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Mapping research achievements on urban air mobility: A systematic literature review

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ABSTRACT

Urban Air Mobility (UAM) is a promising component of future mobility systems. To ensure its smooth and viable implementation, it is crucial that authorities, organizations, public services and stakeholders in general consider not only economic aspects but also environmental, safety and socio-economic factors through a holistic approach. However, the current literature primarily focuses on specific subtopics of UAM individually, failing to address the topic in an integrated and comprehensive manner. This study aims to overcome this limitation by conducting a Systematic Literature Review (SLR) on UAM, analyzing a database of 129 articles published between 2017 and 2023. Specifically, a bibliographic coupling analysis and a Multiple Correspondence Analysis (MCA) were performed. The results include a list of 150 indicators used to assess environmental, safety and socio-economic impacts of UAM, as well as the identification of four core thematic clusters: (1) *UAM Technology and its Sustainability*; (2) *Environmental Assessment*; (3) *Traffic Management for the Airspace Industry*; and (4) *Passenger Transport and Demand Management*. The findings of this research complement existing literature and contribute to the development of the field by shedding light on UAM's key stakeholders, impacts and the indicators used to assess these impacts.

1. Introduction

The concept of Urban Air Mobility (UAM) emerged from technological developments as a solution to address widespread urbanization and sustainability concerns [1,2]. It is defined as an *"emerging concept that envisions a safe, efficient, accessible, and quiet air transportation system for passenger mobility, cargo delivery, and emergency management within or traversing metropolitan areas"* ([3], p. 119). Currently, aviation organizations and logistics companies are developing flying taxi services in an effort to promote UAM, with expectations for a debut in the coming years [4–6]. Thus, UAM is anticipated to provide several advantages across various domains, with potential applications in multiple sectors, including healthcare [7] and law enforcement [8], since "[UAM] *has the potential to disrupt air transportation, providing disruptive innovation not only to aviation but also to mobility systems and urban planning*" ([9], p. 1). Nonetheless, although several authors explore the topic within the same context, a consensus regarding the adequacy of the term "Urban Air Mobility" has not been attained. The literature diverges on this matter, and terms such as UAM, Innovative Air Mobility (IAM), Unmanned Aircraft Systems (UAS) and Advanced Air Mobility (AAM) are frequently used interchangeably [9–11], lacking standardization across publications.

The current literature on UAM consists mostly of Systematic Literature Reviews (SLRs) that focus on specific topics rather than adopting a holistic approach. Within this scope, existing SLRs have examined UAM demand analysis [4], vertiport location and capacity [12], noise [13], security and safety concerns [14], vertiport design and operations [15] and autonomous and electric ground transportation [10]. Among the SLRs analyzed, only one has taken a broader approach to UAM. Kellermann et al. [16] addressed drones for parcel and passenger transportation within the socio-technical debate on drones' utilization for transportation purposes. Nevertheless, these authors identified as a limitation the inability to cover the entire spectrum of articles on the topic due to the high density of information within the thematic areas of research. They suggested that future research should expand the scope of analysis.

The need for a holistic approach to UAM is further emphasized by the upcoming requirement to integrate this type of mobility into Sustainable

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Urban Mobility Plans (SUMPs) to enhance the Trans-European Transport Network (TEN-T) corridors [17]. Achieving this goal necessitates collaboration among multiple stakeholders [16,18]. However, the identification of key stakeholders and their specific roles in UAM implementation remains unclear in the current literature and requires further exploration. Consequently, several aspects must be more thoroughly addressed and researched to develop a detailed understanding of the challenges that must be overcome to ensure the successful implementation of services utilizing UAM technologies [4,12].

Within this scope, the current literature clearly highlights the need for further research on UAM, particularly regarding: (1) social aspects, such as public acceptance and user adoption; (2) environmental aspects, including noise and visual pollution; (3) economic aspects, such as manufacturing and design costs [4]; and (4) safety aspects, encompassing accident scenario planning and travel safety [4,12].

Hence, this study makes two main novel contributions: (1) it adopts a holistic and integrated approach that considers UAM's social, environmental, economic and safety aspects, which are often analyzed separately in the current UAM literature; and (2) it compiles a list of indicators from the literature used to assess environmental, safety and socio-economic impacts of UAM's implementation. This list consolidates social and economic indicators under the same category (*i.e.*, socio-economic impacts), as most of them overlap between these two areas.

This study complements the literature by providing an integrated analysis of UAM's impact areas and indicators. In practice, it offers key insights to local authorities, municipalities and other policymakers, enabling them not only to develop more accurate urban planning strategies that consider both society and sustainability but also to enhance their decision-making processes to ensure the smooth integration of UAM services and increase their likelihood of success. The research questions that this study aims to answer are as follows:

- Who are the main stakeholders and what are their roles in the implementation of UAM?
- What factors influence perceptions of noise, visual pollution and overall acceptance of UAM by citizens?
- What are the main evaluation criteria used to assess the environmental, safety and socio-economic impacts of UAM implementation?

A content analysis of the thematic clusters containing 129 articles was conducted to answer the research questions mentioned above. Moreover, an in-depth bibliometric analysis, including a descriptive analysis, an analysis of the thematic evolution of the main topics and a bibliographic coupling analysis and a Multiple Correspondence Analysis (MCA) were performed to provide a more holistic and comprehensive approach to the topic.

The remainder of this paper is structured as follows: Section 2 explains the methodology adopted. Section 3 presents the bibliometric analysis of the literature, including a descriptive analysis, the thematic evolution of the topic and the bibliographic coupling analysis. Section 4 encompasses the MCA, the presentation of key research themes, geographical scope and methodological approaches along with their respective relevant references and frequencies, and recent research on UAM. Section 5 concludes with the findings, limitations of the study, theoretical and practical impacts, and suggestions for future research.

2. Methodology

Bibliometric analysis *"allows, within a certain research field, influential authors and their interrelations to be identified, providing researchers with a solid basis for positioning their contributions and detecting new avenues for future research"* ([19], p. 904). In the current study, a bibliometric analysis was conducted according to the procedures outlined in Ferreira and Ferreira [20]. The protocol followed comprised six steps: (1) formulation of research questions; (2) selection of a database; (3) formulation of the search string; (4) identification of criteria; (5) review of previous research; and (6) integration of outcomes.

The analysis performed allowed for the identification of the main stakeholders of UAM and their roles in its implementation, the factors contributing to perceptions of noise, visual pollution and overall citizens' acceptance of UAM, as well as the most relevant evaluation criteria used to assess the environmental, safety and socio-economic impacts resulting from the implementation of UAM. Furthermore, this analysis provided insights into the topic regarding the annual evolution of the number of publications, as well as the identification of the most relevant journals, keywords and themes. The bibliometric maps were generated using the Bibliometrix software [21].

The data used were provided by the Scopus database, which "*combines an expertly curated abstract and citation database with enriched data and linked scholarly literature across a wide variety of disciplines*" [22]. The choice of Scopus is justified by its broad coverage, as it includes more journals and publications compared to other databases, such as Web of Science [19,23].

The search string defined for this study comprised the following terms: *("urban air mobility")* OR *("innovative aerial services")* OR (*"advanced air mobility"*) OR (*"unmanned air mobility*"*) OR (*"air taxi*"*) AND (*"soci* accept*"*) OR (*"impact*" OR "assess*"*). The application of this search string, conducted in December 2023, resulted in 568 documents. Several restrictions were imposed to ensure homogeneity: (1) only articles and reviews were included, while conference papers, conference reviews, book chapters, errata and editorials were excluded; (2) only documents published between 2013 and 2023 were considered resulting into 167 articles; and (3) the sample was limited to articles or reviews written in English (Korean, Spanish, Portuguese, Japanese and Chinese were removed). The application of these criteria resulted in 160 documents. Finally, a content analysis was performed on each document's title, abstract, keywords and introduction. As a result, 31 articles were excluded for the following six reasons related to the research content: (1) it was not directly related to UAM; (2) it did not address UAM's stakeholders, impacts or indicators; (3) it focused exclusively on aerodynamics; (4) it focused exclusively on physics; (5) it focused exclusively on optimization; and (6) it focused exclusively on electronics.

The remaining documents were included since they were directly related to UAM and, specifically, to its stakeholders, impacts and/or indicators. Nevertheless, it is important to highlight that, even though the current study was developed within the scope of management/business, the direct removal of articles and reviews from other subject areas without any content analysis would jeopardize the study, as some of these documents offered important insights related to the research questions. Therefore, only documents that focused exclusively on or were restricted to other areas and did not provide any valuable contribution to the present study were excluded. Hence, as illustrated in Fig. 1, the final sample comprised 129 documents.

The database output was refined and standardized by creating a thesaurus file and uploading it to VOSviewer to merge all the different formats of the authors' names. Furthermore, using the Bibliometrix R package, the sources and keywords were standardized through the manual correction of their spelling (*e.g.*, "Urban Air Mobility" and "UAM").

Furthermore, we employed MCA to obtain an in-depth understanding of the data and complement the analyses performed with VOSviewer and Bibliometrix. MCA is an exploratory multivariate method for the numerical and graphical analysis of multivariate categorical data that conducts an indicator matrix homogeneity analysis to create a low-dimensional representation of the original data [21]. The advantages of this technique result from the combination of content analysis and an expert-based approach, allowing *"researchers to synthetize up-to-date findings and graphically depict the intellectual structure of the research field"* ([24], p. 2).

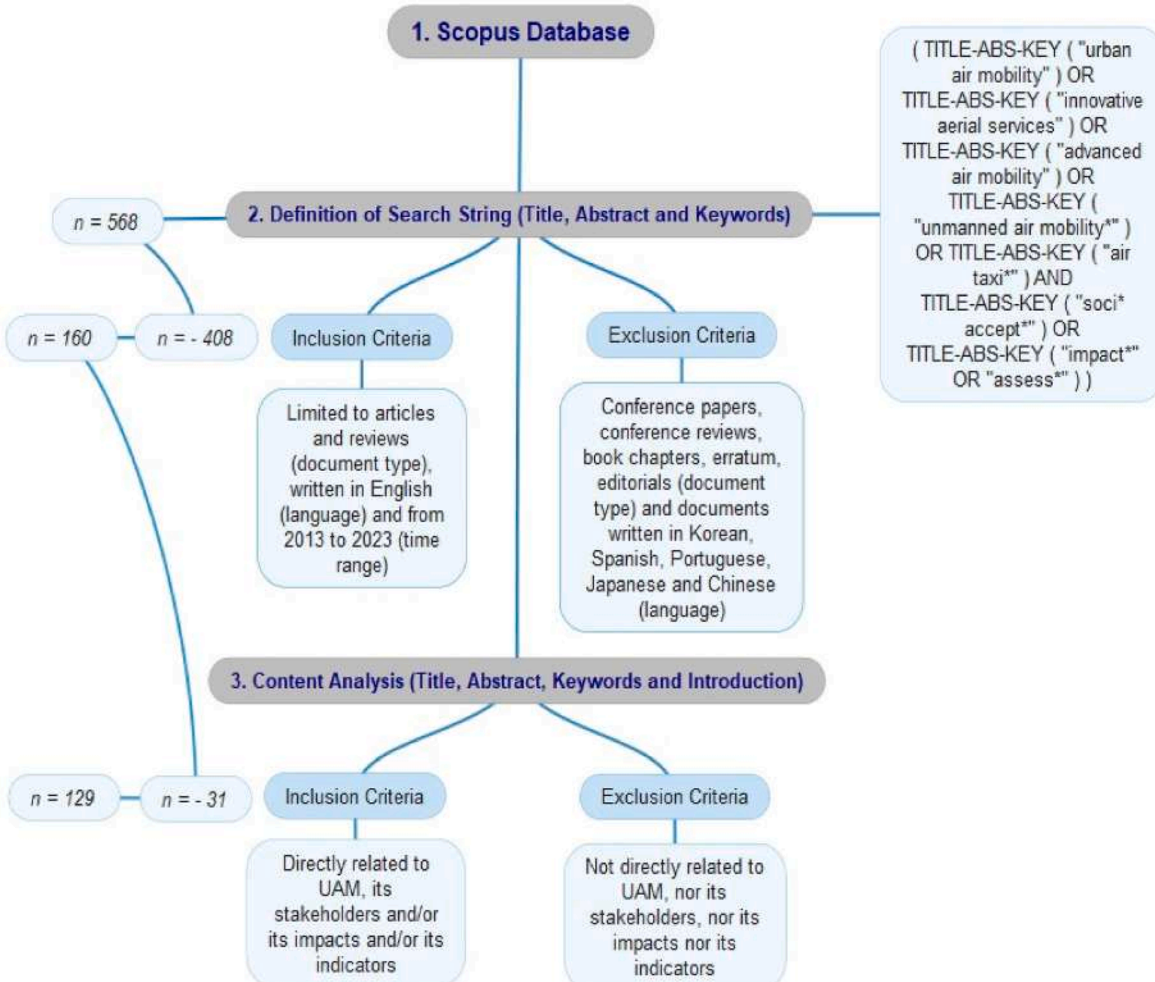

Fig. 1. Sample Selection Process

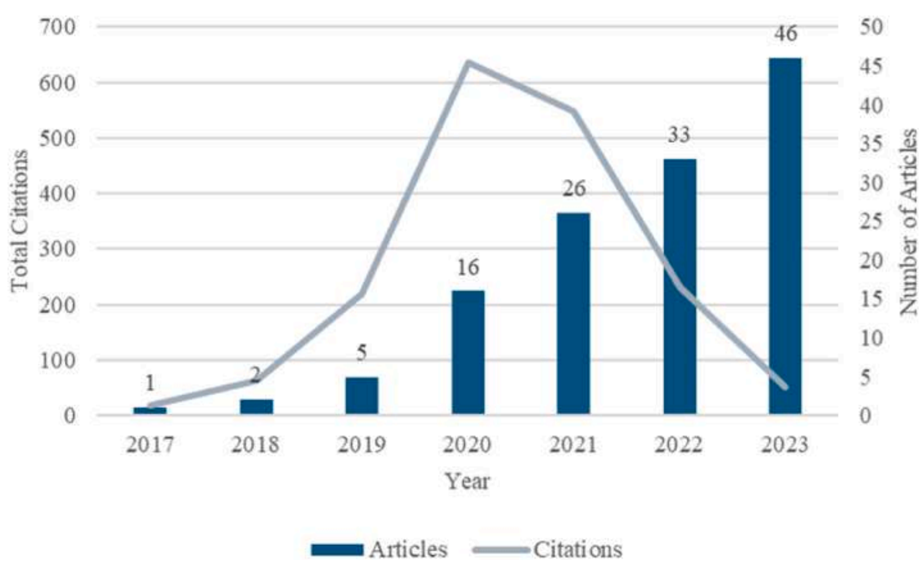

Fig. 2. Evolution of the number of publications.

