A Multilayer and Time-varying Structural Analysis of the Brazilian Air Transportation Network *

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Abstract. *This paper provides a multilayer and time-varying structural analysis of one air transportation network, having the Brazilian air transportation network as a case study. Using a single mathematical object called MultiAspect Graph (MAG) for this analysis, the multi-layer perspective enables the unveiling of the particular strategies of each airline to both establish and adapt in a moment of crisis its specific flight network.*

1. Introduction

Recent analyses of the Brazilian domestic air transportation network focused on flight delay analysis [Sternberg et al. 2016] or aggregated structural analysis of the network [Couto et al. 2015]. Such recent structural analysis of the Brazilian domestic air transportation network [Couto et al. 2015], as well as the global air transportation network [Verma et al. 2014, Wei et al. 2014], were elaborated using aggregated network graphs, containing basically information about airports (localities) and routes (links between airports). This type of analysis disregards the temporal information of scheduling of flights, making information about connecting flights (i.e. network paths) not reliable, since no time information is available to the flights. Therefore, in these network models, it is not possible to guarantee the time sequence of the connecting flights, since there is no temporal information in the route graph. The aggregated view of the air transportation network also conceals the structural subnetwork of each one of the airline companies, thus being oblivious to the particular strategies adopted by each company when defining their specific air transportation network.

In this paper, we analyze the Brazilian domestic air transportation network in such a way that all time scheduling information is preserved. Furthermore, information identifying the company of each flight is also made available, so that the network may be studied as a whole, or using different perspectives such as views from independent airline companies, used routes, and performed flights. In contrast, previous work typically focused on a single aspect of the concerned flight network, such as the aggregated structure [Couto et al. 2015], the multilayer perspective [Tsiotas and Polyzos 2015], or a property of the network such as flight delays [Sternberg et al. 2016].

This paper is organized as follows. Section 2 describes our methodology. Section 3 analyzes the results. Finally, in Section 4, we conclude the paper.

*In [Couto et al. 2015], an extended version of this paper is presented as a research report no. 6/2018 at the National Laboratory for Scientific Computing (LNCC)

2. Methodology

In this section, we describe the methods and tools that we use in the model construction as well as to obtain the results presented in this article.

2.1. MAG

MultiAspect Graph (MAG) [Wehmuth et al. 2016] is a graph generalization that can represent high-order networks, such as multi-layer, time-varying, or time-varying multi-layer complex networks, and so on. In this context, an aspect is an independent feature of the complex networked system to be modeled, such as localities, layers, and time instants. One of the key characteristics of a MAG is to be isomorphic to a directed graph and a companion tuple [Wehmuth et al. 2017]. In this way, with a MAG, it is possible to apply the already available knowledge from graph theory for analyzing directed graphs directly into the MAG environment.

In this work, we model the Brazilian air transportation network as a network composed of localities (airports), layers (corresponding to the individual air transportation network of each airline company), and time instants. However, the results obtained are expressed only regarding locations (airports) and their links (routes). The achieved results take into account the time and layer structure of the model to respect the time sequence of available flights as well as the operating boundaries between different airlines.

2.2. K-Core

In our analysis, we use the K-Core algorithm [Seidman 1983] to identify the network core. The K-Core of a network is obtained through a continuous decomposition of the network that removes all vertices with connectivity lower than the value of k and their respective connections. For example, eliminating all vertices of degree 1, the result is a core with vertices with at least degree 2. The resulting graph in this case is the 2-core. Increasing the value of k, the final round of the algorithm happens when it is impossible to eliminate more vertices, in other words, the network with (k+1)-core is empty. In other words, in this case, the maximum K-Core is achieved. Note that for two cores to be considered equal they must be composed of the same vertices and edges, i.e., they must have the vertices linked by the same topological structure.

By adopting the K-Core algorithm to analyze the air transportation network, the intent in this paper is to focus on a structural analysis of the most relevant vertices of the Brazilian air transportation network (i.e., those that compose the core of the network) under different perspectives as discussed in Section 3.

