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LOCATING AIR TAXI INFRASTRUCTURE IN REGIONAL AREAS THE SAXONY USE CASE

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Abstract

To foster the rising urban and regional air mobility, suitable ground infrastructure is required in urban and regional areas. This takeoff and landing infrastructure can be described as "vertiplace", which is categorized into three types (vertihub, vertiport, and vertistation). Each type is expected to fulfill anticipated certification standards for air taxi operations, further consisting of the turnaround of the vehicle and passenger handling. We assume electric vertical take-off and landing (eVTOL) aircraft configuration to become dominant. Each type of vertiplace has a different scope of anticipated services resulting in distinct equipment levels and space requirements. In this contribution, we evaluate 70+ candidate locations in Saxony representing existing mobility infrastructures (airfields, parking lots, and parking garages) by conducting an operational location assessment. Various factors (e.g., space availability, catchment area, links to other transport modes (intermodality), infrastructure installation costs, environment) are considered to figure out which locations meet best operational requirements. Selecting high-ranked locations, we design a hub-and-spoke network by simultaneously considering operational vehicle characteristics such as maximum range and passenger capacity of eVTOL aircraft to serve the demand. This results in a generalized hub location problem (HLP) methodology designing an air taxi network using demand data, cost estimates for infrastructure installation, distances, and ticket prices for passengers. This methodology is applied to an use case in Saxony. Our paper aims at contributing to efficient integration of vertiplace infrastructures in urban and regional areas by simultaneously minimising excessive costs and considering the operational requirements of Regional Air Mobility (RAM).

Keywords

RAM ground infrastructure; network design; location assessment

1. INTRODUCTION

With the rise of the new business case of Urban and Regional Air Mobility (UAM/RAM) using electric vertical take-off and landing (eVTOL) vehicles in inter-urban transport, new challenges for a corresponding air transport infrastructure appears, which differs significantly from today's airports.

The ground infrastructure shall provide safe and secure touchdown and lift-off areas, as well as aircraft and passenger handling facilities. Since UAM and RAM are intended to operate within a city (intra-city) or between regional and metropolitan areas (inter-city), proper ground infrastructures must be established at strategic locations. In this contribution, previously discovered candidate locations for an UAM concept in Saxony are assessed. The objective is to construct a hybrid hub-and-spoke network for air taxis, where hybrid indicates that there are central hubs, as well as a point-to-point factor that allows direct connections between non-hub nodes for a certain extent. This should cut future travel expenses (costs and duration) for passengers by avoiding detours over hubs.

1.1. State of the art

For the location assessment, it is necessary to summarize relevant aspects concerning the characteristics of air taxi ground infrastructure, which have already been discussed in the literature:

According to [1], it should be determined if the utilization of current mobility infrastructure is appropriate to eVTOL vehicles. Based on the equipment level, the ground infrastructure for eVTOLs is classified according to [2] in various categories of 'vertiplaces' (vertihub, vertiport, and vertistation). In order to meet connectivity requirements, the upper levels of parking garages could be utilised as vertiplace as they are typically positioned close to points of interest or other modes of transport and have adequate space available [3]. Other potential vertiplaces are parking lots near train stations and existing aviation facilities, such as airports and airfields [4]. In [5], capacity envelopes of air taxi ground infrastructure are established by taking operational sensitivity into account. Following this, the vertiplaces are required to maintain a particular (ground) capacity, which is heavily dependent on infrastructure and operating conditions. Generic design solutions for air taxi ground infrastructures are currently being developed by eVTOL manufacturers and other researchers [6–9].

Additionally, a short overview is given about UAM in the context of network design as this research also wants to design an UAM network based on the previous gained results of the location assessment:

Several UAM network design studies have been performed in the United States by using p-hub median location problem [10–12]. In [13, 14] a k-means clustering algorithm is used for identification of potential vertiplace locations in Seoul, Republic of Korea, and [15] have used a constrained clustering approach to reveal potential take-off and landing sites in New York City based on a performed demand estimation.

As most of the previous named studies focuses on a general location identification, the candidate nodes in this contribution are already fixed and only have to be evaluated before the remaining candidate nodes are taken to design a hybrid hub-and-spoke network using a p-hub single allocation problem formulation.

1.2. Focus and structure of the document

As stated in section 1, this contribution evaluates candidate locations in their function as nodes which will be part of a hybrid hub-and-spoke network optimization, taking into account operational, passenger-centric, and environmental factors as well as installation costs for the infrastructure. Specifically, this contribution addresses the question of where to locate hub nodes inside a given region. To respond to this inquiry, this contribution is organized as follows:

Section 2 offers an overview of the distinct vertiplace types and their basic needs for enabling air taxi operations, before presenting the considered location assessment factors and operational network design parameters. The location assessment methodology is introduced in section 3 by describing the evaluation metric. In addition, the hybrid hub location problem is presented together with its mathematical formulation, which takes into account the previously outlined operational characteristics of air taxis.

In section 4, a use case in Saxony, Germany, is introduced by a concise summary of the targeted region.

Examples are provided in section 5 to illustrate the network design outcomes of the linear programming optimizatoin using CPLEX (high and low range network design).

In section 6, conclusions are drawn.

2. OPERATIONAL BACKGROUND

2.1. Vertiplace types and basic requirements

Basically, the final dimension of future air taxi infrastructures vary according to passenger demand. In general, this can be viewed as a trade-off-conflict between airside capacity and space utilization: a large number of flight operational areas results in a high capacity per time unit, but also a massive land use.

Regardless of the actual capacity of a vertiplace, it always requires the following components ([5,6,9]), which are depending on eVTOL vehicle dimensions ('D value' according to [16]):

- Final Approach and Take-Off Area (FATO) and Touchdown and Lift-Off (TLOF) Pad ,
- Parking stands, and
- Passenger facilities.

FATO and TLOF are flight operational areas of a vertiplace, where the take-off and landing occur. Additional parking stands are considered for the turnaround or longer stays at the corresponding location (e.g., maintenance). This also requires taxiways connecting the FATO/TLOF and the parking stands.

