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A SYSTEMATIC REVIEW OF GROUND-BASED INFRASTRUCTURE FOR THE INNOVATIVE URBAN AIR MOBILITY

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Abstract
The increasing level of urbanisation and traffic congestion promotes the concept of urban air mobility (UAM), which has become a thriving topic in engineering and neighbouring disciplines. The development of a suitable ground-based infrastructure is necessary to supply these innovative vehicles, which mainly includes networks of take-off and landing sites, facilities for maintenance, energy supply, and navigation and communication capabilities. Further requirements comprise robust business and operating models for emerging service providers and regulatory frameworks, particularly regarding safety, liability and noise emissions. The objective of this study is to provide an overview of the current results and developments in the field of UAM ground-based infrastructure by conducting a systematic literature review (SLR) and to identify the most relevant research gaps in the field. For the systematic literature analysis, our search string contains vertiports and the equivalents, UAM and equivalents, and search phrases for the individual domains. In the final analysis 64 articles were included, finding a strong focus on simulations and vertiport networks, while specific case studies and related aspects like automated MRO and urban planning appear less frequently. Therefore, this article provides insights for a more holistic perspective on challenges and necessities of future UAM.

Keywords: air mobility, ground-based infrastructure, systematic literature review, vertiport, air taxi
Type of the work: review article

1. INTRODUCTION

New vehicle types for airborne metropolitan passenger traffic create prospects for people and cities. In addition to traffic management, ground-based infrastructure requirements for urban air mobility (UAM) are considered the key success factors for socio-technical integration [1], which include take-off and landing pads, communication, navigation and surveillance infrastructure [2]. The ground-based infrastructure thus impacts different technological and societal dimensions and enforces a paradigm shift within urban planning to enable links with existing mobility networks [3]. Moreover, digitised and

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automated traffic and control systems have to be integrated, as well as sufficient energy management systems. The question of an ideal embedding of ground-based infrastructures moves at the interface of various other issues, such as noise restrictions, the legal framework of air traffic or public acceptance. In addition to pure planning aspects, socio-economic factors such as spatial inequalities or real estates also play a crucial role in defining the space for UAM [2]. Therefore, a comprehensive perspective of critical factors must be developed while maintaining the attention to the specifics of individual elements within the system. This is the purpose of the Innovative Airborne Urban Mobility (i-LUM) research project, which focusses on the integration of UAM in the Hamburg metropolitan region.

The objective of the i-LUM project is fundamental research on the development of holistic mobility concepts in the emerging field of UAM and the application in a toolchain that integrates modules representing the individual research areas. The project includes a multitude of scientific disciplines, which is reflected in the work package structure in Fig. 1.

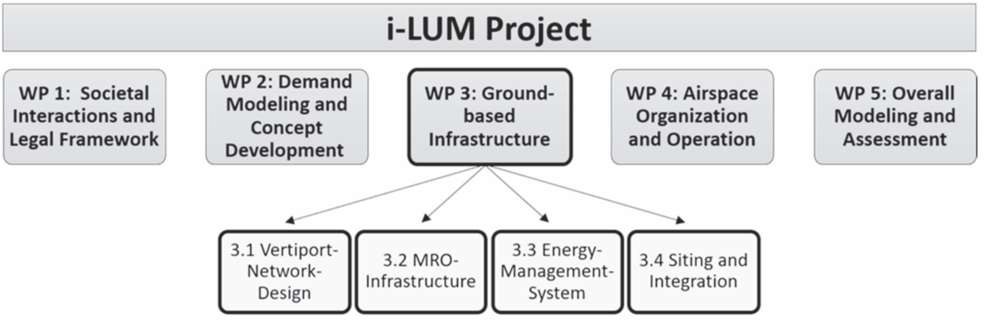

Figure 1. Five work packages of the i-LUM project and the four subworking packages of package three (ground-based infrastructure). *i-LUM, Innovative Airborne Urban Mobility; MRO, maintenance, repair and overhaul; WP, working package.*

The first of five main work packages focusses on societal interactions, for instance, the identification of conditional terms for a broad acceptance of UAM among the public, as well as the prerequisites to maintain a sense of safety and security in the community. Furthermore, the analyses highlight the emerging challenges resulting from the evolving regulatory framework and involve examinations from a legal perspective.

The second main work package provides a detailed demand analysis with a particular emphasis on the passengers and their requirements towards a UAM system, developing use cases and concepts of operation (ConOPS) that allow for a derivation of detailed demand scenarios. A multimodal traffic simulation subsequently processes these scenarios to provide assessment capabilities of UAM regarding individual benefit.

