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Vertiport Ventures: Assessing Operational Feasibility for Evtol Integration in São Paulo's Helipad and Heliport Infrastructure

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CASE STUDY

Vertiport ventures: assessing operational feasibility for eVTOL integration in São Paulo's helipad and heliport infrastructure

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Abstract
This study investigates the feasibility of introducing Electric Vertical Take-Off and Landing (eVTOL) aircraft operations in São Paulo, Brazil, leveraging existing infrastructure and emerging eVTOL technology. With São Paulo being a major financial hub in Brazil, its bustling helicopter operations at numerous helipads make it a prime candidate for eVTOL integration. By analyzing data from the National Civil Aviation Agency (ANAC) and the Airspace Control Department (DECEA), we assess the city's helipad infrastructure and current helicopter operations, concluding that São Paulo possesses the operational capacity to support eVTOL operations, either by replacing helicopters or by supplementing existing flights. Additionally, we explore the environmental benefits of transitioning from traditional helicopters to electric aircraft, highlighting the potential for significant reductions in pollutant emissions and the lucrative market for carbon credits. Projections indicate that, under comparable flight conditions (6.5FH/Day), eVTOL operators could generate substantial revenue, such as €891,580 in the European Union compliance market over a 10-year period per vehicle. This research underscores the promising prospects and environmental advantages of adopting eVTOL technology in São Paulo's urban airspace.

Keywords eVTOL · Electric vertical take-off and landing · Advanced air mobility · São Paulo city · Helipads · Vertiport

Introduction

The objective of this study is to assess the operational viability of introducing Electric Vertical Take-Off and Landing (eVTOL) vehicles in São Paulo and its metropolitan area, utilizing existing helipads and helicopter infrastructure. eVTOL aircraft, capable of vertical take-off and landing like helicopters, differ from traditional helicopters in their propulsion systems, with eVTOLs typically featuring multiple smaller electric motor-driven propulsion units instead of internal combustion engines and mechanical transmissions (Schuchardt et al. 2023). The study specifically targets eVTOLs with the capacity to transport a minimum of four passengers and one pilot for distances of at least 50 km. Appendix provides definitions of key terms and a list of acronyms used throughout the document.

Project definition

The concept of Urban Air Mobility (UAM) within Advanced Air Mobility (AAM) involves using autonomous or piloted electric vehicles capable of Electric Vertical Take-Off and Landing (eVTOL) for passenger and cargo transportation. São Paulo City, with the world's largest helicopter fleet, has emerged as a vibrant market for vertical take-off and landing operations (Salim and Bosco 2020). Research corroborates this, revealing 400 registered helicopters in the city and 700 in the state, collectively making over 1,300 trips daily, surpassing figures from major cities like New York and Tokyo (Salim and Bosco 2020). São Paulo's notorious traffic congestion, epitomized by a record-setting 344-km

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traffic jam during rush hour in 2014, underscores the need for innovative solutions (Andrade et al. 2022). This study aims to address urban traffic issues in São Paulo by exploring efficient and environmentally friendly solutions through the introduction of eVTOL operations leveraging existing helipad and heliport infrastructure.

Problem statement

Is São Paulo City poised to become a major player in the burgeoning air taxi market, akin to Los Angeles? Industry giants like Embraer and Lilium are teaming up with community leaders to pave the way for Electric Vertical Take-off and Landing (eVTOL) aircraft. São Paulo, much like Los Angeles, is seen as an ideal testing ground for this potentially trillion-dollar industry by 2040 (Goyal et al. 2021). Initial air taxi routes may link Guarulhos and Congonhas airports with smaller facilities like Campo de Marte, potentially leading to the development of new vertiports. This study contributes significantly to the eVTOL market by analyzing existing heliport infrastructure in São Paulo and delineating possible routes. By evaluating eVTOL projects based on criteria such as passenger capacity, range, and funding, the study identifies five models suitable for operation in São Paulo. Additionally, the study compares eVTOL and helicopter services, considering factors like flight hours per year, to predict scenarios for eVTOL operations. The aim is to showcase the operational benefits of eVTOL and its potential to meet transportation demands in São Paulo, without necessarily replacing helicopters in the short term.

Goals and scope

The study focuses on identifying helipads and heliports in São Paulo City capable of supporting the operational specifications of selected eVTOL models. By calculating routes from each site, the researchers determine the percentage of routes feasible for each eVTOL based on technical specifications. Similar analyses are conducted for helicopters to provide a comparative assessment. Utilizing data from DECEA, the Brazilian Air Traffic Authority, the research team correlates existing infrastructure limitations with aircraft design. Additionally, the study compares the acquisition costs of eVTOLs and helicopters to assess their benefit–cost ratio, crucial for understanding future demand. Sustainability considerations are paramount, as eVTOLs offer reduced CO_2 emissions compared to conventional aircraft, potentially transforming urban transportation systems. The study aims to demonstrate the environmental benefits of eVTOL operations and their significance for public acceptance in São Paulo (Schuchardt et al. 2023).

