COVID-19 Impact in the Brazilian Multiplex Air Transportation Network

Fernanda Silva Toledo, and Nelson Francisco Favilla Ebecken, *Senior Member, IEEE*

***Abstract*—The Brazilian Air Transportation Network has been changing in the last years, due to an economic recession since 2016, the concession of the main airports and the impact of the COVID-19 pandemic. Air transportation is a complex infrastructure system, in which each airline represents a different layer. Adding the weight of interactions combined with a multilayer approach can make the network description even more detailed than a single-layer analysis, because important network features emerge from the multilayer character. The multilayer approach for complex networks is yet new in the literature. As far as the authors know, there are no studies yet applying multiplex network to analyze domestic and international Brazilian air network to improve the understanding of complex systems and investigate macroeconomic effects of the economic recession and COVID-19 pandemic in the air network. The objective of this paper is to evaluate changes in the Brazilian Air Transportation network from 2019 to 2020, before and during the COVID-19 pandemic, using topology measures for network characterization. We compared the network topology and evaluated COVID-19 impact on airports under concession and on regional aviation, also comparing with the aggregated approach. Results show a network concentration during this period in hub airports, reduced connectivity and reduced density resulting in a sparser network. The airlines strategies were different over this period and the multilayer approach changed the importance ranking of airports compared with the aggregated approach. These analyses indicate an opportunity to improve regional air transportation and the need to enhance regional airport's versatility.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9007

***Index Terms*—Air transportation, airports concession, complex networks, COVID-19, multiplex networks.**

I. Introduction

AIR transportation is a fundamental service that has an important role in economic and social development locally, becoming essential to distant locations and ensuring competitive advantages for countries.

In Brazil, after the crisis of 2006 and 2007, the domestic air network underwent a reorganization, with increasing demand and peaks due to two major events, the 2014 FIFA World Cup and the 2016 Rio Olympic Games.

To prepare for these major events, the Brazilian government invested in the expansion and renovation of the main airports and in 2011 started the airport concession project for the private sector. This scenario led to a major reorganization of the airline network, as regional airports were introduced in the air network, increasing the available destinations and the capacity of main airports. Investments in airports infrastructure reflect on socioeconomic factors and thereby increase interurban centrality.

The aviation sector experienced constant growth in the last decade in Brazil, however in 2016 the number of passengers reduced by 7.3%, a reflection of an economic crisis the country had been going through since 2014. In the first trimester of 2017, Brazilian GDP increased by 1%, the first increase in eight trimesters. Also, consumer credit had lower growth in 2016 and 2017, an important macroeconomic variable in the prediction of air traffic demand in Brazil.

Macroeconomic effects and the airline market instability reduced the number of operating airlines in Brazil during the last years. From 2010 to 2018, 20 airlines operated in Brazil in the domestic market, with only 8 carrying more than 0.5% of the total passengers [1]. Air companies with limited market share disappeared and others emerged during this period. Therefore, considering each airline a different network layer, the air transport network in Brazil had 8 layers from 2010 to 2012, 6 layers in 2013 and 5 layers until 2018. After the bankruptcy of Avianca Brasil (OceanAir), with flights suspended in 2019, the air market in Brazil is mainly concentrated in four airlines: Azul, Gol, Latam and VoePass (formerly Pasaredo).

The air transportation network is a complex infrastructure system that can be analyzed using complex network theory. Moreover the air transportation is intrinsically a multilayer network due to different entities interacting with each other including multiple subsystems and layers of connectivity.

The first approach when analyzing a multiplex system is to flatten the network into a monoplex or aggregated network. However, the aggregation of layers leads to a loss of information as links of different types will be lost and handled differently.

Given that, the air transportation network is better described as a multilayer complex network rather than a single-layer network and the introduction of the weight of interactions and multilayer aspect make their description even more detailed improving the understanding of the complex system.

