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Can Urban Air Mobility become reality? Opportunities and challenges of UAM as innovative mode of transport and DLR contribution to ongoing research

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Abstract
Urban Air Mobility (UAM) is a new air transportation system for passengers and cargo in urban environments, enabled by new technologies and integrated into multimodal transportation systems. The vision of UAM comprises the mass use in urban and suburban environments, complementing existing transportation systems and contributing to the decarbonization of the transport sector. Initial attempts to create a market for urban air transportation in the last century failed due to lack of profitability and community acceptance. Technological advances in numerous fields over the past few decades have led to a renewed interest in urban air transportation. UAM is expected to benefit users and to also have a positive impact on the economy by creating new markets and employment opportunities for manufacturing and operation of UAM vehicles and the construction of related ground infrastructure. However, there are also concerns about noise, safety and security, privacy and environmental impacts. Therefore, the UAM system needs to be designed carefully to become safe, affordable, accessible, environmentally friendly, economically viable and thus sustainable. This paper provides an overview of selected key research topics related to UAM and how the German Aerospace Center (DLR) contributed to this research in the project "HorizonUAM - Urban Air Mobility Research at the German Aerospace Center (DLR)". Selected research results on the topics of market potential and public acceptance, vehicle design (including battery degradation, onboard systems, cabin design, cabin simulation), infrastructure, operations (including U-space, safe autonomy, navigation, communication, cost modeling) and overall system modeling are briefly presented.

Keywords Urban air mobility · Air taxi · Vertidrome · System-of-systems · Market development · Social acceptance

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Abbreviations

AAM	Advanced Air Mobility
ADS	Automatic dependent surveillance
ATC	Air traffic control
DLR	German Aerospace Center
DT	Design thinking
EASA	European Union Aviation Safety Agency
eVTOL	Electrical vertical take-off and landing
FAA	Federal Aviation Administration
FATO	Final approach and take-off
IAM	Innovative Air Mobility
IFAR	International Forum for Aviation Research
IFR	Instrument flight rules
MaaS	Mobility as a Service
ML	Machine learning
MR	Mixed reality
MRO	Maintenance, repair, overhaul
NASA	National Aeronautics and Space Administration
ODD	Operational design domain
SERA	Standardized European Rules of the Air
SOM	Safe operation monitor
SoS	System-of-Systems
STOL	Short take-off and landing
UAM	Urban Air Mobility
UAV	Unmanned aerial vehicle
UTM	Unmanned aircraft system traffic management
VALoS	Vertidrome airside level of service
VFR	Visual flight rules
VR	Virtual reality
VTOL	Vertical take-off and landing

1 Introduction

Urban Air Mobility (UAM) is a new air transportation system for passengers and cargo in urban environments, enabled by new technologies and integrated into multimodal transportation systems [1–3]. The transportation task is performed by electric or hybrid electric aircraft that take off and land vertically, remotely piloted or with a pilot on board. The aircraft used range from small drones for parcel deliveries to air taxis for passenger transport. While the term UAM is widely used in research and media, new terms are evolving such as Advanced Air Mobility (AAM) [4] or Innovative Air Mobility (IAM) [5]. For consistency, the term UAM will be used throughout this paper in the narrow sense of urban passenger transport only, unless otherwise noted.

The vision of UAM comprises the mass use in urban and suburban environments, complementing existing transportation systems and contributing to the decarbonization of the transportation system [6]. Users will benefit from time savings, and if battery electric propulsion systems are used, local emissions from UAM could be close to zero [1]. Safety, security, sustainability, privacy, and affordability are other features of UAM. UAM could thus help to maintain or even improve the quality of life in metropolitan areas despite the ongoing urbanization which is increasing the pressure on urban transportation systems and posing the challenge to large cities and metropolitan areas to ensure an efficient organization of transport [7].

Technological advances in many fields in recent decades have led to a renewed interest in urban air transportation. In particular, new opportunities have opened up for small aerial vehicles, which form the basis for innovative UAM concepts that provide fast and reliable transportation within cities, between suburbs and cities or between points of interest [8, 9]. The European Union Aviation Safety Agency (EASA) expects first commercial flights to take place in 2025 [1]. Furthermore, there are plans to use these novel aircraft to transport passengers during the 2024 Olympic Games in Paris [10], although there is a critical debate in public [11].

In recent years, several research and development activities have been conducted by research institutions, manufacturers and potential UAM operators with the aim of integrating these concepts into existing transportation systems in a way that is both economically viable and socially acceptable. Against the background of persistent challenges of current urban transportation around the world such as congestion, noise, and emissions there are numerous efforts underway to make urban air mobility a part of the overall urban transportation system.

The aim of this paper is to provide an overview of selected key research topics related to UAM and how the German Aerospace Center (DLR) is contributing to this research by combining its competencies in the areas of UAM vehicles, related infrastructure, operation of UAM services, and public acceptance of future urban air transport in the project "HorizonUAM—Urban Air Mobility Research at the German Aerospace Center (DLR)". For this purpose, the technical approaches and research results of the HorizonUAM project are briefly summarized and evaluated with respect to the goal of enabling an economically viable and socially acceptable UAM system.

The paper is structured as follows. Section 2 is dedicated to the visions of UAM and the expected opportunities for potential stakeholders. For this purpose, first the historical development of UAM is considered to derive how technological progress should enable a new era of urban air mobility. In Sect. 3, challenges of implementing UAM as a new part of the transportation system are discussed. In Sect. 4, the key research results of the HorizonUAM project are briefly presented. Section 5 summarizes the insights to date and concludes with their implications for a future urban aerial transportation system. Finally, it provides an outlook on the need for further research.

2 What to expect from Urban Air Mobility: opportunities and visions

The advent of turbine-powered helicopters marked the beginning of a first wave of Urban Air Mobility between the 1950s and 1980s. In the United States, helicopters were used to transport passengers between major airports and downtown business districts in Los Angeles, Chicago, New York, and San Francisco / Oakland [12]. During this period there was a trend towards the use of larger helicopters. Passenger service began in the 1950s with a seven-seat version of the Sikorsky S-55. This was followed by the Sikorsky S-58 and Vertol 44-B, with capacities for 12 and 15 passengers, respectively. In the 1960s, the Boeing Vertol 107 and Sikorsky S-61L entered service with capacity ranging from 25 to 28 passengers.

Similarly, in Europe there were regular international helicopter feeder services to Brussels Airport from Lille (France), Amsterdam and Eindhoven (Netherlands), Cologne-Bonn, Dortmund and Düsseldorf (Germany) [13]. There was also a regular helicopter service connecting London Gatwick and Heathrow airports between 1978 and 1986 to avoid time-consuming transfers for occasional onward flights, which was discontinued with the opening of a freeway [14].

A completely different kind of helicopter commuter service was operated by Air General in the Boston area in the 1960s [12]. Within an 18-mile radius of Boston Logan International Airport, the carrier established about 70 helistops during its lifetime with about 40 of them in operation simultaneously. These helistops were privately owned, their use limited to Air General's helicopters, and generally located in motel parking lots, in the industrial parks, adjacent to businesses or on corporate campuses. The services were directly related to business travelers. The carrier had a fixed schedule, but flights were only operated if a reservation was made at least 30 min prior to the scheduled pickup time. Air General's fleet consisted of Bell Model 47-J2 and Model 47-G4a with three seats. Later in 1968, four-seat Jet Rangers were placed in service.

These initial attempts to create a market for urban air transportation did not remain permanently established. This was due to a lack of profitability and of community acceptance [12, 15, 16]. Operators were forced to cease operations due to the removal of helicopter subsidies by governments and major airlines, increasing public protests against aircraft noise, and safety concerns after several accidents occurred.

As a result, passenger transportation by helicopter today exists only as a niche market in a few metropolitan areas, such as Los Angeles, New York, and Sao Paulo. Charter flights for companies and wealthy individuals as well as sightseeing flights for tourists are the main services offered [16]. In addition, there are helicopter flights for medical purposes, such as rescue missions or transporting patients to and from hospitals in urban areas.

Currently, the helicopter services offered by BLADE Urban Air Mobility probably come closest to the vision of UAM as a means of transport accessible for a broader community. In addition to charter flights, BLADE offers regularly scheduled short-haul flights [17]. Even though the company does not have a license to operate aircraft themselves, it acts as an intermediary between passengers and licensed air carriers. In New York, flights are offered between Manhattan and both John F. Kennedy (JFK) and Newark airports. In Canada, there are connections between downtown Vancouver and the cities of Victoria and Nanaimo, located on offshore Vancouver Island. In France, the Principality of Monaco is connected with Nice Airport via helicopter service. However, the prices for the flight are significantly higher than the prices for a regular taxi trip. For example, BLADE offers transfers between JFK Airport and Manhattan starting at US $195 for a single seat, while taxis charge a flat rate of US $70 or US $75 during peak hours for trips of up to four people [18]. The high prices are one reason why passenger transport between the airport and the city by helicopter has been a niche activity.

Technological advances in numerous fields over the past few decades have led to a renewed interest in urban air transportation. These technologies include energy storage, automation and artificial intelligence, sensors, communications and navigation, as well as simplified ridesharing and trip booking enabled by the proliferation of smartphones [16, 19]. For small aircraft in particular, new opportunities opened up with novel aircraft designs that do not automatically fall into any of the previously common categories. Different from conventional helicopters, these novel designs, which include multi-rotor, tiltwing, tiltrotor, and powered-wing concepts with vertical take-off and landing capabilities, utilize distributed propulsion. An exemplary tiltrotor air taxi configuration is shown in Fig. 1. Propulsion systems range from battery electric to hydrogen electric and hybrid to gas [2]. Considering the related design characteristics,

Fig. 1 Tiltrotor air taxi configuration

these types of novel aircraft are often referred to as (electric) Vertical Take-off and Landing vehicles ((e)VTOL). Although initial operations are expected to be conducted with a pilot on board, such operations are expected to be remotely piloted, automatic and eventually fully autonomous in the future [6, 20]. The aircraft currently being developed for use in urban transport, are expected to be, among other things, small and less noisy than conventional helicopters [21], making continuous and high-density operations in urban areas more conceivable.

Based on this new category of aircraft [22], the concept of Urban Air Mobility is gaining new momentum. Several use cases for urban passenger transport by air have been proposed, with air taxis, airport shuttles, air metro services, and intercity services (Fig. 2) being the most promising forms [20, 23, 24]. Air taxi services are passenger flights performed by small aircraft on demand between all available landing sites within a defined area [3, 9, 16, 23, 24]. Occasionally, on-demand air mobility is also referred to in this context. Airport shuttle services are passenger flights between various points in the city and an airport. The flights are usually operated according to a fixed schedule [3]. It is assumed that airport shuttle services will evolve as first form of UAM, initially for first-class airline passengers and later for all air travelers to and from the airport [23]. The Air Metro service is similar to today's public transportation systems such as subways and busses, and can operate on predetermined routes with fixed stops and according to regular schedules in busy areas of the city [24]. In particular, this service is a transportation alternative for people commuting between suburbs or satellite cities and the city center. Intercity services are passenger flights between two cities that are more distant from each other. In this case, the transport distances are typically larger so that the use of Short Take-off and Landing (STOL) aircraft instead of VTOL aircraft [20] is an additional option. Thus, this use case is quite similar to Regional Air Mobility, which operates from airfields with a runway and with aircraft larger than those used in urban areas.

To provide new air mobility for passengers and cargo within or around cities and regions, novel landing sites suitable for UAM operations are required. Several companies are presenting concepts for vertiports specifically designed for eVTOL aircraft to meet this requirement. Since no vertiports exist and operate today, existing aviation infrastructure such as airports and heliports may be used initially [25]. But retrofitting and upgrading them to meet UAM needs and future standards, such as electric energy supply, firefighting systems, or large passenger throughput [26–29] may be limited and result in more additional investments [30]. Thus, Urban Air Mobility ground infrastructure, referred to as vertidromes in HorizonUAM, can be newly-built, or, if suited, use existing retro-fitted infrastructure. It can vary in size and functionality: Small vertistops with only one single final approach and take-off area (FATO); medium-sized vertiports with a few FATOs, charging/fuelling systems and facilities for minor maintenance repair and overhaul (MRO) operations; large vertiports that can accommodate dozens of FATOs, MRO infrastructure, parking spaces for aircraft and possibly an operations control system or office space for staff [30–33]. An exemplary vertidrome layout is shown in Fig. 3. They can be located on the ground or on the roof of parking lots, train stations, or other suitable buildings. A large number of vertidromes located close to centres of demand or well connected to transit and the road network ensures that many people can rapidly reach the take-off vertidrome from their origin and then quickly reach their final destination from the destination vertidrome. Thus, more customers are attracted to use UAM services leading to growing

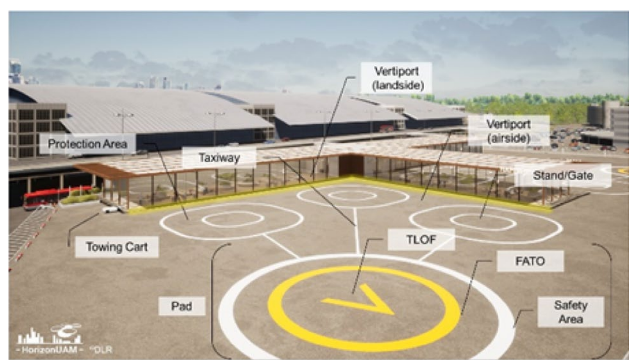
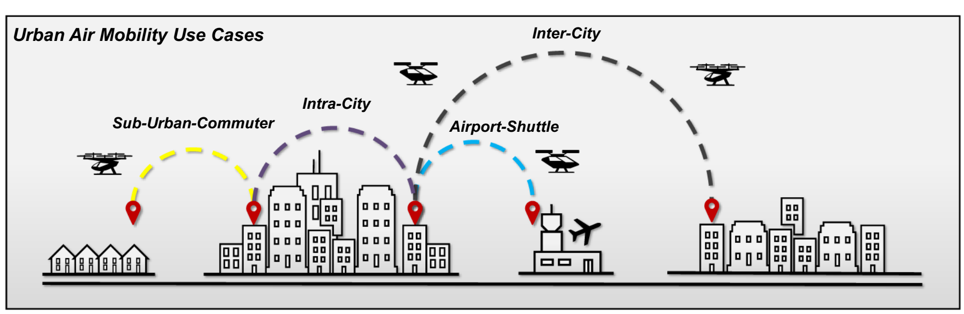


Fig. 3 Exemplary vertidrome layout [30]

Fig. 2 Use cases for Urban Air Mobility [20]



demand with positive operational feedbacks such as higher aircraft utilization as well as lower per-vehicle cost due to high aircraft production volumes [8]. Integrating UAM with Mobility-as-a-Service (MaaS), which aims to provide users with a range of mobility services tailored to their needs, could also help increase the utilization of the UAM system. Ultimately, as the number of users increases, prices for all users could decline.

Urban air mobility has the potential to provide advantages and benefits to multiple stakeholders and in different dimensions: Key benefits for users can be shorter travel times at fares that in the long run can be significantly lower than those of today's helicopter services [23]. Time savings result from the high speed of the aircraft and direct flights in cities, but can be offset by long waiting and processing times at the vertidromes. A large number of vertidromes increases the number of users who benefit from the time savings [34]. The time advantage will become even more important when alternative ground transportation is disrupted during rush hours [35], but UAM is not expected to reduce road congestion or overcrowding on public transport [36, 37]. In addition, UAM can offer shorter travel times on second-tier connections, where demand is not high enough to establish high-quality ground transportation. When combined with MaaS, offering transportation services from multiple transportation providers through a unified gateway, users can benefit from seamless and comfortable transportation.

UAM is also expected to have a positive impact on the economy by creating new markets and employment opportunities for manufacturing and operation of UAM vehicles and the construction of related ground infrastructure. Recent studies predict that up to 5 million UAM vehicles could be in operation worldwide by 2050, most of them for the inner-city use case [38]. Since most UAM vehicle concepts rely on electric propulsions, local emissions from UAM in urban environment could be close to zero [1].

As UAM can benefit the users, the economy and the environment, its development is being promoted by many institutions. For example, the European Commission considers UAM as a system that effectively complements the existing transportation system, contributes to decarbonization, and provides benefits to citizens and communities in its Drone Strategy 2.0 [6]. With this strategy, the European Commission aims to promote the development of the drone ecosystem, including UAM, and contributing to the realization of the vision of UAM. Similarly, the U.S. Department of Transportation established a AAM interagency working group (IWG) which "will develop a national strategy that includes recommendations regarding the safety, operations, security, infrastructure, air traffic concepts, and other Federal investment or actions necessary to support the evolution of early AAM to higher levels of activity and societal benefit" [39]. The Japanese government established the Public–Private Committee for Advanced Air Mobility, which brings together stakeholders from the public and private sectors to realize AAM in Japan [40]. The aim is to launch passenger transport services at Expo 2025. Other countries such as Korea, Saudi Arabia, the United Arab Emirates, Canada and Singapore are also working on launching UAM transportation services in the next few years [41]. In parallel, aviation authorities such as the European Union Aviation Safety Agency (EASA) or the Federal Aviation Administration (FAA) are working on a regulatory framework to enable the deployment and implementation of UAM operational concepts [4, 42, 43].