The third main work package investigates the air space from several perspectives, comprising an interface to legal aspects and regulation, the development of designs that allow for a planning of efficient trajectories with a minimum of delay and energy consumption while maximising the dispatching capacity, as well as the design of new potential strategies for identification and resolution of spatial conflicts between flights to maintain safe operations. Furthermore, research contents throughout this main work package contain sensor and communication technology to ensure a high degree of automatisation in the transport system to design and investigate the resulting noise emissions of the anticipated electrically driven vehicles along flight trajectories.

The fourth main work package examines the design and evaluation of UAM transport systems and combines all investigated subcategories in a holistic system simulation according to the approach presented in Niklaß et al. [4]. The numerical simulation then yields results from multiple aspects, such as vertiport density or vertiport size, and combines the results in comprehensive system metrics that balance partially diverging interests against each other. This methodology will provide a foundation for a target-oriented decision-making when designing UAM systems.

Finally, the last main work package represents a crucial aspect of the overall UAM system design, the ground infrastructure, which is the central subject of investigation throughout this study.

A subwork package devoted to maintenance, repair and overhaul (MRO) systems focusses on the development of concepts for automated, ground-based MRO systems and the identification of required key technologies. Taking existing concepts into consideration, the objective is to develop solutions for highly automated ground-handling processes at vertiports. The conceptual development of energy management systems is another subwork package that aims at efficient integration of new energy carriers the subsystem vertiports and provides optimised strategies for energy supply of the vehicles. A separate subworking package considers the relevant factors for a seamless site integration from a city planner perspective. A further emphasis lies in the development of a methodology to integrate the findings of other subworking packages to design efficient vertiport networks. Beginning with the derivation of models for computing local ground-handling capacities, in a next step, the dependency of transport efficiency regarding time and consumed energy of several network topologies is the subject of investigation, specifically taking the requirements due to the demand scenarios into consideration.

Based on these work packages, our focal point in this review is to highlight current research strands and approaches regarding technologies, concepts, simulations and living lab scenarios for the UAM ground-based infrastructure. Our study follows the primary research question:

"What are the key components for the development of ground-based infrastructure for UAM?"

Based on our content analysis, we identify research gaps concerning each given topic. To provide a comprehensive overview of the descriptive statistical insights and analytical contributions regarding our research areas, we conducted a systematic literature review (SLR).

SLR represents a systematic way to identify relevant studies, to summarise the results, to critically analyse the methods of the studies and, finally, to comment and recommend improvements for future research. For the systematic literature analysis, our search string contains vertiports and equivalents, UAM and equivalents, and further search phrases for the individual domains of the ground-based infrastructure. The article is structured as follows: Section 2 describes the methodology of the SLR, presenting the boundary conditions of the SLR. In section 3, we discuss the results of the literature analysis. Finally, section 4 provides conclusions and an outlook.

2. SLR: CRITERIA AND BOUNDARY CONDITIONS

This systematic review has been performed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines[1]. After the question formulation for our thematic focus, we developed a research string that covers all relevant keywords and possible equivalents to broaden our perspective. We retrieved relevant research articles from the SCOPUS database, which has the largest and most comprehensive collection of academic publications. Screening provided a first overview of potential articles. Based on our inclusion and exclusion criteria, we eliminated articles that did not match our focal point during our study selection process. Ultimately, we reviewed the literature to evaluate and synthesise the existing results and formulate a conclusion to identify research gaps. The review places an emphasis on qualitative insights about the topic but also reflects descriptive data on the identified publications for a general classification. The prism chart (Fig. 2) presents the study selection procedure.

[1] For more information on this methodological approach, see: Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., and Prisma Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Medicine* Vol. 6 No. 7 (2009): p. e1000097.

