# ULTRAS: ITERATIVE DEVELOPMENT OF A COMPREHENSIVE TOOLCHAIN FOR URBAN AIR MOBILITY SIMULATION

J. Berling*, P. Hastedt†, S. T. Wanniarachchi‡, A. Vieregg§, C. Gertz§, V. Turau‡, H. Werner†, V. Gollnick*
* Hamburg University of Technology, Institute of Air Transportation Systems, Hamburg, Germany
† Hamburg University of Technology, Institute of Control Systems, Hamburg, Germany
‡ Hamburg University of Technology, Institute of Telematics, Hamburg, Germany
§ Hamburg University of Technology, Institute for Transportation Planning and Logistics, Hamburg, Germany

Abstract

A modular urban air mobility (UAM) simulation toolchain was iteratively developed in the project ULTRAS (Urban Air Transportation Simulation). Twelve modules combined passenger demand, vertiports, routing, trajectories, sectorized capacities, costs, scheduling, and infrastructure scaling, communication, and control (GNC). Three iterations evolved modules from minimum viable products (MVP) to mature frameworks, adding and adapting assumptions, functionality, and interfaces. In each iteration, modules were integrated to a workflow, enabling comprehensive simulation and evaluation.

Keywords
Urban Air Mobility, Simulation, RCE, Autonomous Agents

## 1. INTRODUCTION

The operation of urban air mobility requires careful consideration of factors such as safety, capacity, potential revenues, and costs [1,2]. In parallel to conceptual development [3], several scientific models for Urban Air Mobility (UAM) are under development [4,5], integrating a variety of systems to create a holistic view. In addition, the European Commission [6], Germany [7], and other government agencies are publishing relevant regulations [8] and policies [9] to provide guidance. As many individual aspects such as passenger demand scenarios [10], vertiports [11, 12], airspace [3], traffic management [13], routing [14], scheduling [15], and evaluation [16] require sophisticated models, it is necessary to continuously improve each model. In the tactical time domain, control [17], and communication [18] should be realised. Discrete event simulation of traffic [5,19] promises such capabilities. In addition, these aspects are highly interdependent, requiring the design of comprehensive systems that are congruent at each stage of development.
Systems of systems, such as UAM, are interconnected and interrelated systems [20, 21]. Iterative design is prominent for complex systems [22], where prototypes [23] or Minimum Viable Products (MVP) [24] can be created to test initial interfaces and functionalities. Data flows for system-of-systems can be organised using XML [25] as in the CPACS schema [26] that is extended for UAM [4]. Modules can be integrated using RCE [27], making them accessible on virtual machines for distributed partners.
To implement the model, functional domains, system granularities, temporal levels, and functional relationships must be identified. Each capability domain or feature may have different levels of complexity. Therefore, each module requires different levels of sophistication and functionality. Some aspects are relatively clear, such as vehicle speed, while others have either unknown numbers, as in the case of cruising altitude, or unknown qualities, as in the case of geo- or no-fly zones. For some aspects, there are different concepts, such as direct flight vs. flight on segments [28], or centralised [29] vs. decentralised airborne conflict resolution. In addition, there are feedback loops between domains, such as the impact of ticket price, travel time, or schedule horizon on passenger demand, or the impact of passenger demand on incentives to build vertiports. A toolchain combines different modules, and a workflow run selects a combination of configurations and runs the modules to produce a result.
The paper is structured as follows: Section 2 gives an overview of the iterative development. Section 3 presents the three developed workflows. The main modules and their updates are discussed in section 4. Finally, section 5 gives a conclusion and directions for further research.