3 Challenges to Urban Air Mobility becoming a reality

Like any transportation system, UAM is a complex system of systems, which is characterized by components (constituent systems) that interact in a variety of ways. Changes in individual components can influence each other in either positive or negative ways, reinforcing or opposing each other. As a change in one component of a system can have an impact on other components and on the behavior of the system in general, the system performance results from the interaction of its components with impact on relevant stakeholders such as users, operators, and society in general as well as on the environment.

In order to create a viable urban transportation system, it is necessary to harmonize the individual system components such as vehicles, infrastructure, and the operational framework including the air traffic management (ATM), or more precisely Unmanned Aircraft System Traffic Management (UTM) in the context of UAM. In order to balance the interests of all relevant stakeholders, it is essential to compare and reconcile costs and benefits when designing and evaluating transportation systems (Fig. 4). By systematically comparing benefits and costs, the efficiency, sustainability, and societal impact of different configurations of system components can be evaluated.

The evaluation of benefits can include different aspects such as travel speed, mass efficiency, network capacity, predictability and frequency of transport services, safety/security and convenience. Costs include monetary costs, such as fares for users, as well as operating costs and investments to build and operate, for example, the transport infrastructure. They also consider external costs, such as environmental and social impacts on residents and communities, like noise pollution. It is critical to ensure a comprehensive and realistic assessment of the new transportation mode by considering these external costs in the evaluation. By minimizing costs and maximizing benefits, a sustainable transportation system is created that meets society's expectations and requirements.

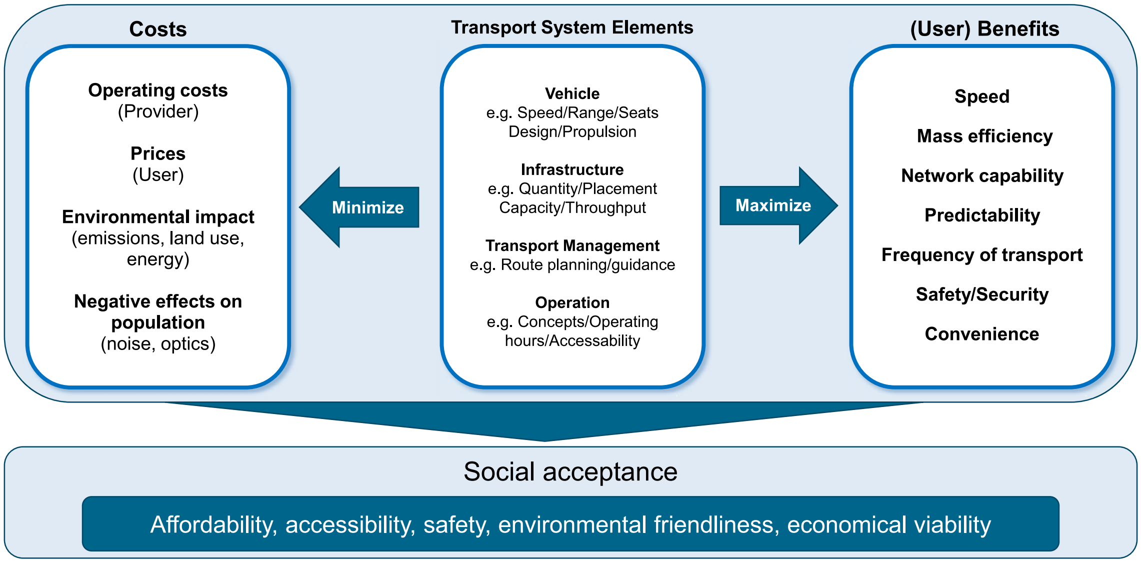


Fig. 4 Social acceptance resulting from balancing the costs and benefits of a transportation system

In contrast to existing transport modes, UAM is still at the concept stage. This means that there are many options for designing the elements of the transportation system to minimize costs and maximize benefits. The challenge is the harmonization of the system elements in such a way that the resulting UAM transportation system is socially accepted.

Social acceptance is seen as the key to a successful implementation of UAM [6]. Although the term is often used, clear definitions of social acceptance are rarely given. A concept of social acceptance originally developed in the field of renewable energy can be used as orientation. According to [44], three dimensions of social acceptance can be distinguished: socio-political acceptance, community acceptance, and market acceptance. Socio-political acceptance refers to the social acceptance of technologies and policies by the public, key stakeholders, and policy makers at the broadest and most general level. In contrast, the specific acceptance by local stakeholders, such as potential users, non-users and local authorities, is referred to as community acceptance. The third dimension of social acceptance is market acceptance, which is evidenced by the adoption of innovative products by consumers and investors' acceptance. These three categories of social acceptance can be interdependent and correspond to different stakeholders.

In the field of UAM, there is a wide variety of stakeholders such as potential users, the UAM industry, governments, public institutions, regulators and indirectly affected third parties, which are important for social acceptance, each with their own motivations, expectations and concerns regarding UAM [1, 2]. Potential users include urban residents, commuters or travelers who expect UAM to save time and provide safe, reliable, convenient and affordable transport from origin to destination. They may be concerned about noise, safety and security, and environmental impact. All entities directly involved in the design, manufacture, operation and maintenance of UAM aircraft and services form the UAM industry and are motivated to make a profit from their activities. This stakeholder group is interested in a stable regulatory framework, minimal bureaucracy, support for the development of a new industry, access to a skilled workforce and favorable taxation. The impact of regulation on the economics of UAM, excessive regulation, public opinion, nimbyism and environmental issues are some of their concerns. Governments, public institutions and regulators are a subset of stakeholders that include bodies and authorities at supranational, national and local levels. Their motivation focuses on public welfare, public safety, an efficient mobility system, limiting congestion and pollution, creating jobs, supporting and building an industry, the environment and public opinion. Their expectations of UAM are positive contributions to the community, income tax and that the industry complies with regulations. This stakeholder group has concerns about public opinion, loss of life, impact on voters, prestige for their respective jurisdictions, under- or over-regulation, and environmental issues. Furthermore, there is an indifferent group of indirectly affected third parties, including private individuals, professionals, associations, extended industry, potential competitors and non-users of UAM. These stakeholders will most likely evaluate UAM based on how it benefits themselves and/or society. In particular, people skeptical of UAM may be concerned of safety, privacy, noise and aesthetics [2].

For UAM to be accepted by society at large, the societal and environmental impacts should be addressed in a way that promotes benefits and minimizes risks, so that UAM as part of the future urban transportation system would be safe, affordable, accessible, and environmentally friendly and thus sustainable [2, 6]. Achieving these characteristics places requirements on the components of the UAM system and their interactions that can be challenging to meet. Further guidance on the development of a sustainability framework for UAM in the context of sustainable urban mobility planning is provided by [45, 46], which give a detailed description of desired characteristics associated with the demand for sustainability. Some of the challenges and their interactions are discussed below.

Concerns about safety may be an initial barrier to the adoption of UAM [1, 2, 47, 48]. There are fears that UAM users, other airspace users, and persons on the ground may be endangered. Novel aircraft designs, types of propulsion, and concepts of operation in an urban environment require the evolution of the regulatory environment to ensure safety and thus drive public acceptance of UAM. EASA has started the regulation process with setting up the new aircraft category VTOL [22], implementing regulations on U-space [49], and prototyping vertidrome specifications [29]. UAM will need to fit into the existing aviation system which has been established and is supported by a large number of regulations and standards. Integrating UAM into this system is expected to be a major challenge for many years to come [50].

Key areas for regulation are [2, 51]:

- Manufacturing, operation, and maintenance of aircraft, especially for autonomous and aircraft without pilot on board.
- Certification of pilots, aircrew, maintenance, and other personnel.
- Certification of aviation facilities, e.g., vertidromes.
- Operation of a network of facilities for air navigation, airspace and (unmanned aircraft system) air traffic management, especially for low altitudes.
- Safe, secure and efficient integration of air taxis into the airspace alongside with manned aviation [49].
- Global harmonization of UAM air navigation procedures facilitating cross-border UAM operations.

There is a need to amend the existing rules for airworthiness, air operations, flight crew licensing and Rules of the Air [42, 43]. The amendment of existing regulations or the creation of new ones can be of a fundamental nature. For example, the existing SERA (Standardized European Rules of the Air) provisions imply that current aircraft operations in an urban area may be performed for a very specific purpose, mainly police helicopters and helicopter emergency medical services [42]. Therefore, changes to SERA are necessary to enable the future transportation of people over densely populated areas with a level of safety that is at least as high as for operations with conventional airplanes or helicopters.

With regard to mixed operations of manned and unmanned aircraft, implications for the preferred routing scheme may occur to meet the goal of safety [42]. Predefined routes allow for systematic deconfliction between aircraft, thus automatically avoiding mid-air collisions. Free routing would require reliable detect and avoid capabilities among unmanned aerial systems, which are under development but not yet certified. If in the future safety can be guaranteed without the need for predefined routes or areas/corridors, then this potential limitation could be removed with positive implications for flexibility, and thus the operating costs and travel times.

With respect to the requirement of a trustworthy UAM system, not only safety but also security is an essential aspect. While safety is concerned with the prevention of accidents and technical failures, security is concerned with the protection against criminal or harmful acts from the outside. A distinction can be made between physical threats and cyber threats [52]. In the context of safe UAM operations, a large amount of data needs to be exchanged, with a particular focus on ground-to-air and air-to-air communications. Artificial intelligence and machine learning as well as their certification also play an important part of the further development of UAM and, therefore has to be evaluated from a cybersecurity perspective [53]. Against this backdrop, these systems must be appropriately secured to protect them from external attacks. In order to achieve this, operational concepts must be developed and harmonized from the outset with cybersecurity in mind to enable safe and secure operations [54].

New regulations may also be required as operations in urban environment may present hazards that are different to or more pronounced than those of conventional aviation in higher altitudes. For example, adverse weather conditions could pose challenges regarding safety, but also reliability of UAM [2, 23, 55]. Extensive urban development with tall buildings impedes the air flow and leads to locally increased turbulence, gusts, channeled flows or blockages with flow diversions and vortex shedding, and vertical wind systems. Therefore, to ensure safe operations in an urban environment, even in moderate weather conditions, additional measures are required. For example, aircraft and vertidromes should be equipped with appropriate meteorological infrastructure, such as high-resolution wind measurement [56], which may have a negative effect on operating costs.

Affordability refers to costs relative to income and, therefore, people's ability to pay for UAM services. In particular, it considers how transportation systems affect the mobility of individuals with lower incomes compared to people with middle or high incomes. There are concerns that UAM may not be affordable for lower- and middle-income households [57]. As part of social acceptance, UAM services should not be limited to the “wealthy few” [6]. However, lack of affordability, and thus lack of social equity, may be a major barrier to social acceptance of UAM [1].

Since operating costs and ticket prices are closely linked, the challenge is to reduce operating costs. Failure to achieve significantly lower operating costs compared to helicopters will jeopardize the affordability and thus market penetration. At present, the costs for transporting passengers with air taxis and thus UAM ticket prices are still highly uncertain [50]. While proponents expect ticket prices to become comparable to those of conventional taxis or even lower than the costs of using a privately owned car [8], the following analyses come to different conclusions. Goyal et al. [23] estimated a passenger price per mile of between US $6.25 (3.75€/km) and US $11.00 (6.60€/km) in the first few years of operation, depending on the size of the aircraft, compared to about US $3.00 (1.80€/km) for the conventional taxi and well below US $1.00 (0.60€/km) for using a private car. Pertz et al. [58] found that short-distance missions within a city, exemplified by intra-city and airport shuttle use cases, result in a fare per kilometer of 4€ to 8€. Regional missions with a longer mission distance can decrease this value to as low as 1€ per kilometer. A high load factor, as well as a certain number of flight cycles per day, are presupposed.

There are many ways to reduce operating costs such as reducing aircraft manufacturing costs, increasing energy efficiency, reducing maintenance and repair costs or cycles, reducing costs to build and operate vertidromes, and improving network efficiency through high utilization and load factors. As often mentioned, automation can play a key role in reducing operating costs by reducing pilot training requirements and eventually not to rely on a pilot on-board at all [59]. At the same time, this leads to technological and regulatory challenges [6, 60].

Furthermore, potential cost reductions will also depend on operators achieving economies of scale [50]. These economies of scale will depend on the specific business model of the UAM operator and on the regulatory landscape that defines operator costs such as potential limitations on landing and take-off infrastructure, restrictions on access to airspace, regulatory requirements that impose costs on operators, or potential public subsidies for the provision of UAM services.

Accessibility in general refers to the ease with which individuals can reach destinations to participate in activities or obtain desired services. In the context of UAM, accessibility refers to the ability to quickly reach the departure vertidrome from the origin of a trip and the destination of a trip from the arrival vertidrome. Analyses have shown that access and egress times to and from the vertidromes (as well as processing times to change modes) strongly influence the attractiveness and thus the demand for UAM [8, 9]. Accessibility can be improved by locating the vertidromes closer to centers of high demand or by reducing travel time to the vertidromes through intermodal connections to transit and the road network [61]. The placement of vertidromes is an optimization task: a balance must be found between site requirements, costs and other issues, such as nuisance to neighbors from noise (see below) and visual pollution to avoid threating social acceptance [6]. Vertidrome placement is also critical to mission composition in terms of flight distances and recharging capabilities. This has a major impact on the optimal aircraft design, fleet composition and the associated trade-off between hover/vertical flight efficiency and cruise efficiency [51], and thus operating costs.

In addition to optimal placement, the right vertidrome throughput capacity is necessary to support the development of UAM. Vertidromes could be one of the most significant capacity limiting and cost driving aspects of UAM [60]. Depending on their structure and size, there is a wide range of vertidrome capacities in terms of aircraft movements and passenger throughput being suggested in the literature. Numbers range from less than 10 to over 1000 operations or up to 1400 passengers per hour [30, 62]. Three archetypes of vertidromes with different sizes and capacities are emerging: small vertistops, medium-sized vertiports, and large vertiports (Sect. 2). In addition, each facility is equipped with approximately twice as many parking spots. Size information varies widely. According to Johnston et al. [32], the footprint of a vertistop with two parking/charging spots is 20 by 30 m with capital expenditures in the range of US $200,000 to US $400,000 and operating costs (without cost of power for charging or refueling) per year between US $600,000 and US $900,000. However, according to Taylor et al. [63], the typical dimensions of a Multi-Function Single Pad without parking / charging spots are 39 by 69 m. When separate staging areas are integrated, the footprint increases to 72 by 99 m, nearly the size of a soccer field. Estimated costs range from US $350,000 to US $950,000. As the largest ground infrastructure, large vertiports are estimated to cover 120 by 55 m and to cost US $6 million to US $7 million to build and US $15 million to US $17 million per year to operate [32]. To justify the land used and the investment and operating costs, there must be a minimum number of passengers and flights, requiring affordable UAM services. Otherwise, “the land would be better allocated as a park or community garden” [64].

The goal of environmentally friendly mobility is to maintain and ensure the mobility of people and goods without placing excessive burdens on people and the environment in terms of greenhouse gas emissions, air pollutants, noise, land use, wildlife and resource consumption [65].

A holistic life cycle assessment usually covers the entire life cycle of a product, i.e., production, use and disposal. For an initial assessment, however, it is sufficient to focus on the use phase [66]. It is important to consider the emissions over the entire process, from the primary energy source (e.g., crude oil) to the final use of the energy. For the assessment of electrically powered ground and air vehicles, which only generate emissions in power plants during operation, the overall environmental impact depends on the cleanliness of the electricity generation resource mix, which is expressed by an electricity mix emission factor (CO_2 emissions per kWh of electricity). A study by Hagag and Hoeveler [67] shows that, based on the average energy mix in Europe and simplified mission profiles with a multicopter, CO_2 emissions during operation are in the range of 23 to 29 percent higher than those of fossil-fuel cars and 108 percent higher than those of hybrid cars. In addition, the study shows that the CO_2 emissions of the air taxi and thus the specific energy consumption are significantly higher than those of electrically powered ground transport (electric cars, public transport), which is important in view of the capacities of renewable energy sources. A similar study by Donateo et al. [68] also shows that the specific CO_2 emissions per person are higher for the air taxi than for the hybrid car, but less high than in the study by Hagag and Hoeveler. The differences in results may be due to different assumptions about the vehicles and operating conditions, and indicate that further research is needed to obtain reliable results. However, both studies also show that the environmental impact of UAM depends critically on the electricity generation mix of the grid that charges the UAM aircraft, so that UAM combined with renewable energy sources can contribute to the decarbonization of the transportation system, depending on the cleanliness of the electricity generation.

Noise is perceived in the literature or by experts as a predominant risk of UAM [1, 59]. This includes the noise generated by the vehicles during take-off, landing and flight. To be accepted, UAM aircraft must be significantly quieter than today's helicopters [3, 8, 21]. This presents a significant challenge to the aircraft design process. As described by Straubinger et al. [51], possible approaches to noise reduction include the distribution of thrust production to multiple rotors, minimizing take-off weight, and/or increasing the rotor area. The latter is in contrast to the requirement for air taxis to be as compact as possible to cope with the limited space in cities, and thus aircraft size and seat numbers could become the limiting factor for the throughput of vertidromes in urban areas.