Regardless of the vertiplace category, each type must fulfill the following functions, which are depicted schematically in figure 1 adapted from [17]. The light blue arrows depict the passenger's path at a vertiplace. It begins with the arrival and access to the vertiplace (grey boxes). Then, it is assumed the presence of a central check-in area, a security check, waiting areas, and restrooms (orange bubbles). In addition, staff rooms and technical facilities are considered necessary for vertiplace operation. The orange circle represents the terminal facility area, which is a tiny version of an airport terminal. The black arrows indicate the staff access to each area within the terminal-like building for assisting passengers or addressing operational difficulties. The green colored circle denotes the airside of a vertiplace with its flight operational areas for air taxi turnaround and take-off and landing. The red part between the terminal and the airside can be seen as a transition to the boarding of the eVTOL. The dashed blue line describes the enclosure of the vertiplace area due to applicable security constraints.

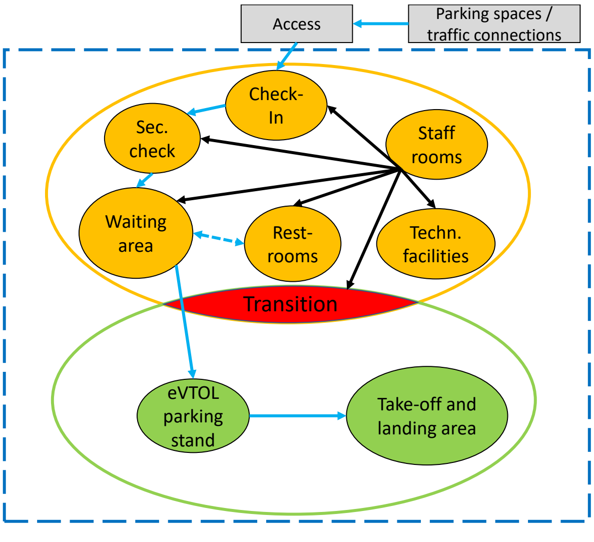

FIG 1. Vertiplace functions required for passenger and flight processing

The categories of vertiplaces (vertihub, vertiport, and vertistation) vary in terms of their dimension. This is supported by their supposed general locations: a vertistation is regarded as the sparsest air taxi ground infrastructure and is therefore assumed to be positioned in rural areas with relatively less demand, where the demand is not deemed to be excessively high. A vertiport is assumed to serve as a key transport hub in urban areas where several modes of transport have already been established. In this case, it is necessary to maintain a particular capacity in terms of passenger and resulting air taxi demand. The vertihub is similar to a depot in that many eVTOL stands are considered for night stops, maintenance events, or in general long-haul stops, resulting in a high space availability that is typically found in rural areas. Following the description of the distinct vertiplace types, it has to be noted that the 'vertihub' does not represent the hub within the hub-and-spoke network. The hub within this network topology is meant by the 'vertiport'.

In accordance with the proportions of the waiting area, technical facilities, staff rooms, and flight operational areas (number of parking stands and takeoff and landing sites), different types of vertiplaces can be differentiated by comparing these aspects to figure 1. The vertihub is believed to be the most comprehensive infrastructure for air taxis in terms of required equipment.

As aforementioned, the vertistation and -hub are typically placed in rural areas, where demand is low and space is available to accommodate the need for a particular storage capacity of eVTOLs. As a result of the assumed lower passenger volumes, the waiting area has the smallest dimension. In comparison, the waiting area at a vertiport is considered to be larger because to its urban location and the anticipated passenger volume from various forms of transportation. For the other components, the requirements grow from vertistation to vertihub, with the maximum number of eVTOL stands at vertihubs due to the required storage capacities.

2.2. Location assessment factors

This section describes the location assessment factors to evaluate the candidate nodes for an air taxi network and includes relevant assumptions for the assessment process.

2.2.1. Space availability

The focus of this paper is the use of already existing mobility infrastructure. Therefore, available space is the most significant issue in determining whether the prospective locations meet the requirements of an air taxi system. These requirements originate from the areas necessary for flight operations (FATO and eVTOL stand) and from the terminal building's specified areas (see figure 1). In addition, obstacle limitation surfaces (OLS) might affect the surrounding area of a vertiplace concerning urban and spatial planning. Within this location assessment, the obstacle clearance is assumed as given and is not considered within the space requirements.

According to [16], the area of a single FATO and an eVTOL stand at a vertiplace is given with 540 m² and 255 m². Based on [18], the space requirements for check-in-, security, and waiting areas are 1.5 m²/pax, 1.1 m²/pax, and 1.7 m²/pax, respectively. The requirements for staff/office rooms are derived from [19] with 7 m²/employee as the base. The required area of the restrooms are estimated according to [20] and is 65 m² for a vertistation, 78 m² for a vertiport, and 97.5 m² for a vertihub. For simplification, the technical rooms are assumed to the same presumptive dimensions as restrooms per vertiplace type. The calculated space requirements, including the fundamental assumptions, are provided in table 1.

Facility	**Station**	**Port**	**Hub**
Assumptions			
Wait. area	10 pers.	30 pers.	10 pers.
no. employees	3	7	9
Security lanes	1	2	1
no. FATO	1	1	2
no. Stand	1	3	10
Resulting space requirements [m²]			
FATO	540	540	1,080
Stand	255	765	2,550
Check-in	15	45	15
Security	11	33	11
Staff rooms	21	49	63
Waiting area	17	51	17
Sanitary	65	78	97.5
Technical rooms	65	78	97.5
Total	**989**	**1,639**	**3,931**

TAB 1. Assumptions and resulting space requirements per vertiplace type

2.2.2. Catchment area

The catchment area around a candidate point determines the amount of individuals who may be assigned to that site. In general, it is assumed that the catchment areas of metropolitan sites are smaller (owing to greater transport mode option flexibility with a superior public transport system) than those of rural regions, where the public transport system is not implemented sufficiently. In this work, the raw data consist of the number of residents in each place [21], which contains the assumed catchment area for the probable location and the map application from [22], which provides the number of residents inside the supposed catchment area. From this perspective, the candidate location seems to be increasingly suited with increasing population size.

