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ORIGINAL PAPER

HorizonUAM: operational challenges and necessary frameworks to ensure safe and efficient vertidrome operations

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Abstract

Urban Air Mobility (UAM) has emerged as a potential game changer for urban transportation, promising faster, more efficient and affordable services. However, beyond the visionary concepts, it is crucial to explore and discuss the opportunities and challenges of UAM and vertidrome operations also from a research perspective. The DLR research project *HorizonUAM* aimed at a holistic research approach in which vertidromes and vertidrome networks play a significant role. This vertidrome centered project report covers various aspects and methodological approaches addressing design and operation, UAM airspace management, network optimization and the integration of air taxi operations into airport environment. Moreover, the conceptual and temporary development of a modular 1:4 scale model city lays the foundation for future UAM flight trials. Based on three years of dedicated research within *HorizonUAM*, we focus here on operational challenges, proposed solutions and required frameworks to ensure safe and efficient vertidrome operations

Keywords Urban Air Mobility · UAM · Vertiport · Vertidrome design · Airspace management · Network optimization · Model city · Airport integration

Abbreviations

ATC	Air Traffic Control
ATS	Air Traffic Services
ConOps	Concept of operations
DLR	German Aerospace Center
EASA	European Union Aviation Safety Agency
eVTOL	Electric vertical take-off and landing
FAA	Federal Aviation Administration
FATO	Final approach and take-off area
FRA	Free route airspace
G	Gust speed
LIEDT	Linear Independent Expandable Drive-Through
METAR	Meteorological Aviation Routine Weather Report
SBA	Slot-based approach
TBA	Trajectory-based approach
TLOF	Touchdown and lift-off area
UAM	Urban air mobility
UAS	Unmanned aircraft system
V-Lab	Vertiport-in-the-lab
VALoS	Vertidrome airside level of service
VFR	Visual flight rules
VTOL	Vertical take-off and landing
W	Wind speed
WA	Wind-advisory
WO	Wind-operational
WS	Wind-shutdown
WW	Wind-warning

1 Introduction

"Joby Aviation's first production air taxi cleared for flight tests. It's on track to start customer deliveries next year and run air taxis by 2025" [1]

"Groupe ADP & Volocopter at Forefront of Electric Urban Air Mobility: A World First in Summer 2024" [2]

Recent statements like these are not science fiction anymore. Air taxi prototypes are already in production. To pave the way for the future deployment, suitable infrastructure,

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new flight rules and air traffic management processes, advanced urban communication and navigation capabilities, successful certification, and finally passengers are required. This leads us to the question: What about the status of (UAM) ground infrastructure? The functional design and the technical equipment of a vertidrome and a vertidrome network are both a challenge and a key driver for the operational deployment of air taxis as well as the provision of UAM services. Instead of introducing a modern version of low-density helicopter services which currently represent a niche market, UAM targets low ticket prices and high throughput. Considering high traffic densities of air taxis operating in urban environment and low level airspace, not only vertical approach and departure procedures are of great interest, but also strategic scheduling, tactical sequencing and efficient ride matching are crucial to utilize the limited capacities of a vertidrome network as efficiently as possible. The coordination and allocation of each individual air taxi within a vertidrome network operating under on-demand characteristics requires a rather flexible, yet a safe and secure framework. The framework needs to be easily adaptable to changing operating conditions and sudden unexpected events such as adverse weather. Furthermore, mixed air taxi fleets with different flight performance characteristics and vehicle dimensions, operational uncertainties and disruptions, and vertidrome operations inside airport environment, are just some of the operational conditions that need to be considered. New approaches and solutions are required to implement UAM and vertidromes successfully into urban environment and airspace.

1.1 HorizonUAM: vertidrome aspects and methodological approaches

The DLR research project *HorizonUAM* brought together researchers from various disciplines to investigate UAM holistically. This includes research on UAM vehicles, infrastructure, operation and public acceptance [3]. The final project outcome is an assessment of challenges and opportunities associated with UAM [4]. As part of the project, the work package *Vertidrome* focused on investigating the operational characteristics and defining requirements of future vertidromes from different perspectives and disciplines. This paper summarizes the individual vertidrome related studies conducted under HorizonUAM, relates the results and suggests areas of remaining uncertainties for future research.

As shown in Fig. 1, this paper covers the design and operation of individual vertidromes on a micro-level (1), but also extended to the macro-level by addressing vertidrome airspace network management (2) and network optimization (3). Moreover, we studied the opportunities and challenges of integrating air taxi services and vertidrome operations into airport environment, thus controlled airspace (4), and introduced the approach of developing a UAM model city (5) to validate our concepts in scaled flight trials.

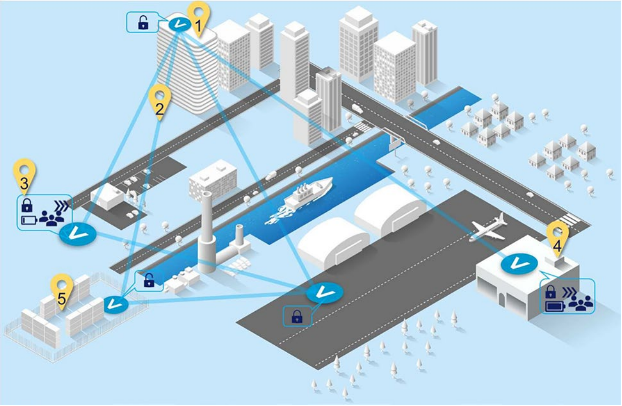

Fig. 1 Overview on *HorizonUAM* vertidrome research topics. (1) Vertidrome design and operation, (2) Vertidrome airspace network management, (3) Vertidrome network optimization, (4) Vertidrome integration into airport environment and (5) UAM model city

For this purpose, we defined individual research tasks and applied various methodological approaches to analyze a future vertidrome from a micro- and macro-perspective:

- Development of a vertidrome simulation module and a corresponding assessment framework to evaluate the airside performance of future vertidromes.
- Development of urban airspace network management concepts for UAM considering different possible route topology and structures.
- Development of a ride-matching algorithm to optimize the distribution of vertidrome network capacities.
- Development of operational processes to safely integrate air taxi operations into airport environment/ air traffic control processes and implementation into a human-in-the-loop simulation setup.
- Conceptual development of a 1:4 scale modular model city to support scaled demonstration and validation flight trials.

We provide a consolidated overview of our *HorizonUAM* vertidrome research topics by focusing on three key aspects in each section. First, we provide an introduction to the specific topic and highlight the operational challenges faced at this stage of UAM and vertidrome development. Second, we present our specific solutions and key findings towards enabling a UAM framework to accommodate safely and efficiently vertidrome operations in different operational environments. Third, we discuss lessons learned and recommendations for the future direction of work in the field of vertidromes.

In the following project report, we start with the vertidrome micro perspective in Sect. 2, which focuses on the individual vertidrome design and operational concept. It is followed by the macro perspectives of vertidrome network airspace management in Sect. 3 and vertidrome network optimization in Sect. 4. We continue the macroperspective in Sect. 5 by investigating the integration of vertidrome operations into airport environment thus controlled airspace. Finally, we transition from a simulation-orientated micro- and macro-perspective to the development of a 1:4 scaled modular model city to support scaled UAM flight trials which is displayed in Sect. 6. We conclude this report with a vertidrome-focused conclusion in Sect. 7.

