

# Impacts of airport closure due to weather conditions on flight delay and CO<sub>2</sub> emission costs

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**ABSTRACT:** *The costs of congestion or delay for airlines and passengers directly impact the means necessary for the resilience of operations and arrival at the destination. They also directly affect the emission of polluting gases caused by aircraft in the terminal control area where the airport is located. Climate predictions show a trend of worsening weather conditions favorable to air operations. This article aims to develop a method for identifying operational bottlenecks and calculating the time aircraft spend in a specific airspace control area during adverse weather conditions. For this purpose, data collected through the ADS-B system and airspace division published on navigation charts will be used. In addition, the article includes a bibliometric study to identify the most used keywords in the literature review. Finally, an analysis of additional CO<sub>2</sub> emissions caused by operational delays will be performed. In the case of the terminal area of Viracopos Airport in Campinas/SP, the results show that the waiting time resulted in 52 minutes more time that the aircraft remained in the airspace or 9.27 tons of additional CO<sub>2</sub> emitted due to flight delays and cancellations.*

**KEYWORDS:** Air Traffic Control. ADS-B. Operational Efficiency. Flight Delay. Emissions.

**RESUMO:** *Este artigo aborda os impactos do congestionamento e atrasos em voos comerciais, tanto para as empresas aéreas quanto para os passageiros. Além disso, destaca a relação direta entre esses custos e as emissões de gases poluentes causados pelas aeronaves na área de controle terminal em que o aeroporto está localizado. Com o objetivo de identificar gargalos operacionais e calcular o tempo de permanência das aeronaves durante condições meteorológicas adversas, o artigo propõe um método que utiliza dados coletados por meio do sistema ADS-B e cartas de navegação. O estudo também inclui uma análise bibliométrica para identificar as palavras-chave mais utilizadas na revisão bibliográfica do estudo. Por fim, é feita uma análise da emissão adicional de CO<sub>2</sub> causada pelos atrasos operacionais. Como exemplo, o estudo analisa a área terminal do Aeroporto de Viracopos em Campinas/SP e mostra que o tempo de espera resultou em 52 minutos a mais no tempo em que as aeronaves permaneceram no espaço aéreo ou 9,27 toneladas de CO<sub>2</sub> a mais emitido devido ao atraso e cancelamento dos voos. O método proposto pode ser utilizado para identificar áreas que requerem atenção para garantir a segurança e a eficiência do tráfego aéreo, especialmente em condições meteorológicas adversas.*

**PALAVRAS-CHAVE:** Controle do Espaço Aéreo. ADS-B. Eficiência Operacional. Atrasos de Voos. Emissões.

## 1. Introduction

On an airway, capacity is restricted when there is an increase in traffic density. Scarpel and Pelicioni [1] state that, across the globe, the increase in aircraft movement is reaching airports' demand absorption capacity. Even after the covid-19 pandemic, the International Air Transport Association (IATA) [34] expects that by the end of 2023 the global movement of aircraft will have reached 103% of traffic compared to 2019. And the situation of operational capacity worsens when there are restrictions due to weather conditions, which is a trend for this decade, according to Lui *et al.* [22].

The cost of this congestion or delay for airlines and passengers directly affects the means necessary for the resilience of operations and arrival at destination [1].

The Air Force Command Instruction (ICA) 100-12 Rules of the Air defines a Terminal Control Area (TMA) as a Controlled Airspace in which, within its dimension, the Air Traffic Service (ATS) of approach and arrival is provided for aircraft in the vicinity of one or more aerodromes [30]. In Brazil, this is managed by the Department of Airspace Control (DECEA), an agency linked to the Air Force Command and the Ministry of Defense. The difficulty of controlling a TMA is that aircraft are flying low, with low speeds, close to each other, performing different types of procedures and on different routes, which causes an increase in the workload of the flight controller and in the pilots' attention. Finally, when there is bad weather or other event of operational disruption at the aerodrome(s) of the TMA immediacy [25], this means

the aircraft will be receiving air traffic control for a longer period, being in the so-called waiting procedure or reducing the speed, thus increasing several operational costs, one of them being the emission of polluting gases.

There are several studies related to performance optimization of the Brazilian Airspace Control System (SISCEAB), as well as of other countries, aimed at developing more direct routes and at sector demand (capacity), concerning care to avoid residential areas that increase noise pollution, predictability, training, technical infrastructure, operational safety, and cost-benefit ([3], [4], [1], [4], [6], [10], [11], [14], [16], [18], [19], [28], [29]). Air Traffic Control is, therefore, a widely debated topic, mainly due to a set of rules and circumstances that further increase the complexity of air transport, and that worsen when they encounter conditions not controlled by man, such as meteorological conditions.

