Impact of COVID-19 pandemic in the Brazilian Air Transportation Multiplex Network

Fernanda Silva Toledo[1], Nelson Francisco Favilla Ebecken[2]

[1]*Dept. of Civil Engineering, Federal University of Rio de Janeiro*
Av. Pedro Calmon, 550, Cidade Universitária, 21941-901, Rio de Janeiro, Brazil
Fernanda.toledo@coc.ufrj.br
[2] *Dept. of Civil Engineering, Federal University of Rio de Janeiro*
Av. Pedro Calmon, 550, Cidade Universitária, 21941-901, Rio de Janeiro, Brazil
nelson@ntt.ufrj.br

Abstract. The COVID-19 outbreak disrupted the Air Transportation system on a large scale and reduced connections worldwide, but the impact is different in each country network. Air transportation is a complex infrastructure system, adding the weight of interactions and a multilayer approach can make their description even more detailed. In this field, studies on the evaluation of network structure and topology characteristics are fundamental to predict and understand dynamical processes. This paper aims to assess the COVID-19 outbreak impact in the Brazilian Air Transportation Multiplex Network, comparing the network topology over time and evaluating the effect on airports under concession and regional aviation. The network is based on air passenger traffic of 2019 and 2020 of the ANAC database, in which the airlines were divided into different layers. The proprieties obtained were used for network characterization. We found that the average degree of airports reduced 11%, connections reduced 47% on average for each layer, increasing the mean path length to reach destinations. Passaredo expanded its network during this period but the connection drop reduced the network density and diameter. Results can facilitate decision-making for market strategies for airlines and incite discussion on government incentives and subsidies to continue operation in remote cities maintaining airline operation.

Keywords: Complex networks, multiplex networks, airport concession, air transportation, COVID-19, regional aviation.

1 Introduction

Air transportation enables increasing mobility due to the enhanced connectivity and efficiency, however, critically contributes to spreading diseases worldwide. The COVID-19 outbreak started in December 2019 and quickly spread worldwide. Given that, travel ban restrictions had a significant effect on the air network and induced a large number of flights cancellations.

Aviation is one of the most affected industries due to the consequences of the pandemic outbreak, even being one of the initial drivers of spreading. As a consequence of the unprecedented pandemic, countries have closed borders and people were unable or reluctant to travel because of look-down measures for each country, reducing air passenger demand. According to ICAO (International Civil Aviation Organization), air passenger traffic had an unprecedented decline ever since WWII in 1945. In this context, the dynamics of domestic airport networks are tightly correlated with the COVID-19 situation in each country (Sun et al [1]).

Air transportation is a complex infrastructure system that is better described using the multiplex approach and the weight of interactions. Multiplex networks are complex systems represented by different multiple layers. Each layer consists of a network with one type of interaction. In this system, all layers are coupled together, given that each node might integrate more than one layer. The evaluation of network structure is fundamental to predict and understand dynamical processes.

The aviation sector has social and economic development role in connecting remote destinations and regional aviation can be the means of accessibility in distant cities in a country with continental extension as Brazil. However, regional aviation still faces major challenges outside large urban centres, the lack of infrastructure, lack of passengers, high prices for aviation items and fares. With the lack of tax incentives, the interest of large companies is reduced for the regional sector, especially with the reduced demand.

The Brazilian air transportation multiplex network had to reorganize after the crisis of 2006 and 2007, followed by an increase in demand with a maximum during the 2014 FIFA World Cup and the Rio 2016 Olympic Games. After that, passengers demand declined in 2016 as a result of the economic crisis and recession but was slowly recovering in the next years.

In 2011 the Brazilian government started the program of airports concession for the private sector, which led to another reorganization of the air network. Regional airports only started to be granted in 2019. Until 2021, 44 airports are in concession and more 16 airports are going to be granted in 2022 in the 7th round.