1.2 Baseline for HorizonUAM's vertidrome research

In July 2020, we started the *HorizonUAM* vertidrome research with a thorough literature review in cooperation with *Bauhaus Luftfahrt e.V.* In total, we sighted 197 sources, covering 49 scientific publications listed in *Scopus* from 2016 to 2021, (inter-) national regulations, standardization, and general publications on vertidrome design and operations in the context of UAM. The literature review published as [5] revealed, that up until recently, the classification and characteristic of UAM ground infrastructure was not harmonized at all. It led to terminologies such as vertiport, vertiplace, vtol port, vertihub, skypark or pocket airport, accommodating either air taxis and/or cargo drones, piloted and/or un-piloted operations, and extreme variations in traffic densities. Since the publication of EASA's Prototype Technical Specification for the design of VFR vertiports [6] in March 2022 and FAA's Engineering Brief No.105 on vertiport design [7] in September 2022, the term *vertiport* has been consolidated for the UAM community. However, the early implementation approach of vertiports as prescribed in [6] and [7] explicitly address VFR air taxi operations on existing Vertical Take-off and Landing (VTOL) ground infrastructure such as heliports or early versions of vertiports with reduced capabilities.

Therefore, in *HorizonUAM* we introduce the generic term *vertidrome* to describe UAM ground infrastructure used by VTOL aircraft as introduced in [8]. This includes also airside and landside jurisdictions as well as a designated airspace surrounding the vertidrome. To reflect the limitations of different operating environments, technical implementation possibilities and time horizons, we further distinguish between *vertiport*, a fully equipped vertidrome with parking and charging spots and a *vertistop*, which solely provides safe take-off and landing capabilities. A *vertiport* might also offer maintenance, repair and overhaul services or act as a "hub" in a hub & spoke network. We must be aware that tomorrow's vertidromes need to accommodate long-term developments of UAM. This means that UAM vertidrome networks and vertidrome air, ground and landside operations need to be scalable.

During the literature review which finished in mid 2022, the vertiport community still lacked essential foundation, especially in terms of standardization and regulation. This started to change as of January 26, 2023 when the European regulatory framework for unmanned aircraft system traffic management *U-space* became applicable for all European Union member states (see the Commission Implementing Regulation (EU) 2021/664 [9]). Together with the Commission Implementing Regulation (EU) 2021/665 [10], 2021/666 [11], and the acceptable means of compliance and guidance material [12], a first reduced U-space framework is now available.

Figure 2, an excerpt from [5], shows the systematic approach into which categories the sighted literature was categorized. In addition to regulation, the topics of security, noise and weather were significantly underrepresented in the sighted literature. Moreover, environmental factors such as wildlife hazards, which did not even get listed, have received little attention so far. In *HorizonUAM*, which aimed at a holistic research approach of UAM, we were able among others to address the underrepresented topics such as safety and security [13, 14], social acceptance and noise perception [15, 16], weather in terms of wind and gusts [17], and wildlife hazards potentially caused by advanced air mobility.

Future UAM airspace operation was widely researched within *HorizonUAM*. The integration of air taxis as new airspace users into the urban airspace is challenging. Depending on the airspace category, different operational requirements ranging from highly to least restrictive should be considered. At the beginning of the project, various Concept of Operations (ConOps) [18–23] were reviewed and used as input for further analysis and enhancement. The analyzed literature sources often provide frameworks that can serve as a starting point for concept evaluations rather than providing precise solutions for future operations.

Successful integration into the airspace and existing air traffic flows is key to ensuring feasible and safe UAM operations. The existing airspace concepts of [20–23] propose independent corridors for air taxis that can operate

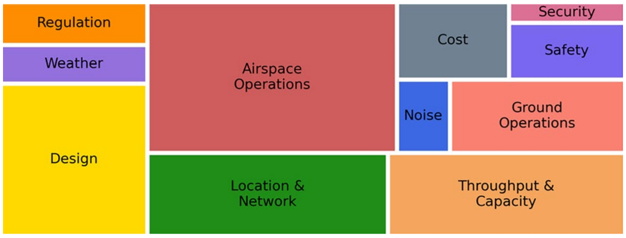

Fig. 2 Vertiport-related topics discussed in scientific literature (49 Scopus-listed scientific publications 2016-2021). Adapted from [5]

independently of existing traffic and without any interaction with Air Traffic Control (ATC). However, existing legislation mandates contact to ATC within control zones such as at airports. In addition, control zones often stretch out to city centers (e.g. Frankfurt, London, Paris), which makes many of the European cities part of controlled airspace. The European approach of accommodating drones and air taxis in European airspace is focused on integration. This means that future U-space airspace will be integrated into current airspace and where necessary, ATC will be provided procedural and collaborative interfaces [24]. Airservices Australia have evaluated the challenges with regard to controller workload and situation awareness within fast- and real-time human-in-the-loop simulations[20]. Based on these results, a concept for the operational air taxi integration has been developed within *HorizonUAM* and tested in human-in-the-loop simulations. Likewise, different airspace management concepts were defined and tested within fast-time simulation. Furthermore, literature review and analysis did not only aim to baseline new concepts, procedures, solutions and ideas paving the way for UAM operations. We also elaborated a comparison framework based on common UAM-tailored metrics introduced by literature such as [25–31].

Another relevant design factor is represented by the resource distribution in a UAM network, i.e. the allocation of capacity requirements to each vertidrome, derived from a demand scenario. In the planning and design phase, it is crucial to ensure that the available resources are allocated in accordance with the demand hot spots, such that ground infrastructure is located in direct proximity to the demand and provides sufficient capacity to handle all passengers. In literature, the mapping of infrastructure to the demand hot spots has mostly been investigated in the course of the vertiport positioning problem, such as in [32] and [33]. In these studies, optimized vertiport positions are derived depending on the achievable time savings of the resulting networks, respectively depending on reachability metrics resulting from the networks. However, these investigations foremost concentrate on optimal positions and density of vertidromes in a network and the resulting benefits. Another optimization approach examining the effects of network design on demand satisfaction has been presented in [34]. While research on derivation of vertiport networks from demand predominantly concentrates on defining optimized positions, the achievable time savings and the resulting monetary costs, there is almost no research available on quantitatively defining vertidrome capacities based on the information gained from demand scenarios. In [35] it is therefore pointed out that the link between demand and resource allocation needs to be examined taking single trips into account, which has been identified as one of the challenges to cope with in *HorizonUAM*.

