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# Applying Airport Centrality as an Operational Continuity Indicator

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### Abstract

**Purpose:** The research aims to propose a methodology to estimate the reliability of the Brazilian airport network (domestic passenger traffic), based on the centrality of airports (Network Theory).

**Design/methodology:** The applied methodologies are related to Network Theory, a branch of Graph Theory, and reliability. Reliability is associated with the good functioning of a product or system, the absence of breaks or failures in each period and the environmental conditions of use of the item. The data used refer to the period 2000-2018 and were obtained from the sector's regulatory body in Brazil. The study allows to estimate the reliability of the airport network, based on the centrality of airports (Network Theory).

*Findings:* The results allow airports to be classified into three groups: adequate context, worrying context and critical context, thus signalling airports that may stop operating regular domestic traffic.

Research limitations/implications: The study does not aim to overlap or replace conventional analyses, recognized by the results, and applied over time. However, to present a new tool that allows the monitoring and preliminary analysis of airport networks, mainly domestic and regional networks, signalling to airport operators, regulators, and airlines the need for intervention (measures to reverse the trend) in the network, thus allowing, economic development and equitable access to all regions.

*Originality/value:* The proposal of a complementary methodology based on the centrality of airports to analyze operational continuity.

Keywords: Air Transport, Airports, Centrality, Network Reliability, Network Theory

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### 1. Introduction

During the twentieth century air transport played an important role in Brazilian economic and social development, being considered as an element of the country's productive dynamics transformation (Ministério do Planejamento, 2011). In this context, the State helped consolidate air transportation as an essential instrument of national integration, through public policies and investments in airport infrastructure and civil air navigation.

The Brazilian airport network underwent significant changes in recent years, aiming to meet the demand for the use of airport services and improve the quality of services provided. In 2011, several investments were made in the transportation infrastructure sector in Brazil. Those related to capacity expansion aimed mainly at meeting the needs related to the World Cup in 2014 and the Olympic Games in 2016 (Brito, 2017). There were also changes in the structure of ownership, management, and operation, highlighting in this sense the process of airport concessions started in 2011. During the period 2011-2018, 11 private airports were granted to the private sector. These accounted for 53.8% of regular domestic passenger traffic in 2018.

Air transport was also included in the Pluriannual Plan (Plano Plurianual – PPA) of the Brazilian government. One of the main axes of the PPA 2012-2015 (Ministério do Planejamento, 2011) was the expansion of the provision of regular air transport, with the incorporation of new airports and new routes, increasing the number of airports and routes served by regular air transportation. The PPA 2016-2019 (Ministério do Planejamento, 2015) includes a specific program for the sector the Civil Aviation Thematic Program, where it is possible to highlight objectives such as to adapt the processing capacity of aircraft, passengers and cargoes to existing, and future demand through studies and investments to increase the availability of infrastructure in the 270 airports covered by the Regional Aviation Program (airports with a movement of less than or equal to 1 million passengers per year). Moreover, to increase the number of scheduled air transportation services for passengers and cargo by increasing the number of routes served by regular air transportation of passengers and cargo to 1,000. The Program was designed to meet the United Nations Development Program's Sustainable, and resilient quality infrastructure including regional and cross-border infrastructure to support economic development and human well-being, with a focus on equitable access and affordability for all.

It is important to note that although the policies have had objectives such as increasing the number of airports and routes, thus increasing the provision of scheduled passenger air transport services, the number of airports with regular flights and the number of connections decreased over the period 2000 -2018, which influenced the centrality of the airports in the network. Airports with low centrality can signal future failures (ruptures), that is, they can signal a possible interruption in the operation of regular flights (inoperability).

According to Grubesic, Matisziw, Murray and Snediker (2008), connectivity issues are fundamental to any network, since its purpose is to establish and maintain connectivity between the set of interacting elements to facilitate the movement of valuable goods and services through a system. According to the authors, disruptions, also known as interdiction, can cause unscheduled loss of service resources within a network, resulting in costly repairs and service interruptions, especially for infrastructure.

Thus, the objective of this study is to analyze the centrality of airports order to estimate the reliability of the Brazilian airport network, classifying them into three groups: adequate context, worrying context and critical context. The classification identifies possible airports that will no longer operate regular domestic traffic. In other words, it identifies the possible ruptures in the network, signaling to the airport operators, regulators, and airlines, where there is a need for interventions (measures to reverse the trend). These interventions could provide economic development and equitable access to all regions.

The study is structured in 5 sections: section 1 is the introduction. Section 2 the review of the literature. The methodology is in section 3, the results and discussions in section 4 and the conclusions in section 5.

# 2. Literature Review

Air transport networks have been studied by several authors. Concerning the use of the Network Theory for the study of air transport networks, Bounova (2009) states that its application has become possible due to the availability of data and the easy representation of airport systems. Among the authors who used the Network Theory applied to air transport, one can cite Guimera, Mossa, Turtschi and Amaral (2005), who studied the global structure of the airport from the perspective of the centrality of the node and the community structure. The authors considered the global airport network, representing it as a graph and applying centrality metrics to classify airports according to their "function" in the network (central, connectors, regional hubs, peripheral airports and ultraperipheral airports).

Burghouwt (2007) analyzed the evolution of aerial networks in Europe aftermarket deregulation, stating that the aviation network is the aggregation of all individual air networks. Concerning the network analysis, the main contribution of the study was the introduction of the network concentration index (NC) to identify the level of concentration of European transporters.

