Sustainable Cities and Society 98 (2023) 104797

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Repurposing urban air mobility infrastructure for sustainable transportation in metropolitan cities: A case study of vertiports in São Paulo, Brazil

Jussan Knupp Ribeiro *, Giovanna Miceli Ronzani Borille, Mauro Caetano, Evandro José da Silva

Aeronautics Institute of Technology (ITA)

A R T I C L E I N F O

Keywords:
Air transport
Business model
Innovation planning
Smart city

A B S T R A C T

Urban Air Mobility (UAM) is an emerging transportation solution for large cities, utilizing electric aircraft with vertical take-off and landing (eVTOLs) capabilities, which operate within a network of vertiports and offer advantages such as reduced noise and emissions compared to traditional modes of transport. The objective of this study is to examine the feasibility of utilizing existing aerodrome and heliport infrastructure for UAM operations. The focus is on determining whether these locations can be repurposed to accommodate the requirements of UAM services. To achieve this, spatial analysis methods have been employed using Geographic Information Systems to investigate the São Paulo metropolitan region in Brazil, with a specific emphasis on access from São Paulo - Congonhas Airport. The results demonstrate that the existing infrastructure holds significant potential for improving urban mobility in the city. This research contributes valuable insights into the operational possibilities of utilizing existing infrastructure for UAM, paving the way for the implementation of sustainable and efficient urban transportation systems.

1. Introduction

The concept of Urban Air Mobility (UAM), coupled with recent technological advancements, has propelled the aviation industry to forge ahead in establishing an urban sustainable air transportation system utilizing innovative electric vertical take-off and landing (eVTOL) aircraft (Bauranov & Rakas, 2021). The development of UAM necessitates an integrated approach encompassing air vehicle technology, UAM infrastructure, and the corresponding business models for its operation. To explore viable implementations of UAM outlined in existing literature, this study investigates various business and operational models (Straubinger, Michelmann and Biehle, 2021; Goyal et al., 2021; Plotner et al., 2020), enabling a deeper reflection about the new mode of air transportation.

The emergence of UAM operations has led to a prominent need for new airline business models in the realm of eVTOL operations (Goyal et al., 2021). Given their expertise as established providers of air transportation services, airlines play a vital role as key stakeholders in guaranteeing the safe and economically feasible integration of this innovative service. Moreover, airport access constitutes a fundamental element within this business framework, as passenger perception greatly relies on travel time and dependability, influenced by anxiety and the apprehension of missing flights. This aspect holds particular significance for business travelers, as highlighted by Paliska et al. (2016). Nevertheless, although the business model for UAM airport access holds promise, its viability hinges upon the strategic positioning of vertiports at strategic locations, providing a level of convenience that complements other modes of transport in smart urban mobility.

Despite the literature on urban development considering aerial mobility as a solution for congestion issues (Christodoulou & Christidis, 2021), air traffic management (Bauranov & Rakas, 2021; Murça, 2021; Willey & Salmon, 2021), and meeting demand (Bulusu et al., 2021; Goyal et al., 2021, Haan et al., 2021; Postorino & Sarné, 2020; Syed et al., 2017), limitations are observed regarding the optimization of urban resources and travel time through the adaptation of existing infrastructure for eVTOL operations. These limitations hinder the feasibility of business models for the utilization of a new sustainable mode of transportation in major urban centers, characterized as a disruptive innovation (Fox, 2020).

The main objective of this study is to develop and test a spatial demand analysis model for UAM and the provision of air transportation infrastructure, aiming to repurpose existing aerodrome infrastructure and improve travel time in major cities. For this purpose, the São Paulo

* Corresponding author.
E-mail addresses: knupp@ita.br (J.K. Ribeiro), ronzani@ita.br (G.M.R. Borille), caetano@ita.br (M. Caetano), evandro@ita.br (E.J. da Silva).

https://doi.org/10.1016/j.scs.2023.104797
Received 14 July 2022; Received in revised form 19 June 2023; Accepted 13 July 2023
Available online 14 July 2023

Acronyms

ABRAPHE	Brazilian Association of Helicopter Pilots
ANAC	Brazilian National Civil Aviation Agency
EASA	European Union Aviation Safety Agency
eVTOL	electric vertical take-off and landing
GIS	Geographic Information System
HDX	Humanitarian Data Exchange
ICAO	International Civil Aviation Organization
KDE	Kernel Density Estimation
MATSim	multi-agent transport simulation framework
OSM	Open Street Map
SBSP	São Paulo - Congonhas Airport
SPMR	São Paulo Metropolitan Region
UAM	Urban Air Mobility

Metropolitan Region (SPMR) was taken into account, with the São Paulo - Congonhas Airport (SBSP) being adopted as the starting point for on-demand UAM operations for citizens' transportation. The Uber movement database (Uber, 2019) was utilized as a proxy for on-demand UAM services to identify the active traffic zones (2019, 1st trimester).

Certain limitations of this approach need to be acknowledged: *i)* Uber data patterns are contingent upon the prevailing conditions at that time, while UAM is still under development, allowing for potential changes in conditions such as urban sprawl; *ii)* Less densely connected areas may be omitted in Uber data aggregation, resulting in an incomplete representation of trips; *iii*) On-demand car transport captures clients across different income strata, whereas UAM may be limited to higher income levels due to factors like operational costs and competition; and *iv*) Land transport is more flexible than air transport due to operational constraints (e.g., obstacle clearance). Despite these limitations, the value of the database is justified, as Uber usage indicates a preference for on-demand services over private and mass transportation options, or when such alternatives are unavailable. Consequently, there is potential for UAM to capture a portion of the existing on-demand land transportation market.

The structure of this paper is organized as follows: Section 2 provides a background on UAM; Section 3 emphasizes the business model for UAM; Section 4 introduces the methods employed; Section 5 presents the results; and finally, Section 6 concludes the paper and provides directions for future research.

2. Urban air mobility

Urban areas, functioning as constructed human habitats, facilitate the provision of essential survival requirements, which can be collectively met more efficiently. These necessities include access to shelter, food, as well as social, cultural, and intellectual opportunities (Sugar & Kennedy, 2021). The trend of population clustering in large urban centers is on the rise. According to the United Nations (2018), approximately 55% of the global population resided in urban areas in 2018, with projections indicating that this figure is expected to approach 70% by 2050. Some of the potential negative consequences of this trend, such as congestion, increased commuting time in cities, urban pollution, noise levels, and accidents (Christodoulou & Christidis, 2021), necessitate the development of innovative solutions for urban transportation, especially in large cities. Given this scenario, UAM emerges as a transport alternative aimed at mitigating these consequences and their effects on the city and the economy (Murça, 2021; Postorino & Sarné, 2020).

UAM is defined by EASA (2021) as a new air transportation system for passengers and cargo in densely built environments, using eVTOL aircraft. Postorino and Sarné (2020) stress that the UAM can meet the concept of "sustainable mobility", conceived as the ideal model of a transportation system as it minimizes environmental impacts and maximizes efficiency and displacement speed. According to Rajendran and Zack (2019), eVTOL aircraft are similar to helicopters as they have vertical take-off and landing capability, but the use of the helicopter compared to an eVTOL is operationally more expensive, energy inefficient, and undesirable in many urban areas due to the high levels of noise from the rotor blades. Furthermore, the estimated cost per mile incurred per helicopter can be 1.5 times the initial operating cost of the eVTOL. For this reason, there is an expectation that eVTOL aircraft will largely replace the use of helicopters and become a high-frequency mass urban transportation mode in the near future.