Multiplex networks allow capturing high levels of complexity from real-world systems. However, working with multilayer networks requires that almost all metrics and algorithms commonly used for complex networks to be redefined or adapted. In this field, studies on the evaluation of the net-

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Fernanda S. Toledo, and Nelson F. F. Ebecken are with the Federal University of Rio de Janeiro, Rio de Janeiro, Brazil (e-mails: fernanda.toledo@coc.ufrj.br, and nelson@ntt.ufrj.br).

work structure and topology characteristics are fundamental to predict and understand also dynamical processes.

To the best of our knowledge, there are no studies applying the multiplex approach to the Brazilian air network considering both domestic and international flights, weights in the connections, in the context of economic crisis and COVID-19 pandemic. The main contribution of this paper is to evaluate changes in the Brazilian Air Transportation network from 2019 to 2020, before and during the COVID-19 pandemic, using multilayer network topology measures.

Thus, we built the multiplex air transport network in Brazil, in which the nodes represent the airports, and the links represent the direct routes between them, for 2019 and 2020. The network layers correspond to the different airlines operating in Brazil. Also, we evaluated macroeconomic effect in airports under concession and regional airports, and compared the airports importance ranking in the multiplex and in the aggregated approach. The correlation and overlapping of the layers were also evaluated to understand the airlines strategy's over this period.

II. Literature Review

Complex networks are a representation of real-world complex systems that uses nodes as the objects and links between them that represents their relation. The multiplex networks are a special type of multilayer network. In multilayer systems, there can be interlayer links between nodes and their counterparts in different layers (multiplex networks) or interlayer links between different nodes in different layers (general multilayer). Some examples of multiplex networks are trade networks between countries, transportation networks, social, biological and financial networks.

In Air Transportation Networks (ATNs), the layers can indicate different types of relation, such as different airlines operating in a region, different groups of airports, different countries, or nature of flights (domestic or international). The multilayer approach can identify important features and behavior not observable in a single layer network. For example, this approach can lead to a different node centrality ranking, because travel can occur through layers changing the importance of airports.

ATNs are scale-free networks where the nodes degree follows a power-law distribution with small world behavior [2]. The airport's centrality measures its importance and influence in a network, in the multilayer approach the centrality measures represent the airport's versatility [3]. The multiplex approach and the addition of link weights can introduce a better understanding of the topology of the aviation system, as new structural features emerge in consequence.

Network topology impacts the system's behavior and is essential to the analysis and modelling of complex networks. In general, research studies on structure analysis are divided into normal situations and disrupted scenarios. The change of international connectivity of an ATN during disruption and the impact of ATN topology has rarely been studied, as the scale of disruptions by COVID-19 is much larger than what has been studied yet [4].

Research studies on the change of networks performance under disruptions usually evaluate topology metrics, measures of robustness, vulnerability and resilience. Demertzis et al [5] use an exploratory time-series analysis to the evolution of the COVID-19 disease in Greece detecting connective communities, where each node was considered a different day. The object of the study was to forecast the disease spread limited to the low availability of data.

Ribeiro et al [6] investigated a likely scenario of COVID-19 spreading in Brazil for the 90 days after the first occurrence. They found that the expansion of the disease was directly proportional to the city closeness centrality. Identifying the city vulnerability to the virus and discussing the weak pandemic control performance. They also emphasize the fragility of Brazilian surveillance in the airport network and encourage policy change to preserve the most remote regions that have a weaker health service.

Zhou et al [4] studied the impact of air transportation network topology on a country robustness to pandemic disruptions and proposed a weighted efficiency and a robustness metric to evaluate connectivity. Their research explores the importance of studying the network topology during emergencies. It is important to evaluate the network density because a country with dense domestic ATN such as Germany have easy transit through a domestic air network if airports suddenly shut down international flights. In sparser ATNs such as Australia, travelers may have to take more transit flights or even lose connection with foreign airports.

Sun et al [7] investigated the impact of COVID-19 on global air transportation network in three different scales: on a worldwide scale, in a scale of international country networks, where the countries are contracted as nodes, and in specific regions and countries for domestic networks. They used an spatial-temporal evolutionary dynamics for a comprehensive empirical analysis of the worldwide network, in a monthly-based analysis. Results indicate that connection reduced 50% worldwide and the average betweenness centrality increases through the pandemic. As some hub airports have been shut down, it increased the importance of other airports, increasing their centrality.