In addition to reducing noise at the source through engine and airframe technologies, there are other ways to reduce noise: through operational measures such as low-noise procedures on ground and in the air and dedicated flight paths, through compatible land use and urban development, and through operational restrictions such as flight quotas, noise limits, or curfews [69]. The application of these measures can help to increase the acceptance of UAM with respect to noise. For example, predefined routes (see above) or no-fly-zones in a free-flight scenario would help to systematically avoid flying over areas and buildings that require noise protection. The same applies to visual pollution and protection of privacy. However, these measures make economic viability more difficult. Predefined routes may be longer, which increases costs, and flight quotas and curfews limit the number of flights that can be offered. As a result, affordability may suffer.

Based on the aspects of safety, affordability, accessibility and environmental friendliness, this chapter has discussed an excerpt of the challenges for a future UAM system. Since a UAM system is characterized by a high degree of complexity, changes in subcomponents usually result in changes in the entire system. Therefore, the overall challenge is to harmonize different stakeholder requirements and optimize the interactions between the individual components of the system in such a way that UAM is fully acceptable by society and successfully integrated into current transportation networks. As Straubinger points out, "successful UAM introduction relies on a broad variety of factors that have to be considered and still a large number of questions stay unaddressed in the existing literature" [51]. With the Horizon UAM project, DLR is contributing to the investigation of UAM. An overview of the results is presented in the following chapter.

4 Addressing the challenges: selected results from DLR's research project HorizonUAM

Research on Urban Air Mobility has been taking place at the German Aerospace Center in recent years focusing on individual fields and challenges. The project HorizonUAM ([70], Fig. 5) has now brought together ten DLR institutes from various fields to research on the vision of Urban Air Mobility holistically. For the first time, HorizonUAM combined

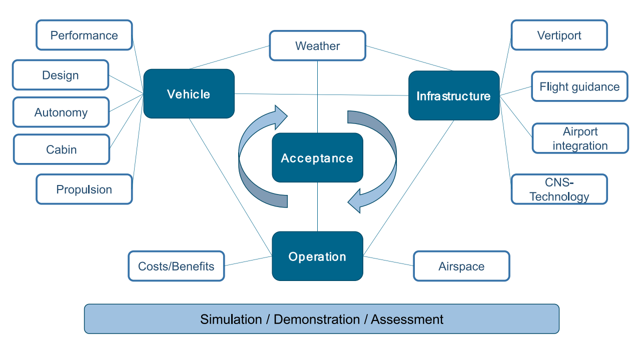


Fig. 5 Central aspects of the HorizonUAM Project

the research about UAM vehicles, the corresponding ground infrastructure, the operation of UAM services, as well as the public acceptance of future urban air transportation. Competencies and current research topics including propulsion technologies, flight system technologies, communication and navigation went along in conjunction with the findings of modern flight guidance concepts and operational techniques at vertidromes and conventional airports. The project also analyzed possible UAM market scenarios up to the year 2050 and assessed economic aspects such as the degree of vehicle utilization and cost–benefit potential via an overall system model approach. Furthermore, the system design for future air taxis was carried out on the basis of vehicle family concepts, onboard systems, aspects of safety and security as well as the certification of autonomy functions. The analysis of flight guidance concepts and the scheduling, sequencing and traffic flow analysis of air taxis at vertidromes was another central part of the project. Selected concepts for flight guidance, communication and navigation technology were demonstrated with drones in a scaled urban scenario.

In order to coordinate the various research focuses, assumptions were defined that form the common basis for the research work in the HorizonUAM project. The key assumptions, which include various use cases as well as technology scenarios, can be found in Appendix A and in Asmer et al. [71].

In the following, selected research results are briefly presented that contribute to making the vision of UAM a reality. Particular, the focus will be on how the technical approaches and research results can contribute to minimizing costs, maximizing benefits, and increasing societal acceptance, considering the requirement that the UAM system needs to be safe, affordable, accessible, and environmentally friendly.

4.1 Market potential and public acceptance of UAM

This section looks at the global market potential for UAM. It also describes DLR's research in the area of public acceptance.

4.1.1 Market potential analysis

This subsection refers to the contribution of Asmer et al., “A city-centric approach to estimate and evaluate global Urban Air Mobility demand” [72] in this issue.

Challenge

A preliminary estimate of the potential global demand for UAM, the associated aircraft movements and the required vehicles is essential for the UAM industry for their long-term planning, but also of interest to other stakeholders such as governments and transportation planners to develop appropriate strategies and actions to implement UAM. The challenge in estimating the global UAM demand is that there is a general lack of empirical data on the demand for UAM and that cities around the world differ in many ways, including size, economic strength, population, geography, etc.

State of the art

Besides initial market studies by consultant companies, Mayaconda et al. [73], Anand et al. [74] and Straubinger et al. [38] provide estimates of the global UAM demand in the academic literature. The studies provide detailed insights into models, assumptions and data. They focus on a few key factors that influence the demand for UAM and use approaches that group cities into clusters and then conduct detailed analyses for a representative city at a time, as a proxy for all cities in the respective cluster. This takes into account the diverse and highly heterogeneous market conditions.

DLR approach and results

As part of the HorizonUAM project, a forecasting methodology is proposed and has been set up to provide estimates of the potential global UAM demand for intra-city air taxi services [72]. The concept is based on a city-centric approach that uses a limited number of city parameters to estimate the total transport demand for each city. A simplified multinomial logit model is used to determine the probability that travelers will choose the air taxi for their individual trips within a city, using travel time and travel costs of each mode as input parameters. Based on the resulting UAM demand, cities with potential for UAM services can be identified. By summing up all city-specific results, an estimate of global UAM demand is provided. Variation of major characteristics of the UAM transportation system allows different scenarios to be developed and analyzed.

Analyses were conducted to investigate the impact of vertiport density as well as ticket prices on UAM demand. As expected, UAM demand is highest when air taxi prices are low. However, it is remarkable how strongly demand declines as air taxi prices increase. More vertiports are only economically justified if they generate sufficient UAM demand so that the additional revenues surpass the associated costs. Considering different development paths for air taxi prices and vertiport density, four potential market development scenarios were outlined. The scenario combining a low air taxi price below 3 €/km with a high vertiport density up to 1 vertiport per 50 square kilometers in wealthy countries yields a market potential for UAM of 19 million daily trips in over 200 cities globally by 2050. Among these cities are international metropole regions such as London, Tokyo, or New York but also major German regions like the Rhine-Ruhr region, Berlin, Munich or Hamburg which are also highlighted in other studies as cities with high UAM potential [1, 38, 75]. The scenarios with a high air taxi price and / or a low vertiport density all result in a significantly lower UAM demand.

Conclusion

The estimation of UAM demand, movements and fleet size strongly depends on the assumptions. Due to differences in the scope, methods and assumptions used in other studies, the results can only be compared to a limited extent. But, as also pointed out for e.g., in Anand et al. [38, 73, 74], the results emphasize the significant impact of low ticket prices and the necessity of high vertiport density to drive UAM demand. This highlights the need to carefully optimize system components to minimize costs and increase the quality of UAM services, which will significantly contribute to the economic feasibility and successful implementation of UAM systems.

4.1.2 Public acceptance

This section refers to the contribution of End et al., "Public Acceptance of Civilian Drones and Air Taxis in Germany: a comprehensive Overview" [76] in this issue.

Challenge

In order for UAM to achieve public acceptance and become reality, citizens' concerns and attitudes need to be considered. Otherwise, new technological concepts would be developed without future users as well as affected residents in mind. This would pose a huge risk to the overall UAM system. However, the major challenge for research on the acceptance of UAM is that UAM is not yet part of citizens' daily life.

State of the art

The existing research literature on the public acceptance of UAM includes a number of empirical studies. For example, Eißfeldt et al. [77] conducted a representative telephone survey among German residents in 2018. In this way, general opinions on civilian drones, approval of various use cases, as well as the prevailing concerns were determined. In addition, different virtual reality studies (e.g., [78, 79] have been realized to enable simulated experience with UAM.

DLR approach and results

Against the background of previous research, Virtual Reality (VR) was used within the HorizonUAM project to give citizens simulated experience, either as pedestrians [80] or as air taxi passengers (see also 4.2.5; [81]). In addition, potential users were involved throughout the process of designing future air taxi cabins (see also 4.2.4; [82]).

To reveal perceived risks and benefits of UAM in a way that is representative for the entire population, a large-scale telephone survey was conducted. Computer-assisted telephone interviews with 1001 respondents were realized to determine current opinions of the German population on civilian drones and air taxis (for a detailed report, see [76]). Overall, civil drones tended to be evaluated rather positively, while no such trend was evident for air taxis in the survey. Answers regarding the attitude towards air taxis ranged from very negative to very positive. The majority of German residents were concerned about the potential misuse of civil drones for criminal purposes as well as the violation of privacy. Moreover, the willingness to use air taxis in the future was most pronounced for use cases involving rural areas.

One way to actively involve citizens is to foster their participation in the assessment of potential impacts of UAM. For instance, the public could be involved in measuring the noise of drone traffic in regional airspace. For this purpose, the smartphone app DroNoise was developed within HorizonUAM according to the concept of Eißfeldt [83]. DroNoise is suitable for both Android and iOS. Acoustic measurements are taken using either the smartphone's internal or a connectable external microphone. When measuring noise, the maximum value of the A-frequency-weighted and F-time-weighted sound level is recorded (LAFmax). In the course of measurement, users are also asked for their subjective noise annoyance. The history of measurements can be displayed and there is a map that can be used to track the user's location.

DroNoise was calibrated and tested during live flight demonstrations with civil drones at DLR's National Experimental Test Center for Unmanned Aircraft Systems in Cochstedt, Germany. It was demonstrated that DroNoise is executable and suitable for measuring and evaluating drone noise. As a next step, it is planned to test the app on a larger sample for its practicability and applicability. In the long term, DroNoise will be distributed in public app stores to provide access to the entire population. In this way, noise exposure maps could be calculated, which, in turn, would allow traffic management systems to distribute UAM noise pollution among the population in an objective and transparent manner (see also [83]).

Conclusion

The results of the research on public acceptance within HorizonUAM emphasize that the overall system should not strictly be limited to urban airspace. Moreover, provided that citizens' needs are taken seriously, safety and security aspects as well as privacy have to be given special consideration in future system design. In addition, the overall UAM system needs to take the public's well-being and health into account. In this context, DroNoise can provide a basis for addressing this challenge.

4.2 Vehicles

In addition to vehicle design, the HorizonUAM project included vehicle-related research on battery degradation, onboard systems, and cabin design.

4.2.1 Vehicle design

Challenge

The vision of UAM comprises comfortable, emission-free, fast, and safe air transportation in densely populated and congested urban centers. With (hybrid-)electric propulsion, autonomous flight, and low-noise vertical lift capabilities under development, the eVTOL vehicles required for air taxi services in the context of UAM certainly face several challenges at the system level alone. However, to facilitate the air taxi services within complex urban environments, many interdependencies between the vehicle and other stakeholders of the UAM ecosystem have to be considered in the early conceptual design phase to ensure smooth simultaneous development of the multiple system elements involved.

State of the art

Due to the wide variety of air vehicle concepts and configurations being developed for urban and regional air mobility, research has focused on the conceptual design and assessment of such vehicles. Typical configurations being considered encompass unwinged multirotor vehicles, winged vehicles with distinct propellers for lift and cruise, and winged vehicles equipped with tilt mechanisms. Some examples of related overall aircraft design and assessment studies that delve into key metrics such as performance and noise, can be found in [84–86]. However, few others, such as [87–89], focused on overall system integration in the design and assessment of these vehicles.

DLR approach and results

Therefore, a system-of-systems approach is adopted to explore such multidisciplinary problems with distributed, interacting system elements, where vehicle design becomes an integrated part of the overall UAM transportation system development. This makes it possible to assess impacts of the vehicle design on the overall system and vice versa to address challenges and opportunities of the UAM vision. The foundation of the system-of-systems approach for the vehicle design studies lies in the integration of agent-based simulations during the conceptual design phase. Employing a simulation toolkit tailored to UAM, the methodology supports standalone simulations of fleet operations [90]. Here, the focus is on vehicle and fleet design, while passenger demand, vertidromes, trajectories, etc., are only modeled in a simplified way or based on assumptions. The fleet simulations enable the assessment of metrics such as transport capacity, dispatch efficiency, energy demand, etc., in the fleet operational context of a UAM transportation system, as demonstrated in [91]. Additionally, a holistic vehicle design workflow is established, integrating aircraft architecture, cabin concepts, and onboard systems. This comprehensive approach allows for the design and assessment of UAM from the subsystem, system, and system-of-systems levels [92]. Life cycle assessments are also incorporated to evaluate the sustainability of battery technology and energy production [93].

With regard to advancing technology levels, two different time horizons are considered. Accordingly, the battery specific energy is assumed to be 250 Wh/kg for the near-term and 500 Wh/kg for the far-term scenario. This makes it possible to capture both the state of the art and a future projection where vehicle performance is less dependent on the underlying battery technology and can be more freely adapted to demanding mission requirements, i.e., higher payload, range, and speed.

Both of our vehicle concepts are designed to carry four persons and are tailored to their respective performance characteristics in terms of speed and range. From literature reviews and sensitivity studies, it is evident that unwinged vehicle configurations are inherently constrained in terms of range and speed due to their flight physics. However, they exhibit favorable hover efficiency and maneuverability, which is particularly important in urban areas. Also, the impact of limited speed becomes less significant over shorter ranges. Regarding enhanced performance beyond urban distances, winged configurations have been identified as more efficient alternatives.

As a result, the multirotor is sized for a mission range of 50 km at 120 km/h with two intermediate stops, and the tiltrotor is sized for a mission range of 100 km at 210 km/h with one intermediate stop. Both concepts are designed to withstand adverse weather conditions and hold minimum energy reserves for a 20-min loiter time. Fleet simulations demonstrate operational results, showcasing average flight hours of about 9.5 flight hours per day for each vehicle concept. In their respective transport network, the multirotor is operated on up to 40 missions with an average range of 22 km, and the tiltrotor performs up to 22 missions at an average range of 82 km. Furthermore, the sensitivities of propulsion technology, operational strategies, and fleet planning are considered. All details about the design process and vehicle concepts can be found in [94].

Conclusion

Making the vision of UAM a reality requires collaborative, multidisciplinary, and simultaneous development of all system elements. Current approaches to UAM vehicle design often fall short by focusing solely on the vehicle domain itself. Therefore, the combination of conceptual vehicle design with a broader system-of-systems perspective is needed. The introduced UAM system-of-systems approach has addressed this challenge and shed light upon several early design phase research questions. This approach should be explored further in research since the integrated connection of various methodologies for vehicle design and assessment could lead to more holistic results in the end.

Throughout the project, we have observed that early adaptations of UAM may be feasible, but are most likely constrained by piloted, low-capacity and short-range vehicles for small scale intra-city missions. Missions over longer ranges suitable for megacities open up the possibility of energy-efficient and time-saving air transport, but require advances over the current state of technology. Thus, continued efforts in (hybrid-)electric propulsion, autonomous flight, and low-noise vertical lift capabilities are needed to unfold UAM's full potential.

4.2.2 Battery degradation

Challenge

The propulsion battery system is one of the main systems of the air taxi and is subject to degradation during operation while it is expected to be a main cost driver from the maintenance perspective. The battery ageing depends on the system design and the way the aircraft is operated. Replacing a degraded battery increases the life-cycle expenses of the vehicle and also consumes resources. Therefore, it is elementary to understand the impact of design and operational decisions on battery ageing.

State of the art

Lithium-ion batteries are exposed to various ageing mechanisms, that either effect the positive or negative electrode the or the battery's electrolyte and can be found, for instance, in [95–97]. The modeling of ageing lithium ion batteries ranges from physical models simulating the impacts on element level [95, 98] to empirical approaches [95, 99] based on ageing experiments to data driven approaches [100, 101], considering battery ageing from an operator perspective, there are three primary stress factors to consider: temperature, state of charge, and the load profile. Hence, empirical models offer an appropriate detail level coupled with swift runtimes.

DLR approach and results

The degradation of batteries is investigated for the wingless multirotor for urban missions and the winged tiltrotor vehicle for suburban or megacity missions and their operation. The aircraft concepts are equipped with Sanyo UR18650E NMC-type lithium-ion batteries. Schmalstieg et al. [99] present an empirical ageing model for lithium-ion batteries, that combines degradation caused by the cycled charge and the calendar ageing independent of the usage. Typically, the ageing of lithium-ion batteries is categorized into three phases: the strong initial degradation, a linear degradation, and the rapid capacity fade [102]. The model by Schmalstieg et al. reproduces the first two phases, but excludes the rapid capacity fade. The tipping into rapid fade for lithium-ion batteries is usually excepted at approx. 80% of the original capacity. However, the data by Schmalstieg et al. is provided down to 75% of the initial capacity and hence, the fading is considered until 75% of the initial capacity.

Our study's assumptions and limitations are following: a constant battery temperature of 26 °C is assumed [103]. All battery cells are equal in terms of ageing. The empirical degradation model by Schmalstieg et al. [99] reflects the battery technology of its year of publication 2014. The battery is charged with 1 Coulomb after each flight mission to a state of charge of 100%.

