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Challenges in urban air mobility implementation: A comparative analysis of barriers in Germany and the United States

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ABSTRACT

Urban Air Mobility (UAM) is a transport system enabling the movement of people and goods within urban areas using electric vertical take-off and landing (eVTOL) aircraft. Nonetheless, this concept remains an emerging technology with various challenges that can hinder its implementation. This research introduces a Multi-Criteria Decision-Making (MCDM) framework to prioritize barriers to UAM implementation in Germany and the USA. We identify 26 barriers across technological, economic, social, environmental, and operational aspects through a comprehensive literature review and expert interviews. Using the Fuzzy Best-Worst Method (FBWM), we determine the weight of each barrier based on input from industry and academic experts in Germany and the USA. Our findings reveal that economic aspects pose the greatest challenge in Germany, followed by social, operational, technological, and environmental aspects. In the USA, operational aspects are the most significant, followed by technological, economic, social, and environmental aspects. The operational aspect shows the largest difference between the two countries, while the environmental aspect shows the least. Globally, the top three barriers in Germany are price affordability, investment uncertainty, and user acceptance concerns. In the USA, the top three barriers are airspace utilization challenges, remote/autonomous operations, and system safety and cybersecurity issues, which rank tenth, twelfth, and sixteenth, respectively, in Germany. We also discuss the potential implications of our findings, offering strategies to effectively address high-priority barriers.

1. Introduction

The idea of urban flying has already been realized through conventional helicopters in major metropolises. The use cases of business trips, airport shuttles, intercity transportation, and connections to suburbs have been found to be the most beneficial (Coppola et al., 2024a; Desai et al., 2021). In the past, Uber Copter operated a shuttle service in New York City between Manhattan and JFK Airport (2019–2020). As of 2024, this service is operated by Blade, connecting Manhattan with the airports of New York (JFK, EWR, LGA) (Blade, 2024). In São Paulo, Brazil (2016–2020) and Mexico City, Mexico (2018–2020), Voom operated intracity trips termed "helicopter hailing" (Al Haddad et al., 2020).

Urban Air Mobility (UAM) is an emerging concept in urban and suburban transportation of people and goods for short distances. In light of technological advances, the first demonstration flights with electric vertical take-off and landing (eVTOL) vehicles have already taken place in various global locations. For example, Volocopter has tested its crewed 2X vehicle in New York and Tampa (Florida, USA), Osaka and Hyogo, Japan, and Seoul, South Korea (Volocopter, 2023; Tampa International Airport, 2023; sUAS, 2023), thus raising expectations for a new transportation system that could address the ensuing issues of congestion and emissions due to increasing urbanization (Pukhova et al., 2021). Since 2024, the EHang EH216-S, which is the first certified pilotless passenger-carrying eVTOL (Global Times, 2024), has been conducting experimental services in Guangzhou, Hefei and Wencheng, China (Bovenizer, 2024). The 2026 Winter Olympic Games in Milan-Cortina, Italy, are planning UAM services to cope with the high number of visitors (Milan Airports, 2024). Interest in UAM is evident through investigations and market studies conducted in numerous cities worldwide, e.g., Seoul, Munich, Zurich, Los Angeles, Dallas, and San

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Francisco. In addition, many governments, intergovernmental organizations, and institutions are supporting the research and development of UAM (Brunelli et al., 2023).

While UAM can offer several opportunities in passenger transportation, it remains an emergent technology, and its adoption can be hampered by various barriers and challenges (Straubinger et al., 2020). These barriers can encompass technical, economic, social, environmental, and operational dimensions. Moreover, the perception and prioritization of these challenges can vary within different contexts and countries. Thus, conducting comprehensive research and comparative analysis is crucial to systematically identify and rank these barriers, especially in pioneering countries introducing UAMs. Such international comparisons and qualifications of barriers can guide policymakers and stakeholders in strategically allocating resources and efforts to address high-priority obstacles and expedite the adoption of UAM.

In this work, we develop a Multi-Criteria Decision-Making (MCDM) framework to study and explicitly prioritize obstacles to the introduction of UAM. This framework enriches the literature by providing a systematic tool that enables policymakers to make quantitative comparisons and rank barriers across multiple dimensions. Moreover, we explore the perspective of stakeholders in both Germany and the United States of America (USA), allowing for a comparative analysis of the prioritized obstacles in each context. These stakeholders include decision-makers from diverse backgrounds in the aerospace industry and government bodies, potential owners and operators of vehicles and infrastructures, as well as researchers in universities or think tanks in relevant fields. Germany and the USA were selected for this analysis due to their relatively advanced UAM ecosystems, the availability of relevant literature and case studies, and the pertinent social, economic, environmental, and regulatory differences between the two countries. Moreover, convenience sampling played a role, as existing contacts with research and industry were crucial for data collection.

The structure of our study is outlined as follows. Section 2 presents a thorough literature review that explores the barriers to the implementation of UAM. In Section 3, we outline our research methodology, detailing the MCDM process used to rank the identified barriers. Section 4 focuses on the results, offering an in-depth comparison of the rankings of barriers in both Germany and the USA. Lastly, Section 5 summarizes our key findings and suggests possible directions for future research.

2. Literature review: UAM barriers and MCDM applications

This section conducts a detailed literature review to recognize the potential barriers to the implementation of UAM. As illustrated in Table 1, these barriers are presented into five categories: technical, economic, social, environmental, and operational. A brief description of each barrier can be found in Table A1 (Appendix A). Furthermore, we review the application of MCDM methods, offering deeper insights into the approach used in our study. Finally, we highlight the research gaps identified in the literature and outline our work's contributions to addressing them.

2.1. Technical barriers

In this part, we discuss the technical challenges hampering the implementation of UAM. Relevant barriers may refer to the vehicle itself, the ground infrastructure, the communication with the vehicle, and the processes needed to produce the necessary equipment for the UAM ecosystem. One of the most critical barriers to scaling operations with eVTOLs could be their limited flight range due to battery capacity (Wu and Zhang, 2020). The current generation of rechargeable batteries provides only limited energy density, which could prevent a sufficient range for the desired missions (Ploetner et al., 2020). Moreover, the uncertainty in the development of new battery technologies extends to other aspects of UAM, e.g., the charging time could affect the size of vertiports, the number of vehicles needed, the number of pilots, and

Table 1
Related barriers to the implementation of UAM.

Category	Criteria	Reference
Technical	Limited range and battery capacity	Ploetner et al. (2020), Liu et al. (2021), Viswanathan et al. (2022), Qiao et al. (2023), Husemann et al. (2024)
	Challenges in remote or autonomous operations	Vempati et al. (2021), Mathur et al. (2019), Lineberger et al. (2018)
	System safety and (cyber) security issues	Kwon et al. (2022), Ertürk et al. (2020), Munir et al. (2023), Wei et al. (2023)
	Vertiport capacity and design limitations	Straubinger et al. (2020), Fu et al. (2022), Willey and Salmon (2021), Pons-Prats et al. (2022), Li (2023)
	Difficulties in scaling vehicle production	Afonso et al. (2021)
Economic	High capital cost	Experts
	Investment return uncertainty	Choi and Park (2022), Rimjha et al. (2021), Straubinger et al. (2021), Coppola et al. (2024b)
	Price affordability	Choi and Park (2022), Holden and Goel (2016), Coppola et al. (2024b)
	Lack of business models	Straubinger et al. (2021), Cohen et al. (2021)
	Insurance and liability challenges	Straubinger et al. (2020)
	Lack of financing options	Experts
	Operational and maintenance costs	Ploetner et al. (2020), Choi and Park (2022), Goyal et al. (2018), Qiao et al. (2023)
Social	User acceptance concerns	Al Haddad et al. (2020); Straubinger et al. (2020), Cohen et al. (2021), Vascik et al. (2018), Çetin et al. (2022), Vascik (2017), Johnson et al. (2022), Chan et al. (2025), Janotta and Hogreve (2024)
	Adverse impacts on non-users	Al Haddad et al. (2020); Straubinger et al. (2020), Cohen et al. (2021), Vascik et al. (2018), Lopes and Silva (2023), Pons-Prats et al. (2022), Yunus et al. (2023)
	Visual impact issues	Al Haddad et al. (2020), Cohen et al. (2021), Lopes and Silva (2023), Pons-Prats et al. (2022)
	Equity and welfare issues	Cohen et al. (2021), Biehle (2022), Straubinger et al. (2022)
Environmental	Material lifecycle issues	André and Hajek (2019), Kasliwal et al. (2019)
	Emissions due to power generation	Cohen et al. (2021), Zhao et al. (2022)
	Negative ecological impact	Experts
Operational	Airspace utilization and air traffic control challenges	Mathur et al. (2019), Straubinger et al. (2020), Cohen et al. (2021), Wang et al. (2021), Vascik and John Hansman (2021), Lineberger et al. (2018), Vascik et al. (2018), Song and Yeo (2021), Wang et al. (2022), Ertürk et al. (2020), Song et al. (2021)
	Lack of expertise in vertiport location selection	Ploetner et al. (2020), Pons-Prats et al. (2022), Schweiger and Preis (2022)
	Complexity of integration with ground transportation	Straubinger et al. (2020), Pons-Prats et al. (2022), Brunelli et al. (2022), Yedavalli and Cohen (2022)
	Difficulty in training personnel for UAM operations	Qi et al. (2004)
	Uncertainty in service reliability	Experts
	Weather condition issues	Ploetner et al. (2020), Adkins et al. (2020), Reiche et al. (2019)
	Route planning challenges	Causa et al. (2022), Neto et al. (2021)

therefore, the final operating costs (Qiao et al., 2023). Researchers agree that batteries with high energy density, long lifecycle, and quick rechargeability are essential for reliable, economical, and efficient operation, as well as for scaling up operations (Liu et al., 2021).

Especially upon introduction, vertiports are expected to be one of the capacity-limiting factors (Ploetner et al., 2020). On the one hand, their placement on rooftops in central districts is going to limit their size and incur high infrastructure costs (Rimjha and Trani, 2021). On the other hand, their landside and airside layouts should be designed to reduce the processing times of passengers and aircraft, respectively (Rothfeld et al., 2018). The ground infrastructure of UAM should operate safely and efficiently within a dense urban environment (Schweiger and Preis, 2022) while also providing sufficient vehicle and passenger throughput and ensuring accessibility to customers through intermodal solutions (Pons-Prats et al., 2022).

In the long run, achieving the full-scale implementation of UAM requires a critical transition towards remotely piloted or fully automated operations. It is necessary to develop fail-safe automated systems that can steer vehicles in densely populated areas with simultaneous operation of numerous eVTOLs (Siewert et al., 2019). Thus, researchers should focus on increasing the safety of autonomous operations, especially considering current findings that indicate components and subsystems exhibiting prohibitive failure rates (Swanke and Jahns, 2022). Researchers expect that remote or autonomous operations will take a toll on the public acceptance of UAM and, as such, assured and trusted autonomy is of uttermost importance (Lopes and Silva, 2023; Chancey and Politowicz, 2020). A related aspect mentioned often by researchers is system safety and cybersecurity, which should eliminate the risk of malicious attacks leading to accidents, with eVTOL vehicles meeting very high safety and certification requirements. Kwon et al. (2022) highlighted the fact that current UAM testbeds rely on public (tele) communication infrastructures, with Munir et al. (2023) adding that this has led to growing concerns about the resilience of UAM operations.

Finally, while market forecasts predict high demand with positive effects on the aerospace industry (Straubinger et al., 2020), the constraints on mass vehicle production (technology, materials, logistics) are often neglected. Husemann et al. (2024) highlighted the importance of vehicle types, battery capacity, and charging infrastructure for cost-efficient UAM operations. All in all, achieving technological maturity will likely require further time and effort.

2.2. Economic barriers

The successful implementation of UAM relies on addressing different economic challenges, which can affect the viability, affordability, and attractiveness of UAM services. Deploying and manufacturing UAM infrastructure and vehicles require considerable upfront costs, which can prevent potential stakeholders and investors from entering the market (Straubinger et al., 2021; Fu et al., 2019). Estimating market demand and revenue potential for UAM operators presents a challenge due to limited historical data and the industry's emerging nature, especially regarding factors such as the potential reliability issues of UAM, individual-specific passenger preferences, and the willingness-to-pay (Choi and Park, 2022; Rimjha et al., 2021). Coppola et al. (2024b) raised issues about the economic viability of UAM for airport access due to the relatively limited target market of business travelers. Therefore, it is also difficult to approximate the necessary initial investment (Tarafdar et al., 2019), which, consequently, could result in unpredictable economic viability for UAM services.

Besides, for successful UAM adoption, services must be competitively priced compared to existing transportation modes. This aspect calls for careful cost management, maximizing operational efficiency, and ensuring that UAM services provide distinct advantages over traditional transportation modes (Pertz et al., 2023; Rimjha et al., 2021). As the UAM industry continues to evolve, uncertainties remain regarding suitable and sustainable business models to support its long-term viability (Straubinger et al., 2021), especially considering that a course towards a common business model does not currently exist (Garrow et al., 2021). The uncertainties associated with the operational, maintenance, and personnel costs, as mentioned by Ploetner et al. (2020), present a significant obstacle in determining the economic properties and estimating the potential financial viability and profitability of the UAM ecosystem.