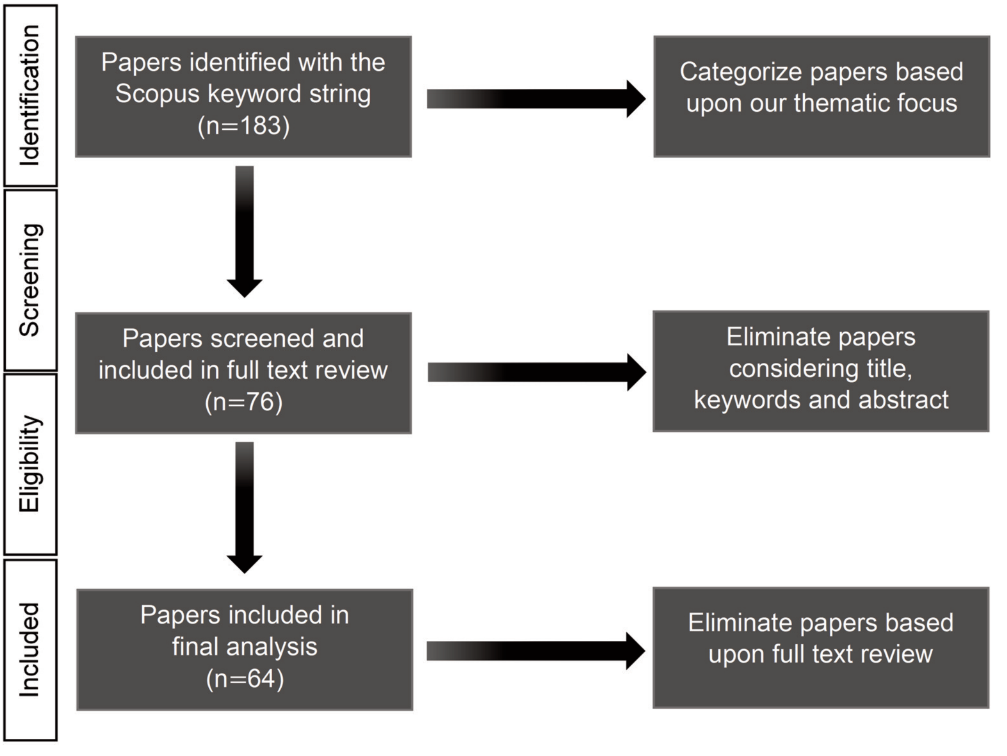

Figure 2. Prism chart of the literature review.

2.1. Methodological approach

We performed a systematic search to identify relevant articles published in the SCOPUS database from 1 January 2010 to 15 July 2021. The search phrase in SCOPUS is as follows:

ALL((vertiport OR vertistop OR vertihub OR vertidrome OR skyport OR droneport OR heliport OR helipad) **AND** (uam OR (urban AND air AND mobility) OR aam OR (advanced AND air AND mobility) OR uav OR eVTOL OR airtaxi OR drone OR taxi-drone OR pav OR (personal AND air AND vehicle)) **AND** (location OR station OR infrastructure OR energy OR grid OR supply OR (fuel AND cell) OR network OR system OR (hub AND location AND problem) OR route OR technology OR (condition AND monitoring) OR mro OR maintenance OR repair OR energy OR soc OR (state AND of AND charge) OR battery OR charging OR power OR (fuel AND cell) OR hydrogen))

The search phrase includes thematic aspects of vertiports, UAM and equivalent expressions to provide a broad and comprehensive screening of the topic. Based on the search phrase, 183 articles were found in the first query. After removing duplicates, we screened the articles regarding their thematic focus, title, keywords and abstract. Applying the exclusion criteria (Table 1), we identified all articles that do not have a clear analytical link to the ground-based infrastructure for UAM.

Table 1. Inclusion and exclusion criteria.

I/E	Criteria	Criteria explanation
Exclusion	Language	No English abstract available for this publication
	Full-text	We are unable to access the text, or the abstract does not provide any analytical insights
	Article type	A paper is not an academic paper or conference paper, e.g. forewords or editorial material only
	Non-related	A paper does not refer to UAM Loosely related A paper refers to UAM but without mentioning the ground-based infrastructure The ground-based infrastructure is only mentioned as an example, keyword or future research direction without any analytical contribution
Inclusion	Closely related	A paper is directly connected to our defined research areas of the ground-based infrastructure for UAM: vertiport networks, automated MRO, energy management, siting and integration
	Partially related	A paper discusses or mentions an important related or additional aspect of the ground-based infrastructure for UAM

MRO, maintenance, repair and overhaul; UAM, urban air mobility.

In addition to the focus on our four project-related categories, articles were also included if they had a broader reference to the ground-based infrastructure, for example, drone deployment. After eliminating the articles without a relevant thematic focus, the full-text analysis included 76 articles.

Ultimately, we excluded all articles where the full-text was not accessible or did not provide any analytical insights regarding our research focus. After the final exclusion, 64 articles were included in the final analysis.

2.2. Statistics, frequency analysis and visualisation of results in general

UAM is a new complex of research subjects. The temporal distribution shown in Fig. 3 represents this fact. In the last 4 years, there has been a significant increase in the number of publications on this research topic. The number for 2021 only covers the articles published before 15 July. The tendency is an increasing quantity of publications in terms of UAM and the related ground-based infrastructure.