The two aircraft concepts are a multirotor and tiltrotor aircraft, that are designed for a near and far term technology level. Different aircraft utilizations are researched, but independent of the utilizations, the degradation is primarily caused by the load cycles rather than the calendar aging. For the multirotor concept, 80% of the original capacity is reached after 1470 to 1610 cycles depending on the payload. For a safe operation under full payload only 55% battery capacity is required. Therefore, extending battery usage below 80% to a capacity fade of 75% could increase battery cycles to 2300 to 2500. Still, the batteries would have to be replaced every two to four months assuming 20 or 40 daily flights with a distance of 22 km.

The tiltrotor concept was developed for longer distances and demands more energy to cover the design range and an additional 20 min reserve. Consequently, the battery is designed that 79% of the original capacity is required. Even if the battery is used until a remaining capacity of 79% is reached, the lifetime reaches only 490 to 560 flight cycles of 82 km each.

The short battery life might create significant challenges for the successful operation of tiltrotor aircraft in the near-term scenario. Thus, the tiltrotor is also evaluated for the long-term scenario. In the far-term scenario, the aircraft technology has improved, while the battery degradation remains unchanged. The capacity fade for the tiltrotor aircraft with enhanced technology is displayed in Fig. 6 for eleven daily flights. The varying line-styles indicate the payload in terms of persons (passengers or a potential pilot). The solid represents a constant transportation of four persons, while the dotted line displays the fade for one person. After 610 to 680 flights, 80% of the original capacity is reached. That battery lifetime is an improvement of a quarter compared to the short-term scenario. Additionally, improved technology decreases the energy required for flight, requiring 71% of the initial battery capacity. Hence, the design allows the usage of further degraded batteries. Approx. 940 to 1,050 flights could be carried out until the battery reaches 75% of its initial capacity, which would extend the battery lifetime by about a half.

Figure 7 shows the corresponding payload-range-diagram for the long-term tiltrotor concept. For example, the range initially is 160 kms with four persons on board, but decreases to 107 kms as the remaining capacity reaches

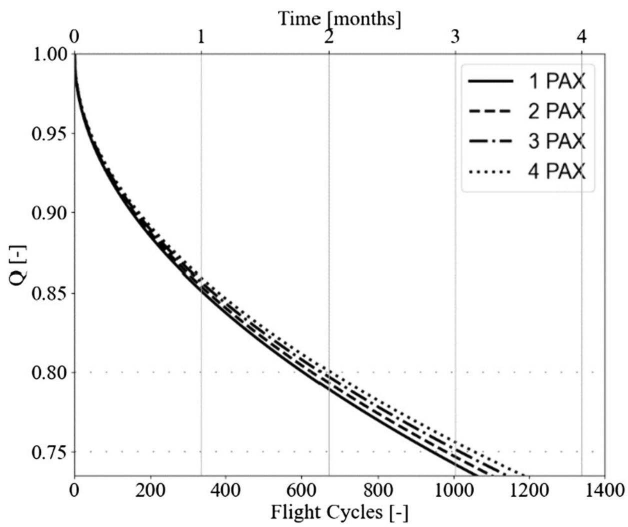


Fig. 6 Fade of capacity (Q) for tiltrotor aircraft with enhanced technology

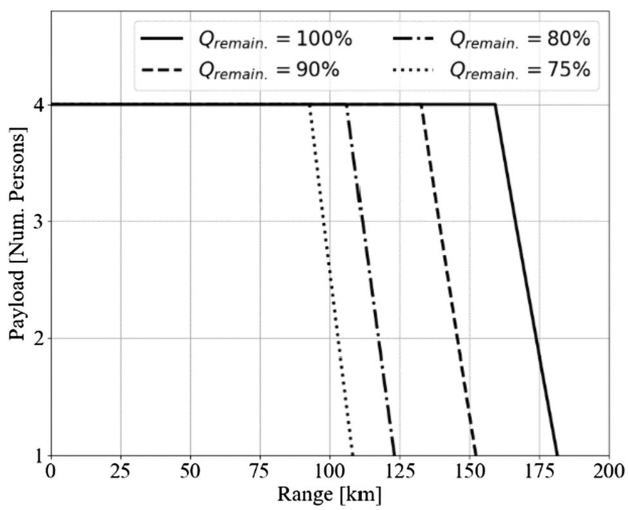


Fig. 7 Payload-range-diagram for a degrading battery

80%. The significant reductions in range and payload due to battery degradation pose challenges for aircraft assignment and planning. The increased complexity of restricted operations, including maintenance considerations, has been initially addressed [104, 105].

Conclusion

Battery degradation and its replacement interval could be a limiting factor for the realization of UAM, as its realization also depends on an affordable price point, shown in Sect. 3. A short-distance multirotor with a near-term design could achieve 1,500 to 2,500 flight cycles per battery. The near-term implementation of tiltrotor aircraft would require a replacement interval of less than two months. For a far-term scenario, the improved aircraft technology could extend the number of battery cycles to 650 to 1000 or 2 to 3 months, depending on the precise ageing characteristics and payload carried.

Clarke and Alonso researched the impact of battery life on the flight operations for UAM applications [106]. The study evaluated various aircraft concepts, including a six-seat tandem tiltwing configuration, which is the most comparable design to our tiltrotor. Their results are compared with those obtained for our configuration. While their flight distances are longer with 60 to 100 nautical miles, they investigated eight daily flights compared to our study, which involved eleven daily flights. In their case, the batteries of the tandem tiltwing aircraft retained a battery capacity of 80% after 30 to 60 days, depending on the distance of the flights. Although we cannot directly compare the vehicles and their utilization, the expected lifetime for the battery is a comparable range. The batteries of our tilt-rotor will reach a remaining capacity of 80% after about 45 to 50 days for the near-term scenario and 55 to 60 days for the far-term scenario.

Lastly, the fading battery capacity has an impact on the dispatchability, thus creating further challenges and potential bottlenecks in flight scheduling, which must be considered in an evaluation for a potential UAM operation.

4.2.3 Onboard systems

This section refers to the contribution of Jäger et al., “Battery-Electric Powertrain System Design for the HorizonUAM Multirotor Air Taxi Concept” [107] in this issue.

Challenge

One of the main challenges preventing VTOL vehicle with passengers on board being already operated today is the unproven safety and reliability of those concepts for commercial passenger operation. Within the last four years the EASA has established rules, named the Special Condition for small-category VTOL aircraft, as well as corresponding means of compliance [22, 108]. Vehicles that are transporting passengers over congested areas fall into the category enhanced of the EASA-SC-VTOL [22]. The safety objectives stated therein for the category enhanced aircraft set high standards similar to commercial aviation. For example, the vehicle must be able for a continued safe flight and landing even if any single system failure occurs and the failure probability for a catastrophic failure must be less than 10^{-9} failures per flight hour. As a reliable propulsion system is crucial for a safe VTOL operation, the design of the vehicle's propulsion system takes over an important role.

State of the art

So far, there has only been little research focus on analyzing the propulsion system reliability and its effects on the safe vehicle operation. However, the research that has already been conducted, indicates that the EASA safety objectives are especially difficult to meet for wingless multirotor concept vehicles [109, 110].

DLR approach and results

Resulting from these challenging safety regulations, a conceptual design process was developed that aims at facilitating the development of a safe propulsion system architecture for multirotor eVTOL vehicles for successful certification. This methodological approach was then applied to design, size and validate the propulsion system for the HorizonUAM multirotor eVTOL concept for an intra-city operation. As a result, a safe battery-electric propulsion system could be designed that is expected to fulfill the EASA SC-VTOL safety requirements. The applied design method is divided in five steps. Within step one, the concept of operation was defined, which includes defining the flight mission and payload requirements. Based on these requirements the vehicle configuration was preselected and the powertrain technology to be used was defined. Within step two several further requirements were developed which are based on the required controllability, the handling quality and allowed noise emission. Within the third step, the propulsion system was defined which can be segregated into defining the flight control system, the power and drive system, the electrical system and the thermal management system considering the previously established requirements. This propulsion system concept was then refined within the safety analysis by taking into account the guidelines ARP4754A [111] as well as the ARP4761 [112]. Thereafter, the vehicle concept was sized as well as validated within the vehicle sizing and simulation step. The system architecture refinement process is usually an iterative process between the concept definition, the safety analysis and the succeeding sizing step and is being conducted until the safety requirements of EASA SC-VTOL can be met. A detailed description of the design process and its application for an exemplary multirotor vehicle and a corresponding propulsion architecture can be found in [107].

Conclusion

The conceptual design method primarily adds value towards improving the design process, with the aim of increasing the reliability of the vehicle and its future operation as well as its safety. It can prevent future high vehicle development costs due to late design adjustments and also help to complete certification procedures quickly and successfully. Furthermore, by increasing the reliability of the design of safe vehicles, the passenger's acceptance can also be expected to be positively influenced.

4.2.4 Cabin design

This section refers to the contribution of Reimer et al., “Applied design thinking in Urban Air Mobility: creating the airtaxi cabin design of the future from a user perspective” [82] in this issue.

Challenge

Designing future UAM cabins is complex and poses several challenges to researchers and designers. Since UAM vehicles are not yet an option for public transportation, the public´s experience level is low and their expectations for this new type of transportation are unclear. Therefore, in addition to technological and safety-related factors, the user acceptance of this future technology is generally expected to play an important role. Within the Horizon UAM project, the user-centered design of future UAM cabins is an important aspect to consider the potential acceptance of newly developed concepts for UAM from the very beginning [113]. To achieve a user-centered design, the so-called Design Thinking Method has proven to be an effective way to involve the user in the early design process [114, 115].

State of the art

In the field of UAM, little to no research has been conducted on specific air taxi cabin preferences. Additionally, there is no detailed information on how current air taxi companies develop new cabin concepts.

In the field of aviation and aircraft cabin development, novel cabin concepts have traditionally not been developed using the Design Thinking Method.

Design thinking (DT) is an approach that emphasizes comprehensive understanding and deep, empathetic insight into user behaviors, desires, fears, and environments [116]. User-centered methods such as DT have proven to be particularly effective for companies and brands such as Nike, Pepsi, Apple or SAP, when it comes to achieving high levels of public acceptance for future innovations [117]. This gives reason to believe that the application of the classical DT process to the design of future and user-centered air taxi cabin concepts can have a positive impact on the level of public acceptance of air taxis.

DLR approach and results

In the design process of the UAM cabin concept, DT was applied [82]. This offers a creative and effective approach that emphasizes users' emotions, enabling more effective solutions for various stakeholder requirements. DT was applied to design cabins for the airport shuttle and the intra city use case.

According to the intra-city use case (see Appendix and [71], the proposed concept accommodates three passengers and a pilot. The orientation of the seats in the direction of flight is evident in all concepts, as is the storage space beneath the seats. Following the acceptance research conducted by DLR, the seats of the UAM cabin concept were slightly rotated towards the outer walls, and adjustable U-shaped headrests were implemented for customizable privacy. Given the negative evaluation of storage beneath the seat, the legroom was expanded, and a storage option with optional access to luggage during the flight journey was realized.

Initial estimates based on commercial aircraft interior masses suggest a possible total weight of 766 kg for the airport shuttle concept. By applying DT and using lightweight components, a minimalist seat design and a simplified luggage storage solution, the cabin mass for an air taxi concept, could be reduced substantially to an estimated range of 380 kg and 579 kg. The weight reduction can have a positive impact on the sizing of the battery and the required power for air taxi transportation.

The storability of a folded standard wheelchair was defined as a fundamental requirement for the positioning of seats and the overall design of the air taxi concept. This wheelchair can be stored in the rear area of the concept. With increased seat width and legroom, enhanced accessibility for individuals with obesity, pregnancy, or elderly individuals is also facilitated.

Conclusion

DT was applied to design cabins for the airport shuttle and the intra city use case and led to important advantages for the development process of the air taxi system as a whole in terms of costs, acceptance and safety, flexibility and convenience.

By combining the airport shuttle and intracity use cases, a multifunctional cabin concept has been developed that covers two different application scenarios. The versatility of the cabin concept results in lower development costs compared to designing separate cabins for each use case. At the same time, the recognition value of the concept increases when used in multiple scenarios, which can have a positive impact on the perceived safety and usability of the cabin features. With its minimalist and interchangeable cockpit design, the cabin can also be converted to a fully autonomous scenario with four passengers in the future.

In addition to improved seating comfort, optimized storage compartments, minimalist design and customizable privacy features, the cabin design incorporates various comfort parameters based on feedback from potential user groups. The deliberate combination of minimalist and easy-to-understand features with futuristic and complex design elements enhances the overall comfort and user experience. Similar to the positioning and design of the seats and luggage compartment, the requirements for other components of the DLR UAM cabin concept are primarily based on the user studies and user preferences within the DT approach. In the course of the user feedback, the consideration of inclusive design proved to play a crucial role. In future steps, the integration of other wheelchair types should be explored and the accessibility of people with reduced mobility in the cabin in general should be further tested and optimized.

The user-centered design process allows for potential cost savings. The early feedback process as well as the direct translation of key requirements into a concept can help to avoid cost-intensive adjustments in the late development process.

In addition, the direct involvement of various user groups in the design process offers great potential for raising awareness of UAM, disseminating information, and addressing concerns and fears. In particular, a focus group study showed an increased acceptance of this novel mode of transport. The influence of passengers on the design can have a positive impact on acceptance and the perception of safety, leading to a higher willingness to use air taxis among the general population. In addition, the development process of autonomous air taxis can lead to increased acceptance in the next step by directly addressing fears, wishes and concerns and incorporating them into the design concept in cooperation with user groups.

4.2.5 Cabin simulation

This section refers to the contribution of Ernst et al., "How does it feel to fly in an Air Taxi? – Exploring modern Head-Mounted Display capabilities for Mixed Reality Flight Simulation" [118] in this issue.

Challenge

A vital aspect for the economic success of a new technology is that potential users accept the technology. User-centered design aims to incorporate the perspective and needs of the users of a systems as early as possible in the design process. One challenge in urban air mobility is that many people neither have a clear understanding of the service nor were able to experience a flight. As a consequence, user requirements are likely be fuzzy and it is unclear on what visions they are based. Therefore, the goal of our work was to develop a human-in-the-loop air taxi cabin simulator that allows passengers to experience an air taxi flight as realistically as possible. At the same time, the simulator must be customizable enough to allow researchers to evaluate the effects of different cabin setups and scenarios. Based on the simulation experience, users should be able to give valuable feedback, from which valid requirements for UAM can be derived.

State of the art

Human-in-the-loop simulation studies are a well-established methodology in flight guidance research to enable users of future systems to gain realistic experiences even at early stages of development. However, recent technology advancements in the field of head-mounted displays and mixed reality (MR) technologies enable researchers to create immersive simulators with less space consumption, easier re-configuration, and costs less than conventional cockpit or cabin simulators. A good example of the capabilities of these new technologies is the EASA-certified helicopter flight training device by Loft Dynamics [119].

DLR approach and results

Within the project HorizonUAM, DLR made use of the advances of MR technologies to set up a human-in-the-loop simulator representing an air taxi cabin was set up within the project HorizonUAM. The Air Taxi Simulator is a fixed-base simulator comprising a life-size cabin mockup and a video-see-through head-mounted display. The cabin can be augmented with virtual elements but also real people interacting with the participants can be included. Mixing reality with virtual content enables a test person to experience a realistic simulation of an air taxi flight without being entirely decoupled from reality like in conventional virtual reality. A detailed description of the simulation implementation and results regarding the immersion and fidelity of the simulator can be found in [118].

As described in [81], an extensive human factors study with 30 participants using the MR Air Taxi Simulator assessed the factors information need, influence of a flight attendant on board and a re-routing of the flight and their effect on perceived well-being and interaction. The results show that the presence of a flight attendant had no statistically significant influence on the well-being of participants and 16 out of 30 participants stated that an attendant on board is not necessary. Nevertheless, eight found it reasonable for the introduction phase and nine remarked an increase in perceived safety due to the flight attendant. Furthermore, the results show that with an attendant on board, the re-routing scenario was rated better compared to the scenario without an additional crew member on board. With respect to information needs, the three top-most relevant information were travel time, changes of flight route due to obstacles or other traffic, and flight route.

Conclusion

The results show that MR simulations are a fruitful tool for the investigation of acceptance aspects to further shape interaction concepts between passengers and highly automated transportation systems. Using the MR Air Taxi Simulator for an empirical study helped to clarify requirements of end users with regards to crew members on board and information needs. The approach is useful to get qualified user requirements for an acceptable concept and technology and offers a more cost-effective manner to make design decisions in the early stage of the development process.

4.3 Infrastructure

This section refers to the contribution of Schweiger et al., "HorizonUAM: Operational Challenges and Necessary Frameworks to Ensure Safe and Efficient Vertidrome Operations" [120] in this issue.

Challenge

UAM ground infrastructure is important for facilitating the safe and efficient integration of UAM operations in the air and on the ground. Vertidromes are specialized (e)VTOL infrastructure components, that serve as essential hubs for future air taxis in urban environments and where users can enter and exit the UAM network. Due to the complex operating environment (urban, often controlled airspace) and high ground and air risks, urban vertidrome networks contribute significantly to the realization of UAM by shaping the air taxi fleet composition, air traffic management, and overall efficiency and throughput capabilities. Therefore, it is crucial to integrate vertidrome research into current UAM development activities.