Moreover, UAM constitutes a new transportation mode and, as such, is expected to require regulatory support, especially upon introduction. The existing literature barely mentions the lack of insurance coverage and liability during incidents and accidents involving eVTOL vehicles and incurring damage to private property and individuals on the ground (Straubinger et al., 2020). Furthermore, Cohen et al. (2021) stressed their concerns about the lack of supportive policies that would help accelerate and streamline UAM adoption through regulation. The lack of official support instruments and, in general, the uncertainty surrounding the economic potential of UAM may result in inadequate financing options (for acquisition, operations, liability, etc.), either through the public or the private sector, as highlighted in our expert surveys. Hence, the introduction and the scaling of UAM operations may be delayed until financing terms and options mature.

2.3. Operational barriers

It is necessary to ensure that UAM, as a novel transportation system, will be compatible with the existing modes on the ground and in the air. Among researchers and practitioners, the issue of vertiport network design, i.e., the identification of a spatial concept for vertiport networks to operate efficiently and capture the emerging demand, has gained significant attention. Pons-Prats et al. (2022) emphasized the importance of integrating the relevant infrastructure elements in the existing urban structure. Willey and Salmon (2021) developed a novel hub location problem that identifies suitable locations for vertiports while also considering vehicle limitations. As UAM is unlikely to exist without integration with other transportation systems, intermodal connectivity will be important (Garrow et al., 2021). This integration refers to common fares, services, electronic platforms, and data exchange schemes (Tuchen, 2020), as well as physical integration with other modes to reduce access and egress times (Rothfeld et al., 2021).

Regarding its incorporation into the existing air traffic control procedures and airspace utilization in densely populated areas, the expected challenges have been a prevailing topic in the bibliography. To coordinate operations with existing traffic management systems and to ensure the safety and efficiency of the system as a whole, a new air traffic control (ATC) strategy that reflects the flight characteristics of eVTOL is essential, especially for the vertiport approach (Song and Yeo, 2021), as the anticipated UAM capabilities and demand are expected to exceed the current aerial traffic management systems (Wang et al., 2022; Ertürk et al., 2020). Managing a high number of such vehicles in a congested urban environment has no precedent (Cotton and Wing, 2018), and therefore, UAM growth could also be limited by airspace management needs (Cohen et al., 2021). Although the integration of UAM in the current airspace structure (especially the National Airspace System of the USA) is seen as a significant challenge due to safety issues ensuing from the potentially high demand (Wang et al., 2021; O'Connor et al., 2018), some approaches to address this issue have already been presented (Song et al., 2021; Vascik and Hansman, 2021). Due to the limitations mentioned above, significant challenges with regard to finding optimal routing that considers safety, air traffic congestion, and regulatory limitations can be anticipated (Causa et al., 2022).

Besides, the current lack of data from operational trials poses important operational repercussions. Reiche et al. (2019) identified potential weather barriers and studied the public perceptions of flying during events of adverse weather. Adkins et al. (2020) added that eVTOL could be susceptible to those weather conditions, considering their relatively low mass. Finally, especially in the first stages of operations, major challenges in finding and training personnel for operations and maintenance can be anticipated; the issue has been highlighted earlier in the case of commercial aviation (Qi et al., 2004) and is expected to impact UAM due to lack of expertise and due to the need for human supervision upon introduction (Janotta and Hogreve, 2024). Those factors may lead to uncertain operational reliability, with consequences that cannot yet be quantified.

2.4. Social barriers

This section examines the critical social barriers affecting the introduction and widespread implementation of UAM services. These challenges have been investigated from different perspectives, including user acceptance concerns, safety considerations encompassing the well-being of people, vehicles, and property on the ground, and issues related to welfare and equity. According to EASA, potential users are particularly concerned about safety, noise, and cybersecurity (EASA, 2021). The Federal Aviation Administration (FAA) has associated the successful adoption with the safety of people, vehicles, and property (FAA, 2020), while Cohen et al. (2021) mentioned concerns about safety as being a potential barrier to growth.

Al Haddad et al. (2020) studied the intended adoption horizon of UAM by its potential users and found safety and trust, data concerns, social attitudes, and sociodemographic characteristics to be significant. Recently, Chan et al. (2025) confirmed the significance of trust (towards the technology) in the adoption of advanced air mobility. In addition, Janotta and Hogreve (2024) have highlighted the importance of human supervision in achieving trust in the use of UAM, especially for risk-averse passengers. Other researchers, such as Karami et al. (2023), found that perceived safety, measured through general safety and the response during a malfunction, was negatively correlated with the attitude towards using UAM, while Johnson et al. (2022) stressed the importance of community acceptance.

According to the literature, UAM's potential effects on the residential quality of life for those living near vertiports and underneath operational areas, including concerns related to privacy violations, land consumption, and the degradation of the living environment, cannot be ignored (Lopes and Silva, 2023; Pons-Prats et al., 2022; Al Haddad et al., 2020). Noise emissions pose another significant issue, requiring spatial and temporal planning considerations to mitigate their impact on the community. The visual presence of UAM infrastructure, such as vertiports and aerial vehicles, can negatively affect the urban landscape. Furthermore, equity and welfare concerns should be addressed to ensure that the UAM deployment does not result in societal welfare losses and that the benefits are equitably distributed among various population groups (Cohen et al., 2021; Straubinger et al., 2021), with concerns being more prevalent during the early stages of UAM adoption (Biehle, 2022).

2.5. Environmental barriers

In this section, we discuss crucial environmental barriers and their implications for the future of UAM. Researchers have proposed that air pollutant emissions should be assessed in comparison to other transportation modes (Donateo and Ficarella, 2022; Zhao et al., 2022) given the association of environmental concerns with UAM adoption (Karami et al., 2023). Due to the substantial energy needs during takeoff and climbing, eVTOLs were found to be less efficient than battery electric ground vehicles but more efficient than internal combustion engine vehicles (Kasliwal et al., 2019). Another vital consideration is the availability of currently limited renewable energy sources to ensure the sustainability of UAM operations, considering that emissions depend largely on the structure of electricity production (Zhao et al., 2022).

The lifecycle and sustainability of UAM materials and components also warrant attention, as they could have far-reaching environmental implications; because many uncertainties in the manufacturing processes and materials exist, the sustainability implications are still unclear (André and Hajek, 2019; Kasliwal et al., 2019). Besides, UAM's ecological impacts cannot be overlooked because they may disrupt local ecosystems and wildlife, affecting habitats and ecological balances, as highlighted in our expert interviews.

2.6. Multi-criteria decision-making studies

MCDM methods serve as valuable tools for structured decision-making, aiding in the evaluation and comparison of alternatives based on multiple criteria. These methods help decision-makers make balanced decisions that take various factors into account. MCDM methods have been broadly applied in transport decision-making studies, including performance assessment of electric vehicles (Ecer, 2021), exploration of factors affecting airport selection during the COVID-19 pandemic (Tanrıverdi et al., 2022), selection of charging strategies for battery electric buses (Sadrani et al., 2023), performance evaluation of urban transportation infrastructure resilience (Liu et al., 2023), sustainability assessment of airlines (Tanrıverdi et al., 2023), assessment of passenger satisfaction in the aviation industry (Usun et al., 2024), and selection of aircraft types in airline companies (Bağcı and Kartal, 2024).

Moreover, MCDM methods have been used as a well-established framework in barrier studies to determine barrier weights, such as barriers to the deployment of battery electric buses (Sadrani et al., 2024), barriers to the adoption of second-use electric vehicle batteries (Gautam and Bolia, 2024), and barriers to urban mobility electrification (Bastida-Molina et al., 2022).

In our study, we evaluate and quantify the ranking of barriers to the introduction of UAM using a Fuzzy Best-Worst Method (FBWM). The FBWM is a fuzzy variant of the original BWM presented by Rezaei (2015). This fuzzy adaptation, developed by Guo and Zhao (2017), enables decision-makers to articulate their judgments using linguistic terms, subsequently transformed into fuzzy numerical values, thus managing uncertainties in decision makers' perspectives during comparisons.

The FBWM method has been employed in diverse fields, such as prioritization of used aircraft acquisition criteria (Gao et al., 2023), identification and assessment of user activity-oriented service requirements for intelligent product service systems (Chen et al., 2020), sustainable supplier selection (Ecer and Pamucar, 2020), determination of the optimal combination of power plant alternatives (Fard et al., 2022), antivirus mask selection (Kaya et al., 2022), and evaluation of hospital performance (Liao et al., 2019).

2.7. Research gap analysis and contribution statement

Here, we summarize the three crucial gaps in the literature and outline the contributions of our study to address them. First, no study in the literature has addressed the barriers to the implementation of UAM using a systematic MCDM methodology. Given the complexity of this issue, our study contributes to the literature by presenting a MCDM framework that allows for a structured analysis of barriers, covering technical, economic, social, environmental, and operational factors.

Second, the significance of these barriers has not been quantified or prioritized in the existing literature due to the absence of a MCDM rating methodology. We address this gap by developing a Fuzzy Best-Worst Method (FBWM) to measure the weights of these barriers. Our ranked list of barriers provides stakeholders and policymakers with valuable information, aiding in the efficient allocation of resources and efforts to address the most prominent obstacles and expedite UAM adoption.

Third, no study has analyzed and compared the significance of barriers among different countries to identify contextual differences. Using our MCDM framework and data gathered from various experts in Germany and the USA, we examine and compare the ranking of barriers in both countries.

3. Method

In this work, we evaluate and rank barriers to UAM implementation using the FBWM in Germany and the USA. For this purpose, we implement four main steps, as illustrated in Fig. 1.

Stage 1: We conduct a thorough literature review to compile an initial list of barriers to UAM implementation.
Stage 2: We enhance the initial list by integrating insights from 10 industry and academic experts from both Germany and the USA. This evaluation helps detect any missing barriers and remove redundancies, enabling us to finalize a list that captures the key obstacles to UAM implementation. The finalized list organizes the barriers into five categories: technical, economic, social, environmental, and operational, with sub-barriers in each group (see Fig. 2).
Stage 3: We develop a FBWM-based questionnaire to gather the perspectives of 18 experts, with 9 from Germany and 9 from the USA.
Stage 4: We apply the FBWM to calculate the significance of barriers at both the first and second levels and compare their rankings between Germany and the USA.

The following section explains the FBWM steps for ranking the identified barriers.

3.1. Fuzzy best-worst method

The BWM is a MCDM method employing pairwise comparisons to assess the relative significance of criteria based on the perspectives of decision-makers. A distinctive aspect of BWM is its use of two reference points: the best and worst criteria, representing the most and least important criteria, respectively. These reference points play the role of anchors throughout the comparison process, helping to reduce anchoring bias (Rezaei, 2015).

Furthermore, BWM requires fewer pairwise comparisons relative to traditional methods such as the Analytic Hierarchy Process (AHP) (Sarkar et al., 2024). For instance, the required pairwise comparisons are $n(n-1)/2$ in AHP and $2n-3$ in BWM. In the context of our study, which focuses on prioritizing a comprehensive list of 26 barriers to UAM implementation in Germany and the USA, minimizing the number of pairwise comparisons in surveys can save respondents' time and enhance the accuracy of their responses during data collection.

In our study, we employ the fuzzy variant of the BWM. By providing a linguistic-based environment for pairwise comparisons of barriers, the FBWM allows decision-makers to articulate their perspectives using linguistic terms. These linguistic preferences are then transformed into fuzzy numerical values, effectively handling subjective judgments in decision-making comparisons. The FBWM has a four-step process, detailed as follows:

Step 1: Identify evaluation criteria (barriers relevant to our study) $\{c_1, c_2, \ldots, c_n\}$.
Step 2: Choose the best and worst criteria, representing the most and least challenging barriers, respectively, in our work context.
Step 3: Determine the fuzzy preference vector of the best criterion to all other criteria(fuzzy best-to-other) and the fuzzy preference vector of all criteria to the worst criterion(fuzzy other-to-worst) using linguistic phrases:

$$\widetilde{A}_B = (\widetilde{a}_{B1}, \widetilde{a}_{B2}, \ldots, \widetilde{a}_{Bn}) \tag{1}$$

Equation (1) denotes the fuzzy best-to-other vector. $\widetilde{a}_{Bj}$ shows the preference of the best criterion over criterion j. $\widetilde{a}_{BB} = (1,1,1)$ illustrates a comparison of the best criterion with itself.

$$\widetilde{A}_W = (\widetilde{a}_{1W}, \widetilde{a}_{2W}, \ldots, \widetilde{a}_{nW}) \tag{2}$$

Equation (2) denotes the fuzzy other-to-worst vector. $\widetilde{a}_{jW}$ shows the preference of criterion j over the worst criterion. $\widetilde{a}_{ww} = (1,1,1)$ illustrates a comparison of the worst criterion with itself. The linguistic phrases are converted into fuzzy numerical values, according to Table 2.