On the other hand, there is still a difficulty in obtaining data, and in the quality of data offered on aircraft movement. Airlines interested in optimizing their operational network and, consequently, in reducing costs, invest in *Flight Operational Quality Assurance* (FOQA), generally applied within the engineering sector, which covers a set of monitoring, analysis, and simulation methods with data obtained from *Flight Data Recorders* (FDR) ([40], [41]). However, the data obtained are mostly used to forecast maintenance and operational safety expenses, and are not shared since such information could be used by other companies in statistical modeling to obtain advantages over the pricing of their airline tickets [41]. Specifically, the Makron Platao® software from Atech®, one of the companies of Embraer™ Group, responsible for supplying the systems that serve the Brazilian Airspace Control, can simulate several scenarios for training purposes, but not to identify from a real scenario the time of delays and other statistical information. In addition, data obtained by the Sagitario® air traffic control system are not available, serving for tactical use and reporting to verify the congestion capacity and post-operational saturation of the Air Navigation Management Center (CGNA) [42]. The National Civil

Aviation Agency (ANAC) provides information on the percentage of flight delay and cancellation, based on the scheduled flight start time, actual flight start time, scheduled landing time, and actual landing time [35], without information on the route, at what time of the flight there was an operational delay and aircraft performance.

Publicly available is the capture of flight data (*timestamp*, UTC time, *callsign*, position, altitude, speed, and direction) that are transmitted through devices of an *Automatic Dependent Surveillance-Broadcast* (ADS-B) system coupled to commercial aircraft and a few general aviation aircraft. These data can be obtained by self-developed receivers or through companies that market this information, such as FlightRadar24™ and FlightAware™.

Given this, there is an opportunity to develop a method for verifying operational bottlenecks and the length of stay of aircraft in a given airspace control area, using data obtained through ADS-B and the division of airspace published in navigation charts, when there are bad weather conditions, which is the objective of this article. In addition, a bibliometric study is presented through a simultaneous occurrence analysis, to verify which are the most used keywords and their relationships in the literature review for this study. Finally, it will also be analyzed what is the additional CO<sub>2</sub> emission caused due to operational delays. Pejovic *et al.* [10], in their study on London Heathrow Airport, also attest to the lack of weather closure information from the aerodrome or the English regulatory agency.

The study will be applied in the terminal area of Viracopos Airport, in Campinas/SP, which is the fourth airport in Brazil with the highest number of landings and takeoffs, as it is a relief and alternative airport in Congonhas, Guarulhos, and Belo Horizonte. In addition, in the last 5 years (2017-2022) flights from destinations to SBKP averaged 5,000 flights per month, and with an average of delays of more than 30 minutes of 6.05%, delays of more than 60 minutes of 2.52%, and average cancellations of 3.23% [35].

Finally, the congestion of the Airspace, whether due to weather conditions or any other reason, also

implies the cost of defense that will require investment in personnel and modernization of procedures and materials for the re-balancing of the sector, as happened in the event that became known as the 2006 Air Blackout [39].

## 2. Bibliographic review

### 2.1 Bibliometric review

According to Carvalho *et al.* [16], flight delays return significant economic problems to society, hence the frequency of this theme in the scientific literature on air transport and the need to carry out a systematic review on the subject.

From the term *weather conditions affect airports operation* on the ScienceDirect® database, 5,377 results related to research articles were found, of which 400 were analyzed for this literature review. Of these, through an empirical analysis of the authors, 28 ([1], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29]) are correlated to the objective of this research. A bibliometric review was carried out, with analysis of co-occurrences, using VOSviewer®. This software allows for the visualization of relationships of the keywords in these publications, so

that this bibliographic review could be guided by the use of these results in the research.

For Marques *et al.* [2], concurrency analysis is a quantitative method of cataloging keywords based on graph theory, with a set of objects that are repeated in different sources.

With this software, two visualizations were extracted and 79 relationships between keywords were generated, in 6 sets. Figure 1 shows the result of this analysis with the network visualization.

In set 1 are the keywords *airport*, *aircraft engines*, *air pollutants*, *aviation emissions*, and *air quality*, in which the word that is most repeated in 'with' searches is *airport*; therefore, this word is the most common among these keywords, as well as among all keywords of the bibliographic reference. In set 2, the most repeated keyword is *climate change*, which is related to the words: *airport closure*, *London Heathrow*, *weather delay*, *sustainable development*, and *disaster risk*. In set 3, *resilience* appears as the most repeated and is related to *severe weather event*, *aviation*, *modal substitution*, and *delay*. In set 4, the word that occurs the most is *risk assessment*, related to *urban clusters*, *China*, *location selection*, and *environmental risks*. In set 5, the word *efficiency* appears together with *performance*, *seaport*, *privatization*, and *developing countries*. Finally, in set 6 is *disruptive weather*, with the keywords *sea-level rise* and *adaptation*.

Figure 1 - Results of keyword occurrences.