For the purpose of identifying a specific catchment area, the cities of the corresponding candidate locations are divided into four groups based on their population size [23]. In table 2, the relevant intervals for city classification and the resulting assumed radius r of the catchment area per city category is displayed. In general, it may be claimed that a city's catchment area becomes less defined as its population increases.

City category	**# inhabitants**	**r catchment area [km]**
Big	$> 100{,}000$	2
Medium-sized	20,000 - 100,000	3
Small	5,000 - 20,000	5
Country	$< 5{,}000$	10

TAB 2. City categories and resulting catchment areas

2.2.3. Intermodality

Intermodality describes the level of accessibility of various modes of motorized transportation. For this reason, the following modes of transportation are distinguished: long-distance, regional, suburban rail, tram, and bus. However, service frequencies and directions are not yet determined for these public transportation options, making it impossible to make a substantiated claim on the quality of service at the candidate location. The use of cars is simply included for comparison purposes (e.g., travel time by public transportation), as every candidate location is accessible by car. Equation 1 describes with R_T the relationship between the travel time by public transport (t_{pt}) and the travel time by car (t_{car}). It measures how well a region's public transportation system has been implemented.

$$R_T = \frac{t_{pt}}{t_{car}} \tag{1}$$

The travel times are measured from the main stations of Dresden (East and Central), Leipzig (Northwest), and Chemnitz (Southwest) to the candidate locations in their respective regions (see table 6). Consequently, the following relationships are possible:

- $R_T > 1$: candidate locations reachable by car in less time,
- $R_T < 1$: candidate locations reachable by public transport in less time, and
- $R_T = 1$: candidate points reachable by car and public transport in the same amount of time.

Moreover, the presence of the aforementioned modes of transportation plays a pivotal role in the following distribution of candidate points to the corresponding vertiplace categories. To become a vertiport, for instance, many linkages to the previously specified forms of transportation (long-distance transport, regional transport, suburban train, tram, and bus) are necessary.

2.2.4. Environment

This factor assesses the region surrounding each location. It takes into account future expansion opportunities (assuming that demand for air taxi services would increase), important facilities (e.g., industrial districts, recreational, etc.), and other potential air taxi locations in the neighborhood.

2.3. Network design aspects

After evaluation of possible locations for the air taxi network, a set of vertiplaces is found which are not yet related to each other. In the next stage, this list is used to design a network that takes the following aspects into account:

- Each vertiplace is only associated with a single hub (p-hub single allocation).
- A direct-link-factor is introduced that permits direct connections between non-hub nodes based on eVTOL range capabilities to maintain a specific state of passenger routing, comfort, and reduced trip expenses.
- At the beginning of the network design, it is preferred that each region of Saxony will have one vertiport.
- Consideration of a discount factor that has a direct impact on the operating costs between hub nodes.
- The establishment costs of a hub node are considered in the model.

To match the capabilities of eVTOLs, more specific assumptions regarding distances, range, demand and passenger capacity between network nodes are made for various aircraft designs (vectored thrust, lift & cruise, and multicopter). Trip cost are modeled distance-based.

2.3.1. Distances

Each of the resulting vertiplace locations are described by a unique four-letter-code (like ICAO does for airports). The distance between all vertiplaces are obtained based on their geographic coordinates and the respective great circle distance.

2.3.2. eVTOL capabilities

In an earlier work, three distinct eVTOL catgeories are considered and assessed in the study by [24]. Table 3 provides a summary of the fundamental outcomes in terms of range and passenger capacity per category.

Category	Range [km]	Seat capacity
Vectored Thrust	115	5 (4 pax; 1 pilot)
Lift & Cruise	73	2 (1 pax; 1 pilot)
Multicopter	52	2 (1 pax; 1 pilot)

TAB 3. eVTOL aircraft capacity and range

2.3.3. Demand

This section presents a method for generating demand data serving as input to the subsequent network design. The passenger demand in the region of our use case is predicted using census and mobility data from 26 locations. Combining the estimated catchment areas (see table 2) with the map tool presented in [22] yields the associated population statistics for each candidate point. This results in around 700,000 individuals residing within all catchment areas. The corresponding modal split statistics for various cities in the future use case region can be found in [25]. For those cities not listed, the mean value is derived from the aforementioned cities.

The calculation of demand takes additionally into account social acceptance in terms of willingness to use and pay for air taxi operations. During the 'SmartFly'[1] research project, the social acceptance is addressed by [26] for a public transport scenario by air taxis. In this survey [26], 14.8% of interviewed people said they would probably use an air taxi in this scenario, while 6.8% said it is even extremely likely they would do so. Concerning the willingness to pay, qualitative assumptions are made based on the anticipated mode of transportation (feet, bicycle, automobile, public transportation), as in [4]:

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[1] https://www.simulplus.sachsen.de/smart-fly-29047.html

- feet and bicycle trips mostly cover short distances, for which a very low willingness to pay is assumed,
- public transportation trips cover medium to long distances with a high price sensitivity (resulting in a low willingness to pay), and
- automobile trips cover medium to long distances with a moderate willingness to pay.

These factors are combined and have an impact on the demand, which is performed by calculating shifting rates from conventional modes of transport for two demand scenarios (probably and extremely likely). The final shifting rates are summarized in table 4. In this contribution, it is assumed that these shifting rates take into account price sensitivity, comfort, and flexibility, as well as concerns about safety/security, reliability, and environmental impact.

Transport mode	**Switching rate [%]**	
	probably	extremely likely
Feet	0.15	0.07
Bike	0.30	0.14
Car	2.22	1.02
Public transport	0.74	0.34

TAB 4. Survey result to modal shift per transport mode to air taxis

Using the computed shifting rates per mode of transport and scenario, it is now possible to estimate the number of expected air taxi users at each candidate point. This results in around 8,900 individuals for the 'probable' scenario and 4,100 individuals for the 'extremely likely' scenario. With the total number of individuals using an air taxi, it is possible to compute the shares of individuals per city required to assign them to their respective vertiplaces. Since there are believed to be two vertiplaces in Dresden and Leipzig, this must be completed at least for these cities. For all other places, a single vertiplace is assumed per city. Scenic flights are excluded in this assignment because they do not result in a change of location. This results in 8,500 individuals who are likely to take an air taxi and 3,900 individuals who are extremely likely to do so.