Step 4: Use the mathematical optimization model in Equation (3) to obtain the optimal fuzzy weights of the criteria $\left(\widetilde{W}_1^*, \widetilde{W}_2^*, \ldots, \widetilde{W}_n^*\right)$. This model minimizes the discrepancy between the fuzzy weights derived

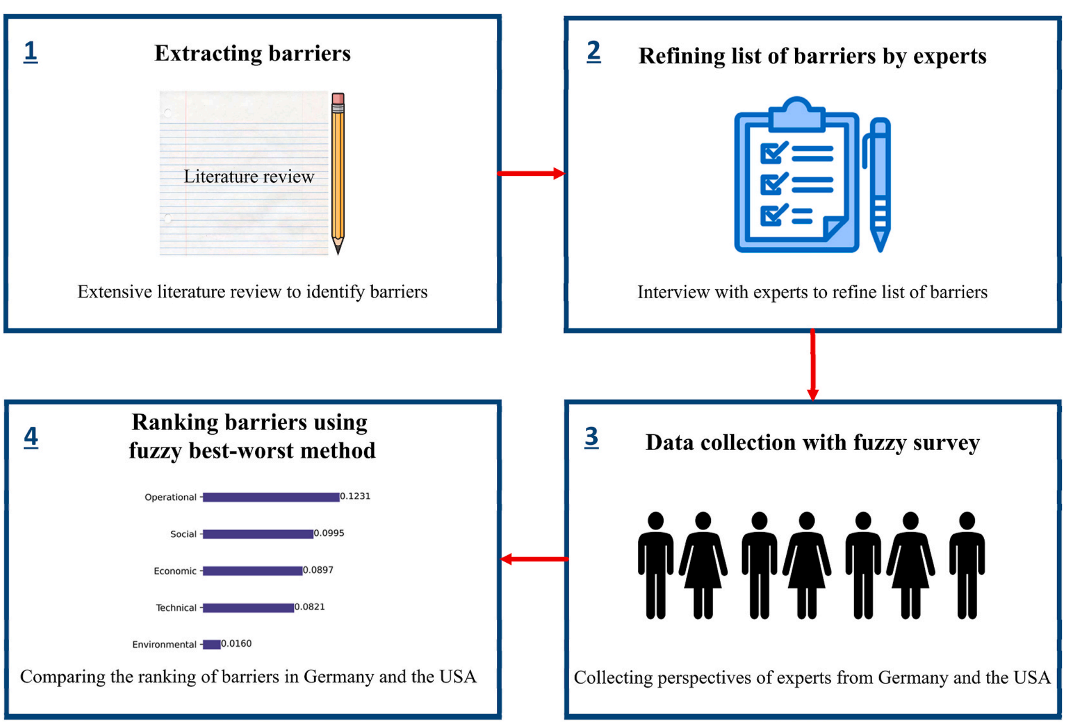

Fig. 1. Flowchart of research stages.

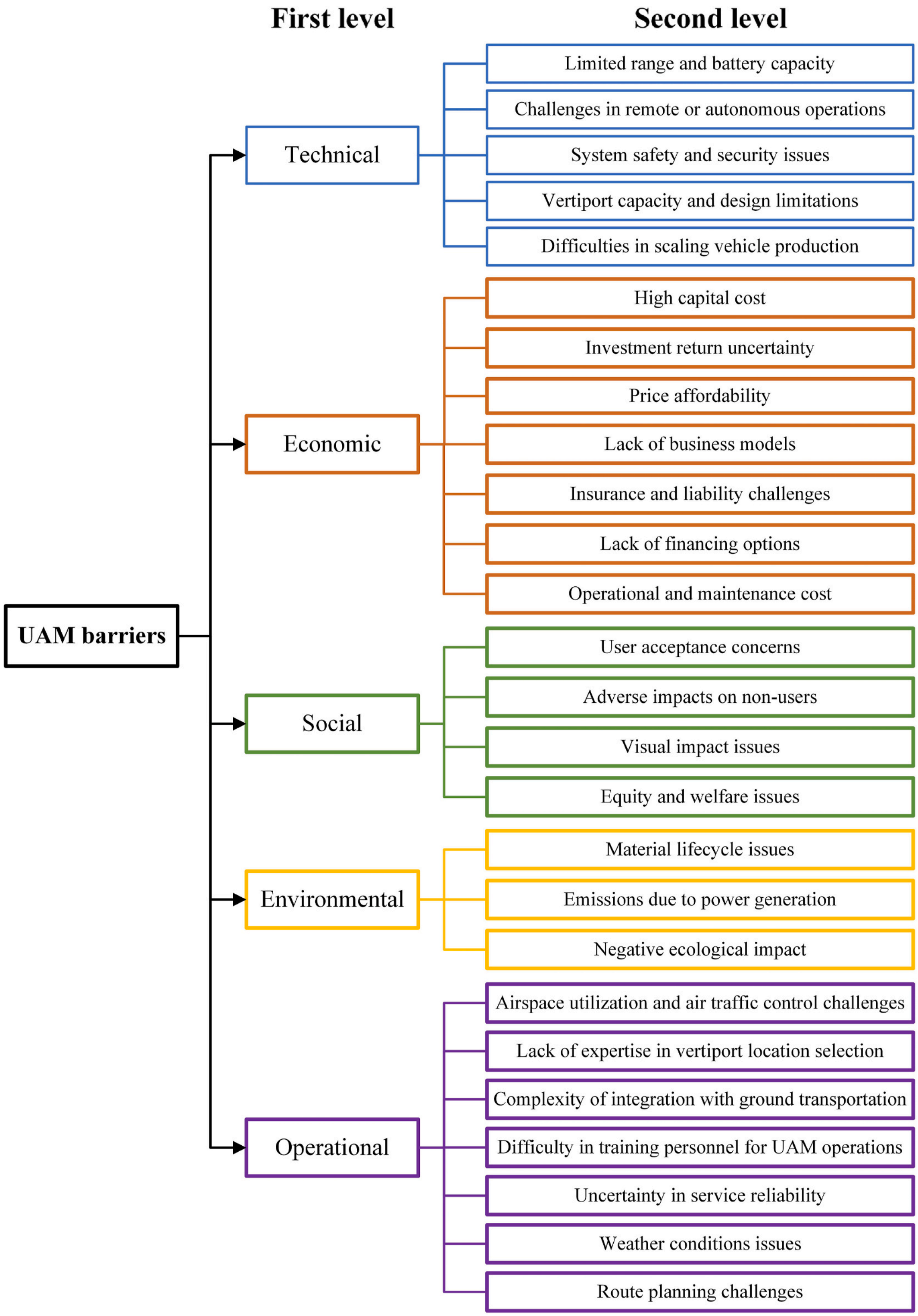

Fig. 2. Barriers to UAM implementation.

Table 2
Fuzzy values corresponding to linguistic expressions, adapted from (Guo and Zhao, 2017).

Linguistic phrases	Fuzzy ratings
Equally important (EI)	(1, 1, 1)
Weakly important (WI)	(2/3, 1, 3/2)
Fairly important (FI)	(3/2, 2, 5/2)
Very important (VI)	(5/2, 3, 7/2)
Absolutely important (AI)	(7/2, 4, 9/2)

from the present comparisons and the ones acquired through entirely consistent comparisons.

$$min\ max_j \left\{ \left| \frac{\widetilde{W}_B}{\widetilde{W}_j} - \widetilde{a}_{Bj} \right|, \left| \frac{\widetilde{W}_j}{\widetilde{W}_W} - \widetilde{a}_{jW} \right| \right\} \quad s.t. \begin{cases} \sum_{j=1}^{n} R\left(\widetilde{W}_j\right) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ \mathrm{j} = 1, 2, \ldots, \mathrm{n} \end{cases} \tag{3}$$

where $\widetilde{W}_B = (l_B^w, m_B^w, u_B^w), \widetilde{W}_j = \left(l_j^w, m_j^w, u_j^w\right), \widetilde{W}_W = (l_W^w, m_W^w, u_W^w), \widetilde{a}_{Bj} = (l_{Bj}, m_{Bj}, u_{Bj}), \widetilde{a}_{jW} = (l_{jW}, m_{jW}, u_{jW})$.

For linearization of the objective function, the above-mentioned equation can be transferred to the following optimization problem:

$$\min \widetilde{\xi} \quad s.t. \begin{cases} \left| \frac{\widetilde{W}_B}{\widetilde{W}_j} - \widetilde{a}_{Bj} \right| \le \widetilde{\xi} \\ \left| \frac{\widetilde{W}_j}{\widetilde{W}_W} - \widetilde{a}_{jW} \right| \le \widetilde{\xi} \\ \sum_{j=1}^{n} R\left(\widetilde{W}_j\right) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ \mathrm{j} = 1, 2, \ldots, \mathrm{n} \end{cases} \tag{4}$$

where $\widetilde{\xi} = \left(l^{\xi}, m^{\xi}, u^{\xi}\right)$.

Equation (4) can be solved as follows considering $l^{\xi} \le m^{\xi} \le u^{\xi}$, and $\widetilde{\xi}^* = (k^*, k^*, k^*)$, $k^* \le l^{\xi}$.

$$\min \widetilde{\xi}^* \quad s.t. \begin{cases} \left| \frac{(l_B^w, m_B^w, u_B^w)}{\left(l_j^w, m_j^w, u_j^w\right)} - (l_{Bj}, m_{Bj}, u_{Bj}) \right| \le (k^*, k^*, k^*) \\ \left| \frac{\left(l_j^w, m_j^w, u_j^w\right)}{(l_W^w, m_W^w, u_W^w)} - (l_{jW}, m_{jW}, u_{jW}) \right| \le (k^*, k^*, k^*) \\ \sum_{j=1}^{n} R\left(\widetilde{W}_j\right) = 1 \\ l_j^w \le m_j^w \le u_j^w \\ l_j^w \ge 0 \\ \mathrm{j} = 1, 2, \ldots, \mathrm{n} \end{cases} \tag{5}$$

Finally, the optimal fuzzy weights for the criteria are calculated by solving the optimization model in Equation (5).

3.2. Crisp weights

The crisp weights of the criteria are calculated by converting the obtained fuzzy weights utilizing Equation (6).

$$crisp\ (\widetilde{N}) = \frac{l_i + 4m_i + u_i}{6} \tag{6}$$

3.3. Consistency ratio

The consistency ratio (CR) is calculated to assess the accuracy of the criteria weights. If $\widetilde{a}_{Bj} \times \widetilde{a}_{jW} = \widetilde{a}_{BW}$, a fuzzy comparison is consistent, where $\widetilde{a}_{BW}$ indicates the preference of the best criterion over the worst criterion (Rezaei, 2015). If $\widetilde{a}_{Bj} \times \widetilde{a}_{jW} \neq \widetilde{a}_{BW}$, the inconsistency rate will increase. $\frac{\widetilde{W}_B}{\widetilde{W}_j} \times \frac{\widetilde{W}_j}{\widetilde{W}_W} = \frac{\widetilde{W}_B}{\widetilde{W}_W}$ can be expressed as:

$$(\widetilde{a}_{Bj} - \widetilde{\xi}) \times (\widetilde{a}_{jW} - \widetilde{\xi}) = (\widetilde{a}_{BW} + \widetilde{\xi}) \tag{7}$$

The highest level of inconsistency is observed when $\widetilde{a}_{jW} = \widetilde{a}_{Bj} = \widetilde{a}_{BW}$. Consequently, Equation (7) is formulated in the following manner to attain the maximum level of inconsistency:

$$(\widetilde{a}_{BW} - \widetilde{\xi}) \times (\widetilde{a}_{BW} - \widetilde{\xi}) = (\widetilde{a}_{BW} + \widetilde{\xi}) \tag{8}$$

Equation (8) can be rewritten as

$$\widetilde{\xi}^2 - (1 + 2\widetilde{a}_{BW})\widetilde{\xi} + (\widetilde{a}_{BW}{}^2 - \widetilde{a}_{BW}) = 0 \tag{9}$$

where $\widetilde{\xi} = \left(l^{\xi}, m^{\xi}, u^{\xi}\right)$, $\widetilde{a}_{BW} = (l_{BW}, m_{BW}, u_{BW})$.

Based on Table 2, the maximum fuzzy value for $\widetilde{a}_{BW}$ is (7/2, 4, 9/2). This indicates that the values of l_{BW}, m_{BW}, and u_{BW} cannot exceed 9/2. Equation (9) ultimately turns into:

$$\xi^2 - (1 + 2u_{BW})\xi + (u_{BW}{}^2 - u_{BW}) = 0 \tag{10}$$

where u_{BW} is equal to 1, 3/2, 5/2, 7/2, and 9/2 sequentially. The highest possible value for ξ is obtained from Equation (10) with different values for u_{BW}.

Equation (11) calculates the consistency ratio for FBWM, considering the consistency index (CI) in Table 3.

$$CR = \frac{\widetilde{\xi}^*}{CI} \tag{11}$$

4. Results and discussion

This section reports and evaluates the weights of barriers and sub-barriers obtained from the FBWM across five dimensions, including technical, economic, social, environmental, and operational, for both Germany and the USA. The required data was collected from 18 experts, including 9 from Germany and 9 from the USA, representing both academia and industry. Detailed demographics of these experts are provided in Tables B1 and B2 in Appendix B.

4.1. First level

This section provides a comparison and analysis of the first-level

Table 3
Consistency index for FBWM (Guo and Zhao, 2017).

Linguistic phrases	Equally important (EI)	Weakly important (WI)	Fairly important (FI)	Very important (VI)	Absolutely important (AI)
$\widetilde{a}_{BW}$	(1, 1, 1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(7/2, 4, 9/2)
CI	3.00	3.80	5.29	6.69	8.04

Table 4
Crisp weights of first-level barriers.

Barriers	Weight		Rank		CR	
	Germany	USA	Germany	USA	Germany	USA
Economic	0.3260	0.2363	1	3	0.0608	0.0528
Social	0.2114	0.1119	2	4		
Operational	0.2054	0.3285	3	1		
Technical	0.1613	0.2434	4	2		
Environmental	0.0959	0.0799	5	5		

barrier weights for both Germany and the USA. Table 4 displays the crisp weights, rankings, and CR values for these barriers in both Germany and the USA. Besides, the corresponding fuzzy weights can be found in Table C1 (in Appendix C).

4.1.1. Germany

Table 4 indicates that the economic issue is the most critical challenge in Germany, followed by social, operational, technical, and environmental aspects. Furthermore, a CR value close to zero reflects strong consistency and precision in the weight calculations.

4.1.2. The USA

Table 4 shows that in the USA, the operational aspect is the most critical challenge, followed by technical, economic, social, and environmental aspects. Across both countries, the environmental aspect ranks as the least significant challenge.

