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INNOVATIVE URBAN AIR MOBILITY FROM THE PERSPECTIVE OF THE HAMBURG METROPOLITAN REGION

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Abstract

For the future of urban mobility, further developments in the fields of automation, communication and energy storage technologies will enable the expansion of traffic space into the air. Various concepts and scenarios of urban air mobility (UAM) are already part of current research. In addition to the investigation of relevant physical effects and system-internal constraints, a view including the external relationships and general conditions is essential for the design, acceptance and success of the UAM systems. Several projects (i-LUM, ULTRAS, UDVeo, LUV, Vertiport) with the participation of various Hamburg research institutions bundle a multitude of competences to develop UAM scenarios for the Hamburg metropolitan region and other regions. UAM scenarios are evaluated i.a. in terms of time, cost, noise, energy consumption, acceptance and the ease of integration. The evaluation considers societal interactions, legal frameworks, demand modeling, concept development, ground-based infrastructure, airspace organization and operation, as well as overall system modeling. This paper gives an overview about the disciplinary and methodical approach and setup of these UAM projects.

Keywords: Urban Air Mobility (UAM), System of Systems, Model Based Development, Model Based Systems Engineering (MBSE), i-LUM, ULTRAS, UDVeo, LUV, Vertiport

1. Introduction

Latest developments in aviation research and their impact on aircrafts can make a significant contribution to the further development of urban mobility, resulting in a sharp increase in activities in the field of urban air mobility [1]. Several start-ups, aircraft manufacturers and service companies with different concepts and prototypes are already active in the development of potential urban aircrafts (including City Bus, Volocopter, Lilium Jet, EHang, and more) [2, 3, 4, 5].

In addition to the potential for urban mobility offered by urban air vehicles due to advances in automation, communication technology and electrical energy storage systems, this also rises challenges in terms of safety and security for a strongly increasing number of (inner-city) flights. New air traffic control (ATC) architectures for low altitude operations in urbanized areas with exposed objects (e.g. buildings, poles, bridges) are required to cope with increasing complexity. Furthermore, public and social acceptance of UAM is an important issue, especially among social classes with limited access to the new technology. Furthermore, the increased presence of air vehicles might cause a disruptive perception in parts of the general public [1, 6]. In the few available studies on social expectation formation and acceptance in the context of e.g. unmanned air traffic, the population's sense of safety and security is a central reference point. Factors that affect the feeling of safety and security in the presence of conducted UAM operations, and how social expectations are formed, are still insufficiently investigated [7].

Furthermore, a lot of factors affecting the level of acceptance, like noise pollution or the integration of the required infrastructure into the urban environment, can be highly dependent on the respective location with regard to their impact. The comparison between different existing surveys is hardly possible and in addition to the mechanisms of social acceptance or reactance, the psychological foundations of these have hardly been investigated [8].

Concepts and ideas for UAM already exist and are being developed by a large number of companies and research institutions, as for instance in Hamburg, where first UAM concepts have been presented (for example [9, 10]). In order to be able to evaluate different approaches, a more detailed investigation is necessary that goes beyond a mere cost-benefit analysis. This investigation must consider all relevant physical and social effects with sufficient accuracy, as well as enable comparability of these, and thus must take into account the interactions of the entire UAM system [11, 12, 13]. However, such multi-criteria assessments are the subject of considerable debates in which technical, social and natural effects to be taken into account regarding their measurement and weighting [14].

In order to meet these diverse and multidisciplinary demands, cooperation and collaboration between manufacturers, air navigation service providers, legislators and civil society stakeholders is essential from the beginning [10]. This requires a very diversified network with a deep understanding of all framework conditions, restrictions, subsystems, system components, interfaces and dependencies. Furthermore, a common use case that can be considered, understood and addressed by all network partners is necessary. Following this introduction, the state of the art is presented in Section 2. The third section describes the challenge and the goal of the network, its approach and structure are presented in the fourth section. Finally, in Section 5, a conclusion and an outlook are given.

2. Related work

A number of UAM questions have already been considered in individual disciplines and have been examined in different ways for individual sub-areas. There are scientific publications on UAM demand forecasting based on surveys [15], models from existing data [16], assumptions and probabilities [17] and agent-based simulations [18, 19].