The expectation observed in the literature is that UAM will be a relevant transportation alternative to combat the problems generated by increasing urban traffic densities and congestion, but Schweiger, Knabe and Korn (2022) point out that improvements in traffic will only occur if UAM is capable of processing a considerable portion of urban transport demand. The authors also mention that one of the major challenges for the feasibility of UAM on this scale lies in the infrastructure for the operation of eVTOL aircraft since these infrastructures do not yet exist. Such challenges are also demonstrated by considering the case of the Silicon Valley Region of California (Syed et al., 2017). However, Willey and Salmon (2021), and Holden and Goel (2016) suggest that initially the infrastructures used for the UAM operation can be adapted from heliports and airports already built, mainly to avoid costly investments in the short term.

In addition to this topic, the study by Robinson et al. (2018) identifies potential locations for UAM using factors such as sprawl, urban density, geography, the number of existing airports, wealth, weather, surface transportation congestion, and the presence of various economic clusters. One objective of their research is to estimate the geo-density of vertiports suitable for UAM. Results for the Miami metropolitan region show an average vertiport geo-density calculation, thus allowing a calculation of vertiport geo-density locations in the selected metropolitan region. Rothfeld et al. (2018) describes the network model for an UAM station in a multi-agent transport simulation framework (MATSim), connecting the ground transport network with the flight network, using the methodology of including UAM stations in the transport simulation. An introduction of the UAM, with its small-scale vehicles and in-town operations, therefore, poses new challenges for MATSim integration. With the introduction of autonomous vehicle simulation assuming on-demand operational models for UAM, the transport modeling of eVTOL vehicles mirrors that of autonomous land taxis. The distinction between these autonomous ground vehicles and the introduction of UAM vehicles is the requirement of eVTOL infrastructure for operation instead of roads and the introduction of different properties, i.e., different combinations of vehicle properties such as speed, range, and maximum payload.

Similar studies have been found in the literature regarding the problem of identifying ideal locations for charging of community electric vehicles in areas with high population density. Charly et al. (2023), using GIS, show that planners around the world will have to investigate how charging infrastructure is brought into cities. By utilizing designated parking lots, their study suggests the ideal location for installing these chargers with the least amount of additional infrastructure expense. The study area was broken up into smaller grids based on how many people lived there. According to the findings, between 2025 and 2030, the proposed charging stations' deployment will significantly increase the population served, as will their accessibility over time. The results of the study show that there should be more charging stations further from the city. The locations were chosen based on how many people lived there, how far away they were from existing charging stations, and how close they were to homes, roads, amenities, and places of work or school, among other factors.

A framework for predicting the future deployment of electric vehicle charging stations was used by Roy and Law (2022) to investigate their disparity across geographic areas. The research examines the spatial disparity and creates an inequity index by utilizing Kernel Density Estimation (KDE). This technique produces a smooth curved surface, enabling researchers to visualize both the general trend as well as instances of spatial heterogeneity, and to better understand the spatial distribution pattern of charging activities and infrastructure, as demonstrated by Kang et al. (2022).

KDE analysis is employed in the present study to create a continuous surface based on the location of heliports and airports. Several questions are yet to be answered regarding UAM implementation and its integration with cities, including the utilization of the existing aeronautical infrastructure and how it connects to other transportation modes.

3. The business model for urban air mobility

The business model was defined by Björkdahl, Fallahi and Holmén (2022) as the way companies create and capture value. For the authors, business model innovation is necessary for some companies to maintain their competitiveness or unlock the value of new technologies. The implementation of business models that identify opportunities for innovation in the airline sector enables a new positioning of airlines in their market relationships, strategies, and value proposition, which can drive progress in these companies (Pereira & Caetano, 2015). The diversification of business models in air transportation seeks for competitive advantages to organizations, as in the case proposed by Moir and Lohmann (2018), in which the competitive advantage of the airline stems from the creation of value, by offering passengers additional products and services through innovation.

New businesses related to UAM necessarily require in-depth studies in new technologies development, because it is a disruptive innovation. Despite that, according to Straubinger, Michelmann and Biehle (2021), the relevant business models for the implementation of this air transport mode has received relatively little attention in the literature, and the concepts of eVTOL operations are not yet consolidated. To improve the understanding of the subject, the authors propose three business model approaches for the passenger UAM service: airport transportation, intercompany transportation, and regional connection.

Studies point to the use of UAM applied to the transportation service between the city and the airport as the fastest sector to be commercialized. According to Straubinger, Verhoef and Groot (2021), many airports around the world face problems related to long times spent by passengers to access the airport using land transportation, due to long distances between the airport and the main urban center, inadequate accessibility through public transportation, congestion on land access roads, or even combinations of all these factors. Therefore, the airport passenger transportation service through UAM can be a solution for airlines that use airports, with a high level of congestion in their accessibility, as key nodes in their network, thus mitigating these problems and competitive disadvantages with other airlines that use more accessible airports, and enhance the passenger experience.

The analysis of the business model for UAM, applied to airport transportation, made by Straubinger, Michelmann and Biehle (2021), pointed out that the operational concept for UAM does not just require a valid business case, expressing a reliable customer demand, but it also depends heavily on a comprehensive view of the overall operating system such as vertiport's accessibility from relevant areas of interest compared to other modes of transport. Goyal et al. (2021) also point out that one of the main challenges for the potential growth of UAM lies in the availability of eVTOL take-off and landing infrastructures, that is, vertiports.

A competitiveness analysis presented by Straubinger, Michelmann and Biehle (2021) identifies airlines as potential operators of passenger UAM when adding UAM services to their portfolio. Adding airport shuttle service through airlines can increase the competitive edge compared to other airlines. The shuttle service is primarily aimed at premium, high-income passengers traveling in first and business class, hence primarily business travelers.

To predict the demand of passengers who would use eVTOL as an air taxi service, Haan et al. (2021) present a combined statistics method, using cell phone data to identify passengers, census data on income characteristics, and a choice model from a preference survey for the 40 most populous US cities. The authors consider that the route of trips using air taxis should be at least between 15 and 25 km, to provide savings in travel time about other modes of urban transport. For the calculation of travel time for an air taxi service, 60 miles (about 97 km) are considered the maximum range of the eVTOL aircraft.

Possible operator models and customer segments are compiled and combined into business model options for urban passenger air mobility. Plotner et al. (2020) develop a model to analyze and quantify the potential UAM demand for access to Munich airport. As the main result of the research, they found that in short distances, up to 10 km, UAM has a modal share of 0.5%. In absolute terms, 84% of UAM demand is concentrated on short distances below 40 km, with 55% of the demand being on routes below 10 km. The survey did not investigate demand if a large number of vertiports are located at points of interest. The UAM must meet urban mobility transporting a significant portion of urban traffic in a metropolitan region. Bulusu et al. (2021) indicate that a substantial amount of passengers could benefit from using eVTOL based on travel time savings during the congested hours of the day and there is substantial mode switching potential to attract public investment.

