DATA-DRIVEN DEMAND ANALYSIS OF VERTIPORT INFRASTRUCTURE FOR PASSENGER TRANSPORTATION

J. Roesing[a1], E. Wille[a], I. de Lima[a]

[a]RWTH Aachen University, Mies-van-der-Rohe-Straße 1, 52074 Aachen, Germany

Abstract

Advanced air mobility (AAM) is experiencing a continuous trend of increased attention in research. The design, location selection, and operation of the required ground infrastructure, named vertiports, are being investigated to enhance the development of this new form of mobility.

This work provides a data-driven method to estimate the demand for vertiports per local administrative unit (LAU), considering existing mobility services. The method is applied for the example of the German federal state of North Rhine-Westphalia. We collect, consolidate, and process socio-demographic data of the inhabitants, connections to central places, transport relations, relevant business and touristic locations, and points-of-interest. The consolidated data indicate the distribution of potential AAM users by identifying which LAUs in North Rhine-Westphalia have above- and below-average demand, regardless of economic considerations. Next, we determine the number of vertiports is required for each cell by considering the capacity of vertiports. The methodology can be used to identify areas with high demand for AAM services. This approach is transferable to other regions and modes of transport. In addition, other relevant attributes can be implemented, and the weighting factors can be changed to focus on specific use cases. The methodology follows a manufacturer-independent approach, that considers both user-specific needs and existing connectivity deficits in terms of the equivalence of quality of life according to the regional planning law. The combination of these factors for an optimal location selection of vertiports differs from previous studies, in which this procedure is focused on an economic point of view, targeting the highest travel time savings, population density, or number of business trips.

Keywords: Advanced Air Mobility; vertiport; demand analysis; data-driven

Acronyms	
AAM	Advanced air mobility
eVTOL	electric vertical take-off and landing aircraft
FAA	Federal Aviation Administration
LAU	Local administration unit
POI	Point-of-interest
TLOF	Touchdown and lift-off area
UAM	Urban air mobility
VFR	Visual flight rules

1. INTRODUCTION

Advanced air mobility (AAM) enabled by electric vertical take-off and landing aircraft (eVTOLs) is experiencing a continuous trend of increased attention in research and development. AAM services are expected to provide a low-noise, low-emission, comfortable, and time-saving form of individual mobility focused on point-to-point connections. According to the current regulatory framework, the operation of eVTOLs requires a dedicated take-off and landing infrastructure, also known as a vertiport. The design, location selection, and operation of vertiports are being investigated to enhance the development of AAM. Vertiports need to be strategically located at key demand points and to be operated as a network. In some regions, existing landing infrastructures can already be used for such a network. At the same time, other sites need to be developed to support the benefits of this new form of mobility. For the strategic network development of vertiports for passenger transport services, suitable locations include either densely populated or rural areas: On the one hand, densely populated areas offer a high demand of potential users. On the other hand, the location of a vertiport can

[1] Corresponding author. Tel.: +492418028257
E-mail address: roesing@via.rwth-aachen.de

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improve the accessibility of poorly connected rural regions. This work provides a data-driven method to estimate the demand for vertiports per local administrative unit (LAU) for passenger transport operations, considering existing mobility services. Based on the example of the German federal state of North Rhine-Westphalia, we collect, consolidate, and process socio-demographic data of the inhabitants, connections to central places, transport relations, relevant business, and touristic locations, and points-of-interest. The attributes are made comparable by a normalization and under consideration of their minimum and maximum values. The results show which LAUs in North Rhine-Westphalia have above-average and below-average demand, regardless of economic considerations. Based on this demand, we determine the number of required vertiports. The methodology can be used to identify areas with high demand for AAM passenger transport services. In addition, other relevant attributes can be implemented, and the weighting factors can be changed to focus on specific use cases.
The methodology follows a manufacturer-independent approach, that considers both user-specific needs and existing connectivity deficits in terms of the equivalence of life quality according to the regional planning law. The combination of these factors for an optimal location selection of vertiports, differs from previous studies, in which this procedure is focused on an economic point of view, targeting the highest travel time savings, population density, or number of business trips.

2. APPROACHES FOR AAM DEMAND ESTIMATION

To investigate the number of required vertiports for passenger transport AAM services, the passenger demand needs to be estimated. There are several studies in the literature that estimate this at different planning stages using various methods and referring to different spatial levels.

Long et al. [1] provided a comprehensive literature review on demand estimation for Urban Air Mobility (UAM) and categorized five approaches for demand estimation as presented in Fig. 1. The survey-based demand estimation serves as a qualitative approach, whereas the other four approaches can be described as quantitative and data-based approaches. With regard to long-term demand estimation, Long et al. distinguished between the demand estimation for a potential city and region and the demand estimation for infrastructure capacity and placement. While the demand estimation for a potential city and region refers to a macroscopic analysis level, the demand estimation for infrastructure capacity and placement is conducted on a meso- to microscopic level.

