Perner's Contacts ***17***(1), 2022
DOI: 10.46585/pc.2022.1.2225

METHODOLOGY OF THE STATUS ASSESSMENT OF AIR NETWORK

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Abstract *The air transport network is one of the most important and critical infrastructures in today's global economy. Air transport would not be able to operate without the air network. This fact significantly contributed to interest in a closer study of the issue of air network status assessment. The aim of this article is to evaluate the European air network by identifying and evaluating major European airports based on scheduled flights. Robustness of this air network was determined with regard to its evaluation.*

According to research, a suitable methodology was chosen which is describing the organization of data, specification of the research area and selection of method. Civil international airports which are located in European countries recognized by their entire size and handled at least 1 million passengers in 2018, were chosen as the basis for the creation of the European air network model and following evaluation. For these airports, individual scheduled flights were searching including their frequency during the selected period on 11-17 November 2019. The method of centrality used in the field of graph theory was chosen to evaluate the air network of these selected airports with regard to their connectivity.

The obtained results identified the most important airports of the European air network and thus represent status assessment of air network during the winter flight schedule 2019/2020. These results were used to monitor the robustness of the European air network as a whole. The robustness of the air network was monitored based on a simulation of the sequent closure of the most important airports in the network with regard to the change of average path length and the size of the giant component. The European air network becomes inoperable when 19-20% of the best evaluated airports in the network are closed.

Keywords *air network, airport, centrality, connectivity, methodology, robustness*

1 INTRODUCTION

The air network can be understood as a system consisting of airports, air transport operators, navigation services and regulators, together creating the air transport infrastructure. The current air transport network is the result of the competitiveness of airlines in order to maximize their profits. Traffic indicators (such as the total number of passengers carried, the number of aircraft movements or the amount of cargo carried) are commonly used to describe airport performance. These are productivity indicators, when their monitoring is desirable for the following determination of the airport's operational capacity and the planning of further development.

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If the air network is the subject of the research, the airport's traffic indicators are not sufficient information. When it is focused on the air network, it is necessary to search scheduled flights of those airports. The concept of connectivity is used to describe the size of the air network, the frequency of individual flights, interconnections and the accessibility to other airports. Connectivity can thus be defined as a way of connection an airport in a network. Based on the calculated connectivity, it is possible to compare individual airports with each other just with regard to their operated air network. [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network; Šerlová, M.; et al., 2018, Advisory Procedures Testing.]

2 METHODOLOGY

Literature research was dealing with the structure of the air network forming a functional air transport infrastructure and connectivity, as a way of evaluating the air network. With regard to made research, a suitable methodology was chosen to achieve the set goals of the issue. The methodology of the issue itself created a comprehensive processing procedure with a description of planning, data organization, specification of the research area and selection of a suitable method.

2.1 Specification of selected air network

In order to evaluate the European air network, it was necessary to define precisely the area of research. The geographical organization of Europe is divided into several separate states, extending into the European continent by all area or only part of it. For this issue, the specification of the area of investigation was limited only to airports located in the area of European states recognized by their entire area.

Furthermore, filtering was performed according to the number of passengers handled, which was chosen with regard to the analysis of international airports in the Czech Republic operating scheduled flights. According to the performed analysis, airports which handled less than 1 million passengers per year can be considered as negligible, if the work focuses only on their scheduled flights. Based on the above specifications, Eurostat statistics describing the number of passengers handled at European airports in 2018 was used to complete selection of airports. The final list includes a total of 185 European airports. Airports located in Belarus and Ukraine were not included into the list (at the time of processing, these airports did not have published data describing the number of passengers handled for 2018). [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network]

2.2 Centrality

A centrality method dealing with the connectivity of the air network was chosen regarding to the specifications of research. The method uses the basics of graph theory and offers the possibility to describe individual airport's air network according to their scheduled flights.

A web application called "Flight Connections" was used as the main source for obtaining the necessary data, providing flight schedules for all civil airports in the world. The application was used to search for each selected airport and then its air network was displayed. Each line was verified if it is operated during winter flight schedule 2019/2020 and for scheduled lines were determined their frequency as well.