Due to the lack of full-scale air taxis and fully functional vertidromes capable of accommodating high-density air taxi traffic, simulation is the preferred approach for conducting research and planning activities for vertidromes and vertidrome-networks. This approach requires appropriate simulation tools whose development should be accompanied by flight trials for validation.

State of the art

A comprehensive overview of the state of the art can be found in [30]. According to this, many vertiport design proposals have been made, offering a wide range of ideas and approaches how to integrate UAM into urban and suburban environments. However, important issues influencing the design of vertiports are only briefly described. It is still uncertain on what basis a vertiport should be dimensioned and which layout is most advantageous, based on the vertiport location and the demand profile. Compared to conventional heliports, ground taxiing is expected and needs to be considered in the analyses. Further research is needed to identify and quantify operational uncertainties and to evaluate the role and limitations of strategic and tactical measures. Different approaches to the structuring of a vertiport network airspace as well as a local airspace of a vertiport and fair access to it are under discussion.

DLR approach and results

Due to the lack of full-scale air taxis and fully functional vertidromes capable of accommodating high-density air taxi traffic, both individual vertidrome and vertidrome-network research and planning activities are currently conducted in simulation. Several simulation tools have been developed for this purpose [120].

To study airside and ground traffic flows, a vertidrome fast-time micro-level simulation model has been developed, which can be used at the strategic planning level considering current vertidrome utilization, occupancy and traffic flows. It allows to determine the operational impact of non-nominal conditions, considering different scheduling methods, operational precision, weather impact, and vertidrome layouts, and thus to evaluate operational capabilities and assess specific vertidrome locations.

Within the vertidrome research topic, the system boundaries have been extended to the vertidrome network perspective by developing fast-time agent-based simulation tools for vertidrome airspace network management and vertidrome network optimization tasks [121]. In addition, a real-time human-in-the-loop simulation setup was developed to evaluate the impact of introducing air taxi operations into the controlled airspace and airport environment on air traffic controller workload. First real-time scaled flight tests in a scaled urban environment were also conducted in our temporary modular test facility at DLR's Experimental Test Center for Unmanned Aircraft Systems in Cochstedt, Germany.

Detailed results showed, among other things, that there is significant potential to reduce fleet and ground infrastructure, depending on battery recharge time [122]. The potential for travel time savings could also be demonstrated by choosing the optimal airspace management approach [123]. Regarding the integration of UAM traffic into the air traffic control (ATC) work processes, the real-time simulations showed an increase in workload and situation awareness, suggesting the addition of a working position dedicated to the handling of aircraft flying under visual flight rules (VFR) and UAM traffic in case of increasing UAM traffic [121].

Conclusion

As summarized in [120], the vertidrome research not only provided valuable detailed results, but also highlighted the complexity of integrating vertidromes into the urban environment and into the pre-existing aviation ecosystem from a procedural and collaborative perspective. There is no one-size-fits-all solution. Therefore, a UAM tailored Vertidrome Airside Level of Service (VALoS) rating concept was used to evaluate the suitability of a specific vertidrome design and location [55, 124, 125]. It is based on stakeholders relevant for each specific use case (e.g., passenger, vehicle operator, vertidrome operator), who are setting requirements and defining corresponding metrics (delay, punctuality). The VALoS rating can be used to evaluate the performance of a specific vertidrome configuration for a given performance target and demand distribution.

Scalable operational concepts, efficient air traffic management, and optimized allocation and use of network resources are critical to ensure that vertidromes evolve sustainably and successfully along with the growing demand for UAM. The developed tools and methods support the design and evaluation of individual vertidromes in the strategic planning phase, the network of vertidromes and the interaction with airspace network management, fleet design and operations. They are a necessary prerequisite for the simulation of the entire UAM system with the aim of optimally tuning the individual components of UAM to design an optimized system adapted to the local conditions.

4.4 Operations

Regarding the operation of air taxis, HorizonUAM considered aspects of airspace integration, autonomy, navigation, communication, and associated operating costs.

4.4.1 U-space

This section refers to the contribution of Schuchardt et al., "Integrating Vertidrome Management Tasks into U-space" [126] in this issue.

Challenge

Air traffic management (ATM) is a mandatory asset for the safe operation of any air vehicle in controlled airspace. This is especially true for potentially high numbers of future airspace users as unmanned aerial systems (UAS) or air taxis [127]. While piloted air taxis could be operated similarly to helicopters today (e.g., under visual or instrument flight rules, VFR/IFR), remotely piloted or autonomous air taxis will require new ATM solutions to be operated in high numbers. The challenge is to conceptualize and implement a functional and scalable UAS Traffic Management (UTM) system from scratch.

State of the art

The European Commission has implemented its U-space regulation [128] as framework UTM. In general, U-space refers to a set of technologies, procedures, and regulations that enable safe and efficient operations of UAS in low-altitude airspace. It encompasses various aspects of operations, including registration, flight planning, communication, surveillance, and conflict resolution. The concept aims to ensure the integration of UAS and air taxis into the existing aviation ecosystem, promoting safety, security, and scalability. Several European research projects have laid the basis for the implementation of the theoretical U-space framework: CORUS-XUAM established an extended concept of operations for U-space including UAM [129]; TINDAiR also dealt with the airspace integration of UAM [130] and in PJ34W3 AURA an interface between ATM and U-space was investigated [131].

DLR approach and results

In HorizonUAM prototypical U-space services were used to demonstrate vertidrome management tasks [126]. A central U-space cloud service was simulated through a local messaging server using the protocol MQTT (Message Queuing Telemetry Transport). A prototypical vertidrome management tool was created to demonstrate the scheduling and sequencing of air taxi flights. The vertidrome manager was fully integrated within the U-space environment and received real-time information on flight plans, including requests for start and landing and emergency notifications. Additional information coming from other U-space services (e.g., weather information) could be accessed on request. The integration was successfully demonstrated in the erected model city at Cochstedt, Germany, as a scaled flight test environment with multicopters (< 15 kg) representing passenger carrying air taxis [126].

Conclusion

A limited number of air taxis can be managed by conventional air traffic controllers, as shown in [121]. In comparison, the use of U-space for vertidrome management, as shown above, has the advantage of being scalable for high-density air taxi operations. The advantage of U-space is the high degree of digitalization inherent in the system. The prototypical vertidrome manager has been integrated into U-space using the conceptual basics established in CORUS-XUAM [132]. Further U-space services useful for the operations at vertidromes are being investigated in the ongoing project EUREKA [133].

The implementation of U-space has direct effects on the feasibility and success of the UAM eco-system. First of all, a high degree of automation on the vehicle side but also on the ATM/UTM side leads to lower personnel costs (pilots and air traffic controllers). Second, U-space is needed to manage and increase airspace capacity. This will result in higher system efficiency and in higher profits for operators. Third, efficient (on-demand) flight planning can increase the speed of transport and user comfort. Furthermore, flight path planning and optimization and also the creation of no-fly-zones using U-space can be used to minimize negative effects on the ground such as noise or visual pollution. Finally, U-space ensures safe operation of UAS and air taxis which is essential for the societal acceptance.

4.4.2 Safe autonomy and safeguarding machine learning components

This section refers to the contribution of Torens et al., "Runtime-monitoring of operational design domain to safeguard machine learning components" [134] in this issue.

Challenge

Safety is arguably the most important factor for any travel modality. Moreover, to achieve truly affordable and ubiquitous air travel, autonomy is also a key component. With increased autonomy, the operating costs can be reduced. The automation can reduce the training costs of the pilot, for both onboard and remote pilots. By operating without an onboard pilot, the weight of the vehicle can be considerably reduced. This reduces the energy required per mile and thus increases the range. Alternatively, one more passenger or additional luggage can be accommodated. Finally, autonomy enables the scalability and seamless operation of air taxi services to large numbers. This would not be possible with the requirement of aviation pilots for each vehicle and manual coordination and management.

One specific machine learning (ML) feature that was explored in the HorizonUAM project was visual person detection. This detection can be utilized for automating the landing approach, so that no person is in danger at a vertidrome. It would be also possible for delivery drones to drop packages in safe distance to persons. Finally, it would be possible to reduce risks in flight by avoiding detected people in the flight path.

State of the art

Although first UAM use cases may start without machine learning components, several efforts exist to support safe integration for the aviation domain, as well as other domains. EASA has published several reports, including the latest guidance Concept Paper First Usable Guidance for Level 1 & 2 Machine Learning Applications [135], that suggests several building blocks for trustworthy AI: AI Trustworthiness Analysis, AI Assurance, Human Factors for AI, and AI Safety Risk Mitigation. In addition to that the joint international working group SAE G-34 / EUROCAE WG-114, Artificial Intelligence in Aviation is preparing guidance material [136]. All of these efforts are backed with recent and upcoming research, spanning one or more of the mentioned building blocks. There are approaches that try to map traditional design assurance standards to machine learning [137] (Building block: AI Assurance). And there are approaches that try to utilize runtime assurance during operation [138] (Building block: AI Safety Risk Mitigation). As a result, there is not one definite methodology to integrate ML components, but that there are several methodologies that complement each other for a safe integration. A more thorough overview on related work can be found in [139] as part of the project work.

DLR approach and results

Recently, machine learning has made significant progress in all domains. The visual person detection is only one example for a safety–critical task that can be performed using machine learning and that otherwise can only be performed by a human pilot. For this, a ML algorithm was developed and flight tests were performed to gather training and validation data. However, the focus of the research is not the development of an ML algorithm, but to research safety aspects of ML in the context of the aviation domain. The existing development standards for software are very demanding. The use of ML is problematic, since it is considered a black box from a verification point of view. As a result, there is a demand for research in the area of ML safety. Our research started with a literature review on the topic of ML safety [139] as well as the existing standards and regulation for the use of ML in aviation [140]. A research focus was on analyzing the environmental conditions of the operation. In the context of automation systems, this is called operational design domain (ODD). The idea is to check if the specific conditions during operation are consistent with the operational conditions that are expected and that were met during development and training of the ML component. As a result, the trust in the ML component is increased, if there is a match between trained, expected and existing operating conditions.

In the project, a safe operation monitor (SOM) was developed and extended to cover aspects of the ODD to safeguard the ML component as well as the operation. Further details on the topic of safe autonomy and safeguarding ML components can be found in [134].

Conclusion

As mentioned in state-of-the-art, there are several methodologies necessary, complementing each other, to enable safe integration of machine learning. There are multiple research efforts regarding the EASA Building block AI Safety Risk Mitigation, which is the main building block that the project research was focused on. The overall research supports that techniques, such as SOM and supervision of the ODD support the safeguarding of the machine learning component and the safety of the overall operation [141–144].

4.4.3 Multisensor navigation

This section refers to the contribution of Zhu: "Towards navigation system integrity for urban air mobility – concept design and preliminary validation" [145] in this issue.

Challenge

The performance of the navigation system is a key factor to the safety of operations in urban air mobility applications. Vehicles are expected to operate in urban environments, especially during the take-off and landing phases at vertiports. In addition, the costs and size requirements of both vehicles and ground infrastructure are more stringent compared to current civil aviation applications. This leads to new technical challenges to the navigation systems. These challenges may even become increasingly critical as the market evolves and the UAM traffic densities increase in the future. In order to simultaneously achieve high accuracy, high availability and high integrity in urban environments, multisensor navigation solutions are required. However, there are still standardization gaps in the certification of safe multisensor navigation systems.

State of the art

The current navigation system design for UAM applications is mainly based on Global Navigation Satellite System (GNSS) due to its certifiability and standardized requirements for drone applications [146]. However, standalone satellite navigation systems may not be able to provide sufficient accuracy and availability for UAM applications in deep urban areas. Moreover, a few technical gaps in the navigation of unmanned aircraft systems have been identified by standardization groups [147].

DLR approach and results

In the HorizonUAM project, we proposed a preliminary architecture design for UAM navigation. The design focuses on the take-off and landing operations at vertiports, which is arguably the most challenging phase for the reliability of the navigation system. Both onboard sensors including GNSS, inertial sensors, camera and barometer as well as the corresponding ground infrastructures to provide augmentation and integrity information are considered. In addition, we developed innovative methods to quantify the integrity of different subsystems, given the fact that standards are missing for some sensors and for the UAM operation environments. Proof-of-concept demonstrations for our system design were carried out in measurement campaigns using multirotors. The details of the system design and tests can be found in [145].

Conclusion

Our developments on reliable multi-sensor navigation systems targets on crucial technical gaps for the UAM application in the state-of-the-art navigation approaches. The developments include the multi-sensor architecture design for the UAM vertiport operation environments, the navigation requirements and performance analysis, as well as the integrity quantification of different sensors which lack standardized integrity description method. As a first investigation, our work in [145] provides a few preliminary results as a basis for further researches towards certifiable high-accuracy, high-integrity navigation systems.

4.4.4 Robust and efficient communication

This section refers to the contribution of Becker et al.: "Towards Robust and Efficient Communications for Urban Air Mobility" [148] in this issue.

Challenge

For the realization of future urban air mobility, reliable information exchange based on robust and efficient communication between all airspace participants will be one of the key factors to ensure safe operations. Due to the high density of piloted and new remotely piloted and autonomous aircraft, air traffic management in urban airspace will be fundamentally different from today. Unmanned Aircraft System Traffic Management (UTM) will rely on pre-planned and conflict-free trajectories, continuous monitoring, and existing communications infrastructure to connect drones to the UTM. However, to avoid collisions and increase overall reliability, unmanned aircraft still lack a redundant, higher-level safety net to coordinate and monitor traffic, as is common in today's civil aviation. In addition, direct and fast information exchange based on ad hoc communication is needed to cope with the very short reaction times required to avoid collisions and the high traffic density. In particular, the urban environment is very challenging from a physical layer point of view, with rich multipath signal propagation as well as shadowing and diffraction events when flying close to surrounding objects such as tall buildings.

State of the art

Safety nets for coordinating and monitoring traffic already exist in different domains. They can be separated into cooperative and non-cooperative systems. Cooperative systems are usually based on direct, ad-hoc communication systems that enable a fast exchange of very precise information about position, direction and speed and do not have to rely on existing communication infrastructure. They consume less power than active systems such as RADAR and LIDAR. Safety nets based on ad-hoc communication are used in today's civil aviation, for example ADS-B systems like Universal Access Transceiver (UAT) or Flight Alarm (FLARM). Recently, EASA has introduced ADS-L to consider the new developments towards U-space regulations and to meet the requirements for future unmanned aviation. However, FLARM is a proprietary system and, like ADS-L, it is operated in an unlicensed SRD860 frequency band that may be subject to interference from other communication systems. In the maritime domain, the Automatic Identification System (AIS) is used to avoid collisions between ships. In the railway domain the German Aerospace Center developed the Railway Collision Avoidance System (RCAS). For road traffic, there are currently two communication standards. The IEEE802.11bd standard, the successor to IEEE802.11p, is based on WiFi, and the 5G C-V2X standard, the successor to LTE C-V2X, is standardized by 3GPP as an extension for mobile communications to support V2X applications. The suitability of cellular communication systems in general as datalink for unmanned aviation was evaluated in several studies. In particular, the high uplink interference in dense urban scenarios revealed performance issues and the need for adjustments. UAM will consist of different applications with different communication requirements and especially safety–critical applications will need reliable communication solutions. Therefore, a multilink approach combining different datalink technologies is mostly aimed in current concepts to increase reliability and provide at least one backup datalink.

DLR approach and results

We are developing a drone-to-drone (D2D) communication and surveillance system, called DroneCAST, which is specifically tailored to the requirements of a future urban airspace and will be part of a multi-link approach. In order to evaluate the reliability and performance of transmission systems, an accurate channel model that takes into account the specific underlying propagation characteristics is essential. As a preliminary step, we have conducted a wideband channel measurement campaign with hexacopters to accurately measure the D2D propagation characteristics in an urban environment. During the HorizonUAM project, we have proposed a novel channel model architecture to model the D2D communication channel for urban environments, which considers the propagation elements and effects identified from our measurements, and shall serve as a basis to easily incorporate further statistics from any related measurements. Furthermore, we presented a multi-link approach with a focus on an ad-hoc communication concept that will help to reduce the probability of mid-air collisions and thus increase social acceptance of urban air mobility. As a first step towards an implementation, we equipped two drones with hardware prototypes of the experimental communication system and performed several flights around the model city to evaluate the performance of the hardware and to demonstrate different applications that will rely on robust and efficient communication. A general discussion on robust communication for urban air mobility and our steps towards DroneCAST can be found in [148].

Conclusion

For the realization of future urban air mobility, reliable communication will play a key role in mitigating mid-air collisions. Communication concepts based on a multilink approach by combining mobile communication with different datalink technologies will increase reliability. However, there is still a lack of a redundant, higher-level safety net like it is already used in different domains and in current civil aviation. DroneCAST is specifically tailored to the requirements of a future urban airspace and can be part of a multilink approach.

4.4.5 Cost modeling

Challenge

As long as passengers decide on their mode of transport based on their willingness to pay, the ticket price remains one of the most critical metrics in transportation. In the long term, a ticket price is directly linked to the operating costs of an UAM operator. Thus, a model for the estimation and forecast of direct operating costs becomes one of the key models that a UAM operator needs to develop. At this moment, many components of the UAM system that contribute to the direct operating cost are not yet known.