Contributions expected

The eVTOL industry holds transformative potential in Urban Air Mobility (UAM), but its realization requires advancements in technology, regulations, and safety standards (Schuchardt et al. 2023). This study aims to showcase São Paulo's suitability for eVTOL integration, highlighting cost–benefit advantages over traditional helicopters and the environmental benefits of reducing CO_2 emissions. Rapid advancements in electric motors and battery design are expected to enhance safety and performance parameters, with near-term operating costs estimated to be significantly lower than helicopters (Howard et al. 2021). By leveraging ridesharing apps, eVTOLs can offer affordable transportation options, potentially revolutionizing urban mobility and facilitating societal needs like organ transport. Ultimately, this study seeks to provide data demonstrating the operational and economic feasibility of eVTOLs in São Paulo while contributing valuable insights to the global research community.

Overview of the literature

This case study investigates the potential introduction of Electric Vertical Take-Off and Landing (eVTOL) vehicles in São Paulo City, Brazil. The research draws upon concepts and insights from the emerging field of Advanced Air Mobility (AAM) to analyze the challenges and opportunities associated with this innovative transportation mode. São Paulo City was selected for its status as a global hub for helicopter operations, offering valuable insights into the feasibility of eVTOL integration in urban environments.

A new paradigm

The advent of eVTOL vehicles represents a significant shift in transportation, with the potential to revolutionize urban mobility. eVTOL technology relies on advancements in structures, electric engines, electronic controls, and autonomous navigation systems, bringing the dream of flying vehicles closer to reality (Schuchardt et al. 2023).

Advanced air mobility ecosystem

The AAM ecosystem comprises six key components, each playing a crucial role in the successful deployment of eVTOL vehicles:

1. Aircraft eVTOL Vehicles: In the eVTOL market, various proponents offer different models and architectures,

each tailored for specific applications. These include wingless multicopters, resembling oversized drones, and lift-plus-cruise models that use separate thrusters for vertical lift and cruise propulsion (Schuchardt et al. 2023). Additionally, vectored thrust models utilize the same thrusters for both lift and cruise, requiring adjustments to thruster orientation mid-flight (Schuchardt et al. 2023). Understanding these architectures is crucial as they vary in complexity and suitability for different use cases (Schuchardt et al. 2023).

2. Regulatory Environment: The timeline for commercial operations of eVTOL aircraft remains unclear, as regulations are yet to be established. However, manufacturers and airline operators have discussed commencing test operations between 2024 and 2025 (Vascik and Hansman 2021). Embraer has initiated the process of obtaining a type certificate for its eVTOL aircraft with the Civil Aviation Agency of Brazil (ANAC) (Agustinho and Bento 2022). Stakeholders emphasize the importance of ensuring safety, efficiency, and minimal noise impact in urban airspace (International Civil Aviation Organization 2016). Roberto Honorato, ANAC's airworthiness superintendent, underscores the significance of safety standards for eVTOL access to the global market (Johnson 2023).

   The Federal Aviation Administration (FAA) currently lacks a clear timeline for finalizing the eVTOL certification process. However, efforts are underway within the US government to accelerate this process. The US Air Force's Agility Prime program aims to establish a robust domestic market for eVTOL aircraft and promote zero-emissions aviation (Vertical Flight Society 2022).

3. Airspace Management: Agustinho and Bento (2022) highlight the formidable challenges associated with ensuring the safety and reliability of Electric Vertical Take-Off and Landing (eVTOL) operations, especially concerning airspace management in urban settings. As eVTOL technology progresses and autonomous capabilities become more widespread, the anticipated surge in eVTOLs operating in low airspace is expected to be significant. This increase in aircraft volume underscores the urgent need for automated traffic management systems capable of efficiently handling the influx of flights. In São Paulo City, where helicopter traffic is already substantial, integrating eVTOLs into the existing airspace presents unique challenges. The White Paper Flight Plan 2030 proposes an urban air traffic management solution aimed at facilitating the seamless integration of eVTOL flights into urban airspace. This solution prioritizes shared situational awareness among stakeholders, equitable airspace access, risk mitigation strategies, and adaptable airspace structures.

4. Infrastructure: Agustinho and Bento (2022) underscore the critical importance of low-altitude urban airspace management, as delineated in Flight Plan 2030, for the advancement of Urban Air Mobility (UAM). This comprehensive plan underscores the imperative for infrastructure development to support the burgeoning UAM industry, including the establishment of sky ports or vertiports. These pivotal facilities will serve as central hubs for eVTOL fleets, offering essential services such as battery swap or recharging and facilitating passenger transit. Fleet operators will assume a central role in overseeing eVTOL fleets and collaborating with sky port operators and booking platforms. The burgeoning UAM sector presents a plethora of opportunities for new businesses and job creation. While our study focuses on evaluating the operational feasibility of integrating eVTOL operations into São Paulo City using existing infrastructure to minimize investment requirements, future advancements may necessitate tailored infrastructure implementations to fully harness the benefits of eVTOL technology in urban landscapes.