3. Results

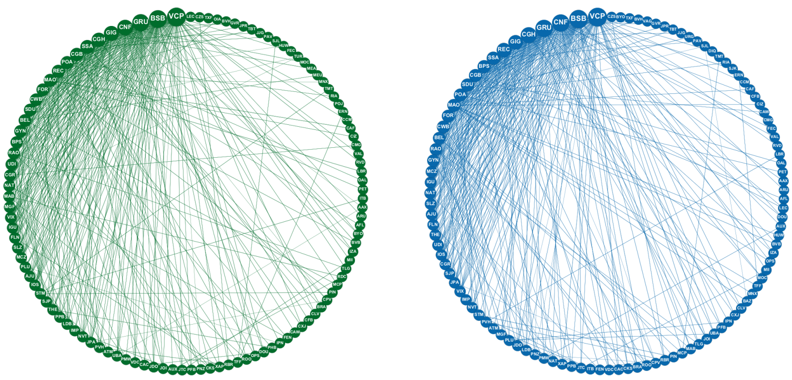
This section presents the adopted datasets corresponding to the Brazilian air transportation network in two different periods of time and the structural analysis of this network taking into account different viewpoints, such as time-varying and multilayer perspectives.

3.1. Model construction

To represent the Brazilian domestic air transportation network, we use two flight schedules: one from June 3, 2015, and the other from May 13, 2016, both published by the National Civil Aviation Agency (ANAC) on its website. These schedule tables contain information about domestic, international, postal, and cargo flights covering a period of one week. We extract from these tables the information about domestic commercial passenger flights, the target of this paper, on both periods (2015 and 2016), separated by approximately 11 months.

The MAG-based model proposed in this paper to analyze the Brazilian air transportation network has four aspects: airports, airlines, flight time instants, and the time period of the dataset. The first aspect contains all airports in Brazil that had at least one flight registered in the week each dataset refers to. There are 110 and 109 airports in the 2015 and in the 2016 dataset, respectively. The second aspect contains all the airline companies. In the 2015 dataset, there are seven airlines (Azul, Avianca, Gol, Map, Passaredo, Tam, and Sete). In the 2016 dataset, there are eight airlines (Azul, Avianca, Gol, Map, Passaredo, Tam, and Sete). We focus our structural analysis on the four largest airline companies, namely Gol, TAM, Azul, and Avianca, as they together concentrate more than 90% of the routes between airports and 95% of the flights that use these routes in the Brazilian domestic air transportation network.

To ease the modeling, we create two layers for each airline: The first layer represents the actual flights and the second layer represents the possible connections between flights, resulting in fourteen layers for the first dataset and in sixteen layers for the second one. In the third aspect, there is information about all the flight times, in minutes, in a week. The forth aspect identifies the corresponding time period of the dataset: The value one is used for the 2015 dataset and the value two for the 2016 dataset.



(a) July 2015 (b) May 2016

Figure 1. Brazilian domestic air transportation network.

3.2. Comparison of the Brazilian air transportation network: 2015 x 2016

The severe economic crisis in Brazil in 2016 directly impacted several sectors of the economy, making them to adapt to the new reality. In this context, civil aviation was no exception, and there has been an adjustment on the part of the airline companies in their availability of flights, resulting in a change in the Brazilian domestic air transportation network from 2015 to 2016 that we start analyzing in this section. Figure 1 shows the full Brazilian air transportation network for both the 2015 and 2016 datasets, sub-determined to show only the first MAG aspect, i.e., the locations (airports). In this representation, a

Table 1. Number of served airports in the Brazilian air transportation network.

Company	# Airports in 2015	# Airports in 2016	Difference (%)
Gol	56	53	-5
Azul	100	94	-6
TAM	43	46	+7
Avianca	23	24	+4

Table 2. Number of routes in the Brazilian air transportation network.