2 Vertidrome design and operation

According to the conclusions of [5], vertidromes are expected to appear in different sizes and layouts, with varying numbers of (FATO), gate parking positions, and parking/charging stands. Vertidromes may have taxi route systems, ground movement equipment responsible for automatically moving the air taxi on the ground. Vertidromes are located in different operational environments, must accommodate different (e)VTOL aircraft designs and process different demand characteristics. All this, together with the strategic scheduling processes, the performance of an air taxi in terms of maneuverability, range, taxiing and re-charging, the size of the air taxi fleet and the number of seats available, determines how many of the on-demand UAM requests can be accepted and executed. Vertidromes are part of a system-of-systems operation but need to be designed and evaluated individually for each location, business case and demand forecast. Hence, there is no one-size-fits-all solution for vertidromes. But how do we develop and evaluate an operational concept for vertidromes when there is no blueprint for air taxi operations in low level urban airspace, no regulatory guidance, and no certainty about Electric Vertical Take-off and Landing (eVTOL) aircraft performance and demand forecast?

As part of the *HorizonUAM* project, we collaborated with *Bauhaus Luftfahrt* e.V., who provided us with their demand estimates for the area of Upper Bavaria, which were developed in the *OBUAM* project [36]. In a first step, this dataset was used to evaluate the developed ConOps for two vertiport designs in a fast-time simulation (V-Lab [37]), meeting low to medium and high density demand characteristics. In a second step, the vertidrome fast-time simulation was implemented into the system-of-systems workflow in which a UAM operation was simulated and evaluated for the *HorizonUAM* reference city of Hamburg considering location specific demand forecasts and vertidrome networks (see contributions such as [38] made by *HorizonUAM* work package 1 "Overall System Simulation").

We started the vertidrome design research by defining the key elements of a vertidrome, thereby focusing on the airside jurisdictions (see Fig. 3). The pad, consisting of the (TLOF), FATO and safety area, is the only essential element required for a vertidrome operation. Touchdown and lift-off procedures are conducted here in obstacle-free and safe environment. However, stands and gates are necessary to release the pad for the next incoming arrival, waiting departure or emergency, which therefore increases a vertidrome's throughput and safety significantly. All vertidrome elements need to be designed based on the maximum dimensions (D-value) of the aircraft type intended to operate at the vertidrome [6].

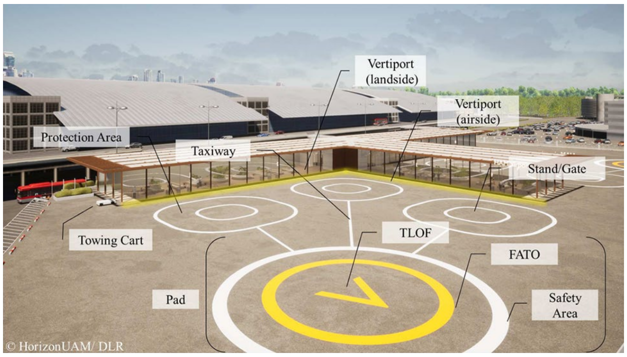

Fig. 3 Infrastructure Elements of a Vertidrome. Adapted from [5]

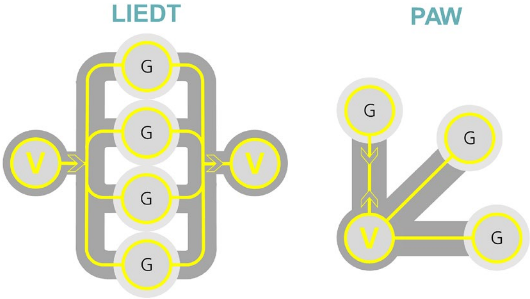

Fig. 4 Vertidrome Layouts: LIEDT (left) [8]. PAW (right) [39]

The operational concept of a vertidrome aligns each vertidrome element's capabilities and capacities by defining clear interactions and procedures. Within the project we developed two vertiport layouts. The Linear Independent Expandable Drive-Through (LIEDT) layout creates a one directional flow in which arrival and departure streams are separated and only share the gate parking infrastructure (see Fig. 4 left). Instead, the PAW layout operates a bi-directional traffic flow and provides a smaller footprint (see Fig. 4 right).

Both vertidromes are surrounded by a terminal airspace which accommodates arrivals and departures. Since the LIEDT layout can operate both traffic streams independently due to two separate approach and departure slopes and FATOs, the terminal airspace can accommodate two air taxis at a time, instead, the PAW layout which shares one FATO for both operations, can only host one air taxi at a time.

In [39] we showed that even though the LIEDT layout is designed for higher throughput scenarios, the full vertidrome capacity potential is only leveraged if strategic scheduling methods are optimizing the harmonization between all infrastructure elements, in our case, pads and stands. Considering an exemplary demand of approx. 1,400 operations per day, the PAW layout was able to perform better on a tactical level due to an optimized scheduling algorithm which set the capacity of the single FATO in relation to the availability of the gate parking positions. However, this resulted in an extreme number of strategic cancellations already during the booking process but prevented tactical gate shortages and thus significantly reduced tactical airborne delay. Based on these results, request cancellations should not become a common practice to increase performance levels. Therefore, demand and capacity must be efficiently balanced during strategic and tactical phases.

The comparison of both vertidrome airside performances was conducted through the (VALoS) framework [40]. Providing a performance assessment framework that evaluates how well a vertidrome's airside operation is performing from different stakeholder perspectives, offers the opportunity to quantify a qualitative vertidrome design in strategic planning phases. For our use-case, we defined the air taxi operator, the passenger, and the vertidrome operator as key stakeholders, who define requirements in terms of delay and punctuality. They may vary depending on the business/use case, operational environment and stakeholder objectives.

As shown in [17], the VALoS framework is also suitable to evaluate the impact on the air traffic flow caused by changing wind and gust speed conditions during the final approach and initial take-off phase at vertidromes (see Fig. 5). Focusing on a case study of Hamburg and Munich, we analyzed a decade (2011-2020) of historical METAR wind and gust speed data, to determine the potential of a vertidrome operation with LIEDT layout located at Hamburg and Munich airport. To conduct this analysis, we extended the vertiport ConOps to meet wind-dependent requirements on a tactical and strategic level and defined four wind categories prescribing the required minimum separation: (WO) W/G≤17kts, Wind-Advisory (WA) 17kts≤W/G≤ 20kts, (WW) 20kts≤ W/G<25kts and (WS) W/G≥25kts [17]. Selecting one representative year for both locations, 2019 for Hamburg and 2012 for Munich, we conclude that over 50% of the annual flight cancellations occurred during the first quarter of the respective year. Especially during midday and early afternoon hours, the VALoS showed performance degradation due to worsening wind and gusts speed conditions. In Fig. 5, the VALoS dashboard for the arrival traffic stream of a vertidrome located at Hamburg Airport is exemplarily displayed for the week from 4-10 March 2019. The stakeholders vertidrome operator, eVTOL operator, and passenger PAX are depicted with their assigned performance metric punctuality, delay, and average delay, respectively. Occurring wind categories are depicted in percent for each day at the bottom left. Green indicates an acceptable VALoS, red a non-acceptable VALoS, gray displays all cancelled flights, dark green and dark red represents time windows with processed flights and cancelled requests. In total, for a vertidrome located at Hamburg airport, this resulted to 11.5 and 10.2 days of cumulative annual operational shutdown due to arrival and departure request cancellations, respectively.