2.3.4. Prospective costs

At this stage of research, there is not yet any information about operational costs of UAM and RAM. This study uses instead travel costs based on the prices of a typical cab. Dresden being the capital of Saxony is selected as a sample city, where a price of 2.00 € per kilometer is listed in [27] for taxi trips exceeding three kilometers. Air taxi trips are generally considered to cost more than normal taxi rides. In this use case, the fare is set to 4.00 € per kilometer.

In addition, the later model takes into account future installation costs for the integration of the air taxi infrastructure. These costs are simplified to three general cost components: flight operational area, charging equipment, and terminal construction.

The expenses for flight operational areas (FATO and stand) are considered to equal the mean of the several helipad types mentioned in [28]. Half of the FATO costs are assessed for the corresponding stands. According to [29], the costs of the charging equipment are divided into hardware, supply, authorization, and installation for different charging performances[2]. The costs for the terminal building are based on the various interior spaces (see table 1) and assumed with 2,000 €/m² [31]. Table 5 provides an overview of the estimated costs. Together with the specifications in table 1, it possible to estimate the integration costs for each vertiplace type.

Component	**Cost**
FATO	1,200,000 €
Stand	600,000 €
11 kW / 22 kW charging station	10,400 €
50 kW charging station	35,700 €
Terminal	2,000 €/m²

TAB 5. Assumed costs per vertiplace components

3. METHODOLOGY

3.1. Location assessment

The location evaluation procedure is described in figure 2. The first step allocates the candidate locations into geographical groups. This maintains a specific level of coverage throughout a vast region. In practice, this means that subsequent evaluation procedures are conducted independently for each cluster.

The second phase determines if the space availability of the candidate points meets the space requirements of any vertiplace type (see section 2). All candidate points that do not meet the space requirements are discarded at this point and will not be considered in subsequent steps.

The third phase examines the previously specified location assessment factors (see section 2), followed by a comparison of the candidate points per cluster based on their performance in the evaluation processes for each location assessment factor. This procedure concludes with the elimination of all candidate sites with insufficient values.

The last phase is a cross-cluster analysis in which candidate locations near to other cluster-borders are compared. After discarding candidate locations with insufficient values, the location evaluation procedure concludes by providing the final set of candidate locations for subsequent hub-and-spoke modeling.

3.2. Hybrid hub location problem

To answer the initial research question (see section 1.2), a hub allocation strategy is applied to determine which of the final candidate locations will become a vertiport. According to [32], hub networks are more cost-effective

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[2] It has to be mentioned that the charging performances given in table 5 could be not sufficient for operation according to [30] but there is a lack of suitable data concerning the implementation costs of higher charging performances.

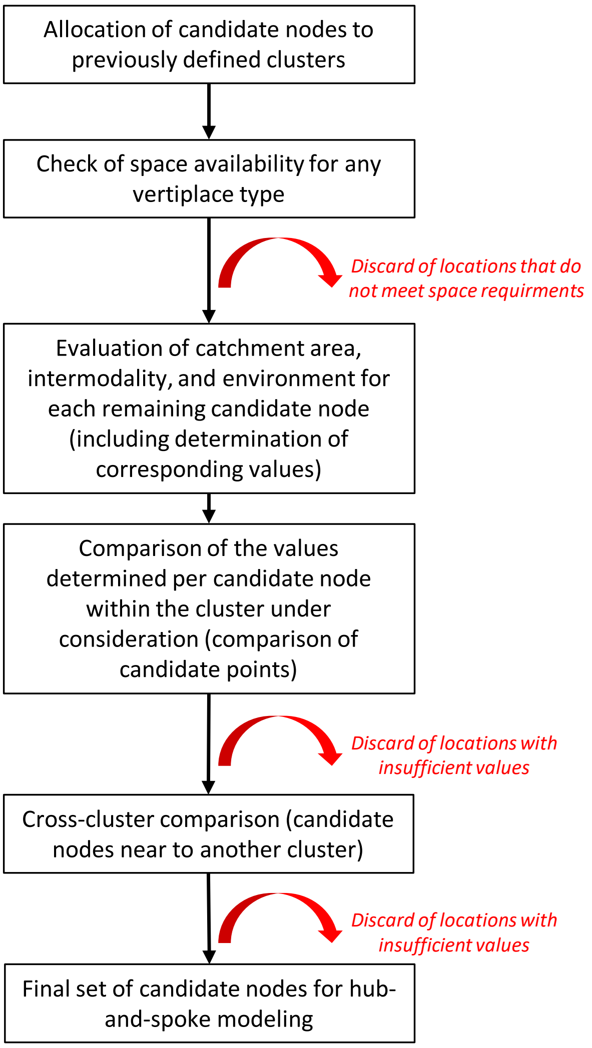


FIG 2. Flowchart of the evaluation of candidate locations as vertiplaces

than point-to-point networks to examine eVTOL passenger operations under diverse scenarios. This study proposes cost-optimal solutions for RAM passenger operations using a hybrid hub allocation method allowing hub to point and point to point connections.
There are three types of hub location problems (HLP): single allocation, multiple allocation, and r-allocation. Single allocation ensures that each non-hub node is assigned to exactly one hub facility (p-hub single allocation), multiple allocation refers to the assignment of a non-hub node to more than one hub, and r-allocation allows each non-hub node to be linked to a maximum of r separate hubs simultaneously [33]. The hub nodes themselves are often fully interconnected, with the cost of each transfer between them typically reduced by a discount factor [34].

3.2.1. Mathematical formulation

The suggested hub allocation problem contains the aforementioned assumptions, the distances between the candidate locations, the capabilities of the eVTOL aircraft (range), cost estimates for each trip per kilometer, and the demand.