3. Bibliometric analysis

3.1. Descriptive analysis

The present SLR was based on 129 articles published between 2017 and 2023, directly related to UAM and focusing on UAM's stakeholders and/or impacts and/or indicators. These publications encompassed a total of 64 sources, 389 authors, 6612 references and 429 author keywords. Based on Fig. 2, it seems evident that the number of publications until 2019 was relatively low, with only one publication in 2017, two in 2018, and five in 2019. However, 2020 marked a shift in this trend, with 16 publications, followed by 26 in 2021, 33 in 2022, and 46 in 2023. Overall, a continuous growth in the number of publications has been observed over the years.

Concerning the journals with the highest number of publications, it is possible to observe in Fig. 3 that these include: *Aerospace Science and Technology* (9); *Drones* (9), *Sustainability (Switzerland)* (8); and *Journal of Air Transportation* (7).

Regarding the five most globally cited documents, these are: Kellermann et al. [16] (147 citations); Al Haddad et al. [25] (127 citations); Bauranov and Rakas [26] (101 citations); Cohen et al. [27] (96 citations); and Fu et al. [28] (91 citations) (see Fig. 4).

The contributions of these five studies are as follows:

- The first study, entitled *"Drones for Parcel and Passenger Transportation: A Literature Review"* [16], is a systematic literature review (SLR) of 111 articles published between 2013 and March 2019 that addresses the technical and social debate on the use of civil drones for transportation. The study sheds light on the expected benefits, potential problems, anticipated barriers and proposed solutions. It offers an interdisciplinary perspective on the use of passenger and delivery drones through the analysis of the following clusters: public acceptance, environmental issues, urban planning and infrastructure, ethics, safety and security, and societal implications.
- The second paper, entitled *"Factors Affecting the Adoption and Use of Urban Air Mobility"* [25], develops adoption and intention to use models for UAM by identifying and quantifying the factors influencing its adoption and utilization. The study aims to enhance the understanding of user perceptions, acceptance and willingness to adopt UAM, based on user profiles and adoption time horizons. The models assume intra-city and on-demand transportation of passengers operated by completely automated electric vertical take-off and landing (eVTOL) vehicles, as well as integration with public transport systems, offering a ride-pooling option.
- The third article, entitled *"Designing Airspace for Urban Air Mobility: A Review of Concepts and Approaches"* [26], reviews concepts related to urban airspace design, pointing out strengths and weaknesses and offering recommendations for a broader approach. It develops a framework for assessing these concepts and identifies structural factors that define urban airspace capacity, size and geometry. These factors are allocated into four groups (vehicle, social, safety and system) that affect the airspace's physical structure. The paper also analyzes proposals for urban airspace management based on the abovementioned factors, identifying commonalities and highlighting best practices in airspace design.
- The fourth study, entitled *"Urban Air Mobility: History, Ecosystem, Market Potential, and Challenges"* [27], focuses on UAM's history, ecosystem, industry state and possible evolution through a multi-method approach, including 106 interviews with industry leaders and two workshops with stakeholders. Regarding UAM's history, present developments and expected milestones, the authors divide them into six distinct phases of historical and expected evolution: (1) concepts of the "flying car" from 1910 to 1950; (2) basic UAM operations using programmed helicopter services from 1950 to 1980; (3) the reappearance of on-demand services in the 2010s; (4) corridor services using vertical take-off and landing (VTOL) intended for the 2020s; (5) hub-and-spoke services; and (6) point-to-point services.
- The fifth paper, entitled *"Exploring Preferences for Transportation Modes in an Urban Air Mobility Environment: Munich Case Study"* [28], explores user preferences for urban transport modes (*e.g.*, public transportation, private cars, autonomous flying taxis, and autonomous taxis) and UAM adoption through a case study in Munich, Germany. This study analyzes the influence of service features on user choices and identifies characteristics of potential UAM users by applying a preference questionnaire to 248 residents of the metropolitan region of Munich.

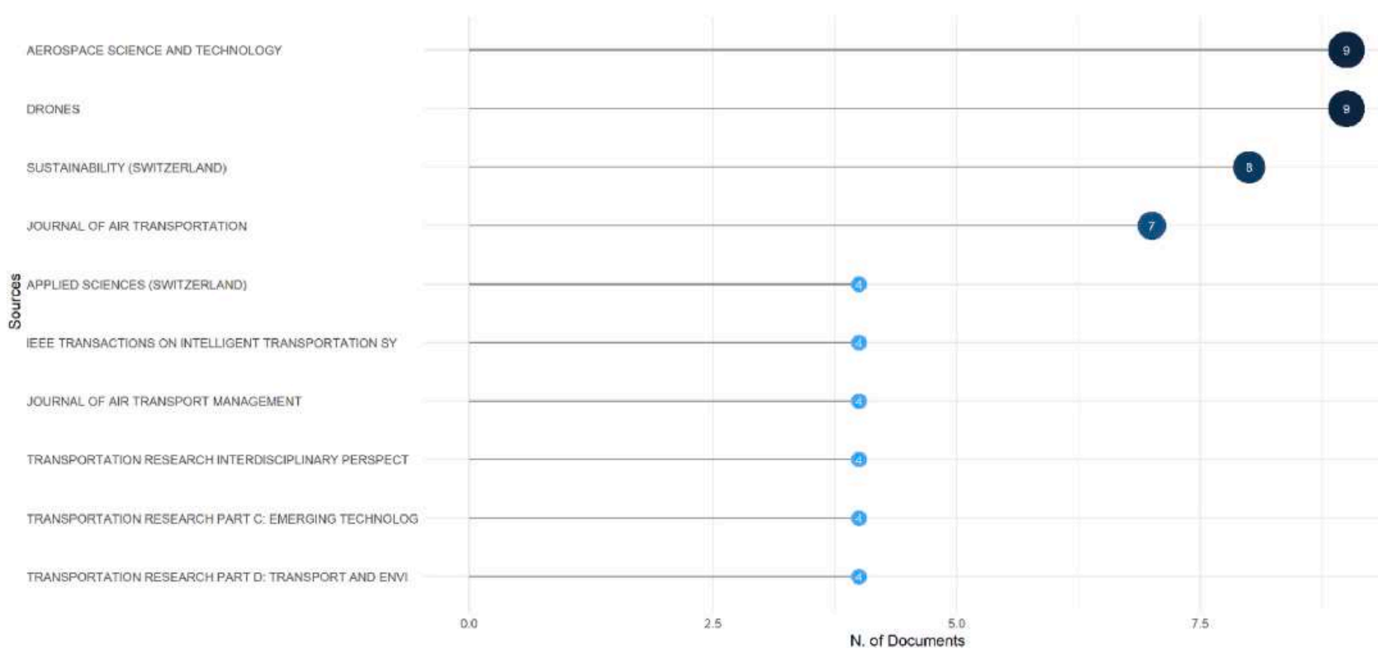

Fig. 3. Top Journals (by number of publications).
Source: Bibliometrix Software

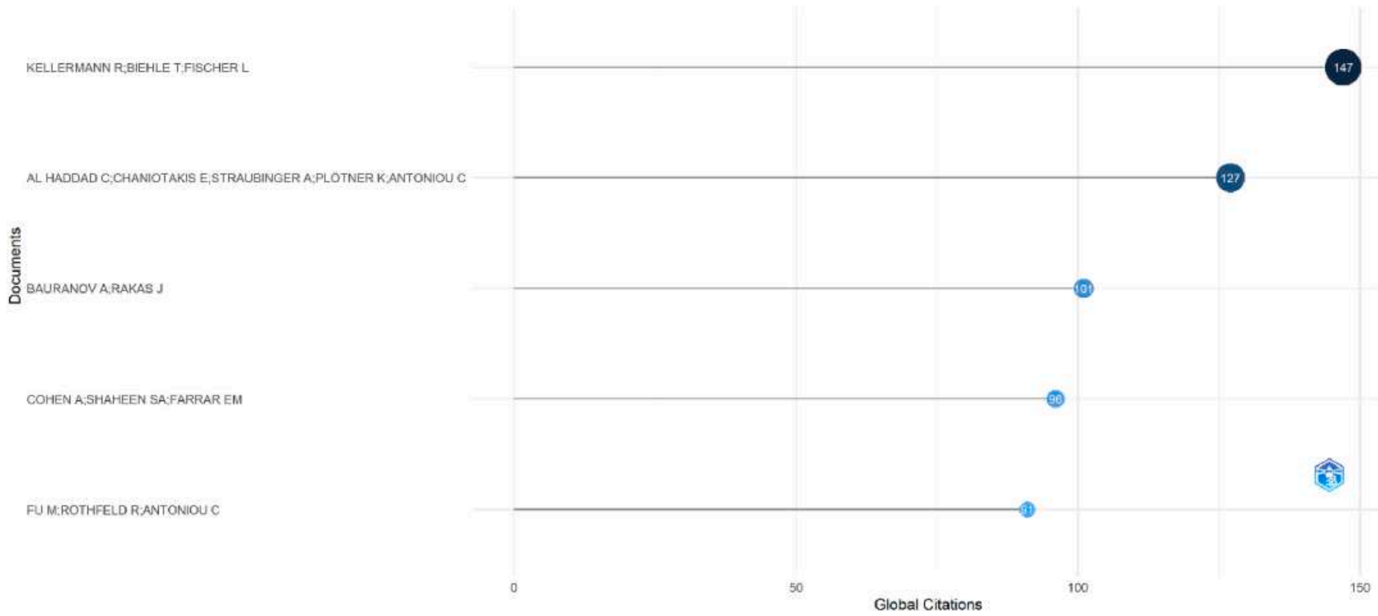

Fig. 4. Most global cited documents.
Source: Bibliometrix Software

Overall, these articles comprehensively address UAM's economic, social and regulatory dimensions, focusing on its stakeholders, impacts and indicators. They contribute to improving the understanding of UAM and its services and provide insights into the three research questions of this study.

3.2. Evolution by themes

To explore publications focused on UAM in the context of its stakeholders and/or impacts and/or indicators between 2017 and 2023, the Bibliometrix software was used, as it allows for obtaining the thematic evolution of keywords over designated timespans. As shown in Fig. 5, the results present the evolution of themes over time based on the authors' keywords.

The timeline was divided into three periods: (1) 2017–2020, which includes 24 articles; (2) 2021–2022, which contains 59 papers; and (3) 2023, which encompasses 46 documents. This division is justified by the difference in the number of articles published each year, as the number of publications was relatively low until 2020. The highest peaks occurred between 2020 and 2021 (with 10 more articles) and between 2022 and 2023 (with 13 more articles). It is seen that the literature has evolved significantly in the last two years. This division provides a clearer view of the most recent trends.

According to Fig. 5, during the first time period (*i.e.*, 2017–2020), the topics were mostly concentrated on "urban air mobility" and "drones". In the second time period (*i.e.*, 2021–2022), new topics emerged, such as "vertiport", "air taxi" and "unmanned aerial vehicle", while the theme "drones" converged with "unmanned aerial vehicle". In the final time period (*i.e.*, 2023), two new topics appeared: "acceptance" and "vertical take-off and landing (VTOL)", while the topic "unmanned aerial vehicle" converged with "urban air mobility", and the term "vertiport" converged with "air taxi" and "acceptance". This analysis helps to understand the thematic development of the literature on the topics under study.