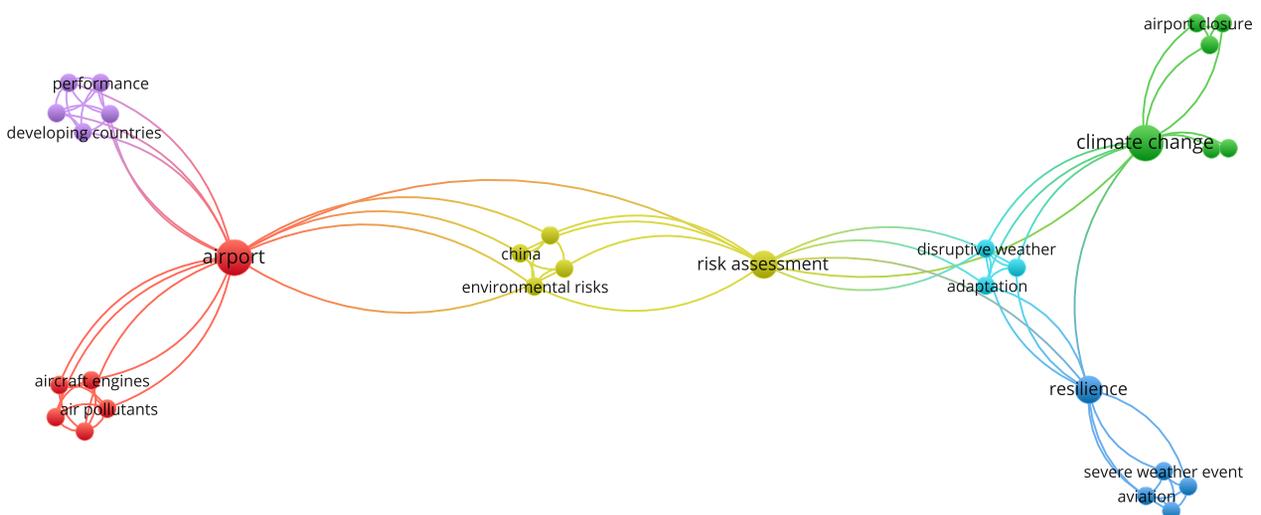


Figure 2 shows the results of occurrence visualization by overlap, in which keywords are shown according to the year they were found in publications. This shows that words related to weather, air quality, and resilience are more recent.

Carvalho *et al* [16] conducted a systematic review on the relevance of flight delay research, identifying the main methods used among 123 articles. It was found that, between 2001 and 2013, the use of descriptive statistics and regression models was more applied. From 2013 to 2017, network analysis methods began to be applied. And from 2017 to 2019, more studies using machine learning were identified. These authors conclude that there is a trend towards the evolution of hybrid models for prescriptive and predictive analysis of air transport.

## 2.2 Operational effects during adverse weather conditions

Airport congestion is caused by poor weather conditions, lack of airport infrastructure capacity, increased demand for air transport, and time lost waiting between landing and takeoff procedures [1] [4] [16] [10].

A good practice of the agency that provides air traffic service is to make a daily analysis of the forecast of weather conditions and air traffic movement. This practice is called *Early Warming Model* (EWM) in the literature [1] [17] [18]. In Brazil, such practice is part of the Air Traffic Flow Management, provided by the Air Navigation Management Center (CGNA) of the Airspace Control Department (DECEA) [31]. The EWM consists of a regression analysis that projects the number of daily movements so that measures are taken, such as the number of personnel employed in air traffic control and airports, and the flight crew schedule at airports where the weather will be bad and those that can receive flights as an alternative.

Postorino *et al* [4] used discrete event simulation models, based on the AnyLogic™ *software*, to estimate unexpected events, in magnitude and duration, that affect the operations of an airport, evaluating the dynamics of each process and its impact within the transport system, which is dynamic and stochastic.

The authors describe the dynamics of air transport in two layers. The first would be an isolated activity, with a certain performance; whereas the second would be the *output* of the first layer, connecting the whole system and showing how a propagation of efficient and inefficient activities are part of the results which, in themselves, represent the system.

As a case study, the authors used the airport in Bologna, Italy. With a capacity of 24 movements per hour, open 24 hours, this airport receives an average of 107 landings and 109 departures per day.

The study considered the arrival and departure of 20 flights per hour, taking actual data from FlightRadar24™, and considered the airport's capacity in relation to the number of stairs; catering, water, cleaning, fuel, and luggage transport trucks, and pushback tractors, so to discover the number of flights that would be delayed, the total and average delay for takeoff, and the variation in time between arrival and departure of the aircraft at the airport. As a result of 20 rounds of random simulation, the authors found that, with the different disruption events, 50% of flights would depart with a delay, 11.5% would depart with more than 1.5 hours of delay, and one aircraft would depart with more than 4 hours of delay. The authors suggest that new studies can estimate the environmental impact of CO<sub>2</sub> and noise emissions, and how this impact would be felt by different stakeholders.