Company	# Routes in 2015	# Routes in 2016	Difference (%)
Gol	324	242	-25
Azul	454	377	-17
TAM	250	234	-6
Avianca	102	109	+6
Total	1130	962	-15

vertex is an airport and an edge is a route between two airports. Table 1 shows the number of served airports by each airline in the Brazilian air transportation network in 2015 and 2016. There are some slight changes with some airlines serving less airports while others started serving more airports. imposing changes in the Brazilian air transportation network. We here analyze not only the changes in the number of served airports, but most importantly we analyze how these airports are served in terms of routes between them and also in terms of the number of flights using these routes. In particular, we show that changes are in general more significant when taking those perspectives into account.

Table 2 shows a reduction of 15% in the number of routes of the main airlines in the Brazilian air transportation network between June 2015 and May 2016. The three largest airlines in the country (Gol, Azul, and TAM) had significant reductions in their number of routes, specially Gol with a 25% decrease in the number of routes in the time period. Nevertheless, Avianca increased the number of routes by 6%, showing that it took advantage of the route reduction made by larger airlines to occupy some niches and expand. Therefore, the average growth of smaller companies in times of crisis is their strategy to partially fill the gaps in routes left by larger companies.

Furthermore, Table 3 shows the difference in the number of flights between June 2015 and May 2016, indicating a 20% decrease in the number of flights. In general, the changes in the number of flights follow a similar trend as in the change in the number of routes, but the intensity of the increase or reduction in the number of flights is even larger in the extreme cases. Considering the number of flights, for instance, Gol had a decrease of 37%, whereas Avianca had an increase of 13% in their number of flight, suggesting that the intensity that the airline companies use the route by offering more or less flights along a week in each route also represents a change in another dimension.

Additionally, *codesharing* is regularly used to optimize occupation in flights on low volume routes. Considering the analyzed datasets, the number of cases of *codesharing* went from 923 to 1234 flights per week, an increase of about 33%. This strategy

Table 3. Number of flights in the Brazilian air transportation network.

Company	# Flights in 2015	# Flights in 2016	Difference (%)
Gol	6644	4188	-37
Azul	5839	5075	-13
TAM	4814	4158	-14
Avianca	1386	1561	+13
Total	18683	14982	-20

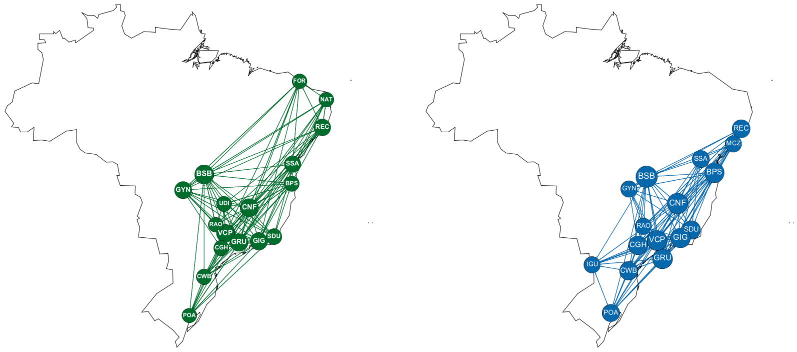
virtually keeps a declared flight active in a per airline view, but it actually represents a reduction in the number of real flights on air.

3.3. Digraph analysis: The route-based perspective

A digraph is a simple directed graph. In our context, a digraph represents the existing routes between the airports, disregarding how busy each route is (i.e., how many daily flights compose the route). We first analyze the Brazilian air transportation network with the digraph format. In contrast to [Couto et al. 2015], which also uses the digraph approach, we apply the K-Core methodology to the Brazilian air transportation network. Moreover, we also apply such a methodology to the flight network of each airline company, allowing a number of different analyses concerning the structure of the network at its basic core structure. These properties of the Brazilian air transportation network were analyzed in two different time periods (2015 and 2016). The resulting central core of the flight network of each airline company indicates the key airports for each company, thus unveiling the strategy of each company in defining its flight network. Therefore, the obtained information with the K-Core methodology allows the analysis of the concentration of the activities of each airline, a comparison of the strategies taken by the companies, and the identification of the hubs of the companies.