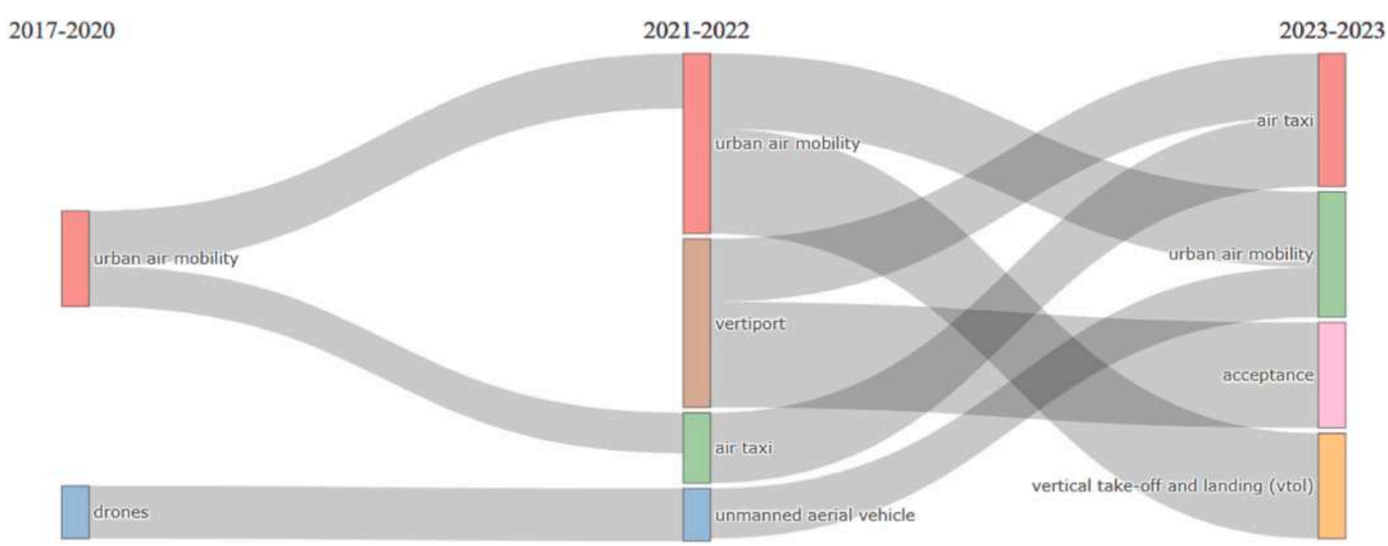

Fig. 5. Thematic evolution map.
Source: Bibliometrix Software

3.3. Key stakeholders and their role in UAM's implementation

To identify the key stakeholders, as well as their role in UAM's implementation, and thus answer the first research question of this study, a content analysis of the articles was conducted. It was verified that the involvement of diverse stakeholders is necessary, namely regulators, authorities, UAM operators, airspace management service providers, infrastructure providers, original equipment manufacturers, UAM users [29], guideline development organizations, governments, agencies and key players in the aviation industry and market, to attain effective implementation of UAM [30]. In a more detailed analysis, Ali et al. [31] highlight the importance of effective collaboration among three groups of stakeholders: UAM manufacturers, end-users and regulators, for efficient and safe UAM operations. Specifically, their roles encompass the following aspects: (1) manufacturers are required to fulfill operational obligations and regulations; (2) regulators are required to identify the mandatory regulations for UAM operations, as well as the operators' training stipulations; and (3) end-users can influence the performance of UAM operations through their interaction with the operator. In turn, Al-Rubaye et al. [32] include consumers and local government agencies in the UAM ecosystem, in addition to vehicle manufacturers, UAM service providers and airspace regulators.

Schweiger and Knabe [33] introduced a Vertidrome Airside Level of Service (VALoS) framework, which merges the requirements of several stakeholders: the vehicle operator, the passenger and the vertidrome operator. Each stakeholder has specific performance targets and metrics [34]. Therefore, this framework allows the alignment of diverse stakeholders' interests while fostering efficient and sustainable vertidrome planning and subsequent operation. Moreover, when necessary, other stakeholders, such as booking platform operators, pilots, air navigation service providers and U-space service providers, can also be included in the framework [33].

In this context, the stakeholders' perspectives concerning UAM's operation, benefits, challenges and risks associated with early use cases are considered crucial for the successful deployment of passenger UAM. These perspectives help establish the right use cases for the current stage of UAM development, leading to improved adoption rates and economically feasible use cases [35]. The stakeholders in the UAM ecosystem include policymakers, consultants, product owners, investors, researchers, pilots, journalists, managers in aviation corporations and supporting institutions [35]. These stakeholders identify emergency/medical services and airport shuttles as the most suitable use cases for the early operations of passenger UAM. These use cases are expected to offer the greatest potential benefits while having low complexity. The main challenges and benefits for implementing passenger UAM, as perceived by the stakeholders, are as follows: community acceptance, infrastructure and regulations are the primary challenges, while higher quality of life, economic gains and environmental impact reduction are the most significant benefits.

Moreover, the stakeholders consider technology failure, physical object interference and air and ground accidents as the key hazards. Regarding risk assessment, community backlash is perceived as the most hazardous risk due to its high probability of occurrence and significant impact on viability, placing it in the very-high-risk zone. Other relevant risks, categorized in the high-risk zone, include turbulent weather, unprofitable business models, accidents, technology failure, object interference, inadequate Air Traffic Management (ATM), battery-related issues and pilot errors [35]. Although the benefits and challenges perceived by different stakeholders may vary, in the context of a holistic approach, they must be considered in an integrated manner. Nevertheless, the stakeholders mentioned above are not the only ones with a key role in UAM's implementation. Apart from the end-users of UAM services, non-users, as citizens, are vital for UAM's success. Their lack of acceptance may represent a significant constraint for the integration of these services into societies. Kellermann and Fischer [36] addressed the public acceptance of drones by analyzing context-, subject- and object-related factors that affect the public's perception of drone utilization. These factors included: (1) regulation, infrastructure and airspace management, and technology's impact on quality of life and the social fabric of the community; (2) people's attitude toward technologies in general; and (3) environmental friendliness, security and safety, and technology usefulness.

3.4. Bibliographic coupling

The next step in this SLR involved the creation of a bibliographic coupling analysis. Bibliographic coupling *"occurs when two articles reference a common third article in their bibliographies, indicating that there is a probability that the two articles address a related subject matter. The 'coupling strength' of two given articles is higher the more citations to other articles they share"* ([37], p. 349). In this regard, a coupling map was developed using the Bibliometrix software and was utilized to identify the key dimensions of this research (see Fig. 6).

In Fig. 6, the four main themes of this study can be identified: (1) *UAM Technology and its Sustainability*; (2) *Environmental Assessment*; (3) *Traffic Management for the Airspace Industry*; and (4) *Passenger Transport and Demand Management*. The clustering process was developed directly by the Bibliometrix software, which allocated the majority of the articles to the corresponding clusters. This process was based on keyword frequency, being important to emphasize that it is expected to exist some topic overlaps among different clusters. Thus, the clusters reflect the thematic directions and general orientations of the studies included in them and they should not be considered as mutually exclusive or absolute. However, since the software only coupled 94 out of the 129 articles, the content of the remaining articles was thoroughly analyzed to accurately allocate them into the respective clusters. As a result, 6 articles were subsequently integrated into Cluster 1, 4 articles into Cluster 2, 16 articles into Cluster 3, and 9 articles into Cluster 4. However, it is important to note that although some articles were automatically allocated to the clusters by the software, their relationship with the main topics of the corresponding cluster is not always evident. Consequently, the following analysis will focus on the most relevant articles. Nevertheless, for each cluster, a list of the indicators identified within all its corresponding articles was created. This list encompasses the main evaluation criteria used to assess three primary impact areas (*i.e.*, environmental, safety and socio-economic) resulting from the implementation of UAM. It provides information regarding each indicator's definition and effect, the type of drone associated with it, how the data was extracted, and whether the indicator was defined and measured (see *Appendix*). The development of the bibliographic coupling analysis enabled the answering of the second and third research questions of this investigation, shedding light on the contributing factors for the perceptions of UAM's noise, visual pollution and general acceptance, as well as on the identification of the main evaluation criteria mentioned above.

1) *UAM Technology and its Sustainability* Cluster. This cluster comprises 35 articles that examine UAM technology and sustainability from a variety of perspectives. These perspectives include the technological aspects of UAM vehicles and their components, the external environmental factors impacting operations, social acceptance issues and the infrastructures and operations necessary for UAM's successful integration into urban systems.

UAM has evolved from initial helicopter flights to on-demand mobility services, which are expected to be followed by the introduction of corridor services utilizing VTOL aircraft [27], marking a new era in the urban transport system [10]. UAM could improve urban mobility [38] and allow citizens to overcome on-ground traffic congestion [5], while reducing travel times between places in urban contexts [39].

Enhancing sustainability is one of the main goals of introducing UAM into mobility systems. Hence, the development of environmentally

Fig. 6. Coupling map.
Source: Bibliometrix Software

sustainable UAM vehicles is vital to decrease environmental issues like noise emissions, climate change and global warming [40]. In this regard, these authors found that sustainable aviation fuels have the same performance as more traditional fuels while causing a significantly smaller environmental impact. Nevertheless, Straubinger et al. [41] stated that UAM services produce fewer CO2 emissions compared to fuel-based cars, but when compared to electric cars, those emissions are higher. In turn, O'Reilly et al. [42] highlight the importance of the existence of a fuel management ecosystem approach to improve sustainability and decrease pollutant emissions, while Zaporozhets et al. [43] state that the electrification of aircraft is perceived as a solution to decrease these emissions and fuel consumption. Moreover, Kiesewetter et al. [44] state that even though hybrid engine designs are considered more pollutant in terms of emissions compared to current public transportation options, the increasing understanding and research on hydrogen and sustainable fuels has the potential to transform them into a more environmentally friendly alternative. Furthermore, Enconniere et al. [45] examined a conceptual coaxial rotorcraft performance and concluded that emissions are significantly reduced at high velocities when flights occur at elevated altitudes.

In addition to the characteristics of UAM vehicles, their specific components also play a key role in improving sustainability, with potential direct impacts on the introduction and utilization of UAM services. In this regard, Johnsen et al. [46] concluded that the implementation of a hybrid turboelectric power system in a UAM vehicle requires the application of several measures related to: (1) thermal management, with the necessity to integrate effective cooling solutions that are adequate to cope with high temperatures; (2) electrical safety features, with the need for the implementation of battery protections; and (3) battery sizing, with the necessity to ensure that the batteries have the appropriate size to fully power the system.

Nevertheless, it is important to acknowledge the challenges faced by UAM technologies in terms of external conditions, particularly related to the environment. In this scope, Wang et al. [47] analyzed electric flights in unpredictable and extreme urban environments, concluding that the performance of electric vehicles is influenced by several external factors, including micro-climate, seasonal variations, wind and the urban heat island effect. In line with this, Reiche et al. [48] state that low temperatures, thunderstorms and strong winds may be some of the biggest weather issues. Thus, the analysis and prediction of weather conditions are vital to ensure the safety and efficiency of UAM operations [49], as well as to enhance citizens' acceptance of UAM and their perception of these services as a safe transportation alternative [48].

Social receptiveness and acceptance, along with the potential adoption of UAM technologies, are also influenced by perceived benefits and concerns, the anticipated fulfillment of urgent social needs, the suitability of UAM per flight purpose, and environmental features and issues [18,50], such as noise [51]. Moreover, aspects related to safety, travel cost, travel time [28], trust, service reliability and automation costs [25] may be vital for consumers' adoption of UAM services. Nonetheless, it is important to note that according to Straubinger et al. [1], who analyzed and assessed a scenario where UAM was introduced, welfare gains were obtained for high-skilled households, whereas welfare losses occurred for low-skilled households.

In general, UAM's success depends on the system's operational efficiency [52]. Therefore, the impacts of flying sensors [53], synthetic sensors [54] and battery performance [55] on UAM operations must be analyzed and optimized. In addition, flight planning and trajectory definition are also vital to minimize operating costs and travel time while supporting and improving operational planning and efficiency [56,57]. In terms of infrastructures, vertiports have a crucial role in UAM's successful implementation and operation. Their placement, reachability, and frequency impact the overall accessibility of UAM [58], while their location is a key factor that impacts the risk of collision in UAM operations [59]. Shao et al. [60] enhanced the importance of a multi-vertiport system to guarantee efficient and safe UAM operations in an elevated flight density context. Nevertheless, it is important to note that vertiports' construction, maintenance and operation cause energy consumption and produce emissions [61].

Based on the analysis of the documents contained in this cluster, it was possible to identify 28 indicators within 11 articles and allocate them into environmental, safety and socio-economic impact areas as shown in Table 1 (in Appendix). The impact area with the most representation pertained to environmental impacts, counting 15 indicators, followed closely by socio-economic impacts with 12 indicators, while the least represented impact area concerned safety impacts with a single indicator. Only four indicators were referred to in these documents more than once: "Effective perceived noise level (EPNL)", mentioned in two papers [44,51]; and "Households", "Low-skilled households" and "High-skilled households", referred to in two articles as well [1,41].

These last three indicators were also the most measured among this cluster, as they were measured in the two articles in which they were addressed. In this context, from the 28 indicators of this cluster, only 16 were measured.

