Modeling Resilience of Air Traffic Management Systems Based on Complex Networks

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ABSTRACT

The air transport market has a strategic character, promotes economic and social development, and has a strong correlation with the level of economic activity. The Air Traffic Management (ATM) system plays an essential role in air transportation and can be characterized as a sociotechnical system that is too complex to research through classical approaches such as systems engineering. In this sense, the application of Complex Network Theory (CNT) analysis and modeling paradigms is driven by the need to accommodate the growth of air traffic within an already saturated ATM infrastructure. The present work describes the development of a resilience evaluation model of ATM systems based on CNT, its metrics and analysis tools. The model was applied to the Brazilian ATM system, demonstrating its usefulness in identifying the air traffic control (ATC) agencies that have the greatest influence on the network. The results also showed that the Brazilian ATM network is resilient to random failures; however, it is particularly vulnerable to targeted attacks to the ATC agencies with the highest centrality. The research findings can be applied to prioritize the deployment of systems and equipment that enhance the resilience and operability of the Brazilian ATM system.

Keywords: Air traffic management; ATM; Complex networks; CNT; Resilience.

INTRODUCTION

The air transport market has a strategic character for countries, promotes economic and social development and is correlated with the level of economic activity. With regard to passenger traffic, demand for air transport continues at its own pace, with positive growth rates. International travel and tourism, in particular, remain unstoppable and supported by the dynamics of the industry, according to the prospective analysis of the Airports Council International.

In the Brazilian market, government actions—such as the airport concessions program, the release of 100% of foreign capital participation in Brazilian companies, tax incentives aimed at reducing costs with aviation kerosene and positive signs for the approval of the *open skies* policy—implemented a project a favorable prospective scenario.

In the view of Stefan *et al.* (2012), to understand an air transport system it is necessary to examine the interactions between the components that make it up, including airlines, airports and, with special attention, Air Traffic Management (ATM), that comprises a sociotechnical system that is too complex to be researched and improved through the use of classical approaches such as systems engineering and human factors.

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The application of complexity science paradigms to the analysis and modeling of future operations is driven by the need to accommodate long-term air traffic growth within an already saturated ATM infrastructure (Blom and Bouarfa 2016).

This management strategy combines, in a strongly integrated way, the work of people with technical subsystems and operational procedures in a complex system characterized by numerous simultaneous interactions between its various components, not being possible to fully understand through the study of its components individually, then adding its characteristics (Cook *et al.* 2015).

In this line of reasoning, the characterization of the ATM as a complex system highlights the relevance of the application of Complex Network Theory (CNT), mainly because it provides modeling tools and analysis techniques that allow discovering fundamental properties and suggest design guidelines to support high-performance nonlinear systems (Strogatz 2001).

Thus, questions arise that instigate critical thinking on the subject: Why is it relevant to model an air traffic system? How to model? How does a system react to eventual or intentional disturbances? How to measure the resilience of an ATM system?

To help reflect on these issues, the present work can be characterized as an investigative approach to the CNT and the process of modeling ATM systems, more specifically as a study on the systematic application of a set of metrics of the CNT to measure the resilience of an ATM system.

Assuming that an air traffic system can be modeled and has its resilience measured based on the CNT, this work has the main objective to develop a model for evaluating the resilience of ATM systems based on the concepts, metrics and analysis techniques of CNT applied to the Brazilian ATM network. This analysis model, in essence, is a major contribution of this research.

The studies on the subject found in the literature are mainly directed to the structural analysis of the implemented airport network (Zanin and Lillo 2013). The annual reports published by the National Civil Aviation Secretariat, for example, portray the reality of the Brazilian air transport with a reference centered on the volume of passengers and the cargo handled at the airports.

The research is, therefore, limited to the analysis of interactions between flight operations and the ATM system, due to the level of complexity of air operations and the volumes of data to be processed to produce the appropriate results.

For the Academy, air traffic modeling according to CNT metrics fills a gap in this area of knowledge. It is expected that the analysis of air traffic networks, based on the air traffic control (ATC) agencies responsible for conducting air operations, will allow the identification of the most important and central of the network, as well as the robustness, the reliability and resilience of the entire ATM system. The establishment of an analysis model also makes it possible to compare the characteristics and structural properties of air traffic systems in different countries.

The research results can be applied, eventually, in the prioritization process for the implementation of systems and equipment that expand the operability of the ATC agencies, which would result, for example, in the expansion of the flight control capacity in the same portion of airspace; in the case of installation of radars; or increasing the probability of aircraft landing at an airport, by installing precision aids for aircraft approaches in adverse weather conditions.

ATM RESILIENCE AND CNT

This part of the work provides the technical basis, theoretical foundation, and a reflection on resilience in air traffic systems, all of them necessary to understand ATM systems, the CNT philosophy, and the real possibility of mapping non-linear systems through CNT metrics and their analysis techniques.

Air Traffic Management

For Stefan *et al.* (2012), in a typical air transport system, air operations result from the dynamic interaction between airlines, airport operations and the ATM system, of which operational concept, according to the International Civil Aviation Organization (ICAO 2019), involves the dynamic and integrated management of traffic and airspace, including air traffic services (ATS), strategic management of airspace and air traffic flow—with order, safety, regularity, economy and efficiency—by through the provision of facilities and continuous services, involving air and ground facilities.

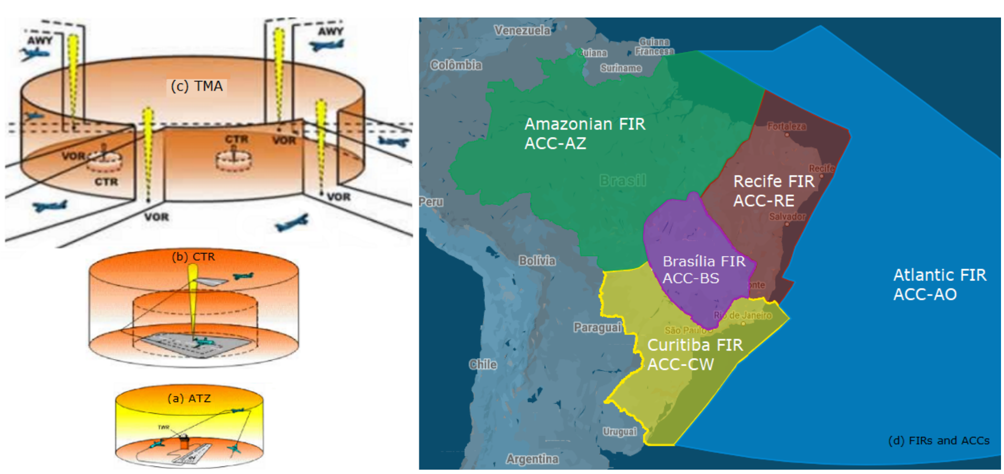
In Brazil, activities involving the management and control of airspace are treated with strategic relevance and national security interest, thus being entrusted to the Brazilian Air Force, with the Department of Airspace Control (DECEA) as the central organization of the Brazilian Airspace Control System. The Brazilian management model integrates civil ATC and military air defense operations, which results in the rationalization of human and material resources, and optimizes the decision-making cycle in processes involving operational safety matters (DECEA 2019a).