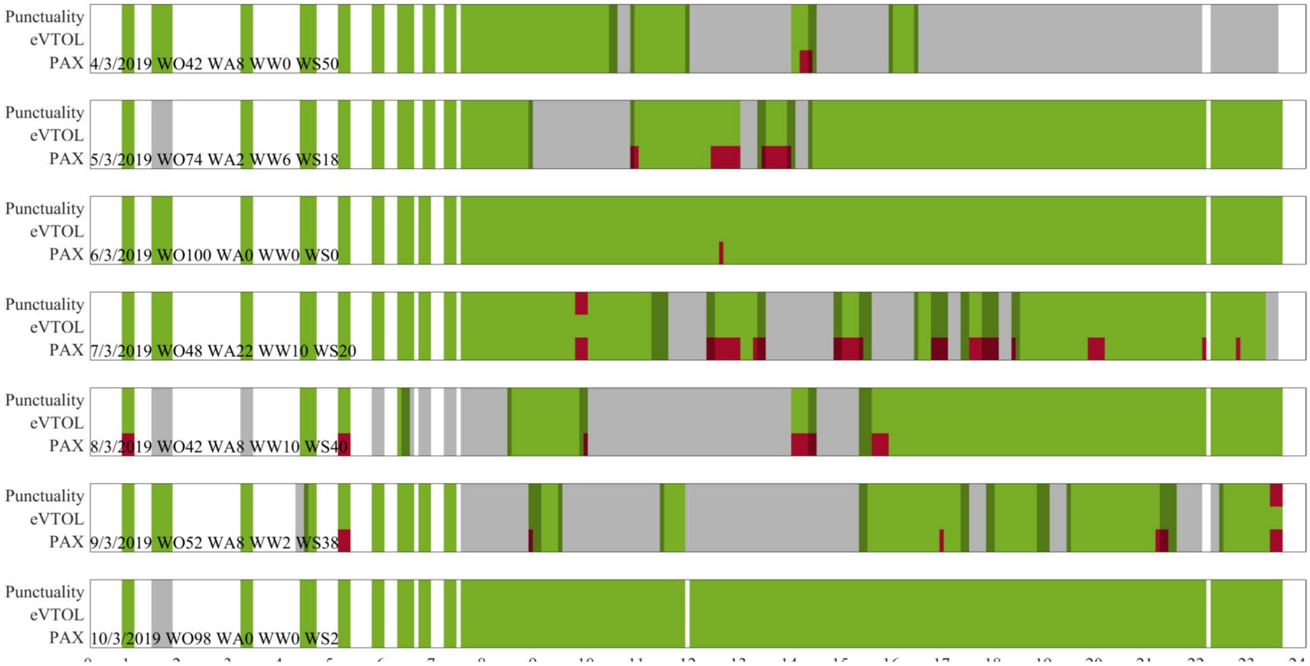

Fig. 5 Weekly/24-hour distribution of the VALoS dashboard for the arrival airside traffic streams at a vertidrome at Hamburg Airport. Adapted from [17]

To conclude our vertidrome design and performance analysis, we investigated the impact of stochastic deviations and short term disruption on the achieved VALoS. In [37], we showed for our test case that the considered stochastic deviations are not creating any significant impact on the airside traffic flow, thus the achieved VALoS. However, short-term disruptions, even if they occur in five to ten minute ranges, are much more relevant in terms of disrupting the airside traffic flow. Depending on the traffic volume and the availability of backup vertidrome infrastructure such as additional pads and stands, the variability of the achieved VALoS changes significantly.

Having concluded the micro-perspective of the vertidrome design and operation, in the next step we enter the macroperspective, where we address the perspective of the vertidrome network airspace management, which connects each vertidrome through an airspace network.

3 Vertidrome airspace network management

A single vertidrome is not sufficient for a feasible UAM operation. Therefore, a safe and efficient way to connect a multitude of vertidromes is necessary. Moreover, due to the predicted high number of simultaneous UAM operations, i.e. air taxi and cargo flights in low level airspace, current air traffic management procedures need to be re-evaluated. And where necessary they need to be adjusted and optimized. Therefore, potential management concepts and procedures for conflict-free airspace operations were investigated. Within this project, two management approaches were developed namely Slot-Based Approach (SBA) and Trajectory-Based Approach (TBA) (see Fig. 6). These approaches were inspired from today's airspace management systems namely fixed Air Traffic Services (ATS) route structure and Free Route Airspace (FRA) [41]. While the TBA is based on direct routes between vertidromes represented as 4D trajectories, the SBA uses a rigid route structure and a time-slot management approach.

The approach focused first on the development of both operational concepts and second, the implementation into in-house software tools. The elements are *GridCity*, functioning as scenario generator [43], and *NDMap*, functioning as conflict detection and resolution tool [44]. In the next step we compared both approaches based on network-specific, vertidrome-specific, and human-centered performance metrics [42, 45]. As part of *HorizonUAM*, a first iteration of both approaches was conducted in nominal conditions. This included, among others, the assumptions of constant speed (15 m/s cruise speed, 3 m/s climb and descent speed), simplified mission profiles (vertical take-off and landing, fixed cruise altitudes), unlimited range and no disturbances and disruptions due to weather or technical failure.

For the SBA, a customized route network was specifically designed for the *HorizonUAM* reference use case Hamburg

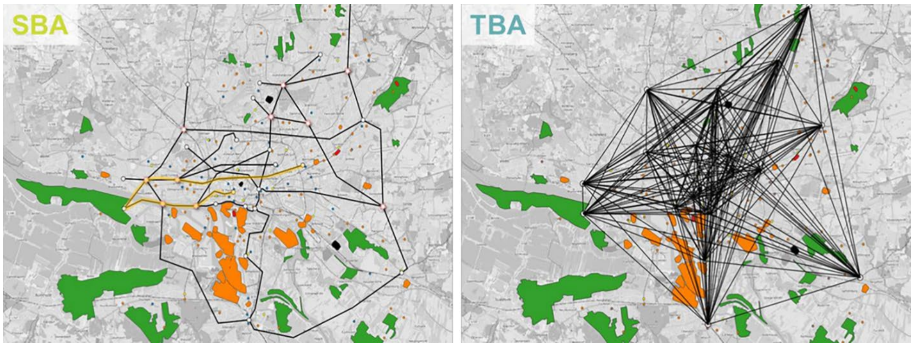

Fig. 6 Vertidrome network airspace management concepts: SBA (left) and TBA (right). Adapted from [42]

[42]. In its final version, the vertidrome network consists of 20 vertidromes. They are distributed across the city of Hamburg, encompassing residential and industrial areas, as well as urban points of interest. We followed the objective, that UAM is supposed to be an addition rather than a competitor to the current public transport system. With that in mind, a geographically independent method to design UAM route networks has been developed. The workflow used in the network design is following a 5-step plan. First, we identified no-fly zones such as industrial plants, government buildings, nature reserves, and residential areas. The basis for selecting an air taxi route as part of the route structure is a potential time saving compared to public transportation. Especially long connections with multiple transfers are best suited to be supported by air taxi operations. Next, additional routes are added to the network, such as connections to tourist attractions and transportation hubs, that are already well-connected, high-performing in terms of travel times, and therefore not previously considered. In the penultimate step, the resulting network is formed by merging routes that share the same destination vertidrome. The final step is to analyze the resulting UAM network with its merging points by comparing it to the public transportation network, and make final adjustments to increase time saving.