## 2. ITERATIVE DEVELOPMENT

The interdisciplinary research project ULTRAS[1] (Urbane Lufttransportsimulation, German for 'Urban

[1]This work was funded by the BMWK - Federal Ministry for Economic Affairs and Climate Action in LuFo VI-1 under grant id 20E1911.



doi: 10.25967/630274

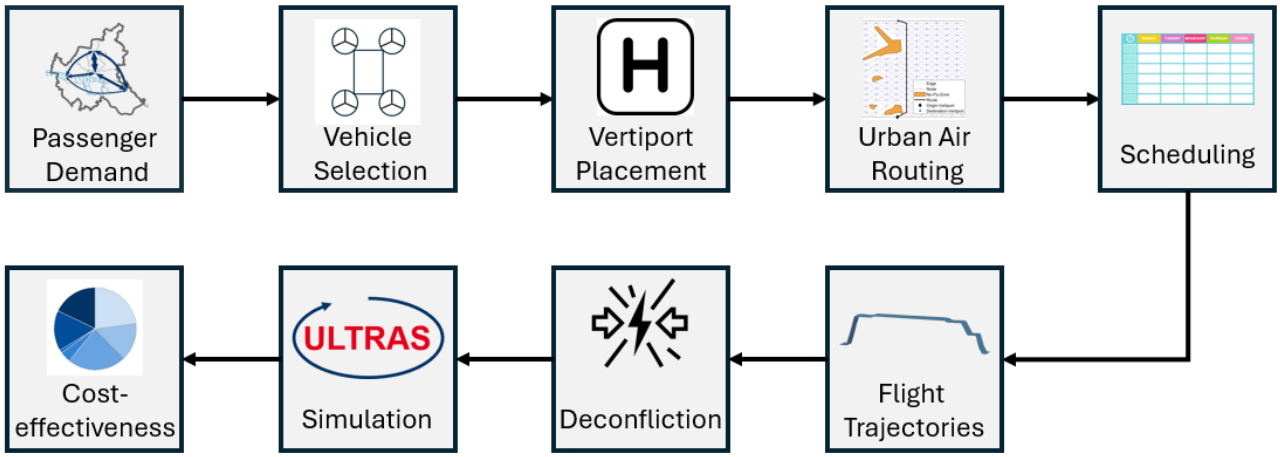


FIG 1. ULTRAS RCE Workflow, Iteration 1 [5].

| module | iteration 1 | iteration 2 | iteration 3 |
|---|---|---|---|
| demand | population & economical | travel-share | dynamic |
| route | direct | waypoint-grid | connectivity |
| scheduling | trip generation between vertiports | economical | dynamic |
| simulation | ideal communication<br>simple control | 5G air-to-ground<br>predictive control | 5G air-to air<br>nonlinear model |

TAB 1. Selected module-capability developments.

Air Transportation Simulation') iteratively designed, modeled, simulated, and evaluated future UAM operations in the Hamburg metropolitan area. In three iterations of approximately one year each, new modules were developed or existing modules were updated, from minimum viable products (MVP) to mature frameworks (see Tab. 1) The iterative process was designed in an agile spirit, incorporating lessons learned from the current workflow into the design, resulting in more informed feature planning. In each iteration, the modules were integrated into an RCE (Remote Component Environment, www.rcenvironment.de) workflow and simulated collaboratively. Since the initial ULTRAS workflow of the first iteration [5], further regulations, operational concepts, and vehicle prototype data have been published and incorporated into module updates.

## 3. RCE-WORKFLOWS

In the iterative process, the initial RCE-workflow (see Fig. 1) has been extended and adapted so that iteration 2 (see Fig. 2) and iteration 3 (see Fig. 3) was reached. New modules have been created and integrated. Because modules are interdependent, certain features have been added or moved from one tool to another, while interfaces have been adapted.