First, we analyze the connectivity of the maximum K-Core in the digraph corresponding to the whole Brazilian air transportation network, thus focusing on the structural analysis of the basic core of the flight network. Figure 2 shows the geo-referenced K-Core of the digraph corresponding to the route-based perspective of the complete Brazilian air transportation network, as indicated by the 2015 and 2016 dataset. The 2015 core network results from the maximum K-Core with K=18, 17 airports, and 196 routes. Similarly, the 2016 core network results from the maximum K-Core with K=18, 16 airports, and 182 routes. As it could be expected, the south and southeast regions, which present the largest share in Brazil's economy, are also the regions that compose the central core of the air transportation network, with a small trend of even stronger concentration in 2016.

We now consider the connectivity of the maximum K-Core in the digraph corresponding to the flight network of each of the four main airline companies in Brazil. Table 4 shows the maximum core number K as well as the number of airports and routes in the maximum K-Core of each of the main airline companies, both in June 2015 and May 2016. The maximum core number K of all airlines remained the same between the two time periods, although the number of airports and routes in the maximum core of the main airline companies has been significantly reduced, except for Avianca, which kept the same core. This indicates that the main airlines have significantly reduced the number



(a) 2015 (b) 2016

Figure 2. Geo-referenced K-Core of the Brazilian air transportation network with a digraph (route-based) perspective as of July 2015 and May 2016.

Table 4. Comparison of maximum K-Cores in the digraph representation.

Company	Core (K)		# Airports		# Routes	
	2015	2016	2015	2016	2015	2016
Gol	12	12	13	8	106	50
Azul	10	10	21	15	174	110
TAM	10	10	13	10	92	64
Avianca	8	8	8	8	42	42

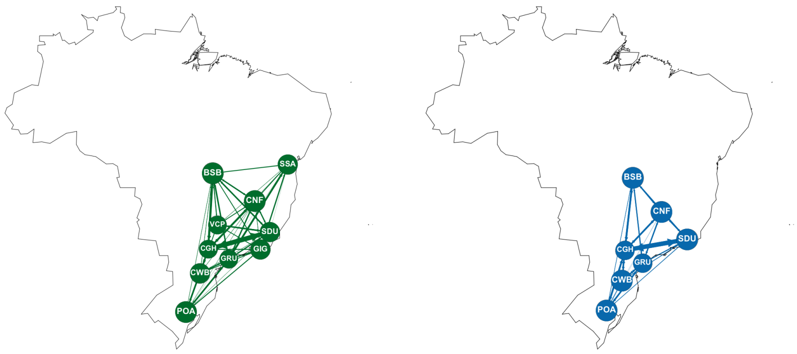
of key airports and routes among them in their core structures, although the same level of connectivity was kept. The exception here is Avianca that kept the same level on its structure (the same K-Core size) with only some slight changes in the structure of its core.

3.4. Multi-digraph analysis: The flight-based perspective

In this section, we analyze the results obtained from the multi-digraph corresponding to the flights in the Brazilian air transportation network. Multi-digraph is the oriented graph that may have multiple (or parallel) edges, i.e., two vertices may be connected by more than one edge. In other words, a single route between two airports, as seen in the digraph format in Section 3.3, can be split into multiple flights that use that route. This feature of the multi-digraph can thus better represent the real usage of a route, since typically many airport pairs are connected by multiple flights along a single day. The multi-digraph representation thus allows quantifying how busy a route between an airport pair is.

Figure 3 shows the geo-referenced K-Core of the Brazilian air transportation network with a multi-digraph (flight-based) perspective for 2015 and 2016. The trend towards concentration emerges in Figure 3(b) showing the busiest airports in the country.

We analyze the connectivity of the maximum K-Core in the multi-digraph corresponding to flight network of each of the four main airline companies in Brazil. Table 5 shows the maximum core number K as well as the number of airports and flights in the maximum K-Core of each of the main airline companies, both in June 2015 and May 2016.