4.1.3. Differences in Germany and the USA

Fig. 3 highlights the differences in calculated crisp weights of obstacles between Germany and the USA at the first level. The operational aspect exhibits the largest difference, while the environmental aspect exhibits the smallest. The high importance of economic concerns in Germany can be partially attributed to the weaker entrepreneurial ecosystem compared to the USA, especially considering cultural, personal, and institutional differences between the countries (Röhl, 2019). Furthermore, the variation in social barrier weights between Germany (0.2114) and the USA (0.1119) can be explained by contrasting social protection policies, with Germany historically following a model of comprehensive protection for all citizens, while the USA adopts a more liberal approach (Seeleib-Kaiser, 2013). Conversely, the low emphasis on environmental concerns in both countries likely reflects the experts' expectations that issues, such as renewable energy production and end-of-life material management, are largely being addressed at the moment, and a solution is imminent. Lastly, as we will explain later, the significant weight of operational barriers in the USA is related to recent policy guidance issued by the FAA.

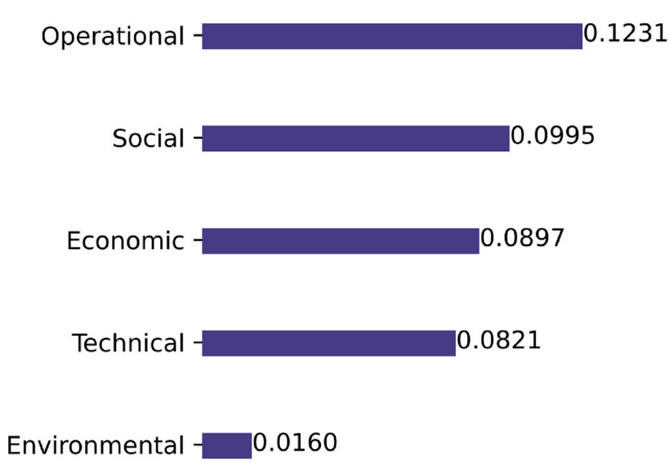

Fig. 3. Discrepancy in weights of first-level barriers.

4.2. Second level

Here, we explain the local weights of barriers at the second level within their corresponding groups (see Fig. 2) for Germany and the USA. Table C2 details the local crisp weights, rankings, and CR values of these sub-barriers, while Table C3 provides the corresponding local fuzzy weights. In Germany, the most challenging barriers in each group are price affordability (economic), user acceptance concerns (social), airspace utilization and air traffic control challenges (operational), system safety and security issues (technical), and material lifecycle concerns (environmental). This pattern is similarly observed in the USA, highlighting that the experts mostly focused on aspects that could be important for just launching UAM as a safe service with high compatibility with existing infrastructure. In contrast, the least challenging barriers in Germany are lack of business models (economic), visual impact issues (social), difficulty in training personnel for UAM operations (operational), difficulties in scaling vehicle production (technical), and emissions due to power generation (environmental), as noted in Table C2. These findings suggest that the least challenging sub-barriers pertain to the scaling of operations and the long-term viability of the service.

4.3. Global weights

To obtain the global weight of each sub-barrier (in Fig. 4), we calculate the product of its local weight and the weight of its corresponding group. In addition, we explore the implications of these results and propose strategies for addressing the most critical barriers effectively.

4.3.1. Germany

As shown in Table 5, the most significant sub-barriers in Germany are price affordability, investment return uncertainty, and user acceptance concerns (see Table C4 for fuzzy weights). In contrast, the least challenging sub-barriers are lack of business models, lack of expertise in vertiport location selection, and difficulty in training personnel for UAM operations.

4.3.2. The USA

As shown in Table 5, the three most significant sub-barriers in the USA are airspace utilization and air traffic control challenges, challenges in remote or autonomous operations, and system safety and (cyber) security issues. In Germany, these sub-barriers are ranked tenth, twelfth, and sixteenth, respectively. In addition, the least challenging sub-barriers in the USA are negative ecological impact, emissions due to power generation, and visual impact issues.

4.3.3. Difference in global weights: Germany vs. the USA

Fig. 5 highlights the differences in global weights of sub-barriers between Germany and the USA. The largest differences appear in visual impact issues, airspace utilization and air traffic control challenges, challenges in remote or autonomous operations, investment return uncertainty, weather conditions issues, and system safety and (cyber) security issues. The sub-barriers with higher crisp weights in the USA (airspace utilization and air traffic control, remote or autonomous

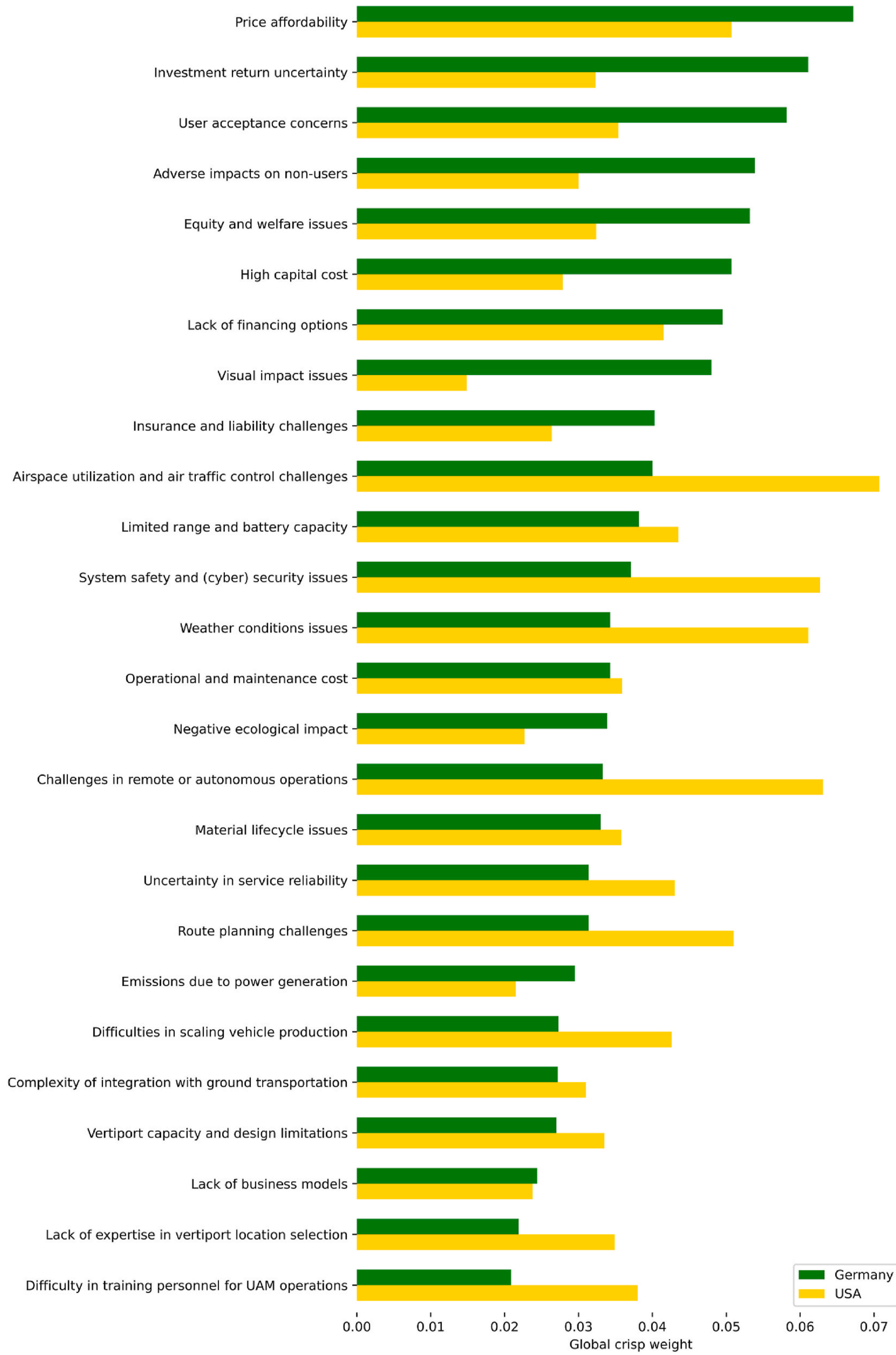

Fig. 4. Global weights of sub-barriers.

operations, weather issues, system safety and cybersecurity) are strongly oriented towards potential operational challenges. In Germany, sub-barriers with higher crisp weights (visual impact concerns and investment return uncertainty) are more related to societal and economic impacts. In contrast, the smallest differences are seen in material lifecycle issues, lack of business models, and operational and maintenance costs.

4.3.4. *Sensitivity analysis of barrier weightings to expert type*

To provide deeper insights into the varying perceptions of UAM

Table 5
Global crisp weights of sub-barriers.

Row	Sub-barrier	Weight		Rank	
		Germany	USA	Germany	USA
1	Price affordability	0.0672	0.0507	1	6
2	Investment return uncertainty	0.0611	0.0323	2	18
3	User acceptance concerns	0.0582	0.0354	3	14
4	Adverse impacts on non-users	0.0539	0.0300	4	20
5	Equity and welfare issues	0.0532	0.0324	5	17
6	High capital cost	0.0507	0.0279	6	21
7	Lack of financing options	0.0495	0.0415	7	10
8	Visual impact issues	0.0480	0.0149	8	26
9	Insurance and liability challenges	0.0403	0.0264	9	22
10	Airspace utilization and air traffic control challenges	0.0400	0.0707	10	1
11	Limited range and battery capacity	0.0382	0.0435	11	7
12	System safety and (cyber) security issues	0.0371	0.0627	12	3
13	Operational and maintenance cost	0.0344	0.0359	13	12
14	Weather conditions issues	0.0343	0.0611	14	4
15	Negative ecological impact	0.0339	0.0227	15	24
16	Challenges in remote or autonomous operations	0.0333	0.0631	16	2
17	Material lifecycle issues	0.0330	0.0358	17	13
18	Route planning challenges	0.0315	0.0510	18	5
19	Uncertainty in service reliability	0.0314	0.0430	19	8
20	Emissions due to power generation	0.0295	0.0215	20	25
21	Difficulties in scaling vehicle production	0.0273	0.0426	21	9
22	Complexity of integration with ground transportation	0.0272	0.0310	22	19
23	Vertiport capacity and design limitations	0.0270	0.0335	23	16
24	Lack of business models	0.0244	0.0238	24	23
25	Lack of expertise in vertiport location selection	0.0219	0.0349	25	15
26	Difficulty in training personnel for UAM operations	0.0209	0.0380	26	11

barriers, we also compare the barrier weights identified by different expert types (academic vs. industry) (see Fig. 6). Our analysis reveals differences in the prioritization of UAM barriers between academic experts and industry professionals in Germany and the USA. Among academic experts, those in Germany prioritize economic and social issues, identifying price affordability, investment return uncertainty, adverse impacts on non-users, visual impact issues, and equity and welfare concerns as the top challenges. In contrast, USA academics emphasize operational and technical challenges, with remote or autonomous operations, airspace utilization and air traffic control, system safety and cybersecurity issues, weather conditions, and route planning emerging as their primary concerns.

When examining industry experts, a similar divergence is observed. In Germany, industry respondents concentrate on market-related issues such as price affordability, user acceptance concerns, investment return uncertainty, high capital cost, and equity and welfare issues. However, USA industry experts focus more on operational integration and technical performance, with airspace utilization and air traffic control challenges, weather conditions issues, price affordability, system safety, and limited range and battery capacity emerging as the top barriers.

Moreover, comparisons between academic and industry panels reveal that in Germany, industry views tend to place a higher emphasis on user acceptance issues, whereas in the USA, the perspectives of academic and industry experts are largely aligned, with slight shifts toward operational challenges in the industry responses.

4.3.5. *Suggested strategies for tackling high-priority barriers*

The global crisp weights of sub-barriers reveal that experts from Germany were particularly concerned about the affordability of UAM. Although UAM was originally not conceived as a public transport means, pricing models (distance-based, time-based, and demand-based) and riding modes (shared and non-shared) are expected to result in diverse schemes that cater for different segments of the market, as has happened with car-sharing and ride-hailing (Becker et al., 2017). On the contrary, regarding the uncertainty in investment return, dynamic pricing, dedicated routing corridors, and market uptake are expected to increase income, while the development and use of infrastructure between carriers are expected to improve economic feasibility (Choi and Park, 2022). Therefore, it becomes evident that the first and the second barriers require conflicting strategies, suggesting that collecting data, optimizing operations, and compromising between supply and demand could be highly important.

As a multitude of sources and the present analysis show, user acceptance could be a significant barrier, especially in the beginning. Lotz et al. (2023) found that automation was an important determinant of acceptance, and therefore, letting a pilot accompany (automated) eVTOL operations could improve users' perception. Other barriers, such as the adverse impacts on non-users could be addressed through regulation, e.g., by limiting operations to certain times of the day, and by developing technology to address technical concerns. Moreover, equity issues can be reduced through hybrid approaches that combine limitations in the number of operations, artificial sound masking, and cruising at higher altitudes (Gao et al., 2024). Finally, pricing strategies and the spatial distribution of vertiports have been found to highly impact welfare (Straubinger et al., 2021), and therefore, policymakers and private companies should jointly consider them in their analyses.