Therefore, a business model for urban air mobility applied to the transportation of passengers to the airport is one of the main uses expected for UAM, but its feasibility is strongly linked to the availability of vertiports and their locations at strategic points. The literature also recommends the adapted use of existing heliports and airports for the initial phase of UAM operations. In this article, data from heliports and airports in the SPMR are compared with the probable areas of demand to estimate if the existing infrastructure would support the introduction of the UAM service. The spatial coverage of these infrastructures directly influences access time and, consequently, the ability to serve potential users.

4. Methods

As a methodological procedure, the spatial data analysis management system in a Geographic Information System (GIS) has been used. According to Miller and Shaw (2015), a GIS is a fundamental computational tool for processing data involving routes and points of geographic coordinates. This type of vector data represents points, lines, and polygons with known geographic coordinates. To operationalize the model, the open-source environment of QGIS software has been used, which allows accessing an environment for viewing, managing, and editing georeferenced data.

4.1. Data sources and case characterization

In this subsection, the reader is introduced to the context being assessed, along with the databases and services utilized to gather the necessary data. These include Uber Movement, the Brazilian National Civil Aviation Agency - ANAC (*Agência Nacional de Aviação Civil*) aerodromes database, the Humanitarian Data Exchange (HDX) population data, and OpenrouteService. The set of potential vertiports used for this study was selected from a file with data from regularized airports and heliports throughout the Brazilian territory, made available by the ANAC (2023). Among the main information associated with this data are the identification codes of each helipad and airport, name, physical characteristics, altitude, type of operation, designation, and geographic coordinates. This dataset comprises a total of 4,610 aerodromes, as shown in Fig. 1, encompassing public and private facilities with a valid status at ANAC (2023). Points in red color represent heliports and helipads, collectively referred to as "heliports" for simplicity. Markedly, the São Paulo region exhibits a significant concentration of heliports, while Midwestern Brazil is characterized by a concentration of

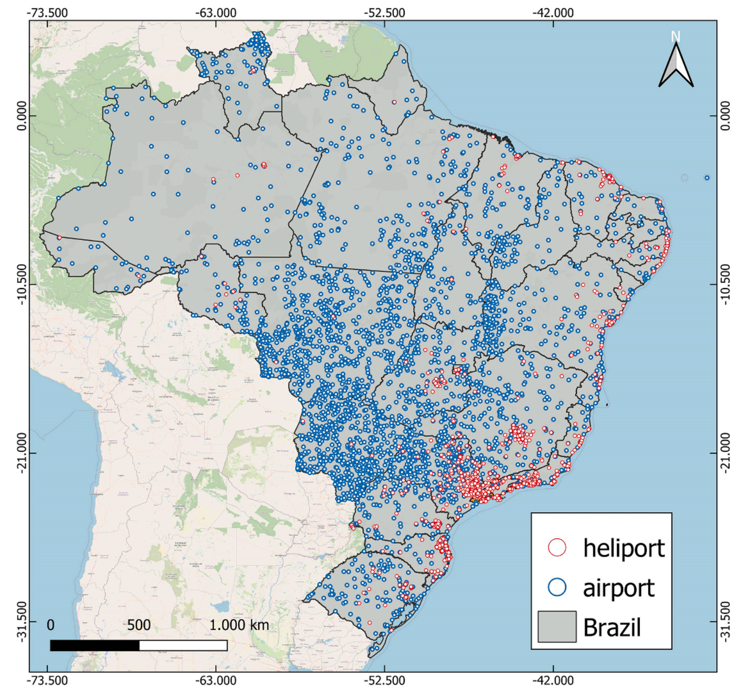

Fig. 1. Location map of Brazilian airports and heliports.
Source: ANAC (2023).

aerodromes specifically dedicated to fixed-wing aircraft operations.

With approximately 20.8 million inhabitants, the SPMR is the largest urban agglomeration in the Southern Hemisphere. In 2017 alone, 42 million daily trips were produced in the SPMR, about 67% of these trips were carried out by motorized modes, and the daily flow of plane passengers, companions, and employees at airports was 217 thousand people (Metrô, 2022).

Economic strength and high levels of congestion in land traffic have made the use of helicopters for urban transport very common in São Paulo city. According to the Brazilian Association of Helicopter Pilots (ABRAPHE, 2023), the SPMR hosts the largest fleet of helicopters in operation in the World, with 411 registered aircraft and about 2,200 daily take-offs and landings.

Located 9 km from the city downtown, the SBSP airport stands out in the Brazilian network for its heavy commercial traffic, with a significant share of business travelers and a high traffic of executive flights. According to Infraero (2022), in December 2019 this airport had a daily movement of 60,932 passengers, with 592 take-offs and landings. For this reason, this airport has been chosen as a strategic reference for the analysis of potential vertiports in the SPMR. Additionally, the SPMR, according to the UAM Geomatics Dashboard Revenue Forecasts Rank (2023), is on par with cities in developed countries, such as Los Angeles, and higher profit than developing cities, such as Mexico City, for the airport shuttle business model.

To identify potential demand regions for UAM transport in the SPMR from SBSP, established traffic zones have been used. Currently, the

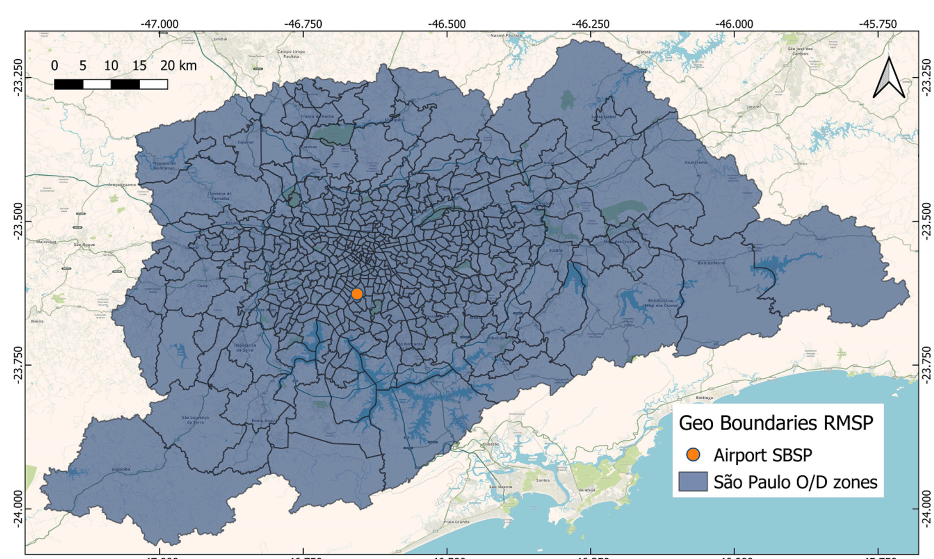

Fig. 2. Map of the São Paulo Metropolitan Region divided by traffic zones.
Source: Research data.

SPMR is divided into 517 traffic zones, as defined by the Origin-Destination Domestic Travel Survey (OD17) carried out in 2017 by the city's Metro Company (Metrô, 2022). The geographic limits of the region comprised by the SPMR and its traffic zones are shown in Fig. 2.