Airspaces can be understood as complex partitioned systems, primarily for purposes of organization, control, adequacy of operational capacity and protection against saturation of available ATC means. The classical ordering of airspace, according to the ICAO (2005), involves the concept of Flight Information Region (FIR), which can be defined as a continuous volume of airspace, delimited by duly established lateral and vertical limits, where ATS are provided. The FIRs are arranged contiguously and cover the entire national territory.

The Brazilian airspace is structured based on five FIRs associated with the respective control centers responsible for each of the regions (Fig. 1d). From this organization, it follows that the Amazonian (ACC-AZ), Recife (ACCRE), Brasília (ACC-BS), Curitiba (ACC-CW) and Atlantic (ACC-AO) control centers are responsible for the respective FIRs that bear their names: Amazonian FIR (SBAZ); Recife FIR (SBRE); Brasília FIR (SBBS); Curitiba FIR (SBCW); and, finally, the Atlantic FIR (SBAO).

The airspace of an FIR is normally divided into smaller fractions called a sector, with the aim of facilitating management and expanding its occupancy capacity for a greater number of flights. There are also other portions of airspace—smaller than an FIR and larger than a sector—destined for specific purposes and managed by specialized ATC agencies. Among these areas, some in which ATC services are provided are detailed below, characterizing them as controlled air spaces (DECEA 2013):

- ATZ – Aerodrome Traffic Zone (Fig. 1a) is an airspace established around an aerodrome for the protection of local air traffic of aircraft under visual flight rules. The Control Tower (TWR) is the ATC agency responsible for this type of airspace;
- CTR – Control Zone (Fig. 1b) is a controlled airspace that aims to protect the trajectories of aircraft under instrument flight rules in departure or arrival procedures at one or more nearby aerodromes. The Approach Control (APP) is the ATC agency responsible for this type of airspace;
- TMA – Terminal Control Area (Fig. 1c) is a controlled airspace to which the air routes to the aerodromes contained in this TMA converge. A TMA can be formed by several CTRs and ATZs, thus protecting the trajectory of the aircraft in procedures of arrival or departure from the aerodromes inserted in it. APP is also the agency responsible for this type of controlled airspace;
- CTA – Control Area is a controlled airspace that contains the lower airways and the TMAs inserted in it, with the Area Control Center (ACC) as the control agency responsible for this type of airspace;
- UTA – Superior Control Area is a controlled airspace similar to the CTA, differing in that it contains the superior airways and other parts of the superior airspace, defined as superior control areas. The ACC is the ATC agency responsible for this type of airspace.



Source: Adapted from DECEA (2019a) and Bastos and Baum (2009).

Figure 1. Airspaces and ATC agencies: (a) Aerodrome Traffic Zone (ATZ); (b) Control Zone (CTR); (c) Terminal Control Area (TMA); and (d) Flight Information Regions (FIRs) and their respectively Area Control Centers (ACCs).

Complementing the set of ATC/ATS agencies, there is the Aerodrome Flight Information Service (AFIS), which is an air traffic service provided to all aircraft operating in the movement area and in flight in the lower airspace, within a radius of 27 nm (50 km), around approved aerodromes that do not have a TWR. AFIS is carried out by an aeronautical telecommunications station, which provides meteorological and coordination information for the safety and efficiency of air operations.

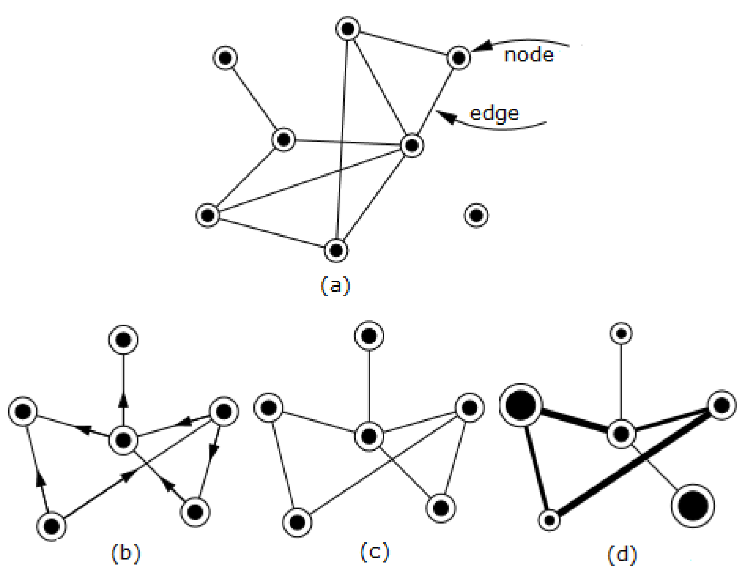
Complex Network Theory

The origins of the CNT, according to Anderson (1972), are related to studies in the field of statistical physics, the dynamics of nonlinear systems and information theory, and can be conceptualized as the multidisciplinary study of complex systems. In this sense, air transport, in general, and ATM can be analyzed and studied through these powerful tools available (Cook *et al.* 2015).

Using CNT, a network can be modeled and represented by a set of nodes, connected to each other by a set of links. The connections between the nodes can also be defined as directed, nondirected, with nodes of the same type or of different types, weighted and, still, of dynamic behavior, when there is variation of the structural elements of the network, nodes, and links, in time function (Zanin and Lillo 2013).

As a practical example of this modeling system (that can be seen in Fig. 2), an air transport network can be formed by airports (nodes), linked by flights from one node to another (directed connection) and weighted based on the number of passengers. If the flights have information about the proposed departure time and duration, the network can be dynamically analyzed with respect to time. Another example of structuring could be observed in a representative network of airspace sectors or navigation points such as nodes, connected by flights (edges) that cross those sectors or fly over these navigation points.

These types of network organization facilitate ATC modeling (Cai *et al.* 2012) and, by analyzing centrality metrics, allow identifying potential traffic bottlenecks. The detection of communities in these types of networks has proved to be an effective instrument to rationalize airspace restructuring based on traffic analysis (Gurtner *et al.* 2014).



Source: Adapted from Newman (2003).

Figure 2. Examples of complex networks: (a) network formed by 8 nodes and 10 edges; (b) directed network, in which each edge has a specific direction; (c) nondirected network with only one node type and one edge type; and (d) network with weighted nodes and edges.