For the TBA, the 20 vertidromes are directly connected with each other (see direct comparison in Fig. 6).

After defining the network details and implementing both concepts into the simulation framework, we focused, among others, on the evaluation of the following four network-specific performance metrics to compare both approaches.

- Average flight time - the average flight time a UAM vehicle is airborne.
- Network occupancy - the (median) amount of airborne UAM vehicles in a defined time frame.
- Travel time saving to ground traffic - the time difference between airborne and ground traffic on a route from origin to destination.
- Demand conformance - the difference between the passenger demand (requested time) and the time slot allocated.

The common metrics, as highlighted and described in more detail in [42] were results of internal and bilateral workshop sessions as part of the ATM-X NASA and DLR collaboration.

To identify bottlenecks in both approaches, different use cases have been considered. Those entail four demand scenarios, named *high frequency*, *nominal*, *low frequency*, and *very low frequency*. They consider 2, 1, 0.5, and 0.2 scheduled take-offs per minute per vertidrome, respectively. With a total of 90,000 simulated flights and ground trips. A summary of the nominal simulation results is displayed in Fig. 7.

The key observations and conclusions that can be drawn from these first simulation runs are the following [46]:

- Air taxis are proven to potentially reduce the passenger travel time (up to 50% reduction of the travel time). In this way they are complementing or/ and supplementing the current conventional public transport means.TBA and SBA offer predominantly time savings.
- Depending on the overall considered traffic density, air taxis could provide on-demand service even with SBA with an average of less than 3 min deviation from the passenger demand.
- The TBA showed a better average flight time due to direct routing with lower network occupancy rate. With the concept of free routing, the trajectory-based approach offers significant potential for UAM. At the same time raises challenges related to deconflicting process, trajec-

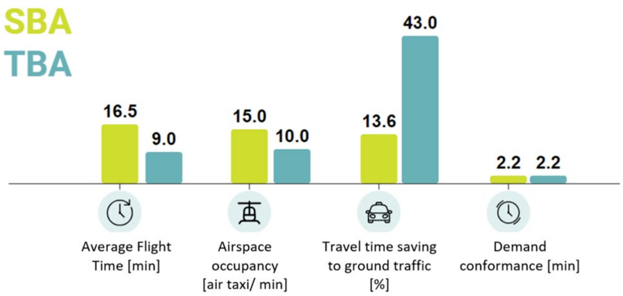

Fig. 7 Comparison of SBA and TBA under nominal conditions based on a set of performance metrics. Graphic based on the results of [46]

tories calculation complexity, integration with conventional traffic, etc.

All in all, a standard solution to be implemented in all cities is not realistic and consequently not feasible. The most adequate approach to be adopted should be tailored to the specific needs of the concerned passengers. It should consider a set of factors and targeted performances including but not limited to the characteristics of the city, targeted traffic density level, the connectivity already ensured by other transportation means, etc. A combination of both approaches could be feasible, seeking the maximum benefits from both approaches, as per today's airline operations. More exhaustive conclusions and findings are summarized in [46].

Considering the simplified assumptions and the adopted method to generate randomized flight plans, the results show a rather positive outcome and tendency. However, for individual routes such as highlighted in orange in Figure 6, time losses of up to 53% are recorded. These differences occur from the fact that the route network is not optimized for certain connections, especially between already well-developed ground traffic routes, that were generated in the randomized origin–destination pairing. With more significant and realistic demand (still randomly generating but by excluding and filtering trips which are not adequate for UAM operations), the results could be even more enhanced and promising. As a next step, and as part of the ATM-X cooperation, we will re-iterate the network design for both SBA and TBA concepts, as well as include realistic demand and capacity restrictions, caused by disruptions or changing weather conditions. Additionally, the simulated nominal use case could serve as baseline for the investigation of further non-nominal scenarios.

In addition to urban airspace, vertidrome network capacity is a critical resource of the UAM network that, if optimized, can reduce the required vertidrome infrastructure and fleet size to a minimum. The next section provides a summary of the relevant parameters and methods considered for an optimization.

4 Vertidrome network optimization

The aim of the network optimization was the development and application of a strategic planning procedure, allowing to derive the minimum local capacities required regarding eligible metrics, like parking stands, charging infrastructure, or the number of feasible traffic movements per minute. To keep the required volume concerning fleet and infrastructure as small as possible, efficient fleet operations are needed, minimizing the share of empty rides and therefore optimizing the fleet-size and -mix, as well as the energy consumption. Therefore, a workflow has been developed and implemented providing a fleet composition and efficient vehicle operating plans which are analyzed to derive the local capacity requirements in the network. This methodology has been presented in [47], demonstrating a capacity requirement analysis based on the use cases of parking stands and battery charging infrastructure. In total, the approach comprises four steps. At first, a UAM network is defined by its vertidrome positions while each vertidrome is initialized with indefinite capacity regarding the examined categories. For the following fleet composition, vehicle types are defined along with the necessary performance characteristics, such as horizontal and vertical operating speed, specific power consumption per mission phase, as well as the battery capacity and the maximum number of passengers. In a second step, a traffic scenario is implemented, setting up a pool of requested revenue missions. Each mission is defined by an origin and destination vertidrome, the number of travelling passengers, and the desired time of departure. In the third step, the fleet is successively generated while allocating entries from the mission pool to the vehicles. Therefore, a graph-based optimization model has been implemented, utilizing the mission pool for graph-generation. On this graph, the Dijkstra Algorithm is applied for the derivation of vehicle specific mission sequences. In this process, three boundary conditions are considered:

- No vehicle can be set up with a mission, if it provides insufficient seat capacity to transport all passengers assigned to that mission.
- The feasibility of a mission sequence must be maintained with regard to time, ensured by the consideration of individual vehicle performance with regard to operating speed. Therefore, time buffers for ground handling, boarding and de-boarding of passengers, battery charging times, and empty relocation flights are considered.
- The feasibility of a mission sequence must be maintained with regard to energetic aspects, ensuring that the battery of a vehicle operates within its boundary values between 0% and 100% of usable energy throughout the mission sequence.

The number of covered passenger kilometers is used as an optimization parameter for sequence generation, effectively maximizing the total distance traveled by passengers per day and implicitly rewarding sequences with fewer empty seat kilometers. In the fleet generation process, all possible combinations of vehicle type and starting position of a vehicle in the network are reviewed and possible mission sequences are determined accordingly. In a concluding optimization step, a linear programming problem is solved to select the most efficient mission sequences while ensuring that each single mission in the pool is allocated to exactly one vehicle. These two phases, mission sequence generation and selection, are repeated until all missions are allocated and step three is completed. In the last step, fleet size and fleet mix are analyzed, and the operating plans are derived specifically per vehicle and per vertidrome, to assess the local load profiles regarding each selected design parameter, namely battery charging power and the number of parking vehicles. Finally, the capacity requirements for each vertidrome can be derived from the load peaks. In the scope of the investigations conducted in [47] a network based in Hamburg City (Germany) has been examined. This network consists of a set of 20 vertidrome positions and two different vehicle types [48] with four and six seats, operating a commuter-based scenario [49, 50] with 2,800 missions. The results showed that a fleet of 275 vehicles is required to operate all missions when assuming a fixed battery installation on board of the vehicles and a constant battery charging power of 50 kW at the vertidromes. When assuming exchangeable batteries, on the other hand, simulations showed that the required fleet size could be reduced to 225 vehicles, caused by a higher achievable degree of vehicle utilization over the day.