Approaches also exist for urban airspace management [20, 21, 22, 23], trajectories and network simulation [10, 24, 25, 18, 26] and for scheduling and de-conflicting [10, 21, 24, 27]. From the hardware-side system view there are scientific work on vehicle design [28, 29, 16, 19], as well as on vertiport design and integration [19, 21, 30, 31, 32]. From the business management research perspective, cost and revenue modeling has been carried out [16, 19] and, in addition, environmental impact assessments of the systems also have been carried out, for example with regard to energy demand [16, 21, 28, 29] and noise emissions [23, 31].

There is only a very limited number of interdisciplinary studies on urban air transport systems [10]. A broad analysis of the existing literature with regard to application potentials and possible problems and realization barriers in urban drone deliveries and urban passenger transport is provided by [33, 34]. A further overview of research fields, current developments and open research questions in the field of UAM is provided by [35].

Nevertheless, a number of consortia and communities have already emerged to address the topic of UAM and to push forward and support research and development in this area. Already in 2012, the European Innovation Partnership "Smart Cities and Communities" (EIP-SCC) was formed. Supported by the EU Commission, this brings together cities, regions, citizens, industry, investors, researchers and other stakeholders with the aim of improving urban life through integrated mobility, energy and transport concepts. The topic of urban air mobility was included in EIP-SCC with the UAM Initiative in May 2018, led by Airbus. A total of 43 cities and regions including Hamburg joined the initiative by June 2019, and its importance was officially endorsed e.g. by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) [36].

Showcase projects are planned, among others, in Aachen, Ingolstadt and Toulouse. In the research project “Mobility of the 3rd Dimension”, which is located in Ingolstadt, first flying vehicles are to be used on protected test sites to carry out experimental applications such as inter-urban inspection flights of rails (see FreeRail project) [37]. In projects such as "OBUAM" and "GABi", new modes of air mobility have been investigated as a complement to existing local passenger transport in upper Bavaria and first human factors (comfort, noise, etc.) are examined [38]. The research project "HorizonUAM", conducted internally by German Aerospace Center (DLR), focuses on air taxi services (including the components vehicle, infrastructure and operation as well as acceptance) with 10 DLR institutes and facilities involved [39].

Furthermore, international approaches, e.g. of MIT or the company UBER, primarily address technological aspects in their research and focus less on the connection between UAM and social aspects, or on the holistic embedding of UAM [40, 41]. Individual papers are known that focus solely on issues of societal acceptance of unmanned aerial systems and consider them apart from the holistic system concept [42].

Since UAM research is a young and growing discipline, there are other research projects that consider further aspects of mobility and unmanned aviation in urban environments, but are still in the early stages of their work or have published limited results to date (including [43, 44]). Many of these projects have a significantly smaller scope in terms of topic diversity and project duration compared to the collaborative project presented here.

In order to achieve a holistic system design, the sub-functions and necessary subsystems must be developed and elaborated in corresponding steps from an initial main function [45]. For an interdisciplinary development and consideration of systems, the dependencies of the individual modules and sub-systems take on an important role. This requires a parameter transfer and the definition of interfaces, both between interdisciplinary modules and modules from clearly separable disciplines [46]. In Niklaß et al [10], a first approach for holistic simulation and steps to create a new UAM model system have been proposed. In this process, all involved parties are first integrated, potential system characteristics are collected, requirements are defined, the potential system is described, information is linked, and dependencies are identified. This is followed by the identification and prioritization of cause-effect relationships; all of these steps require intensive collaboration between all parties involved and the linking of knowledge from different disciplines. Based on this, the overall system is modeled, using existing sub-models, so that finally data can be generated and different ideas and concepts can be tested [10]. These steps are illustrated in Figure 1.