Bounova (2009) studied the growth patterns of the US air transport network concerning routes, showing the existence of transitions of topologies in the history of airlines in the period 1990-2007. The author highlighted the topological similarity of most airline networks. The similarity identified overtime allowed the author to elaborate on a growth model based on the network topology. The author also applied centrality metrics to classify airports according to their function in the network: global centers, connectors, regional hubs, peripheral airports and ultraperipheral airports.

Rocha (2009) investigated the structure and evolution of Brazil's airport network from 1995 to 2006 in terms of routes, connections, passengers, and cargo. Some structural characteristics agreed with the findings for other airport networks. The analysis revealed a dynamic structure, with airports and routes shifting in importance. The results indicate that the network shrank in terms of routes but grew in passenger numbers and cargo volume.

According to Newman (2010), the metrics of centrality in the analysis of networks have different concepts of importance, being very useful to identify and classify the most important nodes or edges in the network. Zhang Cao, Du and Cai (2010) analyzed the evolution of the Chinese airport network using the complex network theory. The study included topology, traffic, and the interaction between them. The authors also analyzed the relationship between network evolution and the development of the Chinese economy.

Rodriguez-Deniza, Suau-Sanchez and Voltes-Dortac (2013) adapted the well-known centrality indicator to the air transport context and developed a new airport connectivity measure, using it to define an alternative airport classification method, the method being applied to the US home network.

Brito (2017) analyzed the evolution of the Brazilian airport network in the period 2000-2015 (international passenger traffic). Applying the methodology of Network Analysis, Gini Index and HHI, the study aimed to identify and explain the main elements that influenced the transformation of the topology of the airport network in Brazil. Wong, Cheung, Zhang and Wang (2017) studied the global air transport network using topological metrics and traffic volume, developing an "airport centrality index (ACI)".

Wong, Zhang, Cheung and Chu (2019) investigated the "myth" that LCCs tend to focus their business on secondary airports. From the Airport Centrality Index (ACI) developed by Wong et al. (2017), the authors established parameters based on centrality metrics to classify airports.

Mazzarisi, Zaoli, Lillo, Delgado, and & Gurtner (2020) focused on metrics of centrality and causality, measuring, respectively, the importance of a node and the propagation of disturbances along the links (links). The authors have proposed generalizations of these metrics, proving that they are suitable for ATM applications. Aydın, Karadayi and Ülengin (2020) proposed a Data Envelopment Analysis (DEA) model integrated with a regression-

based feedback mechanism and social network analysis to assess the performance of the 45 major airlines in the world. The method allowed to classify the efficient Decision-Making Units (DMUs), considering their qualities, using the concept of eigenvector centrality.

Concerning reliability, this topic has been discussed in several studies. Grubesic et al. (2008) reviewed and compared some approaches that evaluate the importance of infrastructures and the vulnerability of networks. The author highlighted the significant differences between the measures of the importance of the infrastructures and network performance, as well as the need for a clear understanding of the risks of interdiction and vulnerability assessment for critical infrastructures.

Kozlowski (2015) presented the question of ensuring continuity of operation at an airport. The author studied problems related to the operation. It was defined a reliability and readiness function related to critical processes (aircraft operations and ground handling) and special processes (technical maintenance of infrastructure, civil aviation protection against acts of unlawful interference, security the state border, rescue, and firefighting).

Burbidge (2016) complemented EUROCONTROL's analysis of operational and business risks at an airport considering the potential consequences of climate change, highlighting the need to develop resilience to these risks.

Baltazar, Rosa and Silva (2018) using the MACBETH approach (measurement of attractiveness using a category-based assessment technique), created a hierarchical additive value model, built with criterion weights and value scales derived from expert judgments and the comparison of different reference levels and performance profiles. The results allowed to identify deficiencies that require urgent intervention and corrective measures for their continuous improvement.

Yang (2020) applied multiple linear regression to identify factors that contribute to the perception of aircraft noise pollution risk among residents near Taoyuan and Kaohsiung International Airports, in Taiwan.

The papers corroborated the understanding of the effectiveness of Network Theory and risk analysis as analysis tools in studies on air transport. The different approaches allowed a new look at these methodologies, thus expanding the insights on the possibilities and forms of their applications to the study of air transport networks.

# 3. Methodology

The first methodology applied to the study is Network Theory, a recent branch of Graph Theory. Bounova (2009) points out that the use of the Network Theory for the study of air transport networks has become possible due to the availability of data and the easy representation of airport systems. According to Burghouwt (2007), the aviation network is the aggregation of all air networks (airlines, airports, and air traffic). This concept is broad and needs to be narrowed. In this study, the idea of a network was associated with the set of airports that operate regular domestic passenger traffic in Brazil. Data on air transport during the period 2000-2018 were obtained from the National Civil Aviation Agency (Agência Nacional de Aviação Civil – ANAC, 2019a), the sector's regulatory agency. The network was classified as not directed due to the use of the passenger's total number on the connections (embarkation and disembarkation). Airports are identified by ICAO code.

