A Configuration Analysis of Ukrainian Flight Routes Network

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***Abstract*—Air transport services compose a continuously growing transportation industry, which became closer to their operational perils. Classical air traffic management system includes a network of flight routes for performing civil airspace operation. In our study, we provide an analysis of flight routes network configuration based on graph theory. Ukrainian flight routes network has been represented in the form of a weighted planar graph. Measures of weighted, closeness, betweenness centrality and waypoints degree are used for configuration analysis. Also, an edge vector was statistically analyzed for Ukrainian flight routes network. Results of analysis identify the most loaded and frequently used waypoints based on network configuration. Obtained data are useful for the development of Ukrainian flight routes network and efficient flight traffic planning procedures.**

***Keywords*—airspace, flight routs, network, analysis, graph, air transport, safety, waypoint, edges, degree, centrality, betweenness centrality**

I. Introduction

Aviation is one of the fastest-growing worldwide industries. In 2018, according to the number of passengers who used air transport services, 4.3 billion were recorded for the year and the number of departures - 37.8 million [1]. Many advantages of air transportation lead to a continuous growing of a number of airspace users. Thus, the number of overalls carried passengers and cargo has been increasing for the last decades too [2], except 2020 due to COVID-19 [3] (Fig.1). Operation of the overall air traffic system is based on safety criteria. Any transportation services should meet particular safety levels to guarantee the safety of air transportation. Unfortunately, capacity of airspace and the airport's facility is limited due to operational and safety boundaries. Currently, many airports operate in congested conditions to satisfy current demand of market, which leads to delays in services [4]. Classical air traffic management (ATM) system uses a network of flight routes with a flight leveling and air traffic control (ATC) service [5]. ATM service is grounded on safety levels of acceptable risk for safe operation [6]. In the case of a significant load on the airspace, the chance of error by ATC service increases and leads to significant risk of a dangerous situation that can be resulted in incident or catastrophe. It also requires information about the state of the airspace: its load, the number of routes, entry/transition points from the airspace, their size, and the number of routes that do not have these points. This information helps the ATC to understand the air situation better and guarantee dispatcher work efficiently.

In order to meet future challenges of air traffic, a Free Route Airspace (FRA) was introduced over the globe at particular volumes [7], [8]. FRA is an airspace volume within which users can freely plan a flight route between enter and exit points. Airspace users can use efficient route planning, including direct flight within FRA [9]. FRA is more capable than classical routes network, but more complicated for ATC. Therefore, FRA is introducing carefully mainly in upper airspace over the globe.

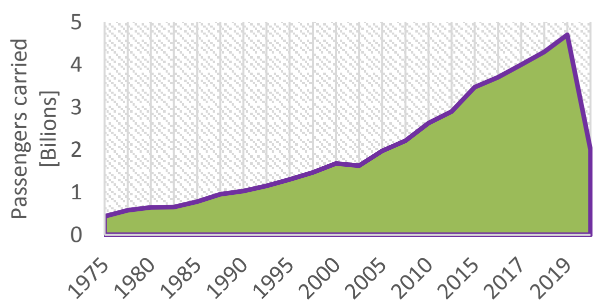

Fig.1. Statistic of air traffic

Also, in order to improve the capacity of ATM, the flexible use of airspace (FUA) concept was introduced in 1996 [10], [11]. FUA considers airspace as one continuous volume which can be allocated in real-time according to

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user requirements. Thus, improved civil-military coordination increases the capacity of airspace due to flexible airspace segregation in real-time [12].

A Gate-to-Gate is another ATM concept [13], [14], which considers a flight as a continuous process that can begin with strategic flight planning in 6 months before the flight. During the entire flight from engines start to their short-down, pilots are on live control by ATC. ATC monitors every pilot action and coordinates him with other air traffic users.

Due to the growing number of air traffic in the world, the issue of optimizing ATC routes and developing methods for more efficient air traffic management is becoming more actual. In our study, we analyze a configuration of current Ukrainian flight routes network with a help of measures and metrics of graph methodology [15], [16], [17]. Air traffic route metrics help to identify an overall network capability to support air transportation services.

II. AN AIRSPACE STRUCTURE

ATM is based on safe separation minimums which define spaces between all airspace users, levels, or airplane tracks. ATM considers two basic types of separation: horizontal and vertical [5]. Each separation type has a particular minimum which depends on airspace type, phase of flight, or air traffic rules in a particular part of airspace.