The region in Fig. 2 where there was the demand for Uber in the SPMR from the SBSP airport zone was determined through the Uber Movement, which consists of a repository with travel time information collected by Uber vehicles in some cities (Uber, 2019). The cities are divided into neighborhoods according to official transit zones or administrative boundaries. Zonal data is aggregated, i.e., for an origin *O*, and a destination *D*, if there was a minimum number of Uber trips between these *O/D*s during the period *P*, then the database includes the average travel time for the *O/D* of these trips (Vieira & Haddad, 2020). Data ranging from January 1, 2019, to March 31, 2019 have been considered, encompassing hourly information (hod – hour of the day), but lacking specific day/month information.

The UAM demand is concentrated (84%) on short distances, below 40 km from the demand generating center, with 55% of the demand being on routes below 10 km (Plotner et al., 2020). The study area aligns with these concepts, and the primary constraint on further expansion is the limited availability of Uber Movement data. Moreover, Table 1 demonstrates a significant clustering of heliports/aerodromes in the central region of the SPMR, with 168 out of 309 aerodromes/heliports located within 10 km from SBSP Airport.

To enhance zonal spatial analysis, the geographic distribution of the population was retrieved from the HDX database (HDX, 2023), which offers population density data at a 30m resolution. Visual inspection against high resolution imagery from Google Earth indicates agreement of the database and inhabited areas for the SPMR, considering the usage in this research, as explained later.

Distances and travel times for car trips used in this research were gathered either from Uber Movement (Zone to Zone) or through the OpenrouteService API (OpenRouteService, 2023), which estimates trip times based on origin-destination coordinate pairs, the Open Street Map (OSM) network, and realistic speeds.

4.2. Modeling

Within this subsection, the methods employed are outlined. The procedure encompassed the following steps:

A Identifying and defining the study area and the destination airport to be served by UAM;
B Acquiring and preparing the necessary data, including traffic zones, airport/heliport locations, zone-to-zone car trip times, population distribution data, and driving times from origin to destination coordinates;
C Formulating the eVTOL flight time model;
D Computing the trip times.

The specifications for step (A) were established in section 4.1 of this article. Step (B) involved the utilization of Python programming and QGIS software to manipulate files of various formats, including TIF for raster data, as well as CSV, GeoJSON, SHP, and XLSX for vector data handling. The employed tools are license-free.

The great-circle distance shown in Eq. 1 allows a straight-forward calculation of distances from geographic coordinates. Such expression is implemented in many computational packages and modules, including Python. For this specific problem, this formulation is precise enough, and working with geographic coordinates is convenient, considering the available data.

$$DIST = arccos[(sin(\varnothing1).sin(\varnothing2)) + (cos(\varnothing1).cos(\varnothing2).cos(\Delta\lambda))].R \quad (1)$$

where $\varnothing1$ is the latitude of point 1; $\varnothing2$ is the latitude of point 2; $\lambda\Delta$ is the longitude difference between point 1 and point 2; and R is the radius of the sphere representing the Earth, equivalent to 6,371 kilometers (km) adopting the WGS-84 model.

The flight time of step (C) adopted the model of Eq. 2.

$$t_{flight} = t_0 + \frac{DIST}{S_{flight}} \quad (2)$$

where the flight time (t_{flight}) depends on a stop and acceleration time (t_0), geodesic distance flown (*DIST*) and nominal speed of flight (S_{flight}). The parameters shown in Schweiger, Knabe and Korn (2022) were adopted, with $t_0=741$ *s* and $S_{fligh}=100kph$.

Step (D) requires different solutions, depending on the available resources and data, with the structure of the Eq. 3.

$$t_{eVTOL} = t_{car} + t_{flight} \quad (3)$$

By Eq. 3, the eVTOL trip time depends on two phases: time spent in car from a given origin to the closest vertiport; and time spent in flight, considering stop and acceleration time, from the vertiport to the destination airport. The driving time requires network analysis, discussed by Papinski and Scott (2011) as tools necessary to perform various tasks, such as identifying the best route, finding the closest resource of interest, calculating service areas, creating origin-destination matrices, and creating destination models route analysis. For the sake of the present approach, the OpenrouteService API was given the parameters ('radiuses': [500], 'profile': 'driving-car'), without specification of the time of the day. By default, the calculations are based on weekdays. Visual inspection of random routes showed reasonable results. The destination was set as the closest aerodrome/heliport to a previously generated set of origins. The origin points have been generated randomly for each zone, overlapping populated areas, with a minimum of 3 points in small zones and a maximum of 10 points in the big ones. Inhabited zones were assigned a unique origin point, in the centroid.

Table 1
Dispersion of aeronautical infrastructure in the SPMR.

Distance to SBSP (km)	0-10	10-20	20-30	30-40	40-50	>50
Elevated Heliport/Helipad	151	41	38	6	2	2
Ground Heliport/Helipad	17	11	19	11	5	2
Aerodrome	-	1	1	1	-	1
Total	168	53	58	18	7	5

Source: ANAC (2023).

5. Results analysis

The results present the existing air transport infrastructures in the SPMR and their distribution in the urban space using the SBSP airport as a reference destination. The distribution of transport infrastructures in the urban space is also compared with the regions where, according to the literature, the main demands for UAM transport are concentrated. The spatialization of the results allow a through view of the UAM potential market.

5.1. Distribution of possible vertiports in São Paulo metropolitan region

In the entire SPMR, it was possible to identify a total set of 305 heliports and 4 aerodromes, in addition to the SBSP airport. The supplementary material (*Aerodrome_Data.xlsx*) presents the International Civil Aviation Organization – ICAO code of each infrastructure and: name; coordinates; great circle distance to SBSP; type (ground-level or elevated); and elevation. The shortest distance to the airport was 1.9 km and the longest was 68.7 km. From the distances, it was also possible to identify that the highest concentration of heliports is found in the areas closest to SBSP, mainly in the areas up to 30 km from the airport, as shown in Fig. 3.

From the map illustrated in Fig. 3, the potential vertiports are represented by the yellow points in the traffic zones where Uber transport