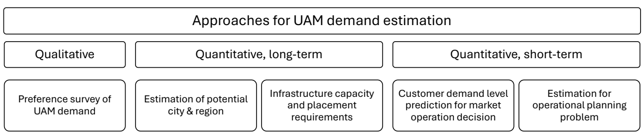

Fig. 1. Approaches for UAM demand estimation. Based on [1]

Long et al. classify studies that determine demand in terms of infrastructure placement and strategic potential decisions as quantitative, long-term approaches. There are several studies that can be categorized in this category. Some of them suggest an approach to estimate the air taxi demand first and build a vertiport network on that basis. For example, Bulusu et al. [2] and Kim, Park et al. [3] investigate vertiport placement in their study as a location problem. They use iterative algorithms to determine the optimal locations for vertiports in relation to the demand distribution. Jin et al. [4] develop a travel mode choice behavior model considering influencing factors such as the fare, the passengers' time value index, the transport time, and the ground transportation time to and from the vertiport. The focus is on the shift from normal and luxury taxis as the primary competitive transport modes to air taxis. Based on this model, the authors aggregate the air taxi demand and determine location-assignment decisions. Zhao and Feng [5] identify potential vertiport locations considering the transport time of the different transport modes and minimize total facility costs and travel distances to vertiports using a k-means algorithm. To estimate the air taxi travel demand they use the value of travel time of the competing transport modes as weighting factors. Senthilnathan et al. [6] use prior estimated air taxi demand and optimize a vertiport network based on factors such as population coverage, access to road facilities, distances to subway, and bike stations. Hagspihl et al. [7] model passenger choice behavior using a discrete choice model. The passenger data which form the basis for the estimation, can be obtained from ticket sales data or surveys. For the choice of the transport mode they include factors such as travel time and travel costs.

The present study can be assigned to the approach of demand estimation for a potential city and region. This category also includes other studies: For example, Rimjha et al. [8] use mode choice models to determine the modal split of the available transport modes including new transport services such as AAM. Long et al. also analyzed the type of methods applied for the different demand estimation categories. For the estimation of potential cities and regions, the applied methods included stated-preference surveys (for data basis provision), discrete choice models, and gravity models. In addition, some individual methods were found in the literature, such as interactive city data sets processed in ArcGIS [9], or a normalization technique [10] on socio-demographic and transportation data. The considered input data for these different methods includes socio-demographic data such as population, economic factors such as the GDP, and transport service-related factors such as travel time, cost, and distance. In their study, NEXA Advisers [9] analyzed different use cases such as airport shuttle services or on-demand air taxi services in a total of 84 cities worldwide. They did not describe their approach in detail. Reiche et al. [10] focused on the US in their study. When analyzing urban areas, they evaluated the different attributes by investigating the minimum and maximum value of each attribute to normalize the metric and achieve comparability between the attributes. The regions with high scores promise great market potential for AAM relative to the other investigated regions. The approach details are not disclosed. They select representative regions in the US with different barriers for more specific analysis.

In the literature review, Long et al. underline the need of a comprehensive and standardized set of parameters for the demand estimation for a potential city and region to serve as a reference for future demand estimation studies in the AAM domain. The present study aims to contribute to this lack of standard. We propose a methodology to identify socio-demographic, business-related, and touristic attributes for different AAM use cases and to use normalization to identify those regions in the study area that can be expected to have a high demand for AAM transport services.

3. USE CASES AND POTENTIAL USER GROUPS

AAM may serve a wide variety of different use cases. Vertiports can be used as infrastructure for passenger transportation as well as for freight transportation. In this paper we examine the demand for commercial passenger transport in use cases from the literature. Depending on the frequence and travel distance, several potential users can be addressed. These can be identified by using data sources such as on transport services, socio-demographic attributes, and employment.

In this study, we refer to commercial passenger transport. The following frequently cited use cases can be categorized and are considered:

- Occasional shuttle services
  - Points-of-interest shuttle [11]
  - Company shuttle [12]
  - Airport shuttle [12–16]
- (Door-to-door) Air taxi service [11, 15]
  - Inter-city [13, 14]
  - Intra-city [13, 14, 17, 18]
  - Regional [12, 13, 17, 18]
  - Services of general interest [14]
- Touristic air taxi services
  - Sightseeing [13, 16]

From the use cases potential users can be derived. These are shown in Table 1.

Use case	Potential user groups
Occasional air taxi services	• Commuters • Airport passengers • Employees • Visitors of points-of-interest • Individuals
Door-to-door air taxi services	• People with reduced mobility • Commuters • Individuals
Touristic air taxi services	• Tourists

Table 1. Potential user groups of air taxi services

From these potential users, the typical socio-demographic, business-related, and touristic attributes can be concluded. Ideally, this would result in user profiles that could be used to identify the potential target groups. However, the required data basis to understand the user profiles is lacking to date, making this task unfeasible. Instead, individual user attributes that are available at LAU level are identified.

Based on the user groups shown in Table 1, we conclude that

- the number of employed persons,
- the number of inbound and outbound commuters,
- the number of branches with more than 250 employees,
- the location of Points-of-Interest and airports,
- the number of tourist arrivals, and
- in rural areas, access to the nearest medium-sized and regional centres

are relevant. In addition, the literature review reveals socio-demographic attributes for individuals who are more likely to use AAM passenger transport services. These include the following for the use cases mentioned:

- Age between 15 and 64 years [19, 20]
- Above-average income [12, 16, 17, 19, 20]
- A-levels or equivalent school qualifications [20, 21]
- Car ownership [16, 21]

These attributes form the basis for the subsequent vertiport assessment. In addition to user profiles based on several attributes, further aspects would be relevant for consideration, for example the willingness-to-innovate [22], expenditure on mobility [16], use of taxi services [5, 23] and the number of visitors to the points-of-interest. However, since these aspects are not covered by detailed data for the study area, they could not be included. Other study areas can benefit from the implementation of the data if it is available.

4. METHODOLOGY TO DETERMINE THE NUMBER OF REQUIRED VERTIPORTS

4.1. Determining of transport demand

After defining the use cases and potential users in Section 3, we develop a methodology to identify the demand of vertiports by estimating the transport demand and considering the capacity of vertiports. The methodology is based on the following demand categories, which are related to specific attributes and potential user groups:

- Sociodemographic attributes
- Business-related attributes
- Touristic attributes
- Location-related attributes (points-of-interest)
- Connection-related attributes (Central places)

The categories and the structure of the methodology are illustrated in Fig. 2.