5. Rise of the Vertiport: The Vertiport, as described by Andrade et al. (2022), is specialized infrastructure designed to optimize eVTOL operations and improve the overall customer experience. Andrade et al. (2022) envision the Vertiport primarily serving routes from airports to city destinations, utilizing existing rooftop landing spots in São Paulo and adaptable sites such as multi-level car park structures. As the network grows, it will gradually expand to connect multiple point-to-point locations, ultimately establishing a comprehensive city-wide transportation network (Andrade et al. 2022).

6. Public Acceptance: Advocates of Urban Air Mobility (UAM), such as Andrade et al. (2022), champion the democratization of aviation, envisioning electric aircraft as a cost-effective transportation alternative from downtown areas to local airports. For instance, a flight from Campo de Marte in northern São Paulo to Guarulhos International Airport could take merely 10 min, costing around 211 Reais ($63), with an additional 30 Reais ($9) for transportation from home to the helipad. Despite the seemingly higher cost compared to ground transportation, the time saved, especially during peak traffic hours, could render it a more appealing option. Nonetheless, the initial benefits of aviation urbanization are likely to be realized through package delivery services rather than passenger transportation. Additionally, eVTOL technology offers significant noise reduction benefits, addressing concerns that have previously led to the limitation of helicopter flights in urban areas (NASA).

The development and implementation of the Advanced Air Mobility (AAM) Ecosystem, encompassing Urban Air

Mobility (UAM), have been collaborative efforts between the private sector and local authorities worldwide. However, several challenges, including regulatory uncertainties, certification issues, and infrastructure limitations such as the availability of vertiports and helipads, have hindered the definitive establishment of the first eVTOL and AAM/UAM ecosystems (Vertical Flight Society, Sep 2022). Programs like the AFWERX Agility Prime in the USA aim to accelerate eVTOL testing phases by defining key milestones for 2023 (Vertical Flight Society, Sep 2022). Additionally, partnerships between aerospace leaders like Embraer and BAE Systems underscore the confidence in eVTOL technology's adaptability beyond urban air mobility, including potential defense applications (Bae Systems, Jul 2022).

Regulatory efforts are also underway in Europe, where the European Union Aviation Safety Agency (EASA) has published rules for eVTOL operation in urban areas, marking the first regulatory action for this mode of transport (EASA 2022). These regulations cover areas such as airworthiness, crew licensing, and air operations, with the goal of safely integrating certified aircraft into urban airspace.

The main challenge lies in developing an urban air traffic management (UATM) solution that enables eVTOL flights to become a mainstream mode of transportation (Agustinho and Bento 2022). This requires a paradigm shift in operational rules for low airspace, which will be shared by drones, regular and business aviation, helicopters, and eVTOLs. The Flight Plan 2030 serves as a market guide, outlining manufacturers' and stakeholders' plans for the effective implementation of the eVTOL operating ecosystem (Agustinho and Bento 2022).

Findings

The Federal Law 12527, enacted on November 18, 2011, governs access to government information in Brazil, allowing citizens to request information from the judicial, legislative, and executive branches at all levels of government. Access is generally granted, with restrictions possible under legal justification. The website FALA.BR (https://falabr.cgu.gov.br/) serves as a platform for requesting information controlled by the federal government, providing users with protocol numbers and response tracking.

This study focuses on the São Paulo metropolitan region, encompassing the city of São Paulo and 38 municipalities defined by State Law No. 1139 of June 16, 2011. These municipalities are divided into five geographical areas: North, East, Southeast, Southwest, and West, each comprising multiple cities.

Helipads

The Departamento de Controle de Espaço Aéreo (DECEA), a Brazilian Air Force agency, manages data on helipads, which are publicly accessible through the website https://aisweb.decea.mil.br/. In São Paulo State, there are 609 helipads, with 308 located in the metropolitan area. Distances between helipads were estimated using latitude and longitude differences, with calculations based on the coordinates of the Sé Cathedral in São Paulo. The combination formula determined that there are 47,278 possible routes between helipads in the metropolitan area. Distances for each route were calculated using a formula, and a Microsoft Excel Spreadsheet facilitated data processing. Figure 1 illustrated the distribution of possible routes at 5 km intervals, with 80% of routes below 28.5 km. Note that the calculated routes do not account for restricted airspace or established helicopter corridors in São Paulo City.

As an acceptable simplification, the routes calculated here do not avoid restricted airspace for Congonhas Airport (CGH) and do not follow the corridors established in São Paulo City for helicopters by DECEA.

Electric vertical take-off and landing (eVTOL)

This study examines Electric Vertical Take-Off and Landing (eVTOL) models meeting specific criteria, utilizing published data from open capital companies and technical specifications provided by manufacturers on their websites. A map of São Paulo City and the Metropolitan Area is employed to assess the operational feasibility of eVTOL operations. Table 1 presents specifications for various eVTOL models, including their range, dimensions, and weight. Additionally, the estimated acquisition costs (ECA) for each eVTOL model are provided.

Helicopters

Data on helicopters were sourced from the Brazilian Civil Aviation National Authority (ANAC) website in August 2022. Using ICAO Doc 8643 classifications, helicopters were filtered based on the CD_CLS column starting with "H" to select only helicopters. Additionally, aircraft with canceled registrations or reservation numbers were excluded. Further filtering was done based on operators registered in the state of São Paulo, resulting in 595 helicopters. City information was obtained from the Brazilian Government website, identifying 371 helicopters operated by companies in the Metropolitan Area (Figs. 2, 3).