The global crisp weights of sub-barriers reveal that experts from the USA were particularly concerned about operational challenges as they relate to airspace utilization and air traffic control. This is not particularly surprising, given that in July 2023, the FAA published its Innovate28 plan that noted: "The FAA is implementing a crawl-walk-run methodology that recognizes early opportunities to support Entry into Service (EIS) operations through existing services and infrastructure with minimal changes" (FAA, 2023). The Innovate28 plan effectively issued guidelines that were more conservative than those being used by original equipment manufacturers and importantly were based on existing air traffic control (ATC) guidelines. This effectively means that the FAA is viewing the next 5 years as having low-tempo UAM operations that will primarily operate under visual flight rules in predominately good weather conditions using existing ATC standards and route planning guidelines. Thus, in terms of scaling to larger-scale operations, we would expect that feedback from initial operations of advanced air mobility aircraft in the existing ATC system will be used to guide future changes in ATC guidelines, and route planning for all weather conditions. This would address the top five sub-barriers identified by experts in the USA related to airspace utilization and air traffic control challenges, weather condition issues, and route planning challenges.

The other two top barriers identified in the USA relate to challenges in remote or autonomous operations and system safety and (cyber) security issues. Programs such as the FAA's unmanned aircraft system (UAS) Integration Pilot Program (IPP), established in 2017 and continued under the BEYOND program in 2020, have brought together different stakeholders "to test and evaluate the integration of civil and public drone operations into our national airspace system" (FAA, 2017, 2020). These pilots include remotely piloted operations and beyond visual line of sight (BVLOS) flights. They also focus on cybersecurity issues, providing critical feedback to shape future policies for larger UAM operations.

5. Concluding remarks

Urban Air Mobility (UAM) refers to a transport system that enables

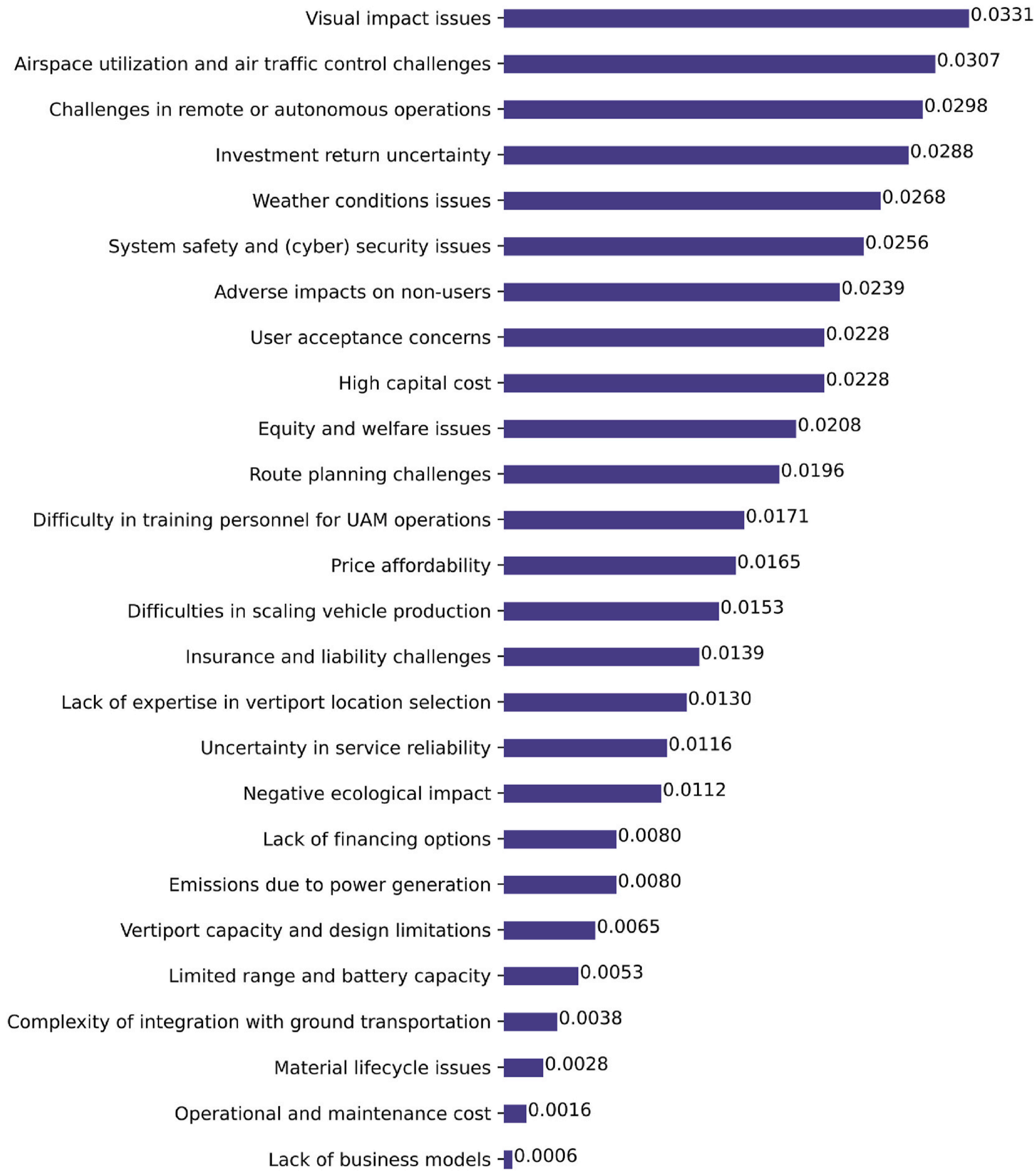

Fig. 5. Discrepancy in global weights of sub-barriers.

the movement of people and goods within urban and suburban areas using electric vertical take-off and landing (eVTOL) aircraft. However, it remains an emerging technology, and its successful implementation can be hindered by various barriers and challenges, such as technical, economic, social, environmental, and operational issues.

In this study, we propose a Multi-Criteria Decision-Making (MCDM) framework to identify and rank the barriers hindering the successful implementation of UAM in various contexts, with a focus on Germany and the USA. The MCDM framework facilitates a structured comparison and ranking of these barriers across multiple dimensions. By exploring the perspectives of stakeholders in both Germany and the USA, we provide a prioritized list of barriers for each context. This comparative analysis offers valuable insights for policymakers and stakeholders, aiding in efficiently allocating resources and efforts to address the most significant obstacles and expediting UAM adoption.

To achieve this, we first identify an inclusive list of 26 potential barriers, covering technical, economic, social, environmental, and operational aspects, through a comprehensive literature review and interviews with UAM experts. We then apply a Fuzzy Best-Worst Method (FBWM) to determine the weight of each barrier, using data gathered from 18 experts—9 from Germany and 9 from the USA—each with industry or academic experience in the UAM field.

The findings indicate that the economic aspect represents the most critical barrier in Germany, followed by social, operational, technical, and environmental aspects. In contrast, in the USA, the operational aspect is the most prominent, followed by technical, economic, social, and environmental aspects. Furthermore, the operational aspect shows the most significant difference between Germany and the USA, while the environmental aspect shows the least difference.

Our analysis reveals that in Germany, the most critical barriers identified in each category are price affordability in the economic sector, user acceptance concerns in the social sector, airspace utilization and air traffic control challenges in the operational sector, system safety and (cyber) security issues in the technical sector, and material lifecycle issues in the environmental sector. The same pattern is observed in the USA.

In Germany, the most significant barriers overall are price affordability, uncertainty in investment returns, and concerns about user

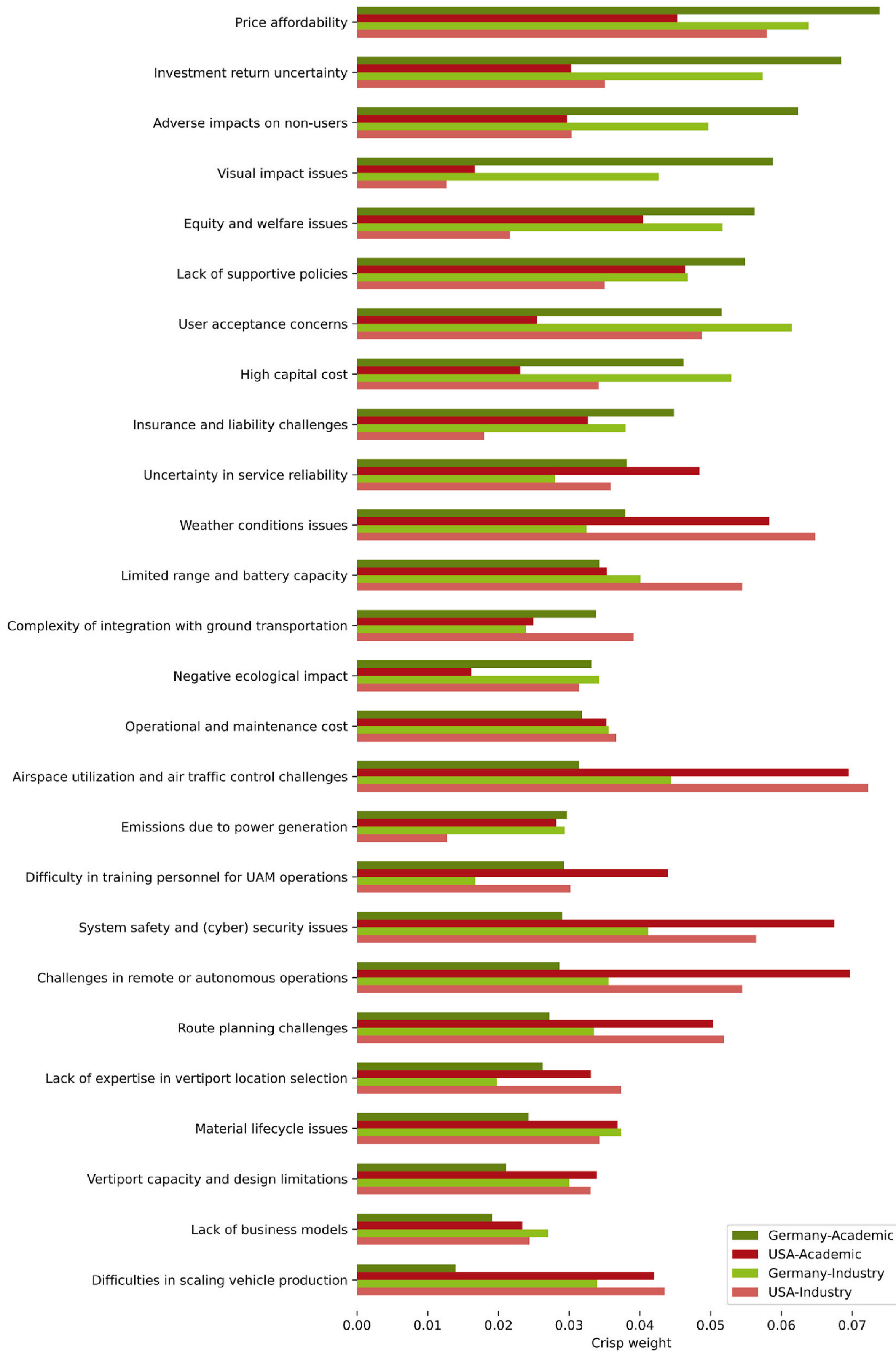

Fig. 6. Academic and industry weightings for UAM barriers in Germany and the USA.

acceptance. On the other hand, the top barriers in the USA are air traffic control challenges, challenges in remote or autonomous operations, and system safety and (cyber) security issues. Interestingly, these same barriers rank lower in Germany, where they hold the tenth, twelfth, and sixteenth positions, respectively.

Moreover, the least challenging barriers in Germany are lack of business models, lack of expertise in vertiport location selection, and difficulty in training personnel for UAM operations. The least challenging sub-barriers in the USA are negative ecological impact, emissions due to power generation, and visual impact issues. In addition, we explore the managerial implications of these results, highlighting strategies for addressing the most critical barriers effectively.

This study has some limitations that should be considered. We focused on only two countries. Future studies could include more countries to attain a broader understanding of UAM barriers globally. Despite incorporating diverse perspectives from academia and industry, the relatively small size and potential homogeneity of the expert panels remain a limitation in this study, which can potentially introduce imbalances in the judgments and results. Future research should consider expanding the expert panel to further validate and enhance the robustness of our findings. Future research could also explore potential solutions to the identified barriers and assess their feasibility and effectiveness in different contexts. Moreover, further MCDM methods can be used to quantify and prioritize the ranking of barriers and compare the results.

CRediT authorship contribution statement

Mohammad Sadrani: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Conceptualization. **Filippos Adamidis:** Writing – original draft, Formal analysis, Conceptualization. **Laurie A. Garrow:** Writing – review & editing, Validation, Investigation, Conceptualization. **Constantinos Antoniou:** Writing – review & editing, Validation, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Criteria description

Table A1
Description of barriers.