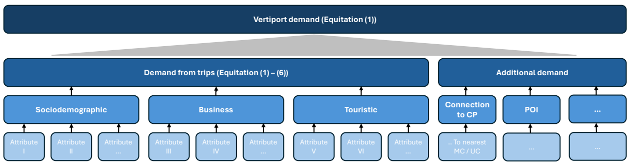

Fig. 2. Methodological structure for determining vertiport demand

We calculate the transport demand by combining the result of the number of trips and a potential additional demand due to an insufficient connection to the nearest central place or relevant point-of-interest according to equation (1). Demand from trips is developed based on potential user groups. This considers private individuals at their place of residence, as well as business trips and commuting and tourist trips that do not take place at the private individuals' place of residence. Potential private individuals are identified by socio-demographic attributes such as age and income. Potential business trips are estimated using attributes such as the number of large company sites or employees in a cell. Tourism potential can be considered based on the number of tourist arrivals in a cell, for example. The additional demand can be addressed by considering the connection to central places, as set out in the Regional Planning Act, and by considering high-volume point-of-interest, such as exhibition locations, which generate significant passenger numbers. Several of these attributes may differ due to operation scenarios, study aims and the chosen use case. There is also the possibility to add further demand categories under 'Additional demand' or attributes to the existing demand categories.

$$\text{vertiport demand}_{LAU} = \text{demand from trips}_{LAU} + \text{demand from } CP_{LAU} + \text{demand from } POI_{LAU} \quad (1)$$

with
CP Central places
POI Point-of-interest

In general, the most recent data available should be used. However, the data for the several attributes may exhibit different survey years. In the present methodology, we consider this by not using the absolute numbers of the attributes for the estimation of transport demand, but by deriving factors from the data of the individual attributes for each LAU cell. These factors represent the relationship between the LAU cell and the whole study area and are therefore compared with the other attributes independently of the survey year. Furthermore, the attributes used must be available for each cell in the study area. For some attributes, the resolution might be lower than LAU. In this case, the information is disaggregated to the necessary higher spatial resolution by an appropriate distribution measure. This procedure always leads to a simplification of reality and should only be used if no spatial resolution data are available.

Demand from trips

In this study, the passenger origin-destination matrix of the Transport Network Forecast 2030 [24] is chosen as database for the transport trips. These data are available at NUTS 3 level and provides a forecast of passenger transport trips for the year 2030. To be used in the methodology, the resolution of the data needs to be LAU level. Therefore, the trips from/into the NUTS 3 cell are distributed to the different LAU cells of a NUTS 3 cell according to the share of the inhabitants of the LAU cell in the inhabitants of the NUTS 3 cell (see equation (2)).

$$trips_{LAU} = \frac{IH_{LAU}}{IH_{NUTS3}} * trips_{NUTS3} \quad (2)$$

with
IH Inhabitants per cell

For socio-demographic, business-, and touristic-related attributes, data are required that is available nationally for each of the cells in the study area. If the data are already available at LAU level, it can be used directly for the methodology. If the data are available at NUTS3 level, it is disaggregated using a relevant distribution measure that must be available at LAU level. Suitable distribution measures are, for example, the number of inhabitants per LAU cell or the area of the LAU cell.

The calculation of the transport requirement is based on the annual distances potentially travelled by AAM passenger transport according to equation (3).

$$\text{demand from trips}_{LAU} = \frac{AAM\_PAX \text{ trip demand}_{LAU}}{365} * \frac{1}{c * o} \quad (3)$$

with
AAM_PAX trip demand$_{Lau}$ AAM_PAX trip demand in the LAU/a
c Vertiport capacity [PAX/h]
o Vertiport operating time [h/d]

The annual demand from trips for AAM passenger transport is derived from the three demand categories: sociodemographic attributes of the target groups, business-related attributes, and touristic attributes. Other categories may be included in the analysis if relevant. Equation (4) is used to determine the annual demand from trips for AAM passenger transport.

$$AAM\_PAX \text{ route demand}_{LAU} = trips_{LAU} * t + trips_{LAU} * t * \sum_{i=1}^{m} d_{LAU,i} * w_i \quad (4)$$

with
trips$_{Lau}$ Trips from and into the LAU/a
t Transfer rate
i Demand categories
d$_{LAU}$ Distribution factor of the LAU
w$_i$ Weighting factor

$$\sum w_i = 1 \qquad \forall\, i \in \{\mathbf{1}, \dots, \boldsymbol{m}\}$$

The distribution factor indicates which cells of the study area exhibit an above-average occurrence of the attribute. It is determined for each demand category. The distribution factor of the cell is determined according to equation (5).

$$d_{LAU,i} = \sum_{j=1}^{n} d_{LAU,ij} * f_{ij} \tag{5}$$

with

d_{LAU}	*Distribution factor of the LAU*
i	*Demand categories*
j	*Attribute*
f_{ij}	*Weighting factor*

$$\sum f_{ij} = 1 \qquad \forall j \in \{\mathbf{1}, \dots, \boldsymbol{n}\}$$

The attributes are assigned to one of the demand categories as shown in Fig. 2. For example, attributes in the sociodemographic demand category include the age or income of the potential user group. Business attributes include the number of employees at the place of work, or branches with more than 250 employees. The number of tourist arrivals in each cell can be used to analyze tourism demand. The distribution factor for each attribute is calculated according to equation (6).