In this context, the multiplex topology of the air network can reflect the expansion or reduction of regional aviation, to achieve internalization of air transport in the national territory. This research aims to assess the impact of the COVID-19 outbreak on the Brazilian Air Transportation Multiplex Network, evaluating the influence on airports under concession and regional aviation, using characteristics and structural properties of the network.

2 Literature Review

Complex networks are a representation of real-world systems using nodes and links between them. In this study, the topological levels are divided into layers. 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, transportations networks, social, biological and financial networks. In air transportation networks (ATNs), the layers can indicate different topics of collaboration, such as airlines. The multilayer approach can identify important features and behavior not observable in a single layer network, as a different node centrality ranking, because travel can occur through layers.

Network topology impacts the system's behavior and is essential to the analysis and modelling of complex networks. 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 (Zhou et al [2]). Research studies about the change of performance on networks under disruptions use topology metrics, measures of robustness, vulnerability and resilience. Demertzis et al [3] 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 study aimed to forecast the disease spread with low availability of data.

Ribeiro et al [4] investigated a likely scenario of COVID-19 spreading in Brazil for the 90 days after the first occurrence. 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 [2] studied the impact of air transportation network topology on the robustness of a country to pandemic disruptions and proposed a weighted efficiency and a robustness metric to evaluate connectivity. Their analysis indicates the importance of studying the network topology during emergencies. The connection density is one important point to evaluate because a country with dense domestic ATN as Germany have easy transit through a domestic air network if airports shut down international flights. In sparser ATNs such as Australia, travellers may have to take more transit flights or lose connection with foreign airports.

Sun et al [1] investigated the impact of COVID-19 on global air transportation network on a worldwide scale, also in a scale of international country networks, where the countries are contracted as nodes, and for domestic networks in specific regions and countries. They focus on spatial-temporal evolutionary dynamics for a comprehensive empirical analysis from January to May 2020, in a monthly-based analysis. They found connection reduced 50% worldwide and the average betweenness centrality increases through the pandemic, as some airports with a hub role have been shut down, increasing the importance of other airports.

However, Sun et al [1] did not use passenger data, load factors or the number of flights, restricting the results 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.

ATNs are scale-free networks where the degree of the nodes follows a power-law distribution. The airport's centrality is a measure of importance and influence of an airport in a network and in the multilayer approach, it represents its versatility. The multiplex approach and the addition of link weights can introduce a better understanding of the pandemic impact and the topology of the aviation system, as new structural features emerge in consequence.

3 Method

This study is based on the fundamental theoretical assumptions and math formalism from the studies of De Domenico et al [5, 6, 7]. The tensorial formulation of multilayer networks 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 one having the set of nodes *N* is represented by the adjacency matrices $\mathcal{A} = \{A^{[1]}, A^{[2]}, \dots, A^{[M]}\}$. With the adjacency matrices, the distance distribution of nodes can be calculated for each node i in layer $\bar{p}$ ($\mathcal{N}_i^{\bar{p}}(d)$). It is the fraction of nodes that are at distance d, the shortest path, of the node i in layer $\bar{p}$ (Oliveira et al [8]). Like single-actor measures, the multilayer distances are computed 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, 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 (De Domenico et al [7]).

In this ATN, nodes represent the airports and the links are direct flights between them, the network is directed (links have directions) and weighted (the weight is the number of passengers carried in that route). The flights for each airline were divided into layers, whose characteristics were calculated 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 produce a node ranking and its 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 analysed 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 $d\ (v_1, v_2)$, where $v_1,\ v_2\ \in V$, indicates the shortest path distance between vertices v_1, v_2 and can be assessed with the equation:

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

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:

$$D = \frac{E}{N(N-1)}\ for\ oriented\ graphs;\ D = \frac{2\,E}{N(N-1)}\ for\ non\ oriented\ graphs \tag{2}$$

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

4 Results and Discussion

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, Gol, Latam and Passaredo. 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 network decreased from 46.42 (in-degree and out-degree) in 2020 to 52.26 in 2019, a variation of 11% indicating the loss of connections. Table 1 shows the topology characteristics of the Brazilian Air Transportation Network in 2019 and 2020 for each layer.