Barriers	Brief description
Limited range and battery capacity	The limitations imposed on the operational range and payload capacity of eVTOL aircraft due to the current constraints in energy density and endurance of battery technology.
Challenges in remote or autonomous operations	Scaling up UAM will require a transition to unestablished remotely piloted or pilotless operations that must safely and efficiently navigate complex urban environments.
System safety and (cyber) security issues	Ensuring that UAM vehicles meet stringent system safety and certification requirements to minimize the risk of accidents and malicious (cyber) attacks.
Vertiport capacity and design limitations	The capacity and design of vertiports can impose restrictions on the volume of movements, processing times, and overall system safety.
Difficulties in scaling vehicle production	Uncertainty in the advancement of UAM vehicle technology and challenges in equipment production, such as chip and material shortages upon widespread introduction.
High capital cost	The significant upfront costs required for acquiring and deploying UAM infrastructure and vehicles.
Investment return uncertainty	Uncertainty in estimating the market demand and revenue potential for operators, leading to unpredictable economic viability.
Price affordability	Ensuring that UAM services are affordable for a broad user base through competitive pricing compared to other transportation alternatives.
Lack of business models	Uncertainty regarding the most suitable and sustainable business models to support the long-term viability of UAM services as the industry continues to emerge.
Insurance and liability challenges	Issues related to insurance coverage and liability in cases of incidents involving eVTOL vehicles, including damages to property and individuals.
Lack of financing options	Lack of financial support from the public or private sector, delaying the introduction and the scaling of UAM services.
Operational and maintenance cost	Costs associated with the ongoing operations, maintenance, and personnel for servicing of UAM vehicles and related infrastructure.
User acceptance concerns	Challenges and uncertainties in public acceptance regarding issues such as UAM technology, safety, and privacy.
Adverse impacts on non-users	The potential effects on the overall quality of life experienced by individuals residing near UAM infrastructures and operational areas, such as electromagnetic field interference.
Visual impact issues	The visual impact of UAM infrastructure, such as vertiports and aerial vehicles, on the urban landscape.
Equity and welfare issues	Challenges in ensuring that UAM does not result in welfare losses for the society and that benefits are distributed equitably between population groups.
Material lifecycle issues	Environmental impacts of materials and components, such as batteries, during their lifecycle, including raw material extraction, production, and recycling with regard to GHG emissions and resource depletion.
Emissions due to power generation	Limited availability of renewable energy sources, such as wind and solar power, to generate clean power for charging eVTOLs.
Negative ecological impact	The potential disruption of local ecosystems and wildlife due to UAM operations, such as impacts on bird and animal habitats, and the ecological balance.
Airspace utilization and air traffic control challenges	Challenges in the safe use of the urban airspace, navigation in airport restricted areas, and coordination of UAM operations with existing air traffic management systems.
Lack of expertise in vertiport location selection	Limited knowledge and data in identifying a spatial vertiport network design to operate efficiently, while considering vehicle limitations and capturing the ensuing demand.
Complexity of integration with ground transportation	Challenging issues to integrate the vertiport network with ground transportation for seamless mobility.
Difficulty in training personnel for UAM operations	Challenges in recruiting and training skilled personnel for piloting, operations, and maintenance, especially during the initial phase of operations before full automation.
Uncertainty in service reliability	Unpredictability of the service due to the reliability of mechanical components and operational stability.
Weather conditions issues	High sensitivity of operations to adverse weather conditions that could affect the stability and safety of operations.
Route planning challenges	Difficulties in finding optimal flight paths, while considering air traffic congestion, navigating safely around obstacles, and adhering to existing infrastructure and regulations.

Appendix B. Details of experts' demographics

Table B1
Demographics of experts from Germany.

Expert No.	Background	Education level	Years of experience	Role	Type of industry/academic field
1	Academia	PhD	20	Full professor	Human-computer interactions
2	Industry	PhD	7	Manager	Economics
3	Academia	PhD	6	Postdoctoral researcher	Human factors
4	Industry	PhD	19	Director of research	Economic policy
5	Industry	PhD	5	Project manager	Infrastructure design and optimization
6	Industry	Master	5	Analyst	Travel behavior
7	Academia	PhD	8	Researcher	Transport planning and modeling
8	Industry	Master	4	Operations analyst	Operations research
9	Industry	Master	2	Junior analyst	Business models

Table B2
Demographics of experts from the USA.

Expert No.	Background	Education level	Years of experience	Role	Type of industry/academic field
1	Industry	Master	8	Operations manager	Service operations
2	Industry	Master	20	Senior executive	Business strategy and infrastructure management
3	Academia	PhD	17	Associate professor	Urban air mobility and transportation
4	Industry	PhD	15	Product intelligence	Transport simulation and optimization
5	Academia	PhD	15	Assistant professor	Transport policy
6	Academia	PhD	9	Associate professor	Travel behavior
7	Academia	PhD	18	Full professor	Travel behavior
8	Industry	PhD	10	Project manager	Operations research and service integration
9	Industry	Master	6	Analyst	Infrastructure and business models

Appendix C. Weights of barriers

Table C1
Fuzzy weights of first-level barriers.

Barriers	Fuzzy Weight	
	Germany	USA
Economic	(0.2962,0.3266,0.3533)	(0.1964,0.2354,0.2799)
Social	(0.1730,0.2094,0.2579)	(0.0930,0.1111,0.1338)
Operational	(0.1711,0.2049,0.2420)	(0.2986,0.3308,0.3491)
Technical	(0.1343,0.1596,0.1946)	(0.2001,0.2438,0.2854)
Environmental	(0.0873,0.0951,0.1077)	(0.0771,0.0800,0.0824)

Table C2
Local crisp weights of second-level sub-barriers.

Group	Sub-barrier	Local Crisp Weight		Local Rank		CR	
		Germany	USA	Germany	USA	Germany	USA
Economic	Price affordability	0.2029	0.2137	1	1	0.0610	0.0640
	Investment return uncertainty	0.1846	0.1352	2	4		
	High capital cost	0.1565	0.1179	3	5		
	Lack of financing options	0.1520	0.1775	4	2		
	Insurance and liability challenges	0.1228	0.1101	5	6		
	Operational and maintenance cost	0.1048	0.1475	6	3		
	Lack of business models	0.0763	0.098	7	7		
Social	User acceptance concerns	0.2836	0.3110	1	1	0.0554	0.0439
	Adverse impacts on non-users	0.2547	0.2683	2	3		
	Equity and welfare issues	0.2459	0.2872	3	2		
	Visual impact issues	0.2159	0.1334	4	4		

(continued on next page)

Table C2 (*continued*)

Group	Sub-barrier	Local Crisp Weight		Local Rank		CR	
		Germany	USA	Germany	USA	Germany	USA
Operational	Airspace utilization and air traffic control challenges	0.2040	0.2143	1	1	0.0630	0.0603
	Weather conditions issues	0.1617	0.1862	2	2		
	Route planning challenges	0.1519	0.1540	3	3		
	Uncertainty in service reliability	0.1444	0.1303	4	4		
	Complexity of integration with ground transportation	0.1308	0.0935	5	7		
	Lack of expertise in vertiport location selection	0.1128	0.1056	6	6		
	Difficulty in training personnel for UAM operations	0.0944	0.1161	7	5		
Technical	System safety and (cyber) security issues	0.2210	0.2573	1	1	0.0628	0.0570
	Limited range and battery capacity	0.2185	0.1748	2	4		
	Challenges in remote or autonomous operations	0.2144	0.2566	3	2		
	Vertiport capacity and design limitations	0.1735	0.1342	4	5		
	Difficulties in scaling vehicle production	0.1727	0.1771	5	3		
Environmental	Material lifecycle issues	0.3558	0.4435	1	1	0.0541	0.0454
	Negative ecological impact	0.3524	0.2854	2	2		
	Emissions due to power generation	0.2919	0.2711	3	3		

Table C3
Local fuzzy weights of second-level sub-barriers.

Group	Sub-barrier	Local Fuzzy Weight	
		Germany	USA
Economic	Price affordability	(0.1833,0.2027,0.2234)	(0.1932,0.2132,0.2362)
	Investment return uncertainty	(0.1649,0.1838,0.2077)	(0.1110,0.1336,0.1660)
	High capital cost	(0.1315,0.1554,0.1859)	(0.0990,0.1165,0.1426)
	Lack of financing options	(0.1303,0.1506,0.1796)	(0.1562,0.1758,0.2059)
	Insurance and liability challenges	(0.1019,0.1220,0.1468)	(0.0943,0.1090,0.1304)
	Operational and maintenance cost	(0.0882,0.1039,0.1253)	(0.1267,0.1459,0.1745)
	Lack of business models	(0.0656,0.0754,0.0905)	(0.0830,0.0966,0.1188)
Social	User acceptance concerns	(0.2488,0.2819,0.3252)	(0.2876,0.3103,0.3372)
	Adverse impacts on non-users	(0.2183,0.2535,0.2958)	(0.2241,0.2675,0.3160)
	Equity and welfare issues	(0.2163,0.2460,0.2749)	(0.2568,0.2862,0.3217)
	Visual impact issues	(0.1959,0.2154,0.2375)	(0.1185,0.1323,0.1528)
Operational	Airspace utilization and air traffic control challenges	(0.1836,0.2035,0.2262)	(0.1915,0.2141,0.2379)
	Weather conditions issues	(0.1405,0.1607,0.1868)	(0.1663,0.1854,0.2091)
	Route planning challenges	(0.1270,0.1503,0.1831)	(0.1278,0.1530,0.1846)
	Uncertainty in service reliability	(0.1215,0.1435,0.1708)	(0.1102,0.1293,0.1544)
	Complexity of integration with ground transportation	(0.1106,0.1297,0.1555)	(0.0792,0.0930,0.1097)
	Lack of expertise in vertiport location selection	(0.0980,0.1120,0.1308)	(0.0898,0.1046,0.1253)
	Difficulty in training personnel for UAM operations	(0.0837,0.0939,0.1072)	(0.0997,0.1155,0.1352)
Technical	System safety and (cyber) security issues	(0.1914,0.2199,0.2546)	(0.2273,0.2571,0.2877)
	Limited range and battery capacity	(0.1913,0.2173,0.2502)	(0.1459,0.1738,0.2080)
	Challenges in remote or autonomous operations	(0.1829,0.2137,0.2486)	(0.2214,0.2557,0.2951)
	Vertiport capacity and design limitations	(0.1479,0.1728,0.2018)	(0.1158,0.1337,0.1547)
	Difficulties in scaling vehicle production	(0.1480,0.1722,0.1995)	(0.1507,0.1763,0.2068)
Environmental	Material lifecycle issues	(0.3100,0.3552,0.4040)	(0.3959,0.4426,0.4950)
	Negative ecological impact	(0.3027,0.3501,0.4112)	(0.2414,0.2842,0.3340)
	Emissions due to power generation	(0.2603,0.2926,0.3206)	(0.2493,0.2702,0.2967)

Table C4
Global fuzzy weights of second-level sub-barriers.

Row	Sub-barrier	Global Fuzzy Weight	
		Germany	USA
1	Price affordability	(0.0551,0.0671,0.0797)	(0.0379,0.0501,0.0660)
2	Investment return uncertainty	(0.0496,0.0607,0.0739)	(0.0218,0.0315,0.0463)
3	User acceptance concerns	(0.0409,0.0567,0.0814)	(0.0270,0.0350,0.0457)
4	Adverse impacts on non-users	(0.0372,0.0526,0.0760)	(0.0206,0.0294,0.0418)
5	Equity and welfare issues	(0.0381,0.0523,0.0718)	(0.0240,0.0318,0.0430)
6	High capital cost	(0.0381,0.0502,0.0651)	(0.0192,0.0271,0.0396)
7	Lack of financing options	(0.0382,0.0489,0.0628)	(0.0301,0.0406,0.0566)
8	Visual impact issues	(0.0358,0.0472,0.0635)	(0.0110,0.0146,0.0203)
9	Insurance and liability challenges	(0.0306,0.0399,0.0515)	(0.0185,0.0258,0.0367)
10	Airspace utilization and air traffic control challenges	(0.0297,0.0396,0.0523)	(0.0572,0.0710,0.0831)

(*continued on next page*)

Table C4 (*continued*)

Row	Sub-barrier	Global Fuzzy Weight	
		Germany	USA
11	Limited range and battery capacity	(0.0271,0.0373,0.0527)	(0.0295,0.0429,0.0599)
12	System safety and (cyber) security issues	(0.0264,0.0363,0.0512)	(0.0451,0.0624,0.0817)
13	Weather conditions issues	(0.0248,0.0338,0.0457)	(0.0496,0.0610,0.0729)
14	Operational and maintenance cost	(0.0259,0.0339,0.0444)	(0.0255,0.0350,0.0495)
15	Negative ecological impact	(0.0268,0.0332,0.0434)	(0.0185,0.0226,0.0274)
16	Challenges in remote or autonomous operations	(0.0233,0.0325,0.0464)	(0.0446,0.0624,0.0845)
17	Material lifecycle issues	(0.0259,0.0326,0.0418)	(0.0308,0.0357,0.0411)
18	Route planning challenges	(0.0218,0.0307,0.0438)	(0.0383,0.0508,0.0644)
19	Uncertainty in service reliability	(0.0221,0.0309,0.0428)	(0.0329,0.0428,0.0539)
20	Emissions due to power generation	(0.0234,0.0291,0.0369)	(0.0191,0.0215,0.0243)
21	Difficulties in scaling vehicle production	(0.0192,0.0266,0.0382)	(0.0293,0.0420,0.0582)
22	Complexity of integration with ground transportation	(0.0189,0.0266,0.0377)	(0.0237,0.0310,0.0384)
23	Vertiport capacity and design limitations	(0.0191,0.0263,0.0377)	(0.0236,0.0332,0.0447)
24	Lack of business models	(0.0190,0.0241,0.0311)	(0.0166,0.0231,0.0337)
25	Lack of expertise in vertiport location selection	(0.0157,0.0215,0.0298)	(0.0268,0.0347,0.0438)
26	Difficulty in training personnel for UAM operations	(0.0154,0.0207,0.0275)	(0.0297,0.0378,0.0471)

References

Adkins, K.A., Akbas, M., Compere, M., 2020. Real-time urban weather observations for urban air mobility. Int. J. Aviat. Aeronaut. Aerosp. 7 (4), 11. https://doi.org/10.15394/ijaaa.2020.1540.