2) *Environmental Assessment Cluster*: This cluster incorporates 48 documents, with many focusing on environmental aspects such as noise and visual pollution. Additionally, the potential environmental impacts of UAM operations, vehicles and their components on the overall introduction of UAM are also explored in these studies. These documents examine how UAM could affect environmental sustainability, emphasizing the need for environmentally friendly solutions to mitigate negative impacts such as noise emissions and visual disturbances.

The introduction of UAM services to urban mobility brings multiple environmental benefits, including a reduction in CO2 emissions due to decreased ground traffic, which contributes to mitigating global warming and climate change, ultimately paving the way toward carbon neutrality [62,63]. Additionally, UAM services promote modal shifts, offering a solution to urban traffic congestion [11,62,63]. UAM for delivery purposes can also reduce greenhouse gas emissions compared to ground vehicles, improving air quality and enhancing sustainable mobility. Furthermore, UAM services offer social benefits, such as improved accessibility and faster medical deliveries [13]. However, it is important to recognize that increasing the number of vertiports and lowering the cost of UAM services could potentially lead to higher emissions [64].

Addressing potential negative environmental impacts, such as noise, is crucial for the successful introduction and adoption of UAM services [65]. This is because excessive noise can undermine the positive social and environmental effects that UAM could offer [13]. Virtual flight simulations show that flight paths significantly influence noise distribution [66,67], while a high-fidelity computational approach reveals that buildings create reflections that amplify the spread of noise [68]. Moreover, because UAM operations occur at low altitudes, noise from these vehicles may not be masked by buildings or ambient noise, potentially disturbing residents [69].

Beyond the propagation and emission of noise, understanding psychoacoustic factors and human perception of noise is essential to mitigating its effects and improving social acceptance [70]. The main psychoacoustic factors linked to noise annoyance include tonality, sharpness, loudness, roughness and impulsiveness [13]. Among these, loudness is the primary cause of noise annoyance. UAM-generated noise is often perceived as more disturbing than that of road traffic or traditional aircraft [13].

Gao et al. [71] proposed the concept of virtual acoustic terrain to support noise-conscious trajectory planning for UAM in complex urban environments. This tool also aids in selecting vertiports that minimize social impact. Addressing noise is critical not only to ensuring public acceptance but also to protecting citizens' health, as noise can lead to cognitive impairment, sleep disturbances, cardiovascular issues and mental health challenges [13].

Regarding visual pollution, Thomas and Granberg [72] identified two main contributors: the number of UAM vehicles and the distance between the viewer and the vehicle. However, visual pollution from UAM vehicles used for medical emergencies is generally more tolerable. Key factors influencing visual pollution include the vehicle's purpose (*e.g.*, passenger transport, cargo, or medical emergency), the environment (urban or rural), appearance, awareness, distance, movement and the temporal component [72]. Visual pollution can lead to anxiety, stress, decreased work efficiency and distraction [72], similar to the health impacts of noise. To mitigate these effects, flight routes can be adjusted to ensure that UAM vehicles fly over water or sparsely populated areas, avoiding sensitive landscapes [26].

Noise, visual pollution, air emissions, energy consumption and space requirements per passenger all contribute to the environmental indicator for UAM assessment, as outlined by Ploetner et al. [73] and Al Haddad et al. [74]. These environmental impacts directly affect public acceptance [75], with acceptance dependent on how UAM services are introduced and the perceived benefits to society [76]. In drone delivery applications, noise, visual pollution and stress due to increased airspace traffic can significantly influence public acceptance [75]. The characteristics of UAM vehicles and their components also play a crucial role in determining the environmental impacts of these services [77]. Factors such as noise, life-cycle cost and sustainability are important when choosing between different fleet options [78], and a balanced fleet heterogeneity is vital for optimizing operational efficiency and service quality [79].

Regarding the environmental impacts of UAM vehicle components, air pollutant emissions are closely tied to the power production system of these vehicles [64]. The use of hydrogen fuel cells offers the potential to reduce key issues associated with batteries and decrease environmental impacts [80]. Furthermore, hybrid hydrogen-powered plants may reduce emissions and energy consumption [81], while hybrid-electric systems help lower NOx emissions and overall environmental impacts [82–84]. Although batteries can also reduce environmental issues, they face challenges regarding duration [85] and safety, which must be addressed for their viability [86]. Solid-state batteries may provide a solution to these challenges.

From the analysis of 52 indicators identified across 8 articles in this cluster, socio-economic impacts emerged as the most significant category, with 38 indicators, followed by environmental impacts (12 indicators) and safety impacts (2 indicators) (see Table 2 in Appendix). The most frequently mentioned indicators were "Energy consumption" and "Air emissions", which appeared in three articles [64,73,74]. Fourteen indicators were only measured once, while the remaining indicators were not measured.

3) *Traffic Management for the Airspace Industry Cluster*: This thematic cluster comprises 25 articles, many of which examine airspace traffic management, particularly in relation to UAM operations and infrastructure.

A proper Air Traffic Management (ATM) system is essential for the successful launch and ongoing development of UAM operations, requiring the collaboration of multiple stakeholders [87,88], such as airline managers, transport system regulators and airport managers [89]. As noted by Vascik et al. [90], the following key questions need to be addressed for UAM operations: (1) "*What airspace volumes may the operators fly in?*"; (2) "*How should traffic be structured in this airspace?*"; and (3) "*How are ATC* [Air Traffic Control] *services provided in this airspace?*" (p. 124). Traffic structure pertains to the trade-offs between structured and unstructured airspace concepts in terms of system performance, while ATC services' provision involves trade-offs between a distributed and centrally managed system [90]. Integrating passenger UAM at airports with traditional runway systems is advised only during off-peak hours or for airports with small runways, as otherwise, it could lead to traffic delays [91]. Furthermore, Rajendran et al. [92] suggest that U-space traffic management decisions should factor in charging time for UAM vehicles, as extended charging periods could significantly reduce vehicle utilization and affect customers' waiting times, thus impacting the overall user experience.

In terms of airspace safety and security management, direction and speed control are important for conflict identification and resolution without compromising safety, unless UAM vehicles are particularly efficient while hovering [93]. Situational awareness is also critical to ensure safety and guide decision-making [94]. In this context, several security and procedural checks must be conducted [95], including preventive measures for adverse weather conditions, to ensure passenger safety [96] and avoid potential hazards for the aircraft [97].

Airspace security remains a significant concern for UAM's operations and traffic management due to the vulnerability of UAM technologies to cyber-attacks [98]. This necessitates the implementation of measures to combat these threats while ensuring data privacy [99] and overall cybersecurity [100]. Additionally, infrastructure is critical to UAM's traffic and operations management [101]. Zhang et al. [102] analyzed vertiport capacity and concluded that congestion is more likely to occur at the landing platform rather than the takeoff platform. Sinha and Rajendran [103] explored the location of these infrastructures based on potential demand and recommended larger vertiports for airports with higher demand. Preis and Hornung [104] examined vertiport airfields' operational dynamics, concluding that there is a threshold beyond which operations become unstable, leading to an exponential increase in passenger delays. Nonetheless, capacity constraints could limit UAM's introduction and operations, with challenges such as insufficient infrastructure opportunities [105] and logistical capacity issues affecting operational efficiency [105,106].

A comprehensive content analysis of this cluster's papers identified 15 indicators, grouped into environmental, safety and socio-economic impact areas. The most significant impact area was socio-economic, with 12 indicators, while environmental impacts had fewer indicators, at only two. Safety impacts were even less represented, with only one indicator (see Table 3 in Appendix). The indicator "Arrival punctuality" was mentioned more than once, appearing in two papers [33,34], and was the most frequently measured indicator, being evaluated in both articles. Out of the 15 indicators identified in this cluster, 11 were measured.

4) *Passenger Transport and Demand Management Cluster*: This theme encompasses 21 articles, many of which focus on the current state of UAM and its prospects for implementation. These studies emphasize the crucial role of public and user acceptance in ensuring the successful integration of UAM services into urban mobility.

Kellermann et al. [16] state that the literature has increasingly addressed the utilization of drones for passenger and delivery transportation purposes, driven by expectations of economic benefits, as well as environmental and social enhancements. Nevertheless, several technical specifics, as well as potential impacts of drones on the environment and society, remain uncertain. To overcome arising barriers and challenges, UAM services should address legal and technical issues, public acceptance, planning and infrastructure aspects, economic considerations, safety and security, and environmental factors.

Concerning the current state of UAM development and the future prospects of UAM passenger transport, Pons-Prats et al. [9] identified the major operational and implementation challenges of UAM, which were divided into five areas: (1) Technology (propulsion systems, autonomous vehicles, vehicle design and 5G network); (2) Infrastructure (take-off and landing areas, network design and integration, communication infrastructure and ATM/U-space); (3) Services (on-demand services, UAM as a Service and high luxury UAM); (4) Societal Considerations (safety, noise reduction, privacy, and land use and visual disruption); and (5) Policies (regulation and certification). All these areas are interrelated and, therefore, must be considered together for the successful introduction of UAM, with direct collaboration between diverse stakeholders playing a crucial role.

To improve social acceptance, mitigation measures can be applied. These may include: (1) limiting the minimum altitude for drone flights; (2) defining no-fly zones for drones; (3) establishing strategic locations for vertiports; (4) developing public knowledge regarding drone operations and technologies; (5) limiting or avoiding drone hovering; (6) promoting the use of renewable energy sources to recharge batteries; (7) ensuring proper battery maintenance to extend their lifecycle; (8) using eco-friendly drones; (9) ensuring that drone service costs align with the value of the activity; (10) fostering a safety and risk culture within the drone industry; (11) flying direct paths to reduce air time and avoid unnecessary route extensions; (12) utilizing various methods to enhance communication security; (13) promoting activities concerning drone operations and technologies to encourage public engagement; (14) highlighting the environmental benefits of drones; and (15) ensuring that the electronic devices on drones cannot be used to violate privacy [107]. Furthermore, marketing strategies must be developed to improve consumers' perceptions of these services while addressing their concerns [108].

Besides general consumer acceptance and perception [109], it is also important to understand consumers' willingness to utilize UAM services [110], which is influenced by six predictors: value, familiarity, happiness, fun factor, fear and wariness of new technology [111]. In this regard, it is vital to understand and analyze the potential demand and market potential of UAM services to provide information for: (1) supporting public sector planning and decision-making processes; and (2) assisting private sector investments and infrastructure development [112]. It is important to highlight that several factors influence UAM's market demand, such as cost, time, congestion, distance, privacy, and safety [4].

Based on the estimated demand for these services, the location of infrastructures and vertiports must be defined. While Rajendran and Zack [6] state that the "willingness to fly" rate and time savings do not significantly affect decisions regarding location and the number of sites, Lim and Hwang [113] argue that the number and location of vertiports significantly affect travel time.

Roy et al. [114] developed a framework to identify the fleet size necessary to meet user demand and concluded that the profitability of an operator is influenced by factors such as income distribution, ticket price, population density, fleet size, vehicle operating costs and top-level aircraft requirements. Meanwhile, Rajendran and Shulman [115] analyzed air taxi operations to determine the number of vehicles needed to meet UAM demand and found that the number of vehicles and ride capacity settings do not significantly affect the total number of customers.

Regarding the selection of the best alternatives for package delivery, Rajendran and Harper [116] concluded that UAM alternatives are not the best sustainable, time-efficient or cost-effective options due to the current lack of operational sites. However, UAM services also provide non-monetary benefits for the environment and society. These benefits include: (1) passengers' travel time savings; (2) reduced passengers' safety costs; (3) cost and delivery time savings in drone package delivery; (4) time and inventory cost savings in eVTOL cargo delivery; (5) savings in bridge inspections' costs and travel time delays; (6) cost savings in agriculture; (7) life-saving benefits of drones in medical deliveries; (8) increased tax revenue for governments; and (9) savings in the social cost of greenhouse gases [117]. Ditta and Postorino [118] suggest an urban air network that incorporates a third (vertical) dimension to assist low-airspace air traffic, while Husemann et al. [119] state that dispatcher parameters, such as the urgency of a request and the frequency of re-optimization, greatly affect fleet efficiency.

In general, the critical success factors with the most influence on the adoption of air-taxi services include: (1) government regulations; (2) a skilled workforce; (3) a conducive research environment; (4) emissions; and (5) battery range [120]. It is also important to highlight that safety is a critical issue in the aviation industry, and UAM for passenger transportation is no exception. Therefore, understanding the main causes of air taxi accidents is essential to finding effective solutions to improve safety. The main sources of accidents are: (1) flight crew errors; (2) technical failures; and (3) environmental factors [121].

Based on the examination of this cluster's documents, 55 indicators across 11 articles were identified and categorized into environmental, safety, and socio-economic impact areas (see Table 4 in Appendix). On the one hand, the two most relevant impact areas were safety impacts, with 27 indicators, and socio-economic impacts, with 24 indicators. On the other hand, the least relevant area was environmental impacts, with only 4 indicators. The most frequently mentioned indicator was "Technological failures of autonomous systems", which was referenced four times [4,16,35,121]. Fourteen indicators were mentioned three times, seven indicators were mentioned twice, and the remainder were cited only once. Only 15 of the 55 indicators in this cluster were measured, and each was measured only once.