Table 1. Air Network Characteristics of 2019 and 2020

	Layers	Nodes	Edges	Density	Density (%)	Diameter	Weakly/Strongly Connected Components	Mean Path Length
2019	Azul (AZU)	119	8839	74.3	62.9	2788	41/44	2,2
	Gol (GLO)	86	6415	74.6	87.8	5364	74/74	2,1
	Latam (TAM)	77	4952	64.3	84.6	7699	83/83	2
	Passaredo (PTB)	31	745	24	80.1	797	130/133	2
2020	Azul (AZU)	133	5125	38.5	29.1	2550	43/54	2.4
	Gol (GLO)	87	3877	44.6	51.8	4372	89/91	2.2
	Latam (TAM)	81	2721	33.6	42.0	9112	95/100	2.1
	Passaredo (PTB)	53	293	5.5	10.6	2226	125/134	2.7

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 the network, especially Azul (+12%) and Passaredo (+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).

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 Passaredo 61% (47% on average among all layers). Passaredo 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.

The other companies also faced a reduction in the network density, but Azul and Gol managed to also reduce the 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 1 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, Passaredo had a higher increase in the mean path length. Therefore, it is possible to assure that the Passaredo strategy during the pandemic may not be the best option given the context. 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. 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 in more components and increasing the mean path length to reach destinations.

Analysing the versatility ranking position (Table 2) of the top-10 busiest Brazilian airports and the airports on concession until 2017, we can notice some changes from 2019 to 2020. The airports of Brasília (SBBR), Salvador (SBSV) and Florianópolis (SBFL) felt ranking positions in all versatility measures. Natal (SBSG), Fortaleza (SBFZ) and Recife (SBRF) airports too, but maintained their PageRank position. The PageRank algorithm identifies important airports that receive many connections, especially from important airports.

Galeão and Congonhas versatility raised from 2019 to 2020, while Santos Dumont and Guarulhos maintained their position. This may indicate the network centralization in the biggest cities such as São Paulo and Rio de Janeiro during the pandemic. The higher importance of Galeão in the air network is positive given their underutilized capacity, as its mandatory infrastructure expansion during the concession contract did not meet the passenger demand.

Confins airport also increased its versatility in the network, with a highlight to Viracopos that moved up several positions. Both airports are important hubs for Azul Airlines, which means the airline concentrated the network even more in those hubs.

Table 2. Air Network Characteristics of 2019 and 2020

Concession Round	Airport	PageRank		Eigenvector		Hub		Authority		Katz		Multiplexity		Kcore	
1	SBSG	22	0	16	▼ -3	16	▼ -1	16	▼ -3	16	▼ -1	1	0.25	18	▼ -3
2	SBKP	2	0	58	▲ 10	58	▲ 9	58	▲ 9	58	▲ 9	1	0	22	▼ -3
2	SBGR	1	0	1	0	1	0	1	0	1	0	1	0	22	▼ -3
2	SBBR	3	▼ -2	2	▼ -1	2	▼ -1	2	▼ -1	2	▼ -1	1	0	22	▼ -3
3	SBGL	11	▲ 3	15	▲ 5	15	▲ 5	15	▲ 5	15	▲ 5	1	0	22	▼ -3
3	SBCF	4	0	9	▲ 3	9	▲ 3	9	▲ 3	9	▲ 3	1	0.25	22	▼ -3
4	SBFZ	12	0	7	▼ -2	7	▼ -2	7	▼ -2	7	▼ -2	1	0.25	18	▼ -4
4	SBSV	8	▼ -2	6	▼ -2	6	▼ -1	6	▼ -2	6	▼ -1	1	0	22	▼ -3
4	SBFL	16	▼ -2	11	▼ -1	11	▼ -1	11	▼ -1	11	▼ -1	1	0.25	21	▼ -1
4	SBPA	10	▲ 3	5	0	5	0	5	0	5	0	1	0.25	22	▼ -3
Public	SBSP	5	▲ 2	3	▲ 1	3	▲ 1	3	▲ 1	3	▲ 1	1	0	22	0
Public	SBRJ	7	▼ -2	4	0	4	0	4	0	4	0	1	0	22	▼ -3
Public	SBRF	6	0	10	▼ -1	10	▼ -1	10	▼ -1	10	▼ -1	0.75	0	22	▼ -3