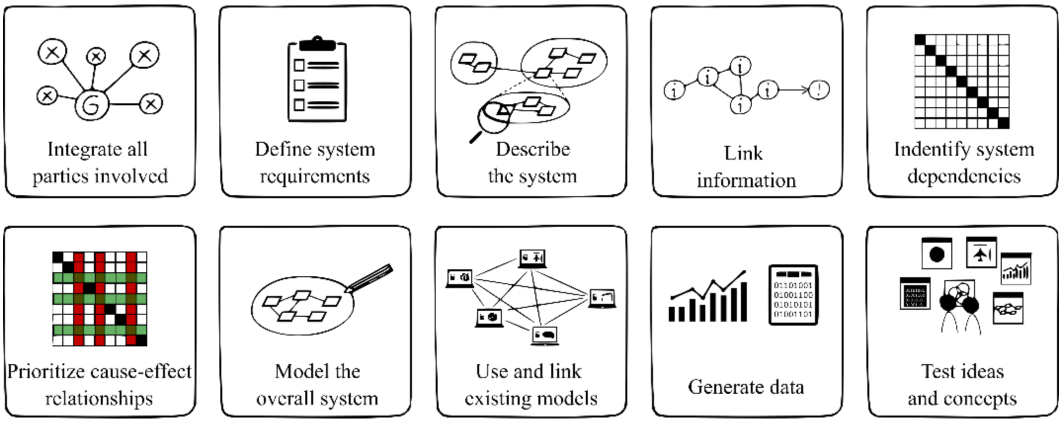

Figure 1 – Design tasks for the creation of an overall model system for UAM acc. to Niklaß et al. [10]

For the holistic simulation and modeling of systems with different existing models, the DLR open-source integration software RCE (Remote Component Environment) is a suitable tool to connect the discipline-specific analysis capabilities. The integration of stand-alone components is realized by the RCE workflow engine, requiring defined inputs and outputs from local and remote sites, which are then integrated into an overall system simulation [47]. A peer-to-peer network is established in which each user can access individual components and execute them as a black box. This enables the execution of workflows for system modeling based on distributed "black boxes". Provided that all necessary input data are available, the components can be executed in a distributed manner. By computing the sub models in parallel, this can result in a reduction of the overall simulation time. The RCE software package has also proven its worth outside DLR (especially in the field of unconventional aircraft design). For example, in the EU-funded project AGILE (Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts), the integration software RCE was used in an international consortium consisting of 19 partners for the collaborative development of optimized aircraft of high complexity [48].

3. Challenge formulation and objective

In the UAM development process, advantage can be taken from decades of civil aviation development and influences, which should be considered. However, in UAM a lot of new and more sensitive influences have to be taken into account. So, neither the “final” result (i.e., the “best” design for the UAM), nor the detailed path to get there are clear [10]. Thus, UAM modeling according to the Cynefin framework, which distinguishes between the domains obvious, complicated, complex, chaotic, and disorder [49], must initially be considered a chaotic project until the level of system understanding increases as the project progresses [10].

As shown in the state of the art, most activities follow a single Technology- or Vehicle-Driven Design approach to UAM. In these, the vehicles (whose construction is enabled by the current technology push) are designed according to the state of the art and then an appropriate use case and deployment scenario are identified. Some of the underlying projects address this challenge following the approach of problem-deduced path, described as “scenario pull” by Ghosh et al. [50]. For this a demand-driven system design approach is followed, first considering whether and how UAM could improve the mobility of a city, and then deriving corresponding requirements for the UAM system. Based on this an overall system architecture considering all relevant elements is created, e.g. demand, airspace structures, vehicle characteristics, vertiport allocation, as an integrated design. This is to be achieved by combining the expertise from the fields of technology, information technology, urban planning, logistics, society and law, bundled into an overall system competence. In contrast to technically driven considerations, the focus of the research is not on the vehicle itself, but on urban planning, airspace organization and operational architecture and integration, as well as the expected benefits for the city, its residents and visitors.

Thus, the objective is the development of methodological, systematic and knowledge-based foundations for the elaboration and evaluation of the feasibility of innovative concepts and technologies for air-supported urban mobility, taking the Hamburg metropolitan region as an example, in various possible scenarios in the near future for current drones up to the years 2040/2050 for passenger drones. A scientific overall system excellence is to be established in the network through an integrating approach of vehicle characteristics, the on-board and ground-based management and information systems, the operating infrastructures, as well as demand and business models and the respective interfaces and interactions of the disciplines and system parts. Questions regarding social acceptance will be elicited by means of social research, legal aspects of feasibility will be scrutinized, and the scalability and transferability of concepts will be examined.

4. Approach and structure of the research network

Due to the high system complexity of urban air mobility, which is still largely unexplored, a high number of interdependencies exists between the particular disciplines of aircraft design, flight guidance, urban planning, transport planning and logistics, as well as impact and acceptance research. Therefore, a collaborative approach is chosen in these joint projects and the knowledge of the scientific institutions based in Hamburg is brought together.