In the understanding of Cook *et al.* (2015) and Sallan and Lordan (2020), metrics are measured with properly established calculation systems that allow understanding or characterizing a network; identify its organization; its critical nodes; and the behaviors that emerge from the dynamic relationships and interactions between its components.

A summary of the CNT metrics that characterize the structure of a network is detailed below, based on the works of Albert and Barabási (2002) and Newman (2003).

The shortest path between two nodes l (m, n) is defined as the path with the fewest intermediate nodes between the origin and the destination. Since L is the set of shortest paths and $|L|$ is the number of shortest paths in the network, the average shortest path in the network R, $l(R)$ can be defined through Eq. 1.

$$l(R) = \frac{1}{|L|} \sum_{\forall\, l(m,n) \,\in\, L} l(m,n) \tag{1}$$

According to Freeman (1979), betweenness centrality represents the control capacity that intermediate nodes have over other nodes that locally depend on this intermediary to connect, that is, it is the relationship between the shortest paths that pass through the node n and the shortest paths between all pairs of nodes. Let N be the set of network nodes, $\sigma_{(m,o)}$ be the number of shortest paths between nodes m and o, and $\sigma_{(m,o)}$ (n) the number of these paths that cross the node n, the betweenness centrality of a node n, $\beta(n)$, can be calculated by Eq. 2. This metric makes it possible to assess the proportion of a given node of a network as a necessary link between different groups belonging to the same network, based on the shortest possible path.

$$\beta(n) = \sum_{m \neq n \neq 0 \,\in\, N} \frac{\sigma_{(m,o)}(n)}{\sigma_{(m,o)}} \tag{2}$$

Proximity centrality represents how close a node is to the other nodes in the network that it can reach. Being $\pi(m, n)$ the length of the shortest path between a node m and any other reachable node n, the proximity centrality $\gamma(m)$ can be defined by means of Eq. 3. Broadly speaking, the analysis of this metric makes it possible to understand how a node is perceived as the center of the network; to what extent does it employ the help of intermediate nodes to reach more distant ones; and how it positions itself (dependent/independent) regarding the structure of the network.

$$\gamma(m) = \left[\sum_{m \neq n, m \,\in N} \pi(m,n)\right]^{-1} \tag{3}$$

The clustering coefficient can be conceptualized as the degree to which the nodes of a network tend to cluster. In practical terms, it represents a measure of the density of edges between the neighbors of a node, that is, if the neighbors are directly connected—number of triangles in the network. It is also known as the network transitivity measure. Equation 4 proposes the formula for calculating the clustering coefficient C of a network N. Here, e_{mo} represents the edges that connect neighboring nodes to node n; v_m and v_o represent the vertices neighboring to node n; R_n defines the neighboring graph to node n; and k_n represents the number of neighbors of vertex n.

$$C(N) = \frac{1}{n} \sum_{i=1}^{n} \frac{e_{mo} : v_m, v_0 \in R_i, e_{mo} \in E}{k_i(k_i - 1)} \tag{4}$$

Equation 5 defines the density D of a network as the ratio between the number of edges $|\epsilon|$ and the total number of possible edges of the complete network, where $|\nu|$ is the number of the nodes. The analysis of this metric allows an understanding of the cohesion of a network, because the higher the density, the more cohesive it will be (Nooy *et al.* 2005).

$$D = \frac{2\,|\epsilon|}{|\upsilon|(|\upsilon| - 1)} \tag{5}$$

The diameter d of a network R can be defined as the longest shortest path between any pair of nodes in the network and can be calculated by Eq. 6. The analysis of this metric allows the understanding of the dispersion of the network.

$$d(R) = max_{\forall\, l(m,n) \in\, L}\, l(m,n) \tag{6}$$

The degree of a node corresponds to the total number of links connected to it and can be divided into in-degree and out-degree. The in-degree of a node n, $k_{in}(n)$, represents the total number of links that arrive at this node. The out-degree, $k_{out}(n)$, describes the total number of connections that leave the node. Thus, the degree of a node n is equivalent to the total number of links that arrive or leave the node: $k(n) = k_{in}(n) + k_{out}(n)$. In this reasoning, the average degree k of a network R (Eq. 7) is the result of the relation between the sum of the degrees of nodes in the network and the total number of nodes $|N|$, where N is the set of nodes in the network. In the case of weighted networks, the strength of a node is defined as the sum of the weights of the node connections, whether input or output.

$$k(R) = \frac{1}{|N|} \sum_{\forall\, n \in N} k(n) \tag{7}$$

Based on several studies on this metric, Barabási (2009) identified a specific type of network that he conceptualized as scale-free network. This conception is mainly supported by studies by Barrat *et al.* (2004) and Guimerà *et al.* (2005), which showed that the probability that the degree (or strength) of a node k is greater than x can be characterized by the power law $P\,(k > x) = Nx^{-g}\, e^{-ax}$, where $1 \leq g \leq 2$ is the tail exponent, a is the parameter that controls the speed of exponential decay and N a normalization constant. As a network with random distribution increases in size, the relationship between nodes with high degrees and other nodes in the network decays. In a scale-free network, however, this relationship remains constant as a function of the size of the network.

The analysis of the average degree metric—strength for weighted networks—allows the identification of the most active and influential nodes in the network, since they have a higher number of links and, consequently, higher values of $k(n)$. For weighted networks, the strength of a node can also be properly correlated with the number of flights and passengers passing through this node (Barrat *et al.* 2004; Guimerà *et al.* 2005).

Resilience

Air traffic management is an example of a complex sociotechnical system, which encompasses interactions between different organizations, technical systems, operational units, regulatory agencies, and consumers (DeLaurentis and Ayyalasomayajula 2009). In this extremely specialized field, technology plays a prominent role and the value of studying ATM resilience is perceived as relevant due to the studies of several researchers, especially Hollnagel *et al.* (2006).

Routinely, the air traffic network coexists with different types of internal and external disturbances, which daily test its resilience. These disturbances can interact with each other, enhancing their cascading effects, which can extend over different scales of time and space. According to Eurocontrol (2009), the management of disturbances in air traffic systems involves adjustments and adaptations in the processes of their subsystems, which result from their inherent complexities, enhanced by the finite human and material resources available in the operational control agencies.

In the Brazilian ATM activities, minor disturbances are managed by control agencies distributed throughout the country, while disturbances that may have global reach in the network are handled by a collegiate decision-making process, with representatives of airlines, airport administrators and ATM agencies. Flights are rerouted, or timed, to allow for more effective accommodation of system-wide disturbances. As an example, in the case of airspace congestion, supervisors of control agencies can coordinate with airlines to redirect or adjust their flight schedules. In these cases, safety and fluidity are prioritized at the expense of the economy, managing conflicting interests that need to be conveniently resolved without generating major inconveniences for passengers.