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

Airports that reached 100% of multiplexity in 2020 were all included in the Passaredo network. Those airports were mostly granted in 2017, which may indicate the concession increase probability for an airport to enter an airline network, although this relation should be further investigated. For this set of airports, only Recife (SBRF) is not yet present in all four layers, as it is still not in the Passaredo network. SBRF was granted only in 2019, making up in the Northeast Cluster, and was the 6th busiest airport in 2020. Therefore, it may constitute the Passaredo network in the following years increasing its multiplexity.

The k-core of those airports is lower than in 2019, but the maximum k-core changed from 25 to 22, therefore most of them are still in the k-core with higher degree connectivity in the network. The airport's average degree decreased 11%, but for this sample, the degree versatility decreased 8% and 51% in average strength.

The ranking of the top-10 busiest Brazilian airports (Table 3) had some changes from 2019 to 2020. Brasília became the second airport with higher passenger movement, ahead of Congonhas. Viracopos moved up two positions and Confins went down two positions. Galeão moved from 4th to 8th busiest airports in Brazil, not following its versatility increase. Congonhas and Galeão had the biggest movement drop of 69.3% and 67.0% respectively in 2020, even though those airports had a versatility ranking increase.

As COVID-19 quickly spread worldwide since the beginning of 2020, travel ban restrictions had a significant impact on the air transportation network and reduced air passenger demand worldwide, Brazil also shows the same connection reduction. Throughout 2020, some airlines had their passenger aircraft retooled for cargo-only transportation to maintain flights and economic balance (Sun et al, [1]), a strategy also taken by Brazilian airlines. Although, those changes do not impact the results in this research that do not include non-passenger flights.

Table 3. Top- 10 busiest Brazilian airports of 2019 and 2020

	2020 Ranking	2019 Ranking	Passengers (mi)	Annual growth rate
SBGR	1	1	20.24	-52.9%
SBBR	2	3	7.89	-53.2%
SBSP	3	2	7.01	-69.3%
SBKP	4	6	6.69	-37.0%
SBRJ	5	7	5.00	-45.3%
SBRF	6	8	4.79	-45.5%
SBCF	7	5	4.77	-56.7%
SBGL	8	4	4.59	-67.0%
SBSV	9	10	3.71	-50.1%
SBPA	10	9	3.48	-58.1%

The obtained results match worldwide studies (Sun et al, [1]) that states that the Southern hemisphere was more affected 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 54.6% in Brazil compared with 2019, from 218.29 million to 99.17 million (equivalent to 2006 of 98.1 million), 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, [1]). 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).

In domestic networks such as the European, the number of connections has been orders of magnitude smaller. 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, [1]), 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 [9]). China recovered its connections in a few months of the pandemic while the US network started changing only after that. Therefore, the changes in each country's network are unsynchronized and have different degrees.

In general, the aviation industry reacted to the pandemic with a delay of about two to there months and the postponing missed the opportunity to avoid the pandemic spreading. The scientific knowledge about the disease offered options for a much more coordinated global response that has been missed (Sun et al, [1]).

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 (Sun et al, [1]). 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 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, but the territorial extension makes distant regions dependent on air transportation to reach big centres and assure viable accessibility.