Centrality is used to evaluate individual airports and subsequently identify important nodes in the network. There are several types of centrality, taking into account various factors that describe the measures of connection of nodes in the network. Based on the calculations, individual nodes can be important within different types of centralities. In the case of air network, the calculated centralities represent the connectivity of the network. [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network]

- **Degree centrality**

This is the basic measure of centrality evaluating individual airports with respect to the degree of a node in the network. In an unoriented graph, the degree of a node is defined as the sum of the direct connections it has with other nodes. The higher degree a node acquires, the more important node gains in the network. Mathematically, degree centrality can be expressed as:

$$k_i = C_D(i) = \sum_{j}^{N} x_{ij} \tag{1}$$

The total air network can be expressed using the adjacency matrix x, where the individual relations (flights) between airports are described by the elements x_{ij}. Node i represents the monitored airport, node j describes all other airports and N represents the total number of airports in the network. Cell x_{ij} = 1, if there is a direct connection between airports i and j, otherwise x_{ij} = 0. [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network° Opsahl, T., Skvoretz, J. 2010. Node centrality in weighted networks: Generalizing degree and shortest paths]

- **Weighted centrality**

The weight is added to the individual edges coming out from the node. This value is represented by the frequency with which the scheduled lines are operated. Weighted centrality monitors the total amount of scheduled flights operated by the airport. This centrality then reflects the size of the airport. Mathematical notation can be expressed as:

$$s_i = C_D^W(i) = \sum_{j}^{N} w_{ij} \tag{2}$$

To calculate the weighted centrality, it is necessary to determine the weighted adjacency matrix w, where the elements of the matrix w_{ij} are greater than 0, if there is a direct connection between the airports i and j. If individual edges in the network are not rated, their value is equal to 1. Conversely, in a network where the edges are rated by weight, their value is greater than 1. N describes the total number of airports in the network. [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network; Opsahl, T., Skvoretz, J. 2010. Node centrality in weighted networks: Generalizing degree and shortest paths]

- **Betweenness centrality**

Degree centrality and weighted centrality describe the traffic at a given airport, ie the number of operated routes and the frequency with which these connections are operated. In particular, they take into account the level of connection of the node in the network and its importance. However, they do not take into account traffic at the airports to which the node is connected. For this purpose, the betweenness centrality of the airport is calculated. This measure helps to find nodes in the network that are important for the transfers. In this way, it is possible to identify the airport hub. Mathematically, betweenness centrality can be expressed as:

$$C_B(i) = \frac{g_{jk}(i)}{g_{jk}} \tag{3}$$

The total number of shortest paths between two nodes is denoted as g_{jk}. Subsequently, the number of these shortest paths passing through node i (denoted by g_{jk} (i) in the formula) is determined for the calculation. The shortest path in the air network can be defined as the minimum number of flights connecting two nodes. [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network; Opsahl, T., Skvoretz, J. 2010. Node centrality in weighted networks: Generalizing degree and shortest paths] The calculated value of betweenness centrality needs to be subsequently normalized. For undirected graphs, such as air networks, normalization is given by dividing the value of C_B (i) by the value (N - 1) (N - 2) / 2, where N is the total number of nodes in the network. Normalization makes it possible to compare the results of nodes from differently sized air networks. [Nikl, M. 2013. Determining the significance of graph vertices: *PageRank and its modification*]

- **Closeness centrality**

Unlike direct centrality and weighted centrality, the closeness centrality in the network can also identify nodes with a lower degree or lower frequency of traffic. Conversely, such nodes can be significant for their location and network connectivity. Based on the centrality of availability, individual airports can be assessed with regard to their proximity to other nodes in the network.

$$\boldsymbol{C_C(i)} = \left[\sum_{j}^{N} \boldsymbol{d(i,j)}\right]^{-1} \tag{4}$$

