DESIGN OF A UAM GROUND INFRASTRUCTURE NETWORK WITH RESPECT TO MAINTENANCE CAPACITY REQUIREMENTS

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Abstract

Before a successful introduction of Urban Air Mobility can be achieved, numerous challenges must be addressed, one of which is the development of efficient traffic networks with all associated components. Previous studies have already examined UAM networks in terms of fleet capacity requirements, energy supply, and parking positions. The aim of this study is the further development of these methods to analyze the necessary capacity of maintenance infrastructure for an eVTOL fleet. Another aspect of this work is to investigate the impact of the centralization degree of a maintenance facility network. While centralized networks have potential to reduce redundancies, decentralized networks may help to reduce detours caused by empty relocation flights to maintenance facilities. Therefore, necessary maintenance intervals are first investigated. Based on these insights, maintenance processes are then planned for an exemplary fleet operating in the City of Hamburg (Germany). Finally, the overall demand for maintenance services is quantified at the network level and the potential benefits of a decentralized maintenance facility network are evaluated with regard to the reduction of empty flights.

Keywords: Urban Air Mobility, Maintenance, Vertiports, Network Design, Fleet Optimization

1. Introduction

A core promise of Urban Air Mobility (UAM) involves the potential for savings in door-to-door travel times. Achieving this goal requires designing vertiport networks that are dense and proximate to demand hotspots. Previous research has delved into several sub-disciplines of network design, linking network density and vertiport positions with UAM demand, transport performance, and time savings (1; 2; 3). Further studies have also explored the processing performance of individual vertiports, examining factors such as topology and approach procedures (4; 5; 6; 7; 8; 9; 10). The study presented in (11) adopts an overarching perspective, utilizing vertiport positions and a traffic scenario as input parameters. The core of that study is a four-step method to determine the necessary capacities of UAM ground infrastructure, offering an analysis of network design. Thus far, this approach has been demonstrated using the example of capacity design for parking positions and required electrical charging power, taking vehicle properties into consideration. Our study builds on this work and aims to exemplarily show how a traffic scenario can be translated into a local capacity demand for ground infrastructure regarding vehicle maintenance. Furthermore, the degree of centralization is investigated for its potential benefits in reducing empty flights.
Previous work in the field of maintenance and inspection of electrical vertical takeoff and landing systems (eVTOLs) is limited to the results from the IFB-funded project Vertiport (12). Within the scope of this project, a literature review was conducted with regard to Maintenance, Repair, and Overhaul (MRO) for VTOLs and their electrical variants. The research was filtered for the keywords *MRO, Aircraft Inspection, VTOL Maintenance, EVTOL Maintenance, EVTOL Inspection*.

Subfield	Keywords	Comments	References
Scheduling			
	Airline maintenance scheduling	Maintenance regulation compliance, efficient resource allocation, competitor cooperation, workshop resource sharing	Sanchez (13) (2020)
	-	Tool for Maintenance Schedules, Downtimes, and Intervals	Eltgen (14) (2023)
	ATS, eVTOL, Current Developments, Challenges, Opportunities, Review	A-Checks: Once per week, Inspection of landing gear, engines, and control surfaces. B-Check: visual inspection and lubrication of parts. Preventive Check: 100h	Rajendran (15) (2020)
	UAM, Agent-based transport simulation, Maintenance Planning, On-demand operation	Identifying challenges in MRO planning for on-demand UAM fleets using agent based simulations	Sieb (16) (2023)
Ground Architecture			
	Ground-based infrastructure, systematic literature review, Vertiport, air taxi	Automated Ground-Based MRO for UAM	Mavraj (17) (2022)
Relevance			
	-	Relevance of maintenance hubs and the extent of monetary percentage that could be saved	Holden and Goel (18)(2016)
MRO Methodologies			
	MRO, Ground-Based Infrastructure, Skyport, UAVs	Technical concepts for inspecting UAVs for damage	Eltgen (19) (2022)
	Maintenance Challenges, Electric Propulsion Concept, Review	Maintenance considerations for electric aircraft and feedback from aircraft maintenance technicians	Naru (20) (2018)
Energy Management			
	Aircraft; MRO; Battery, Fuel cell; Life cycle sustainability assessment	Estimation of maximum operating lifetime of batteries, fuel cells, and electric motors for more frequent replacements.	Barke (21)(2023)
	Electric Aircraft, Battery, Flight Dynamics, Simulation, Optimization	For the Batteries 7,000 charging cycles can be achieved with UAVs	Paek (22) (2020)
	UAM, eVTOL, HUMS, energy harvesting, battery heat monitoring, Data Acquisition Unit	Creation of a health monitoring system (HUMS) for eVTOLs on the example of the Airbus A3 Vahana	Meletis (23) (2021)

Due to the limited number of scientific publications and data in this research area (24), conference papers, journal articles, magazines, and interviews with eVTOL manufacturers were additionaly consulted. A possible explanation for the lack of knowledge may lie in the ongoing development of supply chains or the so-called aftermarket (25). This factor influences the efficiency with which the Original Equipment Manufacturer (OEM) has established a reliable environment for acquiring spare parts, such as replacement batteries and services.

The areas of maintenance planning (scheduling), ground architecture, relevance, methods, and energy management can be divided and categorized, as listed in Table 1.

The research identifies two primary approaches that OEMs are considering to address the maintenance and inspection challenges. The first approach involves outsourcing maintenance services to specialized providers. For example, Orca Aerospace utilizes mixed-reality inspection technology in collaboration with the Hungarian startup AerinX (26). The second approach involves OEMs conducting maintenance operations in-house, as exemplified by Volocopter. The advantage of this method is the higher revenue from in-house maintenance and the use of OEM parts. However, a notable disadvantage is the potential difficulty in accessing spare parts, as manufacturers may not have direct cooperation with service providers.