### 3.1. Changes between iteration 1 and iteration 2

In Workflow II, the deconfliction tool was no longer required as the simulation performed the airborne separation of the aircraft. It was also not possible to remove a flight from the vehicle turnarounds calculated in the Scheduling tool.
The Trajectories module has been moved forward to calculate the reference trajectories required by the Sector and Scheduling tools. The Sector module requires the path and times of the trajectories to adjust the sector design. The Static Scheduling module required the reference trajectories, i.e. the flight times relative to the start.
The Sector modules have been added to limit the capacity in the sectors. The trajectories were used to design the sector geometry and to determine the capacity limits by Monte Carlo method of separation conflicts. By limiting the number of flights in an airspace, the aim was to ensure that separation is successful.
The Direct Operating Cost (DOC) module has been brought forward to allow for economic trade-offs in scheduling by calculating the cost of trajectories and the cost of operating a UAM vehicle. This work therefore calculated the cost of the flight on the basis of its planned use, rather than the estimated number of flights per aircraft.
The reference trajectories were fed into the new scheduling module, which means that the planned take-off times of the flights, together with the reference trajectories, define the landing times and sector entry times. This enables to decide how many vehicles should be used to make the planned round trips.

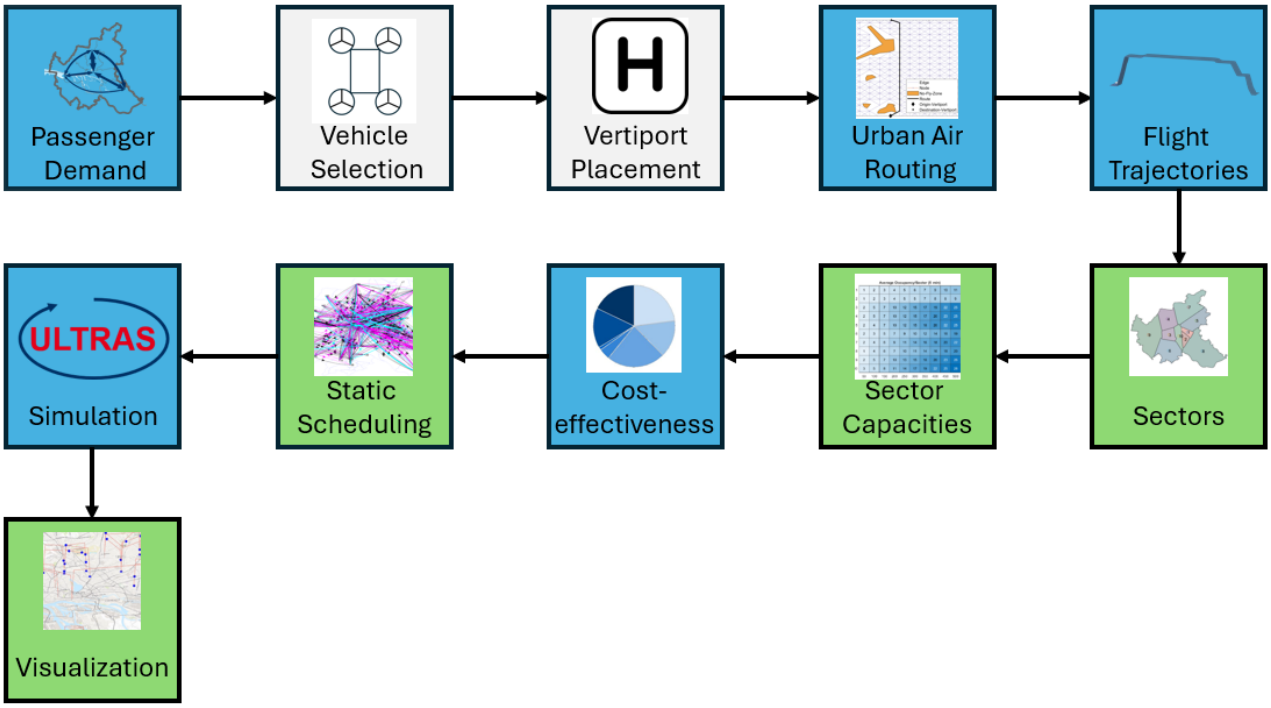


FIG 2. ULTRAS RCE Workflow, Iteration 2 (green: New module. Blue: Adapted or moved module).