The Open Graph Viz (Gephi) platform was used to create graphical representations of the network. Graphic representation is a way of visualizing systems of different sizes and types. Topology is the term that describes your layout and organization, that is, how the elements of a network are arranged and connected. The study network was characterized as scale-free. In this type of network there are a small number of airports that have a high number of connections, known as hubs, which contrasts with many airports with few connections. In this study, Geo Layout and Circle Pack Layout distributions were applied to represent the network. These distributions allow to visualize the network according to the geographic position of the airports and in a hierarchical way (context, region, and centrality), respectively. Airports have been classified as important. The larger the node (airport) is, the higher its centrality in the network. The platform also allows analyzing the relationships among its components through a set of metrics, and it is possible to emphasize aspects such as

airports centrality. The centrality was measured by calculating Eigenvector Centrality (Equation 1), which indicates the most central airports in the network, and its concept was introduced by Bonacich (1972).

$$EC(i) = \mu_1(i) = \frac{1}{\lambda_1} A \mu_1 = \frac{1}{\lambda_1} \sum_{j=1}^n a_{ij} \mu_1(j)$$
(1)

Where  $\mu_l$  is the set of airport neighbours i,  $\lambda_l$  is the largest eigenvalue, A is the adjacency matrix, n is the number of airports (nodes) and  $a_{ij}$  of the adjacency matrix represents the connections from airport i to airport j.

Eigenvector Centrality measures the quality of connections at airports, that is, how significant the connections are, regardless of the number of passengers transported. There are other metrics that measure centrality, such as Betweenness, Closeness and Harmonic Centrality and Eccentricity. Lodan et al (2014), presented a methodology for the detection of critical airports, based on Betweenness Centrality. The study helps develop contingency plans for an appropriate response to the closure of an airport in the global air transport network (ATN) in the event of an attack. Through the work, it is possible to identify the airports, whose isolation would cause the greatest losses in network connectivity. However, Eigenvector Centrality better serves the focus of the current study.

By using the Eigenvector Centrality as the base variable for the operational continuity indicator, it becomes possible to calculate it, considering the importance of the connections. A low Eigenvector Centrality indicates that the airport's connections are of little relevance, thus increasing the possibility of it no longer operating regular traffic (inoperative, for regular flights). A higher Eigenvector Centrality indicates that the airport is connected to other airports with more central positions in the network, that is, it is connected to others with relevant positions in the network, which reduces the possibility of it becoming inoperative (without the operation of regular flights). The interruption in the operation of regular flights affects, mainly, regions where access by other means of transport is reduced or difficult, either due to distance or regional characteristics.

The second methodology applied to the study is related to reliability. Fogliatto and Ribeiro (2009), states reliability, in its broadest sense, is associated with the successful operation of a product or system, the absence of breaks or failures in a period and under environmental conditions of use of the item. In the study, Fogliatto and Ribeiro (2009) states that the risk function h (t), also known as failure rate or risk ratio, is one of the most used in reliability measures and can be interpreted as the amount of risk associated with a unit (component or system) at time t. Still following the author, the risk function is very useful in analyzing the risk to which a unit is exposed over time, serving as a basis for comparison between units with different characteristics. In this study the estimator for  $\hat{h}(t)$  will be applied to large samples:

$$\hat{h}(t) = \frac{\bar{N}(t) - \bar{N}(t + \Delta t)}{\bar{N}(t) \Delta t}$$
(2)

Where  $\hat{h}(t)$  it is the risk rate to be calculated for each class interval.  $\bar{N}(t)$  it is the number of surviving units at time t.  $\Delta t$  is the class interval.  $\bar{N}(t+\Delta t)$  it is the number of failures at time  $(t+\Delta t)$  is the sum of failures at Time T.

Adapting the risk function to the study of the airport network, concerning operational continuity,  $\hat{h}(t)$  it is the risk of an airport failing to operate regular domestic traffic. It is calculated for each class interval of the Eigenvector Centrality of airports that have ceased operating in the network in the period 2000-2018, that is, at time t. Where N is the number of airports that stopped operating regular domestic traffic at time t.  $\bar{N}(t)$  it is the number of airports that continued to operate regular domestic traffic at time t.  $\Delta t$  is the class interval of the Eigenvector Centrality.  $\bar{N}(t+\Delta t)$  it is the number of airports that stopped operating regular domestic traffic at time  $t+\Delta t$ . When the risk rate  $\hat{h}(t)$  was calculated, the values of the variables  $\bar{N}(t)$ ,  $\bar{N}(t+\Delta t)$  and N were transformed into logarithm values as a function of their amplitude deviation in relation to the variable Eigenvector Centrality of airports values.

According to Fogliatto and Ribeiro (2009), there are two basic categories for the risk function: (i) increasing risk function (CRF), which describes cases in which the incidence of risk does not decrease with time; and (ii) decreasing risk function (FRD), adequate to describe situations in which the incidence of risk does not increase with time. It was observed in this study that the risk of an airport ceasing to operate regular traffic does not increase with time; that is, the risk function is decreasing (downward curve). The larger the Eigenvector Centrality, the lower the risk of the airport failing to operate regular traffic (Figure 1).

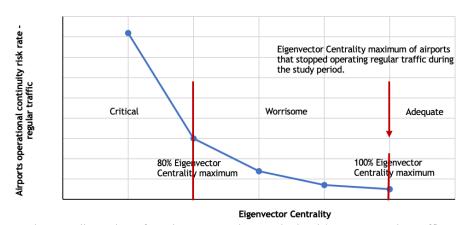


Figure 1. Illustration of an airport operating continuity risk curve - regular traffic

By adapting the Pareto ABC curve principle to the operational continuity risk curve of airports (Figure 1), we can then separate them into three groups: i) adequate context - Eigenvector Centrality at time t above 100% of Eigenvector Maximum centrality of airports which ceased to operate during the study period; ii) worrying context - Eigenvector Centrality at time t above 80%, but below 100%; and iii) critical context - Eigenvector Centrality at time t below 80%. The percentage of values can be adjusted to suit each case.