$$d_{LAU,ij} = N_{BL} + \frac{{v_{LAU,ij}}/{\varnothing v_{A,ij}} - \left(1 - \max\left(\left|{v_{LAU,ij}}/{\varnothing v_{A,ij}} - 1\right|\right)\right)}{\max\left(\left|{v_{LAU,ij}}/{\varnothing v_{A,ij}} - 1\right|\right) * 2} * |\mathrm{N}_{BL} - N_{UL}| \tag{6}$$

with

d_{LAU}	*Distribution factor of the LAU*
i	*Demand category*
j	*Attribute*
N_{BL}	*Bottom limit of the normalization range*
N_{UL}	*Upper limit of the normalization range*
$v_{LAU,ij}$	*Value of attribute j in the LAU*
$\varnothing v_{A,ij}$	*Average of all values j in the study area*

The normalization of the attributes ensures that the magnitude of the attributes is comparable and, therefore, their influence is proportional to each other. The normalization limits are chosen depending on how large the influence of the attribute should be in relation to the transfer rate. The influence of the attributes increases the wider the scaling limits are chosen.

To apply the methodology, the equations are applied in reverse order (equation (6) to equation (2)).

Demand from central places

The connectivity to the nearest central place is examined on the basis of Christaller's central place theory [24]. This specifies how long the travel time from a basic centre to the next medium centre or the next regional centre and from a medium centre to the next regional centre may be (see Table 2).

Connection to [central place]	Travel time by car (in min.)
Nearest medium centre	≤ 30
Nearest regional centre	≤ 60

Table 2. Standard values for the accessibility of central places according to the guideline for the integrated design of networks in Germany (RIN) [25]

To check the connectivity between the LAUs, the first step is to determine the population-weighted centre for each LAU. The basis are the Census data [25]. It can be automated using a geographic information system (for example QGIS). In the next step, the travel time between the weighted centre points by motorised private transport is determined to check whether there is a sufficient connection to the nearest central place for the basic and medium centres. The travel time is based on an empty road network and therefore on a free flow of traffic. By using the empty network and neglecting the traffic volume, comparability between the cells is ensured. Travel times can be determined manually or retrieved automatically via an Application Programming Interface. Additionally, cells are identified in which, even under good transport network conditions, there are insufficient connections. If the connection to the nearest central place is insufficient, at least one vertiport is recommended to be provided. If one or more vertiports are suggested based on the demand from trips, no further vertiport needs to be added.

Demand from points-of-interest

The points-of-interest differ depending on the use case considered. For example, multimodal hubs, exhibition centres, or stadiums can be included [14, 26–28] (see Table 3). These can either be assigned to the cells at LAU level or be precisely localised. The points-of-interest can either be available as a database, for example OSM, or be manually researched.

POI categories	Examples
Multimodal hub	Airports, train stations, car parks
Leisure time	Touristic attractions, large sports facilities, recreational areas, city centres
Business	Industrial estates, business districts, company headquarters

Table 3. Relevant points-of-interest for vertiport demand analysis

For every point-of-interest, a case-by-case assessment is necessary to determine whether the related transport demand makes an additional vertiport necessary or whether the transport demand can be handled by vertiports that are suggested based on the demand from the trips.

Possible points-of-interest could be multimodal hubs such as airports or train stations, or high-volume locations such as a sports stadium, a tourist attraction, or a major business location. The vertiports from the points-of-interest should therefore be shown separately and only be included directly in the vertiport demand if necessary. It should also be assumed that the traffic to and from the points-of-interest is already included in the traffic forecast and therefore only the additional traffic generated by AAM passenger transport services should be considered.

4.2. Determining the number of required vertiports

The aim of this work is to develop a method to determine the number of required vertiports per LAU cell. Section 4.1 describes the methodology for the calculation of number of AAM passenger trips per LAU cell. Based on this number, this section presents the calculation of required vertiports per LAU cell. This calculation is based on the number of passengers per eVTOL flight and the theoretical capacity of vertiports.

The number of passengers per flight depends on the seat capacity of the eVTOLs and on the passenger load factor. Considering the eVTOL concepts that are currently under development (Table 4) and passenger load factors identified in a literature review [29], we assume a passenger load factor of 60% and a seat capacity of 4 passengers. Therefore, the average number of passengers per flight is 2.4. We expect that initial AAM passenger transport services will operate on a semi-scheduled basis or apply pooling of passengers to increase the number of passengers per flight compared to conventional car or taxi usage. Comprehensive information on the different operational modes of AAM passenger transport can be found in Ref. [30].

Manufacturer	Model	Seat capacity
Volocopter	VoloCity	2
Aurora Flight Sciences	PAV	2
Airbus	CityAirbus	4
ASX	MOBi-One	5
Kitty Hawk	Heaviside	1
Joby Aviation	S4	4
Lilium	Lilium Jet	6

Table 4. Relevant eVTOL concepts [29]

The capacity of a vertiport depends on its size, most essentially, the number of touchdown and lift-off areas (TLOFs) and stands. This size is limited by the footprint available at the specific vertiport location. Vertiport size should also be determined considering the expected traffic volume from or to this destination. The scope of this work does not include a detailed vertiport design for every vertiport location. We assume the vertiport capacity based on capacity envelopes as elaborated by Vascik et al. [31]. The smallest possible vertiport in our study consists of one TLOF and one stand. This is the minimum infrastructure to serve passenger transport while providing a vertiport alternate option within a vertiport network. However, this design is not efficient: Turnaround times (processing on stands) are bigger than arrival and departure times (processing on TLOFs). Thus, multiple stands are required to achieve a high utilization of one TLOF. Assuming an arrival and departure time of 60 seconds, a taxiing time of 15 seconds, and a turnaround time of 300 seconds, Vascik et al. [31] showed that five stands are the optimal number to supplement one TLOF. The throughput capacities of vertiports with one TLOF and one or five stands were found to be 4 and 12 flights per 15 minutes, respectively. Assuming 2.4 passengers per flight, we estimate an hourly passenger flow of 38 and 115 passengers for a one-TLOF-vertiport with one stand and five stands, respectively.