However, Sun et al [7] did not use passenger data, load factors or the number of flights, restricting the **links** to the existence of flights and suggest additional information in further studies. They also used data of airport connectivity instead of link weight and did not consider the multiplex aspect of the air network.

In the study of Cardillo et al [8] for London airports, they found that airports that were more central in the aggregate network and have become less important in the multilayer network because they have many connections distributed on a few airlines. Less central airports in the aggregate network can become more versatile as their flights are operated by almost all airlines. The versatility also depends on the contribution of each node to the centrality by layer. In this context, [8] consider a versatility measure instead of the centrality measure when using the multilayer approach.

Brazilian airports centrality was studied in [9], identifying the main airports using h-centrality in 2015, also comparing the network of 2015 and 2019 [10], but not considering the multilayer aspect and characteristics of the network.

Oliveira et al [1] evaluated the evolution of the Brazilian domestic network between 2010 and 2018 using the multiplex approach and the number of passengers as connection weights. In addition, they presented a Multiplex Efficiency Index based on the diversity of the multiplex network, which indicates the variety of connectivity patterns in the structure. The results obtained are fundamental to understanding the history of the Brazilian Multiplex Air Transportation Network. Differently, this study incorporates both domestic and international links and the analysis of specific airports and airlines in a crisis and pandemic scenario.

From this literature review, only Oliveira et al [1] and Cardillo et al [8] applied the multilayer approach in the air transportation network. Oliveira et al [1] evaluated the Brazilian network, however only the domestic network, considering non-directed networks, with a focus on network diversity and efficiency. Cardillo et al [8] explored the network characteristics that emerge from the multilayer approach and the differences between major and low-cost layers. Therefore, both articles did not evaluate all the topological network features, nor the centrality of airports and the similarity of layers.

III. Method

This research is based on the fundamental theoretical assumptions and math formalism from the studies of De Domenico et al [11] [12] [3]. We applied the tensorial formulation of multilayer networks, as this approach can surpass the limitations of individual networks structure for each layer and the aggregated network, approaches that could lead to misleading results and generalize usual centrality measures of the network.

A multiplex network with M layers, each layer having the set of nodes N, is represented by the adjacency matrices $\mathcal{A} = \{A^{[1]},\ A^{[2]},\ \ldots,\ A^{[M]}\}$. With the adjacency matrices, the distance distribution of nodes can be calculated for each node i in layer $\bar{p}$ ($\mathcal{N}_i^{\bar{p}}(d)$). The distance distribution is the fraction of nodes that are at distance d, the shortest path, of the node i in layer $\bar{p}$ (Oliveira et al [1]). Like single-actor measures, the multilayer distances are calculated between pairs of actors.

The path between actors continues on any layer where the corresponding actor is present and can traverse multiple layers. For weighted networks, two matrices need to be described: the adjacency matrix and the matrix of weights. In this research, nodes might (or not) exist in all the layers, which can be measured by multiplexity, the fraction of layers where each node exists, and interlayer links occur only between nodes and their counterparts.

Public data were gathered from the National Civil Aviation Agency (ANAC) from 2019 and 2020 of domestic and international flights of major Brazilian airlines that carried at least 0.5% of the total passengers, except unproductive flights and non-passengers' flights. Data were pre-processed before being imported and then processed on the MuxViz open-source software [12].

In this ATN, nodes represent the airports where the Brazilian companies operate and the links are direct flights between them, the network is directed (links have directions) and weighted (the weight is the total number of passengers carried in that route). Each airline's flights were divided into layers, whose characteristics were calculated such as: the number of nodes, connections, density, the number of connected components, diameter and mean path length. Also, versatility measures were obtained for each airport such as strength, degree, PageRank, Eigenvector, Hub, Authority, Multiplexity, Katz and k-core. Centrality measures are important to identify the most relevant nodes in a network, the indices are used to rank nodes and the obtained measures are accurate for only its context of importance.