4. Discussion

To complement the bibliometric analysis, a MCA based on the authors' keywords was performed. This MCA resulted in a factorial analysis map, which was subsequently analyzed and refined to retain only the keywords relevant to key research themes or methodological approaches. The final factorial analysis map is presented in Fig. 7.

The map projects the two most representative dimensions based on explained variance. Dimension 1 accounts for 25.95% of the explained variance, while Dimension 2 accounts for 16.36%. These dimensions primarily reflect themes related to technology and sustainability, and traffic and demand management, respectively.

Furthermore, to summarize the current state of UAM research and enhance its understanding, the literature was analyzed and classified into three main categories: key research themes, geographical scope and methodological approach. Fig. 8 presents these three overarching topics along with their respective subtopics and the most relevant references associated with each.

Regarding the key research themes, the analysis identifies the following areas: (1) UAM sustainability, addressing the importance of sustainable vehicles and components in promoting environmentally friendly mobility solutions; (2) UAM technology, focusing on the design and performance of vehicles, which are essential for the successful integration of UAM services; (3) UAM infrastructures, emphasizing vertiports—particularly their location, capacity and accessibility—as

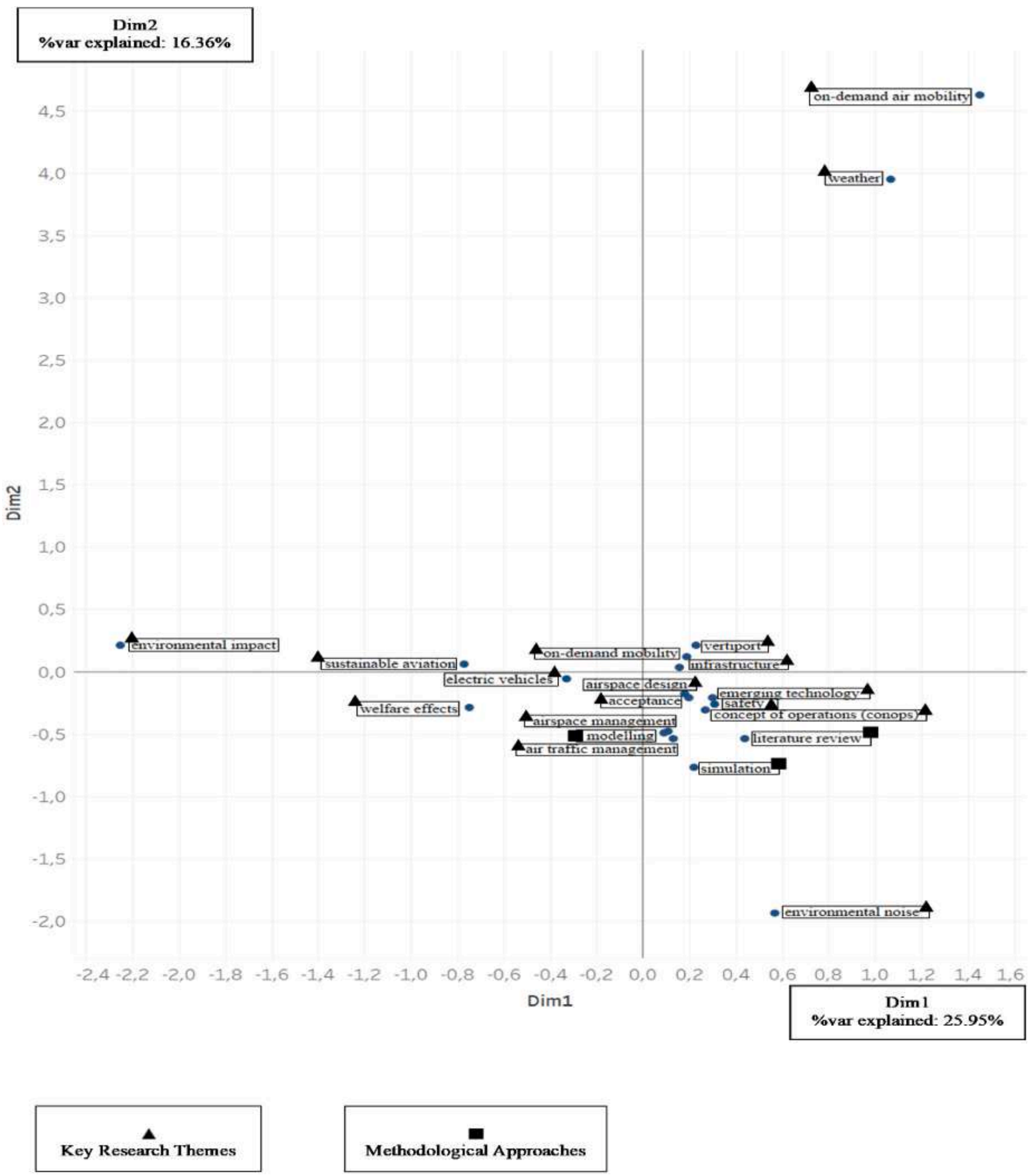

Fig. 7. Factorial analysis map.

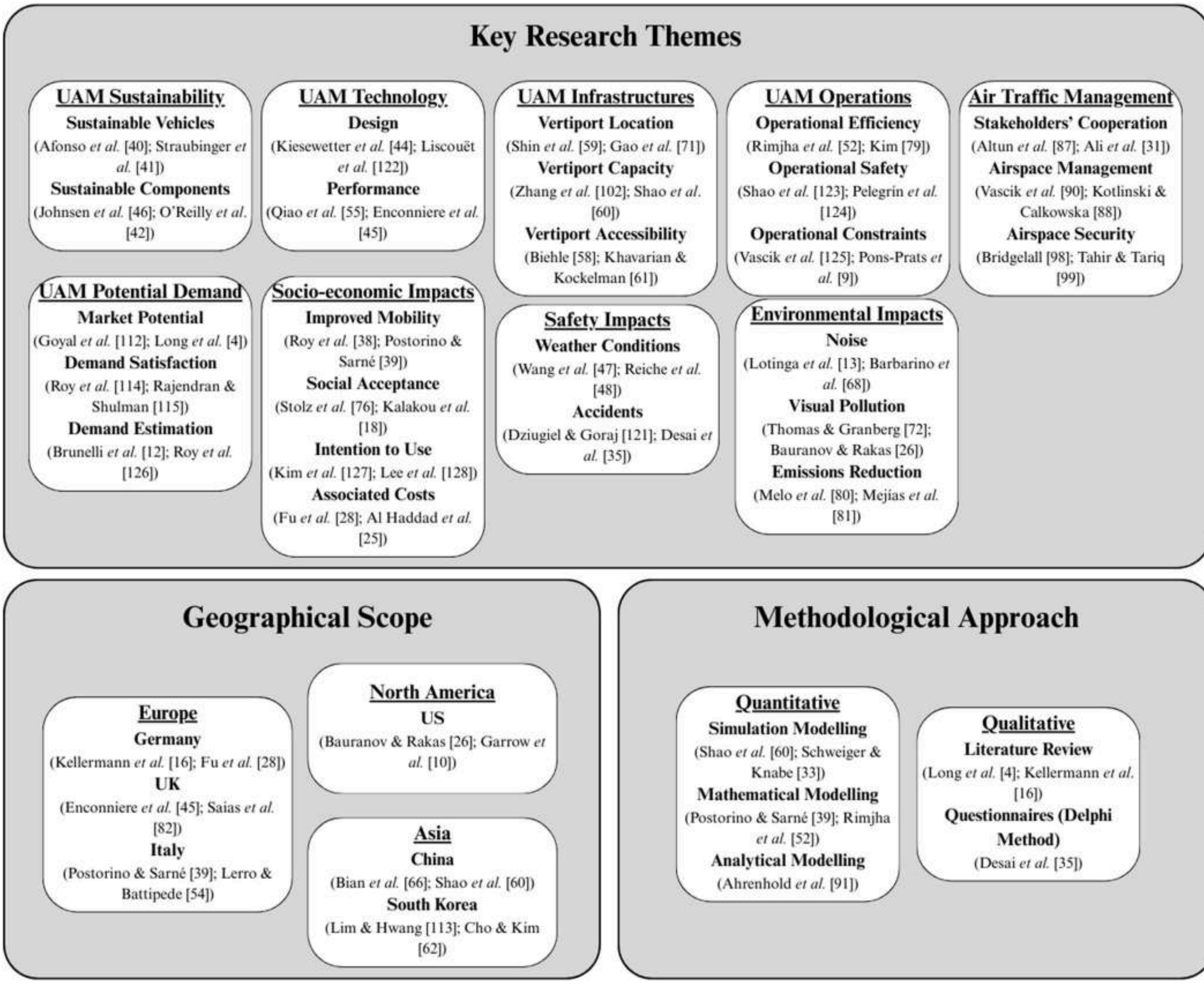

Fig. 8. Relevant references concerning UAM's key research themes, geographical scope and methodological approaches [122–128].

critical factors for the smooth implementation of UAM; (4) UAM operations, encompassing operational efficiency, safety and constraints, all of which must be considered in an integrated manner; (5) airspace traffic management, which requires collaboration among multiple stakeholders for effective management, while also addressing potential security concerns such as cyberattacks; (6) UAM potential demand, exploring market potential, demand estimation and user satisfaction to ensure that the demand for UAM services is adequately met; (7) socio-economic impacts, examining UAM as a means to improve mobility, including aspects such as social acceptance, intention to use and the costs associated with this emerging mode of transportation; (8) safety impacts, related to factors such as weather conditions and accidents, which significantly affect the viability and reliability of UAM; and (9) environmental impacts, addressing potential issues like noise and visual pollution, as well as the benefit of reduced emissions.

These key research themes provide important insights to enhance the understanding of vital elements that ought to be considered in an integrated way to promote the successful integration of UAM in mobility systems. From a stakeholder standpoint, these themes depict various responsibilities of UAM ecosystem players, namely: (1) the role of regulators and manufacturers in improving operational safety and community trust; (2) the role of local authorities and urban planners in incorporating UAM operations in an efficient and safe way into current mobility systems; (3) the role of stakeholders' cooperation to enhance air traffic management; and (4) the promotion of public engagement and consideration of environmental aspects to foster social acceptance. From a policy perspective, these themes highlight the necessity of frameworks that integrate technological, safety, environmental and socio-economic aspects to properly regulate UAM operations and coordinate them with current transport modes. The key research themes pave the way for future research, namely in respect to the development of integrated frameworks for local authorities and other policymakers to successfully integrate UAM services in urban contexts.

Concerning the geographical scope, the countries with the highest research output are located in Europe (*i.e.*, Germany, the UK and Italy, with a combined total of 40 publications), North America (*i.e.*, the United States, with 30 publications), and Asia (*i.e.*, China and South Korea, with a combined total of 20 publications). The listed references correspond to the most cited articles authored solely by researchers from the respective countries.

Based on the methodologies employed in the 36 articles that address UAM indicators, it seems evident that quantitative methods were the most commonly used (*i.e.*, in 24 articles), particularly simulations (used in ten papers), mathematical models (in three articles), and analytical models (in one paper). Although qualitative methods were less frequently employed (*i.e.*, in only 7 articles), literature reviews were used in six papers and questionnaires (including the Delphi method) in one.

In turn, Fig. 9 presents the following information: (1) the key research themes based on the list of indicators identified in the literature for the environmental, safety and socio-economic impact areas, including the frequency of each impact area and the frequency of the respective indicators (both frequencies were calculated from a total of 150 indicators); (2) the number of papers from each geographical region; and (3) the number of articles using each methodological approach (*i.e.*, quantitative or qualitative), as well as the frequency of papers employing each specific methodology (both frequencies were calculated from the 36 articles that include indicators).

