Throughput and operations management of a vertiport with taxing and parking levels

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Abstract

Amidst the increasing aerial traffic and road traffic congestion, Urban Air Mobility (UAM) has emerged as a new mode of aerial transport offering less travel time and ease of portability. A critical factor in saving travel time is the newly emerging electric Vertical TakeOff and Landing (eVTOL) vehicles that need infrastructure such as vertiports to operate smoothly. However, the dynamics of vertiport operations, particularly accommodating battery charging and swapping facilities, remain relatively unexplored. This work aims to bridge this gap by delving into vertiport management by utilizing separate taxing and parking levels. The study also focuses on the time spent by eVTOLs at the vertiport to anticipate delays. This factor helps optimization of the arrival and departure time via a scheduling strategy that cater to hourly demand fluctuations. The simulation results carried out with hourly demands underscore the significant impact of eVTOL battery charging on operational time while also highlighting the pivotal role of parking spots in augmenting capacity and facilitating more efficient scheduling.

1 Introduction

Predictions indicate that by 2030, approximately sixty percent of the global population will live in cities, a trend anticipated to exacerbate congestion within ground-based transportation networks [1]. Leveraging technological advancements, Urban Air Mobility (UAM) emerges as a promising option to ease transportation in the future. UAM describes a pioneering paradigm of air transportation characterized by the safe and sustainable movement of passengers and goods. Deliberations surrounding the scope of the UAM framework are presently underway, resulting in the emergence of expanded terminologies such as Advanced Air Mobility (AAM) [2] and Innovative Air Mobility (IAM) [3]. In Europe, the term IAM has gained prominence, encompassing both intra-urban and inter-regional transit transportation. Research suggests that while IAM holds the potential to reduce travel duration compared to traditional ground-based transportation significantly, its introduction may have a limited impact on the utilization patterns of customers [4]. Nonetheless, projections forecast a global demand of up to 5.5 million IAM vehicles by 2050, necessitating corresponding infrastructural investments in takeoff and landing facilities, namely vertiports [5]. Furthermore, compared to ground-based cars, eVTOLs are expected to have a reduced energy consumption even though they consume a substantial amount for takeoff and climb [6].

The term vertiport originated several decades back and is primarily associated with landing sites for air taxi operations using helicopters, tilt-rotor aircraft and vertical takeoff and landing (VTOL) vehicles [7]. Vertiports are envisioned similarly to that of a helipad, with the difference being the anticipation of the demand for vertiports exceeding the helipad in the coming future [8]. In other words, the vertiports are dedicated areas that supply the infrastructure needed for safe commercial air transport that travel by Vertical takeoff and landing Capable Vehicles (VCA) [9]. As IAM gains prominence, global efforts are underway to establish regulatory frameworks for vertiport operations. Notably, the European Union Aviation Safety Agency (EASA) has introduced regulatory provisions such as the special condition SC-VTOL-01 [10] and the Prototype Technical Specification (PTS-VPT-DSN) for vertiports [11]. In Europe, vertiports are often regarded to be placed within U-space areas, which is envisaged to be a digital ecosystem supporting Uncrewed Aircraft System (UAS) and IAM operations [12].

A critical aspect of vertiport design often revolves around capacity and throughput, both factors intricately linked to cost-effectiveness. As outlined in [13], vertiport capacity is evaluated based on factors such as the number of landing pads, charging positions and parking bays. The maximum throughput is linked to the frequency of aircraft movements (i.e., takeoff and landings) within a designated timeframe, typically measured per hour. Furthermore, vertiport operations encompass all the activities and processes involved in its functioning. This includes tasks such as aircraft landings and takeoffs, passenger boarding and disembarking, ground handling, maintenance and security procedures covering a broader spectrum of activities. Current vertiport designs offer static vertipads for takeoff and landing [14], necessitating hovering the eVTOLs for landing when the vertipads are busy. This problem can be tackled with an escalator-inspired taxing system since time savings depend highly on fast processing at the vertiports. This study proposes a novel vertiport design to facilitate a layered parking system for the eVTOL to reduce time delay and schedule the takeoff and landing operations. In the current work, a comprehensive scheduling algorithm is proposed to allocate resources within the vertiport, considering various factors such as arrival and departure demand, battery charging and swapping requirements, and the availability of vertiport infrastructure.

The rest of the paper is structured as follows: Section 2 reviews the recent studies in the field. Section 3 elaborates on the research problem, while Section 4 explains various terms, operational flows, and the time delays expected during an eVTOL's stay at the vertiport. Section 5 presents an approach to optimize vertiport throughput through scheduling, and the simulation results are discussed in Section 6. Lastly, Section 7 concludes the paper.

2 Related Work

Systematic literature reviews have been conducted on the topic of IAM and vertiports, as evidenced by the work of [15] and [16]. The referenced studies in these literature overviews collectively emphasize the critical role of meticulously designed and integrated ground infrastructure components for the efficient operation of IAM. Especially relevant for smooth integration and efficient IAM operations are, among other things, well-designed departure and arrival procedures, effective communication with other airspace users, and quick on-ground vertiport operations. The optimal layout of vertiports is essential for ensuring smooth and time-efficient operations and minimizing potential risks associated with increased air traffic in urban areas [8]. However, despite the advancements in understanding infrastructure needs, significant gaps still need to be identified in understanding regulatory frameworks, certification processes, and public acceptance of these emerging technologies [4].

In recent years, focus has been given to integrating IAM and vertiport concepts into U-space and (partially) existing Air Traffic Management (ATM) environments, on-demand and dynamic capacity management services and vertiport capacity and throughput enhancements. As an example, [17] provides an overview of air traffic management solutions for IAM and [18] investigated how vertiport management tasks could be integrated into U-space by relying on a vertiport manager being fully integrated within U-space. The findings show that in the first implementation phase, a human operator is required to approve or cancel air taxi operations. In addition, [19] developed an innovative performance measuring matrix specifically tailored to assess the operational efficiency of the airborne traffic flow at vertiports and, as a result, facilitated strategic flight planning at vertiports. However, these references do not specifically address ground-based operations at vertiports nor tackle time-efficient vertiport concepts as proposed by the presented publication. Furthermore, [20] investigated the impact of IAM vehicle design, regulation and operation on the throughput capacity of vertiports but did not put major emphasis on the battery charging time and its effect on the overall vertiport operation time. In addition, the patent of [21] proposes a multi-level fulfilment centre concept in which (smaller) UAS are taking-off and landing from several levels out of one building. This fulfilment centre may have many levels or floors to accommodate parallel UAS operations, thereby saving the time and space needed to operate numerous UAS. In contrast to the work presented in this publication, [21] does not foresee the utilization of elevators to move the UAS between parking levels and battery charging positions. Specific focus on requirements for batteries used in IAM vehicles is given in [22], highlighting the need for fast charging points at vertiports in order to ensure high throughput values and short turnaround times.