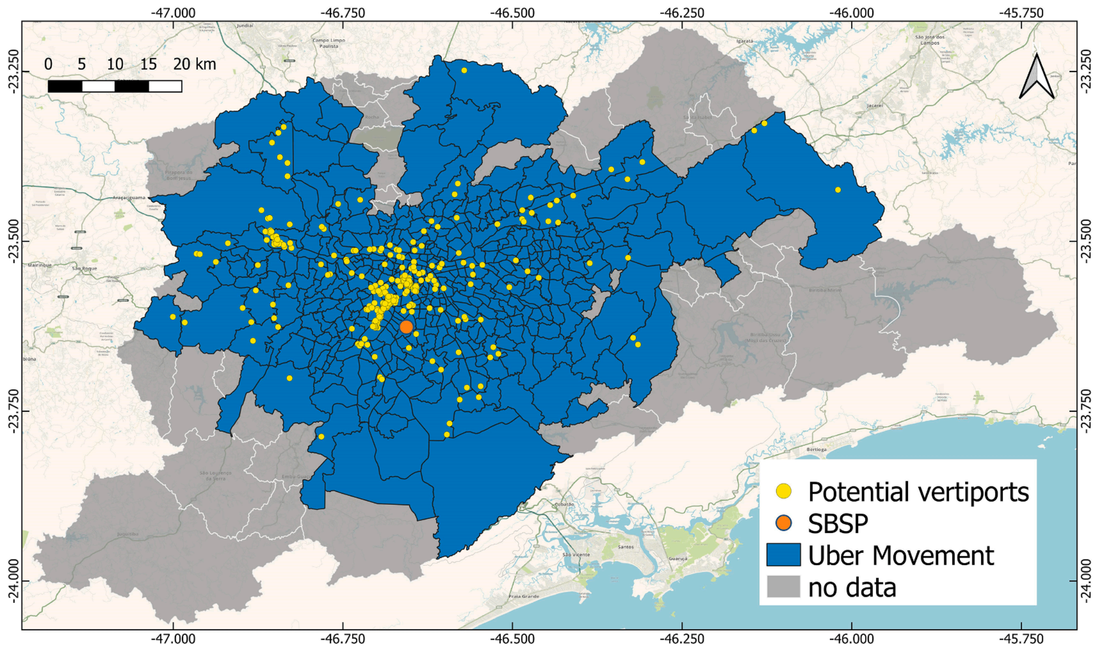

Fig. 3. Existing aerodromes infrastructure in traffic areas where there is demand from SBSP by Uber.
Source: Research data.

demand was identified, depicted in blue color. It can be observed that in this area there are 298 heliports and 4 airports, which represents a total of 98% of the air transport infrastructures of the entire SPMR. This situation demonstrates conformity of the spatial distribution of the infrastructures with the demand expectation pointed out by Ploetner et al. (2020). These infrastructures cover some traffic areas, mainly those located in regions of the metropolis where there is great urban density. This significant number of potential vertiports contrasts the limitations on UAM infrastructure proposed by Schweiger, Knabe, and Korn (2022). The results of this study provide a means of optimizing the existing infrastructure, which also contribute to the enhancement of the transportation system (Vasconcelos & Kaminski, 2013). In addition, it is possible to observe that these infrastructures are spatially distributed to cover long-distance areas, which can provide access to different traffic

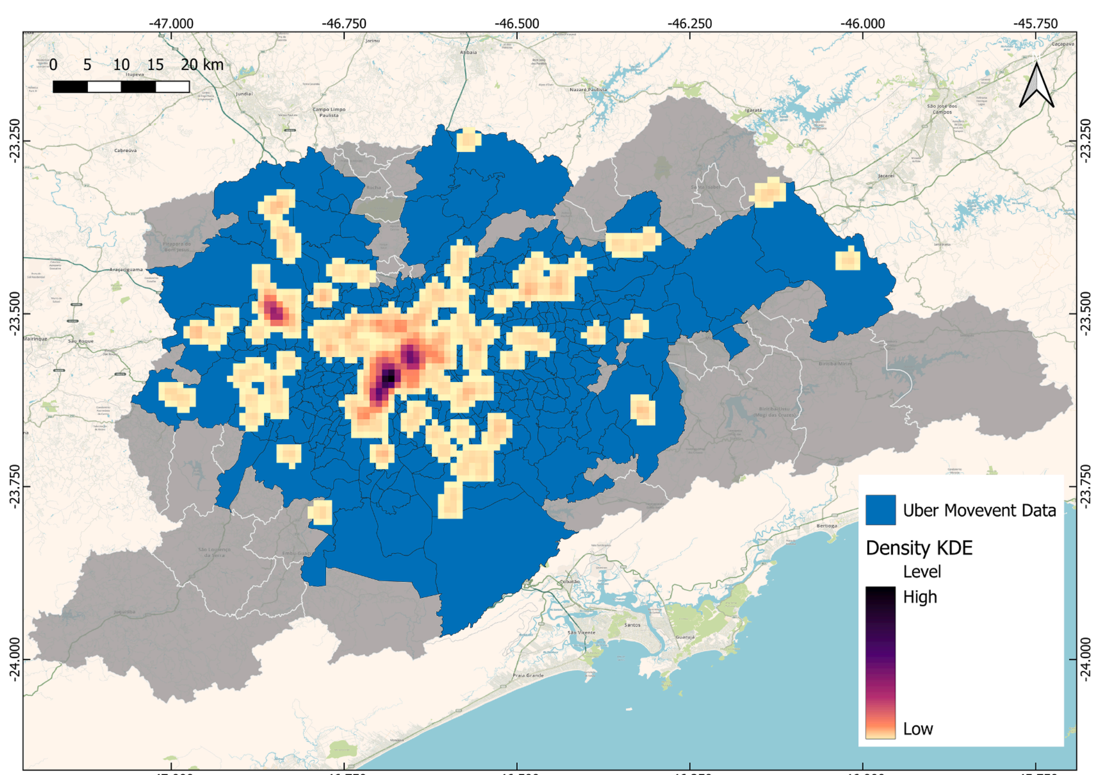

Fig. 4. Kernel Geodensity Analysis map within the on-demand area.
Source: Research data.

zones.

Although there is an expressive number of heliports and airports in the regions ranging 10 to 40 km from the SBSP airport, it can be identified in Fig. 3 that many traffic zones lack nearby infrastructure. As a result, the areas not covered by potential vertiports, but with significant demand for passenger transportation, can be subject of analysis in urban planning for the construction of new infrastructure, which complements the findings of Robinson et al. (2018). Fig. 4 presents density analysis from the Kernel Geodensity Analysis map within the on-demand area.

Based on Fig. 4, the results of this study showcase potential UAM sites and the coverage area relative to the actual demand for future infrastructure deployment. The geodensity calculation identifies suitable stations for eVTOL in the congested metropolitan region. The density level analysis is conducted in a linear distribution kernel across the map, considering the Uber movement data layer and focusing on areas with high demand. Following the approach adopted by Kang et al. (2022), this analysis enables the identification of locations with high spatial density indices (indicating a match) and low indices (indicating a mismatch). Additionally, it highlights areas without vertiport coverage, revealing interesting patterns in their boundaries. The distribution of potential vertiports demonstrates significant spatial heterogeneity, with concentrated high-density zones near the reference airport and lower levels in regions farther away. These results align with expectations for passenger transport demand.

5.2. Travel times by land and air

Considering UAM in comparison to land transportation in terms of travel time within cities, if all potential vertiports could be utilized, the land access to the nearest vertiport in the SPMR would be a maximum of 60 minutes, as presented in Fig. 5.

Comparing land travel times, via Uber, and air travel times, via eVTOL, from SBSP, it is evident from Figs. 6 and 7, respectively, that land journeys range from 3.2 to 93 minutes, even for regions relatively close to the airport, which demonstrate a significant time loss due to congestion (Schweiger, Knabe, and Korn, 2022).

From the analysis of Fig. 7, it is evident that air travel time demonstrates greater efficiency, particularly in regions of higher urban density in the city center, where there is also greater availability of potential vertiports (Willey & Salmon, 2021). By analyzing the travel times by land and air depicted in Fig. 8, it is possible to observe the time savings when considering transportation from the airport in a major city like São Paulo. This time savings varies from 63 minutes in more distant regions to 18.5 minutes for closer regions, as illustrated in Fig. 8.