# 4. Analysis and Discussion

Currently, the Brazilian public airport network is made up of 578 airports (ANAC, 2019b), having reached 715 airports in 2013 (Brito, 2017). All major cities have at least one airport. However, it is essential to note that the distribution of the network across Brazilian territory was influenced by historical and political factors (Brito, 2017). The states of Minas Gerais, São Paulo, Bahia and the Rio Grande do Sul account for 53.5% of public airports (Table 1).

The Central-West region is the second in area and the fourth in population. Its activities are based on agriculture and tourism. It is the region of Cerrado and the Brazilian Pantanal. As well as the Amazon region, depending on the time of year, the aerial mode is also the only way to access some localities.

The Northeast region is the third in area and the second in population. Tourism is the leading region activity, followed by agriculture and extractive industry. The Industrial production is in the coastal strip. The Northern region is the largest in area and the fifth in population, based on primary activities such as extractive industry and agriculture and livestock and secondary, the latter in the Manaus Free Trade Zone. Because it is the Amazon region, access to many localities is difficult depending on the regional characteristics and depending on the time of the year, the aerial mode is the only form of access.

The Southeast region is the fourth in area and the first in population. It corresponds to half the national GDP, having the most significant industrial park in the country, a large tertiary sector, as well as agricultural and oil production. Tourism is representative too. The South region is the fifth in area and the third in population. It has the second largest industrial park in Brazil and agricultural production is modern, making the region the second largest national GDP.

| Region    | State                 | State's capital | Number of Airports |
|-----------|-----------------------|-----------------|--------------------|
|           | Goiás                 | Goiânia         | 30                 |
| Midwest   | Mato Grosso           | Cuiabá          | 28                 |
|           | Mato Grosso do Sul    | Campo Grande    | 21                 |
|           | Distrito Federal      | Brasília        | 1                  |
|           | Bahia (*)             | Salvador        | 66                 |
|           | Ceará                 | Fortaleza       | 13                 |
|           | Paraíba               | João Pessoa     | 12                 |
|           | Piauí                 | Teresina        | 12                 |
| Northeast | Maranhão              | São Luiz        | 11                 |
|           | Pernambuco            | Recife          | 11                 |
|           | Rio Grande do Norte   | Natal           | 5                  |
|           | Alagoas               | Maceió          | 3                  |
|           | Sergipe               | Aracajú         | 1                  |
|           | Pará                  | Belém           | 30                 |
|           | Amazonas              | Manaus          | 24                 |
|           | Tocantins             | Palmas          | 10                 |
| North     | Rondônia              | Porto Velho     | 9                  |
|           | Acre                  | Rio Branco      | 5                  |
|           | Amapá                 | Macapá          | 2                  |
|           | Roraima               | Boa Vista       | 1                  |
|           | Minas Gerais (*)      | Belo Horizonte  | 78                 |
| Southeast | São Paulo (*)         | São Paulo       | 75                 |
|           | Rio de Janeiro        | Rio de Janeiro  | 11                 |
|           | Espírito Santo        | Vitória         | 7                  |
|           | Rio Grande do Sul (*) | Porto Alegre    | 53                 |
| South     | Paraná                | Curitiba        | 37                 |
|           | Santa Catarina        | Florianópolis   | 22                 |

<sup>(\*)</sup> The states that concentrate the most significant number of public airports

Table 1. Geographical distribution of the Brazilian public airport network - 2019 (ANAC data, 2019a)

Comparing the number of passengers transported with the number of airports in operation (Table 2), there is an imbalance between demand and supply of airport infrastructure. While there was a 232.8% increase in the number of passengers in the period 2000-2018, there was a decrease of 20.4% in the number of airports operating regular domestic flights. The geographical distribution, the decrease was 33.3% in the Midwest, 3.6% in the Northeast, 50.0% in the North and 32.1% in the South. However, there was an increase of 48.3% in the region Southeast, due to 14 new airports operation in the state of Minas Gerais in 2018. The imbalance has consequences, two of which can be highlighted. The first is a significant concentration of traffic.

Rocha (2009) indicated this problem in his study, stating that the number of routes in the Brazilian network had reduced in the period 1995-2006, but the number of passengers and cargo had increased. The imbalance has consequences, two of which can be highlighted. The first is a significant concentration of traffic. The concentration generates congestion in one part of the airport network and idleness in another, is explained mainly by two factors: I) air transport is significantly related to economic activity. Regions with higher economic activity have greater volume of people using the air way in their displacements. II) airlines concentrate their operations on routes that guarantee them a higher occupancy rate on aircraft. The latter has the second consequence: the reduction of the number of localities served by scheduled flights and the under-utilization of the airport network.