(a) 2015 (b) 2016

Figure 3. Geo-referenced K-Core of the Brazilian air transportation network with a multi-digraph (flight-based) perspective as of July 2015 and May 2016.

Table 5. Comparison of maximum K-Cores in the multi-digraph representation.

Company	Core (K)		# Airports		# Flights	
	2015	2016	2015	2016	2015	2016
Gol	395	308	2	2	395	308
Azul	288	288	6	6	1131	1120
TAM	381	345	2	2	381	345
Avianca	160	160	2	2	160	160

4. Conclusion

This paper provides a structural analysis of the Brazilian air transportation network in two time periods (June 2015 and May 2016).A comparative analysis between this two time periods brings results on how the economic crisis impacted the Brazilian air transportation network, as it is shown that the main airline companies have reduced the routes they use between airports and the number of flights that use these routes by 15% and 20%, respectively, representing a significative contraction of the Brazilian air transportation network.

Moreover, adopting MultiAspect Graphs (MAGs) [Wehmuth et al. 2016, Wehmuth et al. 2017] for the modeling enabled a multilayer and time-varying structural analysis of the Brazilian air transportation network using a single mathematical object, thus easing the processing and analysis. With such an approach, the multi-layer perspective enabled the unveiling of the particular strategies of each airline to both establish and adapt in a moment of crisis their specific flight networks. Similarly, the time-varying perspective allowed analyses considering different time periods, and thus assessing the impact of the economic crisis, but also analyzing the different airlines concerning their routes as well as the flights that use these routes. Altogether, these different perspectives allowed the analysis of the impact on the Brazilian air transportation network due to economic restrictions. Therefore, besides the multilayer and time-varying structural analysis of the Brazilian air transportation network, this paper also acts as a proof-of-concept for the MAG potential for the modeling and analysis of high-order networks.

Future work includes the development and application of new centrality measures to be applied in MAGs, including time centralities [Costa et al. 2015], in particular considering applications for transportation networks.

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References

Costa, B., Bechara, J. V., Wehmuth, K., and Ziviani, A. (2017). A multilayer and time-varying structural analysis of the Brazilian air transportation network. Technical report. Available at http://arxiv.org/abs/1709.03360.

Costa, E. C., Vieira, A. B., Wehmuth, K., Ziviani, A., and da Silva, A. P. C. (2015). Time centrality in dynamic complex networks. *Advances in Complex Systems*, 18(07n08).

Couto, G. S., da Silva, A. P. C., Ruiz, L. B., and Benevenuto, F. (2015). Structural properties of the brazilian air transportation network. *Anais da Academia Brasileira de Ciências*, 87:1653–1674.

Seidman, S. B. (1983). Network structure and minimum degree. *Social Networks*, 5(3):269–287.

Sternberg, A., Carvalho, D., Murta, L., Soares, J., and Ogasawara, E. (2016). An analysis of Brazilian flight delays based on frequent patterns. *Transportation Research Part E: Logistics and Transportation Review*, 95:282–298.

Tsiotas, D. and Polyzos, S. (2015). Decomposing multilayer transportation networks using complex network analysis: a case study for the Greek aviation network. *Journal of Complex Networks*, 3(4):642–670.

Verma, T., Araújo, N. A. M., and Herrmann, H. J. (2014). Revealing the structure of the world airline network. *Scientific Reports*, 4:1–6.

Wehmuth, K., Fleury, É., and Ziviani, A. (2016). On MultiAspect graphs. *Theoretical Computer Science*, 651:50–61.

Wehmuth, K., Fleury, É., and Ziviani, A. (2017). MultiAspect Graphs: Algebraic Representation and Algorithms. *Algorithms*, 10(1):1–36.

Wei, P., Chen, L., and Sun, D. (2014). Algebraic connectivity maximization of an air transportation network: The flight routes' addition/deletion problem. *Transportation Research Part E: Logistics and Transportation Review*, 61:13–27.