Sets:

$\mathcal{N}$	set of all candidate nodes
$\mathcal{F}$	set of all nodes, which can not become a hub

Parameters:

D_{ij}	distance between nodes i and j
S	eVTOL seat capacity
P	number of available potential hubs
C_{ij}	operational flight cost between nodes i and j
F_i	fixed cost for node i to become a hub
R	maximum air taxi range
Q_{ij}	assumed passenger demand between nodes i and j
α	the cost reduction factor between two hubs
λ	level of point-to-point network
N	the total number of candidate nodes

Variables:

y_i	binary variable – 1 if point i is selected as hub, and 0 otherwise
x_{ij}	binary variable – 1 if node i is assigned to hub j, and 0 otherwise
ρ_{ij}	binary variable - 1 if nodes i and j are connected point-to-point
z_{kilj}	auxiliary binary variable – 1 if nodes i and j are connected through hubs k and l, respectively, and 0 otherwise

(2)
$$\min \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}} \frac{Q_{ij}}{S}\,\rho_{ij}\,C_{ij}\,1.2 + \sum_{i\in\mathcal{N}} F_i\,y_i$$
$$+\sum_{k\in\mathcal{N}}\sum_{i\in\mathcal{N}}\sum_{l\in\mathcal{N}}\sum_{j\in\mathcal{N}} \frac{Q_{ij}}{S}\,z_{kilj}\,(C_{ki}+\alpha\,C_{kl}+C_{lj})$$

S.t

(3)
$$\sum_{i\in\mathcal{N}} y_i \leq P$$

(4)
$$\sum_{i\in\mathcal{F}} y_i = 0$$

(5)
$$\sum_{i\in\mathcal{N}} x_{ij} = 1 \qquad \forall\, j\in\mathcal{N}$$

(6)
$$x_{ij} \leq y_i \qquad \forall\, i,j\in\mathcal{N}$$

(7)
$$z_{kilj} \leq x_{lj} \qquad \forall\, i,j,k,l\in\mathcal{N}$$

(8)
$$z_{kilj} \leq x_{ki} \qquad \forall\, i,j,k,l\in\mathcal{N}$$

(9)
$$\rho_{ij} + z_{kilj} + 1 \geq x_{ki} + x_{lj} \qquad \forall\, i,j,k,l\in\mathcal{N}$$

(10)
$$\sum_{i\in\mathcal{N}} \rho_{ij} \leq \lfloor \lambda\,(N-P) \rfloor \qquad \forall\, i\in\mathcal{N}$$

(11)
$$\rho_{ij} = 0 \qquad \forall\, i,j\in\mathcal{N} \mid Q_{ij}=0$$

(12)
$$\rho_{ij} + x_{ij} \leq 1 \qquad \forall\, i,j\in\mathcal{N}$$

(13)
$$\rho_{ji} + x_{ij} \leq 1 \qquad \forall\, i,j\in\mathcal{N}$$

(14)
$$\rho_{ji} \leq 2 - y_i - y_j \qquad \forall\, i,j\in\mathcal{N}$$

(15)
$$\rho_{ij} = \rho_{ji} \qquad \forall\, i,j\in\mathcal{N}$$

(16)
$$x_{ij}\,D_{ij} \leq R \qquad \forall\, i,j\in\mathcal{N}$$

(17)
$$\rho_{ij}\,D_{ij} \leq R \qquad \forall\, i,j\in\mathcal{N}$$

(18)
$$z_{kilj}\,D_{kl} \leq R \qquad \forall\, k,i,l,j\in\mathcal{N}$$

The objective function (2) minimizes the total network costs by minimizing the cost between two nodes when they are connected point-to-point, the fixed costs when a node becomes a hub, and the cost between two nodes when they are connected through hubs. The discount factor between two hubs (α) is taken into account when two points i and j are connected via hubs k and l, respectively. In addition, the costs for a point to point connection are considered 20% higher for taking into account operational difficulties. Constraint (3) restricts the maximum number of hub locations and allows the model to establish fewer hubs if it would be optimal. Constraint (4) is introduced for saving computational time as it restricts several nodes to become a hub. Constraint (5) ensures each candidate node has to be connected to one (and only) hub in the network. Constraint (6) ensures that a candidate node can be connected to a hub node if that node has been selected as a hub. Constraints (7), (8), and (9) stand for linearization and assure that node i and j are connected through hubs k and l. Constraint (10) specifies the total number of points which are connected via the point-to-point approach. Constraint (11) ensures that if no demand exists between two nodes, they should not be connected directly using the point-to-point approach. Constraints (12) and (13) prevent links between a node and its associated hub to be also connected via the point-to-point approach. In other words, when two points are directly connected, it is because either one of them is hub or they are connected through the point-to-point approach. Constraint (14) prevents two hubs from being connected through point to point approach. Constraint (15) ensures that the point-to-point connection from node i to node j equals the one from j to i. Constraints (16) and (17) ensure maximum range limitations of long-range air taxis for point-to-point and hub connections. Constraint (18) considers the range limitations between hubs k and l, when nodes i and j are connected by them.

4. DESCRIPTION OF USE CASE NETWORK

In this case study, the entire state of Saxony is considerd as a potential RAM network, inclusive intra-city UAM traffic inside cities/regions with multiple vertiplaces.

As stated in section 3.1, the candidate nodes are distributed to four distinct clusters (East, Central, Northwest, and Southwest) based on their location in Saxony. Table 6 shows a list of prospected cities (50), which yields about 70 potential candidate nodes for a subsequent vertiplace. The cities marked in yellow are included in the subsequent network modeling as the result of the completed location assessment. The final set of candidate points consists of 28 locations in total.