Finally, several European research projects addressed the integration of new airspace users and required infrastructure elements within U-space and existing airspaces. The CORUS-XUAM developed a concept of operations for U-space participants, including IAM and vertiport operations, highlighting the need for harmonized procedures at vertiports [23]. Moreover, the recently started EUREKA projects are currently developing U-space services addressing the needs and requirements for vertiport concepts to enable safe and efficient IAM operation in the future [24]. The project aims to accelerate the development of eVTOL operations and vertiports across Europe. However, these European projects do not address the characteristics of different vertiport configurations and do not address the time-saving effects of battery charging bays on different vertiport levels or innovative elevator concepts.

3 Problem Statement

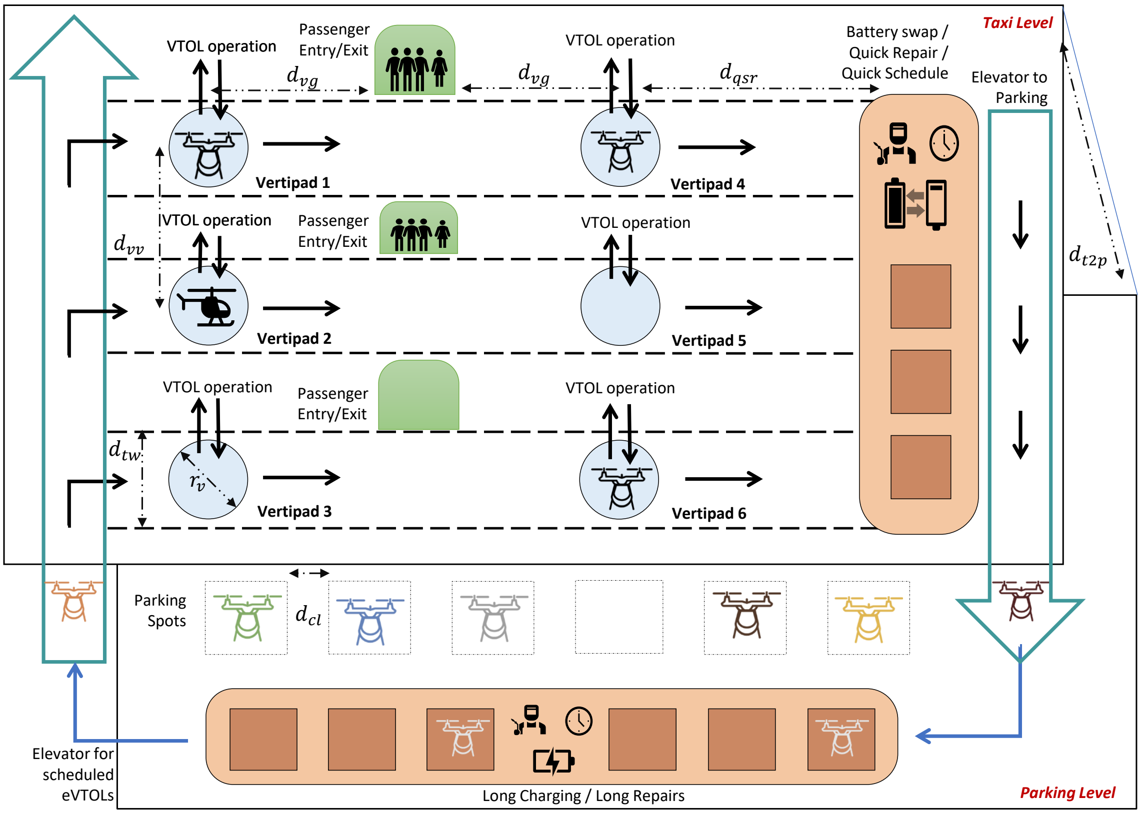


Figure 1: Vertiport design with taxing and parking levels

Figure 1 gives a schematic of the proposed vertiport system. The concept draws the idea of utilizing multiple levels or floors of a vertiport building, termed a taxi level and a parking level, that perform individual functions. The taxi level deals with various operations related to the eVTOL vehicles, such as landing, takeoff, passenger entry and exit from the vehicle, and other activities such as quick scheduling, battery swap and quick repair. On the other hand, the parking level parks the vehicles until their next flight. The parking level also supports functionalities such as battery charging, significant repairs, and eVTOL parking in case of a scheduling delay.

The transition from the taxi level to the parking level is carried out with the help of the elevators. There are two kinds of elevators in the proposed design, as seen from Figure 1, viz., the passenger elevator and the vehicle elevator. As the name suggests, the vehicle elevators mounted on the extreme ends of the taxi level are designed to carry eVTOLs from one floor to the other, whereas the passenger elevator carries people. Utilizing these two levels allows the vertipads in the vertiports to accommodate the next set of eVTOLs with a minimum time delay, thereby improving the vertiport efficiency to handle significant traffic. It also helps with better management of these vehicles and the reduction of their wear and tear owing to the presence of the repair unit.

This study addresses the challenge of efficiently managing vertiport operations, particularly concerning the arrival and departure of eVTOL aircraft. Our goal is to enhance overall efficiency in this process. With our proposed vertiport design, we aim to optimally allocate eVTOLs to vertipads, battery charging and swap stations, and parking spots to fully utilize the vertiport's capacity while meeting all arrival and departure demands. Additionally, we intend to determine the duration of eVTOL presence at the vertiport and adjust operations accordingly, while also monitoring any associated delays. This approach indirectly contributes to throughput optimization by maximizing the use of available resources.

4 Vertiport Elements

This section lays out the basic structure of the vertiport and introduces all the variables needed to address the problem statement. The aim is to explain how the vertiport operates and define the key factors involved in solving the identified issues. This framework serves as a foundation for analyzing and improving vertiport operations in a structured manner.