In addition, the increasing demand for environmentally conscious aviation and the critical importance of these vehicles necessitate high safety standards. In (25), it is highlighted that this process is time-consuming due to the need for defining regulations and maintenance standards by ESA regulations and ConOps. As a result, innovative Maintenance, Repair, and Overhaul (MRO) designs, such as Smart-Hangar or robot-assisted approaches listed by (19), will initially receive less consideration. Instead, traditional maintenance protocols, similar to those used for conventional helicopters and airplanes, will be adapted in a simplified form for (e)VTOL aircraft.

Our primary objective is to determine the ground infrastructure required for maintenance operations. According to (27), electric VTOLs are categorized into four main types: multicopters, lift-and-cruise, tilt-wing, and ducted fans, each with distinct advantages. The analogy between multicopters and helicopters, based on geometry, design, and shape, is a valid comparison supported by both scientific and industrial communities (18). Traditional maintenance subdivisions (e.g., pre-flight, post-flight, and special checks) and their respective frequencies can generally be adapted to UAM. However, it is crucial to identify which component inspections are transferable and which are not (e.g., tail rotor inspections).

In (28), investigations were conducted to develop functional sequences for MRO to estimate the frequency and duration of maintenance cycles for future air taxis. An operational electrified rotorcraft was examined as a reference vehicle. The study quantified the time required for pre- and post-flight checks and represented these tasks using swimlane diagrams. The scheduled A-Check, performed every 200 flight hours, requires approximately 3 hours. In the event of a finding or issue, the maximum time for unscheduled maintenance is set at 8 hours, covering the functional inspection of isolated mechanisms or parts of the vehicle. A more comprehensive B-Check, conducted every 2200 flight hours, necessitates a 72-hour maintenance period.

Electric VTOLs, unlike conventional helicopters with internal combustion engines, are considered low-maintenance (29) due to their electrically commutating motors and fewer moving parts. This results in reduced friction and, consequently, lower component fatigue, leading to significantly higher reliability (30). However, the strong magnetic field generated by the rotor's permanent magnets may cause aging effects on the bearings. These effects, which become relevant after long operational periods, need to be checked during more complex maintenance inspections (C-Check, IL-Check, D-Check).

2. Methodology

The primary objective of this study is the development of a method for quantifying the required ground infrastructure for vehicle maintenance of an air taxi fleet. In (11), a method has been introduced that allows for the quantification of required capacity distributions for parking positions and charging infrastructure in a vertiport network based on exemplary demand scenarios. The method involves first determining the required fleet pool to meet the overall demand for exemplary traffic scenarios. By analyzing the fleet operation plan, the local utilization of initially unlimited local infrastructure is then determined, from which the capacity requirements for individual functional elements of the vertiports are derived. Building on this study, we implement maintenance facilities as an additional functional element. At first, the following section provides a detailed explanation of the algorithms and functional processes applied in steps (1-4). Subsequently, the newly developed steps are discussed, which complement this method to determine the required maintenance capacities. Furthermore, we present our approach to approximate the maintenance intervals.

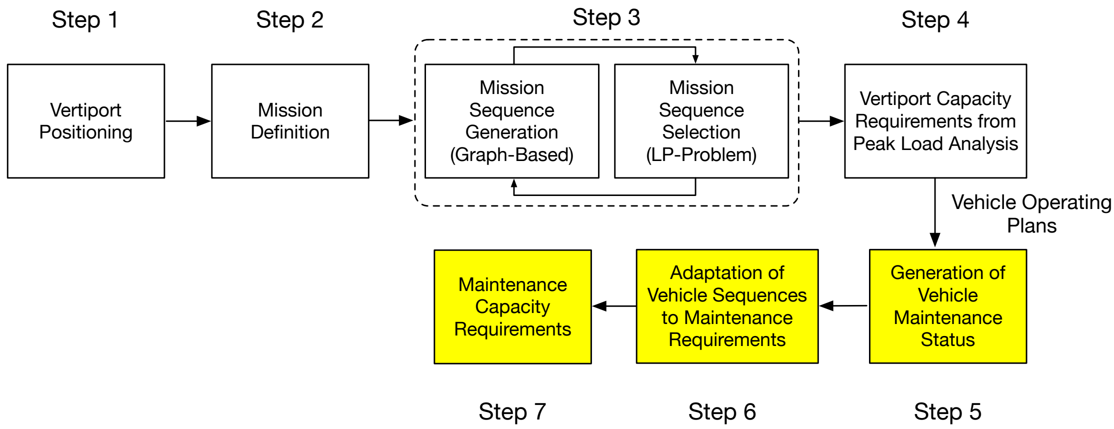

Figure 1 – Demand-pattern-driven derivation of capacity requirements in a vertiport network. Steps 1 to 4, as presented in (11), are extended by additional steps 5 to 7 to derive local capacity requirements for maintenance ground infrastructure.

2.1 Generation of Fleet and Operating Plans

The first step of this approach (see Fig. 1) defines the vertiport positions with regard to their lateral positions. In general, these positions need to be selected in close proximity to demand hot spots. We, however, do not propose an approach to solve the positioning problem itself, but adapt the positions from other studies as part of a system input. The investigated positions neglect topological factors, assuming all vertiports to be located on altitude 0 m. Furthermore, the City of Hamburg (Germany) is used as an exemplary setting. In the second step, a traffic scenario is created, considering one or more use cases. Possible use cases include commuter traffic or feeder flights to the airport, which are reflected in the level and distribution of demand peaks within the scenario. The traffic scenario comprises a variety of missions, each defined by the number of passengers, the departure time, and the origin as well as destination vertiport. The constraint for the subsequent optimization process is that the determined vehicle fleet must be sufficient to complete all missions. Furthermore, an option to perform missions with a reduced number of passengers or with delays is not provided. Additionally, there is no optimization of travel groups.
In step 3, the generation of the fleet, including the planning of all vehicle rotations throughout the day, is conducted as an optimization process. This method combines graph-based and linear optimization. In a series of successive iterations, vehicles are first generated representing candidates for inclusion in the fleet pool. By applying the Dijkstra algorithm to a graph encoding all missions to be completed, potential operating plans are created for all vehicle candidates. These operating plans are generated within an iteration for each combination of vehicle type and vertiport. Finally, all vehicle candidates are evaluated based on their potential to efficiently perform as many missions as possible from the mission pool, as well as the average load factor, and the degree of utilization over time. The vehicle candidates with the most efficient operating plans are then selected conducting a linear optimization and added to the fleet pool, while all serviced missions are removed from the mission pool.