Vertical separation distributes airspace users at different Flight Levels (FL) based on the predefined table of heights allowed to use within a particular airspace volume [5]. Leveling by altitude is grounded on measurements of static pressure and barometrical formula usage. FL counts from standard pressure level in 101.325 kPa [18]. The minimum of vertical separation is 1000 ft at an altitude less than FL290 (area of Reduced Vertical Separation Minimum is not included) and 2000 ft above [19].

Horizontal separation is defined as the safe distance between airspace users in lateral and longitudinal planes [5]. Minimums of horizontal separation take into account the requirements of performance-based navigation (PBN) [20] to on-board positioning system and flight routes structure [21].

The structure of airspace is designed to ensure: the organization of the flow of aircraft and different ways of airspace usage. The airspace is divided into upper – above 275 FL and lower – below 275 FL. In addition, the airspace is divided into areas. There are a flight information area (FIR), flight information area (FIZ), control area (CTA), area (CTR), terminal control area (TMA), and aerodrome control zones (ATZ) [22]. Also, airspace includes numerous restricted or dangerous volumes.

Air routes are an important element of airspace, which is used to direct the flow of air traffic. There are different types of routes:

- controlled route is used in controlled airspace;
- uncontrolled route is located in a part of airspace not covered by surveillance equipment;
- consultation route is an established route in the uncontrolled airspace on which the advisory ATC is provided;
- conditional route is a route that is planned to be used in special conditions.

Conditional routes have three categories [23]

- the first category is the conditional ATC routes that can be used by airspace user on a permanent basis with prior arrangements;
- the second category is the conditional routes of the ATC, the use of which is determined by Air Navigation Service Provider (ANSP);
- the third category includes routes that in no case can be planned by airspace user, and are used only with the permission of the ATC.

Air traffic within the airspace closed to the airport is strictly performed by predefined trajectories. Standard Instrument Departure (SID) route and Standard Terminal Arrival Route (STAR) are used for air traffic separation in departure and arrival flows during flight by instrument rules (IFR) [5]. SIDs and STARs connect the flight routes network with the runway.

The width of flight route is specified with a help of area navigation (RNP/RNAV) specification based on the performance of existing navigation infrastructure [24]. Parameters of flight routes depend on performance of on-board positioning sensor (Global Navigation Satellite System, Inertial Reference Unit [25] or positioning algorithms by pairs of navigational aids [26], [27], [28]). The distance between airspace users on parallel or divergent routes depends on the type of specification [5], [29]:

- RNAV 10 uses 50 NM routes width for oceanic flights;
- RNP 4 uses 23 NM routes width for oceanic flights;
- RNP 2 uses 7 or 15 NM routes width for continental flights;
- RNAV 1 uses 7 NM routes width for aerodrome area, SID, STAR;
- RNP 1 uses 5 NM routes width for aerodrome area, SID, STAR.

The minimums of metrical longitudinal separation are 50 NM for RNP/RNAV 4, 10 and 30 NM for RNP 2, 4 [5].

In Ukraine, air routes are divided into routes with Western direction and Eastern direction, the division goes through one FL. Thus, every even FL goes to the West and odd to the East. The level number starts from 110 FL (3350 m of absolute height) up to 290 FL with a step of 300 m and 600 m above 290 FL [5].

The airspace is divided into special classes: A, B, C, D, E, F and G. Classes A to E inclusively belong to controlled airspace, because in these classes the pilot must obtain an ATC permit to perform the operation. Classes F and G belong to uncontrolled airspace, because they do not require a pilot to obtain an ATC permit to perform the operation. There is also a difference between airspace classes in flight types, maintenance, flight speed limits, radio navigation support, and whether an ATC permission is required.

Also, an air traffic velocity is limited based on altitude and airspace class. Speed limit is 128 m/s at altitudes below 3050 m above mean sea level (AMSL) for classes from C (only for visual flight rule) and for all classes below (D, E, F, and G). Radio communication is required for all classes from A to E only for IFR. Flights in any airspace class can be performed by IFR or Visual Flight Rules (except A, IFR – only allowed). As an example, Ukrainian airspace is divided into classes C, D, and G only.