4.1 Vertiport design considering vehicle dimensions

Consider a vertiport configuration shown in Figure 1. With a total capacity of 21 spots, the vertiport under consideration has six active landing/takeoff vertipads, six parking spots, and three quick battery swap spots to facilitate seamless operations. Additionally, six spots are designated for recharge/repair services and two elevators for vertical access.

In compliance with the EASA prototype guidelines [11], the design and layout of vertiports are meticulously orchestrated to ensure safety and efficiency in air mobility. For instance, the distance between two vertipads, d_{vv}, is maintained at 60 meters for eVTOLs with a maximum takeoff weight (MTOW) of 3175 kg. Table 1 presents details of four vehicles, including their dimensions and seating capacities.

Table 1: Vehicle characteristics of eVTOLs

eVTOL	Tip-to-tip span (m)	Total seats	MTOW (kg)	Battery Capacity (kWh)
Vahana	5.7	3	815	38
eHang 216	5.61	2	620	17
CityAirbus	8	5	1600	110
Volocopter 2X	9.2	2	450	100

We assume that D is the diameter of the smallest circle in meters that contain the projection of the VTOL aircraft on a horizontal plane during takeoff or landing, considering the rotors are in motion. For the maximum tip-to-tip span of 9.2 meters of the expected eVTOLs at the vertiport as given in Table 1, we consider $D = 10$. Consequently, the vertiport diameter must have a 25% clearance according to the EASA guidelines [11]. That is, $r_v = 1.25D$. Similarly, the minimum distance between two taxiways, d_{tw}, must have 50% clearance. Finally, in the eVTOL parking mode, the distance between two vehicles, d_{cl}, is maintained at a minimum of 3 meters.

4.2 Vehicle operation flow through the vertiport

Figure 2 illustrates a typical journey undertaken by an eVTOL aircraft, spanning from its arrival at the vertiport to its departure. Upon touchdown on the designated vertipad, the aircraft proceeds to taxi towards the gate to facilitate passenger disembarkation. Subsequently, the eVTOL undergoes a series of checks, including assessing its battery level and identifying potential repair needs. Suppose the battery level seems near the minimum threshold, typically considered to be 10% of its capacity, the aircraft is directed to a quick charging centre to determine the feasibility of a rapid battery swap. Should this option be unavailable, the eVTOL is relocated to the parking level via an elevator, where it undergoes charging or repairs until its battery level is restored to at least 90% capacity. Based on its scheduled departure time, a decision is made whether to retain the eVTOL at the parking level or return it to the boarding gate.

Figure 2: A typical eVTOL journey through the vertiport

To ensure a timely departure, the eVTOL is typically required to be present at the vertipad a few minutes before its scheduled takeoff time. This buffer allows for passenger boarding, engine start-up procedures, and the loading of the planned route. Finally, the eVTOL taxis from the gate back to the vertipad and takes off. It is important to note that a vertipad remains occupied until both the landing and takeoff times have elapsed.

4.3 Delays introduced by operations

In the context of the current work, specific fluctuations in operational procedures may result in delays arising due to varied process, services, and occupancy duration. Departure and takeoff delays may stem from miscellaneous factors such as pending clearances and fluctuating weather conditions. These time delays are represented with t_{clear}. Furthermore, the time taken to land and takeoff contributes another delay factor, t_{tol}. The start and stop engine times t_{sse} are also considered to cover all the bases.

Upon arriving at the vertiport, the eVTOL taxis to the gate area, where passengers disembark from the vehicle. For departure, passengers board the eVTOL at the gate in preparation for takeoff. The boarding and disembarking process duration is denoted by t_{pbd}, and the time required to travel from a vertipad to the gate is t_{taxi}. It is to be noted that the gate operations entail uncertainties due to human involvement and terminal procedures. It includes checking the health of the vehicle and swapping or charging batteries according to the remaining battery percentage and battery availability. The time to swap batteries, t_{bs}, is much shorter than the time to charge them, t_{bc}.

Additionally, because the eVTOL vehicle charging is located at the parking level, the time needed to use the elevator (t_{ele}) adds extra time. Likewise, the time for repairs (t_r) is taken into account, which can vary based on the severity of the vehicle's condition, ranging from quick fixes that are faster to more extensive repairs that take longer. Equation 1 represents the cumulative delay caused by all the aforementioned factors in transitioning an eVTOL from landing to takeoff.

$$T_{\text{delay}} = t_{clear} + t_{tol} + t_{sse} + t_{pbd} + t_{taxi} + t_{bs}/t_{bc} + t_{ele} + t_r \tag{1}$$

Another delay that may arise is the time discrepancy between the passenger's trip request and the availability of the air taxi for boarding. Moreover, security screenings may introduce additional time requirements influenced by varying traffic conditions across different hours, days, and seasons. Upon reaching the designated gate, the passenger boards while the air taxi undergoes preparation for departure. Decisions regarding the duration of passenger waiting times and booking reservation expirations significantly impact deadhead flights, albeit outside the scope of this investigation.

4.4 Battery Charging Time

In analyzing eVTOL aircraft operations, understanding energy consumption and battery usage is vital. It helps determine the time needed to recharge the battery, which is crucial for efficient operations management. This subsection elaborates on the variables involved in the vertiport scenario and discusses their significance. Let M represent the mass of the eVTOL in kg, which is needed to calculate the energy required for an eVTOL flight. Let the distances travelled by the eVTOL in its previous trip be X_{pt} and the upcoming scheduled trip be X_{nt}, measured in km. Furthermore, the specific energy consumed by the eVTOL in its previous trip, denoted as S_{pt} in Wh/kg, and the battery capacity of an eVTOL is represented by B_{cap} in kWh. To represent the relationship between X_{pt} and S_{pt}, we derive Equation 2 by analyzing the linear relationships as seen in [22], assuming a lift-to-drag ratio of 9 units. In this equation, k denotes the slope of the linear relation, measured in km/Wh/kg. This slope signifies the distance an eVTOL can travel with a specific amount of energy.

$$X_t = kS_t = 1.5S_t \tag{2}$$

Assuming the energy available from the battery is E_{init} kWh and the energy consumed during the previous trip is E_{cons} kWh, then the energy remaining after the trip $E_{rem} = E_{init} - E_{cons}$, in kWh. To initialize, we assume $E_{init} = B_{cap}$, whereas the E_{cons} is the product of the specific energy consumption rate and the mass of the eVTOL, as seen in Equation 3. In terms of the distance travelled in the previous trip, as given in Equation 4, the value of S_t is compared from Equations 2 and 3.