Afonso, F., Ferreira, A., Ribeiro, I., Lau, F., Suleman, A., 2021. On the design of environmentally sustainable aircraft for urban air mobility. Transport. Res. Transport Environ. 91, 102688. https://doi.org/10.1016/j.trd.2020.102688.

Al Haddad, C., Chaniotakis, E., Straubinger, A., Plötner, K., Antoniou, C., 2020. Factors affecting the adoption and use of urban air mobility. Transport. Res. Pol. Pract. 132, 696–712. https://doi.org/10.1016/j.tra.2019.12.020.

André, N., Hajek, M., 2019. Robust environmental life cycle assessment of electric VTOL concepts for urban air mobility. In: AIAA Aviation 2019 Forum, p. 3473. https://doi.org/10.2514/6.2019-3473.

Bağcı, B., Kartal, M., 2024. A combined multi-criteria model for aircraft selection problem in airlines. J. Air Transport. Manag. 116, 102566. https://doi.org/10.1016/j.jairtraman.2024.102566.

Bastida-Molina, P., Ribó-Pérez, D., Gómez-Navarro, T., Hurtado-Pérez, E., 2022. What is the problem? The obstacles to the electrification of urban mobility in Mediterranean cities. Case study of Valencia, Spain. Renew. Sustain. Energy Rev. 166, 112649. https://doi.org/10.1016/j.rser.2022.112649.

Becker, H., Ciari, F., Axhausen, K.W., 2017. Comparing car-sharing schemes in Switzerland: user groups and usage patterns. Transport. Res. Pol. Pract. 97, 17–29. https://doi.org/10.1016/j.tra.2017.01.004.

Biehle, T., 2022. Social sustainable urban air mobility in Europe. Sustainability 14 (15), 9312. https://doi.org/10.3390/su14159312.

Blade, 2024. Fly the future, today. Blade. Retrieved July 12, 2024, from. https://www.blade.com.

Bovenizer, N., 2024. China's EHang celebrates passenger flights on eVTOL aircraft in Wencheng. Airport Technology. https://www.airport-technology.com/news/china-ehang-passenger-flights-evtol-wencheng/.

Brunelli, M., Ditta, C.C., Postorino, M.N., 2022. A framework to develop urban aerial networks by using a digital twin approach. Drones 6 (12), 387. https://doi.org/10.3390/drones6120387.

Brunelli, M., Ditta, C.C., Postorino, M.N., 2023. SP surveys to estimate airport shuttle demand in an urban air mobility context. Transp. Policy 141, 129–139. https://doi.org/10.1016/j.tranpol.2023.07.019.

Causa, F., Franzone, A., Fasano, G., 2022. Strategic and tactical path planning for urban air mobility: overview and application to real-world use cases. Drones 7 (1), 11. https://doi.org/10.3390/drones7010011.

Çetin, E., Cano, A., Deransy, R., Tres, S., Barrado, C., 2022. Implementing mitigations for improving societal acceptance of urban air mobility. Drones 6 (2), 28. https://doi.org/10.3390/drones6020028.

Chancey, E.T., Politowicz, M.S., 2020. Public trust and acceptance for concepts of remotely operated Urban Air Mobility transportation. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 64. SAGE Publications, Sage CA: Los Angeles, CA, pp. 1044–1048. https://doi.org/10.1177/1071181320641251, 1.

Chan, E.T., Li, T.E., Schwanen, T., 2025. Societal acceptance of advanced aerial mobility in China's Greater Bay Area among young-and middle-aged adults. Transport. Res. F Traffic Psychol. Behav. 110, 88–103. https://doi.org/10.1016/j.trf.2025.02.008.

Chen, Z., Ming, X., Zhou, T., Chang, Y., Sun, Z., 2020. A hybrid framework integrating rough-fuzzy best-worst method to identify and evaluate user activity-oriented service requirement for smart product service system. J. Clean. Prod. 253, 119954. https://doi.org/10.1016/j.jclepro.2020.119954.

Choi, J.H., Park, Y., 2022. Exploring economic feasibility for airport shuttle service of urban air mobility (UAM). Transport. Res. Pol. Pract. 162, 267–281. https://doi.org/10.1016/j.tra.2022.06.004.

Cohen, A.P., Shaheen, S.A., Farrar, E.M., 2021. Urban air mobility: history, ecosystem, market potential, and challenges. IEEE Trans. Intell. Transport. Syst. 22 (9), 6074–6087. https://doi.org/10.1109/TITS.2021.3082767.

Coppola, P., De Fabiis, F., Silvestri, F., 2024a. Urban air mobility (UAM): airport shuttles or city-taxis? Transp. Policy 150, 24–34. https://doi.org/10.1016/j.tranpol.2024.03.003.

Coppola, P., De Fabiis, F., Silvestri, F., 2024b. Urban air mobility passengers' profiling: evidence from milan airports, Italy. Transp. Res. Rec. 0 (0). https://doi.org/10.1177/03611981241287537.

Cotton, W.B., Wing, D.J., 2018. Airborne trajectory management for urban air mobility. In: 2018 Aviation Technology, Integration, and Operations Conference, p. 3674. https://doi.org/10.2514/6.2018-3674.

Desai, K., Al Haddad, C., Antoniou, C., 2021. Roadmap to early implementation of passenger air mobility: findings from a delphi study. Sustainability 13 (19), 10612. https://doi.org/10.3390/su131910612.

Donateo, T., Ficarella, A., 2022. A methodology for the comparative analysis of hybrid electric and all-electric power systems for urban air mobility. Energies 15 (2), 638. https://doi.org/10.3390/en15020638.

EASA, 2021. Study on the Societal Acceptance of Urban Air Mobility in Europe. European Union Aviation Safety Agency. https://www.easa.europa.eu/downloads/127760/en.

Ecer, F., 2021. A consolidated MCDM framework for performance assessment of battery electric vehicles based on ranking strategies. Renew. Sustain. Energy Rev. 143, 110916. https://doi.org/10.1016/j.rser.2021.110916.

Ecer, F., Pamucar, D., 2020. Sustainable supplier selection: a novel integrated fuzzy best worst method (F-BWM) and fuzzy CoCoSo with Bonferroni (CoCoSo'B) multi-criteria model. J. Clean. Prod. 266, 121981. https://doi.org/10.1016/j.jclepro.2020.121981.

Ertürk, M.C., Hosseini, N., Jamal, H., Şahin, A., Matolak, D., Haque, J., 2020. Requirements and technologies towards uam: communication, navigation, and surveillance. In: 2020 Integrated Communications Navigation and Surveillance Conference (ICNS). IEEE. https://doi.org/10.1109/ICNS50378.2020.9223003, pp. 2C2-1.

FAA, 2017. UAS integration pilot program. https://www.faa.gov/uas/programs_partnerships/completed/integration_pilot_program.

FAA, 2020. Beyond. https://www.faa.gov/uas/programs_partnerships/beyond.

FAA, 2023. Advanced air mobility (AAM) implementation plan. https://www.faa.gov/sites/faa.gov/files/AAM-I28-Implementation-Plan.pdf.

Fard, M.B., Moradian, P., Emarati, M., Ebadi, M., Chofreh, A.G., Klemeŝ, J.J., 2022. Ground-mounted photovoltaic power station site selection and economic analysis based on a hybrid fuzzy best-worst method and geographic information system: a case study Guilan province. Renew. Sustain. Energy Rev. 169, 112923. https://doi.org/10.1016/j.rser.2022.112923.

Fu, M., Rothfeld, R., Antoniou, C., 2019. Exploring preferences for transportation modes in an urban air mobility environment: Munich case study. Transp. Res. Rec. 2673 (10), 427–442. https://doi.org/10.1177/0361198119843858.

Fu, M., Straubinger, A., Schaumeier, J., 2022. Scenario-based demand assessment of urban air mobility in the greater Munich area. J. Air Transport. 30 (4), 125–136. https://doi.org/10.2514/1.D0275.

Gao, F., Wang, W., Bi, C., Bi, W., Zhang, A., 2023. Prioritization of used aircraft acquisition criteria: a fuzzy best–worst method (BWM)-based approach. J. Air Transport. Manag. 107, 102359. https://doi.org/10.1016/j.jairtraman.2023.102359.

Gao, Z., Yu, Y., Wei, Q., Topcu, U., Clarke, J.P., 2024. Noise-aware and equitable urban air traffic management: an optimization approach. Transport. Res. C Emerg. Technol. 165, 104740. https://doi.org/10.1016/j.trc.2024.104740.

Garrow, L.A., German, B.J., Leonard, C.E., 2021. Urban air mobility: a comprehensive review and comparative analysis with autonomous and electric ground