The structure of Ukrainian airspace is represented in Fig. 2. Class G is applied from the ground height up to 1500 m AMSL, also, they are used in areas of ATZ. From 1500 m to 2900 m class D is located within the CTR and CTA areas. Class C is used from altitudes from 2900 m to 660 FL in TMA and CTA areas [30].

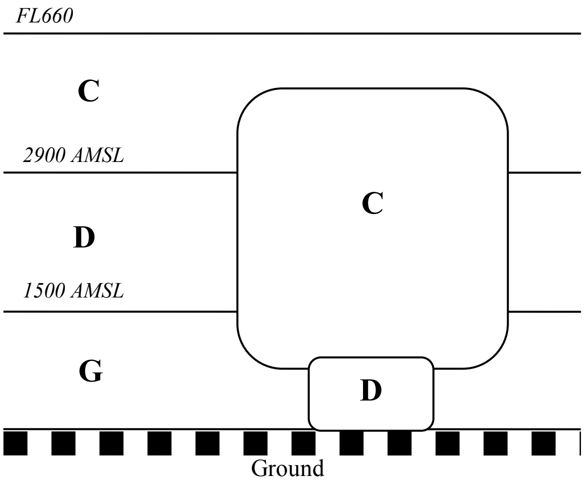

Fig. 2. The structure of the Ukrainian airspace

FRA airspace is allocated in FL 550 and above to increase the efficiency of air traffic. Free routes allow airlines to build shorter routes, which reduce fuel costs and aircraft emissions in the air.

III. Configuration of a flight route network

Flight routes network can be represented in form of a graph with a collection of nodes or vertices connected by edges. Nodes include all waypoints within the investigated airspace volume. Each edge has a predefined range of allowed FL. Edges between waypoints are defined as an adjacency matrix R [31], each element of each can be defined as following: $R_{i,j}$=1, if waypoints i and j have a direct route connection, and $R_{i,j}$=0, if connection is unavailable:

$$R = \begin{bmatrix} 0 & R_{1,2} & \cdots & R_{1,n} \\ R_{2,1} & 0 & & R_{2,n} \\ \vdots & & \ddots & \vdots \\ R_{n,1} & R_{n,2} & \cdots & 0 \end{bmatrix},$$

where n is a number of waypoints.

Location of each waypoint is usually defined by coordinates of latitude and longitude. Thus, flight routes can be represented as a weighted network. The weight of each edge can be associated with a geometrical distance between nodes or utilize an air traffic statistic. Thus, weighted adjacency matrix (A) can be obtained as follows:

$$A=RD, \tag{1}$$

where D is a matrix of geometrical distances between waypoints.

Flight routes network usually can be referred to planar graph due to absence of end edges cross.

Impact of each waypoint into the network performance can be evaluated based on node degree, which utilizes a number of connected edges or weighted degree:

$$c_i = \sum_{j=1}^{N} d_j \,, \tag{2}$$

where d is an edge weight; N is a total number of edges from i node.

Closeness centrality measures the inverse of mean range from a waypoint to other collocated nodes [32]:

$$c_{ci} = \frac{N}{c_i}, \tag{3}$$

A centrality measure indicates the significance of each node with respect to network configuration.

Betweenness centrality measures the extent to which a node lies on paths between other nodes [33]:

$$b_i = \sum \frac{p_{a,b}(i)}{p_{a,b}}, \tag{4}$$

where $p_{a,b}$ is a number of paths between a and b; $p_{a,b}(i)$ is the number of paths crossing ith waypoint.

Waypoints with higher betweenness centrality value may have more influence on air transportation due to their frequent use in case of equally loaded edges of the entire network.

IV. Analysis of Ukrainian flight routs network

Ukrainian airspace analysis covers L'viv, Kyiv, Dnipro, and Odessa zones which include 309 waypoints and 480 edges between them [30]. The total length of edges is 43152 km. The longest edge is 417 km between waypoints "Pobuv" and "Lonla". A histogram of edge length for Ukrainian en-route network is represented in Fig. 3 with bin width in 25 km. A mean edge length is 90 km.