### 3.2. Changes between iteration 2 and iteration 3

The following changes have been made between Workflow II and III. The Queue Demand Tool has been added to determine the timed demand for flights from the hourly passenger demand. It provided the Static and Dynamic Scheduling modules with the demand time and number of passengers.
The new Dynamic Scheduling module used the vertiport sizing and initial vehicle placement from the Static Scheduling module. As the simulation progresses, the schedule was constantly recalculated in a rolling time horizon, as in e.g. [30].

## 4. MODULE ITERATIONS

Modules were developed iteratively and integrated into workflows. This section presents representative module developments and explains their progress.

### 4.1. Passenger demand

The calculation of UAM demand between neighbourhoods was iterated from an economic model combining population data [4] to traffic estimates based on the Hamburg urban transport model [5]. In the new UAM Queue Demand tool in iteration 3, passenger trip requests were derived from hourly demand by simulating a Poisson process. This can replace the calculation of passenger travel times from the Scheduling module. The time at which a passenger demand is known was calculated in the Dynamic Scheduling module.

### 4.2. Routing

2D routing between vertiports has evolved from direct routing around no-fly zones in iteration 1, to routing on a grid with minimal separation between parallel segments in iteration 2, to routing with additional edge directions and a turn penalty based on passenger comfort. The aim was to reduce detours and route lengths. The cost function for the routing algorithm was designed to optimise passenger comfort by reducing large bank angles and thus g-forces [28] (see TAB. 2).

### 4.3. Sector Geography and Capacities

In the second iteration, new sector geography and capacity modules were created. The geography module divided the airspace into a desired number of sectors. Sector centroids were created by k-means clustering of trajectories, based on the idea that similar flights should share the same sector to facilitate separation. Sector shapes were created using the nearest neighbour method and straightening of boundaries. The capacity module provided the maximum occupancy of sectors, i.e. the number of UAM flights that can be in each sector at any one time. It used the sector area and Monte Carlo method of the incoming traffic pattern to estimate the capacity based on thresholds for the expected number of conflicts [32, 33].

### 4.4. Scheduling

In the first iteration, the scheduling module took hourly passenger demand and divided it to a number of flights, based on passenger capacity. Flight demand