Despite the coordinated work, there are times when the resilience of the air traffic system cannot contain significant delays in flights, which can even spread through the network and compromise several control areas and airports for an extended period. Effects caused by bad weather are classic examples of this type of behavior. In addition to more common cases with restricted consequences, there are other atypical cases with very serious consequences. The two cases can be classified into two broad categories, those that produce effects that strongly affect the performance of the system; and catastrophic accidents involving a single aircraft or a group of them.

The examples described in the previous paragraphs highlight a wide range of events with profound consequences. However, due to the resilience of ATM systems, the vast majority of these potential disturbances generate effects that go unnoticed by the users of the system. Despite this, according to Zanin and Lillo (2013), little effort has been devoted to understanding the relationships between the topology of ATM networks and their vulnerabilities. As, in essence, complexity stems from the interaction between various subsystems, CNT modeling tools that focus on interactions are better suited to capture the phenomenon of resilience, which has greater adherence to the approach of sociotechnical systems rather than technical systems.

The value of the CNT for investigating the impact of disturbances on a sociotechnical system, in general terms, can be established based on the capacities to absorb them, adapt to them, and restore its operational performance to pre-disturbance levels (Francis and Bekera 2014).

Absorptive capacity is defined as the extent to which a system can absorb disturbances and minimize their effects. Incorporating an additional time in advance into the effective duration of flights is a proactive action to accommodate delays that increases absorption capacity. The ability of a system to accommodate to disturbances by modifying its internal processes is defined as adaptive capacity, which differs from absorption capacity in that an adaptive system can change its reaction. Restorative capacity refers to the power that a system has to recover from disturbances and restore or improve its operational capacity, based on the level of performance presented before the disturbing event.

Based on these concepts, a system that has only the ability to absorb disturbances is characterized as robust, while a system that has both absorption and restoration capabilities is said to be reliable. Therefore, resilience can be characterized as the attribute of a system capable of absorbing, adapting, and recovering from disturbances. This highlights the need to prioritize the development of adaptive capacity to increase the resilience of a system.

Resilience Analysis Model

We developed a model to assess the resilience of ATM systems based on complex networks, in which the system under analysis is represented by a directed graph $G\ (A, F)$ with the ATC/ATS agencies (A, nodes) connected by fractions of the managed flights (F, links) in which ATM control and services are effectively performed.

We simulated network operations under disturbances and assess resilience in direct and random attack scenarios, removing nodes from the core and using a new metric created by us, the resilience index (I_{re}), which measures the level of resilience comparing interconnections between the ATC/ATS agencies of the initial ATM system and the resulting one after the disturbance simulation.

Resilience Index

Real world networks represent systems that are constantly modified by the removal or addition of new components, involving the establishment of new connections which are influenced by the degree distribution of the network nodes. In the case of the ATC/ATS system, new agencies can be activated to support growing air activities in a region of operational interest, normally associated with a significant increase in air movements or the entry into operation of a new airport.

The resilience of a network is a property that is related to the distribution of degrees, to connectivity—the existence of links between vertices—and, mainly, to the removal of nodes from this network. Normally, the loss of nodes results in a progressive reduction in the operational capacity of the network, so its resilience can be measured by removing its nodes, with different criteria for the removal process, either randomly or directed to the nodes that have higher degree or centrality (Newman 2003).

Considering that the coordination between ATC/ATS agencies for the management and transfer of flights control by adjacent agencies depends on the effective connection between them, then the vertices of the largest component formed after removing a node n of the network still maintain, among themselves, a significant coordination capacity in relation to the original network.

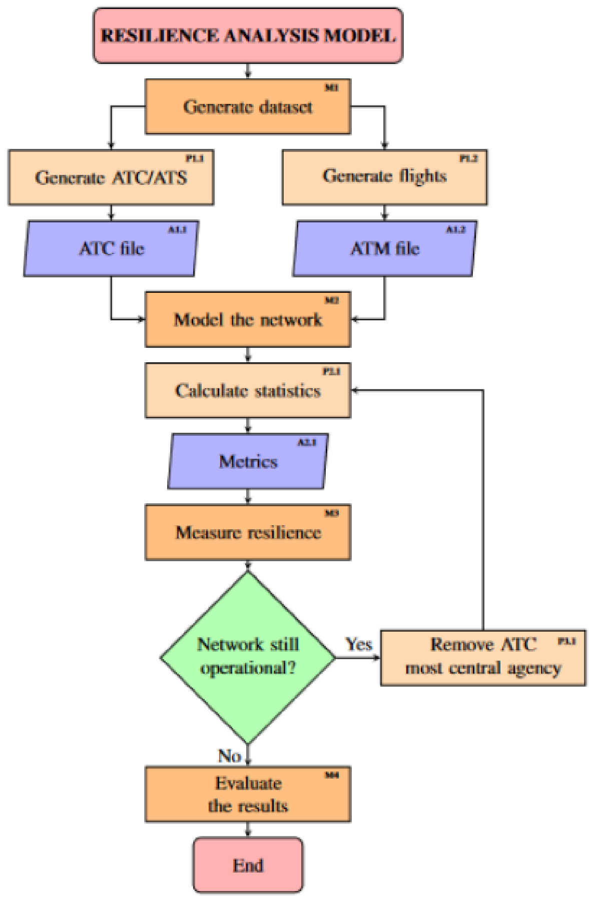
In this line of thought, the resilience index reflects the reduction of the ATM network operational capacity with the unavailability (removal) of a specific ATC/ATS agency, that is, an index of 0.11 means the loss of 11% of the network's operational capacity. In short, the lower the resilience index, the greater the resilience of the network.

Thus, being N the set of nodes of an ATM network, we can define a resilience index, $I_{Re}(n)$, of the network in relation to the loss of a node, n, using the percentage number of nodes of the largest component that remains connected, that is the fraction between the number of vertices of the largest component of the network that remains connected after the removal of this node, $|S_{N-\{n\}}|$, and the total number of vertices of the network before the start of the disturbance ($|N|$) (Eq. 8). Thus,

$$I_{Re}(n) = 1 - \frac{|S_{N-(n)}|}{|N|} \tag{8}$$

Model Development

The flowchart shown in Fig. 3 consolidates the proposed resilience analysis model. The modules and processes used in the model, which appear in the flowchart, are detailed below.



Source: Elaborated by the authors.

Figure 3. Representative flowchart of the Resilience Analysis Model of ATM Systems Based on Complex Networks.