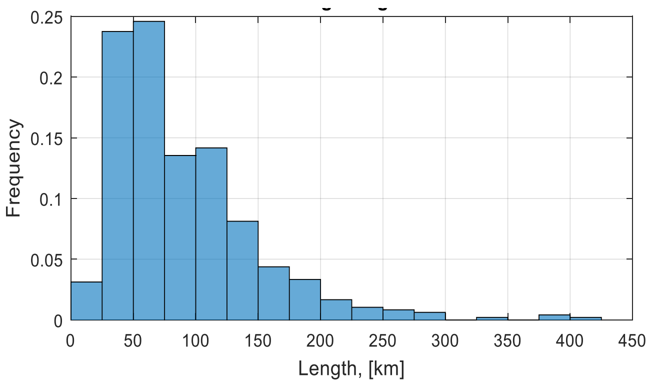

Fig. 3. Histogram of edges length for Ukrainian flight routs network

Ukrainian en-route network in form of a graph is represented in Fig. 4. A result of waypoints degree estimation in form of a number of connected edges indicates that waypoint "Odesa" has a maximum number of associated edges (18), and waypoints "Dnipro" and "BEDBA" have more than 12 connections. A frequency of particular waypoint degree is represented in form of hisporgam in Fig. 5.

Result of waypoint degree estimation indicates that flight routes network is designed equally distributed, mostly.

The mean number of each waypoint connections is approximately equal to 3 and only 3% of waypoints has a degree more than 7.

Weighted degree of network estimated by (2) is represented in Fig. 6 and utilizes a total sum of edges for each node. The mean weighted degree is 280 km and the maximum is 1532 km.

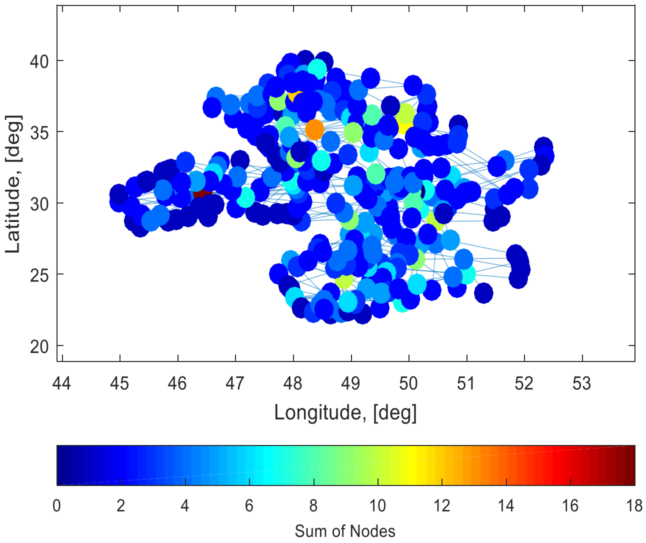

Fig. 4. Degree of a waypoint for Ukrainian flight routs network

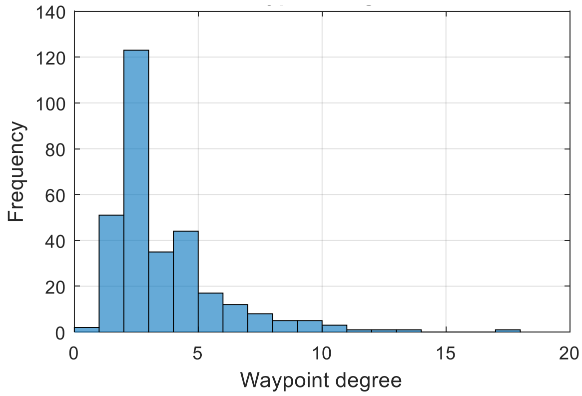

Fig. 5. Distribution of waypoint degree in Ukraininan flight routes network

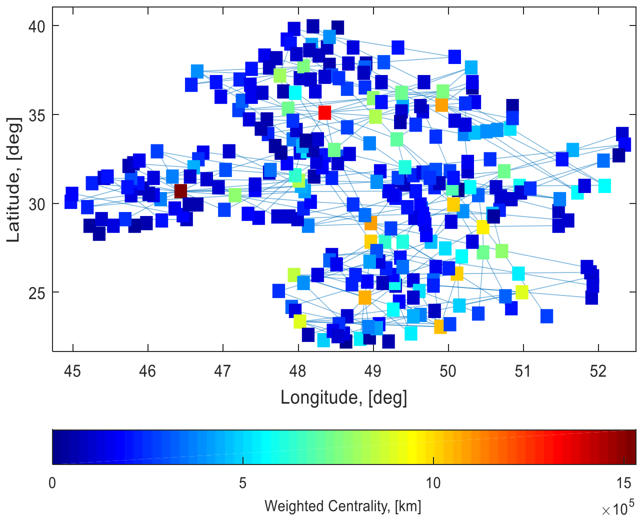

Fig. 6. Weighted degree of Ukrainian flight routs network

Closeness centrality estimation by (3) is represented in Fig. 7. A mean value is 5.4×10^{-9} and the maximal value is 7.7×10^{-9}.