The focus areas and indicators addressed in studies related to environmental impacts account for 22% of the total indicators, comprising the following: emissions savings (9 indicators; 6%), noise (8; 5.3%), power/electricity requirements (6; 4%), vehicle performance (5; 3.3%), visual pollution (3; 2%), infrastructure (1; 0.7%), and biodiversity (1; 0.7%). Safety-related indicators, which represent 20.7% of the total, include accidents (6; 4%), technological aspects (6; 4%), interactions with the environment (6; 4%), human errors (4; 2.7%), weather conditions (2; 1.3%), vehicle safety (2; 1.3%), technological failures (2; 1.3%), infrastructure safety (1; 0.7%), road impacts (1; 0.7%), and risk (1; 0.7%). Socio-economic indicators represent the majority, with 57.3% of the total, and cover mobility experience (41; 27.3%), UAM operations (12; 8%), employment and business development (6; 4%), urban space (5; 3.3%), accessibility (4; 2.7%), social well-being (3; 2%), households (3; 2%), inclusivity (3; 2%), affordability (2; 1.3%), costs (2; 1.3%), housing (2; 1.3%), privacy (1; 0.7%), security (1; 0.7%), and noise (1;

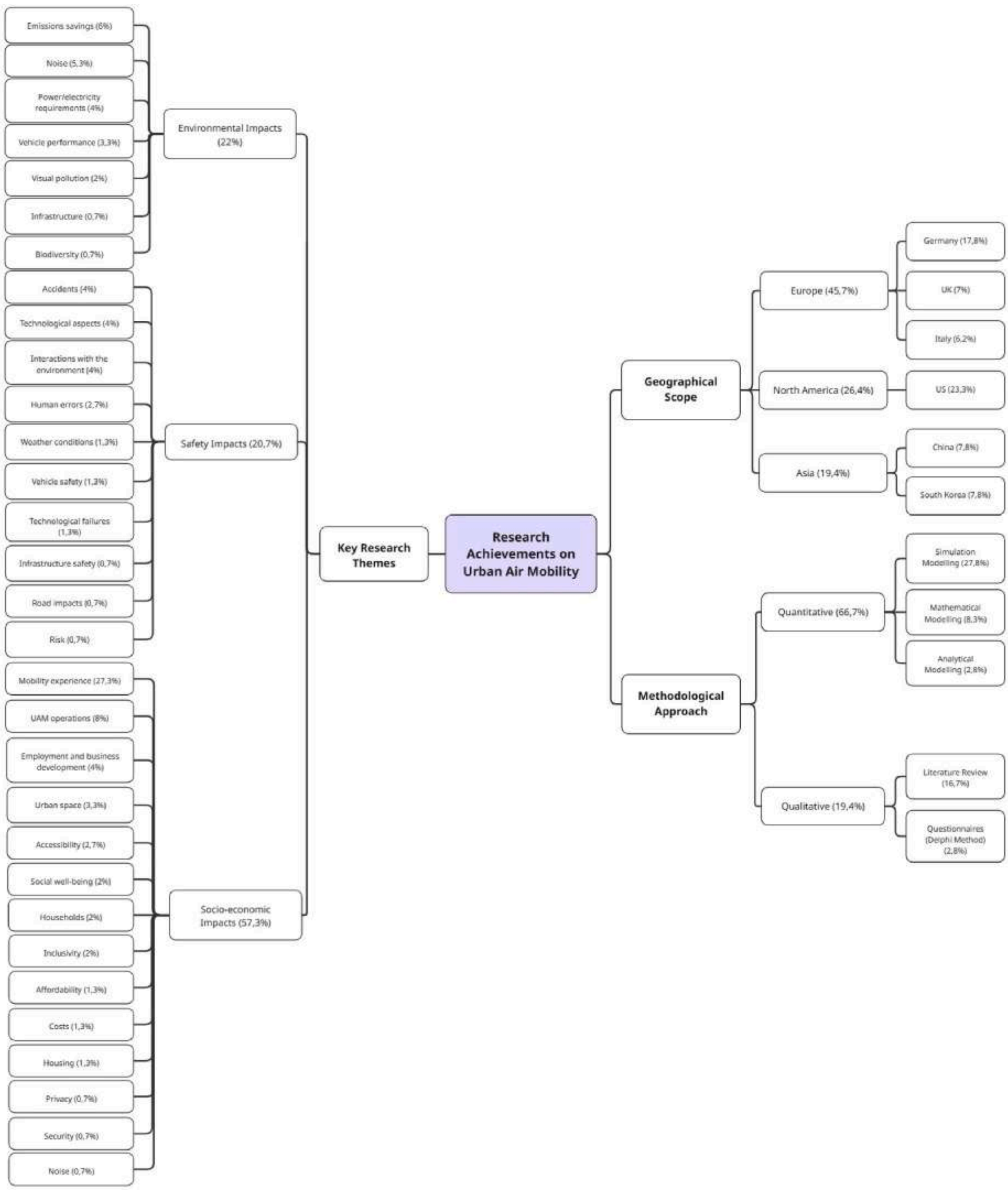

Fig. 9. UAM's key research themes, geographical scope, methodological approaches and their respective frequencies.

0.7%). Considering these percentages, it is possible to verify that the majority of indicators identified in the literature pertains to socio-economic impacts, while the minority concerns to safety impacts. Given that safety is one of the key aspects for UAM operations and their acceptance, further attention should be given to this topic. Moreover, the large majority of studies has a quantitative approach, which highlights the necessity of more qualitative studies to be developed in this area of study.

Regarding geographical distribution, nearly half of the total research output was produced in Europe (45.7%), notably in Germany (17.8%), the UK (7 %), and Italy (6.2%), followed by North America (26.4%), with the US alone accounting for 23.3%, and Asia (19.4%), particularly China and South Korea, each contributing 7.8%.

As for methodological approaches, among the 36 articles that included UAM indicators, more than half (66.7%) employed quantitative methods, primarily simulation modelling (27.8%), followed by mathematical modelling (8.3%) and analytical modelling (2.8%). Meanwhile, 19.4 % used qualitative approaches, such as literature reviews (16.7%) and questionnaires, including the Delphi method (2.8%).

Overall, the insights of this figure provide both theoretical and practical contributions. Regarding the former, it can clarify the current state-of-the-art of the topic and recognize which areas require further investigation. Concerning the latter, it can support policymakers and decision-makers in taking more conscient decisions supported by data.

4.1. Recent research on UAM

In order to gather insights regarding recent research on UAM (*i.e.*, post-December 2023), which is when we applied the search string, we followed the same procedures of our initial analysis, namely the same database (*i.e.*, Scopus), the same search string, and the same inclusion and exclusion criteria. The only difference was the time range, since we only considered articles since January 2024.

Recent research has been addressing public acceptance and recognizing its importance for the implementation of UAM [129,130]. While Li et al. [129] addressed UAM user acceptance, having concluded that perceived safety has a positive impact on trust, perceived usefulness is a solid intention predictor, environmental awareness has a moderate positive effect on acceptance and counterbalances the negative impact of high price sensitivity, Vongvit et al. [130] analyzed the impacts of customer perceived value and trust on the intention to use UAM as a public transportation, concluding that the former positively impacts the latter. Furthermore, in addition to addressing UAM for passenger transportation, recent studies have been addressing UAM for last-mile freight [131,132]. Thus, Farazi and Zou [131] provided an operation planning framework that intends to prepare UAM to be community friendly and economically efficient in the context of package delivery. Specifically, these authors elaborated a method to quantify the noise impact of UAM operations on communities as well as a programming model that optimizes this aspect along with total shipping cost. The results show the trade-off between the reduction of shipping cost and noise impact on community. Zhao and Feng [132] concluded that UAM services, including drone window-docking delivery service, parking fees at the near vertiport and distance to the vertiport are vital elements that affect choosing UAM-friendly neighborhoods, since individuals are more likely to opt for these neighborhoods when they offer these services, provide affordable parking facilities at vertiports and are closer to them.

To understand the type of SLRs that were conducted since January 2024, we added the following term to the search string: AND ("*systematic literature review*"). The results included only two articles: Askarzadeh et al. [133] and Carrera et al. [134]. The first study conducted a SLR regarding the growing drone utilization on road condition monitoring, concluding that drones are a cost-effective and promising tool for infrastructure management due to significant return on investment and cost benefits, being reliability, safety enhancements, cost and time savings, and improved mobility the main drivers behind their adoption. The second study developed a SLR concerning the incorporation of flying cars in urban transportation, concluding that they have become a technically feasible solution to improve urban air mobility, but for its successful integration, it is necessary to overcome challenges related to regulatory frameworks, vehicle design, infrastructure development, energy efficiency and social acceptance.

When comparing the SLR of this study with those of the two articles previously mentioned, it is possible to verify that there are several differences among them. While our study addressed UAM in a holistic way, Askarzadeh et al. [133] provided a more segmented approach focusing on drones in the specific context of road condition monitoring, addressing their applications and benefits, and Carrera et al. [134] focused specifically on flying cars, examining the incorporation of autonomous flight systems, electric propulsion and regulatory frameworks required for their integration in urban environments.

Notwithstanding, some similarities were also verified. Although in the scope of road condition monitoring, Askarzadeh et al. [133] addressed drones' safety and economic aspects and briefly mentioned societal and environmental impacts. In turn, Carrera et al. [134] addressed flying cars' social impacts, such as social acceptance, environmental impacts, including noise, as well as safety and economic aspects.

5. Conclusion

Over the last couple of years, UAM has progressively caught the attention of researchers and entrepreneurs, as evidenced by the continuous growth in the number of publications each year since 2017. This study presents a holistic approach to UAM, aiming to overcome the main limitations identified in the literature through several bibliometric analyses. A descriptive analysis was conducted, providing insights into the evolution of publications, the most productive countries, the top journals in terms of publication volume and the top five most cited studies. The thematic evolution of UAM was then explored, and a thematic evolution map was presented and analyzed. Then, a bibliographic coupling analysis was performed. Finally, a MCA was developed to provide further insights on the data and complement the bibliometric analyses developed with VOSviewer and Bibliometrix. Through the content analysis of the articles included in the four clusters, comprehensive insights were gathered to address the study's three research questions.

Regarding the first research question, which aimed to identify the main stakeholders and their role in UAM's implementation, it was found that the key stakeholders in UAM include airspace regulators, local government agencies, authorities, UAM operators, airspace management service providers, infrastructure providers, vehicle manufacturers, transport system regulators, agencies, airline managers, airport managers, UAM service providers, product owners, consultants, policymakers, investors, researchers, pilots, journalists, managers in aviation corporations, UAM users and citizens. Effective cooperation and synergies among these stakeholders are crucial to ensure the successful launch and development of UAM operations, including proper air traffic management (ATM). Collaboration among UAM's end-users, manufacturers and regulators is especially important for ensuring safe and effective UAM operations. End-users influence UAM operations' performance, manufacturers fulfill operational regulations, and regulators define compulsory regulations and operator training requirements. The perspectives of stakeholders regarding UAM's benefits, challenges, risks and operations related to early use cases are key to the successful introduction of passenger UAM. Defining the appropriate use cases for this stage of UAM's development can enhance adoption rates and ensure economically viable scenarios. Overall, it is concluded that the UAM ecosystem encompasses stakeholders from the technical side (manufacturers, service operators, U-space operators, infrastructure providers), the business side (investors, product developers, consultants), the society (users, non-users, citizens, media), as well as regulators and policymakers. Successful management of this ecosystem requires early collaboration from all involved entities, which may pose as a significant challenge since different stakeholders have different perspectives, responsibilities and priorities. Moreover, stakeholders face several barriers, including regulatory deficiency, elevated investment costs, technological embryonic stages and uncertainty regarding the acceptance of these technologies. Therefore, it is vital that collaborative frameworks that consider these diverse viewpoints and barriers are developed to align expectations, overcome challenges and provide guidelines for the successful implementation of UAM.

The second research question aimed to determine the factors contributing to perceptions of noise, visual pollution and general acceptance of UAM by citizens. It was found that flight paths impact noise distribution, and buildings generate reflections that increase noise spread. The most relevant psychoacoustic factors connected to noise annoyance include tonality, sharpness, loudness, roughness and impulsiveness. Loudness is perceived as the primary cause of noise annoyance. Regarding visual pollution, the two main contributors are the number of UAM vehicles and the distance between the UAM vehicle and the viewer. Other important factors include the vehicle's purpose, appearance, awareness, formation, noise, environment, movement, number of vehicles and the temporal component. The most significant of these factors are: (1) purpose, *i.e.*, whether the UAM vehicle is used for transporting cargo, passengers, or medical emergencies; and (2) environment, which refers to whether the UAM vehicle is seen in a rural or urban setting. Overall, the noise and visual pollution of UAM services affect public acceptance. Acceptance will depend on how these services are introduced and the level of perceived benefits by society. This emphasizes the importance of considering the public's needs and demands when implementing UAM services. Additionally, in the context of drone delivery, anticipated risks, including noise, visual pollution and stress due to lower airspace traffic, significantly impact public acceptance. UAM's social acceptance is influenced by perceived concerns and benefits, the expected fulfillment of urgent social needs, vehicle and service safety, the appropriateness of UAM for specific flight purposes, and environmental issues such as noise and visual pollution.

To answer the third research question, which sought to identify the main evaluation criteria used to assess the environmental, safety and socio-economic impacts of UAM implementation, a list of indicators was created for each impact area. In total, 150 indicators were identified and categorized into three impact areas: (1) Socio-economic Impacts, with 86 indicators, representing the most widely studied area; (2) Environmental Impacts, with 33 indicators; and (3) Safety Impacts, with 31 indicators. These indicators were spread across 36 articles, with 11 articles from Cluster 1, 11 from Cluster 4, 8 from Cluster 2, and 6 from Cluster 3. The analysis revealed that the socio-economic impact area was the most prominent in Clusters 2 and 3, while Cluster 1 focused on environmental impacts, and Cluster 4 addressed safety impacts. The indicators were further classified into subcategories across the three main impact areas: environmental, safety and socio-economic. This study revealed that while numerous studies focus on UAM, only a few analyze the impacts of new UAM technologies and services in populated environments. Specifically, only 37% of the predicted indicators were measured in the publications analyzed, with most studies addressing socio-economic impacts (24%), followed by environmental (11%), and safety (2%). While safety is a fundamental requirement for UAM services, there is a clear need for more research to quantify safety indicators. To facilitate the integration of these indicators into broader mobility and urban planning studies, future research should define the variables used for estimating UAM impacts and provide equations for their quantification. This would allow UAM to be more seamlessly integrated into Sustainable Urban Mobility Plans (SUMPs), enabling evidence-based decision-making regarding the quality of transport systems in cities. Although current research focuses on passenger services, further insights into drone operations are needed, as small drone services are more likely to be deployed before passenger mobility.