In terms of underutilization, 267 airports (46.2%) operated regular domestic traffic at some point in the study period (Table 2). The number of airports in operation and the number of connections decreased over the study period (Table 2), which influenced the centrality of airports (importance), especially those of smaller size. Airports with low centrality can signal future failures in the network, that is, they can indicate a possible interruption in the service and/or output from the operation of scheduled flights.

| Time T       | In an anation | I.a.a.a.a.a. | Total Airports | Number of   | Number of  |  |
|--------------|---------------|--------------|----------------|-------------|------------|--|
| 1 ime 1      | In operation  | Inoperative  | (*)            | connections | passengers |  |
| 2000         | 167           | 100          |                | 1,717       | 27,981,620 |  |
| 2001         | 151           | 116          |                | 1,693       | 29,997,122 |  |
| 2002         | 153           | 114          |                | 1,772       | 29,556,554 |  |
| 2003         | 132           | 135          |                | 1.364       | 27,570,810 |  |
| 2004         | 132           | 135          |                | 1.378       | 31,263,675 |  |
| 2005         | 151           | 116          |                | 2.038       | 37,392,428 |  |
| 2006         | 151           | 116          |                | 2,577       | 39,859,832 |  |
| 2007         | 147           | 120          |                | 2,964       | 42,032,491 |  |
| 2008         | 138           | 129          |                | 2,834       | 48,550,341 |  |
| 2009         | 136           | 131          | 267            | 1,464       | 57,078,874 |  |
| 2010         | 140           | 127          |                | 1,607       | 69,205,465 |  |
| 2011         | 142           | 125          |                | 1,711       | 82,265,430 |  |
| 2012         | 128           | 139          |                | 1,566       | 89,004,000 |  |
| 2013         | 134           | 133          |                | 1,425       | 89,701,610 |  |
| 2014         | 120           | 147          |                | 1,251       | 94,336,178 |  |
| 2015         | 120           | 147          |                | 1,314       | 94,950,156 |  |
| 2016         | 114           | 153          |                | 1,242       | 86,983,361 |  |
| 2017         | 112           | 155          |                | 1,156       | 88,467,153 |  |
| 2018         | 133           | 134          |                | 1,199       | 93,126,895 |  |
| Δ% 2000-2018 | -20.4         | 34.0         | -              | -30.2       | 232.8      |  |

<sup>(\*)</sup> Number of airports operated by regular domestic traffic at some point in the period 2000-2018

Table 2. Context of airports in time T - regular domestic traffic - Brazil (ANAC data, 2019a)

Grubesic et al. (2008) points out that the approaches to evaluate the vulnerability of the network are aimed at answering two questions concerning the importance: i) what the most vital nodes are and/or arcs in a network; ii) how robust a network is for node and/or arc failure. According to Grubesic et al. (2008), interdictions are important in assessing the robustness of the network and that understanding the impacts of faults often depends on obtaining the most complete "image" of the damage that can occur. In this study, we substitute node by airport and arc by connection, as well as the focus of importance is inverted, that is, the focus is the less importance airports in the network. Regarding damages, they are related to the continuity of the service, that is, they are related to the maintenance or development of a quality, reliable and resilient domestic airport network, allowing economic development and equitable access to all Brazilian regions.

A total of 226 failures were observed in the period 2000-2018. The minimum Eigenvector Centrality of the airports that stopped operating the regular traffic during the study period was 0.0019 and the maximum 0.2054. The Eigenvector Centrality (EC) of airports was divided into four classes with an interval of 0.0513, and the risk rate for each class was calculated (Table 3).

| Classes                  | Failures in time <i>t</i> (2000-2018) <i>N</i> | Risk rate $\hat{h}(t)$ | Surviving units at time $t$ $\bar{N}(t)$ | Failures in time $t+\Delta t$ $\bar{N}(t+\Delta t)$ | Class interval |  |
|--------------------------|------------------------------------------------|------------------------|------------------------------------------|-----------------------------------------------------|----------------|--|
| $0.0000 < EC \le 0.0513$ | 171                                            | 5.08                   | 226                                      | 55                                                  | 0.0513         |  |
| $0.0513 < EC \le 0.1027$ | 34                                             | 0.79                   | 55                                       | 192                                                 | 0.0513         |  |
| $0.1207 < EC \le 0.1540$ | 14                                             | 0.41                   | 21                                       | 212                                                 | 0.0513         |  |
| $0.1540 < EC \le 0.2054$ | 7                                              | 0.31                   | 7                                        | 219                                                 | 0.0513         |  |
| ΣΝ                       | 226                                            |                        |                                          |                                                     |                |  |

Table 3. Airport Operational Continuity Risk Rate - Regular Domestic Traffic (ANAC data, 2019a)

Adapting the Pareto ABC Curve principle to the operational continuity risk curve of airports (Figure 2), we can then classify them into three groups: i) adequate context - Eigenvector Centrality at time t above 0.2054; ii) Worrying context - Eigenvector Centrality at time t above 0.1027 and below or equal to 0.2054; and iii) critical context - Eigenvector Centrality at time t less than or equal to 0.1027. The Pareto Curve percentage values (80-20) were adjusted to fit the study best.

The graphical representation of the network allows a better understanding of the airport centrality applicability as an operational continuity indicator, and the classification of airports concerning their context. In 2000, there were 167 operating regular domestic traffic in Brazil: 50 in the adequate context, 53 in a worrying context and 64 in a critical context (Figure 3).

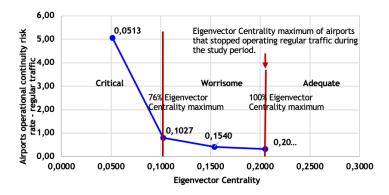
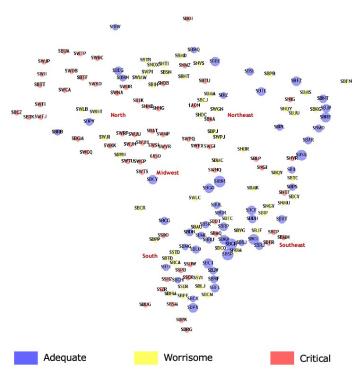


Figure 2. Airports operational continuity risk curve – regular domestic traffic – Brazil (ANAC data, 2019a)

