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ANALYSIS OF UKRAINIAN, TURKISH, MOLDOVA AIR NETWORK USING GRAPH THEORY

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Abstract*—The article considers the application of the analysis method using graph theory to determine critical points in the air networks of Ukraine, Turkey and Moldova. The goal is to identify critical points in the above-mentioned aerial networks. The reason is the probability of resuming air traffic between Ukraine and neighboring countries (with the exception of the Russian Federation). The data on the network is obtained from collections of aeronautical information. Modeling was performed in the Python software environment using libraries for processing and visualizing the received data. The main criteria used to determine the criticality of a radio navigation point are Betweenness centrality and Closeness centrality. In addition, the collection and comparison of statistical data on the number of routes and radio navigation points in each of the studied countries will be performed. The obtained data are useful, because it will give an opportunity to compare the results with those obtained during the study of the Ukrainian network and for air navigation service providers to improve the existing network.*

Index Term—Analysis; graphs; air routes; civil aviation; air transport; network.

I. INTRODUCTION

Despite all the problems that exist in the modern world, technologies continue to develop. Aviation is also not standing still in this matter and has already almost completely recovered from the consequences of Covid-19. However, we face a new challenge in the form of geopolitical instability that has engulfed the planet. Wars and conflicts spread across the planet. Unfortunately, Ukraine has become a place where one of the most active conflicts is taking place. As a result, in order to avoid a threat to civil aviation on the night of February 24, 2022, the state air traffic control agency UkrSATSE decided to close the air patrol over the country due to the armed aggression of the Russian Federation [1], [2]. This decision could not but affect the air situation in Eastern Europe, as those routes and the volume of airspace that were previously used for flights in the middle of the country and transit through it became unavailable. Of course, no conflict will last forever and sooner or later this war will end. Accordingly, this will lead to the return of the restoration of air traffic and the restoration of the load on the air network. However, this event will affect not only Ukraine but its neighbors, so an analysis of their air networks will help identify problem areas. In addition, it will be possible to compare the results with previous studies in this area [3], [4].

II. AN AIRSPACE STRUCTURE

The object of research is airspace and air routes. According to the ICAO (International Civil Aviation Organization) definition, airspace is a part of the atmosphere that is under the control of a certain country, respectively, it refers to the volume of air above the land territory and territorial waters of this country. In aviation, for better control, airspace is divided into controlled and uncontrolled, depending on whether dispatching service is provided in it or not. In addition, it is divided into various structural elements such as TMA, CTA CTR, FIZ, FIR and others, each of which performs its function and is connected with others. There is also a classification of airspace that allows you to understand in which airspace what are the requirements for speed and radio communication, as well as which dispatching service is provided. There are only 7 classes A, B, C, D, E, F and G, however, each country makes its own decisions regarding the use of these classes in general or some individual classes in its airspace [5]. So in Turkey they are not used at all, in Ukraine classes D from 1500 to 2900 m, C from 2900 m to 660 FL, G from the ground to 1500 m are user [6], in Moldova class G from the ground to 55 FL and class C from 55 FL to 660 FL. Air traffic control route is a defined route that is intended to direct the flow of air traffic. There are several types of air routes: controlled, uncontrolled, advisory and conditional routes. Each route connects two radio navigation points, however, route parameters are not limited to the length between two points, each route also has vertical boundaries that determine which echelons or heights it covers and width. The width of the route depends on the characteristics of the radio navigation equipment, the more accurate it is, the narrower the route can be made. According to the requirements for zonal navigation, we can direct the route between navigation points if the radio navigation equipment can maintain the position of the aircraft in the center of the route within the given limits during 95% of the flight. The same requirements determine the route width as follows: RNAV 10 uses routes 50 NM wide for oceanic flight, RNP 4 uses routes with a width of 23 NM for enroute part of flight, RNAV 1 uses a route width of 7 NM and others [7].

III. Problem Statement

To determine the critical points of the air network. It is necessary to conduct an analysis of this same network. In this case, analysis using graph theory will be applied. In order to be able to apply it, it is necessary to create the graph itself, for this a static method will be used. The data were collected from the aeronautical information publications(AIP) of the studied countries. Based on the obtained data, a database of routes and aeronautical points was formed, which I later used for modeling in the python software environment. A network of air routes can be represented as a set of tuples of routes and tuples of radio navigation points that these routes connect. This representation allows you to work with it in the same way as with an undirected graph, where routes are edges and radio navigation points are nodes. The availability of a route between points can be represented in the form of a matrix, the size of which is equal to the number of points in the network. Edges between route points are defined as an adjacency matrix: R_i, $j = 1$ if there is a route between points i and j, R_i, $j = 0$ if there is none. The weighted adjacency matrix (A) can be obtained as follows:

$$A = RD,$$

where D is the matrix of geometric distances between route points.