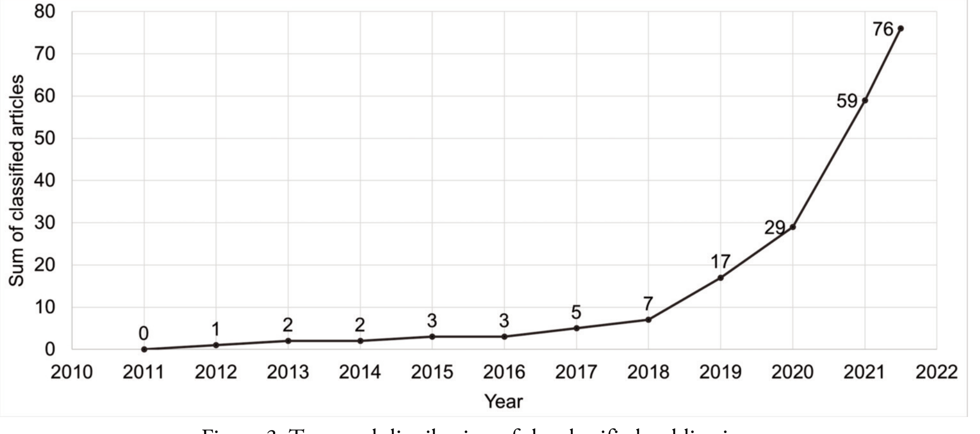

Figure 3. Temporal distribution of the classified publications.

We found 1,468 different keywords with our SCOPUS search string, which are listed in Table 2. The keywords mostly reflect topics regarding vertical take-off and landings (VTOLs) and their landing and flight control systems.

Table 2. Keywords with the highest frequency and their repetition.

Keyword	Frequency
Air mobility	40
Unmanned aerial vehicles	37
VTOLs	32
Urban transportation	27
Antennas	22
Landing	22
Air transportation	22
Aircraft landing	21
VTOL/STOL	19
Taxicabs	16
Flight control systems	16
Heliports	14

VTOLs, vertical take-off and landings; STOL, short take-off and landing.

We classified the results of our research into four research areas and by type of the literature. Therefore, we used the titles and abstracts for the categorisation. Table 3 represents the 76 articles that were part of the abstract screening and their thematic and methodological classification. We conducted a full-text analysis after the first classification. A clear overlapping between the section network modelling of vertiports and spatial integration of vertiports can be found as the literature discusses urban planning aspects often as a side aspect of the vertiport modelling.

Table 3. Results of the systematic literature review (based on abstract analysis).

# Category	Concept/ review	Mathematical/ physical model	Simulation	Living lab/ measurement method	Study/ survey
1 Network design of UAM ground infrastructure	[1,3,5-14]	[6,8,9,15-27]	[5,8,11,15-36]	[37]	[37-39]
2 Automated ground-based MRO	[2,12,14, 40-42]	[2,15,42,43]	[15,28,29,42-44]	[37]	[37]
3 Energy-management-system	[9,13,41, 45-54]	[9,15,26,55-57]	[15,26,28-30, 36,51,53,56,57]	[55,58]	[38]
4 Spatial integration of vertipoints	[1,3,6-8, 11,14, 59-68]	[4,6,8,15,16, 19,21,22,24, 27,69-72]	[4,8,11,15,16,19, 21,22,24,27-29, 31,32,59,61, 68-70,72-76]	[37,71]	[37,38,67]

MRO, maintenance, repair and overhaul; UAM, urban air mobility.

The automated ground-based MRO section delimits strongly from the other sections. Regarding the methodological approach of the studies, most articles used simulations that often closely match to the mathematical and physical models. Living lab approaches and survey occur far less frequently, which indicate that the practical embedding and testing of UAM is still in an early stage. This reveals another research gap, which needs to be filled with new information.

Table 4 lists the most cited publications of the 76 thematically classifiable articles. The categories represent our four thematic focal points, as mentioned in the previous sections. The percentage shows the part of the citations over all citations. Here, it is shown that the categories network modelling of vertiports and spatial integration of vertiports appear more often in the most cited publications than the categories automated ground-based MRO and energy management system.

Table 4. Ten most cited publications.