With the data collected, among the 5 models with the largest presence in São Paulo, the Leonardo AW109 and Bell 429 were chosen as comparison cases for eVTOLs, meeting the criteria outlined in the problem statement.

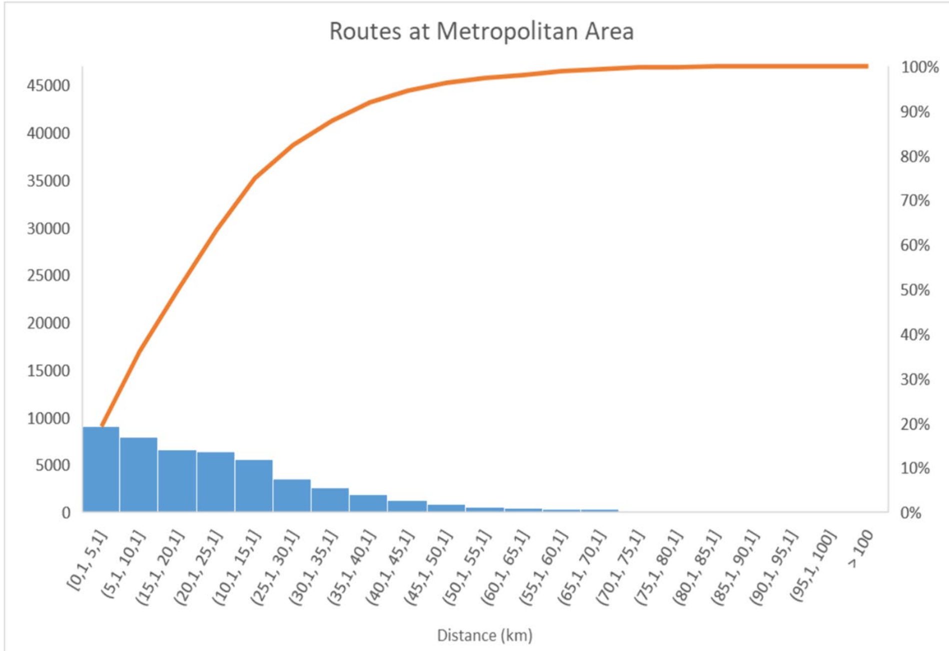

Fig. 1 Distribution of possible routes at metropolitan area at intervals of 5 km

Table 1 Specifications for eVTOL models, including range, dimensions, weight, and estimated cost of acquisition

Model	Range (nm)	Dimension (m)	Weight (tonnes)	ECA
JOBY S4	150	10.7	1815	$1.3M
Eve	60	15.2	1000	$3.3M
Archer	60	12.2	3175	$5.0M
VX4	161	15	3175	$4.0M
Lilium	155	13.9	3175	$4.5M

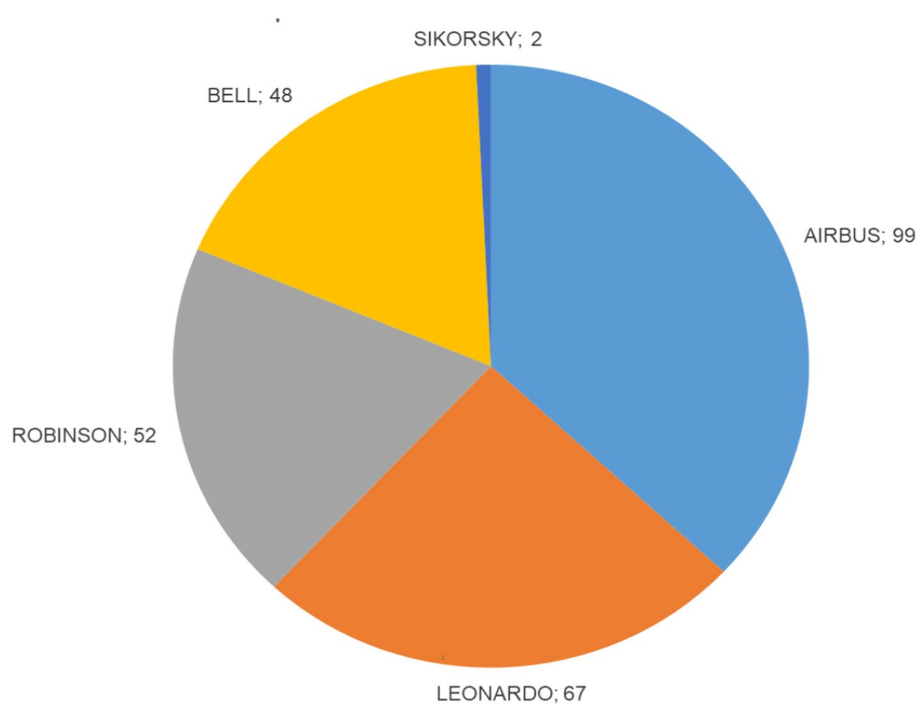

Fig. 2 Number of helicopters with a valid airworthiness certificate registered at São Paulo Metropolitan Area by manufacture