Sequence Creation for Vehicle Candidates The creation of mission sequences for candidate vehicles conducted in step 3 is schematically depicted in Fig. 2. The inputs for step 3 include the missions that still need to be assigned, represented as yellow blocks. Additional inputs are the coordinates of the vertiports from step 1, as well as the vehicle types with all their specific characteristics. These characteristics are defined individually for each mission phase and include battery capacity,

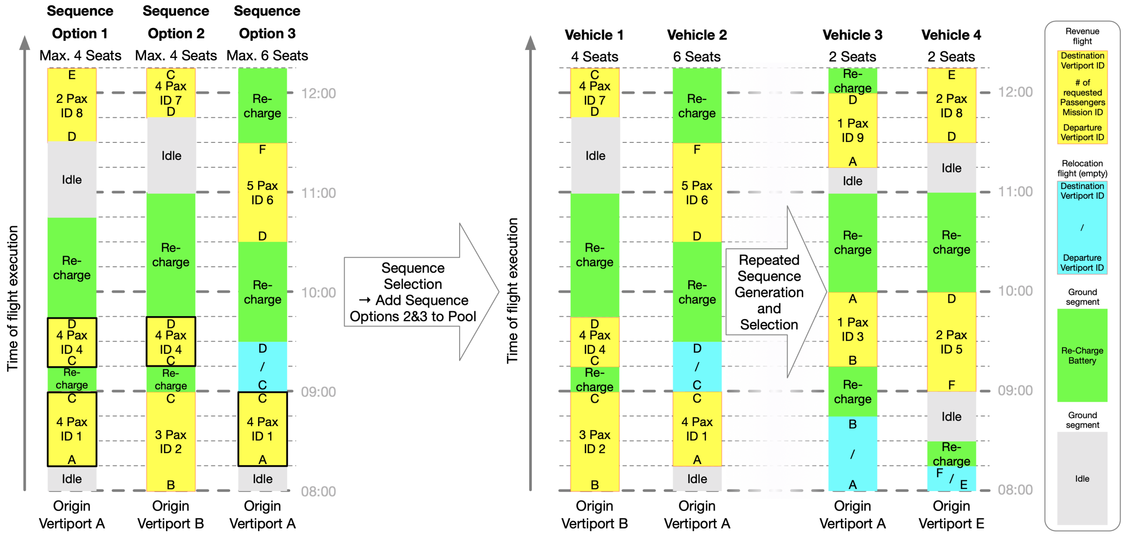

Figure 2 – Sequence generation and selection for fleet generation according to (11)

electrical power demand, and flight speed. Each mission is represented by two nodes, which correspond to the start and end of a mission. These nodes hold information regarding the start time according to the mission list and the end time, which is determined based on the vehicle characteristics. Based on the mission pool, the graph is then generated by connecting the end nodes of one mission to the start nodes of subsequent missions. The addition of these connections to the graph depends on the temporal feasibility of the mission chains, also considering potential empty flights for repositioning. Additionally, missions are not considered during graph creation if they are assigned with more passengers than the vehicle candidate has seat capacity. Finally, for each combination of starting point and vehicle type, a mission sequence on the corresponding graph is determined using the Dijkstra algorithm. The battery status of the vehicle is tracked during the optimization process to ensure that the charge level operates within valid limits. This is achieved by meeting the energy constraint specified by Equation 1. It is verified whether the current battery charge is sufficient to perform a potentially necessary repositioning flight and subsequently still have enough energy to complete the mission with passengers. Possible time reserves are considered in this context to potentially allow for short battery charging segments.

$$E_{\text{BatteryCharge}} \geq E_{DES,m\rightarrow OGN,n} + E_{OGN,n\rightarrow DES,n} - \left(t_{OGN,n} - t_{DES,n} - \Delta t_{Flight:DES,m\rightarrow OGN,n}\right) \cdot P_{Charge} \qquad (1)$$

Energy reserves are considered unusable in the standard operation examined throughout this study and are not part of the optimization process. Therefore, the valid battery charge limits in the optimization process range from 0% to 100%. As exemplarily shown in Fig. 2, the optimization yields sequences in compliance with all constraints regarding time, energy, and seating capacity. In these sequences, repositioning flights (cyan) and charging segments (green) are included between the missions (yellow). Segments that do not fall into any of these categories are considered idle segments and are marked in gray. The charging power is assumed to be $P_{Charge} = 50\text{kW}$. In addition to (11), we have added a third vehicle type with a seat capacity of 2.

Selection of Vehicle Candidates All sequences resulting from step 3.1 are individually created based on the same mission pool. Therefore, the sequences may have redundancies in their missions, which is considered a violation of the constraints in the context of the present optimization problem. To ensure that each mission is assigned to exactly one vehicle in the final fleet pool, this step involves solving a linear optimization problem while meeting this constraint. The input for the linear problem consists of the 25% of mission sequences with the highest number of passenger kilometers flown, minimizing the cost functional defined as:

$$F_i = C + (ASK - RSK) \qquad (2)$$

In this cost functional, ASK represents the Available Seat Kilometers, and RSK represents the Revenue Seat Kilometers. Consequently, the cost functional minimizes the number of empty seat kilometers in a sequence. This includes not only the empty seats during a mission but also the seat kilometers flown for repositioning flights. The term C is an adjustable correction term that shifts the functional into the negative value range.

Capacity Requirement Analysis The operational plans of all vehicles are evaluated in step 4 from the perspective of ground infrastructure. Each vehicle sequence added to the fleet pool is analyzed regarding its takeoffs and landings, as well as its idle times and charging times on the ground. The capacity requirement of a vertiport in any of these categories is determined based on the local peak load over the investigated, exemplary day.