#	**Most cited publications**	**Category**	**Citations**	**Percentage (%)**	**Journal**
1	[52]	3	106	26.90	Nature Communications
2	[68]	4	30	7.61	Geolocation of RF Signals: Principles and Simulations
3	[26]	1, 3	22	5.58	AIAA/IEEE Digital Avionics Systems Conference—Proceedings
4	[37]	1, 2, 4	22	5.58	17th AIAA Aviation Technology, Integration, and Operations Conference, 2017
5	[13]	1, 3	21	5.33	2018 Aviation Technology, Integration, and Operations Conference
6	[14]	1, 2, 4	20	5.08	2018 Aviation Technology, Integration, and Operations Conference
7	[24]	1, 4	17	4.31	AIAA Scitech 2019 Forum
8	[67]	4	17	4.31	17th AIAA Aviation Technology, Integration, and Operations Conference, 2017
9	[53]	3	15	3.81	AIAA Aerospace Sciences Meeting, 2018
10	[27]	1, 4	9	2.28	2018 Aviation Technology, Integration, and Operations Conference

RF, radio frequency; AIAA American Institute of Aeronautics and Astronautics; IEEE, Institute of Electrical and Electronics Engineers

The most cited article [52] deals with energy management for drones in commercial package delivery, followed by an article on the geolocation of RF signals [68]. Both articles address associated topics of UAM for passenger transport. Closely related articles deal with the scheduling for on-demand UAM [26] and operational constraints [37].

3. RESULTS OF THE LITERATURE ANALYSIS

In the following section, we present a structured content analysis based on the four thematic categories. We highlight the primary research streams and apparent research gaps.

3.1. Network design of UAM ground-based infrastructure

The design of a UAM-based transportation system that can handle the demanded traffic volume and provide a significant reduction regarding door-to-door travel time requires a flexible and efficient route network. Therefore, we need to allocate vertiport positions with sufficient throughput capacity and vehicle parking positions to a set of identified demand hot spots. The vertiport positioning problem, as it is also called, is a crucial step in the UAM network design and has been coped with in various degrees of complexity.

A design approach mentioned in Maget et al. [18] considers demographic characteristics and applies a gravity distribution model to identify demand-driven vertiport networks, referred to as vertihubs in this article. The scenario is based on regional inter-urban traffic in Bavaria, Germany. The approach first solves a maximal covering location problem, deriving vertiport positions based on locations of existing central stations, airports and medium-sized towns. Following this procedure, the existing traffic network and the designed UAM system are closely linked to each other. Subsequently, the number of vertiports and the acceptable travel time for passengers to reach these vertiport locations are varied to quantify the population coverage with an adequate access to the network in terms of reachability, depending on the network density. It is shown that the reachability metric is particularly sensitive to the threshold value of the passenger's acceptable travelling time to the vertiport.

Another example of a UAM network vertiport placement problem [16] focusses on the interaction between vertiport locations and potential UAM travel demand and applying an integer programming algorithm. Therefore, several analyses of hub-and-spoke networks are conducted, for instance, regarding the sensitivity of time savings regarding various influence factors.

A formalised optimisation procedure to determine the siting of vertiports using methods from mixed-integer programming is developed in Venkatesh et al. [32]. The investigation analyses a commuter-based regional use case located in South Florida Metro Area, comprising residence and working blocks that are connected by a network of vertiports. Based on assumptions regarding the flight profile and ground-based vehicle travel times, the vertiport placement problem is solved for both cases, with and without specific consideration of local capacities. If defined, the local capacity is set to a homogeneous value throughout the network. As a result, demand satisfaction is determined for the uncapacitated problem, while for networks with pre-defined capacities, the achievable time savings are quantified for optimisation. However, these studies do not present trajectory-based approaches including fleet planning algorithms, thus neglecting important aspects such as the test for availability of suitable VTOLs to conduct field missions, detailed quantification of passenger's waiting times due ground-handling procedures and, in some cases, the ground-handling capacity.

A further study [15] presents a demand estimation methodology. The investigation examines travel behaviour data and sets up an exemplary regional vertiport network in the Southern California counties. The analysed data comprise results from a passenger survey, provided by Los Angeles World Airports, that distinguish between residential and non-residential passengers as well as between business- and non-business trips. Taking parameters such as cost and time into account and considering multiple transportation modes for demand estimation, the area of investigation is discretised into subspaces, referred to as blockgroups, with specific demand values to solve a vertiport placement problem. The centroid of each subspace represents a possible vertiport location. The subspaces are then arranged into a pre-defined number of clusters to define networks with varying numbers of nodes, set between 50 and 100. Depending on the cost per mile and the number of network nodes, the study aims to quantify the regional UAM market share.

In addition to the publications on methodologies of network design, there are detailed analyses of UAM or on-demand air mobility (ODAM), as, for instance, provided by Sun et al. [7], which classifies relevant research categories into methodologies for demand estimation, design and location problems of the ground-based infrastructure, operational planning, competitiveness with other transportation modes and operational constraints. In addition to a detailed analysis of published research on these categories, the results provide a list of possible future ODAM research topics. Relevant suggestions to design highly efficient vertiport networks comprise the application of more elaborate cost functions regarding the vertiport placement problem rather than transportation time or cost, but to apply multi-criteria optimisations instead, including environmental and societal costs. Furthermore, it is suggested to conduct deeper research into models with actual trips assigned to specific vehicles and to choose an appropriate vehicle from the fleet to carry out the demanded mission, or to reject it if necessary.