$$E_{cons} = MS_t \tag{3}$$

$$\text{Using Equations 2 and 3,} \quad S_t = \frac{E_{cons}}{M} = \frac{X_t}{1.5} \implies E_{cons} = \frac{MX_t}{1.5} \tag{4}$$

$$\%B_{rem} = \frac{E_{rem}}{E_{init}} \times 100 = \frac{E_{init} - E_{cons}}{E_{init}} \times 100 = \left(1 - \frac{MX_t}{1500B_{cap}}\right) \times 100 \tag{5}$$

$$t_{bc} = \frac{B_{cap}}{\eta}\left(1 - \frac{\%B_{rem}}{100}\right) \times 3600 \tag{6}$$

Finally, the percentage of battery remaining after the trip, denoted as $\%B_{rem}$, is calculated as the ratio of the remaining energy by the initial energy, as shown in Equation 5. It provides an integral indicator of the eVTOL's battery status post-flight, where the charge power of the charger at the vertiport parking level is η kW. The final charging time t_{bc} needed to fill the remaining battery is calculated with Equation 6 and measured in seconds. It helps determine the exact amount of delay expected for charging the battery and optimizes the scheduling process.

5 Solution Approach

This section describes the solution approach towards the problem of optimizing the vertiport throughput using the vertiport elements described in the previous section.

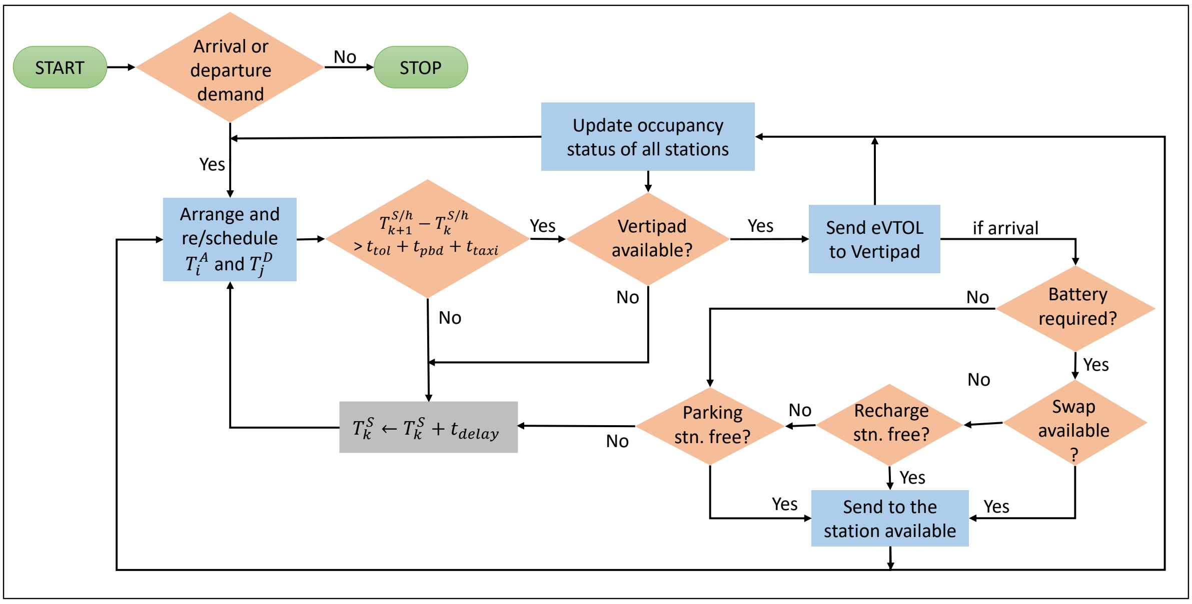


Figure 3: Flowchart depicting the resource utilization planning to maximize throughput process.

Suppose the vertiport experiences an hourly arrival or departure demand of $N^{A/h}$ and $N^{D/h}$, respectively. Let $T^{A/h} = \{T_i^{A/h} | i = 1, 2, \ldots, N^{A/h}\}$ represent the desired arrival times of eVTOLs at the vertiport per hour, and $T^{D/h} = \{T_j^{D/h} | j = 1, 2, \ldots, N^{D/h}\}$ denote the desired departure times of eVTOLs at the vertiport per hour. Here, $N^{A/h}$ and $N^{D/h}$ indicate the number of arrivals and departures per hour, and the indices i and j represent the eVTOLs arriving and departing, respectively. The total demand per hour is given by $N^{S/h}$, calculated as, $N^{S/h} = N^{A/h} + N^{D/h}$. The set indicating the arrival and departure eVTOL demands is given in Equation 7.

$$T^{S/h} = \{T^{A/h}\} \cup \{T^{D/h}\} = \{T_k^{S/h} | k = 1, 2, \ldots, N^{S/h}\} \tag{7}$$

The schematic flowchart shown in Figure 3 depicts the solution to accommodate the total demand per hour. To initiate the scheduling algorithm, specific inputs are necessary, including arrival or demand requests to the vertiports, the occupancy status of each vertipad, and the status of the battery swap stations, recharge stations, and parking stations. Initially, the desired arrival and departure times of eVTOLs are organized in ascending order to determine the time at which the vertipads need to be available.

It is assumed that the vertipad is considered busy from the moment the eVTOL begins hovering to land on the vertiport until the passengers are deboarded and the eVTOL taxis to the gate. It includes the time taken to land, t_{tol}, time taken to taxi the passengers to the gate, t_{taxi}, and the passenger deboarding time from the eVTOL, t_{pbd}. Therefore, to ensure safe distances between two eVTOLs on the taxiway, the difference between the arrival time of one eVTOL and the departure time of another must be Δ_T. In other words, $\Delta_T = T^{S/h}_{k+1} - T^{S/h}_{k} > t_{tol} + t_{taxi} + t_{pbd}$. If this condition is met, no scheduling is required for eVTOLs to land or takeoff from vertipads, provided that the vertipad is free. However, scheduling may still be necessary to optimize the use of other resources related to battery operations and parking. If a vertipad is unavailable, a delay is added to the schedule of the eVTOL, and it is rechecked for vertipad availability.