The analysis is based on operational and complex network indicators. We compare the topological characteristics of the network in 2019 and 2020 to evaluate the impact of the COVID-19. We also analyzed the versatility ranking position of the top-10 busiest Brazilian airports and the airports on concession until 2017 (the first four rounds of concession). After that, we discuss the impact on regional aviation and compare the results with the COVID-19 impact on the air network worldwide.

In complex networks, the distance between two nodes is the number of edges in the shortest path that connects them, the geodesic distance. The average path length (L_G) in a graph G with vertices V, in which $d(v_1, v_2)$ indicates the shortest path distance between vertices v_1, v_2 (v_1, $v_2 \in V$) and can be assessed with the following equation:

$$L_G = \frac{1}{n(n-1)} . \sum_{i=j} d(v_1, v_2) \tag{1}$$

where n is the number of vertices in the network G. A network with a short path distance length has the quicker transfer of information with reduced cost. The average path length changes proportionally to $log\ n$ and is 0 if one vertex cannot reach the other. Most networks have a short average path length, a small world characteristic.

The node degree is the number of edges connected to a vertex. In a directed graph a vertex has both an in-degree and out-degree, the number of in-coming and out-coming edges, and the total degree is their sum.

The network diameter is the length of the longest geodesic path between two vertices, which can be multiple, which means the shortest distance between the two most distant nodes and represent the linear size of a network. For weighted networks, MuxViz considers the edge weight to calculate the diameter.

Density is the number of connections a network has divided by the total possible connections it could have, therefore the ratio of edges (E) to all the possible edges in a network of N nodes. Given that the maximum number of connections in a complete network is $N\ (N-1)/2$, the network density is:

$$D = \begin{cases} \frac{E}{N(N-1)} & \textit{for oriented graphs} \\ \frac{2\ E}{N(N-1)} & \textit{for non-oriented graphs} \end{cases} \tag{2}$$

The network density can also be calculated by the number of edges divided by the number of nodes, the method used by MuxViz.

The measures of similarity between layers used in this paper are: mean global node overlapping, mean global edge overlapping and inter-layer assortativity. The mean global node overlapping is the fraction of nodes which are common to all layers, the mean global edge overlapping measures the fraction of edges which are common to all layers. The Pearson correlation between the node degrees and their counterparts in the other layers is calculated for all pairs of layers to assess the inter-layer assortativity. The Spearman correlation is calculated for the same purpose and is recommended when the assumptions underlying a Pearson test are not satisfied, which is the level of measurement, absence of outliers and linearity.

IV. Results

The Brazilian Air Transportation Multiplex network had 175 nodes and 12,016 links in 2020, a directed and weighted network composed of four layers: Azul (AZU), Gol (GLO), Latam (TAM) and Voepass (PTB). In comparison, the Brazilian ATN had 159 nodes and 20,951 edges in 2019, with the same four airlines in operation.

The total average degree of the Brazilian ATN decreased from 52.26 in 2019 to 46.42 in 2020, considering in-degree and out-degree, a reduction of 11% indicating the loss of connections. Table I shows the topology characteristics of the Brazilian Air Transportation Network in 2019 and 2020 for each layer.

Analyzing the Brazilian Air Transportation Network, we can notice that there was a growth in the number of nodes from 2019 to 2020, which means the airlines tried to expand their operations adding new airports to their network, especially Azul (+12%) and Voepass (+71%). Despite that, they included mostly airports located in other countries or Brazilian airports that received only a few flights during 2020 (mostly non-regular flights), probably to attend isolated cities and ensure medical supplies and to offer connection for patients.

On the other hand, there is a drastic reduction in the number of routes (edges) offered by all Brazilian airlines. Azul reduced 42% of its aviation routes, Gol 40%, Latam 45% and Voepass 61%, airlines on average reduced 47% their connections among all layers. Voepass had the biggest impact on its network topology, the airline tried to expand its network size operating in more airports, even with a few flights, but had to reduce more than half of the connections probably due to the reduction in the number of passengers during 2020. The impact of those changes is the reduction of the network density and the increase in the network diameter.