The overall objective is to establish a model-based holistic system evaluation capability for urban air mobility with the involvement of external partners (these can be from aeronautical research as well as from any other interested research fields beyond the existing research network, regardless of their location). To achieve this, an interdisciplinary evaluation methodology will be developed in order to be able to assess the value of new and various concepts against the performance of the current transport system and to establish comparability. In principle, different UAM concepts are possible, such as a scheduled air shuttle between fixed locations or an on-demand air taxi service. The selection of the operational concept is highly dependent on the technology level, the local topology as well as the existing transport system and significantly influences the selection of the vehicle, the complexity of the network, the dimensioning and positioning of the ground infrastructure (few vertiports or many smaller vertistops), the integrability into the district as well as the local noise pollution. Many factors must be taken into account, and thus the ability to weigh partially conflicting interests must also be developed, i.e., multi-criteria value judgments that consider all relevant physical and social impacts with sufficient accuracy. Examples for technical assessment aspects to be considered are the resulting noise emissions and the energy balance of the system. In addition, the resulting transportation capacity and travel time savings are also important target variables. As part of the network's work, an open platform for associated partners will be created by providing an IT infrastructure for sharing model-based analysis capabilities to ensure cross-site networking and enable expansion.

A development of concrete overall concepts for urban air mobility is carried out based on Hamburg as a representative, exemplary city, taking into account various scenarios and deriving requirements for vehicles, infrastructure and operation [9]. The method of controlled convergence of solution ideas is used to develop efficient overall concepts. In this process, separate concept ideas will first be identified for individual sub-disciplines and a focus on the most promising partial solutions will take place. These are subsequently worked out in detail, modeled and combined with the solutions from the other disciplines. The level of detail of the modeling and evaluation thus increases continuously in the course of the projects and individual areas from the initial solution space are concretized.

In order to address the aforementioned challenges and goals, various main topics need to be worked on.

4.1 Main topics and focus of the research projects

In Fig. 2 some key topics are shown, which are “Societal Interactions and Legal Framework”, “Demand Modeling and Concept Development”, “Ground Based Infrastructure”, “Airspace Organization and Operations” and “Overall System Modeling and Assessment”.