The analysis of the daily peak loads finds a requirement for 422 parking stands in the vertidrome network to conduct the derived operating plans. At the same time, the application of the battery swap strategy, resulting in a smaller fleet, provides a potential reduction of ground infrastructure requirements by –24%. Hence, only 322 parking stands are required in the network (see Fig. 8). The investigation found that the battery swap strategy, in comparison to conventional charging of fixed batteries, may result in higher peak loads regarding charging power. The results show that a fleet consisting of 275 vehicles requires a maximum charging power of 11.1 MW cumulated throughout the network while the smaller fleet, based on battery swap strategy, results in higher charging peaks of up to 16.7 MW throughout the network, mainly caused by a more concentrated power consumption at the vertidrome regarding time. Furthermore, the operational efficiency of the fleet has been examined, quantifying the load factor in comparison to the occupancy rate over the day. In that context, it could be found that average load factors of 45% are feasible while occupancy rates over the day can take values of up to 80%. These first results allow estimating the required fleet size and vertidrome capacity requirements, exemplarily derived for one demand scenario. It underlines the importance of battery charging management and vehicle relocation management in the network to diminish peak loads and therefore the required capacity limits.

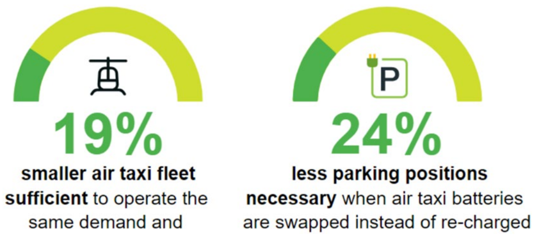

Fig. 8 Savings potential regarding fleet size and ground infrastructure when applying battery swap, caused by a reduction of vehicle downtimes. Graphic based on the results of [47]

5 Vertidrome integration into airport environment

The concepts of operations published so far [20–23] foresee UAM traffic to be performed independently of the current air traffic network and with their own air traffic services. However, in the context of current national legislation (e.g [51]), the contact to ATC is mandatory within control zones such as around airports. This is especially relevant for near-term integration of UAM traffic and for the introduction of one of the major UAM use cases such as airport shuttles. ATC is responsible to ensure a safe and efficient traffic flow. At the airport, this includes the control and coordination of landing and departing traffic as well as supervising traffic in the control zone. Adding air taxis to the traffic flow results in additional airspace users with performance characteristics rather different from conventional fixed-wing traffic. Hence, providing them with take-off and landing spaces away from the runway system and favourably with independent arrival- and departure routes should be aimed at [52]. Moreover, the control task itself should be designed in a way that the responsible air traffic controllers can maintain their situation awareness and that the potential increase in workload remains feasible. On an airport level, safety should not be impaired and runway throughput should not be impacted.

Within *HorizonUAM*, an operational concept for air traffic controllers was developed for the control of additional UAM airspace users [53]. It includes a procedure to assess requested trajectories for operational feasibility prior to flight and communication options to transmit immediate or delayed departure clearances. Tactically during the flight, the tasks of monitoring and options to keep separation minima to all kind of traffic users are defined. Moreover, right of way priorities are presented depending on the opponents involved, their flight performance as well as their current flight phase. The tactical part of that process was tested for feasibility in real-time human-in-the-loop simulations in German Aerospace Center (DLR)'s Apron- and Tower Simulator [54] with ten air traffic controllers for the reference use case Hamburg airport.

As shown in Fig. 9, the setup included a route network for airport shuttles between a vertiport at the airport and nine vertiports in the city, all of them within the control zone [52]. In addition to conventional traffic in a peak hour including 44 movements/hour, fifteen air taxis were added

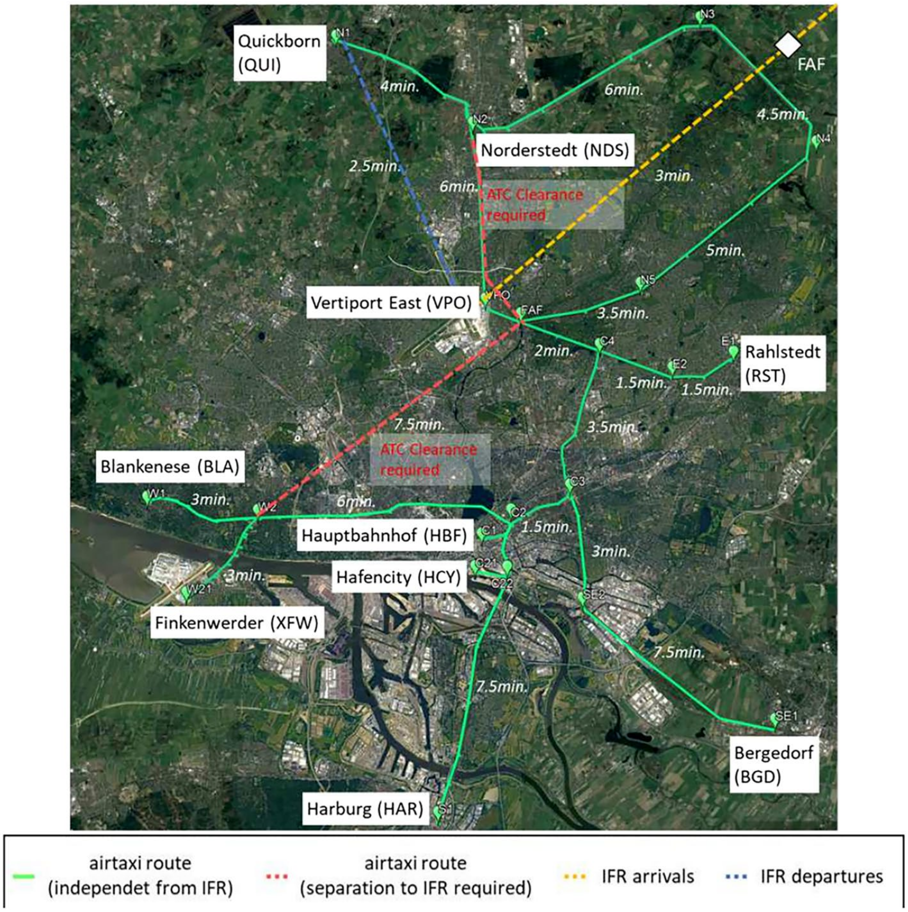

Fig. 9 Route network of Hamburg including the vertiport location at the airport

per one-hour simulation run, since this number proved feasible in terms of air- and vertiport capacity in fast-time simulations [52]. The vertiport at the airport was located on landside just east of the main terminal buildings. It is to be approached independently from conventional air traffic routes except for an alternative route across the extended runway centre line of runway 23 to enable air taxis from the north a substantial travel time reduction. Air taxi routes were visualized and active routes were highlighted on the radar screen to support controllers in their tasks. A detailed description of the simulation setup and the results can be found in [55].