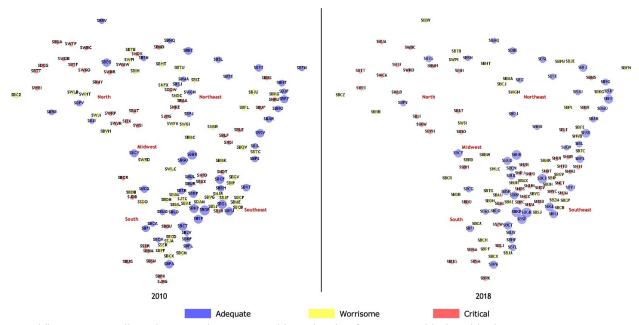


Note: There was a small gap between airports to avoid overlapping from geographical positioning Figure 3. Context of the airport network in 2000 - regular domestic traffic (ANAC data, 2019a)

The Eigenvector Centrality of the airports in the study period was not constant and consequently, there were variations in the context of the airports. In 2010, there were 140 operating regular domestic traffic in Brazil: 50 in the adequate context, 48 in a worrying context and 42 in a critical context. In 2018, the scenario was 133 airports in operation, 44 in the adequate context, 43 in a worrying context and 46 in a critical context. The variations can best be observed in Figure 4, which presents the network context in the two periods.

When considering the geographic distribution, it can be observed that, in the period 2000-2010, the North and Central-West regions had the most significant reduction in the number of airports in operation (25.0%), followed by the South (17.9%) and Northeast (13.8%). The Southeast was the only region in which the number of airports in operation increased during the period 2000-2010 (6.7%). Concerning the period 2010-2018, it can be seen in Figure 4 that the North region had the most substantial reduction in the number of airports in operation (33.3%), followed by the South (17.4%) and Central-West (11.1%). The Southeast region had the most significant increase in the number of airports in operation in the period 2010-2018 (34.4%), followed by the Northeast region (8.0%).

Regarding the airports that stopped operating (Figure 5), of the 167 airports operating in the year 2000, 56 moved into the inoperative context in 2000-2010 (33.5%). However, five airports returned to operation (3.0%), and 51 remained inoperative (30.5%). Considering the period 2010-2018, another 24 airports became inoperative (14.4%), totaling 75 airports in the period 2000-2018 (44.9%).



Note: There was a small gap between airports to avoid overlapping from geographical positioning

Figure 4. Context of the Brazilian airport network in 2010 and 2018 - regular domestic traffic (ANAC data, 2019a)

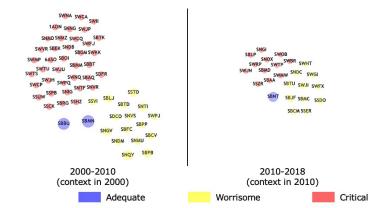
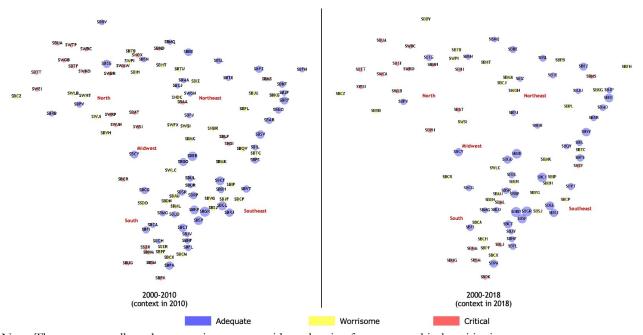


Figure 5. Airports were operating in 2000 and stopped operating the regular traffic in the periods 2000-2010 and 2010-2018 (ANAC data, 2019a)

However, when one considers continuous operation that is, operation without service disruptions at any time, the results diverge significantly, thus demonstrating the turnover and disruptions in the operation the regular traffic of the airports. Of the 167 airports operating in 2000, 91 airports operated without interruptions until 2000-2010 (54.5%) and 78 airports until 2000-2018 (46.7%). When considering the geographical distribution, it

can be observed that in the period 2000-2010 the Central-West region had the most substantial reduction in the number of airports in operation (70.8%), followed by the South (53.6%), North (46.4%), Southeast (33.3%) and Northeast (27.6%). Concerning the period 2000-2018, it can be observed in Figure 6 that the Central-West region maintained the percentage reduction in the number of airports in operation the regular traffic (70.8%) than in the period 2000-2010. The second region with the most significant decrease was the North region (58.9%), followed by the South (57.1%), the Southeast (40.0%) and the Northeast (37.9%) regions.



Note: There was a small gap between airports to avoid overlapping from geographical positioning

Figure 6. Airports operating regular domestic traffic in the periods 2000-2010 and 2000-2018 without breakages (failures) (ANAC data, 2019a)

Aiming to corroborate the applicability of airport centrality as an indicator of operational continuity, the classification of airports was quantified according to the context in which they were, and their evolution is presented in Table 4. In 2001 (time t+1), of the 50 airports operating in the adequate context in 2000 (time t), 43 remained in the adequate context, six moved into the worrisome context and one moved into the critical context. For the 53 that was in the worrisome context, four airports moved into the adequate context, 37 remained in the worrisome context, seven moved into the critical context and five moved into the inoperative context. For the 64 airports that were operating in the critical context, none went into the adequate context, three moved into the worrisome context, 42 remained in the critical context and 19 moved into the context inoperative. Of the 100 airports that were in the inoperative context, eight became operational, 1 in the adequate context, 2 in the worrisome context and five in the critical context.