Considering the Fig. 8, an expected result is that the vicinity of SBSP is better served by land transport, however, red regions appear southward. For instance, from the Bororé region, reaching the closest heliport is equivalent to reaching the SBSP airport, as evidenced by Fig. 9.

The land travel time from Bororé to SBSP of 80 minutes, is very close to the travel time from that location to the nearest aerodrome, which is 70 minutes away, as presented in Fig. 9. This is an indication that a new infrastructure would be required for making UAM competitive in some areas.

UAM represents a market opportunity in the transportation sector, leading to numerous studies being conducted across different research fields for its implementation. By comparing these locations in the SPMR with the projected areas of demand mentioned in the literature, it is possible to determine whether the existing infrastructure can adequately support the anticipated demand and facilitate the launch of UAM operations. This analysis enables the development of business models centered around UAM, in line with the findings of Syed et al. (2017) regarding the analysis of requirements in vertiports operations, supporting the feasibility of this emerging mode of sustainable urban transportation.

6. Conclusions and future research directions

In this study, an UAM business case applied to the transport of passengers from the airport has been verified, but its viability is strongly linked to the existence of infrastructures for its operation. Therefore, in this study, the geographic locations of pre-existing structures have been identified to determine the spatial distribution of potential vertiports in

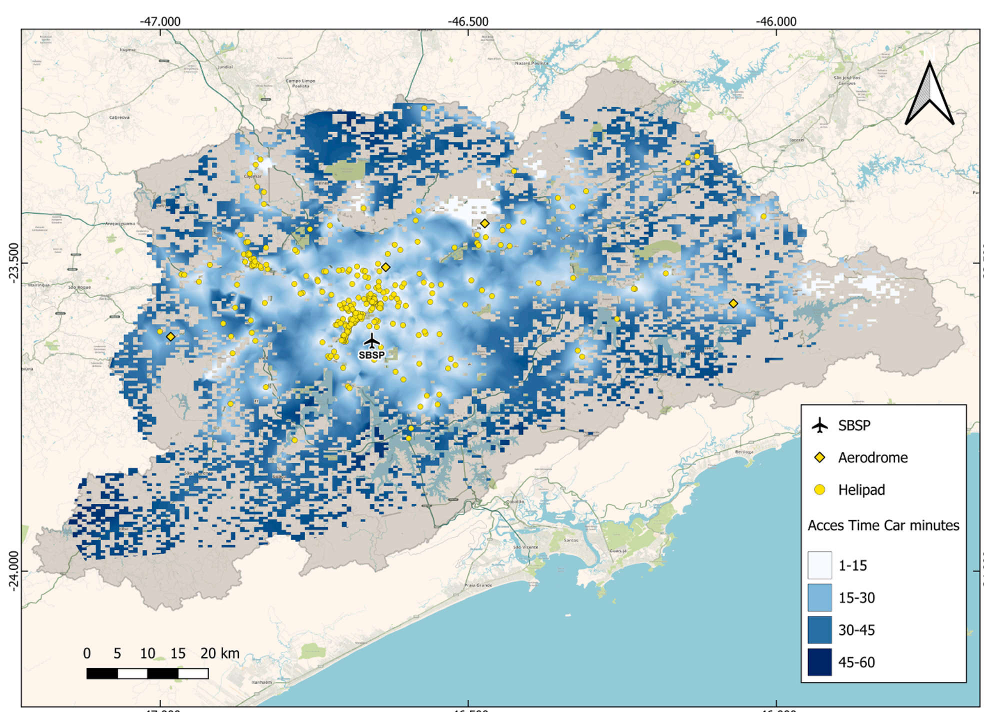

Fig. 5. Driving time to the vertiports.
Source: Research data.

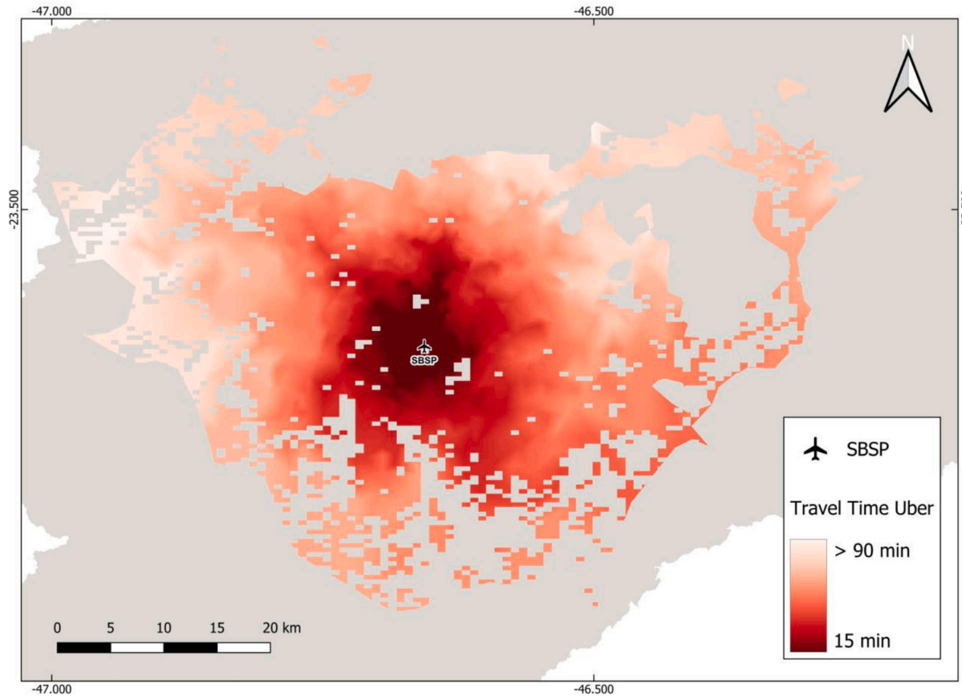

Fig. 6. Uber travel time (minutes).
Source: Research data.

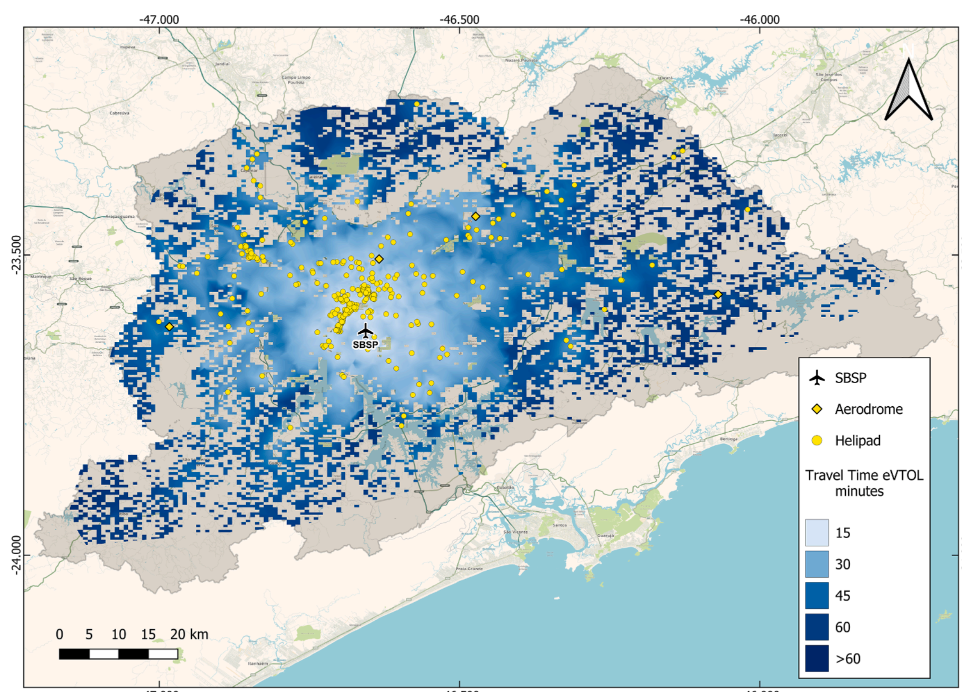

Fig. 7. eVTOL travel time (minutes).
Source: Research data.