transportation for informing future research. Transport. Res. C Emerg. Technol. 132, 103377. https://doi.org/10.1016/j.trc.2021.103377.
Gautam, D., Bolia, N., 2024. Fostering second-life applications for electric vehicle batteries: a thorough exploration of barriers and solutions within the framework of sustainable energy and resource management. J. Clean. Prod. 456, 142401. https://doi.org/10.1016/j.jclepro.2024.142401.
Global Times, 2024. Ehang wins 1st production certificate for eVTOL aircraft. https://www.globaltimes.cn/page/202404/1310205.shtml.
Goyal, R., Reiche, C., Fernando, C., Serrao, J., Kimmel, S., Cohen, A., Shaheen, S., 2018. Urban air mobility (UAM) market study (No. HQ-E-DAA-TN65181). https://ntrs.nasa.gov/api/citations/20190026762/downloads/20190026762.pdf.
Guo, S., Zhao, H., 2017. Fuzzy best-worst multi-criteria decision-making method and its applications. Knowl. Base Syst. 121, 23–31. https://doi.org/10.1016/j.knosys.2017.01.010.
Holden, J., Goel, N., 2016. Uber Elevate: fast-forwarding to a future of on-demand urban air transportation. Uber Technologies. Inc., San Francisco, CA. https://evtol.news/_media/PDFs/UberElevateWhitePaperOct2016.pdf.
Husemann, M., Kirste, A., Stumpf, E., 2024. Analysis of cost-efficient urban air mobility systems: optimization of operational and configurational fleet decisions. Eur. J. Oper. Res. 317 (3), 678–695. https://doi.org/10.1016/j.ejor.2023.04.040.
Janotta, F., Hogreve, J., 2024. Ready for take-off? The dual role of affective and cognitive evaluations in the adoption of Urban Air Mobility services. Transport. Res. Pol. Pract. 185, 104122. https://doi.org/10.1016/j.tra.2024.104122.
Johnson, R.A., Miller, E.E., Conrad, S., 2022. Technology adoption and acceptance of urban air mobility systems: identifying public perceptions and integration factors. Int. J. Aerosp. Psychol. 32 (4), 240–253. https://doi.org/10.1080/24721840.2022.2100394.
Karami, H., Abbasi, M., Samadzad, M., Karami, A., 2023. Unraveling behavioral factors influencing the adoption of urban air mobility from the end user's perspective in Tehran – a developing country outlook. Transp. Policy 145, 74–84. https://doi.org/10.1016/j.tranpol.2023.10.010.
Kasliwal, A., Furbush, N.J., Gawron, J.H., McBride, J.R., Wallington, T.J., De Kleine, R. D., Kim, H.C., Keoleian, G.A., 2019. Role of flying cars in sustainable mobility. Nat. Commun. 10 (1), 1555. https://doi.org/10.1038/s41467-019-09426-0.
Kaya, S.K., Pamucar, D., Aycin, E., 2022. A new hybrid fuzzy multi-criteria decision methodology for prioritizing the antivirus mask over COVID-19 pandemic. Informatica 33 (3), 545–572. https://doi.org/10.15388/22-INFOR475.
Kwon, D., Son, S., Park, Y., Kim, H., Park, Y., Lee, S., Jeon, Y., 2022. Design of secure handover authentication scheme for urban air mobility environments. IEEE Access 10, 42529–42541. https://doi.org/10.1109/ACCESS.2022.3168843.
Li, X., 2023. Repurposing existing infrastructure for urban air mobility: a scenario analysis in southern California. Drones 7 (1), 37. https://doi.org/10.3390/drones7010037.
Liao, H., Mi, X., Yu, Q., Luo, L., 2019. Hospital performance evaluation by a hesitant fuzzy linguistic best worst method with inconsistency repairing. J. Clean. Prod. 232, 657–671. https://doi.org/10.1016/j.jclepro.2019.05.308.
Lineberger, R., Hussain, A., Mehra, S., Pankratz, D., 2018. Elevating the Future of Mobility: Passenger Drones and Flying Cars. Deloitte Insights.
Liu, A., Li, Z., Shang, W.L., Ochieng, W., 2023. Performance evaluation model of transportation infrastructure: perspective of COVID-19. Transport. Res. Pol. Pract. 170, 103605. https://doi.org/10.1016/j.tra.2023.103605.
Liu, T., Yang, X.G., Ge, S., Leng, Y., Wang, C.Y., 2021. Ultrafast charging of energy-dense lithium-ion batteries for urban air mobility. ETransportation 7, 100103. https://doi.org/10.1016/j.etran.2021.100103.
Lopes, D., Silva, J., 2023. Urban air mobility (UAM) in the metropolitan region of São Paulo: potential and threats. J. Airl. Airpt. Manag. 13 (1), 1–11. https://doi.org/10.3926/jairm.345.
Lotz, V., Kirste, A., Lidynia, C., Stumpf, E., Ziefle, M., 2023. User acceptance of urban air mobility (UAM) for passenger transport: a choice-based conjoint study. In: International Conference on Human-Computer Interaction. Springer Nature Switzerland, Cham, pp. 296–315. https://doi.org/10.1007/978-3-031-35678-0_20.
Mathur, A., Panesar, K., Kim, J., Atkins, E.M., Sarter, N., 2019. Paths to autonomous vehicle operations for urban air mobility. In: AIAA Aviation 2019 Forum, p. 3255. https://doi.org/10.2514/6.2019-3255.
Milan Airports, 2024. Urban Air Mobility: the city is getting closer. Retrieved July 12, 2024, from. https://milanairports.com/en/sustainability/all-sea-projects/urban-air-mobility-city-getting-closer.
Munir, M.S., Dipro, S.H., Hasan, K., Islam, T., Shetty, S., 2023. Artificial intelligence-enabled exploratory cyber-physical safety analyzer framework for civilian urban air mobility. Appl. Sci. 13 (2), 755. https://doi.org/10.3390/app13020755.
Neto, E.C.P., Baum, D.M., de Almeida, J.R., Camargo, J.B., Cugnasca, P.S., 2021. A trajectory evaluation platform for urban air mobility (uam). IEEE Trans. Intell. Transport. Syst. 23 (7). https://doi.org/10.1109/TITS.2021.3091411.
O'Connor, C.J., Kennedy, K.D., Underwood, M.C., Harrivel, A.R., Stephens, C., Comstock, J.R., Last, M.C., 2018. Development of a simulation platform to evaluate integration of UAM traffic into the NAS. In: 2018 Aviation Technology, Integration, and Operations Conference, p. 3850. https://doi.org/10.2514/6.2018-3850.
Pertz, J., Niklaß, M., Swaid, M., Gollnick, V., Kopera, S., Schunck, K., Baur, S., 2023. Estimating the economic viability of advanced air mobility use cases: towards the slope of enlightenment. Drones 7 (2), 75. https://doi.org/10.3390/drones7020075.
Ploetner, K.O., Al Haddad, C., Antoniou, C., Frank, F., Fu, M., Kabel, S., Llorca, C., Moeckel, R., Moreno, A.T., Pukhova, A., Rothfeld, R., 2020. Long-term application potential of urban air mobility complementing public transport: an upper Bavaria example. CEAS Aeronaut. J. 11, 991–1007. https://doi.org/10.1007/s13272-020-00468-5.
Pons-Prats, J., Živojinović, T., Kuljanin, J., 2022. On the understanding of the current status of urban air mobility development and its future prospects: commuting in a flying vehicle as a new paradigm. Transport. Res. E Logist. Transport. Rev. 166, 102868. https://doi.org/10.1016/j.tre.2022.102868.
Pukhova, A., Llorca, C., Moreno, A., Staves, C., Zhang, Q., Moeckel, R., 2021. Flying taxis revived: can Urban air mobility reduce road congestion? J. Urban Mob. 1, 100002. https://doi.org/10.1016/j.urbmob.2021.100002.
Qi, X., Bard, J.F., Yu, G., 2004. Class scheduling for pilot training. Oper. Res. 52 (1), 148–162. https://doi.org/10.1287/opre.1030.0076.
Qiao, X., Chen, G., Lin, W., Zhou, J., 2023. The impact of battery performance on urban air mobility operations. Aerospace 10 (7), 631. https://doi.org/10.3390/aerospace10070631.
Reiche, C., McGillen, C., Siegel, J., Brody, F., 2019. Are we ready to weather urban air mobility (UAM)?. In: 2019 Integrated Communications, Navigation and Surveillance Conference (ICNS). IEEE, pp. 1–7. https://doi.org/10.1109/ICNSURV.2019.8735297.
Rezaei, J., 2015. Best-worst multi-criteria decision-making method. Omega 53, 49–57. https://doi.org/10.1016/j.omega.2014.11.009.
Rimjha, M., Trani, A., 2021. Urban air mobility: factors affecting vertiport capacity. In: 2021 Integrated Communications Navigation and Surveillance Conference (ICNS). IEEE, pp. 1–14. https://doi.org/10.1109/ICNS52807.2021.9441631.
Rimjha, M., Hotle, S., Trani, A., Hinze, N., 2021. Commuter demand estimation and feasibility assessment for urban air mobility in northern California. Transport. Res. Pol. Pract. 148, 506–524. https://doi.org/10.1016/j.tra.2021.03.020.
Röhl, K.H., 2019. Entrepreneurship: a comparative study of the interplay of culture and personality from a regional perspective. J. Small Bus. Enterpren. 31 (2), 119–139. https://doi.org/10.1080/08276331.2018.1462621.
Rothfeld, R., Balac, M., Ploetner, K.O., Antoniou, C., 2018. Agent-based simulation of urban air mobility. In: 2018 Modeling and Simulation Technologies Conference, p. 3891. https://doi.org/10.2514/6.2018-3891.
Rothfeld, R., Fu, M., Balać, M., Antoniou, C., 2021. Potential urban air mobility travel time savings: an exploratory analysis of Munich, Paris, and San Francisco. Sustainability 13 (4), 2217. https://doi.org/10.3390/su13042217.
Sadrani, M., Mirqasemi, R., Tirachini, A., Antoniou, C., 2024. Barriers to electrification of bus systems: a fuzzy multi-criteria analysis in developed and developing countries. Energy Convers. Manag. 314, 118700. https://doi.org/10.1016/j.enconman.2024.118700.
Sadrani, M., Najafi, A., Mirqasemi, R., Antoniou, C., 2023. Charging strategy selection for electric bus systems: a multi-criteria decision-making approach. Appl. Energy 347, 121415. https://doi.org/10.1016/j.apenergy.2023.121415.
Sarkar, B.D., Shardeo, V., Dwivedi, A., Pamucar, D., 2024. Digital transition from industry 4.0 to industry 5.0 in smart manufacturing: a framework for sustainable future. Technol. Soc. 78, 102649. https://doi.org/10.1016/j.techsoc.2024.102649.
Schweiger, K., Preis, L., 2022. Urban air mobility: systematic review of scientific publications and regulations for vertiport design and operations. Drones 6 (7), 179. https://doi.org/10.3390/drones6070179.
Seeleib-Kaiser, M., 2013. Welfare systems in europe and the USA: conservative Germany converging towards the US model? Int. J. Soc. Qual. 3 (2). https://doi.org/10.3167/IJSQ.2013.030204.
Siewert, S., Sampigethaya, K., Buchholz, J., Rizor, S., 2019. Fail-safe, fail-secure experiments for small UAS and UAM traffic in urban airspace. In: 2019 IEEE/AIAA 38th Digital Avionics Systems Conference (DASC). IEEE, pp. 1–7. https://doi.org/10.1109/DASC43569.2019.9081710.
Song, K., Yeo, H., 2021. Development of optimal scheduling strategy and approach control model of multicopter VTOL aircraft for urban air mobility (UAM) operation. Transport. Res. C Emerg. Technol. 128, 103181. https://doi.org/10.1016/j.trc.2021.103181.
Song, K., Yeo, H., Moon, J.H., 2021. Approach control concepts and optimal vertiport airspace design for urban air mobility (UAM) operation. Int. J. Aeronaut. Space Sci. 22, 982–994. https://doi.org/10.1007/s42405-020-00345-9.
Straubinger, A., Michelmann, J., Biehle, T., 2021. Business model options for passenger urban air mobility. CEAS Aeronaut. J. 12 (2), 361–380. https://doi.org/10.1007/s13272-021-00514-w.
Straubinger, A., Rothfeld, R., Shamiyeh, M., Büchter, K.D., Kaiser, J., Plötner, K.O., 2020. An overview of current research and developments in urban air mobility–Setting the scene for UAM introduction. J. Air Transport. Manag. 87, 101852. https://doi.org/10.1016/j.jairtraman.2020.101852.
Straubinger, A., Verhoef, E.T., de Groot, H.L., 2022. Going electric: environmental and welfare impacts of urban ground and air transport. Transport. Res. Transport Environ. 102, 103146. https://doi.org/10.1016/j.trd.2021.103146.
sUAS, 2023. Volocopter wins over young hearts with first Osaka and Hyogo flight. sUAS News – The Business of Drones. Retrieved July 12, 2024, from. https://www.suasnews.com/2023/12/volocopter-wins-over-young-hearts-with-first-osaka-hyogo-flight/.
Swanke, J.A., Jahns, T.M., 2022. Reliability analysis of a fault-tolerant integrated modular motor drive for an urban air mobility aircraft using Markov chains. IEEE Trans. Transport. Electr. 8 (4), 4523–4533. https://doi.org/10.1109/TTE.2022.3183933.
Tampa International Airport, 2023. Tampa International Airport hosts the first successful "air taxi" test flight in Florida. https://news.tampaairport.com/tampa-international-airport-hosts-the-first-successful-air-taxi-test-flight-in-florida/.
Tanrıverdi, G., Ecer, F., Durak, M.Ş., 2022. Exploring factors affecting airport selection during the COVID-19 pandemic from air cargo carriers' perspective through the triangular fuzzy Dombi-Bonferroni BWM methodology. J. Air Transport. Manag. 105, 102302. https://doi.org/10.1016/j.jairtraman.2022.102302.

Tanrıverdi, G., Merkert, R., Karamaşa, Ç., Asker, V., 2023. Using multi-criteria performance measurement models to evaluate the financial, operational, and environmental sustainability of airlines. J. Air Transport. Manag. 112, 102456. https://doi.org/10.1016/j.jairtraman.2023.102456.
Tarafdar, S., Rimjha, M., Hinze, N., Hotle, S., Trani, A.A., 2019. Urban air mobility regional landing site feasibility and fare model analysis in the greater northern California region. In: 2019 Integrated Communications, Navigation and Surveillance Conference (ICNS). IEEE, pp. 1–11. https://doi.org/10.1109/ICNSURV.2019.8735267.
Tuchen, S., 2020. Multimodal transportation operational scenario and conceptual data model for integration with UAM. In: 2020 Integrated Communications Navigation and Surveillance Conference (ICNS). IEEE. https://doi.org/10.1109/ICNS50378.2020.9223002, 2C1-1.
Usun, S.O., Bas, S.A., Meniz, B., Ozkok, B.A., 2024. Passenger satisfaction assessment in the aviation industry using Type-2 fuzzy TOPSIS. J. Air Transport. Manag. 119, 102630. https://doi.org/10.1016/j.jairtraman.2024.102630.
Vascik, P.D., 2017. Systems-level Analysis of on Demand Mobility for Aviation. Doctoral dissertation, Massachusetts Institute of Technology.
Vascik, P.D., John Hansman, R., 2021. Evaluating the interoperability of urban air mobility systems and airports. Transp. Res. Rec. 2675 (6), 1–14. https://doi.org/10.1177/0361198121991501.
Vascik, P.D., Hansman, R.J., Dunn, N.S., 2018. Analysis of urban air mobility operational constraints. J. Air Transport. 26 (4), 133–146. https://doi.org/10.2514/1.D0120.
Vempati, L., Geffard, M., Anderegg, A., 2021. Assessing human-automation role challenges for urban air mobility (UAM) operations. In: 2021 IEEE/AIAA 40th Digital Avionics Systems Conference (DASC). IEEE, pp. 1–6. https://doi.org/10.1109/DASC52595.2021.9594358.
Viswanathan, V., Epstein, A.H., Chiang, Y.M., Takeuchi, E., Bradley, M., Langford, J., Winter, M., 2022. The challenges and opportunities of battery-powered flight. Nature 601 (7894), 519–525. https://doi.org/10.1038/s41586-021-04139-1.
Volocopter, 2023. Volocopter dazzles with first flight in New York city. https://www.volocopter.com/en/newsroom/vc-flies-in-nyc.
Wang, Z., Delahaye, D., Farges, J.L., Alam, S., 2021. Air traffic assignment for intensive urban air mobility operations. J. Aero. Inf. Syst. 18 (11), 860–875. https://doi.org/10.2514/1.I010954.
Wang, Z., Delahaye, D., Farges, J.L., Alam, S., 2022. Complexity optimal air traffic assignment in multi-layer transport network for Urban Air Mobility operations. Transport. Res. C Emerg. Technol. 142, 103776. https://doi.org/10.1016/j.trc.2022.103776.
Wei, S., Li, L., Chen, G., Blasch, E., Chang, K.C., Clemons, T.M., Pham, K., 2023. ROSIS: resilience oriented security inspection system against false data injection attacks. In: 2023 IEEE Aerospace Conference. IEEE, pp. 1–11. https://doi.org/10.1109/AERO55745.2023.10115584.
Willey, L.C., Salmon, J.L., 2021. A method for urban air mobility network design using hub location and subgraph isomorphism. Transport. Res. C Emerg. Technol. 125, 102997. https://doi.org/10.1016/j.trc.2021.102997.
Wu, Z., Zhang, Y., 2020. Optimal eVTOL charging and passenger serving scheduling for on-demand urban air mobility. In: AIAA Aviation 2020 Forum, p. 3253. https://doi.org/10.2514/6.2020-3253.
Yedavalli, P., Cohen, A., 2022. Planning land use constrained networks of urban air mobility infrastructure in the San Francisco bay area. Transp. Res. Rec. 2676 (7), 106–116. https://doi.org/10.1177/03611981221076839.
Yunus, F., Casalino, D., Avallone, F., Ragni, D., 2023. Efficient prediction of urban air mobility noise in a vertiport environment. Aero. Sci. Technol. 139, 108410. https://doi.org/10.1016/j.ast.2023.108410.
Zhao, P., Post, J., Wu, Z., Du, W., Zhang, Y., 2022. Environmental impact analysis of on-demand urban air mobility: a case study of the Tampa Bay Area. Transport. Res. Transport Environ. 110, 103438. https://doi.org/10.1016/j.trd.2022.103438.