5. NETWORK DESIGN RESULTS

According to section 3.2.1, the mathematical model is solved using CPLEX. To specify the network design outcomes, the following parameters are varied: the maximum number of hubs P ($P = 3$ in the given network examples), the level of point-to-point network λ, and the maximum air taxi range R. The seat capacity S is set to five and the discount factor α for inter-hub connections is set to 0.4 in all depicted network design solutions (figures 4, 5, and 6). Additionally, the direct connections are considered with a higher fare (20%) than connections via hubs to take into account operational efforts for additional point-to-point flights (e.g., aircraft rotation). The remaining parameters demand Q_{ij}, distance D_{ij}, and costs F_i, C_{ij} are input data and invariant.

East	Central	Northwest	Southwest
Bautzen	Dresden	Böhlen	Chemnitz
Kamenz	Arnsdorf	Taucha	Oberschöna
Rothenburg	Bad Schandau	Löbnitz	Zwickau
Görlitz	Coswig	Oschatz	Auerbach
Großdubrau	Freital	Torgau	Großrückersw.
Hoyerswerda	Großenhain	Makranstädt	Plauen
Zittau	Heidenau	Schkeuditz	Freiberg
Weißwasser	Klingenberg	Markkleeberg	Glauchau
Löbau	Königsbrück	Leipzig	
	Meißen	Döbeln	
	Pirna	Wurzen	
	Priestewitz	Delitzsch	
	Radeberg	Grimma	
	Radebeul	Eilenburg	
	Riesa		
	Sebnitz		
	Tharandt		
	Weinböhla		
	Wilsdruff		

TAB 6. Set of regions with suitable infrastructure for vertiplaces and resulting candidate nodes for network design (yellow)

Throughout these studies, it is evident that in all network design results three hubs (yellow triangle) are identified independent from the possibility to choose less than three (see table 7 and figures 4, 5, and 6). The orange lines in these figures represent inter-hub connections (hub triangle). The green nodes correspond to non-hub nodes, which have direct connections to other non-hub nodes (green lines). Within the figures 4a and 4b, there are also red nodes. These ones are non-hub nodes, which have no other direct connections and are only connected to their hub.

The influence of R is significant because it affects many connections in the range limited case. R becomes crucial when meteorological conditions are taken into account (e.g., battery capacity losses due cold temperature, headwind) and a robust network solution for these cases is necessary. In consequence, the hub triangle (orange lines) is getting closer. For the high range network designs, the hubs are located in Dresden (city), Leipzig (city), and Chemnitz (see figures 4a, 5a, and 6a). Within the lower range network designs (see figures 4b, 5b, and 6b), only Chemnitz remains as a hub where the other ones are shifted from Dresden to Radeberg and from Leipzig to Grimma because the distance to the other locations is higher than the assumed R (85 km) in this case.

λ describes the level of point to point connections in our model. The higher λ is set, the more point to point connections are allowed in the network (see figure 5), and the lower the objective value (see table 7). The objective value further decreases to 509,965 for the high range scenario when $\lambda = 0.8$. At the end, more point to point connections also result in more flexibility and comfort for the passengers.

The highest objective values are obtained when the networks become a pure hub and spoke network (see figure 6 and table 7). In general, it can be observed that the low range networks have higher objective values (costs) than the high range ones for all parameter settings (between 0.2 - 0.5%; see table 7) but nevertheless, operating an air taxi network in adverse meteorological circumstances remains possible.

In all network design results (figures 4, 5, and 6), all hub nodes can be physically connected to one another and give good coverage and connection over the entire region. The selected hub locations satisfy the necessary space availability requirements, allowing them to be operated as vertiports within an air taxi network.

Parameter setting	Network scenario	
	High R (115 km)	Low R (85 km)
$y[i] = P; \lambda = 0.1$	538,011	540,085
$y[i] \leq P; \lambda = 0.1$	537,993	540,085
$y[i] = P; \lambda = 0.2$	522,001	524,670
$y[i] \leq P; \lambda = 0.2$	522,001	524,670
$y[i] = P; \lambda = 0$	558,909	561,939
$y[i] \leq P; \lambda = 0$	558,909	561,939

TAB 7. Objective values for different network design results

An additional network scenario is analyzed with only one hub. In this case, the selected hub is at Dresden (city) and all other nodes can be assigned to it considering $R = 115\ km$. For a corresponding $\lambda = 0.2$, the network design is depicted in figure 3 with an objective value of 708,346. This value is 35.7 % higher than the optimal solutions shown in table 7 and indicates that increasing the number of hubs reduces the total network expenses.

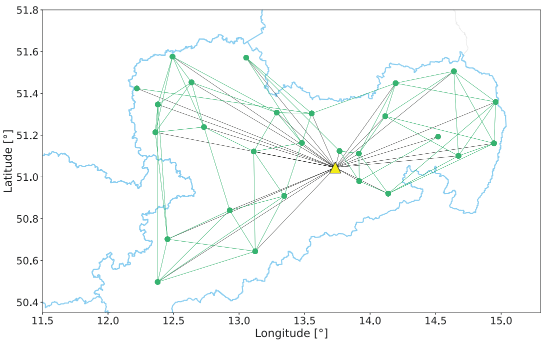


FIG 3. High range network design with only one hub

Due to the distances between the candidate nodes, the model cannot support a low range network scenario with $R = 85\ km$ and a single hub. Here, two hubs are required at least.

Finally, the following findings can be summarized:

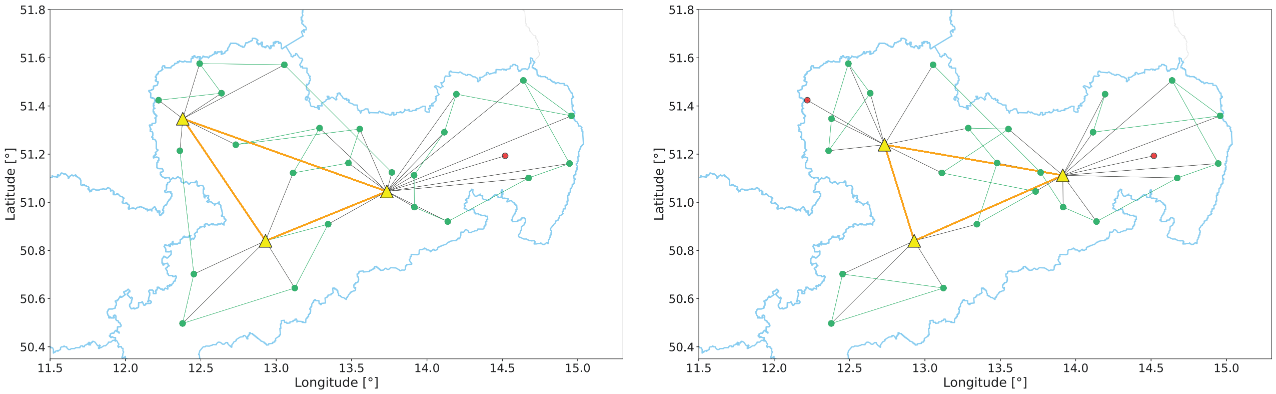
- The range R has a substantial impact on the network design, as it directly determines feasible connections based on the distance to be covered.
- A lower anticipated maximum range alters the positions of the hubs from urban to more rural regions since shorter distances are required.
- An increasing number of hubs (up to three) reduces the total network expenses for our use case.
- Pure hub-and-spoke network designs are generally more cost-effective than point-to-point network designs, but less cost-effective than hybrid network designs with additional point-to-point connections.
- The cost reduction factor α has no effect on the hub locations and only affects the objective value.

6. DISCUSSION AND CONCLUSION

This contribution begins with a assessment of more than 70 possible locations in Saxony, Germany, to determine which ones could be part of a hub-and-spoke air taxi network with point-to-point connections (hybrid hub and spoke). Multiple evaluation parameters are analyzed per candidate location (space availability, catchment area, intermodality, and environment). At some steps during this location assessment, further information may have been offered. For instance, the assessment of the required space per vertiplace, the definitions of catchment areas, and the estimation of prospective investment costs (as input parameter to the mathematical model) are based on (reasonable) assumptions. In addition, the intermodality component may have been highlighted by public transportation quality aspects (e.g., service frequency). The evaluation of the environment has to be done in more detail for defining OLS, which might have a huge influence on the space requirements.

Concerning the network design aspects, the eVTOL capabilities in terms of maximum range are very uncertain and only are assessed in a former publication [24]. Demand between all nodes is also complex to model and subject to uncertainty. The trip costs are based on distances. A dynamic pricing could be more realistic for future air taxi services. Nonetheless, these factors serve as inputs for the optimization model, which is capable of generating appropriate air taxi network design results. The red nodes in figure 4a could be operated as deposits for night stays and MRO as these nodes correspond to existing airfields where space requirements are given.

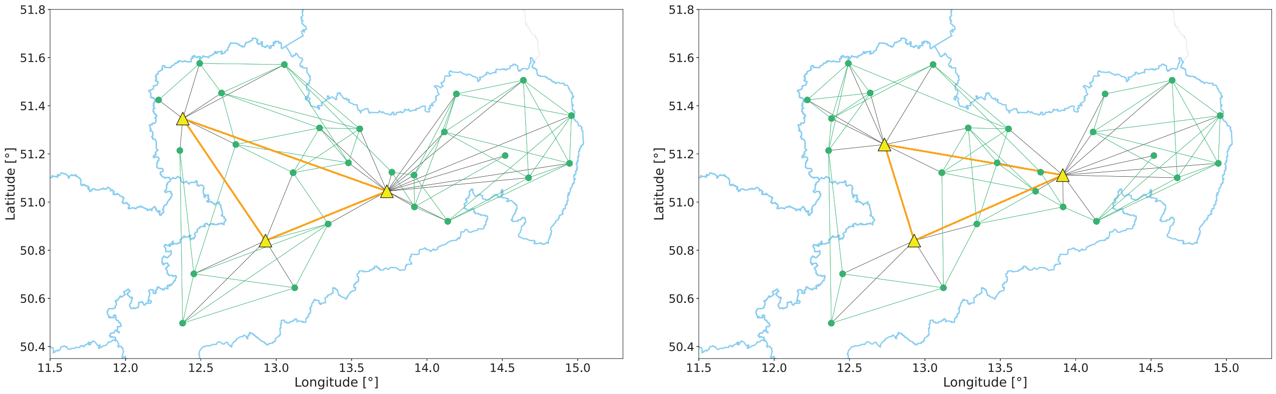
The network design results reveal hybrid hub and spoke networks with a given level of direct connections. In summary, a network design for standard operation and a network design that takes into account factors that restrict the maximum range of air taxis are proposed. In future research, a capacity analysis should be conducted to answer the concerns of how many eVTOLs are required to meet passenger demand and how much eVTOL stands must be reserved for eVTOLs. Additionally, the impact of climatic conditions on battery capacities (resulting in a decreased maximum range) should be analyzed in more detail.



(a) High range network design

(b) Lower range network design

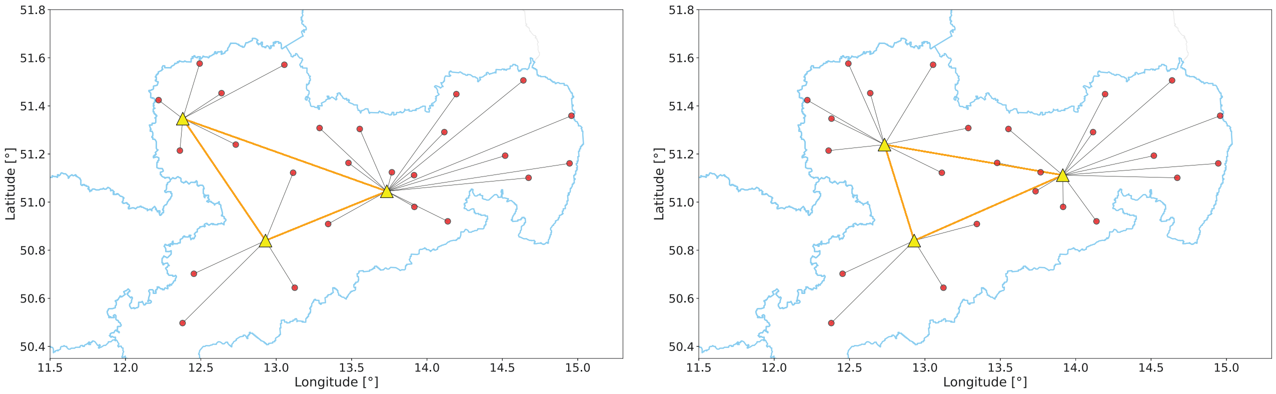
FIG 4. CPLEX network designs for $P = 3$ and $\lambda = 0.1$ (first row of table 7)