This research, like any other, has limitations (1) a single database (*i.e.*, Scopus) was used, potentially limiting the scope of articles included; (2) the study period was limited to December 2023, so more recent studies were not included, being just briefly addressed on the "*Recent Research on UAM*" sub-section; and (3) conference papers, reviews, book chapters and non-English documents were excluded to ensure a homogeneous sample. Future research may address these limitations by incorporating more recent publications, other document types, and different languages to complement the results obtained.

Additionally, further studies could explore the quantification of UAM's environmental, safety and socio-economic impacts, developing standardized metrics for urban planning and mobility management. There is also a need for research into integrating UAM into existing urban mobility frameworks, such as Sustainable Urban Mobility Plans (SUMPs), and understanding the public's perception and social acceptance of UAM services. Further, examining safety risks, economic viability and environmental sustainability, alongside cross-disciplinary collaboration, will be essential for the successful deployment and integration of UAM systems in cities worldwide. Overall, future research should focus on the development of integrated frameworks and roadmaps that take into account: (1) the perspectives of diverse UAM stakeholders; (2) environmental, safety and socio-economic impacts; and (3) the importance of community engagement.

CRediT authorship contribution statement

Margarida R. Santos: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sofia Kalakou:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Fernando A.F. Ferreira:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Appendix

Table 1
Indicators of Cluster 1 – *UAM Technology and its Sustainability*.

Impact Areas	Indicators Title	Measured	Effect	Definition	Defined	Type of Drone	How the data was extracted	Sources
Environmental Impacts	CO_2 emissions gasoline car	Yes	-	*"CO2 emissions in kg/km gasoline car"*	Yes	Passenger	Model Numeric Simulation	Straubinger *et al.* ([41], p. 16)
	CO_2 emissions electricity	Yes	-	*"CO2 emissions in kg/kWh electricity"*	Yes	Passenger	Model Numeric Simulation	Straubinger *et al.* ([41], p. 16)
	Electricity electric car	Yes		*"Electricity per kilometre electric car"*	Yes	Passenger	Model Numeric Simulation	Straubinger *et al.* ([41], p. 16)
	Electricity UAM flight	Yes		*"Electricity per UAM flight for take-off and landing"*	Yes	Passenger	Model Numeric Simulation	Straubinger *et al.* ([41], p. 16)
	Electricity travel UAM	Yes		*"Electricity per kilometre horizontal travel UAM"*	Yes	Passenger	Model Numeric Simulation	Straubinger *et al.* ([41], p. 16)
	Carbon Credits	Yes	+	*"Number of carbon credits to be invested and purchased to neutralize the emissions"*	Yes	Passenger and Cargo	Case Study	O'Reilly *et al.* ([42], p. 8)
	Sound exposure level (SEL)	No		*"A single event metric that considers both the noise level and duration of the event, relative to a standardized duration of 1 s"*	Yes	Passenger and Cargo	Literature Review	Kiesewetter *et al.* ([44], p. 24)
	Maximum sound level (Lmax)	No		*"A single event metric that represents the maximum A- weighted sound level recorded during an event"*	Yes	Passenger and Cargo	Literature Review	Kiesewetter *et al.* ([44], p. 24)
	Equivalent sound level (Leq)	No		*"A cumulative measure of a continuous sound level that represents the total energy of sound experienced over a specific time period"*	Yes	Passenger and Cargo	Literature Review	Kiesewetter *et al.* ([44], p. 24)
	Time above (TA)	No		*"A time-based measurement that indicates the duration, in minutes, during a specific period when aircraft-related noise exceeds a predetermined A-weighted sound level"*	Yes	Passenger and Cargo	Literature Review	Kiesewetter *et al.* ([44], p. 24)
	Number Above Noise Level (NANL)	No		*"The cumulative count of occurrences where the noise surpasses a predetermined threshold level"*	Yes	Passenger and Cargo	Literature Review	Kiesewetter *et al.* ([44], p. 24)
	Time Audible	No		*"The length of time during which a varying sound level, detectable amidst ambient noise, is audibly perceivable by a human observer with normal hearing who is actively attentive to aircraft noise"*	Yes	Passenger and Cargo	Literature Review	Kiesewetter *et al.* ([44], p. 24)
	Effective perceived noise level (EPNL)	No		*"The perceived noise level of a sound source, considering the sensitivity of human hearing"*	1) Yes; 2) No	1) and 2) Passenger and Cargo	1) and 2) Literature Review	1) Kiesewetter *et al.* ([44], p. 24); 2) Kim [51]
	Power battery life cycle	Yes		*"Number of complete charge/discharge cycles it can undergo before its capacity decays to a certain level under ideal temperature and humidity conditions"*	Yes	Passenger and Cargo	Mathematical Model	Qiao *et al.* ([55], p. 4)

	Average power consumption	Yes		"*Average power consumption per flight*"	Yes	Passenger and Cargo	Simulation	Shao *et al.* ([60], p. 20)
Safety Impacts	Weather Impacted Hours	Yes	-	"*The average number of weather impacted hours during the UAM operational day (7AM–6PM Local Time)*"	Yes	Passenger and Cargo	Survey and Statistical Analysis	Reiche *et al.* ([48], p. 6022)
Socio-Economic Impacts	Travel time	Yes		"[Amount of time spent] *to move between origin/destination pairs*"	Yes	Passenger	Mathematical Model	Postorino & Sarné ([39], p. 2)
	Households	1) and 2) Yes		"*Total number of households*"	1) and 2) Yes	1) and 2) Passenger	1) and 2) Model Numeric Simulation	1) Straubinger *et al.* ([1], p. 11); 2) Straubinger *et al.* ([41], p. 16)
	Low-skilled households	1) and 2) Yes	-	"*Total number of low-skilled households*"	1) and 2) Yes	1) and 2) Passenger	1) and 2) Model Numeric Simulation	1) Straubinger *et al.* ([1], p. 11); 2) Straubinger *et al.* ([41], p. 16)
	High-skilled households	1) and 2) Yes	+	"*Total number of high-skilled households*"	1) and 2) Yes	1) and 2) Passenger	1) and 2) Model Numeric Simulation	1) Straubinger *et al.* ([1], p. 11); 2) Straubinger *et al.* ([41], p. 16)
	In-vehicle travel time (IVTT)	Yes		"*Time spent in a motorized vehicle, such as auto, subway train, or UAM aircraft*"	Yes	Passenger	Mathematical Model	Rimjha *et al.* ([52], p. 515)
	Out-of-vehicle travel time (OVTT)	Yes		"*Time spent out of a motorized vehicle, such as walking or waiting*"	Yes	Passenger	Mathematical Model	Rimjha *et al.* ([52], p. 515)
	Affordability of public transport for the poorest group	No	+	"*Share of the poorest quartile of the population's household budget required to use public transport*"	Yes	Passenger	Literature Review	Biehle ([58], p. 4)
	Inclusivity for mobility-impaired groups	No	+	"[Number of] *people with reduced mobility* [that] *can actively and fully participate in society rather than experience discrimination and accessibility restrictions on public transport due to their condition*"	Yes	Passenger	Literature Review	Biehle ([58], p. 4)
	Access to mobility services	No	+	"*How much distance people have to bridge in order to reach public transport services and how often these services are provided for the respective locality*"	Yes	Passenger	Literature Review	Biehle ([58], p. 4)
	Satisfaction with public transport	No	+	"*Citizens' perceptions towards the affordability, safety, reliability and easiness to obtain a particular mode of transport*"	Yes	Passenger	Literature Review	Biehle ([58], p. 4)
	Quality of public spaces	No	+	"[Level of] *Satisfaction of local populations with public spaces such as pedestrian areas and green spaces such as parks*"	Yes	Passenger	Literature Review	Biehle ([58], p. 4)
	Average delay time	Yes	-	Flights' average delay time (in seconds)	No	Passenger and Cargo	Simulation	Shao *et al.* [60]

Not clustered by the software.

Table 2
Indicators of Cluster 2 – *Environmental Assessment*.

Impact Areas	Indicators Title	Measured	Effect	Definition	Defined	Type of Drone	How the data was extracted	Sources
Environmental Impacts	Energy consumption	1) and 2) No; 3) Yes	-	*"Total energy consumption (kWh)"*	1) Yes; 2) and 3) No	1), 2) and 3) Passenger	1), 2) and 3) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]; 3) Zhao *et al.* [64]
	Air emissions	1) and 2) No; 3) Yes	-	*"Total air emissions (CO2, NOx)"*	1) Yes; 2) and 3) No	1), 2) and 3) Passenger	1), 2) and 3) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]; 3) Zhao *et al.* [64]
	Noise emissions	No	-	*"Index based on dB emitted at a zone divided by the population density in this zone"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Visual pollution	No	-	*"Index based on kilometres travelled above a zone divided by the population density in this zone"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Average space required per transported passenger	No	-	*"Vertiport area (Sqm)/Passenger"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Impact of construction	No	-	*"Environmental impact resulting from construction or infrastructure needed"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Life cycle	No	+	*"Life cycle or sustainability of an alternative (how much does it last, or is it reusable?)"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Animal impact	No	-	Number of animals affected by UAM operations	No	Passenger	Case Study	Al Haddad *et al.* [74]
	Fleet energy (kWh)	Yes	-	*"Total energy used by the UAM network or UAM SoS* [System of Systems] *fleet"*	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Energy per kilometer (kWh/km)	Yes	-	*"Energy used by network divided by the total distance travelled within the network"*	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Energy per passenger-kilometer (kWh/km)	Yes	-	*"Energy used by the aircraft per kilometer accounting for the load factor"*	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Visual density	Yes	-	*"Number of drones flying in the vicinity"*	Yes	Passenger, Cargo and Sensing	Group discussion, Simulation	Stolz *et al.* ([76], p. 839)
Safety Impacts	Safety (number of accidents)	No	-	*"Number of accidents"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Safety level	No	-	*"Number of fatalities per passenger-mile"*	Yes	Passenger	Literature Review	Bauranov & Rakas ([26], p. 20)
Socio-Economic Impacts	Privacy	No	-	*"Sum of affected dwellings due to take-offs and landings in a buffer area around each vertiport"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Equity	No	+	*"Equity in the incomes of UAM users (percentage difference in incomes of UAM users vs. non-UAM users)"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Affordability	No	+	*"Percentage of household income devoted to transport"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Accessibility to employment	No	+	*"Average accessibility to employment per zone"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)

	Accessibility to certain areas	No	+	Average accessibility to certain areas when compared to other transportation modes	No	Passenger	Case Study	Al Haddad *et al.* [74]
	Total travel time saved	No	+	*"Total travel time saved compared with status-quo (minutes)"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Congestion (ground)	No	-	*"Congestion on the ground (hours or vehicle-kilometres travelled)"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Inconvenience (Access, egress, waiting time)	No	-	*"Total time spent in access, egress, and waiting time (minutes)"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	On-time performance	No	+	*"Reliability or on-time performance of the alternative"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Induced demand	No	-	*"Induced demand for transport (increase in number of trips) resulting from the chosen alternative"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Public transport modal share	No	+	*"Percentage share of public transport"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Total number of passenger trips	No	+	*"Total number of trips travelled"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Total passenger kilometres	No	+	*"Total kilometres travelled"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Investment costs	No	-	*"Investment costs of the chosen alternative"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Operating costs	No	-	*"Operating costs of the chosen alternative"*	1) Yes; 2) No	1) Passenger; 2) Passenger	1) Case Study; 2) Case Study	1) Al Haddad *et al.* ([74], p. 232); 2) Ploetner *et al.* [73]
	Security	No	-	*"Perceived security of passengers"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Quality of life	No	+	*"Quality of life or welfare of the community"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Social inclusion	No	+	*"Social inclusion of groups with reduced mobility"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Job impact	No	-	*"Impact of alternative on jobs (due to automation in the case of UAM)"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Housing relocation	No	-	*"Housing relocation as an impact of land-use change from UAM"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Urban sprawl	No	-	*"Urban sprawl as an impact of land-use change from UAM"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Income distribution over space	No	-	*"Change of income distribution over space as an impact of land-use change from UAM"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Housing cost	No	-	*"Change in housing cost as an impact of land-use change from UAM"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Population density	No	-	*"Change in population density as an impact of land-use change from UAM"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Impact of doubters	No	-	Impact of doubters on the implementation of UAM	No	Passenger	Case Study	Al Haddad *et al.* [74]
	Restrictions (luggage and group size)	No	-	Number of restrictions pertaining luggage and group size on UAM services	No	Passenger	Case Study	Al Haddad *et al.* [74]
	Relocation of companies	No	-	Companies' relocation as an impact of land-use change from UAM	No	Passenger	Case Study	Al Haddad *et al.* [74]
	Scalability	No	+	*"Extent to which alternative is scalable (in the case of UAM, a change in vertiport configuration without big efforts)"*	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)

	Utilization rate	No		"*Time used vs time on the ground*"	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Efficiency	No	-	Number of "*empty flights*"	Yes	Passenger	Case Study	Al Haddad *et al.* ([74], p. 232)
	Revenue passengers	Yes	+	"*Total number of passengers transported*"	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Wait time	Yes	-	"*Elapsed time from demand creation in the simulation until take-off*"	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Average wait time	Yes		"*Average wait time of all revenue passengers*"	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Success percentage of wait time	Yes	+	"*Percentage of revenue passengers waiting less than the target wait time of 15 min*"	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Deadhead ratio	Yes	-	"*Ratio of deadhead flights (non-passenger carrying flights)*"	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)
	Vehicle utilization	Yes	+	"*Ratio of the number of passengers to the seating capacity*"	Yes	Passenger	Algorithms	Kim ([79], p. 8)
	Maximum number of passengers	Yes		Maximum number of passengers supported by the drone, including the pilot	No	Passenger	Mathematical Formulas	Melo *et al.* [80]
	Load factor	Yes		"*Average load factor of all revenue and deadhead flights (computed excluding the pilot)*"	Yes	Passenger	Case Study Simulation	Prakasha *et al.* ([78], p. 8)

Table 3
Indicators of Cluster 3 – *Traffic Management for the Airspace Industry*.