a metropolitan region. In addition to the infrastructure, its compatibility with the regions with expected demands for this transport has been analyzed. The results provide an initial and fundamental perspective that supports the introduction of UAM operations, considering economically viable application scenarios, while at the same time meeting real transport demands. As UAM is a promising market, companies can use this result to implement a viable business model available to the broad market of potential consumers.

Despite the results consider the case of the São Paulo – Congonhas Airport and the São Paulo Metropolitan Region, this region is known for the high use of helicopters as a transport alternative, which is also evident in major urban centers such as New York, Los Angeles, Tokyo, London, and other cities with a significant helicopter fleet. For this case, it is appropriate to mention that the spatial distribution of the existing infrastructure could support the beginning of UAM in this region, by the expected demand, avoiding costly investments in the short term in new

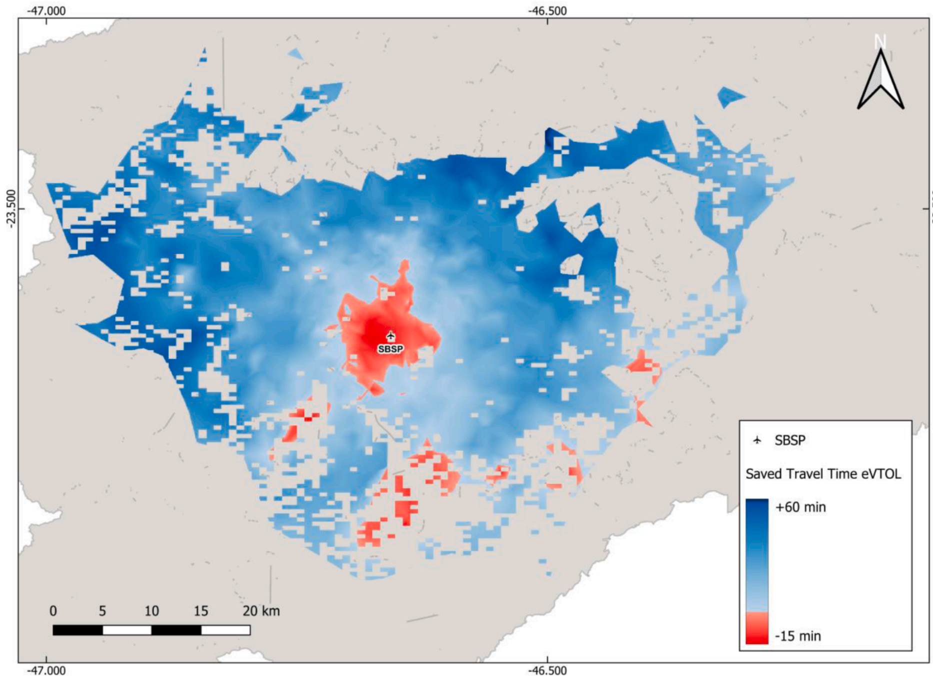

Fig. 8. Travel time saving.
Source: Research data.

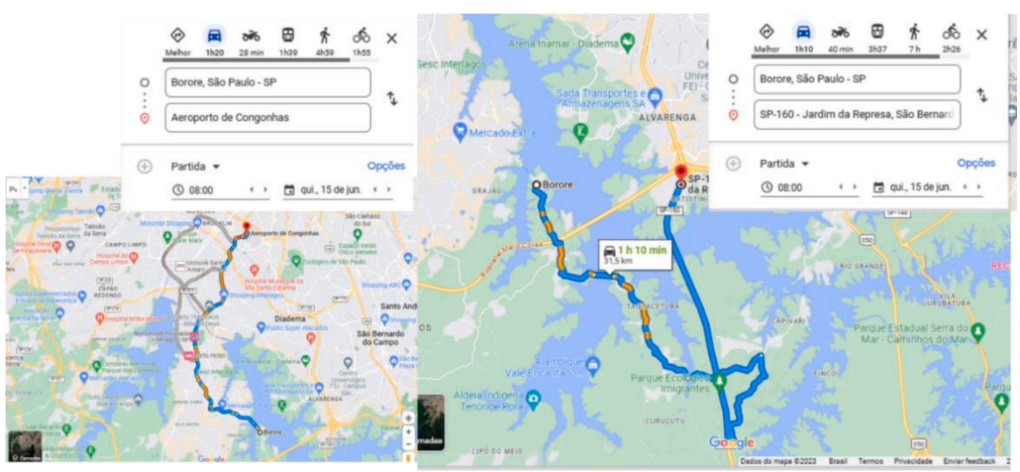

Fig. 9. The example case of Bororé area.
Source: Google Maps.

infrastructure specific to the UAM.

The methodology herein proposed and tested can be applied and extended in future research to cases of other big cities, where the companies intend to operate the UAM services. UAM represents a promising area of study, yet it faces challenges due to a lack of data in various domains, such as noise emissions, operational costs, ticket prices, traffic patterns, and others. Despite its innovative nature, UAM can benefit from established methodologies to assess potential compatibility issues and supply decision-makers with valuable insights when implementing this novel transportation service. To further extend the methods presented in this article, the following research possibilities are suggested:

- ➢ Determining the critical spatial density required to enable cost-effective and time-efficient on-demand aerial services. Drawing upon existing on-demand land services can serve as a useful starting point for this investigation;
- ➢ Further exploring integration strategies with existing transportation modes and infrastructure to streamline passenger processing in UAM operations;
- ➢ Investigating the potential impact of UAM on urban development by assessing how the ability to travel longer distances in shorter timeframes may contribute to intensified urban sprawl;
- ➢ Assessing time of the day effects on land and air transport, as well the effects of the pandemic on transport network performance.

By investigating these research opportunities, it is possible to enrich the understanding of UAM and lay the groundwork for its efficacious implementation in forthcoming urban environments.

Declaration of Competing Interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgments

Conselho Nacional de Desenvolvimento Científico e Tecnológico – CNPq (National Council for Scientific and Technological Development – CNPq), and special thanks to the Editor and anonymous Reviewers for their significant contributions to the improvement of the article.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104797.