State of the art

The OEM eHang offers a 20-min flight for approximately 50€ in Southeast Asia without providing proof of economic viability [149]. Furthermore, Archer has already announced a long-term goal that aims for a cost per mile between $3 and $4 [150]. According to the literature, a fare per kilometer of 3 to 4€ seems necessary to expect significant demand and to run a business [23, 151]. However, a UAM airline has to establish a business that can enable those ticket prices.

DLR approach and results

A model for the estimation of the direct operating costs was developed [58]. Where applicable, models of cost components from manned aviation were adapted to estimate UAM parameters. Where this was not feasible, assumptions with an accepted and predictable level of uncertainty were incorporated into the operating cost model.

Direct operating costs were evaluated for different use cases. Depending on their requirements, each use case can be served by various vehicle configurations. Using this information, the cost model calculated different cost scenarios based on a set of input parameters, considering uncertainties. By providing optimistic and conservative scenarios for the direct operating cost as a share of the total cost, indirect costs were also estimated.

The analysis showed that the nature of the direct operating costs depends on the use case and its vehicles. The fare per kilometer highly depends on the considered mission length. The direct operating costs for the intra-city, airport shuttle, and inter-city use cases were estimated. Fares would need to be at least between 4.10€ and 8.50€ per km to cover total operating costs and to achieve a 10% profit margin for the first two use cases, respectively. Minimum fares for the intercity use case are estimated to be between 1.00€ and 1.40€ per km. All estimates are based on a hypothetical load factor of 1, which illustrates the challenge of making urban air mobility affordable through low operating costs. Similar approaches in the United States lead to comparable fares per km [152]. Admittedly, all cost estimations include uncertainty, which should be mitigated when distinct cost elements evolve to a final version.

Conclusion

The operating cost and its resulting ticket fare represent some of the most critical metrics for UAM operators. The results presented demonstrate that both mission design and vehicle configuration have a significant impact on the total operating cost per flight. UAM operators need to carefully consider different vehicle configurations, particularly when demand is low and larger vehicles are operating with lower load factors, as reducing operating costs and thus fares is critical to generating sufficient demand to be profitable [58]. Another option could be autonomous vehicles, leading to a reduction in operating costs per seat. While the affordability could increase with the absence of a human pilot, passenger acceptance could potentially decrease. Further work on cost estimation is needed as not all components of UAM have been fully elaborated yet, leading to operating costs calculated with a level of uncertainty that may challenge the guarantee of a profitable airline business. In the future, the current cost model can be expanded with additional insights of UAM components.

4.5 Overall system modeling: system of systems simulation

This section briefly describes the system of systems simulation developed within the HorizonUAM project. This section refers to the contribution of Naeem et al., “A collaborative system of systems simulation of Urban Air Mobility” [153] in this issue.

Challenge

Since UAM is a complex system of systems (SoS), with various technical, operational, regulatory, and social components interacting, a holistic approach is essential. The complexity results from the necessary integration of the constituent systems such as aircraft, infrastructure, air traffic management and flight operations into the urban transportation system. Each of the domains within the UAM SoS represent active research fields in the literature due to the innovative and novel nature of the UAM paradigm and the many challenges that need to be addressed. However, as the domains are highly interlinked, a singular focus on one domain may miss potential cross effects from the other domains. Therein lies the challenge of UAM, that a holistic view is required, even if the focus is on a single constituent system.

State of the art

Simulations are often employed to analyze specific UAM components, and can be found in the literature of various domains. The studies vary from those using simulations to evaluate trajectories in UAM operations [154], to assess the level of service in vertiport airside operations [125], to derive top-level aircraft requirements from an operator perspective [91, 155], to estimate demand for UAM in the transport network [156], and more. In doing so, these studies tend to emphasize isolated constituent systems. However, the focus on a single system usually comes at the often necessary expense of modeling fidelity of the other constituent systems, as the time and computing cost increases significantly with the number of models to be developed and their fidelities. This is challenging in a UAM SoS that relies on close integration of the systems. While analyzing a constituent system on its own has its merits and allows for significant insight to be derived, as can be seen in the literature, it may not capture cross effects from or to other constituent systems. As a high level of interconnectivity is required for the functioning of UAM, it is advantageous to consider its other constituent systems when designing a UAM system. Modeling all domains of UAM in one work may not be feasible for one person, however, it can be achieved through collaboration across people and domains.

Since UAM is currently subject to significant uncertainty due to its early stage of development, integrated modeling of the UAM system of systems can serve as a powerful tool for understanding and reducing uncertainty. In doing so, uncertainties associated with any one of the systems can be evaluated in considering their impact on other constituent systems and the overall SoS.

DLR approach and results

To understand and evaluate the systems of a UAM SoS and their interdependencies, a collaborative agent-based simulation of urban air mobility was developed within the HorizonUAM project. In this context, models for the air-side operation of the vertidrome [125], urban airspace management, passenger demand and mode choice estimation, vehicle operator costs and revenues [58], vehicle allocation [122], fleet management based on vehicle design performance, and mission planning were integrated into an agent-based simulation of urban air mobility [157]. The developed collaborative simulation follows a concept of operations that considers a Mobility as a Service (MaaS) Provider acting as the interface between the passengers and the other service provider. The MaaS provider offers several travel options composed of car and UAM flight legs to the passenger's travel request after coordinating with the UAM Vehicle Operator, which in turn coordinates with the ATM/UTM and Vertiport Operators to find a suitable flight path and FATOs, respectively. The collaborative simulation models the UAM SoS from flight request to flight fulfillment over the course of the day for thousands of potential passengers. The collaborative simulation is capable of simulating any combination of vertiport placements, vehicle concepts, fleet combinations, multiple airspace management techniques, vertiport layouts, and demand patterns. Although the focus of the development of the simulation was an intra-city use case centered in Hamburg, the use case or region can be flexibly changed given the required inputs.

The flight request processing logic of the collaborative simulation is as follows: for each flight request received, it is first assessed whether the request can be allocated to an existing scheduled flight. If this is not possible under the defined criteria, a new flight must be scheduled. The flight scheduling process consists of first selecting a vehicle from the fleet considering its position, available energy and availability; computing departure and arrival slots and a deconflicted flight trajectory. The flight information and ticket price alongside alternate mode options are then passed on to the mode choice model for the passenger's final decision. If UAM is chosen by the passenger, their seat on the flight is fixed, and if not, the seat (and potentially the flight) is not fixed.

The integration of the individual modules (or constituent systems) into the agent-based simulation was achieved through the use of the Remote Component Environment (RCE) [158, 159], which served the crucial function of seamlessly connecting the models hosted across several cities and institutes. By modeling the key subsystems involved in UAM, and simulating over the course of hours/days, the influence of subsystem level parameters on the overall network can be analyzed. The integration and orchestration of closed models located at different sites within an agent-based simulation, thereby constituting a collaborative system of systems simulation, was demonstrated within the HorizonUAM project and the process of implementation, performance optimization and proof of concept is presented in [153].

Conclusion

Such a comprehensive approach allows to capture the multi-layered interactions and interdependencies within the UAM ecosystem. By taking a holistic view it is possible to understand and assess the challenges, opportunities and potential of UAM to support the effective integration and sustainable success of urban air mobility as a new mode of transportation.

In this project, it has been demonstrated that a collaborative simulation can be built integrating closed-source geographically-distributed tools that bring together experts from different domains on a single platform. The developed collaborative simulation allows studies in any of the participating domains to be performed while capturing cross-domain effects and without compromising the modeling fidelity of the other domains.

Furthermore, such an approach can also allow the combined optimization of the individual constituent systems and the overall system of systems.

In future work, specific studies from the involved domains of the collaborative simulation will be presented. In addition, aforementioned cross-domain effects will be demonstrated to show the advantage of the developed collaborative simulation. Furthermore, optimization as mentioned above may be another avenue of research.

5 Summary and conclusion

For UAM to become reality, it needs to be socially accepted in the broadest sense. Here, acceptance includes aspects of socio-political acceptance, community acceptance and market acceptance. Thus, UAM has to meet the expectations of all UAM stakeholders such as potential users, industry, governments, public institutions, regulators and indirectly affected third parties, reconciling their own motivations, expectations and concerns. For this, the UAM system needs to be designed in a way that promotes benefits and minimizes risks, so that UAM as part of the future urban transportation system is safe, affordable, accessible, environmentally friendly, economically viable and finally sustainable.

To optimize the UAM system with regard to the desired characteristics, it has to be considered as a highly complex system-of-systems, where the overall system performance results from the interaction of its components. Not only the individual system components should be optimized. A holistic view on the overall UAM system considering the interaction between the individual components is mandatory.

Many stakeholders are working to make UAM become reality. The industry has demonstrated eVTOL flights in urban environments on several occasions, most recently in New York City [160]. Aviation authorities such as the European Union Aviation Safety Agency (EASA) or the Federal Aviation Administration (FAA) are working on a regulatory framework to enable the deployment and implementation of UAM. Based on information provided by aircraft manufacturers, many air taxi models could enter service in the next few years [54]. In parallel, government authorities in several countries have developed or are developing strategies to support the market introduction of AAM and its integration into the overall transportation system, e.g., in Europe, the US, and Japan. Local authorities are working with industry to implement UAM services in the coming years. All of these activities demonstrate a common interest in UAM. But despite all this activity, it is still uncertain to what extent the vision of UAM as a means of mass transportation can be realized. On the one hand, there are technical challenges to be overcome to scale up UAM. On the other hand, there are doubts that the cost of using UAM will be low enough to make UAM an affordable form of everyday transportation for the masses [37, 161]. Finally, lack of social acceptance can be a massive barrier, as the example of Paris shows: the planned launch of commercial flights by Volocopter and Groupe ADP on the occasion of the 2024 Olympic Games was opposed by the Paris City Council. Criticism focuses on noise pollution, energy consumption and the high price of a flight [11].

The DLR project HorizonUAM has contributed to both aspects of UAM research, the development of individual components as well as their harmonization for use in an optimized overall system, by combining research on UAM vehicles, related infrastructure, operation of UAM services, and public acceptance of future urban air transport. In particular, the complexity of Urban Air Mobility with its interdependencies has been addressed by the project.

Key results of HorizonUAM are:

- A simplified model-based estimation, taking into account size and wealth of cities, shows that in 2050 there could be high market potential for UAM in more than 200 cities worldwide if air taxi prices are low enough and the density of airports is high (fare below 3 €/km and vertiport density about 1 vertiport per 50 square kilometer according to our model calculation). Among these cities are international metropole regions such as London, Tokyo, or New York but also major German regions like the Rhine-Ruhr region, Berlin, Munich or Hamburg. Future research should also include regional operations.
- Making UAM affordable through low operating costs is a challenge. Current estimates of the air taxi price suggest, that under realistic conditions fares would need to be significantly higher than 4.10 €/km. However, cost and fare estimates are subject to uncertainty, as many UAM components and their costs have not yet been fully elaborated.
- Passengers' and pedestrians' perspective on UAM and attitude of the German population were evaluated to assess acceptance of UAM by users and non-users. The German population is currently undecided about UAM. Answers regarding the attitude towards air taxis ranged from very negative to very positive. Acceptance was highest for use cases including rural areas. Further research should also be dedicated to the design of human–machine-interfaces for passenger of vehicles without pilot on board.
- Models from different domains were integrated to a system-of-system simulation suitable for the analysis of UAM systems. Here, tools for vertidrome assessment, vertidrome airspace network and fleet management optimization go in hand with tools for demand estimation, cost and revenue estimation, and mode choice and vehicle design.
- Vehicle concepts suitable for intra-city and sub-urban use cases were designed. A quadrotor configuration was suggested for ranges up to 50 km and a tiltrotor configuration for longer ranges up to 100 km.
- A Drone Communications and Surveillance Technology (DroneCAST) was developed to enable drone-to-drone communications for collision avoidance in urban airspace.
- A Safe Operation Monitor was developed to address certification aspects of machine learning for improving the reliability and trustworthiness of artificial intelligence functions.
- A Vertidrome Level of Service framework was established that is suitable to rate vertidrome airside operations unifying multidisciplinary stakeholders.
- Vertidrome integration into airport environment and thus controlled airspace was assessed with air traffic controllers and revealed the limitations in runway capacity and acceptable workload. An exclusive air taxi working position and further automation of processes is recommended. The establishment of scalable U-space services for traffic management of drones as well as passenger carrying air taxis is key to solve these issues.

- A modular model city was erected as a scaled environment for demonstration of airspace integration, vertidrome management, artificial intelligence functions, and urban communication and navigation. This model city is flexible in design and available for future UAM evaluations and demonstrations.

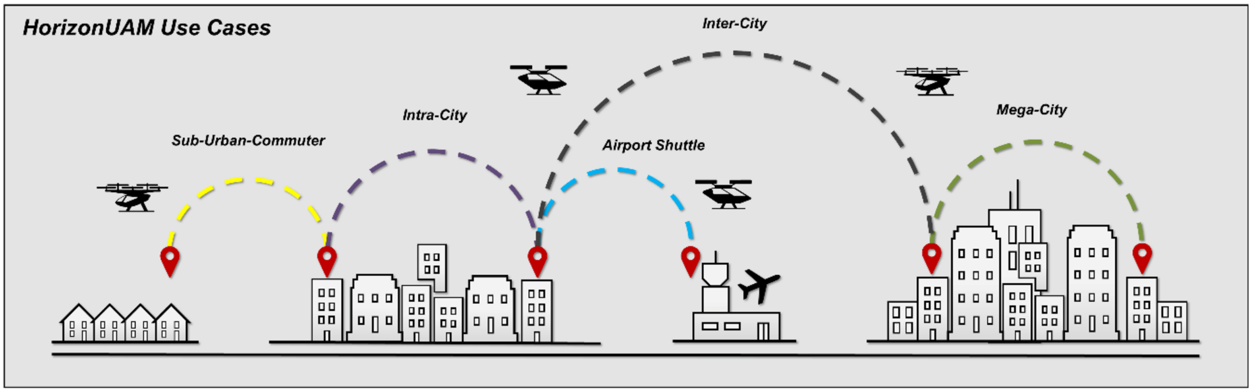
The results of HorizonUAM indicate that UAM could become technically feasible in the near future. However, the following key challenges need to be addressed before UAM can be widely implemented:

- Profitability: for their widespread adoption and acceptance by users, manufacturers and investors, it is essential to ensure that air taxi services are economically viable even with low ticket prices. This requires to minimize direct and indirect operating costs of the UAM transportation system. Suitable business models need to evolve for UAM to become more than a niche market. The evolving regulatory framework for UAM needs to be matured and harmonized internationally to ensure safety, security, and environmental sustainability but also scalability to make UAM financially feasible.
- Complexity of the UAM system: managing complexity and filling existing knowledge gaps to remove uncertainties is necessary to achieve high efficiency of the UAM system. This results in a complicated distribution of responsibilities among UAM stakeholders including users, industry, governments, public institutions, regulators and communities. All of these stakeholders must work together to shape the transportation system of the future. In particular, the interactions of the individual UAM system components, its interdependencies and the effects on the feasibility of the overall transportation system need to be further investigated to develop an economically viable and scalable UAM system that maximizes the benefits not only for the users but the society in general.
- Social acceptance and in particular community acceptance: acceptance may be one of the critical factors in UAM implementation in many societies. Appropriate measures will need to be taken to address the key concerns of noise, actual and perceived safety and security, high energy consumption, visual pollution and land use. In order to offer seamless transportation, the integration of UAM into existing transportation networks is essential and can improve the efficiency of the overall transportation system with benefits for users and society. It is of highest importance to keep the general public informed about urban air mobility and its implications. Communities have to be actively engaged in the design of a potential future transportation system to make it a success. Therefore, information based on scientific analysis but tailored towards a non-scientific audience should be provided by the UAM community. Real live demonstrations are recommended to increase the familiarity with UAM in the general public.

In conclusion, it has been shown that UAM might complement existing transportation systems in the future. Ultimately, it is a matter of the constituent systems working together in a way that the overall system is both economically feasible and socially acceptable.

DLR will continue to work on the idea of Urban Air Mobility. Future research will be extended by considering new multimodal and regional use cases. Thus, the initial urban scope will be extended to evolve form Urban Air Mobility over Advanced Air Mobility to Innovative Air Mobility with the overall goal of integrating drone and air taxi services into existing transportation systems.