The M1 module is responsible for generating the dataset of the analysis model, consisting of the processes that generate the ATC/ATS file (P 1.1) and the ATM flight file that can be managed (P 1.2). Process P 1.1 generates the file of control and ATS agencies, based on the information obtained through research carried out in the Internet Aisweb portal (DECEA 2019b) and in Chapter 5 of ROTAER (DECEA 2019c). The P 1.2 process aims to create the ATM flights file, which correspond to the manageable fractions of the original flights file (ANAC 2019). For each of the records in the National Civil Aviation Agency (ANAC) flights file, the shortest route between the origin and destination airports is established, which makes it possible to identify, based on the analysis of this route in the respective Aeronautical Route Chart (DECEA 2019b), all ATC/ATS agencies that will be responsible for managing the entire flight.

As an example, during a flight from Fortaleza International Airport (SBFZ) to Manaus International Airport (SBEG), the aircraft receives ATC service from six different ATC agencies, one at a time: Fortaleza Tower (TWR-FZ), Fortaleza Approach Control (APP-WZ), Recife Area Control Center (ACC-RE), Amazonian Area Control Center (ACC-AZ), Manaus Approach Control (APP-WN) and Eduardo Gomes Tower (TWR-EG). Transfers of control occur within the limits of operational responsibility between two adjacent ATC agencies. In this example, processing one single record in the file of active scheduled flights (ANAC 2019)—(SBFZ, SBEG)—will result in five transfers of control records in the ATM flights file: (TWR-FZ, APP-WZ); (APP-WZ, ACC-RE); (ACC-RE, ACC-AZ); (ACC-AZ, APP-WN); (APP-WN, TWR-EG).

For the network modeling (M2 process) the dataset formed by the two files generated in P 1.1 and P 1.2 is used. It starts with importing the dataset into the Gephi workbench, with special attention to the type of graph to be selected (directed) and the merge strategy for edges (sum), therefore, for flights with similar origin and destination, the system will create only one origin/destination edge with weight equal to the sum of the occurrences of parallel edges in the ATM file.

The following CNT metrics used in the model, along with the resilience index (I_{re}, Eq. 8) have their use justified by the ability to characterize a network and identify its organization, robustness, reliability, and resilience: average shortest path (Eq. 1); betweenness centrality (Eq. 2); proximity centrality (Eq. 3); clustering coefficient (Eq. 4); density (Eq. 5); diameter (Eq. 6); and average degree (Eq. 7).

For the statistical treatment and graphic visualization of the dataset that serves as the basis for the modeling of the complex structured network, the interactive free software platform Gephi version 0.9.2 (Bastian *et al.* 2009) is used. Metric calculations (P 2.1 process) are performed using the tools available in the Statistics Tab, selecting each of the metrics of interest. Calculation results are automatically entered into fields in the graph nodes file.

In order to measure the resilience of the network (module M3), the results obtained through the statistical calculations, summarized in the metrics file (A 2.1), are analyzed regarding the maintenance of the minimum operational capacity of the network, which includes the verification of the operability of the system in terms of absorption, accommodation, and response to disturbances, through the evaluation of updated metrics generated at each iteration. This step is terminated when the minimum operational capacity of the network is verified, which occurs when the number of vertices of the largest component of the network that remains interconnected after the removal of a node is less than 50% of the number of nodes in the undisturbed network ($|S| < 0.5$).

As long as the network remains operational, the most central ATC/ATS agencies are removed from the network (process P 3.1), one at a time, and the calculation of the statistics is iteratively reworked, up to the point where the network loses its operational capacity ($|S| < 0.5$), when then, the process is terminated. During this process, the metrics file (A 2.1) is indexed based on the betweenness centrality and the most central node in the network—the ATC/ATS agency with the highest centrality value—has all its links excluded, that is, all flights referring to that node are eliminated from the graph. The flow is directed to a new statistical calculation (P 2.1) with generation of a new set of metrics.

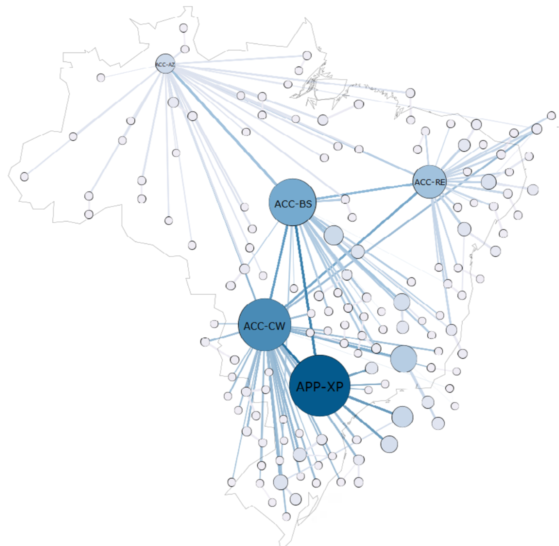
The process of discussing the results (module M4) involves, in a generic way, the identification of the general characteristics of the ATM network based on the calculated metrics; the assessment of established communities, which makes it possible to understand the dependencies between control agencies; understanding of dynamic behavior over time; and the analysis of resilience, which ultimately reflects the system's ability to maintain its operability in situations of degradation.

RESULTS AND DISCUSSION

This section details the results and describes the discussions carried out with the application of the resilience analysis model to the Brazilian ATM system. The subsections that compose it are structured with a focus on the results achieved, specifying the general characteristics of the network (General Analysis), deepening research on the resilience of the Brazilian ATM system (Resilience Analysis), identifying the communities present in the structure (Community Analysis), and evaluating the weekly distribution of flights in relation to days and times (Dynamics Analysis).

General Analysis

The Brazilian air traffic network was modeled having as nodes the ATC/ATS agencies (146), linked by fractions of flights (17,347) in which ATM, control and services are effectively performed. Figure 4 visually presents the weekly distribution of scheduled flights in Brazil, registered with ANAC on August 12, 2019, with a focus on the ATC and service agencies that exert the greatest influence on the network Brazilian airline.



Source: Elaborated by the authors.

Figure 4. Brazilian ATM network: weekly distribution of scheduled flights, highlight for the most influential ATC/ATS agencies classified by the volume of managed air movements.

Table 1 summarizes the global metrics of the network, where "Connected ATC/ATS agencies" represents the ability of an agency to connect to other agencies in the network, with values ranging from 0% (no connection possible) to 100% (all agencies can connect to each other directly or via intermediary agencies); "Average clustering coefficient" represents a measure of the density of connections between adjacent agencies; "Average managed flights" expresses the average number of flights managed by each of the agencies in the network; "Average shortest path" translates the average of all paths connecting an origin agency to any destination agency, with the fewest passes through other intermediary agencies; "Average degree" is the result of the ratio between the sum of the degrees of all agencies (the total number of direct connections, links arriving or leaving each agency) and the total number of agencies in the network; "Diameter" is defined as the longest of the shortest paths between any pair of agencies in the network; and finally "Density", which is defined as the ratio of the number of flights transferred by all ATC agencies to the total number of possible transfers of flights across the entire network.