During the study period, 90.8% of the airports classified in the appropriate context in time *t* remained in the adequate context in time *t+1*, 9.0% became worrying, 0.1% critical and 0.1% inoperative. In the inoperative context, attention is drawn to the airports SBBU (Bauru) and SBMN (Ponta Pelada), which had their situation aggravated in the period 2000-2010. Attention is also drawn to the year 2014, when the operations of Augusto Severo Airport (SBNT) were closed, due to the inauguration of the new Natal Airport - São Gonçalo do Amarante (SBSG). The new Natal Airport was built to meet the demands of the World Cup games. It should be noted that a significant part of the airports that remained in the adequate context throughout the study period is in the capitals of the Brazilian states.

Time t

| Context in time <i>t</i> | Context in time $t+1$ | 2000(a) | 2001 | 2002 | 2003 | 2004    | 2005 | 2006 | 2007 | 2008    | 2009    |
|--------------------------|-----------------------|---------|------|------|------|---------|------|------|------|---------|---------|
| In operation             | _                     | 167     | 151  | 152  | 131  | 132     | 151  | 151  | 147  | 138     | 136     |
| - Adequate               | _                     | 50      | 48   | 43   | 42   | 42      | 46   | 51   | 56   | 56      | 47      |
| - Worrisome              | _                     | 53      | 48   | 50   | 55   | 50      | 47   | 34   | 40   | 35      | 48      |
| - Critical               | _                     | 64      | 55   | 59   | 34   | 40      | 58   | 66   | 51   | 47      | 41      |
| Inoperative              | -                     | 100     | 116  | 115  | 136  | 135     | 116  | 116  | 120  | 129     | 131     |
| Total (d)                |                       |         |      |      | •    | 267     |      | •    | •    |         |         |
|                          |                       | 2010    | 2011 | 2012 | 2013 | 2014(b) | 2015 | 2016 | 2017 | 2018(c) | Average |
| In operation             | _                     | 140     | 142  | 128  | 134  | 121     | 120  | 114  | 112  | 133     | 51.3%   |
| - Adequate               | _                     | 50      | 54   | 50   | 48   | 49      | 50   | 44   | 42   | 44      | 18.1%   |
| - Worrisome              | _                     | 48      | 48   | 51   | 46   | 34      | 37   | 38   | 43   | 43      | 16.7%   |
| - Critical               | _                     | 42      | 40   | 27   | 40   | 38      | 33   | 32   | 27   | 46      | 16.5%   |
| Inoperative              | -                     | 127     | 125  | 139  | 133  | 146     | 147  | 153  | 155  | 134     | 48.7%   |
| Total (d)                |                       |         |      |      |      | 267     |      |      |      |         |         |

### Time t+1

|                   |                          |         |          |         | lime t+ | 1        |      |      |        |         |          |
|-------------------|--------------------------|---------|----------|---------|---------|----------|------|------|--------|---------|----------|
| Context in time t | Context in time t + 1    | 2000(a) | 2001     | 2002    | 2003    | 2004     | 2005 | 2006 | 2007   | 2008    | 2009     |
| In operation      | -                        |         | 43       | 41      | 39      | 38       | 40   | 46   | 49     | 53      | 45       |
| In operation      | -Adequate                | _       |          | 7       | l       | 38<br>4  | 2    | 0    | 2      |         | 45<br>11 |
|                   | -Worrisome<br>- Critical | _       | 6<br>1   | 0       | 4 0     | 0        | 0    | 0    | 0      | 3 0     | 0        |
| Adagasta          | - Chucai<br>-Inoperative | _       | 0        | 0       | 0       | 0        | 0    | 0    | 0      | 0       | 0        |
| - Adequate        | -                        | _       | 4        | 2       | 3       | 3        | 6    | 5    | 5      | 1       | 2        |
| In operation      | -Adequate<br>-Worrisome  | -       | 37       | 35      | 38      | 39       | 36   | 27   | 25     | 25      | 27       |
|                   | - Wornsome<br>- Critical | _       | 7        | 5       |         | 39<br>10 | 5    | 11   | 25     | 25<br>7 | 3        |
| - Worrisome       |                          | _       | 5        | 6       | 4<br>5  | 3        | 3    | 4    | 2      | 7       | 3        |
|                   | -Inoperative             | _       |          | 0       | 0       | 0        | 0    |      |        |         | 0        |
| In operation      | -Adequate<br>-Worrisome  | _       | 0        |         | 9       | 3        | 5    | 0 3  | 2<br>7 | 1<br>5  | 10       |
|                   | - Wormsome<br>- Critical | _       | 3<br>42  | 4<br>41 | 26      | 20       | 27   | 47   | 37     | 39      | 30       |
| - Critical        |                          | _       | 42<br>19 | 10      | 26      | 20<br>11 | 8    |      | 20     |         | 7        |
|                   | -Inoperative             | -       |          |         |         |          |      | 8    |        | 6       |          |
| In operation      | -Adequate                | _       | 1        | 0       | 0       | 1        | 0    | 0    | 0      | 1       | 0        |
|                   | -Worrisome               | _       | 2        | 4       | 4       | 4        | 4    | 4    | 6      | 2       | 0        |
| T                 | - Critical               | _       | 5        | 13      | 4       | 10       | 26   | 8    | 12     | 1       | 8        |
| - Inoperative     | -Inoperative             | -       | 92       | 99      | 107     | 121      | 105  | 104  | 98     | 116     | 121      |
|                   |                          | 2010    | 2011     | 2012    | 2013    | 2014(b)  | 2015 | 2016 | 2017   | 2018(c) | Average  |
| In operation      | -Adequate                | 43      | 48       | 48      | 43      | 45       | 44   | 43   | 39     | 40      | 90.8     |
|                   | -Worrisome               | 4       | 2        | 6       | 7       | 3        | 4    | 7    | 5      | 2       | 9.0      |
|                   | - Critical               | 0       | 0        | 0       | 0       | 0        | 0    | 0    | 0      | 0       | 0.1      |
| - Adequate        | -Inoperative             | 0       | 0        | 0       | 0       | 0        | 1    | 0    | 0      | 0       | 0.1      |
| In operation      | -Adequate                | 6       | 6        | 2       | 5       | 4        | 6    | 1    | 3      | 4       | 8.6      |
|                   | -Worrisome               | 39      | 37       | 39      | 37      | 27       | 24   | 26   | 29     | 34      | 72.2     |
|                   | - Critical               | 3       | 3        | 3       | 7       | 11       | 4    | 7    | 4      | 5       | 12.5     |
| - Worrisome       | -Inoperative             | 0       | 2        | 4       | 2       | 4        | 0    | 3    | 2      | 0       | 6.8      |
| In operation      | -Adequate                | 0       | 0        | 0       | 0       | 0        | 0    | 0    | 0      | 0       | 0.3      |
|                   | -Worrisome               | 3       | 5        | 5       | 1       | 3        | 7    | 5    | 8      | 6       | 12.2     |
|                   | - Critical               | 34      | 29       | 23      | 25      | 24       | 22   | 20   | 22     | 21      | 67.5     |
| - Critical        | -Inoperative             | 4       | 8        | 12      | 1       | 13       | 9    | 8    | 2      | 0       | 20.0     |
| In operation      | -Adequate                | 1       | 0        | 0       | 0       | 0        | 0    | 0    | 0      | 0       | 0.2      |
|                   | -Worrisome               | 2       | 4        | 1       | 1       | 1        | 2    | 0    | 1      | 1       | 1.9      |
|                   | - Critical               | 5       | 8        | 1       | 8       | 3        | 7    | 5    | 1      | 20      | 6.2      |
| - Inoperative     | -Inoperative             | 123     | 115      | 123     | 130     | 129      | 137  | 142  | 151    | 134     | 91.7     |