Appendix A—HorizonUAM Use Cases and Technology Scenarios



Use Cases

Intra-City Use Case

- *Transport range:* up to 50 km
- *Speed:* up to 100 km/h
- *Seats:* up to 4

- Flights on-demand within core areas and built-up urban areas of cities in Germany
- High traffic density and flights in urban environments over short distances
- Flight mission with up to two intermediate stops without need for recharging

Mega-City Use Case

- *Transport range:* up to 100 km
- *Speed:* up to 150 km/h
- *Seats:* up to 6

- Flights on-demand within core areas and built-up urban areas of global mega-cities
- High traffic density and flights in urban environments over large distances
- Flight mission with no or one intermediate stop without need for recharging

Airport Shuttle Use Case

- *Transport range:* up to 30 km
- *Speed:* up to 150 km/h
- *Seats:* up to 4

- Scheduled flights between airports and selected locations (e.g. city center, CBD)
- Vehicle with higher payload capacity and space to store luggage
- Flight mission between two vertiports with charging capability after each flight

Suburban-Commuter Use Case

- *Transport range:* up to 70 km
- *Speed:* up to 150 km/h
- *Seats:* up to 4

- Scheduled flights between suburbs / surrounding satellite cities and the city center
- Economically challenging due to high peak demand and low off-peak demand
- Flight mission between two vertiports with charging capability after each flight

Inter-City

- *Transport range:* over 100 km
- *Speed:* over 100 km/h
- *Seats:* up to 10

- Scheduled flights between two cities
- Vehicle for long distance flights with high comfort for passengers
- Flight mission between two vertiports with charging capability after each flight

Technology Scenarios

	2025	2050
Propulsion technology	*Fully electric or hybrid electric based on conventional fuels*	*Fully electric or hybrid electric, also hydrogen-based*
Level of autonomy	*Onboard-Pilot / Remote-Pilot**	*Highly automated to autonomous*
U-space Service Level	*U-space Service Level U1 (first U-space services)*	*U-space service Level U2-U3 (advanced U-space services)*
Communication	*Multilink communications approach relying on existing comm. infrastructure*	*Multilink communications approach with specifically designed datalink*
Navigation	*GNSS and supporting multi-sensor navigation*	*Certified multi-sensor navigation including GNSS*

* For the intra-city and mega-city use cases an onboard pilot is assumed, and for the use cases airport shuttle, suburban and intra city a remote pilot.

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Declarations

Conflict of interests Bianca I. Schuchardt is a guest editor of the CEAS Aeronautical Journal for the specialissue on the HorizonUAM project, but was not involved in the review of this manuscript. The other co-authorshave no competing interests to declare that are relevant to the content of this article.

References

1. EASA, Study on the societal acceptance of Urban Air Mobility in Europe. EASA (2021). https://www.easa.europa.eu/en/domains/drones-air-mobility/drones-air-mobility-landscape/urban-air-mobility-uam
2. Cohen, A.P., Shaheen, S.A., Farrar, E.M.: Urban air mobility: history, ecosystem, market potential, and challenges. IEEE Trans. Intell. Transp. Syst. **22**(9), 6074–6087 (2021). https://doi.org/10.1109/Tits.2021.3082767
3. Baur, S., et al.: Urban air mobility: the rise of a newmode of transportation. Roland Berger (2018). www.rolandberger.com
4. FAA, Advanced Air Mobility (AAM) Implementation Plan. FAA (2023). https://www.faa.gov/
5. EASA, Opinion No 03/2023, Introduction of a regulatory framework for the operation of drones (2023). https://www.easa.europa.eu/sk/document-library/opinions/opinion-no-032023
6. Scott, B.I., Andritsos, K.I.: A drone strategy 2.0 for a smart and sustainable unmanned aircraft eco-system in Europe. Air Space Law **48**(3), 273–296 (2023)
7. Garus, A., et al.: Impact of new mobility solutions on travel behaviour and its incorporation into travel demand models. J. Adv. Transp. (2022). https://doi.org/10.1155/2022/7293909
8. Holden, J., Goel, N.: Uber-Elevate: Fast-Forwarding to a Future of On-Demand Urban Air Transportation. Uber (2016)
9. Seeley, B.A.: Regional sky transit. In: 15th AIAA Aviation Technology, Integration, and Operations Conference. 2015. https://sustainableaviation.org/RST/papers/Regional.Sky.Transit.Seeley.Final.pdf
10. Volocopter, www.volocopter.com 2021
11. The Local France, Paris's Olympic flying taxi plans hit city council setback. 2023. https://www.thelocal.fr/20231115/pariss-olympic-flying-taxi-plans-hit-city-council-setback
12. MIT Flight Transportation Laboratory, Concepts studies for future intracity air transportation systems. 1970, Massachusetts Institute of Technology, Department of Aeronautics and Astronautics, Flight Transportation Laboratory. https://dspace.mit.edu/
13. Müller, W.: Historisches Luftfahrtarchiv der Stadt Köln. 2023. http://www.luftfahrtarchiv-koeln.de/
14. Ashpole, W.: *Gatwick/Heathrow Airlink 1978–1986*. 2023 [cited 2023 19.09.]; https://www.ashpole.org.uk/gatwickheathrow-airlink-2/.
15. Plötner, K., Kaiser, J.: Urban Air Mobility: Von der Nische hin zum Massenmarkt? Luft- und Raumfahrt, 2019. 1/2019
16. Vascik, P.D.: Systems-level analysis of On Demand Mobility for aviation. Massachusetts Institute of Technology (2017)
17. BLADE, Urban Air Mobility Fly the future, today. (2023). https://www.blade.com/
18. The Port Authority of New York and New Jersey, John F. Kennedy International Airport: Taxi, Car, and Van Service. 2023. https://www.jfkairport.com/to-from-airport/taxi-car-and-van-service
19. Goyal, R., et al.: UAM Market Study - Technical Out Brief. 2018, Booz Allen Hamilton, NASA. https://ntrs.nasa.gov/citations/20190000517
20. Asmer, L., et al.: Urban air mobility use cases and technology scenarios for the HorizonUAM project. In: AIAA Aviation 2021 Forum (2021)
21. Grandl, G., et al.: The future of vertical mobility. A porsche consulting study (2018). https://www.porsche-consulting.com.
22. EASA, MOC SC VTOL: Second Publication of Proposed Means of Compliance with the Special Condition VTOL. EASA (2021). https://www.easa.europa.eu/en/domains/drones-air-mobility/drones-air-mobility-landscape/urban-air-mobility-uam
23. Goyal, R., et al.: Urban Air Mobility (UAM) Market Study - Final Report. Booz Allen Hamilton, NASA (2018). https://ntrs.nasa.gov/citations/20190001472
24. Hasan, S.: Urban air mobility (UAM) market study. NASA (2019). https://ntrs.nasa.gov/citations/20190026762
25. NUAIR (Northeast UAS Airspace Integration Research Alliance, I., High-Density Automated Vertiport Concept of Operations. NASA (2021). https://ntrs.nasa.gov/citations/20210016168
26. Solanki, B., et al.: Federal aviation administration vertiport electrical infrastructure study, National Renewable Energy Laboratory (2023).www.nrel.gov/publications
27. Cesconetto, G.I.: AAM infrastructure: What are the differences between heliports and vertiports? (2022). https://canadianaam.com/2022/06/28/aam-infrastructure-what-are-the-differences-between-heliports-and-vertiports/
28. Taylor, M., Saldanli, A., Park, A.: Analysis of alternate vertiport designs. In: IEEE ICNS Conference 2020. 2020. Dulles Virginia (Virtual) DOI: https://doi.org/10.1109/ICNS50378.2020.9222989. https://catsr.vse.gmu.edu/pubs/IEEEConferencePaper_AnalysisAlternateVertiportDesignsICNS.pdf
29. EASA, Vertiports - Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category. EASA (2022). https://www.easa.europa.eu/en/document-library/general-publications/prototype-technical-design-specifications-vertiports
30. Schweiger, K., Preis, L.: Urban air mobility: systematic review of scientific publications and regulations for vertiport design and operations. Drones (2022). https://doi.org/10.3390/drones6070179
31. Lineberger, R., et al.: Infrastructure barriers to the elevated future of mobility. In: Deloitte Series on the Future of Mobility. 2019, Deloitte
32. Johnston, T., Riedel, R., Sahdev, S.: To take off, flying vehicles first need places to land. In: McKinsey Center for Future Mobility. McKinsey (2020). https://www.mckinsey.com

33. Schweiger, K., Knabe, F., Korn, B.: An exemplary definition of a vertidrome's airside concept of operations. Aerosp. Sci. Technol. (2021). https://doi.org/10.1016/j.ast.2021.107144
34. Rothfeld, R., et al.: Potential urban air mobility travel time savings: an exploratory analysis of Munich, Paris, and San Francisco. Sustainability (2017). https://doi.org/10.3390/su13042217
35. Naser, F., Peinecke, N., Schuchardt, B.I.: Air taxis vs. taxicabs: a simulation study on the efficiency of UAM. In: AIAA: ARC (2021). https://doi.org/10.2514/6.2021-3202
36. Pukhova, A., et al.: Flying taxis revived: Can Urban air mobility reduce road congestion? J. Urban Mobility (2021). https://doi.org/10.1016/j.urbmob.2021.100002
37. Plötner, K., et al.: Putting Urban Air Mobility into perspective. Bauhaus Luftfahrt (2023)
38. Straubinger, A., et al.: Proposing a Scenario-based Estimation of Global Urban Air Mobility Demand. In: AIAA AVIATION 2021 FORUM. Virtual: AIAA. (2021). https://doi.org/10.2514/6.2021-3207
39. US Department of Transportation, AAM IWG Report to Congress. (2024). https://www.transportation.gov/aamiwg/report
40. Japan Ministry of Economy, T.a.I.M., Advanced Air Mobility in JAPAN 2021. (2021). https://www.mlit.go.jp/koku/content/Advanced_Air_Mobility_in_JAPAN_2021.pdf
41. Urban Air Mobility News, The global timetable for AAM and UAM launch and development. (2023). https://www.urbanairmobilitynews.com/sponsored-editorial-right-column/the-global-timetable-for-aam-and-uam-launch-and-development/
42. EASA, Introduction of a regulatory framework for the operation of drones (Notice of Proposed Amendment 2022–06). EASA. (2022). https://www.easa.europa.eu/
43. FAA, Urban Air Mobility (UAM): Concept of Operations. FAA (2023). https://www.faa.gov/
44. Wüstenhagen, R., Wolsink, M., Bürer, M.: Social acceptance of renewable energy innovation: an introduction to the concept. Energy Policy (2007). https://doi.org/10.1016/j.enpol.2006.12.001
45. UIC2 UAM Initiative Cities Community, EU's Smart Cities Marketplace: Urban Air Mobility and Sustainable Urban Mobility Planning – Practitioner Briefing. European Commission (2021)
46. Aerospace Security and Defence Industries Association of Europe (ASD), Urban Air Mobility and Sustainable Development. ASD (2023). www.asd-europe.org
47. Al Haddad, C., et al.: Factors affecting the adoption and use of urban air mobility. Transp. Res. Part A Policy Pract. **132**, 696–712 (2020). https://doi.org/10.1016/j.tra.2019.12.020
48. Stolz, M., Laudien, T., Assessing social acceptance of urban air mobility using virtual reality. In: Digital Avionics Systems Conference (DASC).: Portsmouth. USA (2022). https://doi.org/10.1109/DASC55683.2022.9925775
49. EASA, Commission Implementing Regulation (EU) 2021/664 of 22 April 2021 on a regulatory framework for the U-space. (2021)
50. International Transport Forum (ITF), Ready for Take-Off? Integrating Drones into the Transport System. In: *ITF Research Reports, OECD Publishing*. OECD, Paris (2021)
51. Straubinger, A., et al.: An overview of current research and developments in urban air mobility–setting the scene for UAM introduction. J. Air Transp. Manag. **87**, 101852 (2020). https://doi.org/10.1016/j.jairtraman.2020.101852
52. Stelkens-Kobsch, T.H., Predescu, A.V.: Contribution to a secure urban air mobility. In: 2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC) (2022). https://doi.org/10.1109/DASC55683.2022.9925845
53. Leipold, A., et al.: DEPA 2050 – Development Pathways for Aviation up to 2050 (Final Report). DLR (2021). https://www.dlr.de/en/media/publications/miscellaneous/2021/dlr-study-depa-2050
54. International Forum for Aviation Research, Scientific Assessment for Urban Air Mobility. IFAR (2023). https://ifar.aero/
55. K. Schweiger, R. Schmitz, Knabe, F.: Impact of wind on eVTOL operations and implications for vertiport airside traffic flows: a case study of Hamburg and Munich. Drones, vol. 7, p. 464 (2023). https://doi.org/10.3390/drones7070464
56. Gerz, T.: Beschreibung der meteorologischen Rahmenbedingungen. In: Horizon UAM Projektbericht, Meilensteinbericht MST 1.5.1. 2023, DLR
57. Cohen, A.P., Shaheen, S.A., Farrar, E.M.: Urban air mobility: history, ecosystem, market potential, and challenges. IEEE Trans. Intell. Transp. Syst. (2021). https://doi.org/10.1109/Tits.2021.3082767.p.6074-6087
58. Pertz, J., et al.: Estimating the economic viability of advanced air mobility use cases: towards the slope of enlightenment. Drones **7**(2), 75 (2023). https://doi.org/10.3390/drones7020075
59. Vascik, P.D., Hansman, R.J.: Evaluation of key operational constraints affecting on-demand mobility for aviation in the Los Angeles basin: ground infrastructure, air traffic control and noise. In: 17th AIAA Aviation Technology, Integration, and Operations Conference (2017)
60. Straubinger, A., Michelmann, J., Biehle, T.: Business model options for passenger urban air mobility. CEAS Aeronaut. J. **12**(2), 361–380 (2021). https://doi.org/10.1007/s13272-021-00514-w
61. Vascik, P.D., Systems analysis of urban air mobility operational scaling. Massachusetts Institute of Technology (2020)
62. Kallies, C., et al.: Development and evaluation of a U-space route structure for the city of Frankfurt connecting airport and trade fair via fast-time simulation. In: Integrated Communication, Navigation and Surveillance Conference (ICNS) (2023). https://doi.org/10.1109/ICNS58246.2023.10124254
63. Taylor, M., Saldanli, A., Park, A.: Design of a vertiport design tool. In: Integrated Communications, Navigation and Surveillance Conference, ICNS. IEEE, Herndon, VA, USA (2020). https://doi.org/10.1109/ICNS50378.2020.9222989
64. Seeley, B.A.: Regional Sky Transit II. In: 16th AIAA Aviation Technology, Integration, and Operations Conference (2016). https://sustainableaviation.org/RST/papers/Regional.Sky.Transit.II.Seeley.Final.pdf
65. Umweltbundesamt (UBA), Sustainable mobility. (2022). https://www.umweltbundesamt.de/en/topics/transport/sustainable-mobility
66. Vascik, P.D., Hansman, R.J.: Systems-level analysis of On Demand Mobility for aviation. Massachusetts Institute of Technology (2017)
67. Hagag, N., Hoeveler, B.: The feasibility of electric air taxis: balancing time savings and CO_2 emissions - A joint case study of respective plans in Paris. CEAS Aeronaut. J. (2024) (under review)
68. Donateo, T., Ficarella, A., Surdo, L.: Energy consumption and environmental impact of Urban Air Mobility. In: IOP Conf. Series: Materials Science and Engineering. 2022. https://doi.org/10.1088/1757-899X/1226/1/012065
69. Filippone, A.: Aircraft noise prediction. Prog. Aerosp. Sci. **68**, 27–63 (2014). https://doi.org/10.1016/j.paerosci.2014.02.001
70. Schuchardt, B.I., et al.: Urban Air Mobility Research at the DLR German Aerospace Center - Getting the Horizon UAM Project started. In: *AIAA Aviation Forum* (2021)
71. Asmer, L., et al.: Urban Air Mobility Use Cases, Missions and Technology Scenarios for the HorizonUAM Project. In: AIAA Aviation 2021 Forum, 2–6 August 2021, Virtual. (2021). https://doi.org/10.2514/6.2021-3198.