Table 1. Brazilian ATM network: global metrics and parameters.

Metric / Parameter	Value
ATC/ATS agencies connected	100%
Average clustering coefficient	5.3%
Average managed flights	407 managed flights
Average shortest path	3.272 flight transfers
Average degree	2.171 direct connections
Diameter	6 flight transfers
Density	1.5%

Source: Elaborated by the authors.

In a comprehensive way, the degree of network nodes follows a power law, revealing the joint existence of a few operational ATC agencies that manage many flights and many agencies that provide ATS to a few aircraft in flight. In this way, the Brazilian air traffic network can be characterized as a scale-free network. Far from being just an abstract classification, identifying the type of network resulting from modeling a real air traffic system provides relevant information to rationalize it and mitigate its vulnerabilities.

It is known from studies by Albert *et al.* (2000) that scale-free networks are intensely resilient to random failures, since the vast majority of nodes have a small number of connections. Removing nodes of this type, therefore, would not affect the overall functionality of the network too much. In the opposite direction, however, scale-free networks are particularly vulnerable to attacks targeting the most central and influential nodes in the network. Sun and Wandelt (2021) reinforce these ideas by analyzing the different impacts of attacks, concluding that targeted attacks are more harmful to ATM systems than random failures.

Regarding the connectivity of the Brazilian air traffic network, the graph generated by the modeling is fully connected, forming a single large component (Fig. 4), showing that it is possible to reach all operational ATC agencies from any of them. However, connectivity between control agencies is low, since each ATC/ATS agency is directly linked, on average, to 2.171 of them, about 1.5% of the total operational agencies.

As for cohesion, that is, how close to having direct connections between all its vertices, the air traffic network has a low density (1.5%), reflecting the existing hierarchy in the Brazilian airspace control system with few direct connections between the ATC/ATS agencies.

Regarding the dispersion of the network—with reference to the definition of unitary distance as the one that separates two directly connected vertices—the flights that most need ATM involve the participation of seven ATC/ATS agencies with six transfers of control (network diameter).

The Brazilian network is also characterized by a low level of redundancy in the connections between the control agencies, since, according to the metrics obtained, the average of clustering coefficients shows that each ATC/ATS unit has only 5.3% chance of being connected to a neighboring control on this network.

In practice, however, this is not entirely correct to say, as the ACCs and some of the larger APPs (e.g., São Paulo and Rio de Janeiro) are subdivided into operational sectors, each operating as an independent ATC agency, that is, there is internal redundancy in these operational units, but it is not perceived by the calculated metrics due to the structuring of the dataset used in the modeling. It is also possible to connect the TWRs directly with the ACCs, in the event of an APP failure.

The general characteristics of the Brazilian air traffic network, identified in this initial analysis, can be explained by the hierarchy of the structure of the control agencies in spatially restricted areas, since, in a situation of operational normality, the TWRs are connected to the ACCs through the APPs. In situations of operational degradation of approach control, however, a TWR can be linked directly to the ACC responsible for the FIR where it operates. Regarding the AFIS, the connection with the ACCs is carried out directly.

This differentiation is justified by the complexity of ATC compared to the flight information service provided by AFIS. Control agencies are responsible for controlled airspaces with a high volume of air traffic, while agencies that provide ATS are responsible for uncontrolled airspaces, normally with low flight traffic.

Turning to the quantitative analysis of the results, the Table 2 expresses the classification of Brazilian ATC/ATS agencies in relation to relevance in the national network, based on the volume of air movements managed in a period of one week, betweenness centrality and proximity centrality, respectively. While betweenness centrality allows assessing the ability of a given node to present itself as a necessary link for the connection between groups in the network, proximity centrality helps in the perception of which ATC/ATS agencies are responsible for the initial management of flights with the lowest number of control transfers. The two metrics together show the most relevant ATC agencies.

The data presented show that the São Paulo approach control (APP-XP) concentrates the largest volume of managed air movements (17,662), even surpassing all ACC. This result comes from the direct connection of this APP with three of the busiest TWRs in Brazil: Guarulhos (TWR-GR) with 4,336 movements; Congonhas (TWR-SP) with 2,964; and Campinas (TWR-KP) with 1,514 weekly movements controlled.

Table 2. The 10 most relevant ATC/ATS agencies classified by number of flights managed during a week of operation, betweenness centrality and proximity centrality.

Rank	Flights managed	Betweenness centrality	Proximity centrality
1	17,662 APP São Paulo	0.5499 ACC Curitiba	0.52 ACC Curitiba
2	14,911 ACC Curitiba	0.4538 ACC Amazonian	0.49 ACC Amazonian
3	13,051 ACC Brasília	0.3339 ACC Recife	0.48 ACC Brasília
4	8,428 ACC Recife	0.3030 ACC Brasília	0.48 ACC Recife
5	6,236 APP Rio de Janeiro	0.0680 APP São Paulo	0.41 ACC Atlantic
6	4,336 TWR Guarulhos	0.0410 APP Rio de Janeiro	0.37 APP São Paulo
7	3,855 ACC Amazonian	0.0275 APP Belo Horizonte	0.35 APP Vitória
8	3,824 APP Brasília	0.0275 APP Recife	0.35 APP Rio de Janeiro
9	3,004 APP Belo Horizonte	0.0275 APP Londrina	0.34 APP Curitiba
10	2,964 TWR São Paulo	0.0275 APP Bauru	0.34 APP Florianópolis

Source: Elaborated by the authors.

Likewise, the approach control of Rio de Janeiro (APP-WJ) ranks significantly in fifth place with 6,236 controlled flights, behind only the approach control of São Paulo and the Curitiba, Brasília, and Recife ACCs. With an operational structure similar to that used in São Paulo, the APP-WJ manages the air flow of the TWRs at Santos Dumont (TWR-RJ) and Galeão (TWR-GL) airports.

The establishment of these two regions of intense movement can be understood by the correlation of air traffic with economic activity in the two largest Brazilian cities in terms of population and gross domestic product, resulting in the creation of the air bridge between Rio de Janeiro and São Paulo, one of the busiest routes around the world.

Also noteworthy are the results of the approach control and the control tower in Brasília (APP-WR and TWRBR) with, respectively, 3,824 and 1,917 movements, demonstrating the relevance of the federal capital in the Brazilian air network.

Once again, the hierarchy of the ATC structure of the Brazilian network can be used to justify the results of centrality obtained, since the ACCs are responsible for liaising with the APPs and with the AFIS at isolated aerodromes in their areas of operational responsibility. The APPs act in the same way, intermediating the links between TWRs and ACCs.