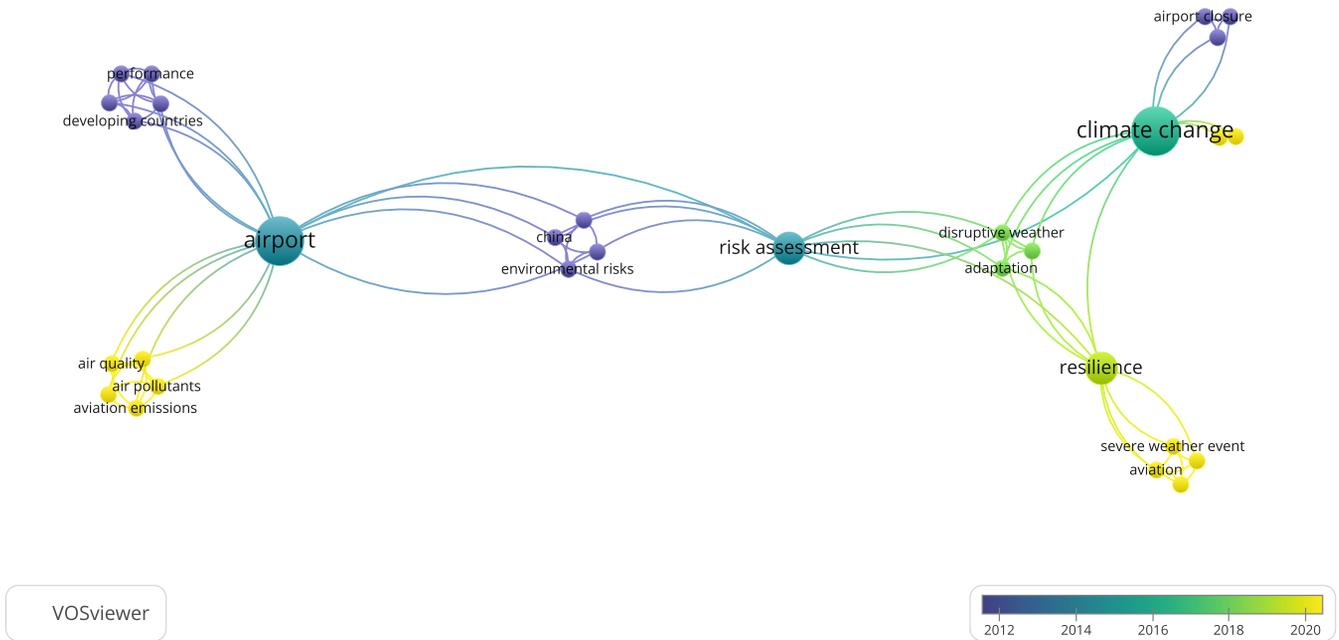
To make weather forecasting at airports more accurate, Larraondo *et al* [7] developed a new method of analysis with machine intelligence through Numerical Weather Prediction (NWP). The algorithm for his model was developed in Python and is available as a free software in the author's GitHub™ repository (<https://github.com/prl900/AeroCirTree>).

This system makes use of the National Oceanic and Atmospheric Administration (NOAA) database, seeking weather information from the Global Forecast System and the METAR Code database distributed by the WMO Global Telecommunication System (GTS). As a scenario, they used the airports of Berlin Tegel (EDDT), Heathrow (EGLL), Barcelona (LEBL), Charles de Gaulle (LFPG) and Milano Malpensa (LIMC), using 8,760 METAR information from each airport in the years

2011, 2012 and 2013. To compare the method effectiveness, they used linear prediction models and the circular regression tree model, known as Lund Method. Results show the method proposed by Larraondo *et al* [7] is more effective in the long term, and the linear method

is more effective in the short term, adjusting to small variations in the long term; on the other hand, the Lund Method in the medium term is more advantageous than the machine learning created by the authors for the accuracy of weather forecasting at airports.

**Figure 2** - Result of keyword occurrences by year of publication.



To find the meteorological impact on the performance of landings for domestic flights in Brazil, Oliveira [11] used the history of planned and performed flights, meteorological data and estimated by a logit model to analyze how the various weather conditions affect the probability of flight delays. Results show that there is significant evidence about the delay of flights due to weather events, but visibility and ceiling conditions resulted in a negative coefficient, while conditions such as rain and wind gusts are more significant for delays.

### 3. Method

#### 3.1 Obtaining aerodrome closure time information

To achieve our goal, the first step is to find out at what times the airport was closed due to adverse

weather conditions. Through the REDEMETS API, a DECEA weather information service [32], it is possible to obtain the history of the METAR Code, which provides information on day, date, time, airport, wind speed and intensity, vertical visibility, cloud cover and cloud height, present weather, present weather phenomena, air temperature and dew point phenomena, and on-site atmospheric pressure in hPa. The following is an example of a METAR Code from Viracopos Airport (SBKP), in Campinas/SP. Decoding is done through ICA 105-16 [33].

2022081003 - METAR SBKP 100300Z 02008KT 7000 -RA BKN007 OVC013 18/17 Q1017=

In the METAR code shown, the information is August 10, referring to 3 hours in Greenwich Mean Time (Z), the wind is 020° with 08 kt of intensity, visibility of 7,000 feet, with decreasing rain (-RA), cloudy (BKN)

at 700 feet, covered (OVC) at 1,300 feet, with air temperature of 18°C and dew point temperature of 17°C, and the pressure to adjust the altimeter is 1017 hPa.

To find out the hours when the airport was closed and to make the descriptive statistics of the sum of these results, an algorithm was developed in Python (see appendix) that informed the time (timestamp) when the aerodrome did not operate in Visual Flight Rule (VFR), Special VFR, procedures under Instrument Flight Rule, ILS operation, LNAV, LNAV (Performance A and B), LNAV (Performance C and D), and RNP 0.3. The restriction of visibility for each of these types of procedures depends on air traffic standards and what is published in the approach and takeoff charts of each aerodrome.