In general, all companies reduced the network density, but Azul and Gol managed to also reduce their diameter. Latam, however, had an increase in its network diameter. Although the calculated diameter considers the connection weight, which is also reduced according to the passenger traffic demand. In Table I we compare the MuxViz density and the calculated density (%) using Equation (2). All airlines reduced their network density, especially PTB that reduced from 80.1% to 10.6%. GLO and TAM continue to be the densest layers.

Given that all airlines reduced their number of connections, we can observe an increase in the mean path length, as more connections had to be made to reach a destination from a specific airport. Following the observed results, Voepass had a higher increase in the mean path length. Therefore, it is possible to assure that the Voepass strategy during the pandemic may not have been the best option given the context of the economic crisis and the pandemic. The other three companies also reduced their connections and mean path length but not significantly expanding their network size.

There was also an increase in the number of connected components, both strongly and weakly connected components. The weakly connected component identifies a collection of nodes in which there is a path from any node to any other, disregarding the link direction. In a strongly connected component, there is a directed path from one node to another. This increase reinforces the statement on the loss of connection detaching the network in more components and increasing the mean path length to reach destinations.

Besides, there were changes in the versatility ranking position (Table II) of the top-10 busiest Brazilian airports and the airports on concession until 2017, from 2019 to 2020. The airports of Brasília (SBBR), Salvador (SBSV), Florianópolis (SBFL), Natal (SBSG), Fortaleza (SBFZ) and Recife (SBRF) moved up in the ranking in all versatility measures.

The PageRank algorithm identifies important airports that receive many connections, especially from important airports.

Galeão and Congonhas versatility reduced from 2019 to 2020. Santos Dumont moved up in the Pagerank, while Guarulhos maintained its position. This may indicate the network centralization in the biggest cities such as São Paulo and Rio de Janeiro during the pandemic, but also in specific airports such as Guarulhos and Santos Dumont.

The lower importance of Galeão in the air network has a negative impact given its current underutilized capacity, and even create hurdles to fulfill the mandatory infrastructure expansion during the concession contract, which do not depend on the passenger demand.

Confins airport also reduced its versatility in the network, and Viracopos dropped down several positions, but both maintained their PageRank position. Both airports are important hubs for Azul Brazilian Airlines, which might indicate a negative effect in the airline network and the concentration in only one hub instead of both.

Guarulhos (SBGR) continues to be the most important airport in the versatility ranking and only reduced 5.9% of its connections. However, the airport has only 54% of its strength in 2020 compared with 2019, considering connections and the number of passengers.

The 12 airports that reached 100% of multiplexity in 2020 were all included in the Voepass network. Some of those airports were granted in 2017, (SBFZ, SBFL, SBPA), SBSG and CBCF were granted in 2011 and 2013, respectively, SBMO granted in the 5th round, SBFI and SBAR granted in the 6th round (2021). SBPS and SBIL were granted by the state of Bahia, SBCG was only granted in 2022, and SUMU is the only international airport in this list.

This result may indicate that the concession increases probability for an airport to enter an airline network, although this relation should be further investigated. Among the busiest

TABLE I
AIR NETWORK CHARACTERISTICS OF 2019 AND 2020

	Layers	Nodes	Edges	Density	Density (%)	Diameter	Weakly/Strongly Connected Components	Mean Path Length
2019	Azul (AZU)	119	8.839	74.3	62.9	2.788	41/44	2.2
	Gol (GLO)	86	6.415	74.6	87.8	5.364	74/74	2.1
	Latam (TAM)	77	4.952	64.3	84.6	7.699	83/83	2
	Voepass (PTB)	31	745	24	80.1	797	130/133	2
2020	Azul (AZU)	133	5.125	38.5	29.1	2.55	43/54	2.4
	Gol (GLO)	87	3.877	44.6	51.8	4.372	89/91	2.2
	Latam (TAM)	81	2.721	33.6	42.0	9.112	95/100	2.1
	Voepass (PTB)	53	293	5.5	10.6	2.226	125/134	2.7

and granted airports until 2017, only Recife (SBRF) was not present in all four layers, as it was not in the Voepass network. SBRF was granted only in 2019, making up in the Northeast Cluster, and was the 6th busiest airport in 2020. Therefore, we expected it would constitute the Voepass network in the following years increasing its multiplexity. And only in 2023 Voepass started to operate in Recife.