For LAU cells with a large number of potentially required vertiports, benefits may arise from building vertiports with more than one TLOF as these vertiports may benefit from higher flexibility and achieve higher utilization. The following Table 5 provides a summary of recommended vertiport size based on the number of passenger trips n_{trips} per peak hour.

Range of passenger trips per peak hour	Recommended vertiport size
$n_{trips} < 38$	No vertiport recommended
$38 \leq n_{trips} \leq 115$	1 vertiport with 1 TLOF and 1-5 stands
$n_{trips} > 115$	> 1 vertiports, or > 1 TLOFs per vertiport with 1-5 stands each

Table 5. Vertiport size recommendation based on peak hour passenger trips per LAU cell

4.3. Considering existing ground-based transport infrastructure

Mode choice depends on the available mode options for each trip. Therefore, the mode choice for AAM passenger transport services will depend on the given mode options offered by road-based and railway-based modes of transport. To consider these mode options in the methodology for the demand estimation, a comprehensive database of the road network and railway network is needed.

The road network in Germany is categorized in different classes: the highest category of roads are highways, followed by main roads, etc. Due to the travel range that is relevant for AAM passenger transport services, highways constitute the most important road infrastructure for the demand estimation. We therefore defined highway-related parameters: Highway length and the number of junctions were considered for assessing network quality. These two parameters indicate both the expansion and the accessibility of the network. To normalize the parameters for each LAU cell, they were divided by its area size.

Road-based public transport services (i.e. scheduled and regional buses) were not included in the analysis of the road network. This is due to two reasons: First, for most of the AAM passenger transport service use cases considered in this study, this alternative would not be suitable as a mode of transport. Second, although data on road-based public transport services are largely publicly available, they are lacking a uniform standard. Therefore, a processing effort would be required to prepare comparable data. However, the present methodology could be expanded by considering road-based public transport services as an additional mode of transport.

To assess the quality of the railway network, we chose the railway tracks and railway stations as the two key parameters since they address the expansion and the accessibility of the railway network. The number of railway stations was differentiated between long-distance stations (i.e. a station that offers at least one long-distance connection) and regional stations. Again, the parameters were normalized to the area size of the LAU cell.

Another parameter for analyzing the quality of railway transport would be the number and frequency of connections at the individual stations. However, similar to road-based public transport, a uniform standard would be required for further analysis that goes beyond the publicly available and frequently updated data found in this study. Moreover, the methodology could be extended by considering further railway infrastructure: Suburban railway, underground and tram railway tracks and stations were not considered in this study.

With the mentioned key indicators for the existing infrastructure, the required number of vertiports as result from Section 4.2 can be adapted. Therefore, we define different cases. Depending on the availability of the ground transport modes (road and rail), the vertiport demand is adjusted upwards or downwards, assuming that the modes are considered as substitutes to potential users. However, the number of required vertiports is only adapted if the influence of the existing infrastructure exceeds a defined limit. If usable aerodromes are identified within the cell, the number of required vertiports is reduced by the number of usable aerodromes. It is assumed that an existing airfield replaces one new vertiport to be built. Total demand does not change as there are currently no air transport modes that can be considered as substitutes for AAM passenger transport.

Case 1 - No vertiport planned, good connection to existing infrastructure

If no vertiport is required based on the transport demand and there is an above-average connection to existing infrastructure within the cell, the vertiport demand is not adjusted and remains to be zero.

Case 2 - No vertiport planned, poor connection to existing infrastructure

If no vertiport is required based on the transport demand and there is a below average connection to existing Infrastructure within the cell, the procedure is according to equation (7). If the vertiport demand is negative, it is set to zero.

$$vertiport\ demand_{LAU,infra} = vertiport\ demand_{LAU} - a_{LAU} + \sum_{g=1}^{o} h_g * d_{LAU,infra,g} * (-1) \quad (7)$$

with

vertiport demand$_{LAUiInfra}$	*Vertiport demand considering infrastructure in the LAU*
vertiport demand$_{LAU}$	*Vertiport demand from demand determination*
a_{LAU}	*Number of existing usable airfields in the LAU*
g	*Ground-based infrastructures*
h_g	*Weighting factor ground-based infrastructures*
$d_{LAU,infra,g}$	*Distribution factor ground-based infrastructure in the LAU*

$$\sum h_g = 1 \qquad \forall\ g \in \{\mathbf{1}, \dots, \boldsymbol{o}\}$$

Case 3 - Vertiport recommended

If at least one vertiport is recommended based on the demand determination, the vertiport demand should be adapted based on equation (8). If the vertiport demand is negative, it is set to zero.

$$vertiport\ demand_{LAU,infra} = vertiport\ demand_{LAU} - a_{LAU} + \sum_{g=1}^{o} h_g * vertiport\ demand_{LAU} * d_{LAU,infra,g} * (-1) \quad (8)$$

with

vertiport demand$_{LAUiInfra}$	*Vertiport demand considering infrastructure in the LAU*
vertiport demand$_{LAU}$	*Vertiport demand from demand determination*
a_{LAU}	*Number of existing usable airfields in the LAU*
g	*Ground-based infrastructures*
h_g	*Weighting factor ground-based infrastructures*
$d_{LAU,infra,g}$	*Distribution factor ground-based infrastructure in the LAU*

$$\sum h_g = 1 \qquad \forall\ g \in \{\mathbf{1}, \dots, \boldsymbol{o}\}$$

The weighting factors h_g are determined individually for each mode of transport and indicate the extent to which the existing ground infrastructure influences transport demand in each case.