### 3.2 Airspace delimitation and flight data

According to Campos [37], for statistical sampling in transport surveys, the best day of the week to be observed is Thursday. Thus, this was the day chosen for the calculations, after obtaining the results of the aerodrome closure times. From then on, the files in kml and csv for each flight performed on a Thursday would be obtained on the FlightRadar24™ platform. These files provide information on timestamp, UTC time, callsign, altitude, speed and direction, and it is then possible to calculate the time traveled by the aircraft at the entrance of the TMA area until the final approach of the runway.

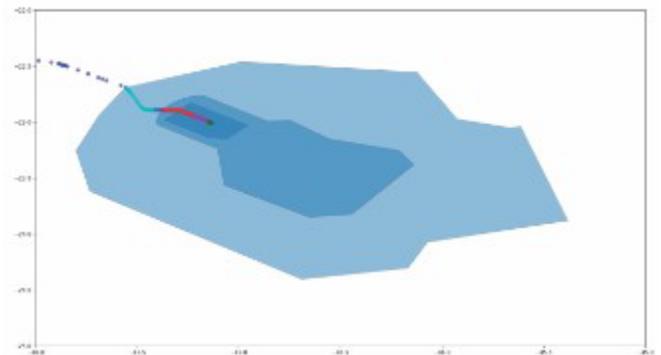
DECEA [34] publishes data of the Repetitive Flight Plans, in which the scheduled flights for a given day are shown. With this information, the flights scheduled on a day when the aerodrome was not closed due to meteorological reasons were compared with a day when it was closed, thus allowing for the estimate of time difference for aircraft length of stay until exit of terminal area, after takeoff, or until landing.

The airspace boundaries in csv format were obtained from the GEOAISWEB directory, which is maintained by DECEA. Alternatively, it could be obtained through a Letter of Route (ENRC). Having the coordinates of the area vertices and the altitudes in relation to sea level, one could reproduce the geographical space

through the second algorithm developed (see repository <https://github.com/embarquetec/adatfm>).

This algorithm imports the flight path and identifies the moment when the aircraft passes through one of the edges of the generated map. Then, the time flown between each zone of the airspace is subtracted. Figure 3 shows the airspace boundaries and flight trajectory. Table 1 shows the outputs generated to determine the time at which the aircraft passes through each zone of airspace or phase of flight, e.g., takeoff, cruise, descent, and landing. The results also show an error, which is a correction for more that corresponds to the time for the capture of aircraft position information by the Automatic Dependent Surveillance – Broadcast (ADS-B) system – and the confirmation of the aircraft position. These time points are subtracted from the total time.

**Figure 3** - Reproduction of the airspace limitation with the flight path of the aircraft.



**Table 1** - Flight identification outputs

Outputs	Description
<i>code</i>	IATA Flight Identification Code
<i>departure_iata</i>	Departure airport IATA code
<i>arrival_iata</i>	Destination Airport IATA Code
<i>takeoff_time</i>	Departure time

Outputs	Description
<i>takeoff_time_error</i>	Takeoff time error
<i>level_off_time</i>	Time it reaches cruise level
<i>level_off_time_error</i>	Error of the time when it reaches the cruise level
<i>descent_init_time</i>	Time when the descent of the cruise phase begins
<i>descent_init_time_error</i>	Error of the time when the descent of the cruise phase starts
<i>touchdown_time</i>	Time of landing
<i>touchdown_time_error</i>	Landing time error
<i>flight_time</i>	Total flight time
<i>flight_time_error</i>	Total flight time error
<i>before_takeoff_ground_duration</i>	Time the aircraft remained on the ground prior to takeoff
<i>before_takeoff_ground_duration_error</i>	Time the aircraft remained on the ground prior to takeoff
<i>climb_duration</i>	Climb duration time
<i>climb_duration_error</i>	Climb duration time error
<i>cruise_duration</i>	Cruise flight time duration
<i>cruise_duration_error</i>	Cruise flight time duration error
<i>descent_duration</i>	Descent duration
<i>descent_duration_error</i>	Descent duration time error
<i>after_landing_ground_duration</i>	Taxi time after landing
<i>after_landing_ground_duration_error</i>	Taxi time after landing error

Outputs	Description
<i>air_space_1_entry</i>	Airspace Entry Time
<i>air_space_1_entry_error</i>	Airspace Entry Time Error
<i>air_space_1_exit</i>	Airspace Departure Time
<i>air_space_1_exit_error</i>	Airspace departure time error
<i>inside_air_space_1</i>	Time within airspace
<i>inside_air_space_1_error</i>	Time within airspace error
<i>total_time_inside_air_space</i>	Flight time within selected airspace sections
<i>total_aircraft_fuel_inside_air_space</i>	Total fuel within the selected airspace
<i>total_passenger_CO2_inside_air_space</i>	Total CO <sub>2</sub> emitted within the selected airspace
<i>total_cost_CO2</i>	Total cost of CO <sub>2</sub> emitted according to the current quotation

To find the total cost of CO<sub>2</sub> emitted according to the current price, the market value of BRL 383.62 per ton is used, considering the closing of the futures market on November 1, 2022 [38].