The closeness centrality is defined as the inverse sum of the shortest routes from the monitored airport i to all other nodes in the network j. The total number of nodes in the network is represented by N. The higher value of closeness centrality, the closer the node is to all other nodes in the network. [1,2] The calculated value of the closeness centrality needs to be subsequently normalized. For undirected graphs, such as scheduled air networks, normalization is given by multiplying the value of $\boldsymbol{C_C}$ (i) by the value (N−1), where N is the total number of nodes in the network. Normalization makes it possible to compare the results of nodes from differently sized air networks. [Nikl, M. 2013. Determining the significance of graph vertices: *PageRank and its modification*]

2.3 Calculation

Scheduled lines operate within the same weekly frequency, so it was necessary to select a specific monitoring period (one calendar week) for data collection and subsequent analysis of the selected airport's network. The time period 11-17 November 2019 was chosen to monitor the air network of individual European airports, so the results will represent the situation during the winter flight schedule 2019/2020.

The "Node XL Pro" software was used to calculate all the centrality measures described above. In total 6,375 scheduled lines and 110,197 flights were analyzed. [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network]

2.4 Robustness of air network

After evaluating the individual selected airports using different measures of centrality, it is possible to start looking at the network from the point of view of its robustness (in case the network would be limited or disrupted). The principle of examining the network's robustness is a gradual closure of airports according to the importance within calculated centrality.

The European air network was monitored during the period 11-17 November 2019, without any disruption or limitation (we take into account only serious disruptions such as natural disasters, terrorist attacks, etc.). Therefore, the disruption was simulated based on the gradual closure of the most important airports in the network. That is the way how to monitor network's robustness.

The airport with highest value of degree centrality was closed as the first one. After the closure, all the airport's measures were recalculated, as their assessment may change with the gradual removal of the most important airports in the network. Airports can now increase or decrease in importance depending on how they are connected to the network. Furthermore, the airport with the highest value of the given degree centrality was again removed from the network and this procedure of removing airports and recalculating centralities was repeated until the network inoperable as a whole (when the average length path is zero and the giant component could no longer be clearly determined). In the second cycle of repetition, it was the closure of airports from the network according to the highest value based on betweenness centrality. The "Gephi" software was used to illustrate the model of the European air network and the subsequent simulation of airport closures.

The weighted centrality is not taken into account because it represents only the frequency of the scheduled lines and the purpose of closing the airport is to cancel all connections in general. The closure of airports according to the closeness centrality representing the achievement of all other nodes in the network, so it is irrelevant in this case. [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network]

3 RESULTS

Fig.1 shows the average path length changing during closure airports according to degree and betweenness centrality. Zero value is reached in the case of degree centrality after closure of 157 airports representing 20.1% of the total). Zero value is reached in the case of betweenness centrality after closure of 148 airports (which represents 19% of the total).

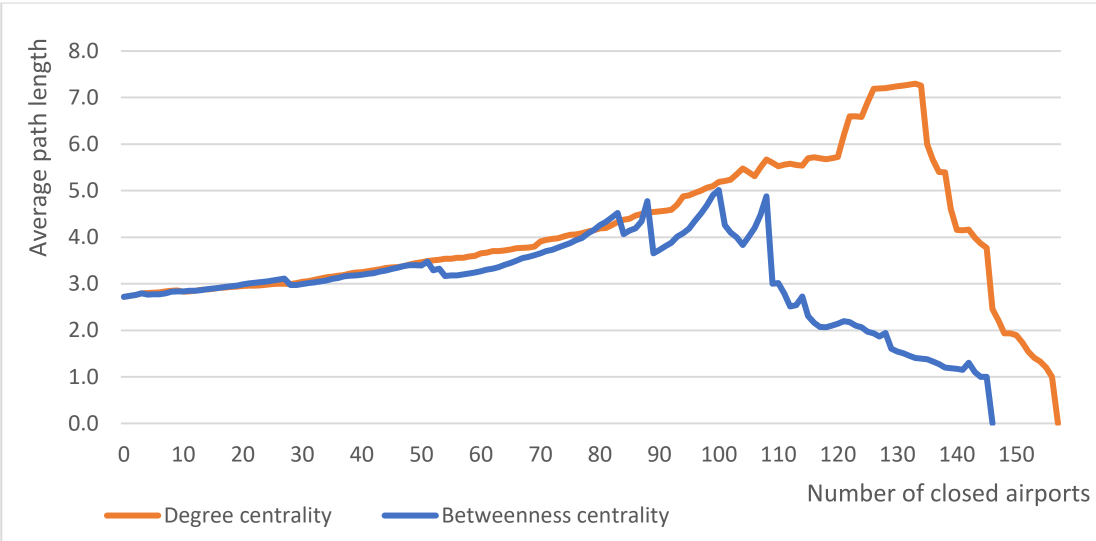

Fig. 1 Robustness of the European aviation network - an indicator of the average path length [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network]

