low levels when the air taxi ticket price is above about 4.00 € per km. On the other hand, demand for UAM rises with an increase in vertiport density. This implies that in order to boost the demand for UAM, the air taxi prices should be lowered and the vertiport density should be increased. However, more vertiports usually mean higher costs and are also problematic in terms of non-user acceptance and land-use. More vertiports only make sense if they generate significantly more UAM demand, so that the costs for the additional vertiports are exceeded by the additional revenues, which needs to be further investigated in the context of a holistic cost and revenue analysis.

Considering different development paths for air taxi ticket prices and vertiport densities, four potential market development scenarios were outlined. The results show that significant UAM markets are not expected by 2040, regardless of the level of air taxi ticket prices. If air taxi ticket prices are low, demand may increase significantly by 2050, creating a mass market. However, if prices remain high, UAM demand in 2050 is likely to remain at the low level of a niche market. The results indicate that a low air taxi ticket price is more important than a high vertiport density for high demand. In the best-case scenario, a low air taxi ticket price and a high density of vertiports could result in a market potential for UAM of 19 million daily trips in over 200 cities worldwide by 2050. The study shows a regional variation in demand for UAM, with the highest market shares expected in North America, with over 2% in selected metropolitan areas.

In addition, the market scenarios indicate that market introduction could be problematic and requires “staying power” on the part of manufacturers and operators, as the market development is characterised by low market growth in the initial phase and strong market growth thereafter. It is important to note, however, that the results shown depend on assumptions about the development paths of air taxi ticket prices and vertiport density. Lower air taxi ticket prices at the beginning of market introduction and a rapid decline in prices are conducive to market development.

The study highlights the critical role of low ticket prices and the importance of high vertiport density for fast access and egress to the UAM system to increase UAM demand. Comparing the results of this study with the findings of Pertz et al. [39], there is currently a dissonance between the air taxi ticket prices of at least 4.00 € per km required for profitable operations and those needed to generate high UAM demand. This underscores the need to carefully optimise system components to minimise costs and maximise the quality of UAM services. Such an approach would contribute to the economic viability and successful deployment of UAM systems.

As long as UAM is still in the development stage, there are many uncertainties in forecasting global UAM demand. In addition, trying to make a global forecast with limited resources involves a high degree of abstraction. The forecasting approach leaves much room for further research and improvement of the proposed methodology. This includes a critical evaluation of the simplification of real urban structures to circular cities. Furthermore, the number of alternative transportation modes should be extended to distinguish between public and private transport. In this context, the parameters for the mode choice model should also be reviewed and improved. In this study, the values for external factors, such as the number of trips per person, the distribution of trip distances, travel speeds or air taxi price per km, are kept constant for different cities. Further adjustment of the data to specific city characteristics should be considered. Although the study considers only GDP per capita as a major determinant, it should be noted that other relevant factors, such as the income distribution, may also play an important role. A broader consideration of these factors could help to further substantiate the results. Similarly, waiting times, passenger pooling and vehicle availability are not currently taken into account when determining movements and fleet size and should be considered in the future work. Further aspects, such as passenger kilometres (PKM) flown, vehicle kilometres performed and energy consumption by UAM, are planned to be explored in more detail in separate studies. In addition, the assumptions for the development of the UAM system components should be improved and integrated into the method. Last but not least, coupling the current approach with Geographic Information Systems (GIS) is another option that adds another dimension to the study of global UAM demand.

The flexible design of the forecasting methodology permits the specification of all parameters, with new findings taken into account, in order to enhance long-term demand estimation for UAM and analysis of market potential across urban areas. Overall, the long-term goal is to develop a methodology that combines the benefits of high local resolution with global generalisation to provide a comprehensive analysis of UAM demand.

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Data Availability There are no data obtained for this report.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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