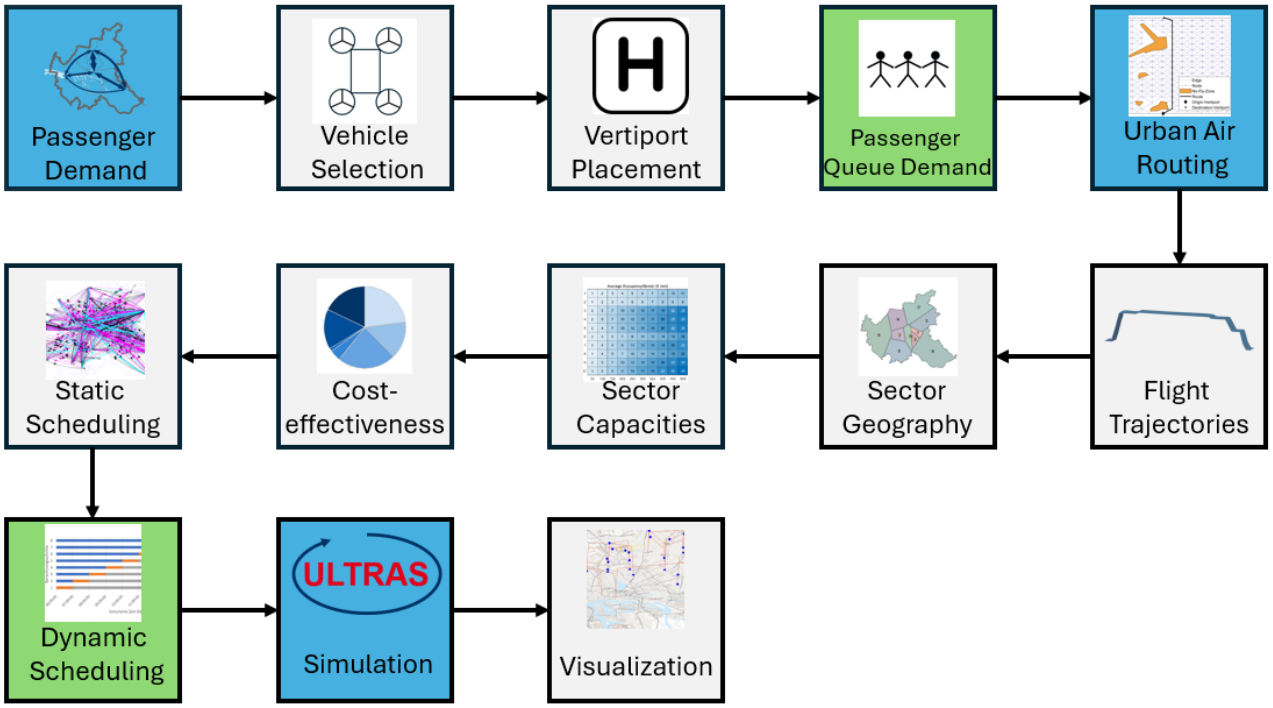


FIG 3. ULTRAS RCE Workflow, Iteration 3 (green: New module. Blue: Adapted or moved module).

| functional area | iteration 1 | iteration 2 | iteration 3 |
|---|---|---|---|
| grid network | layered route nodes | minimum separation distance | different distances |
| segments | connecting layers | squares and diagonals | additional directions |
| routing | shortest path | penalise turn-angles | passenger comfort |

TAB 2. Routing Feature development in three iterations. Iteration 1 uses the tool initially developed in [31] and applied to UAM in [4]. Iteration 2 uses the Waypoint Routing tool from [5] and iteration 3 uses the further development in [28].

was randomly distributed over the hour and vertiport limitations were introduced. [4]
In the second iteration, a new scheduling module was created to perform optimisation trade-offs. It can e.g. optimise for cost, while considering the revenue of flights and cost of each vehicle. The other option is to trade-off the number of flights or revenue kilometres against the number of flights. Moreover, the scheduling module was used to dimension vertiports, that is, it included costs for gates and pads, either monetary cost based or using a scaling factor against flights. The optimisation took into account vehicle availability, vertiport constraints like turn-around times and gate and pad availability, as well as airspace capacities.
In the third iteration, a dynamic scheduling module was created to handle passenger demand that becomes known throughout the day. The tool recalculated in rolling horizon fashion throughout the day (see TAB. 3)

### 4.5. Deconfliction

In the first iteration, deconfliction was performed in pre-departure time between planned trajectories. The module maximised the number of flights under the constraint that there are no conflicts [5]. In the second iteration, the static deconfliction module was removed as in-flight deconfliction was performed by the dynamic simulation (see below).

### 4.6. Dynamic Simulation

The dynamic agent behavior was implemented in a multi-agent simulation framework leveraging OMNeT++ (www.omnetpp.org) [34], a modular discrete event simulation environment primarily employed for network simulations [5]. The framework was enhanced to simulate increasingly intricate and realistic communication and guidance, navigation and control (GNC) of complex vehicles. By effectively combining communication and control simulations, this framework delivers an integrated platform for evaluating performance and reliability under diverse operating conditions

#### 4.6.1. Communication

In the first iteration, the communication channel was modeled as ideal without interference [5]. The sec-

| functional area | iteration 1 | iteration 2 | iteration 3 |
|---|---|---|---|
| operational objective | passenger demand | trade-off | dynamic demand |
| vehicle | trajectory times | vehicle availability | energy consumption |
| capacity | vertiport limitations | vertiports & sectors | battery charging |

TAB 3. Scheduling Feature development in three iterations. Iteration 1 uses the tool developed in [4]. Iteration 2 uses a newly developed tool for optimised scheduling. Iteration 3 uses a newly developed tool for dynamic scheduling.

ond iteration developed a 5G-air-to-ground communication network using the Simu5g framework [35]. A channel model to suit the air-to-ground communication was also developed taking into account realistic channel conditions. This further involved ground network planning considering Hamburg metropolitan area as a use case. [36]. In the third iteration, the simulation was extended to include 5G-air-to-air communication enabling message transmission between nearby air taxis. Along side that, further enhancements to uplift the communication performance in terms of air taxi to air taxi communication by a reinforcement learning based dynamic resource allocation technique was utilised [37].