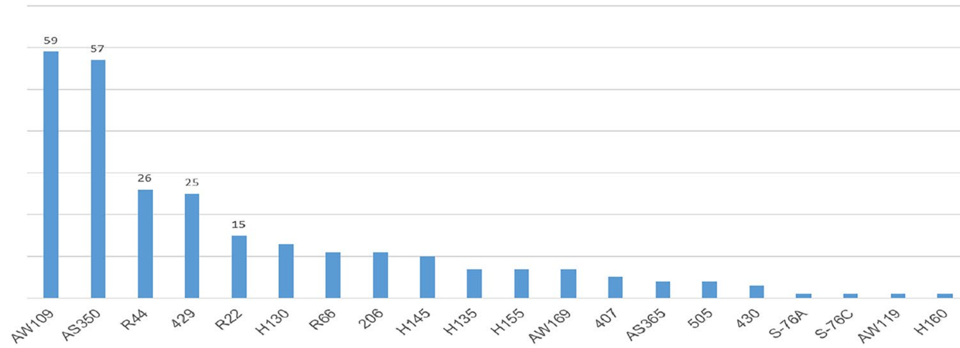

Fig. 3 Models of the helicopters with a valid airworthiness certificate registered at São Paulo Metropolitan Area

Table 2 Percentage of routes achievable for each vehicle

Helicopters		eVTOLs				
AW109	429	S4	Eve	Vx4	Lilium	Archer
97%	65%	99%	97%	65%	65%	64%

Table 3 Helipads able to be used by helicopter model

Helicopter	Helipads	%
429	249	80.8
AW109	303	98.4

Table 4 Helipads able to be used by eVTOL model

eVTOL	Helipads	%
Joby	307	99.7
Eve	306	99.4
Archer	249	80.8
VX4	249	80.8
Lilium	249	80.8

The center of São Paulo city sits at an elevation of 780 m above sea level (Topographic, n.d.), equivalent to 2560 ft. The average daily temperature in São Paulo is 22.5 °C (Climate, 2022). From the manufacturers' data, various graphs were examined to determine speed and fuel consumption, selecting the one that closely matched the altitude and temperature conditions of São Paulo. The recommended cruise speed was utilized, and when unavailable, the maximum endurance was chosen. The helicopter was considered at its maximum weight.

Table 5 Flight hour between years

Helicopter type	Interval of years			
	2018–2019	2019–2020	2020–2021	Average/year
H1P	21,557,62	13,834,08	10,621,2	15,338
H1T	25,456,01	22,885,99	21,386,17	23,243
H2T	17,207,54	17,232,54	18,811,61	17,751

Comparison between eVTOLs and helicopters

To utilize any of the 47,278 possible routes, a vehicle must possess a range equal to or greater than the distance between the two helipads. In this study, the range for helicopters was considered half of their actual range. Conversely, for eVTOLs, the entire range was considered, considering it will be easier to recharge an electric vehicle than a liquid-fueled one. However, this assumption may change with more information on the subject.

In addition to range considerations, the weight of the vehicle must not exceed the maximum weight limit of either helipad. Furthermore, the larger dimension of the vehicle cannot exceed the smaller dimension of either of the two helipads, as per RBAC 155, 2018 regulations (Table 2).

Another aspect of comparison is the total number of helipads that each helicopter or eVTOL can operate, as illustrated in Tables 3 and 4.

Helicopter flight hours

For the estimates of helicopter flying hours in São Paulo, we relied on the Airworthiness Verification, which is a mandatory annual task for all helicopters registered in Brazil. Failure to perform this task results in the automatic loss of airworthiness status (RBAC 91, 2021).

When the helicopter operator or the responsible workshop performs this check, they are required to fill out an online registration on the website of the National Agency of Civil Aviation (ANAC).

Table 6 Helicopter fuel burned in São Paulo last 3 years

Helicopter type	Average flight (hours/year)	Fuel consumption (kg/h)	Fuel (tonnes)
H1P	15,338	36 (1)	552
H1T	23,243	126 (2)	2929
H2T	17,751	172 (3)	3053

FALA.BR was utilized to officially request the hours registered in the years 2018, 2019, 2020, 2021, and 2022 for all helicopters registered in the city of São Paulo. This information can be found in Annex 2. After organizing the data, the values in Tables 5 and 6 were obtained.

Table 7 CO_2 emission yearly by helicopter in São Paulo last 3 years

Helicopter type	Fuel (tonnes)	FCFf	CO_2 emissions (tonnes)
H1P	552	3.16	1744
H1T	2929	3.16	9256
H2T	3053	3.16	9647
		Total CO_2 emissions per year (tonnes)	20,647

Carbon emissions

To calculate the potential carbon emissions that can be avoided through eVTOL operations, it was necessary to compute the amount of fuel burned by an equivalent helicopter compared to the selected eVTOL model for this study. This calculation was performed using the same leg distance with standardized load and number of passengers.