Upon arrival of an eVTOL, its battery level is examined after the passengers disembark. If an eVTOL requires charging to undertake its next scheduled trip, it is directed to the battery swap station. If no batteries are available to swap or all swap stations are occupied, the eVTOL is redirected to the charging station. Since the swap station is at the parking level, an additional time to travel t_{qsr} is added. However, the charging stations are at the parking level, which adds an extra elevator travel time, t_{ele}. If an eVTOL reaches the charging station but is occupied, the vehicle is parked, waiting for its turn to charge. Alternatively, if the charging station is free, the eVTOL is charged and returns to the vertipad at the scheduled time. Throughout these processes, the occupancy status of all stations is updated to maintain the vertiport's capacity.

In a scenario where an eVTOL is approaching for arrival, and the distance between its previously scheduled eVTOL and the next scheduled eVTOL meets the minimum desired time, but the vertipad is unavailable, then the vehicle is either redirected to another nearby vertiport or a delay is added to its arrival time. However, the latter option may create a chain reaction and affect subsequent scheduled eVTOLs. In such cases, one workaround is to fill the vertiport near capacity by accommodating eVTOLs in any available station, preferably parking stations, to accommodate incoming vehicles. The algorithm concludes when all arrival and departure demands have been met.

6 Simulation Results

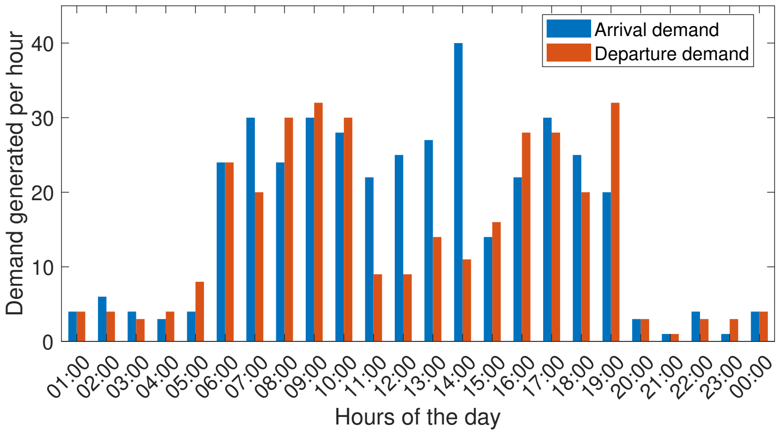
To evaluate the effectiveness of the proposed method, simulations are conducted using a sample arrival and departure demand generated for a typical day. In the vertiport setup depicted in Figure 1, we assume a total of $\mathcal{N}_V = 6$ vertipads available for takeoff and landing, $\mathcal{N}_S = 3$ available swapping stations, $\mathcal{N}_C = 6$ available charging stations, and $\mathcal{N}_P = 6$ parking spots. Therefore, the vertiport has the capacity to accommodate a maximum of 21 eVTOLs simultaneously. Additionally, Table 2 provides a summary of the key parameters and their corresponding values considered for the problem.

Table 2: Parameters

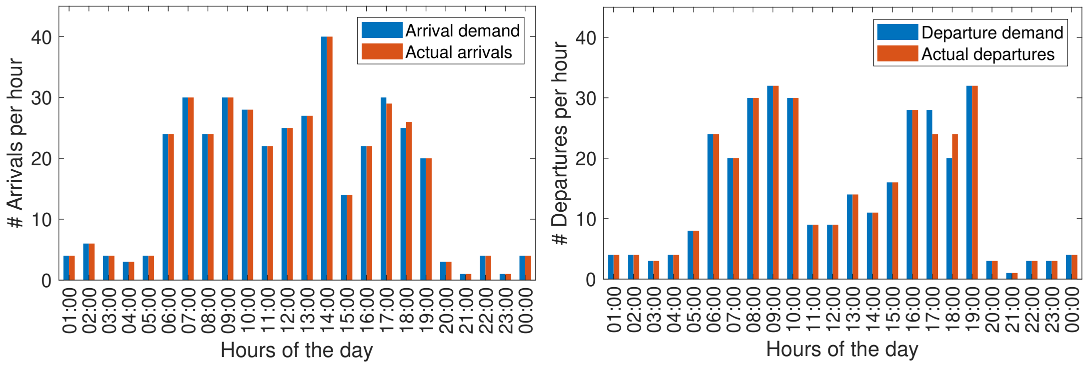
Sr. No.	Parameter	Description	Type	Value	Units	Reference
1	t_{bc}	Battery charging time	variable	[0 5400]	s	Equation 6
2	t_{bs}	Battery swapping time	fixed	300	s	[25]
3	t_r	Repairing eVTOL	variable	[0 3600]	s	Assumed
4	t_{pbd}	Passenger de/boarding	fixed	92.6	s	[8]
5	t_{tol}	Takeoff/landing time	fixed	99.2	s	[8]
6	t_{sse}	Engine start/stop	fixed	4.75	s	[8]
7	V_{ee}	Elevator speed	fixed	0.4	m/s	Assumed
8	d_{vv}	Vertipad to vertipad distance	fixed	60	m	[11]
9	d_{t2p}	Distance between taxing and parking levels	fixed	8	m	Assumed
10	d_{qsr}	Vertipad to quick battery swap	fixed	30	m	Assumed
11	d_{vg}	Distance between vertipad and gate	fixed	30	m	Assumed
12	η	Charge power	fixed	100	kW	Assumed

Analyzing vertiport demand dynamics and operational efficiency provides crucial insights into the challenges of managing eVTOLs. Figure 4 offers a detailed overview of the hourly vertiport demands, showcasing the comparison between the expected demand and the actual number of accommodated eVTOLs. Figure 4(a) shows that the total number of vertiport demands is 735 eVTOLs that need to be accommodated on the vertiport, out of which 395 eVTOLs are the arrival requests on to the vertiport, and 300 eVTOLs want to depart from it. These demands are generated randomly considering the working hours going in between 0600 hours till 1900 hours, and the demand subsidizes at night time. For instance, at 0700 hours, a demand of 30 arrivals and 20 departures is generated.