The efficiency of each point of the route can be evaluated by the degree of the node, that is, the sum of the number of edges coming from it, multiplied by the weight of each edge. The degree of a node is a basic indicator of the configuration of a graph, which is the total number of edges connected to each node:

$$d_j = \sum_{i=1}^{n} g_{i,j}.$$

The centrality index in graph theory indicates the importance of a vertex. The degree of centrality of a node is the proportion of nodes with which it is connected. Closeness centrality of a node is the inverse of the average distance along the shortest paths from all adjacent nodes to a given node.

$$C_j = \frac{n-1}{\sum_{i=1}^{n-1} d_{ij}},$$

where d_{ij} is the shortest path between points i and j; $(n - 1)$ is the number of nodes reachable from j.

The load centrality of a node is the share of all the shortest paths passing through it. The degree of intermediation represents the sum of the shares of the shortest paths passing through the node [8], [9].

IV. Problem Solution

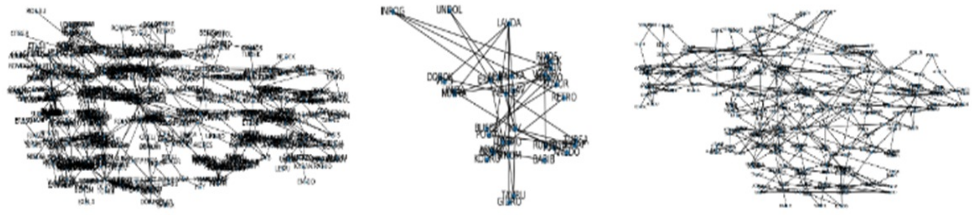
Against the background of Russia's military aggression against Ukraine, deepening relations with our neighbors is important, particularly in the aviation industry. A large part of the air flow coming from Europe to Asia passes through Turkey, when Ukraine opens its airspace, a part of this flow will fall, and therefore the analysis of air networks will allow us to identify potential problem points that may be overloaded with a large flow of air planes. As a result of the study, it was analyzed more than 1000 points more than 1800 routes. It was revealed that the air route network of Moldova consists of 38 air navigation points and 42 routes, Turkey has 661 air navigation points and 1230 routes, Ukraine has 381 air navigation points and 570 routes [10] (Fig. 1).

Among all the radio navigation points of Turkey, the following points 'BAG': 0.21833, 'BUK': 0.29295, 'HAKAN': 0.20525 have the greatest value betweenness centrality in Fig. 2.

For Moldova, the following points have the highest values for this parameter: 'LIPTA': 0.17635, 'KIV': 0.31495, 'LUSAV': 0.21574. The value for the point 'KIV' is the largest among all investigated networks, but it should be noted that this parameter was calculated only taking into account the air network of Moldova and its routes (Fig. 3).

In Ukraine, according to this parameter, the points: 'ODESE': 0.12859, 'ODNIV': 0.12186, 'NIROV': 0.20178 have the greatest value. As you can see, 'NIROV' has the largest value in Ukraine, while the rest of the points do not exceed the value of 0.13 (Fig. 4).

Equally important is the value of closeness centrality, the larger this value, the greater the centrality of the node. For Turkey, the following points have the greatest values: 'BAG': 0.16773, 'BUK': 0.16511, 'HAKAN': 0.16405. As you can see in Fig. 5, the closest values were obtained by the same points as for the betweenness centrality parameter.



a) b) c)