#### 4.6.2. Control

In the first iteration, simple control algorithms with linear agent models were considered [5]. The second iteration then extended the control algorithms to model predictive controllers with distributed separation capabilities In the third iteration, nonlinear vehicle models and dynamic separation constraints were introduced.

### 4.7. Evaluation

Overall, the framework enables the evaluation of key performance indicators such as travel time differences, energy consumption per person kilometer, and number of conflicts between vehicles.

## 5. CONCLUSION & FUTURE WORK

This paper presents a toolchain for UAM simulations, developed iteratively in the scope of the ULTRAS project. To cover essential aspects of UAM, interdependent modules were created, with each module having several options for configuration. Utitilising such workflows allows the evaluation and comparisons of concepts. Modules can be adapted or expanded to include new functionalities or react to new regulations. Moreover, new modules can be introduced that can facilitate sophisticated UAM Scenarios. In the future, several scenarios can be simulated and evaluated, allowing conclusions about future urban air mobility.

ACKNOWLEDGEMENT:

This research builds on modules provided by DLR-Air Transportation Systems (refer to [4]) and on modules developed in [5]. We thank Marina Prado-Lenza, Nick Wester, Johannes Moosburger, and Lucas Niebuhr for their contributions to individual modules.

Contact address:

jan.berling@tuhh.de

References

[1] Parker D. Vascik, R. John Hansman, and Nicholas S. Dunn. Analysis of Urban Air Mobility Operational Constraints. Journal of Air Transportation, 26(4):133–146, 2018. DOI: 10.2514/1.D0120.

[2] David Thipphavong, Rafael Apaza, Bryan Barmore, Vernol Battiste, Christine Belcastro, Barbara Burian, Arik-Quang Dao, Michael Feary, Susie Go, Kenneth Goodrich, Jeffrey Homola, Husni Idris, Parimal Kopardekar, Joel Lachter, Natasha Neogi, Hok Ng, Rosa Oseguera-Lohr, Michael Patterson, and Savita Verma. Urban Air Mobility Airspace Integration Concepts and Considerations. In 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, Georgia, June 2018. DOI: 10.2514/6.2018-3676.

[3] Aleksandar Bauranov and Jasenka Rakas. Designing airspace for urban air mobility: A review of concepts and approaches. Progress in Aerospace Sciences, 125:100726, 2021. DOI: 10.1016/j .paerosci.2021.100726.

[4] Malte Niklaß, Niclas Dzikus, Majed Swaid, Jan Berling, Benjamin Lührs, Alexander Lau, Ivan Terekhov, and Volker Gollnick. A Collaborative Approach for an Integrated Modeling of Urban Air Transportation Systems. Aerospace, 7(5), 2020. DOI: 10.3390/aerospace7050050.

[5] J. Berling, P. Hastedt, S.T. Wanniarachchi, A. Vieregg, C. Gertz, V. Turau, H. Werner, and V. Gollnick. A Modular Urban Air Mobility Simulation Toolchain with Dynamic Agent Interaction. In Deutscher Luft- und Raumfahrtkongress (DLRK), 2022. DOI: 10.25967/570247.

[6] Commission implementing regulation (eu) 2021/665 amending implementing regulation (eu) 2017/373 as regards requirements for providers of air traffic management/air navigation services and other air traffic management network functions in the u-space airspace designated in controlled airspace of 22 april 2021.

[7] Luftverkehrs-Ordnung vom 29. Oktober 2015 (BGBl. I S. 1894), die zuletzt durch Artikel 2 der Verordnung vom 9. Juli 2024 (BGBl. 2024 I Nr. 251) geändert worden ist.