Figures 4(b) and 4(c) delve deeper into the comparison between desired and actual arrivals and departures. It can be seen from Figure 4(b) that at 1700 hours, the actual arrivals are 29 eVTOLs against the desired 30. The remaining eVTOL arrived in the next hour span, that is, at 1800 hours. This results in having 26 actual arrivals of eVTOLs instead of the 25 requested. Similarly, for Figure, 4(c), instead of departing the demanded 28 eVTOL,



((a)) Demands generated for eVTOL arrivals and departures



((b)) Arrived eVTOLs: actual vs. desired

((c)) Departed eVTOLs: actual vs. desired

Figure 4: Vertiport demands generated per hour and actual demand fulfilled

the algorithm could depart only 24, and the remaining departed at the next hour. It suggests that the algorithm can effectively accommodate and manage eVTOLs efficiently without causing much delay since the arrival and departure demands match the actual arrivals and departures at all the other hours of the day. Figures 4(b) and 4(c) also suggest that the vertiport throughput remains almost 100% with the given demand.

Figure 5 offers insights into the occupancy status of vertipads and various stations within the vertiport. Specifically, Figure 5(a) shows the number of eVTOLs landed or taken off from the vertipads 1 to 6. The trend follows that of Figure 4(a), where the non-peak hours are the night time going from 2100 hours till 0500 hours, witnessing reduced activity. Additionally, battery swapping and recharging/repairing stations experience variable occupancy levels in Figures 5(b) and 5(c), respectively. As depicted in Figure 5(d), the utilization of parking slots per hour showcases optimal resource allocation to maximize the vertiport efficiency.

Figure 6(a) gives the number of eVTOLs subject to rescheduling per hour considering the demand. The delays encountered due to these rescheduled eVTOLs, as depicted in Figure 7(a), may impact overall vertiport throughput. Similarly, the average rescheduling delays per eVTOL is given in Figure 7(b). The average time eVTOLs spend on the vertiport, as shown in Figure 6(b), is caused by activities ranging from takeoff/landing procedures to battery management tasks. For example, the time spent at 1800 hours by 50 eVTOLs is 3579 seconds, which averages about 71.58 seconds per eVTOL, as seen in Figure 6(b).

In conclusion, the total time spent by 735 eVTOLs on the vertiport in 24 hours is 228901 seconds. Therefore, the average time spent by the eVTOLs on the vertiport getting rescheduled in the events of delays or the time spent on charging the battery is 311.43 seconds per eVTOL utilizing the services. Consecutively, the average delay per eVTOL is 58.33 seconds per hour, and the average rescheduling delay was 16.4 seconds per hour.

A detailed scenario analysis further underscores the impact of different operational scenarios on eVTOL dwell time. Consider a scenario where only one eVTOL lands at the vertiport and is scheduled to depart. One of the following scenarios can happen: (1) no battery charging or swapping is required, (2) the battery swapping is needed, and (3) charging of eVTOL is required (consider Volocopter 2X from Table 1 with $B_{rem} = 30\%$). Then,

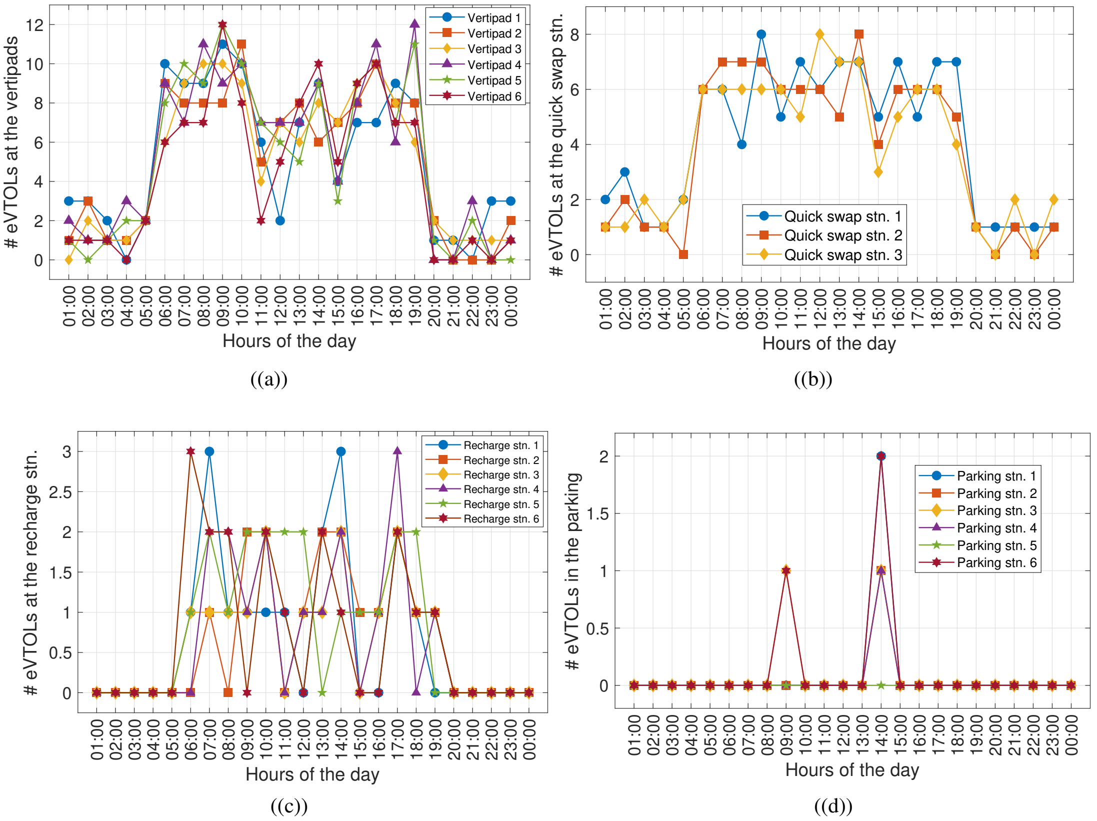


Figure 5: Vertiport eVTOL occupancy status at each hour of the day for (a) Vertipads, (b) Battery swap stations, (c) Battery charge stations, and (d) Parking stations.