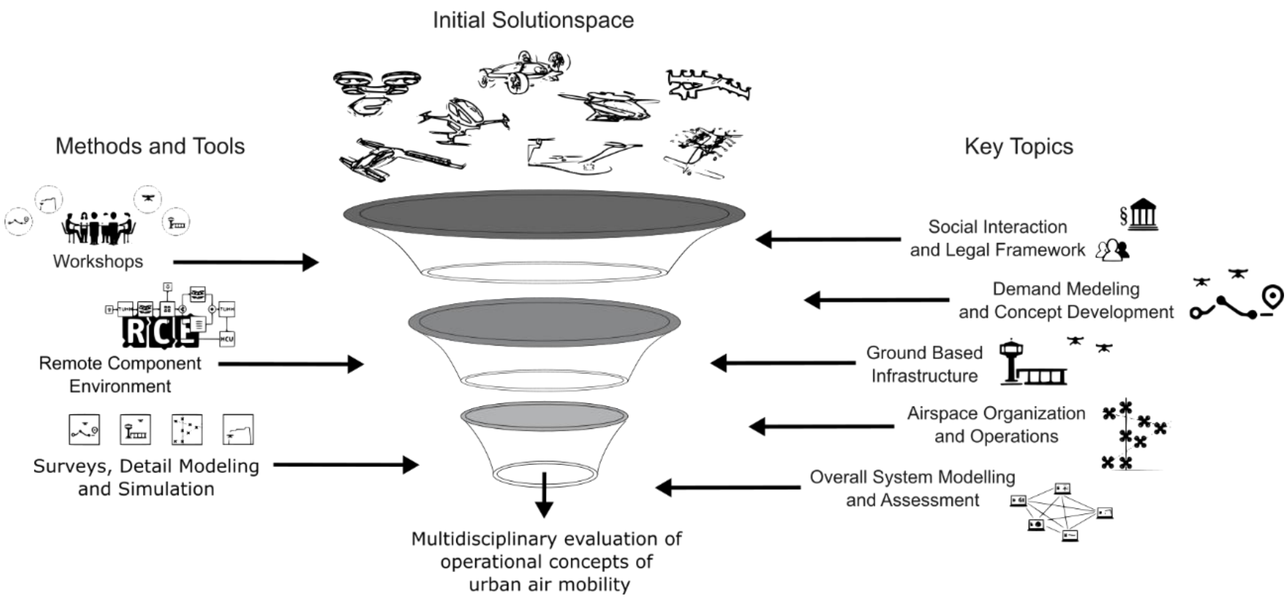

Figure 2 – Structure and Approach of the UAM research network

4.1.1 Societal Interactions and Legal Framework

The “Societal Interactions and Legal Framework” topic addresses the fact that minimizing risks and hazards to individual rights worthy of protection (life and health as well as protection of personality including data protection) emanating from aviation is at the same time a requirement for the sense of security and social acceptance of air traffic, which will increase in the future. The sense of safety and security is a fundamental human need that should not be affected by the use of aviation in urban areas. Structures, strategies and instruments of airspace management are explored from a legal perspective. The connected aspects of people's sense of safety and social acceptance of air traffic, including increasing drone flight, are the subject of societal science and (experimental) psychological research. Regulation of regional air traffic is a component and manifestation of governmental risk management for airspace. In the emerging regulatory concept, as currently formulated by Regulation (EU) 1138/2018 and its delegated and implementing regulations, the risk-based approach to airspace regulation can be identified and analyzed. A key objective of airspace surveillance systems is to minimize risks and threats to legal interest worthy of protection in the field of aviation. The subtasks in this topic are not only interlinked with each other, they also affect other topics and subtasks, for example to societal acceptance influence demand, to noise emissions, integrability of UAM into the city and safety concepts.

4.1.2 Demand Modeling and Concept Development

Particular to the topic of “Demand Modeling and Concept Development” is that the introduction of urban air mobility concepts as a technology push must go along with a market pull, if this new way of moving shall be successful and accepted. To assess the scope of these changes and incorporate them into the urban air transportation system design process, this topic conducts subprojects with concept workshops; derives potential user groups and, based on these, models potential demand while considering displacement effects in the overall transportation system in the urban area.

4.1.3 Ground Based Infrastructure

The subject of the “Ground Based Infrastructure” topic is the planning, modes of operation, modeling and application scenarios of the ground-based infrastructure for the future flight vehicles. The subtasks deal with different aspects of the development of vertiport networks. The goal is to develop a methodology for calculating the mobility capacity of ground infrastructure, both at the single-node and network level. In addition to the vertiports in their function as traffic sources and sinks, the maintenance facilities for the air vehicles are also considered as elements and examined at the vertiport level concerning the requirements. Different charging function concepts to enable optimized vehicle operation in the derived network design will be developed. An urban sociological knowledge base will be built, for example, to evaluate the integrated ground infrastructure network in terms of consequences due to changing land use or its potentials to overcome natural boundaries. In a vertiport network, there are a wide variety of requirements for the functions that a vertiport has to fulfill. Depending on these, different configurations of the individual vertiports in the network are required, ranging from vertistops (a vertiport location with minimal size and cost) to flex vertiports (which can be used flexibly and temporarily), traffic hubs (vertiport locations with high flight frequency and passenger volume), and maintenance hubs (vertiports with a focus on vehicle MRO). To span such a solution space, one strategy to be followed is that of modularization.

In the project "Vertiport" the focus is on the development and investigation of such modular vertiports [51]. The question of how a modular vertiport can be built and organized and how it fits into the existing urban development is examined. The aim of this project is to develop a modular building block concept that can be adapted for a local vertiport network and thus can be adapted to the circumstances of a wide variety of metropolitan regions. For an exemplary implementation, the city of Hamburg is used as a reference metropolitan region. The questions of modularization focus on the adaptability to different types of vehicles from different manufacturers as well as the different energy supply of them (battery, electricity, hydrogen, etc.) and the scalability that can be achieved in this way. Furthermore, the requirements for safe operation of vertiport and vehicle through appropriate processes and automated service and maintenance concepts are also being investigated.