The distribution factor of the ground-based infrastructures $d_{Lau,infra}$ can be determined according to equation. The structure of the equation (9) is based on the equation (6) for determining the distribution factor d_{Lau}.

$$d_{LAU,infra,g} = S_{Infra,BL} + \frac{{v_{LAU,g}}/{\emptyset v_{A,g}} - \left(1 - \max\left(\left|{v_{LAU,g}}/{\emptyset v_{A,g}} - 1\right|\right)\right)}{\max\left(\left|{v_{LAU,g}}/{\emptyset v_{A,g}} - 1\right|\right) * 2} * \left|\mathrm{N}_{Infra,BL} - N_{Infra,UL}\right| \quad (9)$$

with

$d_{LAU,Infra,g}$	*Distributions factor of the LAU*
g	*Ground-based infrastructures*
$N_{Infra,BL}$	*Bottom limit of the normalization range for the consideration of infrastructure*
$N_{Infra,UL}$	*Upper limit of the normalization range for the consideration of infrastructure*
$v_{LAU,g}$	*Value of infrastructure g in the LAU*
$\varnothing v_{A,g}$	*Average of all values g in the study area*

As in section 4.1, normalization ensures that the scale of the metrics is comparable. Therefore, their influence is proportional to each other. The normalization limits are selected independently of the limits selected in section 4.1.

To apply the methodology, the equations are applied in reverse order (equation (7) to equation (9).

4.4. Considering the usability and capacity of existing airfield infrastructure

To develop a wide-spread infrastructure landscape of vertiports, an often-made assumption is that existing helipads and airfields may easily be usable by eVTOLs and therefore integrate into vertiport networks. One aim of this study was to investigate the validity of this assumption. To do so, the first step was to collect data on airfields and heliports (for the area of NRW or Germany). Useful data sources on airfields and heliports were provided by Destatis [32] (Federal Statistical Office of Germany), the DFS Deutsche Flugsicherung (German air navigation service provider) [33, 34], and the district government of Dusseldorf [35]. Additional data focusing on heliports were provided by the Federal Agency for Cartography and Geodesy [36]. The collected data included information on airfield category, location, traffic type and traffic volume. Airfields and heliports can be distinguished by the type of vehicles allowed to operate (for example. engine powered airplanes, gliders, or helicopters), and by the type of operational services (public service or private use).

The demand for vertiport infrastructure was estimated in section 4.2. However, this demand estimation did not yet consider existing airfield infrastructure. We hypothesized that the demand may be reduced since some air taxi services may operate at existing airfield infrastructure. To determine if and how much the demand may be reduced, the usability and capacity of the existing airfields need to be investigated.

First, it was assumed that private airfields and airfields that are approved for gliders only cannot be considered as usable airfields in general. As the operation of eVTOLs would constitute a major change of their intended use, these airfields would need to undergo another approval process which might include assessments on traffic forecast and environmental impact, among others. Additionally, heliports in Germany serve as public interest sites (with very few exceptions). As the heliports must remain available for their primary function (for example emergency landing platform for hospitals), other usages cannot be accommodated. Public airfields that are approved for helicopter operations, however, were considered as potentially viable infrastructure for eVTOL operations (once eVTOLs have received type certification).

The capacity of these airfields can be determined by the lowest capacity of its subsystems, including at least the runway, the taxiways, and the parking positions. While taxiways and parking positions varied greatly with the different existing airfields, the runway system of the vast majority of airfields consisted of a single runway which is operated according to visual flight rules (VFR). To estimate the runway capacity, we applied the method as described by the Federal Aviation Administration (FAA) [37]. The hourly capacity base C* was determined to be 105 movements per hour, assuming a mix index of 0% (i.e. no aircraft type C or D operating) and a share of arrivals and departures of 50% each. The hourly capacity was then found to be 102 movements per hour, assuming a touch-and-go factor of 1.04 (which corresponds to 1-10% of touch-and-go's) and an exit factor of 0.94.

However, this runway-based capacity estimation may not be valid for most of the airfields as they may instead be limited by the capacity of taxiways or parking positions. Also, the introduction of air taxi services will very likely require further infrastructure such as hangars, passenger terminal infrastructure, and others. To further investigate the usability of airfields for air taxi services, expert interviews were conducted with different airfields operators. Although only a small number of interview partners could be found for the investigation area of NRW, the interviews revealed a broad range of expansion potential for air taxi services.

First, the current utilization of aircraft infrastructure varied greatly: While some airfields were aiming to increase air traffic and gain customers, others were already operating at their limits which were determined by runway capacity or parking positions. Also, the expandability of the airfield was only a possible scenario for part of the considered airfields. Thus, the construction of additional parking positions or hangars would present a challenge. Another infrastructure that would need to be added to existing airfields is passenger handling facilities. As none of the airfields considered offer regular airborne passenger transport services yet, they do not hold passenger handling facilities similar to a general aviation terminal. However, some airfield operators considered specific buildings or parts of it at the airfield as a suitable location for passenger handling, while others did not consider the integration of passenger handling facilities possible at all.