International airlines are discussing their market strategies and business plan to restructure following the impact of the coronavirus pandemic. Lufthansa, for example, plans to reduce fleet size and to cut additional jobs in the next two years to reduce costs through restructuring. The enterprise seeks a smaller, more agile and sustainable business to maintain its leading position worldwide. However, 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 (Sun et al, [1]).

The biggest impact of the COVID-19 outbreak is in regional aviation that probably will need more time to recover as some airports still have no airlines operating in 2021. 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 (Ventura et al, [10]). This reduction indicates the optimization of routes and the search for profitability in air routes for remote regions. As a consequence, we have a reduction in the aviation service in 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 be considered a limiting factor to encourage competition in routes with low-density in traffic (Ventura et al, [10]).

Moreover, Brazilian airlines do not receive any incentive or subsidy to maintain operation in remote cities, and they choose routes that can guarantee profitability for the operation. Given that, government policies for subsidizing 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, for example.

5 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 Passaredo 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). Passaredo had the biggest changes in network topology because even 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 the airline strategy was not the best option in this context.

Brazilian airlines concentrated flights even more in their hubs, contributing to a sparser network and the need for more connections to reach their destination. In general, flights concentrated even more in São Paulo, Rio de Janeiro and Brasília. The Brazilian Air Transportation Network has been more concentrated in the past years due to the economic crisis and now with the COVID-19 pandemic. For future research, monthly data or different periods can be used as the pandemic was declared on 11 March 2020.

The obtained results along with literature incite the discussion on government incentives and subsidies to maintain operation in remote cities that cannot always maintain profitability, to gather regional air transport implementation inducing economic development and accessibility. The study helps the understanding of relevant mechanics in the Brazilian multiplex air network to fundament decision-making on the development required in infrastructure and connections in the next years.

Acknowledgements. The authors acknowledge the support and funding of CAPES and FAPERJ.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] Sun, X., Wandelt, S., & Zhang, A. “How did COVID-19 impact air transportation? A first peek through the lens of complex networks”. *Journal of Air Transport Management*, 89, 101928, 2020.
[2] Zhou, Y. et al. "The impact of network topology on air transportation robustness to pandemics," *IEEE Transactions on Network Science and Engineering*, 2021.
[3] Demertzis, K., Tsiotas, D., & Magafas, L. (2020). “Modeling and Forecasting the COVID-19 Temporal Spread in Greece: An Exploratory Approach Based on Complex Network Defined Splines”. *International Journal of Environmental Research and Public Health*, 17(13), 4693.
[4] Ribeiro, S. et al. “Severe airport sanitarian control could slow down the spreading of COVID-19 pandemics in Brazil”. *PeerJ*, v. 8, p. e9446, 2020.
[5] De Domenico, M. et al. “Mathematical formulation of multi-layer networks.” *Phys. Rev.* X 3, 041022, 2013.
[6] De Domenico, M. et al. “Ranking in interconnected multilayer networks reveals versatile nodes”. *Nat. Commun*. 6:6868, 2015.
[7] De Domenico, et al. “MuxViz: a tool for multilayer analysis and visualization of networks”. *Journal of Complex Networks, 3(2),* 159–176, 2014.
[8] Oliveira, I.M., Carpi, L.C. & Atman, A.P.F. “The Multiplex Efficiency Index: unveiling the Brazilian air transportation multiplex network—BATMN”. *Sci Rep* 10**,** 13339, 2020.
[9] Silva, C. J. L. et al. “Subsidized Regional Airlines as a Sustainable Development Mechanism for Remote Locations Heavily Dependent on Air Transportation”. *Journal of Sustainable Development*, v. 14, n. 4, 2021.
[10] Ventura, R. V., Cabo, M., Caixeta, R., Fernandes, E., & Aprigliano Fernandes, V. “Air transportation income and price elasticities in remote areas: The case of the Brazilian Amazon region”. *Sustainability*, 12(15), 6039, 2020.