### 3.3 Calculation of pollutant emissions

The calculation of CO<sub>2</sub> emission uses the International Civil Aviation Organization (ICAO) API [38] for the calculation of the individual passenger emission. This method uses a fixed variable multiplying by the total fuel with the passenger load factor divided by the number of seats for the economy category (Y) with the passenger quantity factor stipulated for each continent.

$$CO_2\text{ per pax} = 3,16 \times \frac{(tf \times pfc)}{(nys \times plf)} \quad (1)$$

Wherein:

- = Total fuel;
- = Load factor for passenger;
- = Number of seats for category Y;
- = Passenger quantity factor by region.

The values of the total fuel consumed in each section flown are obtained through the return of the ICAO API [38]. For this, the average of the history of all flights of the airlines that pass this information to the ANAC Database is used.

## 4. Case Study

The scenario chosen was that of Campinas/Viracopos International Airport (SBKP). Campinas is the fourth airport in Brazil with the highest number of landings and takeoffs, with 109,230 movements recorded at the end of 2022, losing to Guarulhos (192,280 movements), Congonhas (130,820 movements) and Brasília (117,736 movements) [36]. The city of Campinas is located in a mountainous region, in addition to the Capivari, Jaguari, Capivari-Mirim and Atibaia rivers, which favor the conditions for the formation of a cluster of water droplets that are suspended in the atmosphere. It is this fog that restricts visibility for landings and takeoffs, causing delays and cancellations.

According to ANAC data [35] of percentages of delayed and canceled flights originating in SBKP from December 2017 to September 2022, there are, on average, 5,027 flights per month, with an average delay of more than 30 minutes of 7.03%, with delays of more than 60 minutes of 2.36%, and with an average cancellation of 2.81%. Regarding flights from destinations to SBKP, we have an average of 5,000 flights, with an average of delays of more than 30 minutes of 6.05%, delays of more than 60 minutes of 2.52%, and an average of cancellations of 3.23%.

### 4.1 Aerodrome closure data

Table 2 shows the restrictions by cloud ceiling and visibility for the operation by flight rule and type of procedure.

**Table 2 - Operating conditions by flight rule and procedure for Viracopos Airport**

Procedures	Conditions
VFR	Ceiling > = 1,500 ft
	Visibility > = 5,000 ft
Special VFR	Ceiling > = 1,000 ft
	Visibility > = 3,000 ft
ILS	Ceiling > = 200 ft
	Visibility > = 800 ft
LNAV	Ceiling > = 357 ft
	Visibility > = 1,100 ft
LNAV (Performance A and B)	Ceiling > = 430 ft
	Visibility > = 800 ft
LNAV (Performance C and D)	Ceiling > = 430 ft
	Visibility > = 1,500 ft
RNP 0.3	Ceiling > = 339 ft
	Visibility > = 1,000 ft
RNP 0.15	Ceiling > = 339 ft
	Visibility > = 800 ft

September 15 and 22, 2022 were stipulated. Table 3 shows the number of hours the aerodrome did not operate for each type of procedure.

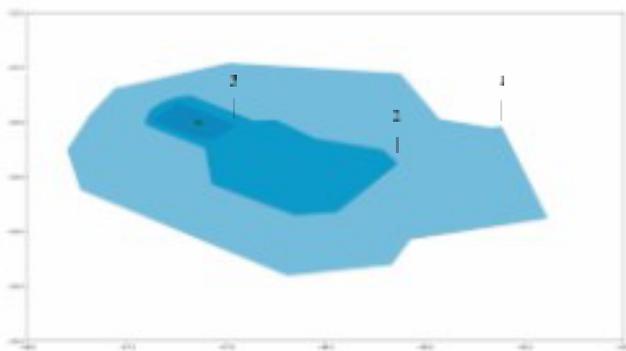
**Table 3 - Time that each procedure remained unavailable for operation**

Procedure	Time (hr) day	Time (hr) day
	09/15	09/22
VFR	00:00	18:00
Special VFR	00:00	08:33
ILS	08:00	04:48
LNAV	00:00	03:00
LNAV (Performance A and B)	00:00	03:33
LNAV (Performance C and D)	00:00	03:33
RNP 0.3	00:00	3:00
RNP 0.15	16:00	21:12

#### 4.2 Airspace delimitation and flight data

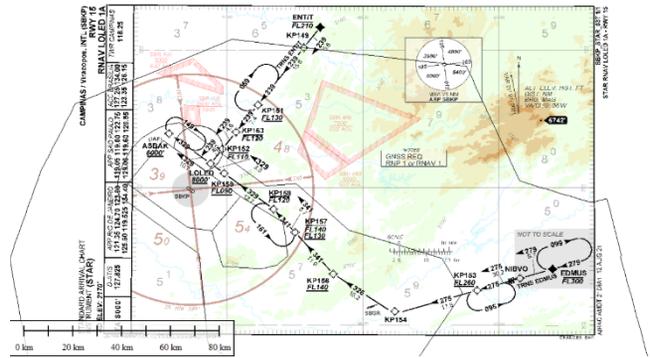
For landing and takeoff procedures at Viracopos Airport, the aircraft pass through CTR Campinas (3), TMA São Paulo 2 (2) and TMA São Paulo 1 (1). Figure 4 shows the sections of the air spaces delimited for this study.