In general, the interest in integrating air taxi services or other forms of AAM into the airfield's operations varied greatly as well. For example, if the airfield operator was a private club of hobby pilot members and the airfields were already highly utilized by this purpose, the interest in introducing other air operations was low as it would interfere with its current function. On the contrary, an airfield operator organized as a company in public hand was interested in supporting its community by offering air taxi services that increase the attractiveness of the airfield's and municipality's location.

In conclusion, the expert interviews highlighted the great variation in the ways existing airfields were suitable to integrate air taxi services into their operations and infrastructure. Given the varying airfield capacity that might be available for air taxi operations, a case-specific analysis is recommended for every airfield if it should be used for air taxi operations. However, as a general conclusion to be drawn for estimating the vertiport demand, we assumed that the vertiport demand can be reduced by one vertiport for each existing public airfield in the same LAU cell.

5. CASE STUDY OF NORTH RHINE-WESTPHALIA

In this study we estimate the vertiport demand by applying the presented methodology for North Rhine-Westphalia, which is located in western Germany. North Rhine-Westphalia is characterised by a densely populated metropolitan region consisting of several cities at its centre. The surrounding areas are more rural and less densely populated.

In section 3, the relevant AAM passenger transport use cases and potential user groups were presented. Referring to these use cases and user groups, we use the attributes and data sources listed in Table 6 to estimate the demand from trips.

Attribute	Available spatial level	Distribution measure	Reference
Age	LAU	-	[25]
Income	LAU	-	[38]
School qualification	NUTS3	Inhabitants	[39]
Employment	LAU	-	[40]
Car stock	LAU	-	[41]
Employees at place of work	LAU	-	[42]
Branches	NUTS3	Employees at place of work	[43]
Inbound commuters	LAU	-	[44]
Outbound commuters	LAU	-	[44]
Tourist arrivals	LAU	-	[45]

Table 6. Attributes for applying the methodology to North Rhine-Westphalia

Afterwards, we use the equations from section 4 to estimate which LAUs in North Rhine-Westphalia have above-average and below-average demand and to derive the number of required vertiports. The results of the methodology indicate how many vertiports are recommended within each LAU under the assumptions made. It is assumed that each vertiport is fully and evenly utilised throughout the day. This implies an over-estimation of handled flights and passengers as vertiports will realistically operate below their capacity in off-peak times. However, the actual utilisation of the vertiport depends on its location and user profile (for example, a vertiport used by commuters working in a financial district opposed to a vertiport connecting a leisure point of interest). Since the estimated number of required vertiports shall indicate a starting point of vertiport development, a conventional assumption regarding the resulting number of vertiports was made.

Influencing factors such as price or public acceptance are only reflected in the assumed transfer rate and are not examined in detail. The specific number of vertiports represents the order of magnitude and must be verified for each individual cell. The location of the vertiports within the cell is not covered in this study.
The choice of weighting factors is relevant for the interpretation of the results. Depending on the use case, the demand categories or attributes can be emphasised by the weightings. To examine the influence of the weightings and assumptions, different scenarios are considered. The weighting factors of the demand categories, the weighting factors of the attributes within the demand categories, the transfer rate, the assumed operating hours, and the normalization limits of the attributes are varied. In the base scenario, all attributes and demand categories are equally distributed. A transfer rate of 1%, 16 hours of operation per day, and normalization limits of +/- 10% were assumed. The transfer rate is based on the results of an agent-based transport model [46]. Another market analysis stated that up to 5% transfer rate can be expected in 2050 [47].Table 7 shows the example scenarios and their changes compared to the base scenario.

	Varied parameter	Relative difference to base scenario
Demand category	Socio demographic (100 %)	- 0,5 %
	Business (100 %)	+0,2%
	Touristic (100%)	+0,5 %
Transfer rate	0,5 %	-50,6 %
	2,0 %	+97,7 %
Operating hours	12 h	+31,9 %
Normalization limits	+/- 50 %	+4,3 %
	+/- 100 %	+9,0 %

Table 7. Variation of parameters compared to the base scenario

The evaluation of the scenarios shows that the transfer rate has an enormous influence on the overall result. The normalization limit of +/- 10% causes that the attributes have a small influence on the overall result. For this reason, the results are presented below with normalization limits of +/- 100%. Replacing the assumptions with actual values or forecasts will improve the accuracy of the results.

Fig. 3 shows the results of exemplary scenarios with a normalization of +/- 100% and without considering existing infrastructure using the geographic information system QGIS.

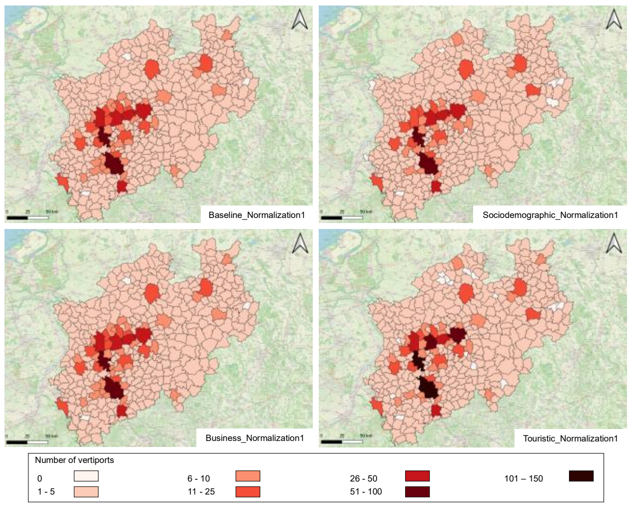

Fig. 3. Recommended number of vertiports by exemplary scenarios

Based on these results, we consider the existing infrastructure and determine the recommended number of vertiports within each LAU (see section 4.3). For the use case of North Rhine-Westphalia, the identified open data sources are presented in Table 8.