The equation for calculating CO_2 emissions was designed following the standards outlined in IATA RECOMMENDED PRACTICE—RP 1726, which provides the methodology for developing a Carbon Emissions Calculator (Table 7).

Carbon credit

As established by CORSA and adopted in the carbon marketplace, 1 CO_2 tonne is equivalent to 1 Carbon Credit. Considering the main environmental benefit of eVTOL operations as "ZERO" CO_2 emissions, it can be assumed that companies operating eVTOLs will be able to generate Carbon Credits. As per the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), global regulations regarding neutralizing emissions impose obligations on companies to create carbon offsetting programs.

CarbonCredits.com Live Carbon Prices	Last	Change	YTD
Compliance Markets			
European Union	€66.25	+3.05 %	−17.41 %
California	$26.85	-	−16.15 %
Australia (AUD)	$30.75	-	−39.71 %
New Zealand (NZD)	$78.00	−0.64 %	+13.95 %
South Korea	$19.09	+10.00 %	−15.90 %
China	$8.08	−0.86 %	+6.05 %
Voluntary Markets			
Aviation Industry Offset	$3.96	-	−50.50 %
Nature Based Offset	$8.18	−1.09 %	−41.90 %
Tech Based Offset	$1.96	-	−61.42 %

Fig. 4 Carbon credit value by market (Source: carboncredit.com)

Table 8 Possible carbon credit value generated by replacing helicopter for eVTOL in São Paulo

Market		Fuel (tonnes)	Price	Value
Compliance	European Union	20,647	66.25	€ 1,367,864
Compliance	Australia	20,647	30.75	US$ 634,895
Coluntary	Aviation Industry Offset	20,647	3.96	US$ 81,762

Consequently, carbon markets transform CO_2 emissions into a commodity, assigning them a price. Currently, this industry presents significant opportunities for companies to save or earn money.

Using historical flight hours data collected from DECEA related to helicopters operating in São Paulo City, and applying a simplified equation, it was possible to determine the amount of fuel burned by helicopters on routes between helipads and heliports defined in this study. Additionally, with these data, a hypothetical scenario was created to predict the equivalent CO_2 emissions that could potentially be avoided by using eVTOLs instead of helicopters in the São Paulo atmosphere. Once the number of flight hours to be operated by eVTOLs in place of helicopters is defined, the number of fuels burned to be avoided can be determined by applying the equation $CO_2 = \Sigma \text{ Mf} * \text{FCFf}$, yielding the total CO_2 emissions avoided.

According to information available on specialized websites like carboncredits.com, carbon credits can be sold in the carbon marketplace through two primary channels:

1. Regulated Market: Governed by "cap-and-trade" regulations at regional and state levels. This market operates within legal frameworks set by authorities, where companies are required to meet emissions reduction targets or purchase credits to offset excess emissions.

2. Voluntary Market: In this market, businesses and individuals purchase carbon credits voluntarily to offset their carbon emissions. Unlike the regulated market, participation in the voluntary market is not mandated by law but is driven by environmental consciousness and corporate social responsibility initiatives (Fig. 4; Table 8).

Concluding remarks

This chapter focuses on presenting four key conclusions from our research on eVTOL operations in São Paulo City. Each conclusion provides an analysis of literature, data collection methods, and findings regarding the operational feasibility of eVTOLs, along with other identified benefits. A significant outcome of this study relates to sustainability, particularly CO_2 emission reductions and potential financial gains through carbon credit generation. The utilization of eVTOLs aligns with global commitments, such as those outlined in the Paris Agreement, offering substantial opportunities for transformation. The results also indicate that implementing eVTOLs in São Paulo can contribute to the country's CO_2 emission reduction goals and provide financial benefits through carbon credit generation.

Given the commitment made by 195 countries during COP 21 on December 12, 2015, at the Paris Agreement, aimed at reducing greenhouse gas emissions, the utilization of eVTOL presents a significant opportunity to contribute to this global transformation. In line with this, the primary goals set by the Brazilian government within this agreement include reducing greenhouse gas emissions by 37% by 2025 compared to 2005 levels, and by 43% by 2030.

The key conclusions are as follows:

1. **The current infrastructure of helipads and heliports supports eVTOL operations:**

Data Gathering: Information on helipads was sourced from https://aisweb.decea.mil.br, and helicopter data were obtained from ANAC's website.

Results: The analysis revealed that São Paulo City has 371 registered helicopters, with 268 in airworthy condition. Additionally, there are 308 helipads capable of supporting eVTOL operational specifications, providing a scenario with 47,278 possible routes between them.

Conclusion: The current infrastructure supports eVTOL operations, with the technical analysis indicating coverage of 64% to 99% of routes currently operated by helicopters.

2. **Financial results related to carbon credit generated by eVTOL operations:**

Data Gathering: Flight hour data for helicopters were requested from ANAC via the FALA.BR portal, and carbon credit values were sourced from carboncredits.com.