The airport's average degree of this study decreased 11%, from 2019 to 2020. For the busiest airports and granted airports until 2017, the degree versatility decreased 8% and decreased 51% in the average strength. For future studies, it is suggested to use smaller time windows to map changes in the network.

Comparing the multilayer network and the aggregated network of 2019 (Table II), alterations were identified within the centrality of the airports. These alterations signify a distinct ranking of relative importance, reflective of the multilayer methodology. In terms of node degree analysis for both networks, Brasília surpasses the importance of Congonhas and Confins in the multilayer approach, while Recife ranks lower than Galeão and Congonhas. PageRank analysis elevates Viracopos to second place, with Confins surpassing Brasília. Comparing eigenvector and Katz centrality's, Congonhas is most central in the aggregated network, whereas Guarulhos takes the top spot in the multilayer approach. Therefore, the multilayer approach evidence the higher importance of Guarulhos Airport in the Brazilian air network.

Comparing the layers similarity in 2019 (Table III), the highest node overlapping was between Gol and Azul (0.41) and Gol and Latam (0.34), while Voepass has the smallest node overlapping, due to the the network size.

The highest edge overlapping was between Gol and Latam (0.65), and Gol and Azul (0.26). While Voepass has also the smallest overlapping.

Azul is known to offer more regional flights and has specific hubs such as Viracopos, Confins and Recife. Gol and Latam usually have a similar market share, but Latam has a bigger hub at GRU, probably because of the international flights.

Latam and Gol have the highest Pearson correlation (0.93) followed by Gol and Azul (0.68). Voepass has a higher correlation with Gol in 2020, higher than Azul and Gol. But in general all the overlapping and correlations are the same from 2019 to 2020. The raise of correlations between Voepass and Gol, probably induced the agreement between Gol and Voepass, in which regional network would be developed and operated by Voepass, operating in medium and low-density markets, and connected to routes operated by Gol. This was a capacity purchase agreement in all Voepass slots at GRU in 2022, for example.

The obtained results match worldwide studies [7] that states that the Southern hemisphere air network was more affected by COVID-19 than the Northern, regarding connectivity drop. Connectivity reduction is a measure expected to reduce the pandemic spread but should be taken place much earlier worldwide and especially in Brazil.

In 2020, the passenger demand decreased 55% in Brazil compared with 2019, from 218 million to 99 million (equivalent to 2006 figures), reaching its minimum in April 2020. Although the domestic demand was largely reduced in Brazil, the pandemic has stronger impacts on international passenger traffic than domestic, the same impact observed worldwide (Sun et al [7]). In Brazil, the international and domestic passenger demand reduced by 71.7% and 52.5%, respectively, but domestic traffic represented 93.2% in 2020 (89.0% in 2019). Although, the market dynamics change the behaviour of the network [9] and also the airlines strategies.

In European domestic networks, the number of connections were orders of magnitude smaller after the COVID-19 outbreak. China slightly reduced its connections but re-covered the connectivity until May 2020. Meanwhile, the US had less severe changes than Europe (Sun et al, [7]), one reason is that the US kept financial support to maintain the network activity with less impact which enabled flights with a low load factor, an important topic to discuss in Brazil (Silva et al [13]). China recovered its connections in a few months of the pandemic while the US network started changing only after that.

Lufthansa and other airlines count on governmental support with stabilization funds. US airlines also recovered faster than European airlines with federal subsidies. Other aspects that support US airlines are the dimensions of their domestic market and the relatively accelerated vaccination campaign [7]. Even though, the COVID-19 impact in each country's network vary in timing and intensity.