Thus, the results presented are coherent, classifying the ACC in the first positions, followed by the APP. The TWR and AFIS, in the opposite direction, have the lowest centrality values, since they are positioned at the ends of the network.

Specifically in relation to the betweenness centrality, the classification of APPs is supported by direct connections with more than one TWR/AFIS in their respective areas of operational responsibility and in the volume of managed flights.

Resilience Analysis

The resilience analysis of air traffic systems is relevant due to the need to know and understand the impacts caused on the functionality of the network in cases of unavailability of ATC agencies, especially the ACCs, which act as intermediaries in flights from different FIRs, linking the APPs and connecting isolated AFIS. Air traffic systems have occasional failures in equipment and subsystems, but they rarely lead to loss of global network functionality. This stability is normally attributed to the redundant links present in its structure.

In general, scale-free networks are little affected when their nodes are randomly removed, that is, this type of network has strong resilience to undirected node loss. In the case of the Brazilian air traffic network, such behavior can be understood by the predominance of ATC/ATS agencies with a low number of managed flights, so the impact on the global operability of the network by the loss of this type of agency is not significant.

The results recorded in Table 3 prove that the random removal of ATC/ATS agencies from the Brazilian network has a reduced effect on its operability, because even after the simultaneous unavailability (removal) of 10, the network resilience index remained at $I_{Re} = 1 - 77.40 / 100 = 0.226$, where 77.40 is the is the percentage number of nodes connected in the largest component after the random removal of 10 ATC/ATS agencies.

Table 3. Resilience analysis: random failures.

Metric / Parameter description	Values										
N. ATC/ATS agencies removed	0	1	2	3	4	5	6	7	8	9	10
ATC/ATS agencies disconnected	–	106	49	118	23	18	24	15	16	10	4
Flights removed	0	20	265	12	992	1,504	916	1,790	1,514	2,964	7,534
Flights on the network (%)	100.00	99.98	99.78	99.99	99.17	98.74	99.23	98.50	98.73	97.52	93,69
Largest comp. – Qty of nodes connected (%)	100.00	99.32	98.63	97.95	96.58	95.89	94.52	93.15	92.47	91.78	77,40
Connec. ATC/ATS agencies groups	1	2	3	4	6	7	9	11	12	13	28
Largest connected ATC/ATS agency – comps.	146	145	144	143	141	140	138	136	135	134	113
Average managed flights	407	407	407	407	400	390	383	371	361	340	289
Average degree	2.171	2.130	2.103	2.089	2.055	2.041	2.014	1.979	1.966	1.952	1.664
Density	0.015	0.015	0.015	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.011
Diameter	6	6	6	6	6	6	6	6	6	6	6
Average shortest ATC/ATS path	3.272	3.281	3.284	3.288	3.284	3.276	3.268	3.260	3.254	3.248	3.188

Source: Elaborated by the authors.

In the opposite direction, however, the removal of a node with a high degree of distribution or centrality—targeted attack on a critical node identified, according to Sun and Wandelt (2021)—usually has a devastating effect on the operational capacity of the network, as can be seen in Table 4, which show the results obtained by the selective removal of ATC/ATS agencies with a higher degree of betweenness centrality. The interdiction of the Curitiba ACC, the ATC agency with the highest degree of centrality in the network, causes an immediate loss of 31% of network operability ($I_{Re} = 0.31$).

It is still possible to assess the resilience of the network in situations of simultaneous unavailability of ATC/ATS units. Checking the column corresponding to ACC-AZ in Table 4, it appears that the removal of ACC-CW and ACC-AZ together reduces the operational capacity of the network to 44.52%, that is, resilience index ($I_{Re} = 0.55$).

Finally, it is proved that the Brazilian ATM network presents a behavior similar to that of scale-free networks, being strongly resistant to random failures, but with a relevant loss of its operational capacity in situations of attacks directed at its most relevant ATC agencies.

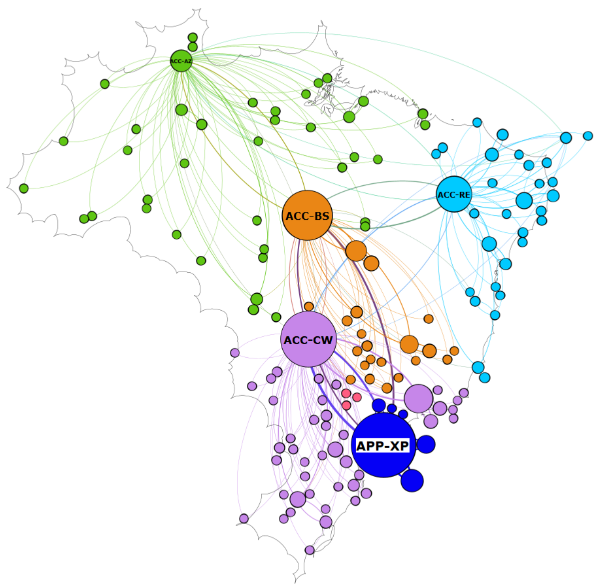
Table 4. Resilience analysis: targeted attacks.

Metric / Parameter description	Values			
ATC/ATS agency removed	Complete Network	ACC-CW	ACC-AZ	ACC-BS
Total number of ATC/ATS agencies removed	0	1	2	3
Flights removed	0	14,911	3,855	13,051
Flights on the network (%)	100.00	87.51	84.28	73.34
Largest component – Qty of nodes connected (%)	100.00	69.18	44.52	20.55
Connected ATC/ATS agencies groups	1	30	58	76
Largest connected ATC/ATS agency – comps.	146	101	65	30
Average managed flights	407	307	279	208
Average degree	2.171	1.644	1.205	0.945
Density	0.015	0.011	0.008	0.007
Diameter	6	5	5	4
Average shortest ATC/ATS path	3.272	3.207	3.115	2.451

Source: Elaborated by the authors.

Community Analysis

The analysis of communities allows the understanding of the relationships of dependence between air traffic agencies, whether structural, organizational, or even economic, when carefully observing the areas of operational responsibility where these control agencies provide their specialized services. It is also possible to infer knowledge about the commercial interests of airlines, through a critical look at the concentration of flights originating in or destined for a specific control area. Figure 5 depicts the Brazilian air traffic network with the ATC/ATS agencies grouped into five identified communities, of which identification process was carried out using the Newman–Girvan algorithm.



Source: Elaborated by the authors.

Figure 5. Brazilian ATM network: ATC/ATS agencies grouped into communities, by color, with the size of the nodes proportional to the volume of flights managed.

In general, these communities reflect the influence exerted by the ACC in their respective areas of operational responsibility, being approximately equivalent to the FIR in geographic terms. Thus, the region covered by the green community, for example, shows the Amazonian FIR; the light blue community reflects the distribution of FIR Recife's control agencies; the orange one covers the Brasília FIR; and the purple-colored community overlaps the Curitiba FIR.