Within the simulation trials, it proved to be feasible to integrate air taxis into current airport operations [55]. Even though the introduction of UAM traffic led to an increase in reported workload by 44% while situation awareness reduced by 18%, all controllers reported that the changes were all within tolerable limits (see Fig. 10).

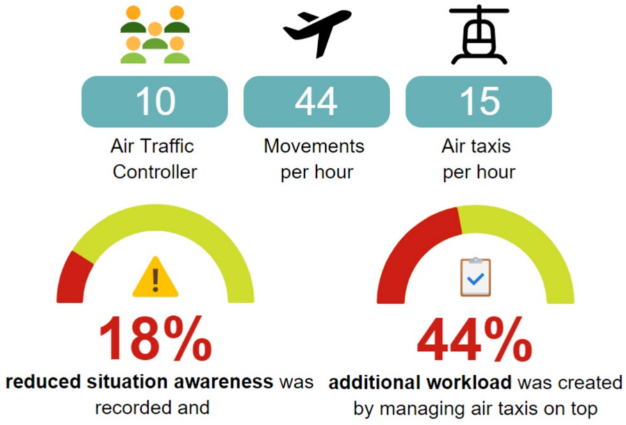

Fig. 10 Changes in situation awareness and workload of air traffic controllers when introducing air taxis. Graphic based on the results of [55]

Moreover, they all agreed that the visualization of air taxi routes supported their overview of the air traffic situation. While the throughput of conventional fixed-wing traffic decreased by 9%, the overall airport capacity increased by 75% in comparison to the baseline scenario due to the addition of air taxi services. Within a partnering study extending the described set-up to present the controllers with information about critical wildlife in the control zone (cf. [56], a training effect was observed. Despite increased complexity, the workload was reduced by 8 % compared to the scenario including air taxis described here, while situation awareness increased by 8 %. Moreover, a slight increase in overall throughput (conventional and air taxi traffic) was observed while progressing through the scenarios of this as well as the partnering study [56]. Therefore, it is expected that with a well-structured training scheme to integrate air taxi operations into control procedures, workload can be decreased to levels almost similar to regular operations for moderate numbers of air taxis to be controlled. All controllers agreed that in case of higher numbers of air taxis, it should be aimed for an additional working position in charge of all general aviation and UAM traffic, especially at times with high traffic loads to ensure feasibility.

6 UAM model city

To support UAM (flight) testing, demonstration and vehicle certification, a modular model city scale 1:4, representing an exemplary European urban environment, has been conceptualized. When completed, this model city will be an extension of the DLR National Experimental Test Center for (UAS) at Magdeburg-Cochstedt airport. It targets a variety of users and customers including DLR institutes, external research facilities as well as relevant stakeholders in the UAS and UAM industry. The model city is intended to address the lack of real urban environment testing opportunities due to increased air and ground risk and therefore high regulatory barriers. To offer a safe environment to test and validate developed theoretical concepts, operational procedures and technical features, the model city will provide a representative urban setup for all kinds of UAS and UAM applications, use cases and operational environments. Moreover, the model city will offer ideal capabilities to conduct interdisciplinary studies on, e.g. flight guidance procedures, flight system requirements as well as environmental and public acceptance. Regarding disciplines such as performance of communication and navigation technologies the testing possibilities could be limited since the propagation of electromagnetic waves does not scale in the aimed dimension. However, this does not exclude these topics from the object of research within the model city.

In general, it is not sufficient to simply re-build a specific city in a scaled manner, but rather to represent typical areas of a larger central European city.

Based on the analysis of representative European urban areas, as conducted in [57], a concept for a model city was developed. The analysis is based on the categorization of building density, introduced in [58] and [59]. The relevant main categories (single family houses, city apartment buildings and residential inner-city complexes) where arranged in three different types (single, in line and positioning around a courtyard).

Throughout the project *HorizonUAM*, we included a wide range of stakeholders into the discussion determining what features and capabilities a future model city needs to offer. In addition, also external users/customers of the testing grounds in Cochstedt were interviewed about their possible needs for an urban test infrastructure. The variety of use cases that might be addressed in a test facility for UAM, requires a modular approach which allows adjustments and variations rather than a permanent setup. The scale was set to 1:4 to achieve a satisfactory ratio of building height and street width on the intended building area at the test site. The resulting dimensions of the defined basic building blocks are shown in Fig. 11.

While the actual process of building the model city at DLR site in Cochstedt is still ongoing, a temporary modular city environment consisting of shipping containers was set up on the airport's apron (see Fig. 12 right). Also, FATO markings were placed on the ground in the vicinity of the temporary modular city. This enabled the project partners in *HorizonUAM* to perform individual flight test campaigns for their specific scenarios and use cases. This included, e.g. the detection of people around a targeted FATO and navigation of a single UAS through a street canyon using the modular city as obstacles affecting the lines of sight [60–62].

During the individual and multidisciplinary flight campaigns, it was possible to leverage successfully the model city and its surroundings and the feedback was overall positive.

7 Conclusion

From a *vertidrome design and operation* perspective, we reached a level of certainty purely based on simulation. We showed that it is possible to simulate air taxi traffic flows, to determine operational repercussions due to non-nominal conditions and leveraging different scheduling methods and vertidrome layouts. The VALoS framework provides

Fig. 11 Different building classes represented in the model city with the respective scaled dimensions of the modular components (1:4) [57]

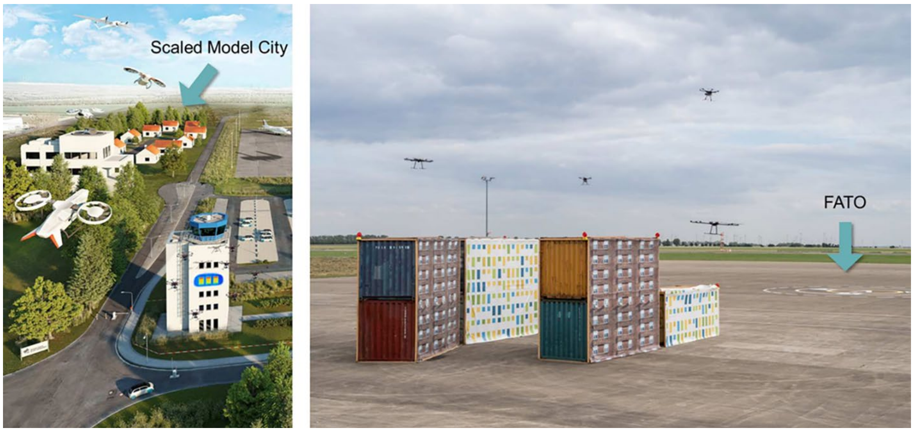

Fig. 12 Vision of a possible urban test environment at DLR UAS test center at the Magdeburg-Cochstedt airport (left). Temporary setup with container modules,tarpaulins and FATO markings used for *HorizonUAM* flight trials (right)