4.1.4 Airspace Organization and Operations

The topic “Airspace Organization and Operations” deals with the fact that, depending on real demand, sufficient airspace capacities are required, especially if restrictions like the civil airport airspace in Hamburg have to be considered. Some first estimates of orders have been made, [9]. Therefore, there is a need for efficient and agile planning, monitoring and control of air vehicle movements by means of an urban air traffic management (UATM or U-Space) system. In the light of the permanent growth in urban air traffic due to UAV operations in the past years, it is foreseeable that an approach of higher automation compared to the structures and modes of today’s airspace management will be needed for the purpose of UAM, as the current structures already reach their limits. Alternatives for a regional, urban ATM in conjunction with a higher-level ATM will be investigated and modeled so that their performance can be tested in the overall system simulation. Overall, the organization of airspace is subject to a large number of requirements and constraints, which are deduced from the three areas described previously.

The UDVeo and LUV projects deal with scenarios of airspace organization in the near future. The UDVeo project (Urban Drone Traffic Efficiently Organized) aims to develop practical concepts and solutions for the integration of UAS in urban airspace [52]. Taking into account the European U-Space Regulation (Commission DVO (EU) 2021/664 of 22.04.2021), an overall, i.e. both technical and legal, concept for drone traffic management is being developed [53] in which essential processes such as registration, flight clearance [54] and strategic and tactical conflict management [55] are implemented within the framework of a prototype ground control station. In particular, this prototype is responsible for strategic conflict management and the authorization and monitoring of flights. For tactical conflict management, the UAS themselves are considered, they should be able to communicate with each other and be equipped with the necessary intelligence to be able to react dynamically to changing environmental conditions and thus increase safety in UAS traffic. From the UAS hardware perspective further parts of the project comprise communication (drone to X) and e-registration technology development. Within the LUV project (solutions and recommendations for the national implementation of the U-Space regulation) [56], a U-Space operational concept is developed and considered, which is operated by one S-CISP (Single Common Information Service Provider) and at least two USSPs (U-Space Service Providers). Based on this operational concept, process models for the technical and operational implementation of U-Spaces are developed and then different business models and pricing concepts are considered. The results will be validated with the help of simulation studies and will be used together with an assessment of the legal situation and an elaboration on acceptance promotion to develop recommendations for action for the national implementation of the U-Space regulation (including the design of roles, responsibilities and requirements for the technical equipment of air traffic participants).

The consideration of the airspace for a point in time further in the future (with integration of a passenger transport) has an essential role in the project ULTRAS (Urban Air Transportation Simulation). In this project, potential traffic demand for UAM is combined with a dynamic simulation that includes control systems, communication and air traffic research. This will be built in a modular and extensible simulation chain and implemented in a RCE simulation. To integrate the dynamic behavior of flight vehicles, a multi-agent simulation environment will be developed and integrated.

4.1.5 Overall System Modeling and Assessment

The topic “Overall System Modeling and Assessment” addresses a model based overall understanding of the urban air transportation system that does not yet exist, combining the knowledge of the specialists involved and mapping the relevant physical and societal effects of airborne urban mobility. In order to identify and simulate these effects and interdisciplinary influences, various analysis capabilities and modules are built and extended, which will be combined to form an interlinked, spatially distributed overall system modeling.

The short-term goal of developing a modular UAM system simulation is to perform comparative analyses of different subsystem designs to quantify cause-effect relationships at the system level. In the long term, the UAM system simulation should enable the derivation of key figures for specific UAM market studies.

All of the projects already mentioned in the paper make an important contribution to holistic system simulation and evaluation with their work and findings. Also, depending on the respective project scope, corresponding simulations and simulation chains are built and used in the different projects. The i-LUM research project with its objective of developing methodological, systemic and knowledge-based foundations for the elaboration and evaluation of the feasibility of innovative concepts and technologies for air-supported urban mobility for the Hamburg metropolitan region in future scenarios (2040/2050) [57], strives for the implementation of a holistic system modeling and evaluation. The project includes in its subprojects work from all 5 key topics presented in this paper, which also define the basic structure of the main work packages of i-LUM. In order to achieve a holistic overall system modeling and assessment, different analysis capabilities and modules will be built up or extended in the project and then merged. This is done by linking modules and partial simulations in a system-of-systems overall simulation in the RCE environment. The setup of the overall simulation with its simulation modules is realized in a server network, which allows an authorized user to apply the simulation methods of the i-LUM consortium in the form of black-box models.