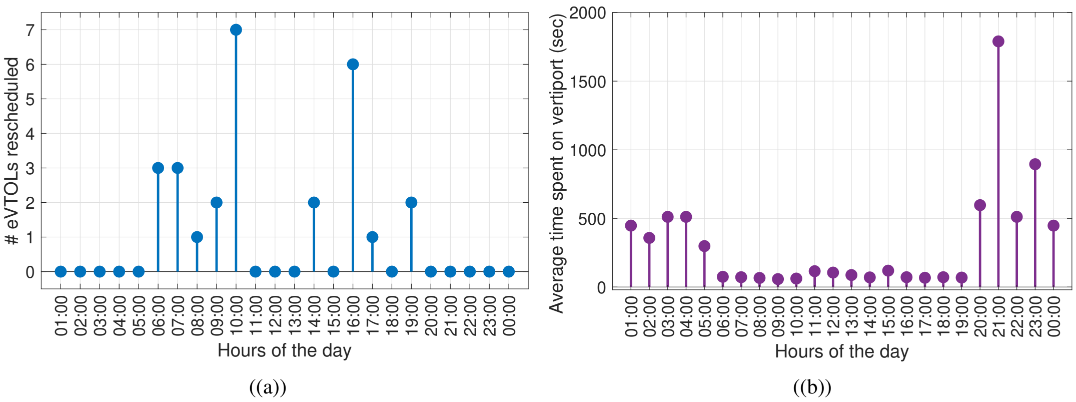
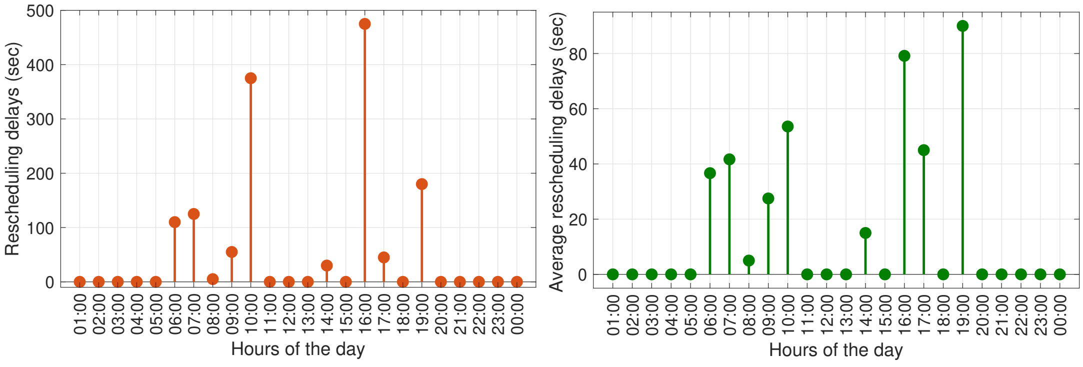


Figure 6: (a) Number of eVTOLs rescheduled and (b) average time spent on he vertiport.

the time spent by the eVTOL on the vertiport on cases 1, 2 and 3, that is, T_1, T_2 and T_3, are calculated as follows:

$$\begin{aligned}
T_1 &= 2 \times t_{tol} + 2 \times t_{sse} + 2 \times t_{pbd} + 2 \times d_{vg}/V_{taxi} \\
&= 2 \times 99.2 + 2 \times 4.75 + 2 \times 92.6 + 2 \times 30/0.5 = 513.1 \ \text{ seconds} \\
T_2 &= 2 \times t_{tol} + 2 \times t_{sse} + 2 \times t_{pbd} + 2 \times (2d_{vg} + d_{qsr})/V_{taxi} + t_{bs} \\
&= 2 \times 99.2 + 2 \times 4.75 + 2 \times 92.6 + 2 \times (2 \times 30 + 30)/0.5 + 300 = 1052.3 \ \text{ seconds} \\
T_3 &= 2 \times t_{tol} + 2 \times t_{sse} + 2 \times t_{pbd} + 2 \times 2 \times (2d_{vg} + d_{qsr})/V_{taxi} + t_{bc}(\eta) + 2 \times d_{p2t}/V_{ele} \\
&= 2 \times 99.2 + 2 \times 4.75 + 2 \times 92.6 + 4 \times 180 + 3600 \times 100 \times 0.7/100 + 2 \times 8/0.4 = 3673 \ \text{ seconds}
\end{aligned}$$



((a)) ((b))

Figure 7: Delays caused due to eVTOL rescheduling (a) per hour, and (b) at an average.

The calculated dwell times for the three scenarios reveal stark differences. Case 1 requires only 513 seconds, while case 2 takes 1,052 seconds. However, case 3 stands out with an astonishing 3673 seconds, of which 2520 seconds are needed to charge the remaining battery. This considerable discrepancy highlights the significant impact of battery charging time on vertiport operations. This extensive charging time substantially prolongs the eVTOL's stay at the vertiport, which can severely disrupt vertiport throughput and potentially lead to delays and operational disruptions.

The flow can be understood with an example scenario at 0100 hours, where the arrival demand is four eVTOLs, and departure demand is four eVTOLs, with a total demand of 8 eVTOLs to be accommodated. In this case, vertipad 1 handles three eVTOLs, vertipad 4 handles two eVTOLs, and vertipads 2, 5 and 6 handles one eVTOL each. For a quick battery swap, station 1 receives two eVTOLs for swapping its battery, whereas stations 2 and 3 receive one eVTOL each. This sums up to four eVTOLs that swap their battery. Since there is no need for the other four eVTOLs to change/charge their battery, they directly go to the vertipad again and execute takeoff according to their departure time. Hence, the recharging stations receive no eVTOLs, and neither does the parking station. This means that no eVTOL comes down to the parking level at 0100 hours. Since no rescheduling is done, the delays are non-existent, but the average time spent by these eight eVTOLs is 447.4 seconds.

7 Conclusions

The paper is focused on addressing the challenges related to vertiport capacity and throughput management. A vertiport with two different taxing and parking levels, with operations of battery swapping, recharging and parking available, was proposed and tested for a reference demand scenario for a day to access the throughput. A scheduling algorithm was proposed to arrange and reschedule the arrival and departure of eVTOLs in the event of unforeseen delays. The vertiport capacity was enhanced with eVTOLs placed in the parking, as well as the battery charging operations. The average time spent by the eVTOLs on the vertiport was found to be 311.43 seconds for 735 eVTOLs. Consecutively, the average delay per eVTOL was found to be 58.33 seconds per hour, and the average rescheduling delay was 16.4 seconds per hour. Future work in this area includes testing the algorithm through multitudes of demands generated by various eVTOL vehicles.

References

[1] United Nations. "Policies on spatial distribution and urbanization have broad impacts on sustainable development". In: *Department of Economic and Social Affairs* 2 (2020), p. 1. URL: https://www.un.org/development/desa/pd/content/policies-spatial-distribution-and-urbanization-have-broad-impacts-sustainable-development.