On average each airport in the worldwide network lost 50% of their connections, reducing efficient connectivity, with fluctuation in the airport's importance during pandemic [7]. While in Brazil the biggest impact was in the number of edges than the average degree.

Another aspect to evaluate is the ground transportation in each region. For example, China and Europe have an effective

TABLE II
AIRPORTS VERSATILITY IN THE MULTIPLEX NETWORK AND AGGREGATED NETWORK

	2019 Multiplex				2019 Aggregated				2020 Multiplex			
Degree Rank	Airport	Degree	PageRank	Katz	Airport	Degree	PageRank	Katz	Airport	Degree	PageRank	Katz
1	SBGR	393	1	1.00	SBGR	198	1	0.96	SBGR	185	1	1.00
2	SBKP	244	2	0.04	SBKP	160	4	0.34	SBBR	113	3	0.64
3	SBBR	229	5	0.75	SBCF	133	5	0.62	SBKP	106	2	0.01
4	SBCF	222	4	0.44	SBRF	107	7	0.44	SBSP	98	5	0.54
5	SBGL	220	8	0.31	SBGL	104	6	0.49	SBGL	86	11	0.19
6	SBSP	183	3	0.91	SBBR	99	3	0.75	SBCF	87	4	0.28
7	SBRF	171	6	0.27	SBSP	86	2	1.00	SBSV	86	8	0.40
8	SBSV	167	10	0.42	SBSV	81	11	0.44	SBRF	83	6	0.26
9	SBPS	153	21	0.11	SBPA	77	9	0.58	SBRJ	67	7	0.52
10	SBPA	150	7	0.48	SBPS	75	23	0.14	SBPA	65	10	0.41

rail/high-speed rail system, meanwhile, the US rely on air transportation in terms of long-distance travel.

In Brazil, infrastructure investment has been more focused on road transportation in the last years, but the territorial extension makes distant regions dependent on air transportation to reach big centres and assure viable accessibility.

The biggest impact of the COVID-19 outbreak is in regional aviation that probably will need more time to recover as some airports still do not have any airline operating in 2023. The number of remote cities in Brazil covered by regular air transportation reduced in the past years concentrating the network due to the economic crisis and recession that even reduced the GDP (Gross Domestic Product) in 2015 and 2016. Also, the population quantitative potentially covered by the aviation system are minimizing in the North region since 2011 [14]. This reduction indicates the optimization of routes and the search for profitability in air routes for remote regions. Consequently, we have a reduction in the aviation service in those remote cities.

The number of airlines operating regular flights in Brazil evidences the fragility regarding the competitiveness in the domestic air market, also their fleet standardization in large aircraft may pose a limitation on encouraging competition in routes with low traffic density [14].

Moreover, Brazilian airlines do not receive any incentive or subsidy to maintain operation in remote cities, and airlines have chosen routes that can guarantee profitability for the operation. Given that, government policies for incentives in air transport in Brazil is an important topic that needs to be discussed to guarantee accessibility in remote places and to assure the safe transport of vaccines and health care.

V. CONCLUSIONS

This research presents an operational and empirical analysis regarding the impact of the COVID-19 pandemic on the Brazilian air transportation multiplex network, covering domestic and international passenger traffic from 2019 to 2020. We used a multiplex approach with weighted links to analyze the network topology, for a better understanding of features that emerge in a multilayer system.

The pandemic impact in the Brazilian air network resulted in a drastic connection drop, following the results worldwide. Nevertheless, Brazilian airlines tried to expand their network, especially Voepass that increased 71% of the number of airports where they operated, but this expansion represents only a few flights to different airports (mostly non-regular flights). Voepass had the biggest changes in its network topology, with an increase in the network size, the reduction in connection resulted in a sparser network with a greater mean path length and diameter. Therefore, results suggest that Voepass strategy was not the best option in this context.