[8] Luftfahrt Bundesamt (LBA). Guidance for dimensioning of flight geography, contingency volume and ground risk buffer, new revision from 01.02.2023, 2023.

[9] Bundesministerium für Digitales und Verkehr (BMDV). Konzept Einrichtung von U-Spaces in Deutschland, November 2022.

[10] M. Rimjha, M. Li, N. Hinze, S. Tarafdar, S. Hotle, H. Swingle, A. Trani, and Jeremy C. Smith. Demand Forecast Model Development and Scenarios Generation For Urban Air Mobility Concepts. Virginia Tech and NASA, 2020. Technical Report 20205005881.

[11] Gazmend Mavraj, Jil Eltgen, Tim Fraske, Majed Swaid, Jan Berling, Ole Röntgen, Yuzhuo Fu, and Detlef Schulz. A systematic review of ground-based infrastructure for the innovative urban air mobility. Transactions on Aerospace Research, 2022(4):1–17, 2022. DOI: 10.2478/tar-2022-0019.

[12] Karolin Schweiger and Lukas Preis. Urban Air Mobility: Systematic Review of Scientific Publications and Regulations for Vertiport Design and Operations. Drones, 6(7):179, 2022. DOI: 10.3390/drones6070179.

[13] N. S. Labib. Distributed unmanned aerial vehicles traffic management system. PhD thesis, Universite Du Luxembourg: The Faculty of Science, Technology and Medicine, 2021.

[14] Zhengyi Wang, Daniel Delahaye, Jean-Loup Farges, and Sameer Alam. Route network design in low-altitude airspace for future urban air mobility operations: A case study of urban airspace of Singapore. In International Conference on Research in Air Transportation (ICRAT 2020), Tampa, Florida, United States, June 2022.

[15] Majed Swaid, Jan Pertz, Malte Niklaß, and Florian Linke. Optimized capacity allocation in a uam vertiport network utilizing efficient ride matching. In AIAA Aviation Forum 2023, Juni 2023. DOI: https://doi.org/10.2514/6.2023-3577.

[16] Christelle Al Haddad, Mengying Fu, Anna Straubinger, Kay Plötner, and Constantinos Antoniou. Choosing Suitable Indicators for the Assessment of Urban Air Mobility: A Case Study of Upper Bavaria, Germany. European Journal of Transport and Infrastructure Research, 20(4):214–232, 2020. DOI: 10.18757/ejtir.2020.20.4.4464.

[17] Irene M Gregory. Urban Air Mobility: A Control-Centric Approach to Addressing Technical Challenges. In IEEE CSS Forum On Robotic and Control Engineering seminar. NASA, 2021.

[18] Yongs Zeng, Qingqing Wu, and Rui Zhang. Accessing From the Sky: A Tutorial on UAV Communications for 5G and Beyond. Proceedings of the IEEE, 107(12):2327–2375, 2019. DOI: 10.1109/JPROC.2019.2952892.

[19] Suchithra Rajendran and Jake Shulman. Study of emerging air taxi network operation using discrete-event systems simulation approach. Journal of Air Transport Management, 87:101857, 2020. DOI: 10.1016/j. jairtraman.2020.101857.

[20] M. C. Jackson and P. Keys. Towards a system of systems methodologies. The Journal of the Operational Research Society, 35(6):473–486, 1984.

[21] Mo Jamshidi. System of systems engineering - new challenges for the 21st century. IEEE Aerospace and Electronic Systems Magazine, 23(5):4–19, 2008. DOI: 10.1109/MAES.2008.4523909.

[22] David C Wynn and Claudia M Eckert. Perspectives on iteration in design and development. Research in Engineering Design, 28(2):153–184, April 2017. DOI: 10.1007/s00163-016-0226-3.

[23] Alan Howard. A new rad-based approach to commercial information systems development: the dynamic system development method. Industrial Management amp; Data Systems, 97(5):175–177, August 1997. DOI: 10.1108/02635579710785456.