Fig.2 shows the giant component changing during closure airports according to degree and betweenness centrality. Zero value is reached in the case of degree centrality after closure of 151 airports representing 19,3% of the total). Zero value is reached in the case of betweenness centrality after closure of 146 airports (which represents 18,7% of the total).

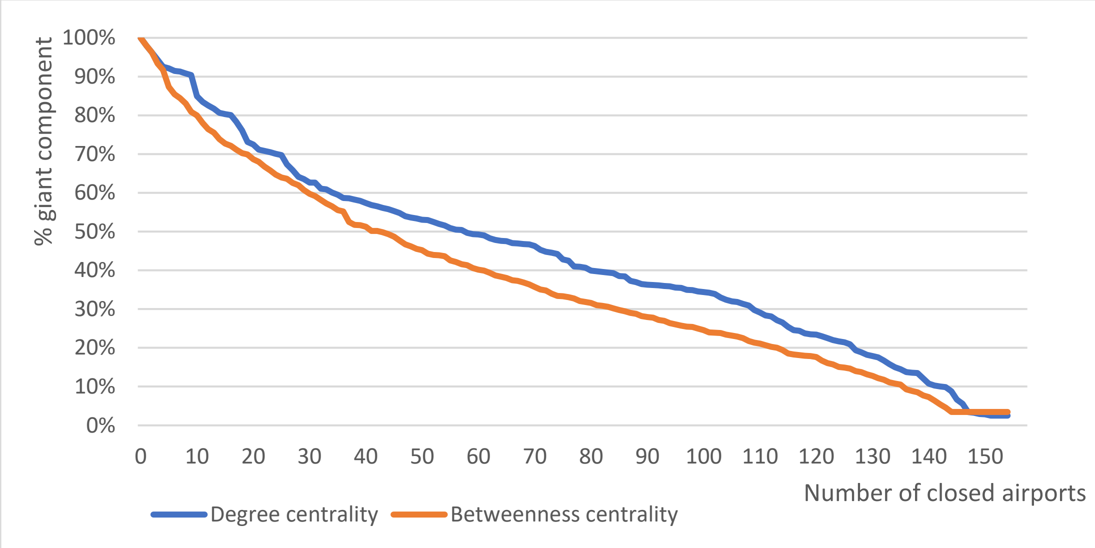

Fig. 2 Robustness of the European aviation network - an indicator of the giant component [Kaločayová, M. 2020. Methodology of the Status Assessment of Air Network]

4 CONCLUSIONS

Overall, the air network is a relatively complex issue, in which it was necessary to assess several factors at once, such as the number of scheduled lines, the frequency of individual connections, the way the airport is connected to the network, the availability of other airports in the network. Monitoring the status of the air network is subject to several limitations that affect the results of the issue. The availability of the necessary data regulates the subsequent processing methodology, the specification of the observed period (summer and winter flight schedules) and the definition of the research area (national, continental or global level) is then reflected in the resulting values. According to the obtained results, the evaluation of the air network is strongly dependent on the specification of input parameters, thanks to which the scope and methodology of the research can be modified. By repeating the same methodology of issue and using data within a different time period, it is possible to monitor the development of the air network over time. The principle of examining the network's robustness is a gradual closure of airports according to the importance within calculated centrality. Robustness of European air network for the winter flights schedules 2019/2020 is 19-20%.

Acknowledgements

This research has been supported by the grant TA ČR Éta TL01000421 Hodnota letecké dopravy pro Českou republiku. CTU in Prague, Faculty od Transportation Sciences, Department of Air Transport.

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