The Brazilian airlines concentrated their flights even more in their hubs, contributing to a sparser network and the need for more connections for passengers to reach the final destination. In general, flights in Brazil concentrated even more in the cities of São Paulo, Rio de Janeiro and Brasília. The Brazilian ATN has been more concentrated in the past years due to the economic crisis Brazil is facing since 2016 and now with the COVID-19 outbreak. For future research, monthly data or different periods can be used to compare the topological changes.

The obtained results along with the literature incite the discussion on government incentives to maintain airports operation in regional and remote cities that cannot always achieve profitability, to supply regional air transport demand and induce economic development and accessibility in those regions. Big markets with government financial support can preserve connectivity, to the detrimental of countries in development [15].

This study helps the understanding of relevant mechanics in the Brazilian multiplex air network to support decision-making on the development required in infrastructure and air connections in the next years. The study is limited to the variables analyzed and can be extended using more data in the link's weight and exploring the statistical effect of macroeconomic variables in the network measures.

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TABLE III
AIR NETWORK LAYERS OVERLAPPING OF 2019 AND 2020

	2019				2020			
Node overlapping	Azul	Gol	Latam	Voepass	Azul	Gol	Latam	Voepass
Azul	1	0.41	0.34	0.16	1	0.41	0.32	0.26
Gol	0.41	1	0.37	0.12	0.41	1	0.33	0.17
Latam	0.34	0.37	1	0.11	0.32	0.33	1	0.15
Voepass	0.16	0.12	0.11	1	0.26	0.17	0.15	1
Edge overlapping	Azul	Gol	Latam	Voepass	Azul	Gol	Latam	Voepass
Azul	1	0.26	0.20	0.01	1	0.25	0.19	0.00
Gol	0.26	1	0.65	0.00	0.25	1	0.69	0.00
Latam	0.20	0.65	1	0.00	0.19	0.69	1	0.00
Voepass	0.01	0.00	0.00	1	0.00	0.00	0.00	1
Pearson Degree	Azul	Gol	Latam	Voepass	Azul	Gol	Latam	Voepass
Azul	1	0.68	0.54	0.30	1	0.58	0.47	0.33
Gol	0.68	1	0.93	0.48	0.58	1	0.93	0.62
Latam	0.54	0.93	1	0.57	0.47	0.93	1	0.60
Voepass	0.30	0.48	0.57	1	0.33	0.62	0.60	1
Spearman Degree	Azul	Gol	Latam	Voepass	Azul	Gol	Latam	Voepass
Azul	1	0.60	0.51	0.29	1	0.58	0.44	0.39
Gol	0.60	1	0.72	0.18	0.58	1	0.68	0.26
Latam	0.51	0.72	1	0.20	0.44	0.68	1	0.23
Voepass	0.29	0.18	0.20	1	0.39	0.26	0.23	1

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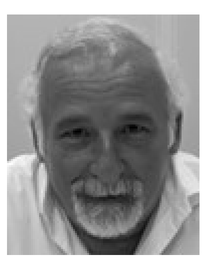
Fernanda S. Toledo received a B.S. in Civil Engineering from Federal University of Triângulo Mineiro, Brazil, in 2016, an M.S. degree in Transportation Engineering from the Military Institute of Engineering, Rio de Janeiro, Brazil, in 2018 and is a Ph.D. candidate in Civil Engineering in the Federal University of Rio de Janeiro, Brazil. Her research focuses on airports' productive efficiency, complex networks applied to air transportation, and discussion on public management and airport concessions.



Nelson F. F. Ebecken received the M.S. and Ph.D. degrees in civil engineering from Universidade Federal do Rio de Janeiro, Brazil, in 1973 and 1977, respectively. Currently, he is the Professor of Computational Systems at the Engineering Graduated Center (COPPE), Universidade Federal do Rio de Janeiro, Brazil. He has published more than 200 papers in journals and conference proceedings. His research focuses on basic methodologies for modeling and extracting knowledge from data and their application across different disciplines. He develops and integrates ideas and computational tools from statistics and information theory with artificial intelligence paradigms. Dr. Ebecken started the International Conference on Data Mining, Rio de Janeiro, Brazil, in 1998. In 2005, he was awarded a membership of the Brazilian Academy of Sciences.