2.2 Maintenance Capacity Requirements

The procedure described in step 3 favors vehicles with high passenger kilometer revenues in the selection process. Since necessary upcoming maintenance can impact the potential for high passenger throughput, the procedure described by steps 1-4 tends to discard vehicles with impending maintenance requirement. To determine the required maintenance capacities of a fleet using an extended procedure, additional process steps are added. Building on the finalized fleet from step 3, the vehicles receive new attributes that define their respective status concerning their maintenance cycles, A and B. These attributes are assigned in step 5. In step 6, all mission sequences are analyzed to match the number of conducted flight hours performed throughout the day against the maintenance requirements. Once a vehicle falls below a threshold of one remaining flight hour in one of its A or B maintenance cycles, it heads to the closest vertiport location with a maintenance facility. Depending on whether it is an A-Check or B-Check, an inspection time of 3 or 72 hours, respectively, is inserted into the vehicle's operational plan (Step 5). A random generator is used to determine if damage or wear is detected, requiring additional maintenance. Since the B-Check takes 72 hours and the scenario in this study only covers one day, the vehicle undergoing a B-Check is assigned to a maintenance station for the rest of the day and cannot perform any further missions. In the case of an A-Check, the vehicle becomes operational immediately after the inspection period ends. Once the maintenance process is complete, the vehicle resumes its remaining mission sequence at the earliest possible time. All missions that could not be conducted due to maintenance are added to a new mission pool.

In Step 7, the updated operational plans of all vehicles that required inspection are evaluated for operational efficiency. The impact of network density and maintenance station locations on efficiency is quantified.

The detour is calculated, and the number of missions that could not be performed due to maintenance is analyzed. This analysis is conducted for each vertiport as a potential location. Subsequently, the study examines how efficiency in terms of additional flight distances and energy consumption is affected by the number of available maintenance sites, as well as the statistical number of required maintenance pads. The required capacity of maintenance pads is derived from the peak value of the demand curve throughout the day, in analogy to step 4. To make a statistical statement, this investigation is conducted with a high number of repetitions. Finally, the number of necessary takeoff and landing pads is quantified based on the number of local traffic movements.

During the flight operations, the remaining operational times before the next maintenance for both intervals are continuously updated and checked. In this context, flight times are counted, while taxi and boarding times are excluded.

2.3 Approximation of the Maintenance Intervals

The daily maintenance routine depends on the existing basic architecture, which is considered within the network. We assume that at a vertistop, the walkaround, which is part of the pre-flight check, is performed more frequently. The interior check can also be conducted at a vertistop or vertipad, as it does not require extensive equipment and assesses the functionality of the navigation and communication systems. A stop can be understood as a repurposed helipad where almost no heavy

mechanical equipment or spare parts (with the exception of the Minimum Requirement List) are stored.
At a stop, if no maintenance personnel are present, the pilot can, due to his training, inspect the vehicle for superficial and acoustic anomalies. At a vertiport or vertihub (the literature contains many terms, including vertiplace, VTOL port, skypark, pocket airport, or vertidrome), more comprehensive maintenance is performed, which we have divided into transferred A, B, and special checks. Additionally, there is the overnight check, to which the interior Check is also subordinated.

2.3.1 Maintenance Frequency, Duration and Data Basis

The maintenance frequency for eVTOLs or VTOLs is divided into Pre/Post Flight Check, Interior Check, Special Check, as well as A and B Check. These regular eVTOLs use electric motors that utilize a direct electrical energy source. The maintenance of these systems focuses on the inspection of electrical connections, batteries, motor controls/regulations, and the motors themselves. Furthermore, the maintenance of the batteries is crucial, including the state of health monitoring (SoH), charging capacity, and thermal management which is why the batteries have an extra path separate from maintenance (16). However, battery systems require more detailed specific knowledge and safety procedures. To effectively analyze battery maintenance, a database for realistic operation must be created. Currently, there are few sources that provide these basics in laboratory tests. What is missing is the impact of pressure differences, various temperature gradients, and alternating charge and discharge cycles over time (23). In comparison to helicopters, multicopters have multiple rotors (sometimes up to 16 or more), which leads to an excess of active degrees of freedom (redundancy). This aspect increases safety in the event of propeller failure, but also means that each rotor and propeller system must be regularly maintained and calibrated.

Pre-/Post Flight Check/Daily/Overnight We have based our daily routines on helicopter maintenance, specifically focusing on the processes of a Robinson R44 and its electric sub-variant from Tier company. A detailed analogy examination was documented in our last paper (28). The Interior Check includes checking the emergency equipment for the cockpit, including flashlights, fire extinguisher, Protective Breathing Equipment (PBE), life jackets, emergency equipment in the cabin (if available), door slides (if available), megaphone (if available), first aid kit (if required), and ballast (if available) secured. This "Check" encompasses a maximum duration of up to 30 minutes. The pre- and post-flight checks must be carried out once a day for eVTOLs before the flight missions in combination with the interior check. Similarly, the overnight check is carried out after the end of operations. These two checks have no direct influence on the simulation of the fleet, as this only depicts missions during operation. For a more detailed analysis, see (31).

Weekly/ Monthly/ Yearly/ A- und B-Check An "A-Check," or an approximated Monthly Check for an eVTOL, corresponds to a relatively light routine inspection compared to more thorough checks. In our case, it is carried out after about 200 active flight hours approximated due to maintenance reports (20) and papers (16). The AOG (Aircraft on Ground) time, during which the vehicle is at a Vertistop or Vertiport, is not included. An A-Check is more comprehensive than a Walkaround before flight but still focuses on ensuring operational safety without requiring extensive disassembly. In summary the A-Check or monthly check includes the inspection of the propellers and rotors in terms of damage, wear or deformation. This includes checking the edges, surfaces, and attachments of each blade, performing visual inspection of electric motors for signs of overheating, damage, or leaks. The complete description of the checks for eVTOLs would go beyond the scope of this study, which is why we refer here to maintenance checks for helicopters, as these are largely carried out by the OEMs. An inspection, which depends on the service life of the parts of the vehicle, sets the minimum limit after the most maintenance-prone part. As the B-Check is intended to test the various parts of the (e)VTOL for safety and functional checks, it is treated as the most comprehensive inspection. The B-Check is approximated to be performed every 6-8 months or every 2200-2400 active flight hours. It is also called the Yearly Check in this sense. It is based on a more intensive A-Check, which also requires extensive disassembly. The lifespan of parts of the eVTOL must be checked, which can lead to a vehicle outage of several days to several weeks (if a Finding/Defect is found).