(a) High range network design

(b) Lower range network design

FIG 5. CPLEX network design with minimal costs (third and fourth row of table 7)



(a) High range network design

(b) Lower range network design

FIG 6. CPLEX network designs with $\lambda = 0$ (pure hub and spoke networks (last two rows of table 7))

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References

[1] Federal Ministry of Transport and Digital Infrastructure. *Abflug in die dritte Dimension - Aktionsplan der Bundesregierung für Drohnen und Lufttaxis [German]*. 2020.

[2] R. Lineberger, A. Hussain, M. Metcalfe, and V. Rutgers. Infrastructure barriers to the elevated future of mobility. 2019.

[3] Joby Aviation. *Joby Aviation Announces Infrastructure Partnership With Largest Mobility Hub Operator in North America*. 2021.

[4] W. Finkeldei, E. Feldhoff, and G. S. Roque. *Machbarkeitsstudie Köln Bonn Airport Flugtaxi Infrastruktur [German]*. 2020.

[5] P. Vascik and J. Hansman. Development of vertiport capacity envelopes and analysis of their sensitivity to topological and operational factors. In *AIAA SciTech Forum*, 2019.

[6] Lilium. *Designing a scalable vertiport*. 2020.

[7] Volocopter GmbH. *VoloPort*. 2021.

[8] K. Schweiger, F. Knabe, and B. Korn. An exemplary definition of a vertidrome's airside concept of operations. *Aerospace Science and Technology*, 125:107144, 2022.

[9] S. Zelinski. Operational analysis of vertiport surface topology. In *2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, pages 1–10. IEEE, 2020.

[10] L. C. Willey and J. L. Salmon. A method for urban air mobility network design using hub location and subgraph isomorphism. *Transportation Research Part C: Emerging Technologies*, 125:102997, 2021.

[11] Z. Wu and Y. Zhang. Integrated network design and demand forecast for on-demand urban air mobility. *Engineering*, 7(4):473–487, 2021.

[12] S. Rath and J. Y. J. Chow. Air taxi skyport location problem for airport access. *arXiv preprint arXiv:1904.01497*, 2019.

[13] E. Lim and H. Hwang. The selection of vertiport location for on-demand mobility and its application to seoul metro area. *International Journal of Aeronautical and Space Sciences*, 20(1):260–272, 2019.

[14] J. Jeong, M. So, and H.-Y. Hwang. Selection of vertiports using k-means algorithm and noise analyses for urban air mobility (uam) in the seoul metropolitan area. *Applied Sciences*, 11(12):5729, 2021.

[15] S. Rajendran and J. Zack. Insights on strategic air taxi network infrastructure locations using an iterative constrained clustering approach. *Transportation Research Part E: Logistics and Transportation Review*, 128:470–505, 2019.

[16] European Union Aviation Safety Agency (EASA). *PTS-VPT-DSN*. 2022.

[17] Skyports. *Vertiport Security*. 2022.

[18] International Air Transport Association (IATA). *Is your Airport Terminal Operating At An Optimum Level?* 2019.

[19] Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA). *ASR A1.2 - Raumabmessungen und Bewegungsflächen [German]*. 2013.

[20] Geberit Vertriebs GmbH. *Kompetenzbroschüre Sanitärraumplanung - Planung und Ausstattung von Sanitärräumen [German]*. 2020.

[21] Statistisches Landesamt des Freistaates Sachsen. *Bevölkerungsstand, Einwohnerzahlen [German]*. 2021.

[22] Statistische Ämter des Bundes und der Länder. *Zensus 2011 [German]*. 2021.

[23] M.-S. Neumair. *Gabler Wirtschaftslexikon - Stadtdefinition [German]*. 2018.

[24] R. Brühl, H. Fricke, and M. Schultz. Air taxi flight performance modeling and application. In *ATM Seminar*, 2021.

[25] R. Gerike, S. Hubrich, F. Ließke, S. Wittig, and R. Wittwer. *Sonderauswertung zum Forschungsprojekt Mobilität in Städten-SrV 2018*. 2020.

[26] P. Planing and L. Riza. *Studie zur Zahlungsbereitschaft von Flugtaxis im Großraum Dresden*. 2022.

[27] Der Innenspiegel. *Taxitarife in Deutschland [German]*. 2021.

[28] Helipad.consulting. *Landeplätze [German]*. 2022.

[29] Nationale Plattform Elektromobilität. *Ladeinfrastruktur für Elektrofahrzeuge in Deutschland [German]*. 2015.

[30] R. Brühl and H. Fricke. Assessment of minimum ground time for air taxis based on turnaround critical path modeling. In *ICRAT*, 2022.

[31] Statistisches Bundesamt. *Bauen und Wohnen [German]*. 2021.

[32] C. Y. Justin, A. P. Payan, and D. N. Mavris. Integrated fleet assignment and scheduling for environmentally friendly electrified regional air mobility. *Transportation Research Part C: Emerging Technologies*, 138:103567, 2022.

[33] S. A. Alumur, J. F. Campbell, I. Contreras, B. Y. Kara, V. Marianov, and M. E. O'Kelly. Perspectives on modeling hub location problems. *European Journal of Operational Research*, 291(1):1–17, 2021.

[34] R. Z. Farahani, M. Hekmatfar, Alireza B. A., and E. Nikbakhsh. Hub location problems: A review of models, classification, solution techniques, and applications. *Computers & industrial engineering*, 64(4):1096–1109, 2013.