[24] Jürgen Münch, Fabian Fagerholm, Patrik Johnson, Janne Pirttilahti, Juha Torkkel, and Janne Jäarvinen. Creating minimum viable products in industry-academia collaborations. In Brian Fitzgerald, Kieran Conboy, Ken Power, Ricardo Valerdi, Lorraine Morgan, and Klaas-Jan Stol, editors, Lean Enterprise Software and Systems, pages 137–151. Springer Berlin Heidelberg, 2013.

[25] Carmen Parisi, Ferat Sahin, and Mo Jamshidi. A discrete event xml based system of systems simulation for robust threat detection and integration. In 2008 IEEE International Conference on System of Systems Engineering, pages 1–8, 2008. DOI: 10.1109/SYSOSE.2008.4724187.

[26] Marko Alder, Erwin Moerland, Jonas Jepsen, and Björn Nagel. Recent Advances in Establishing a Common Language for Aircraft Design with CPACS. In Aerospace Europe Conference 2020. CEAS, 2020.

[27] Brigitte Boden, Jan Flink, Niklas Först, Robert Mischke, Kathrin Schaffert, Alexander Weinert, Annika Wohlan, and Andreas Schreiber. RCE: An Integration Environment for Engineering and Science. SoftwareX, 15:100759, 2021. DOI: 10.1016/j.softx.2021.100759.

[28] Lucas Niebuhr, Jan Berling, and Volker Gollnick. Verbesserte Struktur eines Urbanen

Luftverkehrsstrassennetzwerks in Hamburg mit Penalisierung von grossen Kursänderungen und Gegenverkehr. In Deutscher Luft- und Raumfahrtkongress (DLRK), Hamburg, 2024.

[29] J. Berling and V. Gollnick. Simulation of Transport Drones in Hamburg City with Central Conflict Resolution. In Deutscher Luft- und Raumfahrtkongress (DLRK), 2023. DOI: 10.25967/610463.

[30] Alexander Lau, Robert Budde, Jan Berling, and Volker Gollnick. The Network Flow Environment: Slot Allocation Model Evaluation With Convective Nowcasting. In 29th Congress of the International Council of the Aeronautical Sciences (ICAS), St. Petersburg, September 2014.

[31] Majed Swaid, Kai quan Cai, Majed Linke, Benjamin Lührs, and Volker Gollnick. Wind-optimal ATS Route Redesign: A Methodology and its Application to Route A461 in China. In 16th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), 2016. DOI: 10.2514/6.2016-4360.

[32] Vishwanath Bulusu and Valentin Polishchuk. A threshold based airspace capacity estimation method for uas traffic management. In 2017 Annual IEEE International Systems Conference (SysCon), pages 1–7. IEEE, 2017.

[33] Shulu Chen, Peng Wei, Antony D Evans, and Maxim Egorov. Estimating airspace resource capacity for advanced air mobility operations. In AIAA AVIATION 2022 Forum, page 3317, 2022.

[34] András Varga. The OMNET++ discrete event simulation system. Proc. European Simulation Multiconf. (ESM '01), 2001.

[35] Giovanni Nardini, Dario Sabella, Giovanni Stea, Purvi Thakkar, and Antonio Virdis. Simu5G–An OMNeT++ Library for End-to-End Performance Evaluation of 5G Networks. IEEE Access, 8:181176–181191, 2020. DOI: 10.1109/ACCESS.2020.3028550.

[36] Shashini Thamarasie Wanniarachchi and Volker Turau. A study on the influence of 5g network planning on communication in urban air mobility. In 2023 IEEE 24th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), pages 394–399, 2023. DOI: 10.1109/WoWMoM57956.2023.00070.

[37] Shashini Thamarasie Wanniarachchi and Volker Turau. Dynamic resource allocation for 5g device-to-device communication based on expected sarsa. In Armando Castañeda, Constantin Enea, and Nirupam Gupta, editors, Networked Systems, pages 231–246, Cham, 2024. Springer Nature Switzerland.