[2] National Aeronautics and Space Administration (NASA). "Advanced Air Mobility: What is AAM?" In: *Student Guide* 05 (2020), pp. 1–6. URL: https://www.nasa.gov/wp-content/uploads/2020/05/what-is-aam-student-guide_0.pdf?emrc=482a27.

[3] European Commission. “A Drone Strategy 2.0 for a Smart and Sustainable Unmanned Aircraft Eco-System in Europe”. In: *COM/2022/652 final* SWD(2022) 366 fina (2023), pp. 1–25. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0652.

[4] Kay Plötner et al. “Putting Urban Air Mobility into Perspective”. In: *Bauhaus Luftfahrt - The Aviation Think Tank* Whitepaper (2022), pp. 1–12. URL: https://www.bauhaus-luftfahrt.net/fileadmin/user_upload/News/Whitepaper/UAM_White_Paper_2022.pdf.

[5] Bauhaus Luftfahrt. “Marktpotenzial von Fluggeräten für urbane und regionale Luftmobilität”. In: *Bauhaus Luftfahrt - The Aviation Think Tank* Webpage (2024), p. 1. URL: https://www.bauhaus-luftfahrt.net/de/forschungsbereiche/urban-regional-air-mobility/marktpotenzial-von-fluggeraeten-fuer-urbane-und-regionale-luftmobilitaet.

[6] Akshat Kasliwal et al. “Role of flying cars in sustainable mobility”. In: *Nature Communications* 10.1 (2019). DOI: 10.1038/s41467-019-09426-0.

[7] Robert Carroll. “We really, really need vertiports - A successful take-off begins on the ground”. In: *Airframe* Webpage (2023), p. 1. URL: https://airframe.substack.com/p/we-really-really-need-vertiports?utm_medium=reader2.

[8] Lukas Preis and Mirko Hornung. “Vertiport operations modeling, agent-based simulation and parameter value specification”. In: *Electronics* 11.7 (2022), p. 1071.

[9] European Union Aviation Safety Agency (EASA). “Vertiports in the Urban Environment”. In: *EASA Light* Webpage (2024), p. 1. URL: https://www.easa.europa.eu/en/light/topics/vertiports-urban-environment.

[10] European Union Aviation Safety Agency (EASA). “Special Condition Vertical Take-Off and Landing (VTOL) Aircraft”. In: *SC-VTOL-01* 1 (2021), pp. 1–31. URL: https://www.easa.europa.eu/sites/default/files/dfu/SC-VTOL-01.pdf.

[11] European Union Aviation Safety Agency (EASA). “Vertiports Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN)”. In: *PTS-VPT-DSN* 1 (2021), pp. 1–179. URL: https://www.easa.europa.eu/downloads/136259/en.

[12] Tim Felix Sievers et al. “Initial ConOps of U-Space Flight Rules (UFR)”. In: *C/2021/2671* 1 (2024), pp. 1–39. URL: https://www.dlr.de/fl/de/PortalData/14/Resources/dokumente/DLR_Blueprint_UFR_ConOps.pdf.

[13] Matto Brunelli, Chiara Caterina Ditta, and Maria Nadia Postorino. “New infrastructures for Urban Air Mobility systems: A systematic review on vertiport location and capacity”. In: *Journal of Air Transport Management* 112 (2023), pp. 1–8. URL: https://doi.org/10.1016/j.jairtraman.2023.102460.

[14] Lukas Preis and Mirko Hornung. “A Vertiport Design Heuristic to Ensure Efficient Ground Operations for Urban Air Mobility”. In: *Applied Sciences* 12.14 (2022). ISSN: 2076-3417. DOI: 10.3390/app12147260. URL: https://www.mdpi.com/2076-3417/12/14/7260.

[15] Karolin Schweiger and Lukas Preis. “Urban Air Mobility: Systematic Review of Scientific Publications and Regulations for Vertiport Design and Operations”. In: *MDPI Drones* 6 (2022), p. 179. URL: https://doi.org/10.3390/drones6070179.

[16] Anna Straubinger et al. “An overview of current research and developments in urban air mobility – Setting the scene for UAM introduction”. In: *Journal of Air Transport Management* 87 (2020), pp. 1–12. URL: https://www.sciencedirect.com/science/article/pii/S0969699719304302?via%3Dihub.

[17] Bianca I Schuchardt et al. “Air Traffic Management as a Vital Part of Urban Air Mobility—A Review of DLR’s Research Work from 1995 to 2022”. In: *Aerospace* 10.1 (2023), p. 81.

[18] Bianca I. Schuchardt, Aditya Devta, and Andreas Volkert. “Integrating Vertidrome Management Task into U-space”. In: *arXiv preprint* (2023), pp. 1–13. URL: https://doi.org/10.48550/arXiv.2309.09584.

[19] Karolin Schweiger and Franz Knabe. “Vertidrome Airside Level of Service: Performance-Based Evaluation of Vertiport Airside Operations”. In: *Drones* 7.11 (2023). DOI: https://10.3390/drones7110671.

[20] Lukas Preis and Manuel Hack Vazque. “Vertiport throughput capacity under constraints caused by vehicle design, regulations and operations”. In: *Delft International Conference on Urban Air-Mobility (DICUAM)* (2022), pp. 1–12.

[21] James Christopher Curlander et al. *Multi-level fulfillment center for unmanned aerial vehicles*. US Patent 9,777,502. Oct. 2017.

[22] Xiao-Guang Yang et al. “Challenges and key requirements of batteries for electric vertical takeoff and landing aircraft”. In: *Joule* 5.7 (2021), pp. 1644–1659.

[23] CORUS-XUAM Project. “U-space Concept of Operation (ConOps)”. In: 1 (2023), pp. 1–1168. URL: https://sesarju.eu/sites/default/files/documents/reports/Uspace%20CONOPS%204th%20edition.pdf4.

[24] EUREKA Project. “EUREKA - European Key solutions for vertiports and UAM”. In: *European Commission* (2023), p. 1. URL: https://www.sesarju.eu/projects/EUREKA.

[25] Cedric Y Justin et al. “Power optimized battery swap and recharge strategies for electric aircraft operations”. In: *Transportation Research Part C: Emerging Technologies* 115 (2020), p. 102605.