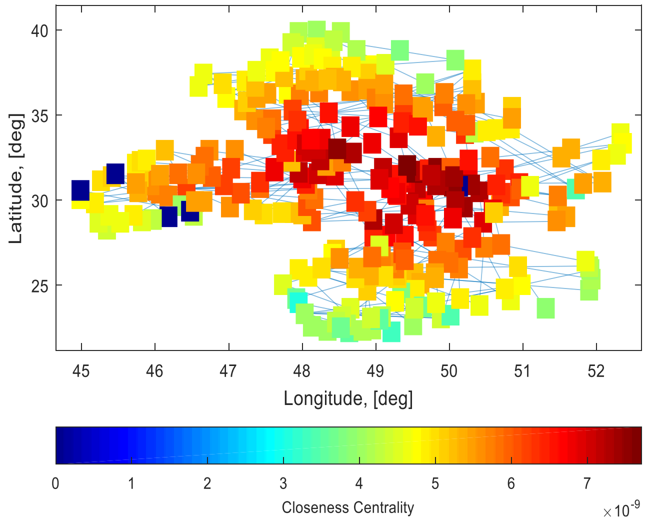

Fig. 7. Closeness centrality of network

Betweenness centrality is represented in Fig. 8. Results of betweenness centrality estimation indicate that waypoints “Nirov” (8292), “Oslan” (6800), “Odesa” (6448) are the most frequently used based on the shortest path between nodes.

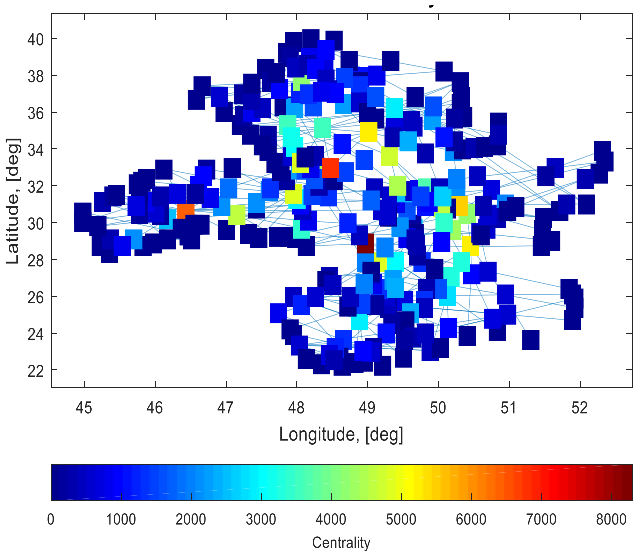

Fig.8. Betweenness centrality of network

Based on obtained results, we can conclude that, the Ukrainian network of flight routes is quite developed, in terms of air safety according to Fig.8. There are only a few waypoints "Nirov", "Oslan", and "Odesa", which may be overloaded in case of simultaneous applied large air traffic via Ukrainian flight-routes network. We can advise Ukrainian air navigation service provider to pay attention to these waypoints and take measures of traffic statistics to avoid overloading them.

Regarding the number of routes crossed at one point, the most problematic can be “Odesa” waypoint as it is a hub in its region. Also, due to the closed airspace over the Crimea region, most air traffic coming from the South (from the Black Sea side) must fly along the routes with usage "Odesa" waypoint.

V. Conclusion

In research, we analyzed the Ukrainian flight routes network configuration. A flight routes network representation in form of a planar graph makes it possible to estimate network configuration based on metrics of degree, centrality, and betweenness. Results of estimation indicate that each waypoint has 3 connected routes at the mean. The total length of edges in the network is 43152 km. Waypoints of "Odesa", "Dnipro" and "Bedba" were detected as the most connected in the network. Also, results of betweenness centrality estimation indicate that waypoint "Odesa" appears in the many paths through the network.

Obtained results of configuration analysis are useful for flight route development by domestic air navigation service providers.

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