4.2 The competencies of the Hamburg Advanced Air Mobility (AAM) Innovation Hub

The previously mentioned key topics and focal points of the various research projects will be brought together in the "Hamburg Advanced Air Mobility (AAM) Innovation Hub". The competencies from the different projects will be collected and bundled for a comprehensive overall system analysis. The work and main results are shown in figure 3.

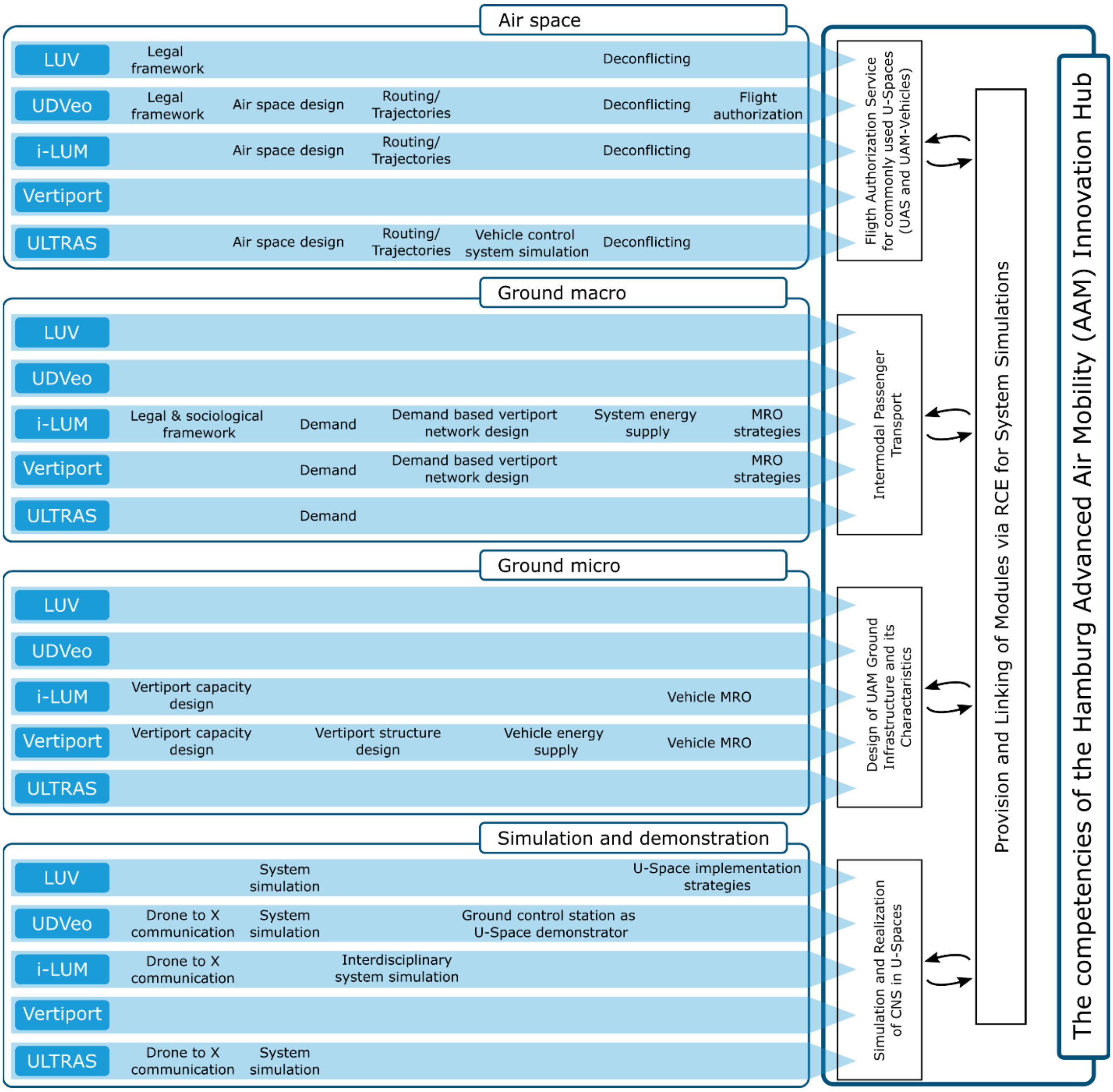

Figure 3 – Research fields, results and competencies of the Hamburg AAM innovation hub