Fig. 1. Graphs: (a) Turkey; (b) Moldova; (c) Ukraine

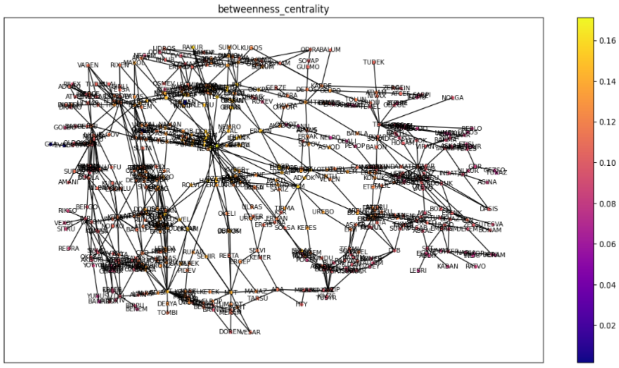


Fig. 2. Betweenness centrality of Turkish network

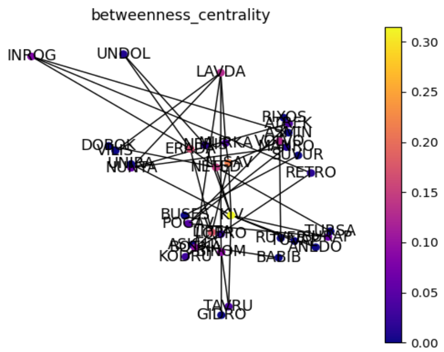


Fig. 3. Betweenness centrality of Moldova network

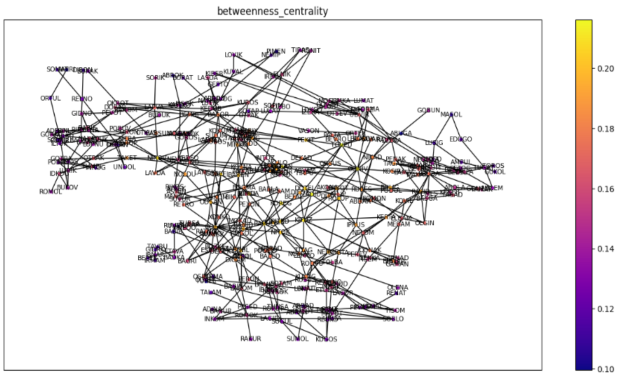


Fig. 4. Betweenness centrality of Ukraine network

We can observe a similar situation in Moldova, the highest values were obtained by the same points as in the previous parameter: 'LIPTA': 0.36127, 'KIV': 0.37612, 'LUSAV' (Fig. 6).

In Ukraine, in contrast to Turkey and Moldova, other points received the highest values for this parameter: 'TADID': 0.20803, 'TOVPU': 0.21113, 'ODNIV': 0.20862 (Fig. 7).

If you look at other studies, you can see that certain problem points have already been found, for example, by ‘ODESE’ and ‘NIROV’ during the analysis of Ukrainian airspace and 'BAG' in Turkey airspace [3], [4].

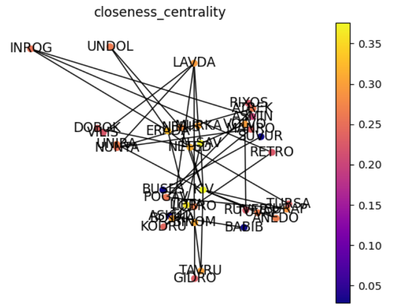


Fig. 6. Closeness centrality of Moldova network

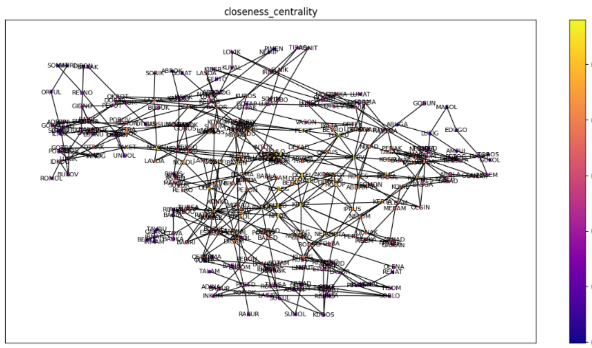


Fig. 7. Closeness centrality of Ukraine network

V. CONCLUSIONS

As a result of the analysis, it can be said that the aviation networks of each of the studied countries are quite developed. The points with the most connections are "ODESE" in Ukraine, "KIV" in Moldova and "BAG" in Turkey, taking into account that these points are also among the busiest, this should be taken into account by both air navigation service providers and pilots. when planning the route.

The obtained data intersect with the results of other studies for Ukraine the point 'ODESE' remains just as problematic, and for Turkey the point 'BAG'.

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О. Р. Іващук. Аналіз української, турецької, молдавської повітряної мережі за допомогою теорії графів

У статті розглядається застосування методу аналізу за допомогою теорії графів для визначення критичних точок в повітряних мережах України, Туреччини й Молдови. Метою є визначити критичні точки у вище згаданих повітряних мережах. Причиною є ймовірність відновлення повітряного сполучення України з сусідніми країнами (за виключенням Російської Федерації). Інформацію щодо мережі отримано зі збірників аеронавігаційної інформації. Моделювання виконувалося в програмному середовищі Пайтон з використанням бібліотек з обробки і візуалізації отриманих даних. Основними критеріями за якими буде визначатися критичність радіонавігаційної точки центральність за близькістю і центральність за посередництвом. Крім того буде виконано збирання та порівняння статистичних даних стосовно кількості маршрутів і радіонавігаційних точок у кожній з досліджуваних країн. Отримані дані є корисними, адже це дасть можливість порівняти результати з отриманими при дослідженні української мережі і провайдерам аеронавігаційних послуг покращити наявну мережу.

Ключові слова: аналіз; графи; повітряні маршрути; цивільна авіація; повітряний транспорт; мережа.

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