**Figure 4 - Delimitation of the airspace of the study.**

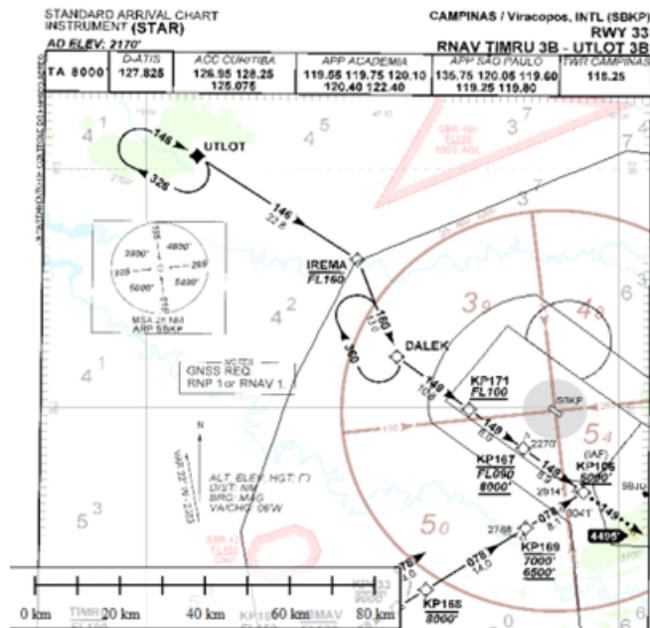


Within this delimitation, we have the *Standard Terminal Arrivals* (STAR) procedures entitled RNAV LOLED 1A (Figure 5), RNAV TIMRU 3B – UTLOT 3B (Figure 6) and RNAV VURAV 2A (Figure 7).

**Figure 5 - STAR RNAV LOLED 1A procedures.**



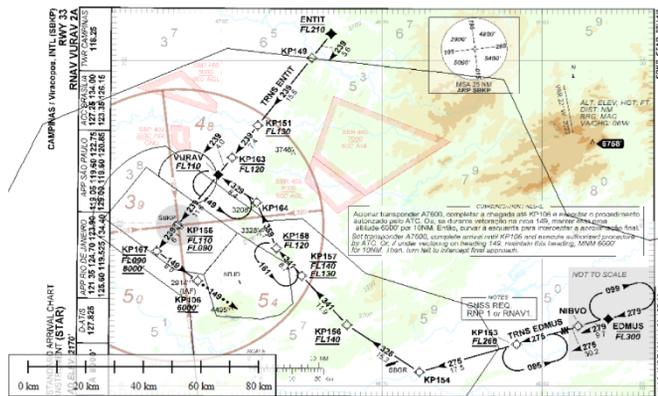
**Figure 6 - STAR RNAV TIMRU 3B – UTLOT 3B Procedure.**



From the analysis of the DECEA Repetitive Flight Plans database and the FlightRadar24™ flight database, the same flight numbers and respective routes were segregated for comparison. There were 44 flights analyzed (AD4025, AD4276, AD4385, AD4942, AD4326, AD2942, AD2874, AD4047, AD4099, AD4708, AD4242, AD4386, AD2954, AD4027, AD4638, AD4310, AD4871, AD4555, AD2030, AD4805, AD2953, AD2021, G31771, AD4449, AD4033, G31712, AD4885, AD4285, AD4341, AD4361, AD4853, AD4872, AD4451, AD2740, AD4356, AD4789, AD4424, AD2697, AD4034,

AD2824, AD4340, AD2736, AD4763, AD4322). Of these, no flights were delayed on 09/15 and 6 flights were delayed on 09/22, and no flights were diverted to another airport.