The exceptions are the dark blue community—which shows the influence of São Paulo APP, with Guarulhos, Congonhas, Campinas and São José dos Campos control towers—and the Atlantic ACC—located in the upper flights between Brazil and Europe, which has connections only with Amazonian, Recife, and Curitiba ACCs, absorbed by the Recife ACC community.

Dynamics Analysis

The results of the previous analysis are based on fixed information in relation to time, not reaching the effects caused by the duration of the flights, their distribution throughout the day or even on different days of the week. In this sense, in order to better understand these impacts on the Brazilian air traffic system, it is necessary to investigate the network metrics referenced in days and times when flights occur.

Table 5 consolidates the information on the air movements of the Brazilian network, during the period of one week. The data is totaled by day of the week, divided into 4–6-h intervals. From the data analysis, it appears that the daily cycle of ATM has a practically constant volume of flights from Tuesday to Friday, regarding the daily total of movements. Mondays are the busiest days of the week, as opposed to Saturdays and Sundays when air activity is reduced. With regard to the daily distribution of flights, Table 5 allows the inference that air activity is significantly intensified in the afternoon and at night on week-days. The movements, especially the low air traffic on Saturday and Sunday, are not explained by the resilience analysis model, but may be related to external factors not evaluated in this study—whether financial or operational by the airlines - exceeding the scope of this research.

Table 5. Brazilian ATM network: Dynamics analysis.

Day of the week	00–06 UTC	06–12 UTC	12–18 UTC	18–00 UTC	Daily subtotal
Sunday	1,090	2,169	4,297	4,994	12,550
Monday	3,874	4,332	6,376	6,545	21,126
Tuesday	3,194	3,563	5,249	5,344	17,349
Wednesday	3,109	3,891	5,924	6,071	18,995
Thursday	3,135	3,768	5,697	5,979	18,579
Friday	3,178	3,858	5,914	5,800	18,750
Saturday	3,146	2,913	3,224	2,739	12,023

Source: Elaborated by the authors.

CONCLUSION

We developed a resilience analysis model of ATM systems based on complex networks and applied it to the Brazilian ATM network. For that, we also gathered and integrated different data sources to build the complex network representation of the analyzed system and, by using metrics and analysis techniques from CNT, evaluated the characteristics and resilience level of it.

The Brazilian air traffic network is a scale-free network, that is, there are few control agencies that manage a large number of flights and many agencies that provide ATS to a few aircraft. Therefore, the Brazilian network is resilient to random failures; however, it is particularly vulnerable to targeted attacks to the nodes with the highest centrality.

The graph generated by the modeling is fully connected, demonstrating that it is possible to reach all operational ATC agencies from any of them. The network is also not very cohesive, with a low density (0.015), reflecting the existence of few direct links between the ATC/ATS agencies. The average shortest path is low (3.272), meaning that few transfers of control, three to four on average, are required when managing flights in Brazilian airspace. The characteristics identified in the Brazilian air traffic network can be explained by the hierarchy of the structure of control agencies in spatially restricted areas and justified by the complexity of the ATC system.

From the quantitative analysis of the air movements managed by ATC/ATS agencies, the results prove that the area control centers play a prominent role in the national context, however, the approach control of São Paulo (APPXP) concentrates the largest volume of air movements (17,662), surpassing all area control centers in the country. This expressive result comes from the direct connection of this APP with three control towers with significant air movement in the country: Guarulhos (TWR-GR) with 4,336 movements; Congonhas (TWR-SP) with 2,964; and Campinas (TWR-KP) with 1,514 controlled weekly movements.

With an operational structure similar to the one used in São Paulo, the Rio de Janeiro approach control (APPWJ), which manages the airflow from the control towers at Santos Dumont (TWR-RJ) and Galeão (TWR-GL) airports, it ranks significantly in fifth place with 6,236 air movements, behind only the approach control of São Paulo and the control centers of Curitiba, Brasília, and Recife.

The existence of these two regions of intense flight movement, established between the terminal control areas of São Paulo and Rio de Janeiro, can be understood by the correlation of air traffic with economic activity in the two largest Brazilian cities in population and economic terms, the which results in one of the busiest routes in the world, the Rio-São Paulo aerial bridge.

The analysis of communities makes it possible to understand the dependency relationships between air traffic agencies. In general, the distribution of communities in the Brazilian air traffic network reflects the influence exerted by the control centers in their respective areas of operational responsibility, being approximately equivalent to the FIR in geographic terms. Thus, five large communities were identified with ATC/ATS agencies distributed, grouped, along the Amazonian, Recife, Brasília, and Curitiba FIRs, and a fifth highlighted community, which portrays the influence of the approach control of São Paulo and of its busy control towers in Guarulhos, Congonhas and Campinas.

Regarding the dynamic analysis of data on the daily cycle of ATM, the results show that the volume of flights has a small variation from Tuesday to Friday, regarding the daily movement total. Mondays are the days with the most air traffic during the week—21,126 movements—as opposed to Saturdays and Sundays, when air activity is the least. As for the variation of movements during the day, the air activity intensifies considerably in the afternoon and night periods, with the highest average movement close to 6,000 in the night period from Monday to Friday.

The practical results that may come from the analysis of air traffic systems through modeling tools that employ the CNT showed high potential to identify bottlenecks in the networks, expand operational capabilities and raise the levels of operational safety of the air operations. Thus, there are great opportunities for future research in this area of knowledge, and some of the following can be glimpsed: to model and analyze an ATM system taking into account the sectorization of airspace under the responsibility of the ACC and APP, treating each sector as an independent operational ATC agency; and to structure the network nodes based on the navigation points of the air routes, in order to identify bottlenecks in the airways, with the purpose of rationalizing the design of the airspace structure.

Studies on complex networks have developed rapidly in recent years, as shown by the significant attention of scientists from different areas to the field of complex systems, signaling the relevance of this knowledge area for the Academy and for society. In this thought, it is expected that studying and modeling the Brazilian ATM system based on complex networks will contribute to shed a little more light on this specialized and strategic path for the social and economic development of Brazil.

AUTHORS' CONTRIBUTIONS

Conceptualization: Sampaio FCG; **Methodology:** Sampaio FCG; **Software:** Sampaio FCG; **Validation:** Sampaio FCG; **Formal analysis:** Sampaio FCG; **Investigation:** Sampaio FCG; **Resources:** Sampaio FCG; **Data Curation:** Sampaio FCG; **Writing - Original Draft:** Sampaio FCG; **Writing - Review & Editing:** Sampaio FCG; Costa Filho RN and Guterres MX; **Visualization:** Sampaio FCG.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

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