Impact Areas	Indicators Title	Measured	Effect	Definition	Defined	Type of Drone	How the data was extracted	Sources
Environmental Impacts	CO2 Emissions	Yes	-	"*Total CO2 emissions for conventional air traffic* [in kg]"	Yes	Passenger	Analytical Model	Ahrenhold *et al.* ([91], p. 13)
	Energy Consumption	Yes		"*Total energy consumption for air taxis* [in kWh]"	Yes	Passenger	Analytical Model	Ahrenhold *et al.* ([91], p. 14)
Safety Impacts	Monitor Alert Parameter (MAP)	No		"*The maximum number of aircraft an Air Traffic Control (ATC) controller can handle at any given time*"	Yes	Passenger and Cargo	Simulation	Bulusu & Sengupta ([93], p. 2)
Socio-Economic Impacts	Waiting time	Yes	-	"*Waiting time at interconnections*"	Yes	Passenger	Simulation Model	Di Vito *et al.* ([101], p. 13)
	Breakdowns/maintenance delays	Yes	-	"*Frequency (probability) of delays from breakdowns/maintenance*"	Yes	Passenger	Simulation Model	Di Vito *et al.* ([101], p. 13)
	Accessibility of wayside infrastructures	No		"*Number of architectural barriers encountered/number of obstacles*"	Yes	Passenger	Simulation Model	Di Vito *et al.* ([101], p. 13)
	Modes in a single ticket	No		"*Number of modes included in a single ticket*"	Yes	Passenger	Simulation Model	Di Vito *et al.* ([101], p. 13)
	Cost of travel	Yes		"*Total cost of travel* [EURO/PAX]"	Yes	Passenger	Simulation Model	Di Vito *et al.* ([101], p. 13)
	Departure punctuality	Yes	+	"*Percentage of flights departing on-time from the gate parking position that meets the off-block delay (dOB) target which considers the additional time required to leave the gate (dDGS)*"	Yes	Passenger	Simulation	Schweiger & Knabe ([33], p. 7)

	Arrival punctuality	1) and 2) Yes	+	*"Percentage of flights arriving at the gate parking position meeting the in-block delay (dIB) target and which equals the dTF"*	1) Yes; 2) No	1) and 2) Passenger	1) Simulation; 2) Case Study	1) Schweiger & Knabe ([33], p. 7); 2) Schweiger *et al.* [34]
	Punctuality	Yes	+	*"The individual resulting delay for each flight at gate arrival (TAIBT) and departure (TAOBT)"*	Yes	Passenger	Simulation	Schweiger & Knabe ([33], p. 7)
	Travel Time	Yes		*"Total travel time"*	Yes	Passenger	Simulation Model	Di Vito *et al.* ([101], p. 13)
	Response time to service interruptions	Yes	+	*"Average* [time] *to restore the service"*	Yes	Passenger	Simulation Model	Di Vito *et al.* ([101], p. 13)
	Practical hourly capacity	No		*"Average number of operations that can be accommodated within an acceptable average delay for a given demand"*	Yes	Passenger	Simulation	Schweiger & Knabe ([33], p. 5)
	Customers Served	Yes		*"Number of customers served per vehicle per day"*	Yes	Passenger	Case Study; Simulation Model	Rajendran *et al.* ([92], p. 9)

Not clustered by the software.

Table 4
Indicators of Cluster 4 – *Passenger Transport and Demand Management.*

Impact Areas	Indicators Title	Measured	Effect	Definition	Defined	Type of Drone	How the data was extracted	Sources
Environmental Impacts	Reduction of pollution	No	+	Reduction in the number of pollutant emissions due to decrease in traffic	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Carbon emissions reduction	No	+	Reduction in the number of carbon emissions	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Indirect CO2 emissions	Yes	-	"[Number of] *CO2 emissions linked to aerial vehicles (such as those related to operational and disposal phase charges)"*	No	Passenger and Cargo	Simulation Scenario	Ditta & Postorino ([118], p. 1)
	Greenhouse gas emissions	No	-	Number of greenhouse gas emissions	No	Passenger and Cargo	Simulation Scenario	Ditta & Postorino [118]
Safety Impacts	Improvement of road safety	No	+	Decrease number of road accidents due to lower traffic	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Technological Failures of powertrain	No	-	Number of powertrain failures	No	1) Passenger; 2) Passenger (Light Aircraft)	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]
	Technological Failures of GPS/receiver	No	-	Number of GPS/receiver failures	No	1) Passenger; 2) Passenger (Light Aircraft); 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics; 3) Literature Review	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]; 3) Long *et al.* [4]
	Technological Failures of autonomous systems	No	-	Number of problems with the autonomous systems	No	1) Passenger; 2) Passenger (Light Aircraft); 3) Passenger and Cargo; 4) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics; 3) Literature Review; 4) Literature Review	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]; 3) Long *et al.* [4]; 4) Kellermann *et al.* [16]

	Collision with birds	No	-	Number of collisions with birds	No	1) Passenger; 2) Passenger (Light Aircraft); 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics; 3) Literature Review	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]; 3) Long *et al.* [4]
	Collision with tall buildings	No	-	Number of collisions with tall buildings	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Collision with power lines	No	-	Number of collisions with power lines	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Pilot errors	No	-	Number of errors made by pilots	No	1) Passenger; 2) Passenger (Light Aircraft); 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics; 3) Literature Review	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]; 3) Long *et al.* [4]
	Passenger interference	No	-	Number of passenger interferences with the systems	No	1) Passenger; 2) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]
	Cyber-hacking	No	-	Number of cyber-hacking situations	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]
	Hijacking of the autonomous aircraft	No	-	Number of hijacking situations of autonomous aircrafts	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]
	Battery failure	No	-	Number of hazardous situations regarding battery failure	No	1) Passenger; 2) Passenger (Light Aircraft); 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics; 3) Literature Review	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]; 3) Kellermann *et al.* [16]
	Inadequate ground crew training	No	-	Number of ground crew members that are not trained for maintaining safety margins	No	1) Passenger; 2) Passenger (Light Aircraft); 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics; 3) Literature Review	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]; 3) Long *et al.* [4]
	Air and ground accidents	No	-	Number of air and ground accidents	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]
	Weather conditions	No	-	Amount of turbulence	No	1) Passenger; 2) Passenger (Light Aircraft); 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Mathematical Modelling; Statistics; 3) Literature Review	1) Desai *et al.* [35]; 2) Dziugiel & Goraj [121]; 3) Long *et al.* [4]
	Physical object interference	No	-	Number of physical object interferences with UAM	No	1) Passenger; 2) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]
	Onboard subsystems malfunctioning	No	-	Number of malfunctioning occurrences of onboard subsystems	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]
	Ground systems malfunctioning	No	-	Number of malfunctioning occurrences of ground systems	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]
	Malicious passenger behavior	No	-	Number of occurrences of passenger malicious behavior	No	1) Passenger; 2) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]
	Improperly designed infrastructure	No	-	Number of infrastructures improperly designed	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	MTBIA	Yes	-	"*Mean Time Between Incidents and Accident*"	Yes	Passenger (Light Aircraft)	Mathematical Modelling; Statistics	Dziugiel & Goraj ([121], p. 659)

	MTBCF	No	-	*"Mean Time Between Critical Failures"*	Yes	Passenger (Light Aircraft)	Mathematical Modelling; Statistics	Dziugiel & Goraj ([121], p. 659)
	Light Aircraft Accidents	No	-	Number of light aircraft accidents	No	Passenger (Light Aircraft)	Mathematical Modelling; Statistics	Dziugiel & Goraj [121]
	Engine Failure	No	-	Number of engine failure occurrences	No	1) Passenger (Light Aircraft); 2) Passenger and Cargo	1) Mathematical Modelling; Statistics; 2) Literature Review	1) Dziugiel & Goraj [121]; 2) Long *et al.* [4]
	Landing gear failure	No	-	Number of landing gear failure occurrences	No	Passenger (Light Aircraft)	Mathematical Modelling; Statistics	Dziugiel & Goraj [121]
	Air traffic controller error	No	-	Number of air traffic controller errors	No	Passenger (Light Aircraft)	Mathematical Modelling; Statistics	Dziugiel & Goraj [121]
	Value of Statistical Life (VSL)	Yes		*"How much an individual is willing to pay to lower a specific degree of risk or how much risk an individual is ready to tolerate by not paying for the risk reduction"*	Yes	Passenger	Data-driven quantitative cost-benefit analysis	Dulia *et al.* ([117], p. 9)
Socio-Economic Impacts	Faster Travel and Reduced travel times	No	+	Reduced travel time between two points when compared to traditional transportation means	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]
	Reduced traffic congestion	No	+	Reduced number of vehicles on the roads associated with implementation of UAM	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]
	Reduced commute travel times	No	+	Reduced time for commute travel due to the reduction of traffic congestion	No	1) Passenger; 2) Passenger and Cargo; 3) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review; 3) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]; 3) Kellermann *et al.* [16]

	Community backlash	No	-	Number of citizens against UAM	No	1) Passenger; 2) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review	1) Desai *et al.* [35]; 2) Kellermann *et al.* [16]
	Improved Connectivity	No	+	Number of regions more easily accessible through UAM	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Noise levels	No	-	Noise levels during take-off and landing	No	1) Passenger; 2) Passenger and Cargo	1) Stakeholders' session; Surveys; 2) Literature Review	1) Desai *et al.* [35]; 2) Long *et al.* [4]
	Unprofitable business	No	-	Income losses	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Certification's investment	No	-	Amount of necessary investment for certifications	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Air taxi certification costs	No	-	Price for air taxis to obtain certifications	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Cities' development	No	+	Number of streets converted into green spaces	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Labor expansion	No	+	Number of jobs created	No	Passenger	Stakeholders' session; Surveys	Desai *et al.* [35]
	Job losses	No	-	Number of jobs losses	No	Passenger and Cargo	Literature Review	Kellermann *et al.* [16]
	Airport shuttle and air taxi markets' potential demand regarding daily trips	Yes		Number of daily trips potential demand	No	Passenger	Travel demand modeling; Simulations; Constraint Analysis	Goyal *et al.* [112]
	Airport shuttle and air taxi markets' potential demand regarding daily passengers	Yes		Number of daily passengers' potential demand	No	Passenger	Travel demand modeling; Simulations; Constraint Analysis	Goyal *et al.* [112]
	Annual market value of potential demand	Yes		Market value of potential demand annually (USD)	No	Passenger	Travel demand modeling; Simulations; Constraint Analysis	Goyal *et al.* [112]

	Air taxis potential demand	Yes		*"Number of air taxis required to fulfil the potential demand for UAM in New York City"*	Yes	Passenger	DMADV (Define, Measure, Analyze, Design, and Verify) Approach	Rajendran & Shulman ([115], p. 1)
	Operating Cost	Yes		Operating Cost for eVTOL ($/h)	No	Passenger	Framework	Roy *et al.* [114]
	Intention to use air taxis	Yes		Number of people that intend to use air taxis	No	Passenger	Surveys	Astfalk *et al.* [110]
	Value of Travel Time Savings	Yes		*"Amount of money that travelers are willing to pay to reduce the travel time"*	Yes	Passenger	Data-driven quantitative cost-benefit analysis	Dulia *et al.* ([117], p. 7)
	eVTOL passenger trips	Yes		*"Estimated number of passenger trips by eVTOL in year"*	Yes	Passenger	Data-driven quantitative cost-benefit analysis	Dulia *et al.* ([117], p. 9)
	Mean Waiting Time	Yes		*"Arithmetic mean of the waiting times of all served requests. The waiting time is defined as the time between the passenger's requested boarding time and the actual start of the boarding time."*	Yes	Passenger	Simulation; Modelling	Husemann *et al.* ([119], p. 10)
	Maximum waiting time	Yes		*"The longest time any of the passengers served had to wait."*	Yes	Passenger	Simulation; Modelling	Husemann *et al.* ([119], p. 10)
	Pooling share	Yes		*"Percentage of how many passengers were pooled with other passengers"*	Yes	Passenger	Simulation; Modelling	Husemann *et al.* ([119], p. 4)
	Mean pooling share	Yes		*"The share of passengers, that were pooled vs. the total number of passengers served"*	Yes	Passenger	Simulation; Modelling	Husemann *et al.* ([119], p. 10)

Not clustered by the software.

Data availability

Data will be made available on request.

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