an easy, self-explanatory and visual rating of the airside traffic flow performance for the vertidrome of interest. Predominantly, it can be used on a strategic planning level, to determine a future vertidrome's bottleneck from a time (24-hour/week/month/year) and traffic flow perspective, and to evaluate operational capabilities and rate specific vertidrome locations. In addition, it can also support vertidrome airside traffic management on a tactical and monitoring level. However, the vertidrome simulation and assessment only provides reliable conclusions if we have an accurate demand forecast, an initial understanding of relevant performance targets, and if all relevant stakeholders in the vertidrome network share their information. This is the reason why flight trials are, at this stage, rather complex in preparation and implementation due to the magnitude of required interfaces between different, currently independent stakeholders and systems. This is even increased if vertidromes operate in controlled airspace where additional stakeholders must be involved in strategic and tactical phases of air taxi flights. Each location, business/use case and operating environment needs to be evaluated individually from a feasibility and performance perspective. Therefore, there is no one-size-fits-all solution for the design and the operational development of a vertidrome, but with the VALoS we established a performance assessment framework which is usable for all kinds of UAM ground infrastructure.

In the context of *optimizing a vertidrome network and fleet design*, a workflow was developed and implemented, allowing the integrated design of operating fleets and the derivation of ground infrastructure requirements from resulting operation plans. The application of this workflow quantified the fleet requirements for an exemplary scenario based on a commuter use case. However, it is important to note that the presented results do not give a final quantification of future requirements in the City of Hamburg. Instead, they demonstrate a novel approach how to transfer traffic scenarios into demand-adapted vertidrome networks while considering traffic load profiles. The investigations revealed a significant potential for reducing the fleet and ground infrastructure, depending on the battery charging time. However, further aspects need to be examined in future work, such as the availability of additional vehicle types with various operating speeds, passenger capacities, and ranges. Future use cases for this method include deriving and statistically analyzing fleet and ground infrastructure for multiple demand scenarios. Considering the uncertainty regarding future demand, the methodology could be applied to identify fleet compositions and infrastructure distribution that provide potential for efficient operations across a wide range of demand scenarios. As vertidrome networks are expected to experience organic growth in cities, further improvements of the method may allow for the derivation of optimized vertidrome network expansion, considering predefined initial capacities and accommodating growing or shifting traffic flows. An essential aspect for future revisions will be considering spontaneous flight bookings and their impact on fleet and infrastructure requirements.

From an airspace network perspective, it is not finalized which *vertidrome airspace network management* approach should be preferred. A hybrid approach utilizing a rigid route structure (SBA) in the vicinity of vertidromes (i.e. within the terminal airspace), and direct trajectories (TBA) during the en-route phase could be considered. How both airspace management approaches perform under advanced assumptions (e.g. static and dynamic no-fly zones, multi-level/lane trajectories, tactical conflict detection, battery management) and more realistic demand scenarios, will be part of the next years of the *ATM-X* project collaboration between *NASA* and *DLR*. According to the preliminary results developed under nominal conditions, UAM shows the potential of travel time savings, if the optimal airspace management approach is chosen. As for the vertidrome layout, size and operation, this will vary for the airspace network for each area and business case. It should be noted that the current TBA and SBA route networks need to be adjusted according to public requirements in terms of privacy and noise.

With regard to the integration of UAM traffic within the ATC work processes, the real-time simulations showed an increase in workload and situation awareness. However, according to feedback of all involved controllers, they still felt comfortable considering both aspects. In case of increasing UAM traffic, it is suggested to add a working position dedicated to the handling of VFR and UAM traffic. This should facilitate feasibility in higher traffic densities as well.

Lastly, the *DLR Experimental Test Center for Unmanned Aircraft Systems* in Cochstedt (Germany) is an ideal test environment for future investigations, since it also provides an active airport environment. The model city was first implemented on the apron as a temporary modular model city using shipping containers. This setup was used for a series of flight tests within the project *HorizonUAM* as well as for external users. During the flight trials, the containers served as obstacles representing urban canyons, and two vertidrome pad markers were used to allow drones to automatically detect objects and land safely. As a next step, the scalability of the results needs to be further investigated. This includes the propagation of electromagnetic waves and other physical aspects in narrow surroundings as well as on the surfaces of the buildings that at the moment might limit the variety of testing possibilities. The modular approach of the (temporary) model city allows a variable arrangement of all building units, therefore scenarios like scaled vertidrome operations in built-up environment as well as public acceptance studies within the scaled city could be aimed at in future trials. This can contribute positively to future research and perhaps also to future certification processes. The scaled model city should enable and support exactly these investigations. Therefore, it is planned to complete the scaled model city in its entirety over the next years to expand the capabilities at the test site at Magdeburg-Cochstedt airport.

As part of *HorizonUAM*, the vertidrome research has been carried out by observing the basic vertidrome principles, developing operational concepts, performance evaluation methods and optimization algorithms, which resulted in the experimental validation by fast-time and human-in-the-loop simulation. With the achievements in *HorizonUAM* and the current global state of vertidrome research, we have reached a good foundation in terms of vertidrome (network) design and corresponding operational concepts. The next step in vertidrome (network) research, is to move to the development and deployment phase, which corresponds to a technology readiness level of 4+. Only then can we assess the realistic feasibility of our concepts, validate, adjust and fine-tune our simulations accordingly.

8 Outlook

In the following, we conclude this report by summarize the key uncertainties of current vertidrome research which must be addressed in the future by the UAM community.

1) Demand forecast: The greatest uncertainty is the future demand for UAM, which will drive the design of the vertidrome network, resource distribution, throughput and performance requirements. Since the urban implementation of vertidromes will be challenging, we need to ensure that the operational concepts we develop are scalable and therefore sustainable.
2) eVTOL aircraft performance data: Aircraft flight test data are necessary to validate our operational concepts and to adapt operational procedures on vertidrome micro- and macro-level to the capabilities of the eVTOL aircraft.
3) Weather: Varying weather conditions must be part of future vertidrome network analyses to evaluate the impact on vertidrome operation and usability, and thus fleet management, network size and overall business case.
4) Scaled vs. full scale flight tests: Detailed investigations are necessary to determine the extent to which scaled flight tests at vertidromes are scalable and representative of full-scale air taxi behavior and vertidrome performance.
5) Vertidrome as part of a system-of-systems operation: A single vertidrome is not sufficient to host UAM operations. Neither is a UAM network without a detailed representation of each vertidrome node. To evaluate the capabilities of a vertidrome network we need to determine details on micro- and macro-level and derive interdependencies at both ends.

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Data availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest Author Bianca I. Schuchardt is also guest editor for the special issue on the HorizonUAM project but has not been involved in the review of this manuscript. The remaining authors have no Conflict of interest to declare that are relevant to the content of this article.

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