Another analysis [14] presents three major scaling constraints that represent significant factors of limitation in a UAM system. These factors comprise the scalability of air traffic control systems for urban air spaces on low flight levels, the availability of the ground infrastructure in areas of high UAM passenger demand, and the public acceptance of UAM operations. That analysis presents a quantification of the severity of each factor for the UAM system. In the field of the ground infrastructure, the geographic proximity to demand and the throughput capacity of take-off and landing areas are determined to be major influences for the scalability of a UAM system.

The presented approaches and analyses show that most of the current research on UAM network design concentrates on metrics such as time savings, monetary costs and reachability of vertiports, but relevant factors as, for instance, the distribution of ground-handling capacities throughout a vertiport network or the need for further functional elements, such as parking positions for vehicles, maintenance facilities and the distribution of battery-charging infrastructure in the network, have not been investigated in a combined analysis.

Furthermore, there are various studies investigating subcategories that are relevant for the task of the vertiport network design. The studies [17,24,28–30,33,37], for instance, conduct analyses on the capacity of vertiports, depending on parameters such as the number of landing pads, vehicle charging rates, service times, parking positions, taxiways, the number of gates and ground operations. Further relevant aspects for the capacity of singular vertiports are represented by scheduling and sequencing of vehicle arrivals and departures, which have been examined in Refs. [23,25,26,34,35]. Since the allocation of passengers to vehicles and to vertiports might also have a significant impact on network design, on fleet mix and on fleet size, first results are available in Rajendran and Pagel [10] and Wu and Zhang [16].

In the context of the i-LUM project, we are planning to develop a trajectory-based network design approach that solves the demand-based vertiport positioning problem under consideration of these aforementioned aspects.

3.2. Automated ground-based MRO

To ensure safe and efficient aviation, it is essential to establish an MRO system that is automated as much as possible. In this systematic literature analysis, one articles is found, which summarises aspects of the fleet maintenance of VTOLs [41]. The U.S. Federal Aviation Administration (FAA) suggests recurring maintenance depending on the system under inspection and the load cycles of the system and proposes predictive maintenance at an interval of 100 h. However, it is a complex task to estimate adequate time periods such as the serviceability and thus to ensure safety of a flight system while the maintenance intervals do not compromise economic profitability. Moreover, the changing designs of the VTOLs make it challenging to develop a uniform MRO system.

In the remaining literature, there is sparse information on MRO systems. While some approaches exist for maintenance operations, there are no concepts for the repair sections. In addition to guidelines for helicopters, ideas for the design of VTOLs and vertiports can be found, from which possible MRO tasks could be derived.

In addition to the FAA regulations mentioned before [41], there are a few examinations of legal requirements for the ground-based infrastructure at airfields [40]. As yet, no legal basis exists. The International Civil Aviation Organization (ICAO) of the United Nations (UN) ranges with its annexes, documents and circulations internationally. The ICAO promotes, with its guidelines, the sustainable growth of the global civil aviation system. Therefore, requirements for the MRO of UAM vehicles derive from an international basis. For the European area, the European Union, with its regulations and implementing regulations, and the EASA (European Union Aviation Safety Agency), with its certification specifications, special conditions and opinions, are reliable and provide more detailed information than the ICAO on an international basis. In Germany, which is the investigated location due to the i-LUM project, the competent authorities are the Federal State with its laws and the Federal Ministry of Transport with its regulations. These institutions could provide helpful requirements beyond the international and European basis for the development of the ground-based infrastructure of vertiports, including the MRO. In the interim, we can derive meaningful requirements from data for helicopters and heliports [37].

The ground-based infrastructure depends on the urban area surrounding it. In one article, the authors conduct a case study for the Los Angeles International Airport [15]. They highlight the necessity that no unauthorised people or systems stay in the safety zone. Furthermore, they perform a demand estimation of UAM for Los Angeles in which 10 areas with the highest ground access are identified. This information can help localise reasonable places for the MRO [15].

It is essential to know the possible throughput, which is dependent on the ground-based infrastructure [14] of a vertiport, to estimate time slots where the predictive maintenance can be executed without obstructing the flow too much. Vertiports should have a high departure performance, and the space requirement in the urban area should be as low as possible [29]. For the San Francisco case, the authors schedule service times of under 10 min [28]. It becomes clear that a centralised MRO in the near urban area station is a reliable option.