Notes:

Table 4. Context of airports in time t and time t + 1 - regular domestic traffic (ANAC data, 2019a)

<sup>(</sup>a) In order to measure the result of 2000 as time t+1, 1999 data (time t) would be necessary, but were not available.

<sup>(</sup>b) Although the airport has moved from the adequate context in 2014 (time t) to the context inoperative in 2015 (time t + t), this refers to the closure of Augusto Severo Airport (SBNT) operations due to the operations of the new Natal Airport - São Gonçalo do Amarante (SBSG)

<sup>(</sup>c) The data for 2019 are not closed, and it is not possible to measure the result of 2018 in time t + 1.

<sup>(</sup>d) Total number of airports that operated regular domestic traffic at some point in the period 2000-2018.

Regarding those classified in the worrying context in time t, on average, 8.6% went to the adequate context in time t+1, 72.2% remained in the worrying context, 12.5% passed to critical and 6.8% to inoperative (ceased to operate regular traffic). 20.8% of the airports classified in the context of concern had their context aggravated. The airports classified in the critical context in time t, on average, 0.3% went to the adequate context in time t+1, 12.2% to the worrying, 67.5% remained in the critical context and 20.0% went into context inoperative.

Several factors may have influenced the change in the context of airports, such as: i) the crisis in Brazilian commercial aviation since 2001 (Burle, 2003), which led to a higher concentration of movement at the central airports, and was explained mainly by the retraction of the economic activity in the Country; ii) closure of Transbrasil and Vasp and Varig operations; iii) the restructuring of the sector through Law 11182/2005, which created the National Civil Aviation Agency (Agência Nacional de Aviação Civil - ANAC) and established the regime of freedom of routes and tariffs, which significantly influenced the results in the period 2006-2008; iv) the global economic crisis in 2008, mainly reflected in 2009; v) the beginning of works to expand the capacity of the airport network in 2011, in order to meet the needs of the games of the 2014 FIFA World Cup; vi) Fusion of Trip, the largest regional airline in Latin America, with Azul Linhas Aéreas in 2012; vii) the World Cup in Brazil and the beginning of the Brazilian economic crisis; viii) the worsening of the Brazilian economic crisis and the readjustment of airport tariffs from 2015.

### 5. Conclusions

The indicator was applicable, and the results allowed to classify the airports into three groups: adequate context, worrying context and critical context, thus signaling airports that could stop operating regular domestic traffic. The information can contribute to the development of reliable, resilient quality airport networks, especially home and regional networks, as they signal to airport operators, regulators, and airlines where they need intervention (measures to reverse the trend). Thus, enabling economic development and equitable access to all regions.

As future research, it is suggested to study the evolution of the Brazilian domestic network until 2025. This would allow comparing the results obtained with the policies and actions included in the PPA 2016-2019 and with the actions adopted in 2017, whose purpose is the fulfilment of SDG 9, goal 9.1 of the "Transforming our world: the 2030 Agenda for Sustainable Development" (United Nations, 2015). It would also allow to verify the influence of the entry of the first foreign airline, Air Europa, into the Brazilian domestic market. Other suggestions would be the application of the indicator in other domestic networks or even in a larger scope, such as the worldwide airport network.

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