3. Results and Discussion

In this chapter, the insights on maintenance intervals derived before are applied to the method described in Section 2to estimate the necessary maintenance capacities.

3.1 Demand for Maintenance Services

The fleet for these analyses on maintenance requirements is based on a traffic scenario described in (11) was initially calculated. The scenario includes 2720 transport requests within a network of 20 Vertiport locations in the city of Hamburg. As shown in Figure 3, the fleet consists of 338 vehicles, composed of 3 vehicle types. The vehicle types each have an individual number of seats, individual range, horizontal and vertical speeds, and battery capacities. The horizontal axis represents the temporal utilization of the vehicles. Since the scenario mainly depicts commuter traffic, no flights are requested during nighttime hours, limiting the temporal utilization. The vertical axis shows the share of occupied seat kilometers. The seat occupancy rate varies between 38% and 40%, depending

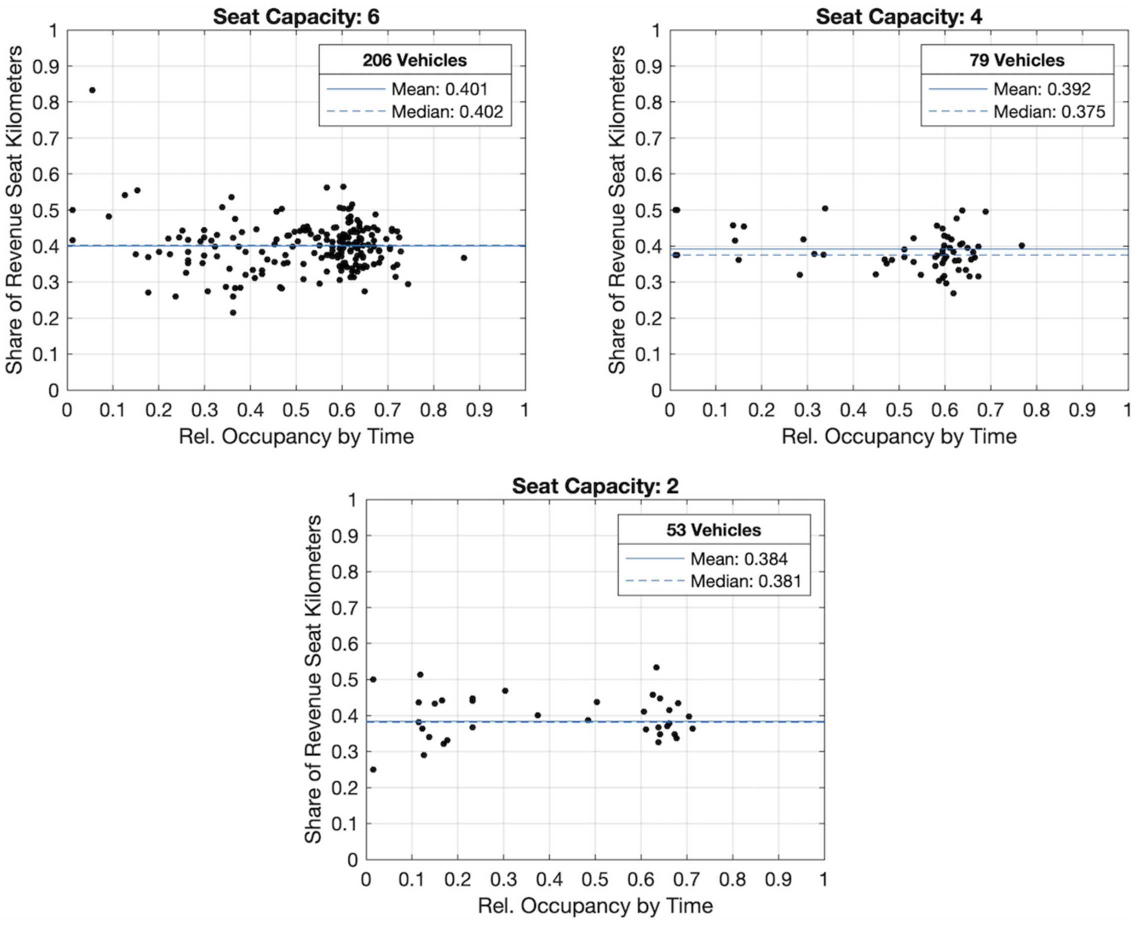

Figure 3 – Analysis of the fleet in terms of occupied seat kilometer utilization and temporal utilization.

on the vehicle types. If a passenger group does not fully occupy the seating capacity of a vehicle, the empty seat is marked as unoccupied, reducing the share of flown Revenue Seat Kilometers. In the case of repositioning flights that are necessary to pick up passengers from other vertiports, all seats are marked as unoccupied, further reducing the share. Since travel groups are calculated with random values between 1 and 6, full occupancy is not possible in this context either. Especially for vehicles with low utilization rates, however, the consideration of discrete time slots can result in multiple vehicles exhibiting identical combinations of occupation and share of RSK. Consequently, some points in the diagram may correspond to multiple vehicles within the fleet.