References

ABRAPHE, Brazilian Association of Helicopter Pilots. Available at: https://abraphe.org.br/. [Acess in. June, 15, 2023].
ANAC, 2023. Agência Nacional de Aviação Civil (National Civil Aviation Agency). List of registered civil aerodromes [Lista de aeródromos civis cadastrados]. Available at: https://www.gov.br/anac/pt-br/assuntos/regulados/aerodromos/lista-de-aerodromos-civis-cadastrados. [Acess in. June, 15, 2023].
Bauranov, A., & Rakas, J. (2021). Designing airspace for urban air mobility: A review of concepts and approaches. *Progress in Aerospace Sciences, 125*, Article 100726.
Björkdahl, J., Fallahi, S., & Holmén, M. (2022). Explaining business model innovation processes: A problem formulation and problem-solving perspective. *Industrial Marketing Management, 105*, 223–239.
Bulusu, V., Onat, E. B., Sengupta, R., Yedavalli, P., & Macfarlane, J. (2021). A traffic demand analysis method for urban air mobility. *IEEE Transactions on Intelligent Transportation Systems, 22*, 6039–6047.
Charly, A., Thomas, N. J., Foley, A., & Caulfield, B. (2023). Identifying optimal locations for community electric vehicle charging. *Sustainable Cities and Society, 94*.
Christodoulou, A., & Christidis, P. (2021). Evaluating congestion in urban areas: The case of Seville. *Research in Transportation Business and Management, 39*, Article 101579.
EASA, 2021. European Union Aviation Safety Agency. [Online]. Available at: www.easa.europa.eu/light/topics/urban-air-mobility. [Acess in June, 1, 2022].
Fox, S. J. (2020). The 'risk' of disruptive technology today (A case study of aviation – Enter the drone). *Technology in Society, 62*, Article 101304, 2020.
Goyal, R., Reiche, C., Fernando, C., & Cohen, A. (2021). Advanced air mobility: Demand analysis and market potential of the airport shuttle and air taxi markets. *Sustainability, 13*, 7361.
Haan, J., Garrow, L. A., Marzuoli, A., Roy, S., & Bierlaire, M. (2021). Are commuter air taxis coming to your city? A ranking of 40 cities in the United States. *Transportation Research Part C: Emerging Technologies, 132*, Article 103209.
HDX, 2023. The Humanitarian Data Exchange. Brazil - Population Counts. [Online] Available at: https://data.humdata.org/dataset/worldpop-population-counts-for-brazil. [Acess in May, 5 2023].
Holden, J. & Goel, N., 2016. Fast-Forwarding to a Future of On-Demand Urban Air Transportation UBER Elevate. s.l.:s.n.
Infraero, 2022. Empresa Brasileira de Infraestrutura Aeroportuária. [Online] Available at: https://transparencia.infraero.gov.br/estatisticas/. [Acess in May, 5 2022].
Kang, J., Kong, H., Lin, Z., & Dang, A. (2022). Mapping the dynamics of electric vehicle charging demand within Beijing's spatial structure. *Sustainable Cities and Society, 76*.
Metrô, 2022. Pesquisa Origem-Destino 2017. Secretaria de Transportes Metropolitanos. [Online]. Available at: https://www.metro.sp.gov.br/pesquisa-od/. [Acess June, 3, 2022].
Miller, H. J., & Shaw, S. L. (2015). Geographic information systems for transportation in the 21st century. *Geography Compass, 9*, 180–189.
Moir, L., & Lohmann, G. (2018). A quantitative means of comparing competitive advantage among airlines with heterogeneous business models: Analysis of U.S. airlines. *Journal of Air Transport Management, 69*, 72–82.
Murça, M. C. R. (2021). Identification and prediction of urban airspace availability for emerging air mobility operations. *Transportation Research Part C: Emerging Technologies, 131*, Article 103150.
OpenRouteService, 2023. OpenRouteService. [Online] Available at: https://openrouteservice.org/. [Acess in June, 10, 2023].
Paliska, D., et al. (2016). Passengers' airport choice and airports' catchment area analysis in cross-border Upper Adriatic multi-airport region. *Journal of Air Transport Management, 57*, 143–154.
Papinski, D., & Scott, D. M. (2011). A GIS-based toolkit for route choice analysis. *Journal of Transport Geography, 19*, 434–442.
Pereira, B. A., & Caetano, M. (2015). A conceptual business model framework applied to air transport. *Journal of Air Transport Management, 44–45*, 70–76.
Ploetner, K., et al. (2020). Defining and categorizing shared mobility. *Transportation Research Part A: Policy and Practice, 140*, 367–390.
Postorino, M. N., & Sarné, G. M. L. (2020). Reinventing mobility paradigms: Flying car scenarios and challenges for urban mobility. *Sustainability, 12*.
Rajendran, S., & Zack, J. (2019). Insights on strategic air taxi network infrastructure locations using an iterative constrained clustering approach. *Transportation Research Part E: Logistics and Transportation Review, 128*, 470–505.
Robinson, J. N., Sokollek, M.-D. R., Justin, C. Y., & Mavris, D. N. (2018). Development of a methodology for parametric analysis of STOL Airpark Geo-Density. In *Atlanta, AIAA Aviation Forum*.
Rothfeld, R., Balac, M., Ploetner, K. O., & Antoniou, C. (2018). Agent-based simulation of urban air mobility. In *Atlanta, AIAA AVIATION Forum. Modeling and Simulation Technologies Conference*.
Roy, A., & Law, M. (2022). Examining spatial disparities in electric vehicle charging station placements using machine learning. *Sustainable Cities and Society, 83*, Article 103978.
Schweiger, K., Knabe, F., & Korn, B. (2022). An exemplary definition of a vertidrome's airside concept of operations. *Aerospace Science and Technology, 125*, Article 107144.
Straubinger, A., Michelmann, J., & Biehle, T. (2021). Business model options for passenger urban air mobility. *CEAS Aeronautical Journal, 12*, 361–380. April.
Straubinger, A., Verhoef, E. T., & de Groot, H. L. F. (2021). Will urban air mobility fly? The efficiency and distributional impacts of UAM in different urban spatial structures. *Transportation Research Part C: Emerging Technologies, 127*, Article 103124.
Sugar, L., & Kennedy, C. (2021). Urban Scaling and the Benefits of Living in Cities. *Sustainable Cities and Society, 66*, Article 102617.
Syed, N., Rye, M., Ade, M., Trani, A., Hinze, N., Swingle, H., Smith, J. C., Dollyhigh, S., & Marien, T. (2017). Preliminary considerations for ODM air traffic management based on analysis of commuter passenger demand and travel patterns for the silicon valley region of California. In *AIAA 2017-3082. 17th AIAA Aviation Technology, Integration, and Operations Conference*. June 2017.
Uber. (2019). *Uber Movement*. [Online]Available at https://movement.uber.com/ [Acess June, 10, 2023].
United Nations. (2018). *Revision of world urbanization prospects: 2018, s.l.* Department of Economic and Social Affairs.
Vasconcelos, D. M., & Kaminski, P. M. (2013). Development of a supplier and purchase order management product/service under the 4PL logistics concept: a case study. *Product, 11*(2), 125–135. https://doi.org/10.4322/pmd.2013.021. n.
Vieira, R. S., & Haddad, E. A. (2020). A weighted travel time index based on data from Uber Movement. *EPJ Data Science*, (9), 24. Volume.
Willey, L. C., & Salmon, J. L. (2021). A method for urban air mobility network design using hub location and subgraph isomorphism. *Transportation Research Part C: Emerging Technologies, 125*, Article 102997. Volume.