72. Asmer, L., et al.: A city-centric approach to estimate and evaluate global Urban Air Mobility demand. CEAS Aeronaut. J. (2024) (under review)
73. Mayakonda, M., et al.: A Top-Down Methodology for Global Urban Air Mobility Demand Estimation. In: AIAA Aviation 2020 Forum. (2020). https://doi.org/10.2514/6.2020-3255
74. Anand, A., et al.: A Scenario-Based Evaluation of Global Urban Air Mobility Demand. In: AIAA Scitech 2021 Forum. (2021). https://doi.org/10.2514/6.2021-1516
75. Brauchle, A., et al.: Business between Sky and Earth - Assessing the Market Potential of Mobility in the 3rd Dimension. (2019). www.horvath-partners.com
76. End, A., et al.: Public Acceptance of Civilian Drones and Air Taxis in Germany: a comprehensive Overview. CEAS Aeronaut. J. (2024) (under review)
77. Eißfeldt, H., et al.: The acceptance of civil drones in Germany. CEAS Aeronaut. J. **11**, 665–676 (2020). https://doi.org/10.1007/s13272-020-00447-w
78. Aalmoes, R., Sieben, N., Visual and audio perception study on drone aircraft and similar sounds in an Urban Air Mobility setting. In: Inter Noise. Institute of Noise Control Engineering (2021). https://doi.org/10.3397/IN-2021-2160. https://www.semanticscholar.org/paper/Visual-and-audio-perception-study-on-drone-aircraft-Aalmoes-Sieben/cc69d9748c801afac809fd65606888b49fe94b92
79. Aalmoes, R., Bruijn, B.D., Sieben, N.: The Influence of Contextual Non-Auditory Factors on Drone Sound Perception. Institute of Noise Control Engineering (2023). https://doi.org/10.3397/NC_2023_01_1105, https://www.semanticscholar.org/paper/The-Influence-of-Contextual-Non-Auditory-Factors-on-Aalmoes-Bruijn/9d3688b382ccb145113b0333a37a223e31d28890
80. Stolz, M., Laudien, T.: Assessing social acceptance of Urban Air Mobility using Virtual Reality. In: *EEE/AIAA 41st Digital Avionics Systems Conference (DASC)*. IEEE, pp 1–9 (2022). https://doi.org/10.1109/DASC55683.2022.9925775
81. Papenfuß, A., et al.: Experiencing Urban Air Mobility: How Passengers Evaluate a Simulated Flight with an Air Taxi. CEAS Aeronaut J (2024) (under review)
82. Reimer, F., et al.: Applied design thinking in Urban Air Mobility: creating the airtaxi cabin design of the future from a user perspective. CEAS Aeronaut. J. (2024) (under review))
83. Eißfeldt, H.: Sustainable urban air mobility supported with participatory noise sensing. Sustainability **12**(8), 3320 (2020). https://doi.org/10.3390/su12083320
84. Johnson, W., Silva, C.: NASA concept vehicles and the engineering of advanced air mobility aircraft. Aeronaut. J. **126**(1295), 59–69 (2022). https://doi.org/10.1017/aer.2021.92
85. Brown, A., Harris, W.L.: Vehicle design and optimization model for urban air mobility. J. Aircr. **57**(6), 1003–1013 (2020). https://doi.org/10.2514/1.C035756
86. Clarke, M.A., Alonso, J.J.: Evaluating the Performance and Acoustic Footprint of Aircraft for Regional and Urban Air Mobility. In: AIAA Aviation 2021 Forum. 2021. August 2–6, Virtual (2021). https://doi.org/10.2514/6.2021-3205
87. Kohlman, L.W., Patterson, M.D., Raabe, B.E.: Urban Air Mobility Network and Vehicle Type—Modeling and Assessment, NASA, (2019). https://ntrs.nasa.gov/citations/20190001282
88. Sells, B.E., Crossley, W.A.: Exploring vehicle and fleet design spaces for profitable urban air mobility operations. In: AIAA Aviation Forum.: Chicago. IL, USA & Virtual (2022). https://doi.org/10.2514/6.2022-3486
89. Husemann, M., Kirste, A., Stumpf, E.: Analysis of cost-efficient urban air mobility systems: optimization of operational and configurational fleet decisions. Eur. J. Oper. Res. (2023). https://doi.org/10.1016/j.ejor.2023.04.040
90. Kilkis, S., Prakasha, P.S., Naeem, N. and Nagel, B.: A python modelling and simulation toolkit for rapid development of system of systems inverse design (SoSID) case studies. In: AIAA Aviation (2021). https://doi.org/10.2514/6.2021-3000
91. Prakasha, P.S., et al.: Aircraft architecture and fleet assessment framework for urban air mobility using a system of systems approach. Aerosp. Sci. Technol. (2022). https://doi.org/10.1016/j.ast.2021.107072
92. Prakasha, P.S., et al.: System of systems simulation driven urban air mobility vehicle design and fleet assessment. In: AIAA Aviation 2021 Forum, 2–6 August 2021, Virtual. (2021). https://doi.org/10.2514/6.2021-3200
93. Prakasha, P.S., et al.: Urban Air Mobility Vehicle and Fleet-level Life-Cycle Assessment Using a System-of-Systems Approach. In: AIAA Aviation 2021 Forum, 2–6 August 2021, Virtual. (2021). https://doi.org/10.2514/6.2021-2457
94. Ratei, P.: Development of a Vertical Take-Off and Landing Aircraft Design Tool for the Application in a System of Systems Simulation Framework. 2022, Hamburg University of Applied Sciences (HAW Hamburg): DLR report. DLR-IB-SL-HF-2022–66
95. Edge, J.S., et al.: Lithium ion battery degradation: what you need to know. Phys. Chem. Chem. Phys. **23**(14), 8200–8221. (2021). https://doi.org/10.1039/d1cp00359c
96. Reniers, J.M., Mulder, G., Howey, D.A.: Review and performance comparison of mechanical-chemical degradation models for lithium-ion batteries. J. Electrochem. Soc. **166**(14), A3189–A3200 (2019). https://doi.org/10.1149/2.0281914jes
97. Birkl, C.R., et al.: Degradation diagnostics for lithium ion cells. J. Power. Sources **341**, 373–386 (2017). https://doi.org/10.1016/j.jpowsour.2016.12.011
98. Xu, B., et al.: Modeling of lithium-ion battery degradation for cell life assessment. IEEE Trans. Smart Grid **9**(2), 1131–1140 (2016). https://doi.org/10.1109/TSG.2016.2578950
99. Schmalstieg, J., et al.: A holistic aging model for Li(NiMnCo)O_2 based 18650 lithium-ion batteries. J. Power. Sources **257**, 325–334 (2014). https://doi.org/10.1016/j.jpowsour.2014.02.012
100. Liu, K., et al.: A data-driven approach with uncertainty quantification for predicting future capacities and remaining useful life of lithium-ion battery. IEEE Trans. Industr. Electron. **68**(4), 3170–3180 (2021). https://doi.org/10.1109/TIE.2020.2973876
101. Li, Yi., et al.: Data-driven health estimation and lifetime prediction of lithium-ion batteries: A review. Renew. Sustain. Energy Rev. **113**, 2019 (2019). https://doi.org/10.1016/j.rser.2019.109254
102. Preger, Y.: Degradation of Commerical Li-ion Cells beyond 80% Capacity. In: Battery Safety Council Forum 8 (2019)
103. Rosenberg, J.: Modellierung, Simulation und Analyse des thermischen Verhaltens von elektrischen Energiequellen für neuartige eVTOL-Konzepte. TU Braunschweig, DLR: Braunschweig (2021)
104. Sieb, P., et al.: Heuristic Approach for Aircraft Assignment and Maintenance Scheduling of On-demand Urban Air Mobility Vehicles. In: AIAA AVIATION 2023 Forum. San Diego, CA and Online: American Institute of Aeronautics and Astronautics (Reston, Virginia) (2023)
105. Sieb, P., et al.: Identifying challenges in maintenance planning for on-demand UAM fleets using agent-based simulations. CEAS Aeronaut. J. **14**(3), 637–660 (2022). https://doi.org/10.1007/s13272-023-00665-y
106. Clarke, M.A., Alonso, J.J.: Forecasting the operational lifetime of battery-powered electric aircraft. J. Aircr. (2023). https://doi.org/10.2514/1.C036851
107. Jäger, F., et al.: Battery-Electric Powertrain System Design for the HorizonUAM Multirotor Air Taxi Concept. CEAS Aeronaut. J. (2024) (under review)

108. EASA, Special Condition Vertical Take-Off and Landing (VTOL) Aircraft. EASA (2019). https://www.easa.europa.eu
109. Darmstadt, P.R., et al.: Hazards analysis and failure modes and effects criticality analysis (fmeca) of four concept vehicle propulsion systems. NASA (2019). http://ntrs.nasa.gov/
110. Darmstadt, P.R., et al.: Reliability and Safety Assessment of Urban Air Mobility Concept Vehicles. NASA (2021). https://ntrs.nasa.gov/citations/20210017185
111. SAE, Guidelines for Development of Civil Aircraft and Systems (ARP4754A). (2010). https://www.sae.org/standards/content/arp4754a/
112. SAE, ARP4761: Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment. (1996)
113. Reimer, F., et al.: Safety & Privacy in Urban Air Mobility (UAM) – A User Centric Design Approach Providing Insights into People´s Preferences for UAM Cabin Designs. In: 13th International Conference on Applied Human Factors and Ergonomics (AHFE Conference). New York City (2022). https://doi.org/10.54941/ahfe1002494
114. Shanks, M.: An Introduction in Design Thinking Process Guide, Stanford. (2010). https://web.stanford.edu/~mshanks/MichaelShanks/files/509554.pdf
115. Potsdam, H.P.I.U., Die sechs Schritte im Design Thinking Innovationsprozess. [24.01.2024]. https://hpi.de/school-of-design-thinking/design-thinking/hintergrund/design-thinking-prozess.html
116. Buhrmester, M.: Design Thinking – die neue alte Kreativität. (2016). https://www.uid.com/de/aktuelles/hcd-design-thinking
117. Everand.com, Design thinking as a Strategy for Innovation. (2019). https://de.everand.com/article/450374892/Design-Thinking-As-A-Strategy-For-Innovation.
118. Ernst, J.M., Laudien, T., Lenz, H.: How Does it Feel to Fly in an Air Taxi? – Exploring Modern Head-Mounted Display Capabilities for Mixed Reality Flight Simulation. CEAS Aeronaut. J. (2024) (under review)
119. Loft Dynamics, About the Robinson R22 FSTD. (2023). https://www.loftdynamics.com/flight-training-solutions/products/r22-simulator/
120. Schweiger, K., et al.: HorizonUAM: Operational Challenges and Necessary Frameworks to Ensure Safe and Efficient Vertidrome Operations. CEAS Aeronaut. J. (2024) (under review)
121. Schier-Morgenthal, S., Metz, I.C.: Impact of Airtaxi operations in the controle zone of air traffic controllers. CEAS Aeronaut. J. (2024) (under review)
122. Swaid, M., et al.: Optimized capacity allocation in a UAM vertiport network utilizing efficient ride matching. In: AIAA Aviation 2023 Forum, Jun. (2023). https://doi.org/10.2514/6.2023-3577
123. Abdellaoui, R., et al.: Comparative Performance assessment of different Airspace Management Concepts for Urban Air Mobility. CEAS Aeronaut. J. (2024) (under review)
124. Schweiger, K., Knabe, F., Korn, B.: Urban Air Mobility: Vertidrome Airside Level of Service Concept. In: AIAA AVIATION 2021 FORUM. VIRTUAL EVENT: American Institute of Aeronautics and Astronautics (2021). https://doi.org/10.2514/6.2021-3201
125. Schweiger, K., Knabe, F.: Vertidrome Airside Level of Service: Performance-based Evaluation of Vertiport Airside Operations. MDPI Drones (under review)
126. Schuchardt, B.I., Devta, A., Volkert, A.: Integrating Vertidrome Management Tasks into U-space. CEAS Aeronaut. J. (2024) (under review)
127. Schuchardt, B.I., et al.: Air traffic management as a vital part of urban air mobility - A review of DLR's research work from 1995 to 2022. Aerospace **10**(1), 81 (2023). https://doi.org/10.3390/aerospace10010081
128. European Commission, Commission implementing regulation (eu) 2021/664 of 22 april 2021 on a regulatory framework for the u-space. (2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R0664
129. European Commission, Concept Of Operations For European U-Space Services - Extension For Urban Air Mobility. European Commission (2022). https://cordis.europa.eu/ DOI: https://doi.org/10.3030/101017682
130. European Commission, Tactical Instrumental Deconfliction and in flight Resolution. European Commission (2020). https://cordis.europa.eu/, https://doi.org/10.3030/101017677
131. European Commission, PJ34-W3 AURA "ATM U-SPACE INTERFACE". European Commission (2020). https://cordis.europa.eu/, https://doi.org/10.3030/101017521
132. CORUS-XUAM, U-space Concept of Operations (ConOps), Fourth Edition, SESAR JU. (2023). https://www.sesarju.eu/
133. European Commission, European Key solutions for vertiports and UAM. (2023). https://cordis.europa.eu/, https://doi.org/10.3030/101114799.
134. Torens, C.: Runtime-monitoring of operational design domain to safeguard machine learning components. CEAS Aeronaut. J. (2024) (under review)
135. EASA, Concept Paper: Guidance for Level 1 & 2 Machine Learning Applications. (2023). https://www.easa.europa.eu/en/newsroom-andevents/news/easa-artificial-intelligence-concept-paper-proposedissue-2-open
136. SAE International, SAE G-34, Artificial Intelligence in Aviation, "Artificial Intelligence in Aeronautical Systems: Statement of Concerns. SAE (2021). https://www.sae.org
137. Dmitriev, K., Schumann, J., Holzapfel, F.: Toward Design Assurance of Machine-Learning Airborne Systems. In: AIAA SCITECH 2022 Forum. San Diego, CA & Virtual: ARC (2022). https://doi.org/10.2514/6.2022-1134
138. Cofer, D., et al.: Run-Time Assurance for Learning-Based Aircraft Taxiing. In: 2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC). IEEE, San Antonio, TX, USA (2020). https://doi.org/10.1109/DASC50938.2020.9256581
139. C. Torens, et al.: Machine Learning Verification and Safety for Unmanned Aircraft - A Literature Study. In: AIAA SCITECH Forum. AIAA, San Diego, CA, USA (2022). https://doi.org/10.2514/6.2022-1133
140. Torens, C., Durak, U., Dauer, J.C.: Guidelines and Regulatory Framework for Machine Learning in Aviation. In: AIAA SCITECH Forum. AIAA, San Diego, CA, USA (2022). https://doi.org/10.2514/6.2022-1132
141. M. Skoog, L. R. Hook, Ryan, W.: Leveraging ASTM Industry Standard F3269-17 for Providing Safe Operations of a Highly Autonomous Aircraft. In: IEEE Aerospace Conference. Big Sky, MT, USA (2020). https://doi.org/10.1109/AERO47225.2020.9172434
142. L. R. Hook, et al.: Certification Strategies Using Run-time Safety Assurance for Part 23 Autopilot Systems. In: IEEE Aerospace Conference. Big Sky, MT, USA (2016)
143. He, Y., Schumann, J., Statistical Analysis and Runtime Monitoring for an AI-based autonomous Centerline Tracking System. In: PHM Society Asia-Pacific Conference. Tokyo, Japan (2023). https://doi.org/10.36001/phmap.2023.v4i1.3738
144. ASTM, Standard Practice for Methods to Safely Bound Behavior of Aircraft Systems Containing Complex Functions Using Run-Time Assurance. (2021)
145. Zhu, C., Towards navigation system integrity for urban air mobility – concept design and preliminary validation. CEAS Aeronaut. J. (2024) (under review)
146. European Union Agency for the Space Programme (EUSPA), Report on aviation and drones. European Union Agency for the

Space Programme (EUSPA) (2023). http://www.euspa.europa.eu/
147. Radio Technical Commission for Aeronautics (RTCA), DO-397 guidance material: Navigation gaps for unmanned aircraft systems (UAS). Radio Technical Commission for Aeronautics (RTCA) (2022)
148. Becker, D., Schalk, L.M.: Towards robust and efficient communications for Urban Air Mobility. CEAS Aeronaut. J. (2024) (under review)
149. Lye, G.: EHang 216 flying taxi car testing in Bali this October, public use in 2022 2021. https://paultan.org/2021/09/06/indonesia-to-begin-testing-flying-taxis-in-bali-this-october/.
150. Garsten, E., Archer Electric VTOL Air Taxi Demo Passes Major Test. (2021). https://www.forbes.com/sites/edgarsten/2021/12/20/archer-air-taxi-demo-passes-major-test/
151. Goyal, R., et al.: Advanced air mobility: demand analysis and market potential of the airport shuttle and air taxi markets. Sustainability **13**(13), 7421 (2021). https://doi.org/10.3390/su13137421.
152. Rimjha, M., et al.: Commuter demand estimation and feasibility assessment for urban air mobility in Northern California. Transp. Res. Part A Policy Pract. **148**, 506–524 (2021). https://doi.org/10.1016/j.tra.2021.03.020
153. Naeem, N., et al.: A collaborative system of systems simulation of Urban Air Mobility. CEAS Aeronaut. J. (2024) (under review)
154. Pinto Neto, E.C., et al.: A trajectory evaluation platform for urban air mobility (UAM). IEEE Trans. Intell. Transp. Syst. **23**(7), 9136–9145 (2022). https://doi.org/10.1109/TITS.2021.3091411
155. Ratei, P., Naeem, N., Prakasha, P.S.: Development of an urban air mobility vehicle family concept by system of systems aircraft design and assessment. In: 12th EASN International Conference. IOP Publishing, Barcelona, Spain (2022). https://doi.org/10.1088/1742-6596/2526/1/012043.
156. Plötner, K.O., et al.: Long-term application potential of urban air mobility complementing public transport: an upper Bavaria example. CEAS Aeronaut. J. **11**, 991–1007 (2020). https://doi.org/10.1007/s13272-020-00468-5
157. Naeem, N., Ratei, P., Prakasha, P.S.: Modelling and simulation of urban air mobility: an extendable approach. J. Phys. Conf. Ser. **2526**(1), 012104 (2023). https://doi.org/10.1088/1742-6596/2526/1/012104
158. Boden, B., et al.: RCE: an integration environment for engineering and science. SoftwareX **15**, 100759 (2021). https://doi.org/10.1016/j.softx.2021.100759
159. Boden, B., et al.: RCE (10.0.0) 2019: Zenodo. https://doi.org/10.5281/zenodo.3691675
160. FlightGlobal, Joby and Volocopter fly air taxis in New York City. (2023). https://www.flightglobal.com/aerospace/joby-and-volocopter-fly-air-taxis-in-new-york-city/155818.article
161. Biehle, T.: Social sustainable urban air mobility in Europe. Sustainability **2022**, 14 (2022). https://doi.org/10.3390/su14159312