Results: Helicopters burned 19,602 tonnes of fuel over 3 years, emitting 61,942 tonnes of CO_2. By switching to eVTOLs, significant carbon credit values could be generated annually and over a 10-year period, ranging from €1,367,884 (European Union – Compliance Market), $6,842,093 (Australia – Compliance Market), and $81,763 (Aviation Industry Offset – Voluntary Market).

In a conservative 10-year scenario, with an estimated eVTOL fleet of approximately 431 vehicles and an average daily flight time of 6.5 h, the potential carbon credit generation is as follows:

- €114.466.828 in the European Union compliance market
- $53.129.886 in the Australian compliance market
- $6.842.093 in the Aviation Industry Offset voluntary market.

Conclusion: There is a substantial opportunity for future eVTOL operators to generate revenue through carbon credit sales, aligning with sustainability goals.

3. **Relationship between helicopter and equivalent eVTOL (cost–benefit analysis):**

Data Gathering: Literature analysis and manufacturer information were used.

Results: Comparing the purchase prices of vehicles capable of similar flight missions, AW109 and Bell 429 helicopters are priced between 354 and 427% higher than the eVTOL JOB S4, and 31% to 52% higher than the Lilium eVTOL, which is most similar in performance and passenger capacity. In terms of carbon credit generation over a 10-year period with an average daily flight time of 6.5 h, an eVTOL operator can expect to generate approximately:

- €891,580 in the European Union compliance market
- $413,828 in the Australian compliance market
- $53,293 in the Aviation Industry Offset voluntary market.

The analysis demonstrates that the eVTOL JOBY S4 could generate up to 67% of its purchase price in carbon credits in the European Union compliance market over the 10-year period, with other eVTOL models ranging from 13 to 30%. This indicates a significant potential for return on investment through carbon credit generation, considering the higher purchase prices of helicopters compared to similar eVTOLs and the anticipated lower operating and maintenance costs of eVTOLs.

Conclusion: Based on our calculations and analysis, the eVTOL was determined to have superior cost–benefit characteristics, costing up to 77% less than an equivalent helicopter. Additionally, there is potential for a return on investment through carbon credits, estimated at around 67% for the JOBY S4 model.

4. **eVTOL utilization for traffic congestion alleviation in São Paulo City:**

Data Gathering: Passenger transit data from Congonhas Airport, car CO_2 emissions data, and Brazilian GDP historical data were utilized.

Results: eVTOL operations could potentially reduce up to 8.6% of total cars in São Paulo City traffic, equivalent to 559,075 fewer cars annually and 5,665,120 fewer cars over 10 years. This could result in a significant reduction in CO_2 emissions, reaching 5,179,622 tonnes annually and 52,266,079 tonnes over 10 years.

Conclusion: Introducing eVTOL operations in São Paulo City could alleviate traffic congestion by reducing the number of cars on the streets by 8.6%. This would also serve as a sustainability initiative, leading to significant environmental benefits by avoiding approximately 52,266,079 tonnes of CO_2 emissions over a 10-year period.

These conclusions underscore the potential of eVTOLs to not only revolutionize transportation but also contribute significantly to sustainability efforts and financial gains in São Paulo City and beyond.

Teaching ideas

To enhance understanding and engagement with the case study on eVTOL operations in São Paulo City, educators can employ various teaching strategies that encourage critical thinking, problem-solving, and interdisciplinary learning. Below are several teaching ideas designed to deepen students' comprehension of the case study while fostering discussion, analysis, and creativity.

1. Case Study Analysis: Divide students into small groups and assign each group a specific aspect of the case study to analyze in depth, such as the operational feasibility of eVTOLs, environmental impact assessment, regulatory challenges, or financial implications. Have each group present their findings to the class and facilitate a discussion on the strengths, weaknesses, and implications of each aspect.
2. Policy Proposal: Challenge students to develop a policy proposal outlining the regulatory framework and guidelines for the introduction of eVTOL operations in São Paulo City. Students can research existing policies and regulations related to aviation and urban transportation, as well as consider the specific needs and challenges of São Paulo. Encourage students to think critically about the potential implications of their policy proposal and present their recommendations to relevant stakeholders.
3. Debate or Panel Discussion: Divide students into groups representing different stakeholders, such as government officials, urban planners, environmentalists, transportation experts, and citizens. Assign each group a specific perspective to research and present in a debate or panel discussion format. Topics for discussion could include the feasibility of eVTOL operations, environmental impact, regulatory considerations, and public acceptance.

Discussion questions

These discussion questions are prompts designed to stimulate conversation and critical thinking among students or participants about the case study on eVTOL operations in São Paulo City. They cover various aspects of the topic, including the potential benefits and challenges of eVTOL technology, its environmental impact, regulatory considerations, public acceptance, urban planning implications, financial aspects, and avenues for future research. The questions aim to engage participants in analyzing, synthesizing, and discussing the information presented in the case study, as well as encouraging them to think critically about the broader implications of eVTOL technology in urban transportation systems.