In addition to the location, the specific characteristics of the technologies are crucial for integrating an efficient MRO system [2,42,43,44]. Out of this, life cycles and mechanical loads of the tiltrotor systems can be derived.

As shown, the maintenance part of the MRO will be designed as a predictive maintenance based on the loads of the vehicles and the resulting life cycles, as well as a redundancy part for the safety aspects. In-flight safety has been a very sensitive subject since the occurrences on 11 September 2001. Therefore, there is a need for (fleet) monitoring, which can also help detect possible damage during a flight, especially autonomous flights. The result of this monitoring can be an even safer flight and reduced maintenance time needs because a part of the damage detection takes place in the air during the flight and does not need to be performed at the ground-based station.

For the repair and overhaul or operations parts of the MRO system, we need more future research for a better holistic understanding. Foremost, the maintenance needs a certificate and a legal framework. A documentation of the necessary MRO processes will allow us to retrace every step in the event of a questionable incident. Most articles intend a short time frame for the service between every landing and departure, which leads to multi-part maintenance considerations. The minimum MRO is necessary before every departure, while a full maintenance becomes mandatory after a certain number of flight hours. Furthermore, we need to consider the location of maintenance. Possible solutions are a decentralised MRO system at every vertiport that exists, a centralised MRO vertiport at a spot that is further away or hybrid forms of these ideas. The MRO for vehicles in the UAM directly relates to vertiport networks and spatial integration since it may require additional locations and must be considered in the location determination process. To decide and develop concepts for these MRO vertiports, it is important to determine the MRO demands.

3.3. Energy management system

In order to increase the lifespan and achieve good performance, VTOLs generally use a hybrid power system architecture. A hybrid energy architecture can combine multiple energy sources, such as fuel cells, batteries and solar cells. An optimal energy management system is therefore crucial to enabling the efficient operation of advanced VTOLs. In the context of battery-powered UAM platforms, this section suggests a critical review of the state of the art in energy management systems to identify research gaps and recommendations for future research.

Battery-based drones enable continuous operations, applying technologies like swapping, laser beam inflight recharging and tethering. Swapping offers the possibility to recharge depleted batteries during the mission using docking stations. Light energy can transfer to drones in-flight using a laser beam. Batteries can then charge after converting light power to electricity. To cope with the high planning complexity, the authors [9] develop a model to determine an optimal system design considering key parameters like battery capacity, charging infrastructure, time restrictions and additional technical specifications such as payload and range capacities of vehicles.

Some authors [13] consider UAM system implications of different energy storage systems on UAM vehicles. They compare fully battery electric vehicles to vehicles with multiple hybrid electric powertrains, which consist of different energy conversion systems and fuels.

An energy-efficient trajectory optimisation of VTOLs for a given required time of arrival as the arrival phase is the most safety-critical flight phase with much higher air traffic density and limited battery energy is presented in Kleinbekman et al. [26].

Another publication [36] proposes a joint scheduling methodology to handle the optimal routing and charging tasks for the autonomous electric aerial vehicle system. The problem is formulated by integrating charging features into the classic vehicle routing problem with time windows.

In the article [45], the authors describe vision-based navigation systems for charging pad detection and wireless power charging. By using ANSYS Electronics software, they analyse parameters like mutual inductance, coupling coefficient and the distance between the coils for effective power transmission.

To meet the assigned required time of arrival and achieve an energy-efficient arrival trajectory for a given concept of operation, which is a critical enabler for the safe and efficient future aircraft operations for passenger transportation and cargo delivery, the article [51] proposes a multiphase optimal control problem formulation, and the numerical solution enables a VTOL aircraft.

An economical comparison between battery refilling and recharging platforms has been proposed in Nemoto et al. [58]. It was shown that refilling stations are a good choice when the coverage is low; otherwise, it is preferable to use exchange stations.

The future research field for the energy management system is summarised into three points as follows: How to estimate the energy consumption of a fleet of UAMs on the basis of a certain demand and calculate the charging profiles to support the design of the charging infrastructure? How to realise the optimal charging control strategy for VTOLs through combining routing and charging scheduling to reduce the operating costs? How to use artificial intelligence technology to analyse data during flight to accurately predict the power demand and achieve real-time charging control?

3.4. Spatial integration of vertiports

The question regarding urban integration of the ground-based infrastructure is closely linked to one of the primary success factors for UAM, namely, the public acceptance of the innovative vehicle type. An urban planning and development perspective, therefore, bridges the technological and societal aspects of UAM. As vertiports are cost-intensive and highly complex structures, it can take years to build or relocate them [74]. Thus, understanding the territory and societal context of an urban environment is crucial for tackling these long-term risks, as regulations and expectations can also differ spatially [67].