Type of infra-structure	Provider	Regional coverage	Last updated	Refe-rence
Railway stations	DB Station& Service AG	Germany	Jan 20	[48]
Railway tracks	DB Netz AG	Germany	Nov 19	[49]
Road network NRW	Geoportal	NRW	2018	[50]
Public transport stations and stops; Public transport timetables	Opendata ÖPNV	Germany	2023	[51]

Table 8. Open data sources on ground-based transport infrastructure

Case 1 does not occur for the base scenario with the normalization limits of +/- 100% for the attributes and for the infrastructure influence. Case 2 occurs for five of the 396 cells. Case 3 occurs in the remaining 391 cells. The number of vertiports is reduced in 41 cells. In the remaining cells it does not change. Overall, the total number of vertiports is reduced by approximately 12% in this scenario and under consideration of the existing infrastructure. In some cells although there is a below-average connectivity, no additional vertiport is recommended.

Fig. 4. shows the change in vertiport demand considering the existing infrastructure. The existing modes of transport are also shown for comparison. The results show that the demand for vertiports can be reduced in densely populated areas because they exhibit a well-developed infrastructure.

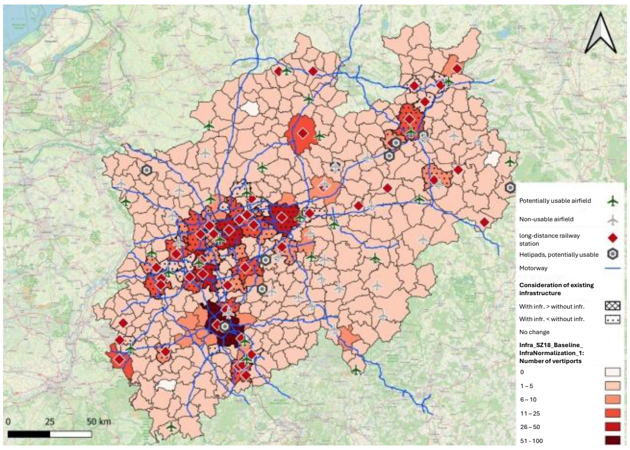

Fig. 4. Recommended number of vertiports considering the existing infrastructure[2]

6. CONCLUSION

In this study, we develop a data-based methodology for estimating the demand for vertiports and applied it to the case study of North Rhine-Westphalia in Germany. The demand is calculated based on socio-demographic data, connectivity to central places, transport relations and volumes, relevant business locations, and touristic arrivals. Points-of-interest could not be considered in the methodology as no comprehensive open-data basis could be found. The methodology can be adapted by applying weighting factors corresponding to different AAM use cases. The resulting vertiport demand is adapted by considering the existing road and railway transport network connections. The methodology follows a manufacturer-independent approach that considers both user-specific needs and existing connectivity deficits in terms of the equivalence of life quality according to the Regional Planning Act[3]. The combination of these factors is used for estimating the number of required vertiports and differs from previous studies, in which the approach usually follows an economic point of view, targeting the highest travel time savings, population density, or number of business trips.

The methodology has been developed to be transferable to other projects and use cases. This applies to both spatial and content levels. The study area can be changed to any other area for which data is available. It is also possible to examine smaller or larger areas, for example, to carry out an analysis on national scale. In addition to spatial transferability, temporal transferability is also possible. By using forecast data for future years, results can be produced for the target year. It is important to note the years for which data on individual attributes is available and to take this into consideration when interpreting the results. Furthermore, the methodology can be applied to other use cases related to AAM passenger transport operations or alternative mobility solutions. To achieve this, it is essential to adapt the attributes examined and the weighting factors in accordance with the specific objectives of the study.

This study allows to derive different conclusions and recommendations that are relevant to providers of public data, infrastructure planners, and other stakeholders. The quality of the results achieved is closely correlated with the quality of the data used. To further enhance the quality of the results, additional information on a range of other attributes, such as the willingness-to-innovate, the use of taxi services, or expenditure on mobility, would be conducive to more accurate outcomes. However, these pieces of information are not available at the desired level of detail for the country of Germany. Furthermore, public data should be made available small-scaled and as georeferenced files to ensure an optimal further use. The study also shows that defining the relevant use cases is important to decide which demand categories and characteristics should be considered. As this is essential for both the data required to describe potential user groups and the resulting demand, it should be considered at an early stage of infrastructure planning, whether for determining a region's potential or for conducting specific site selection.

[2] Map: OSM

[3] Regional Planning Act of December 22, 2008 (BGBl. I p. 2986), last amended by Article 1 of the Act of March 22, 2023 (BGBl. 2023 I No. 88)

We also found that in accordance with the Regional Planning Act, air taxi services have the potential to enhance the connection of the municipalities to central locations. As no route infrastructure is required, air taxi services can improve connectivity in rural or poorly connected regions with little infrastructural effort. The presented methodology helps to estimate the demand of vertiports for AAM passenger transportation per LAU. It does not provide an approach on how to locate these vertiports within each LAU. Consequently, further research will be necessary to select the precise locations for the proposed number of vertiports. Location selection should consider several location factors, including but not limited to local weather conditions, availability of area, technical specifications for flight operations, and legal requirements (for example on urban planning and noise impact). The extension of the presented methodology by an approach for vertiport location selection may provide a more comprehensive set of tools for vertiport planning and development.

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