This is structured in such a way that four major research areas are named on the left-hand side. Within each, the five research projects described in the paper (i-LUM, ULTRAS, Vertiport, UDVeo, and LUV) and their major contributions to the area are displayed. The research areas cover airspace, with legal framework, air space design, routing/ trajectories, deconflicting and flight authorization. The next area is the ground side system view on a macro level with legal but also social (acceptance) framework, demand, demand based vertiport network design, system energy supply and MRO strategies. The ground side system consideration on a micro level, focuses on infrastructure topics such as vertiport capacity design, vertiport structure design, vehicle energy supply and vehicle MRO.

The simulation and demonstration area includes communications, (interdisciplinary) systems simulation, ground control station as u-space demonstrator, and u-space implementation strategies. The work in each area (for example, deconflicting) is part of several projects that can take advantage of synergies and work on similar cases, but also look at the same work from very different perspectives (for example the near future in UDVeo versus the years 2040/50 with air taxi traffic in i-LUM). The work in the different projects results in the competencies of the Hamburg advanced air mobility (AAM) innovation hub (displayed on the right side of figure 3). These include the focus areas "Fligth Authorization Service for commonly used U-Spaces (UAS and UAM-Vehicles)", "Intermodal Passenger Transport", "Design of UAM Ground Infrastructure and its Characteristics" and "Simulation and Realization of CNS in U-Spaces". Within the framework of the projects and in the competence areas, a wide variety of simulations have already been built and will continue to be built. These are provided and linked with the help of RCE. This enables a comprehensive system simulation that can be individually adapted and extended. Furthermore, it is also possible to use the established simulation chains for simulations in the subareas in order to generate input for new specific simulations.

Figure 4 shows the time frame of the projects mentioned in the paper with their project durations and a very brief mention of the main project outcomes. Further projects and partners are affiliated to these projects and more projects are planned for future research.

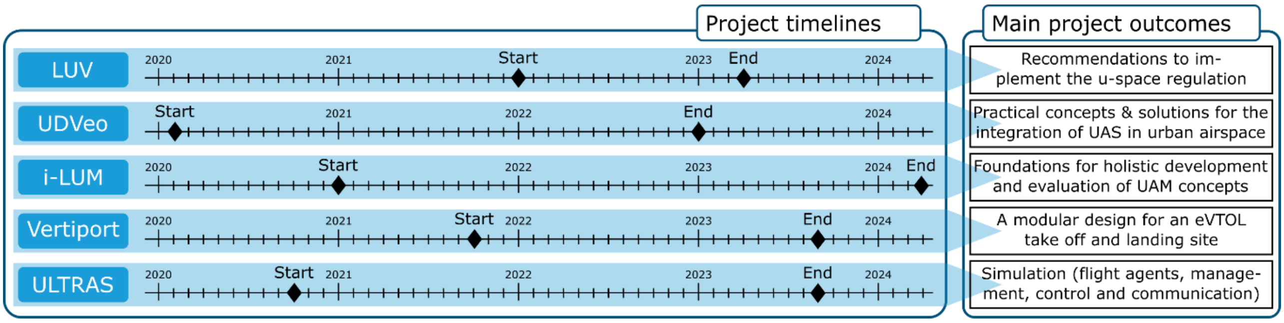

Figure 4 – Project timelines of the mentioned Hamburg AAM innovation hub projects

5. Conclusion and outlook

The presented research shows the work of different research projects and their intersections in the Hamburg metropolitan region. These enable work on an interdisciplinary approach to developing conceptual proposals for urban air mobility solutions in an integrated architecture. In this process, aeronautical and social sciences work together to find technical and operational solutions that meet societal expectations. The methodology followed is problem-oriented and needs to be adapted to the experience gained during the projects. In addition to the described goals of an interdisciplinary and holistic investigation of urban air mobility as well as the creation of a simulation and evaluation possibility of different UAM concepts using the example of the Hamburg region, a further goal is the development of structures for the targeted training and qualification of young scientists and the development of scientific excellence in the field of UAM, for which purpose international scientists are also to be specifically involved. The combination of humanities and social sciences, technological and neuropsychological issues is to be emphasized in order to develop innovative and accepted technical mobility solutions.

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7. Copyright Statement

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