Based on the determined maintenance intervals, random-based status values regarding maintenance intervals were generated in a total of 100 iterations for all vehicles from the underlying operation plans. It is assumed that the vehicles of an operating fleet can exhibit significant differences in their maintenance states over long periods of operation. Accordingly, we assume that each vehicle can be assigned a random value representing the remaining operating time in the maintenance interval before the vehicle requires maintenance. These states range from 1 hour to 200 hours for the A-interval and from 1 hour to 2200 hours for the B-interval.
Once the maintenance states have been assigned to each vehicle in the fleet, the operation plans of all vehicles are checked for potential maintenance needs. For this purpose, the duration of each vertical and horizontal flight segment throughout the entire operation plan is subtracted from the maintenance status. If the maintenance status for A or B falls below one remaining flight hour, a repositioning mission is inserted into the vehicle's operation plan from that segment onwards, directing the vehicle to a maintenance facility. In the case of a necessary A-Check, a 3-hour ground segment is then inserted into the operation plan to simulate the execution of the A-Check. Finally, another ground segment with a random duration between 0 and 5 hours is added to simulate the required maintenance due to possible detected defects. For an A-Check, the vehicle occupies a maintenance facility for a time window of 3 to 8 hours and cannot perform missions initially assigned to it in step 3. After this time window, the vehicle resumes its assigned missions at the earliest possible time. The unfulfilled missions are returned to the mission pool to be reassigned to a replacement vehicle later.
In the case of a necessary B-Check, it is assumed that the vehicle remains in maintenance for 72 hours and therefore cannot perform any further missions that day. All missions following the onset of this condition are returned to the mission pool.

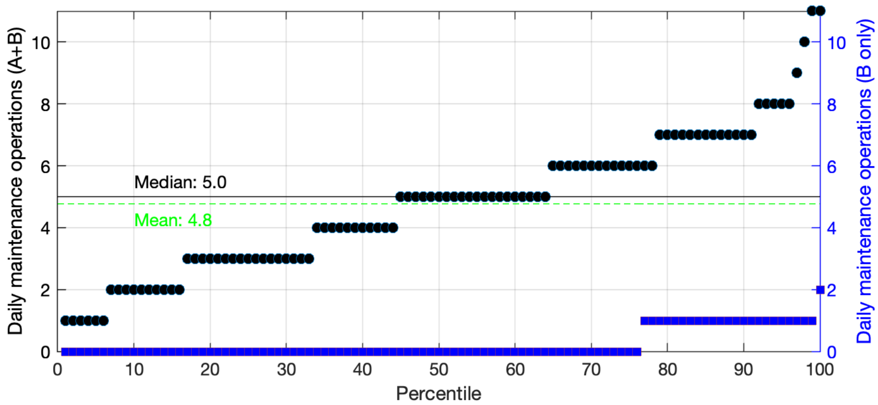

Figure 4 – Statistical analysis of the likelihood of an A-Check or B-Check within the fleet. The left scale (black) shows the total number of necessary checks over one operational day, while the right scale (blue) represents the proportion of B-Checks.

This procedure was applied 100 times to the exemplary fleet. Figure 4 quantitatively represents the necessary A- and B-Checks as a distribution curve. The left scale (black) shows the cumulative necessary A- and B-Checks, while the right scale (blue) quantifies only the subset of necessary B-Checks. The median is 5 checks per simulation run, while the mean is 4.8 checks. Therefore, it is expected that on a standard operational day, a total of 5 vehicles in the analyzed fleet will complete one of their maintenance cycles and require maintenance. The peak value at the 100th percentile also indicates that on exceptional days, up to 11 vehicles may simultaneously require inspection and possibly maintenance, with one instance showing two concurrent B-Checks. According to this distribution, it is expected that in approximately 23% of all cases, at least one vehicle will require a B-Check.
The same simulation results are presented in Figure 5 regarding the required service time in the maintenance operation. Depending on the inspection results, each vehicle may require varying amounts of service time. For A-Checks, this need varies between 0 and 5 hours after inspection. According to the results shown here, the median and the arithmetic mean are approximately 25 hours, while in

the maximum case, up to 58 hours of necessary service time can be required for a single operational day. Ideally, and with round-the-clock operation of the maintenance infrastructure, this maintenance workload could be managed with only three pads.

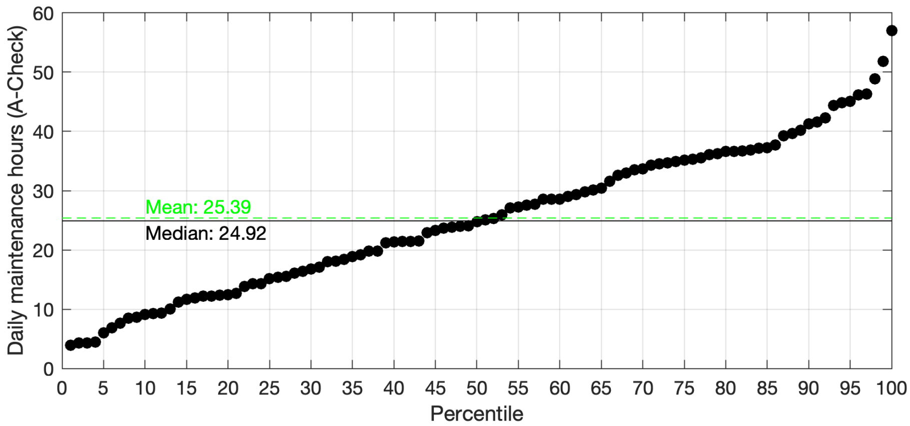

Figure 5 – Requirements on maintenance service in hours

Since predictive maintenance planning has not been implemented in these studies, maintenance processes overlap in the current results, leading to a peak demand of up to 9 simultaneously used maintenance pads. The quantification of the potential for reducing peak loads through predictive measures is planned for future studies. Two exemplary profiles regarding the local demand for maintenance infrastructure are shown in Figure 6.