1. What are the potential advantages and challenges of integrating eVTOL operations into urban transportation systems like São Paulo City?
2. How do you think eVTOL technology can contribute to reducing carbon emissions and addressing environmental concerns in densely populated areas?
3. What role do you see government regulations playing in the widespread adoption of eVTOL technology, particularly in cities with complex airspace and infrastructure like São Paulo?
4. How might the introduction of eVTOL operations impact existing transportation networks, including public transit and traditional aviation services?
5. What considerations should be made in terms of public acceptance and perception of eVTOL vehicles, especially in crowded urban environments like São Paulo?
6. How could eVTOL technology potentially change the dynamics of urban planning and development in cities like São Paulo?
7. What implications does the cost–benefit analysis presented in the case study have for potential investors and operators in the eVTOL industry?

8. What are some potential future research directions to further explore the feasibility and impacts of eVTOL operations in São Paulo City and other metropolitan areas?

Recommendations, future research, and lessons learned

This study examined helipad data and registered helicopters in São Paulo and its metropolitan area, concluding that the existing infrastructure is suitable for accommodating the operational requirements of the analyzed eVTOLs. Based on our findings, we propose several recommendations for future research to facilitate the successful implementation of eVTOL operations in the region.

Recommendations

Recommendation 1

We advise potential investors and aviation industry operators, including companies like UBER, to collaborate with Brazilian authorities and manufacturers to discuss necessary adaptations to the 308 helipads and heliports analyzed in this study. Guidance from the FAA ENGINEERING BRIEF #105 issued on September 21, 2022, can serve as a reference for these discussions.

Recommendation 2

We recommend that potential operators and major Brazilian Airlines conduct thorough analyses of return on investment, develop business plans, and consider the predicted demand for eVTOL operations in São Paulo City (post-2025). Additionally, emphasis should be placed on leveraging potential carbon credit generation through CO_2 emissions reduction.

Recommendation 3

Given the need for infrastructure adaptations at existing helipads, it is imperative to prioritize locations for charging stations based on the 308 helipads identified in this study.

Recommendation 4

Recognizing the potential benefits of eVTOL operations in alleviating traffic congestion and reducing CO_2 emissions, we suggest that the state government collaborates with potential eVTOL operators to establish joint working groups between the public and private sectors. These groups can work together to define the future needs and requirements for implementing eVTOL operations in São Paulo.

Future research

Infrastructure adaptation driven by future regulations: Analyzing the changes needed in helipads for charging and electric infrastructure, as well as marking, lighting, and visual aids, to comply with future regulations for eVTOLs.

Impacts for São Paulo city related to electrical consumption: Studying the projected increase in electrical consumption due to eVTOL operations and its impact on the city's energy matrix.

Public acceptance: Investigating the level of public acceptance of eVTOL transportation in Brazil, considering potential concerns about noise and safety.

Complementary infrastructure necessary: Analyzing the need for additional parking areas, heliports, helipads, and skyports to support the eVTOL system and avoid bottlenecks.

Accurate cost analysis assumptions: Predicting future maintenance costs, certification expenses, and infrastructure adaptation costs to generate accurate fare predictions and investment payback calculations.

Adaptation needs on existing rules for airspace: Examining efforts by government, aeronautic authorities, and the industry to address airspace management rules to facilitate the implementation of eVTOLs.

Lessons learned

Data collection: The comprehensive data collected on helipads and helicopters in São Paulo's metropolitan region can be valuable for future research endeavors.

eVTOL benefits: Recognizing the importance of eVTOLs in providing sustainable transportation solutions and potentially alleviating traffic congestion in urban areas.

Revenue generation: Understanding the potential for revenue generation through carbon credits for companies involved in eVTOL operations.

Appendix: definitions of terms and list of acronyms

Definitions of terms

ANAC—The Agency is responsible for the regulation, inspection and certification of aircraft, companies, manufacturers, aircraft maintenance organizations, aerodromes, schools, and civil aviation professionals. The government agency works to ensure civil aviation safety and security and to improve the quality of services, fostering a competitive market.

DECEA—The Department of Airspace Control (DECEA) is responsible for the management of all the activities related to the safety and efficiency of the Brazilian airspace control. Its mission is to manage and control the air traffic in the Brazilian sovereign airspace as well as to guarantee its defense.

EASA—Agency of the European Union with primary responsibility for Civil Aviation Safety carries out certification, regulation, and standardization and performs investigation and monitoring.

FAA—The Federal Aviation Administration (FAA) - The FAA is a United States government agency responsible for regulating and overseeing all aspects of civil aviation. This includes issuing and enforcing regulations for manufacturing, operating, and maintaining aircraft, certifying airmen and airports that serve air carriers, conducting research to improve aviation safety, and developing systems and procedures for air navigation and air traffic control to ensure a safe and efficient aviation system.

List of acronyms

AAM—Advanced Air Mobility
ANAC—Agência Nacional de Aviação Civil
DECEA—Departamento de Controle do Espaço Aéreo
EASA—European Union Aviation Safety Agency
ECTOL—Electric Conventional Take-Off and Landing
ESTOL—Electric Short Take-Off and Landing
eVTOL—Electric Vertical Take-Off and Landing
FAA—Federal Aviation Administration
GAMA—General Aviation Manufacturers Association
SAE—International Society of Automotive Engineers
UAM—Urban Air Mobility
VFS—Vertical Flight Society

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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