Most articles review the urban or regional context as a side aspect of vertiport capacity and networks but rarely reflect the actual impact on urban planning. The research focusses on simulations that base on transport data like time savings, generalised costs, demand estimation or routes [19,69]. Other articles focus on more specific regional demands like tourism [60] or flood risk management [21]. However, these simulations hardly consider actual stakeholder knowledge about the specific spatial context. Other authors [61] use a multi-indicator perspective on their application modelling for the greater Munich area, drawing from expert workshops, environmental and socio-economic factors. Moreover, practically all simulations and case studies focus on large metropolitan areas, primarily in the United States as well as in Asia or Europe. This raises the question of the applicability and scalability of the research results [7] as little attention is paid to smaller towns or countries that are no forerunners in technological development. Rural areas can potentially benefit from UAM integration as well; however, these welfare aspects are rarely discussed [61].

Furthermore, the research often remains at a regional level, placing a vertiport on the macro-scale but does not define the integration process into a specific urban district or microenvironment. Some authors [73] emphasise the need for a more localised analysis that enriches the simulations with socio-spatial indicators. Some articles focus on the existing aviation ground infrastructure as practical vertiport locations [3,59], while others place vertiports in the central business district of a city [60]. However, these approaches have the risk of overlooking suburban regions and satellite cities of a metropolitan area as they do not have these infrastructures yet, and often aggregate existing helipads within the central business districts [37]. These ideas also focus heavily on structural features of North American cities but do not provide a holistic global framework. Therefore, the authors [37] highlight the importance of more creative ways to integrate vertiports within existing urban infrastructures, like on floating barges, vertiports co-located with stores or gas stations, or near highway cloverleaves.

Due to the early development of UAM transport systems, there is a lack of empirical research and practical implications for the embedding of the ground-based infrastructure within a specific urban context. Socio-technical and urban research is poorly represented so far. Some authors underline that transportation time or costs should not be the sole indicators for vertiport integration, but there need to be an emphasis on accessibility, environmental and societal costs as well [7,73].

We summarise these open-ended research questions in two major topics: first, critical acceptance indicators within a specific urban context; this also raises questions regarding sustainability and urban inequality. How do urban planning and development practices have to adapt for integrating UAM? How can we integrate UAM without additional land sealing? Second, the actual topography and physical geography of a city or region. How can lagging regions like rural areas potentially benefit from UAM? How do physical elements like valleys or waterfronts impact the demand and integration of UAM?

4. CONCLUSION AND OUTLOOK

The main objective of this SLR is to provide insights into the current state of research of the different elements of ground-based literature for UAM. Our goal was to identify key components of the main topics and discuss the current literature to gain insights into this young research field. Therefore, we defined a search string to deliver a broad overview of the topic.

We applied appropriate inclusion and exclusion criteria to identify articles that match the purpose of our research question. The review with the academic and interdisciplinary database SCOPUS identified 64 articles that we included in the final analysis. In the content analysis, we focussed on four categories of the ground-based infrastructure for UAM: the network design of the UAM ground infrastructure, automated MRO, energy management systems and spatial integration.

Based on the preceding analysis, research on UAM is so far discussed primarily on a conceptual level or with simulations. The topic of vertiport networks appeared to be one of the wider discussions. The articles primarily deal with demand-based siting of vertiports and resulting time-saving potentials. Further subjects of investigation relevant for a vertiport network design, such as modelling of ground-based operations, routing and vehicle allocation and the design of network topologies, are mostly not examined in a network-based context.

Regarding the necessary MRO processes, we highlight that a more detailed investigation and conceptualisations in future studies are useful to better understand the connections between several MRO steps. In addition to the legal framework for the operation, the management of the multi-part maintenance as well as the (de-)centralised locations are key aspects for successful integration.

An optimal energy management system is crucial to enable the efficient operation of (hybrid) electric drive concepts, energy supply networks, hydrogen and fuel cell technologies for drones. While many articles address the topic of spatial integration, few articles considered the actual impact of UAM on urban planning and the urban environment. This involves physical geographic as well as societal aspects of the specific city or region.

We have shown that research on the different dimensions of the ground-based infrastructure for UAM became a thriving topic in the last few years. However, there is a lack of living labs and case study approaches as well as a sufficient connection between the different research strands so far. Future studies need to put a stronger emphasis on a holistic perspective regarding siting, operation and management of vertiports, as well as the technological and societal dimensions involved in this debate.

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