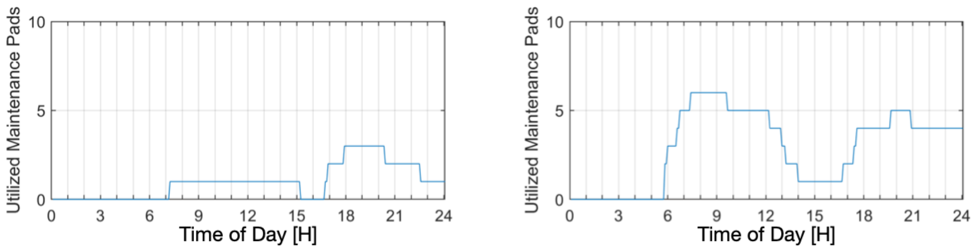

Figure 6 – Local maintenance demand profiles for Vertiport 16 (Rahlstedt) with two random maintenance distributions. Left: Peak load of 3 pads in the evening. Right: 11 checks throughout the day, requiring 6 pads.

Using vertiport location 16 (Rahlstedt) as an example, the utilization of maintenance pads throughout the day is shown for cases with two random distributions of maintenance states. In the left figure, an A-Check is observed, occurring directly in the morning around 7 AM. Later in the afternoon, three more checks become due. In the left case, the capacity-defining load would thus be given by three simultaneously used maintenance pads. In the right case, however, a total of 11 checks are observed, required by the vehicles throughout the day. These are distributed over the day, so this scenario would require a minimum of 6 maintenance facilities. This representation clearly shows that the necessary maintenance capacity could be reduced by a more even distribution throughout the day.
Since the operation plans of the vehicles are interrupted in the event of impending maintenance, the resulting unfulfilled missions are returned to the mission pool. The number of affected missions depends on the vehicle's temporal utilization and the duration of the maintenance process. To still carry out these missions, a pool of additional reserve vehicles is provided according to the proposed method. Figure 7 quantifies how many missions must be assigned to a vehicle from this reserve pool due to upcoming maintenance processes. The mean and median show an expected value of approximately 16 and 15 missions, respectively, which can typically be handled by two to three additional vehicles. The peak value at the 100th percentile, which occurs in the event of unexpectedly high maintenance demand, is quantified at 40 missions, which can be handled by an average of 8 additional vehicles. Overall, the results indicate that the impact of maintenance processes on fleet

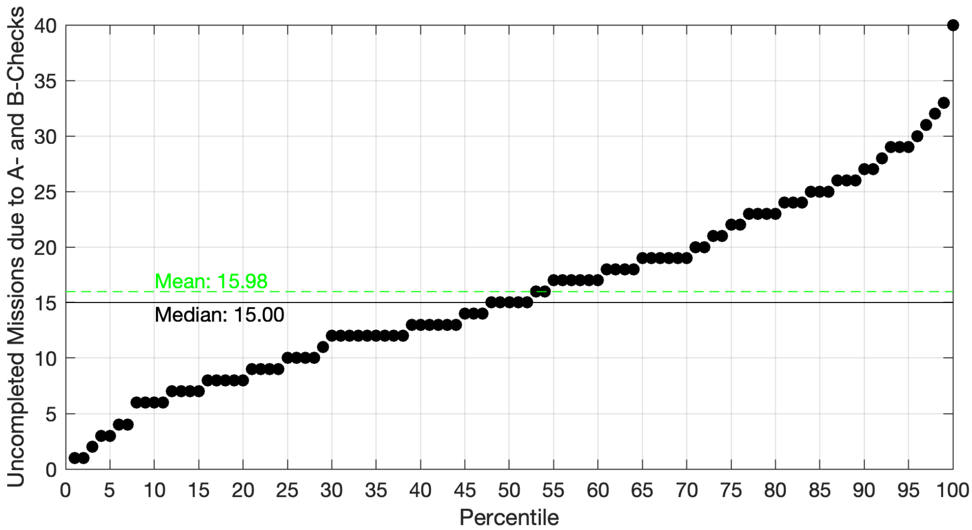

Figure 7 – Quantification of missions that cannot be completed by the assigned vehicle due to upcoming A- and B-Checks.

planning is minimal with such long maintenance intervals.

3.2 Maintenance Network Design

In addition to fleet size and necessary maintenance capacity at the system level, the network design also raises the question of optimal capacity distribution. While consolidating maintenance infrastructure can offer advantages by reducing redundancies, it is also worth considering whether distributing maintenance infrastructure across the network can reduce empty flights and lower vehicle downtime. Figure 8 shows all examined locations of ground infrastructure (see (11)).

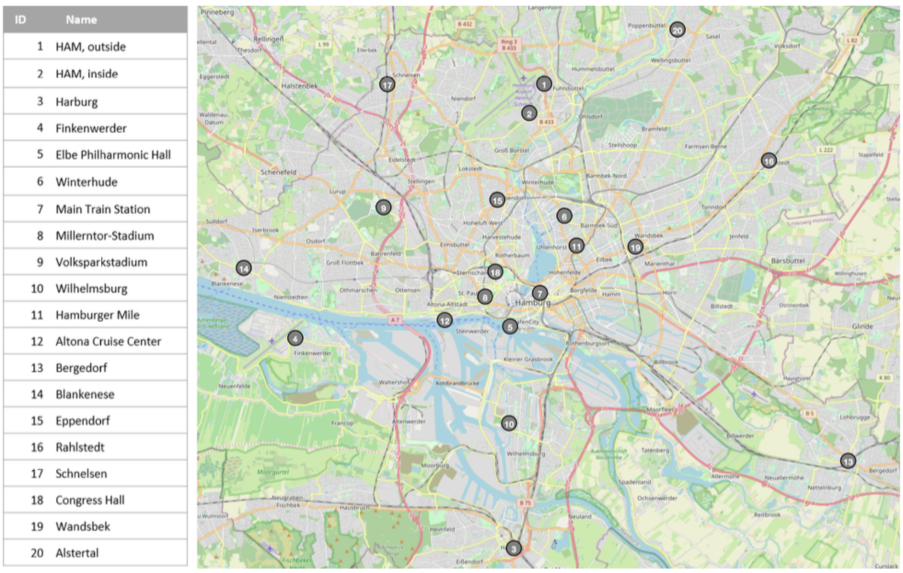

Figure 8 – Distribution of ground infrastructure locations examined (see (11)).