**Figure 7 - STAR RNAV VURAV 2A procedure.**



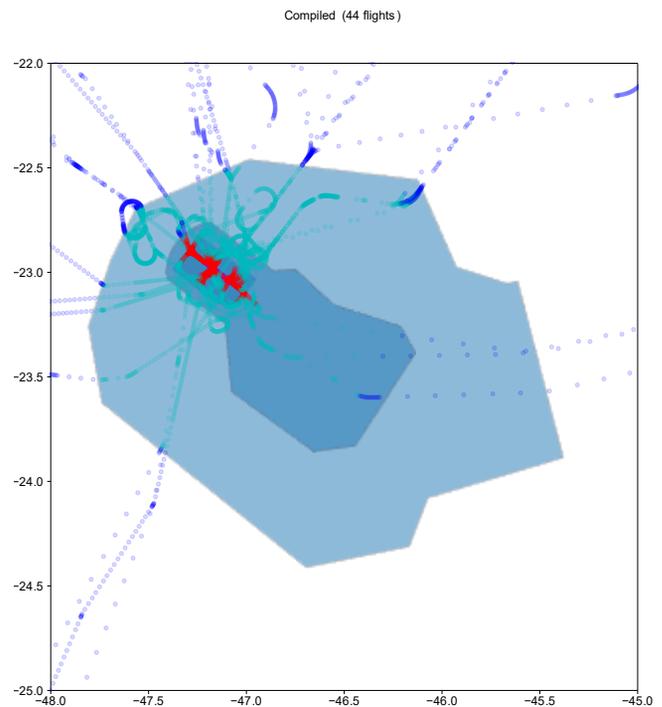
### 4.3 Application result

Figure 8 shows the route of flights with delays. In it, one can observe the orbit procedures that generated the delay. The time for each orbit procedure depends on the performance of the aircraft, but each leg of the procedure takes around 1 minute, and should consider the time for the aircraft to enter the procedure and other deviations. The darker the color of the route, the longer the aircraft were on that path.

The figure shows that, in the area of TMA São Paulo 1, the most congested areas are at the limits of the terminal, mainly in the orbit procedure on the DALEK fixed (see Figure 6) with 00:30:53 h and 13 aircraft, and in the orbit of the KP151 fixed (see Fig. 2) with 00:12:52 h and 3 aircraft.

Table 4 shows the total flight hours per day, within each airspace, and the sum of the flight hour. The difference between the routes between the day that there was no delay and the day that there was an extra flight was 00:52:29.

**Figure 8 - Compiled flights on 09/22.**



**Table 4 - Flight time within each section of airspace**

Outputs	Time (hr) day 09/15	Time (hr) day 09/22
<i>inside_tma_sao_paulo_1</i>	06:49:21	07:05:35
<i>inside_tma_sao_paulo_1_error</i>	00:25:39	00:29:38
<i>inside_tma_sao_paulo_2</i>	00:55:01	01:13:34
<i>inside_tma_sao_paulo_2_error</i>	00:00:11	00:00:14
<i>inside_ctr_campinas</i>	00:43:13	01:07:01
<i>inside_ctr_campinas_error</i>	00:13:04	00:15:24
<i>total_time_inside_air_space</i>	07:48:41	08:41:10

#### 4.4 Result of pollutant emission

According to the ICAO manual [38], flights within the South American continent are considered 82.6% and 77.27%. On the verified routes, the aircraft used are the A76, A32N, 73G and E95 models, for the A76 the occupancy of 53 passengers is considered, and for the other aircraft, 87 passengers are considered. The total fuel spent on each flight leg was obtained through the ANAC database.

Table 5 shows the result in which the delays identified in the sample generated the consumption of 9,278.74 kg/CO<sub>2</sub> more emitted into the atmosphere and with a cost of BRL 3,559.47 more in the used quotation of tons of CO<sub>2</sub>.

**Table 5** - Total emission in kg/CO<sub>2</sub> and cost

Outputs	day: 09/15	day: 09/22
total_aircraft_fuel_inside_air_space	44,587.86 kg	49,637.34 kg
total_passenger_CO2_inside_air_space	81,933.04 kg/CO <sub>2</sub>	91,211.78 kg/CO <sub>2</sub>
total_cost_CO2	R\$ 31,430.80	R\$ 34,990.27

#### 5. Final considerations

The relevance of this research is proven by the bibliometric occurrence analysis, in which keywords related to severe meteorological events, air transport resilience, and emission of polluting gases appear in more recent publications.

Based on the data presented in Table 4, one can conclude there was an increase in the total flight time within the internal airspace of TMA São Paulo 1 and

TMA São Paulo 2, as well as the internal airspace of Campinas traffic control, between 09/15 and 09/22. In addition, the values presented for errors in the different control areas also increased compared to the same period. In particular, the total flight time within TMA São Paulo 1 increased from 06:49:21 on 09/15 to 07:05:35 on 09/22, while the total flight time within TMA São Paulo 2 increased from 00:55:01 to 01:13:34 in the same period. Similarly, the total flight time within Campinas traffic control increased from 00:43:13 to 01:07:01. Based on these results, it is possible to identify areas that require attention to ensure the safety and efficiency of air traffic in the region.

The application of an airspace congestion weather forecasting and analysis system would also contribute to ATFM measures taken with information obtained through the Severe Weather Avoidance Plan (SWAP), whose activation is already aimed at mitigating air traffic disruption from the analysis of weather conditions.

The results show the difference in consumption between the same routes without the flight delay and in a day of operation with some delayed flights. This difference resulted in a consumption of approximately 5 tons more fuel or approximately 11 tons more kg/CO<sub>2</sub> emitted into the atmosphere. This shows the importance of investing in infrastructure, technologies, and pilot training so that aircraft can operate with increasingly restricted visibility and without causing damage to flight operational safety.

The impact of aircraft dwell time for each bedside was not considered in this model; this analysis would be interesting for future research on this topic. Another method would be the use of the Corsia methodology, which uses the power of the engines during the landing and takeoff cycles, in which the aircraft power regime is different.

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