To quantify the added value of a distributed maintenance infrastructure in the network, this study focused on the potential reduction of empty flights. Figure 9 shows how the distances flown for repositioning flights to maintenance can be reduced with an increased number of Vertiports with maintenance infrastructure. Each maintenance location was initially evaluated by simulating it as the sole maintenance location in the network, which all vehicles requiring maintenance must use. This results in a total distance value at the fleet level, based on the geographic position, that was flown additionally due to maintenance-related repositioning. Due to its central location and thus lower average detours, location 11 (Hamburger Mile) proved to be the optimum according to Figure 9.

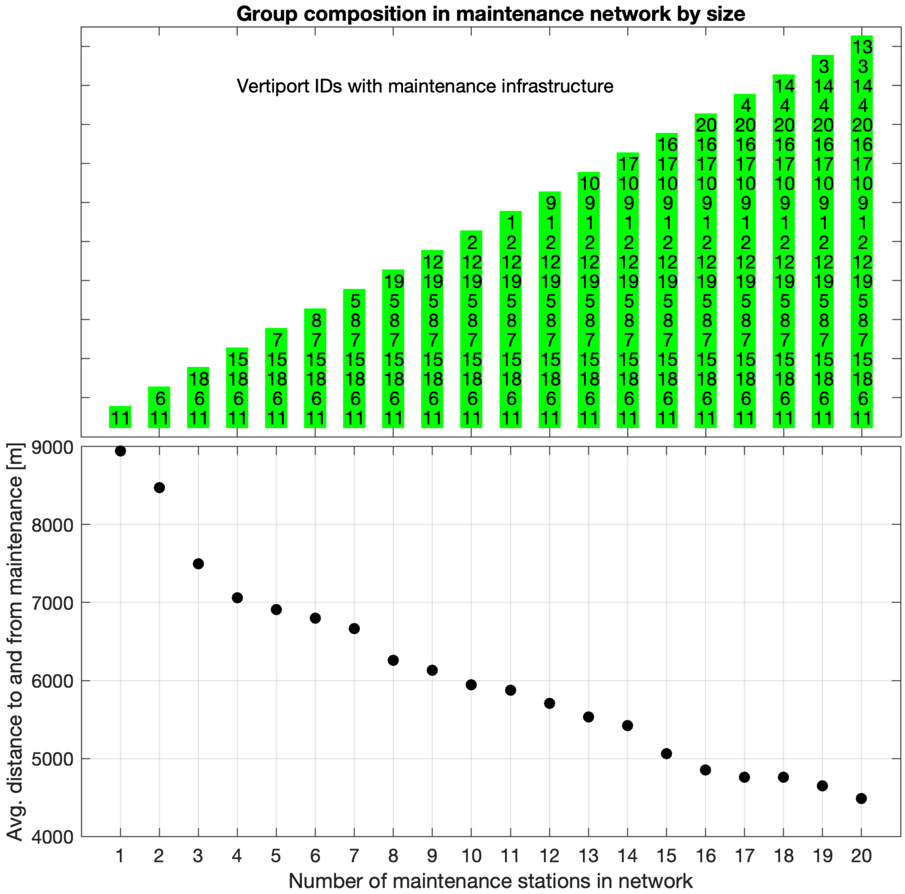

Figure 9 – Average detour per vehicle with increasing number of maintenance stations. Vertiport IDs in green indicate selected locations for each solution.

Finally, all Vertiport locations were evaluated as potential sole maintenance hubs in the network, using the resulting means of additionally caused flight distances as a measure. According to this criterion, Vertiport location 13 (Bergedorf) proved to be the option with the least suitability. Subsequently, the network of maintenance stations was gradually expanded from one location to 20 locations, with each vehicle always integrating the most favorable maintenance location into its operation sequence. Figure 9 shows that the average detour per vehicle in the case of only one maintenance station is 9000 m, which could be reduced to 6000 m for 10 maintenance stations and to a minimum of 4500 m for a maximum of 20 maintenance stations. The Vertiport IDs shown above in green indicate the selected Vertiport positions for each of these solutions across all 20 networks. As the analysis of daily maintenance demand has already shown, these detours have little impact on the overall system level when a maximum of 11 flights to maintenance facilities are required per day. Therefore, it must be emphasized that establishing a maintenance facility in a central location such as position 11 would be associated with high monetary costs, making it more economically viable to establish a maintenance center in more remote areas.

4. Conclusion and Outlook

This research focused on optimizing the maintenance infrastructure for an air taxi fleet. Based on a method for operation planning and fleet design, the necessity and distribution of maintenance capacities were analyzed. A simulated traffic scenario in Hamburg with 2720 transport requests and 338 vehicles showed that daily maintenance cycles, particularly A- and B-Checks, significantly impact fleet availability. Quantitative analyses revealed a median of 5 maintenance checks per day, with up to 11 vehicles requiring maintenance on peak days. About 23% of cases required a B-Check. The study of local maintenance needs demonstrated that an even distribution of maintenance over the day can significantly reduce the required capacity. A simulation of all vertiport locations as sole maintenance hubs indicated that position 13 (Bergedorf) had the least suitability. Expanding the network from one to 20 maintenance locations reduced the average detour per vehicle from 9000 m to 4500 m. However, these detours are minor at the system level when a maximum of 11 flights to maintenance facilities per day is required. Centrally located maintenance facilities, like position 11 (Hamburger Mile), would be expensive, making more remote maintenance centers potentially more economically viable. In summary, the study shows that an even distribution of maintenance infrastructure and consideration of vehicle maintenance cycles are crucial for fleet efficiency. Optimized maintenance processes and strategic location choices maximize vehicle operational times and minimize additional costs. Future studies should develop predictive maintenance strategies to further reduce peak loads and enhance system efficiency.

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6. Ackowledgments

This study was carried out as part of the projects *UAM Vertiports – Design and Entwicklung eines Modularen Vertiports*, funded by *Hamburgische Investitions- und Förderbank (IFB)*, and *i-LUM - Innovative Airborne Urban Mobility*, funded by *Landesforschungsförderung Hamburg*.

7. Copyright Statement

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