Automated flight planning method to facilitate the route planning process in predicted conditions

Grzegorz Drupka
Department of Avionics and Control Systems
Rzeszow University of Technology
Rzeszow, al. Powstancow Warszawy 12, 35-959 Rzeszow
g.drupka@prz.edu.pl

Tomasz Rogalski
Department of Avionics and Control Systems
Rzeszow University of Technology
Rzeszow, al. Powstancow Warszawy 12, 35-959 Rzeszow
orakl@prz.edu.pl

Andrzej Majka
Department of Aircraft and Aircraft Engines
Rzeszow University of Technology
Rzeszow, al. Powstancow Warszawy 12, 35-959 Rzeszow
andrzej.majka@prz.edu.pl

Abstract—**The primary purpose of this study was to elaborate a method that facilitates aircraft operation at the flight planning stage by automating the flight planning process. This paper describes the impact that external factors, such as airspace structure or weather conditions, have on flight efficiency. The proposed method was based on the discrete airspace model and a specifically designed manner of data processing in respect to the conditions data set in this model. The entire process makes it possible to interpret store data to seek and suggest the path according to user preferences. By specifying the departure and arrival aerodromes, the user obtains data about distance, flight duration, fuel consumption, route charges, overall cost of the en-route phase, and the impact of turbulences.**

The solution was developed using the C++ programming language. The Floyd–Warshall algorithm was applied to find the shortest ("lowest cost") path. However, before the path seeking algorithm was employed, several methods had been used to evaluate the data inserted into the model with regard to aircraft performance and the predicted position. The predicted position within the location on the model was established using graph theory and applying a Voronoi diagram. The obtained result demonstrated that the elaborated method can be used to obtain information about benefits from individual path variants. After entering the aerodrome of departure and aerodrome of arrival requests, the user obtains a flight path according to the criteria provided in the request. As proven in the discrete airspace model, even more advantageous paths can be found than the one based on the shortest route.

The elaborated method can bring benefits in a variety of transportation problems. It involves a useful solution that allows the application of the Floyd-Warshall algorithm in seeking a "low-costs" route based on more than one criterion. It may be useful in planning autonomous missions for remotely piloted aircraft systems. In aviation, the adoption of this method could even contribute to reducing the discrepancy between the planned flights submitted to the processing system and the actual network situation. That, as a result may decrease time-related deviations, and reduce the workload of Air Traffic Control Officers.

TABLE OF CONTENTS

1. INTRODUCTION

The growing air traffic volume has made it necessary to establish services and introduce rules that ensure effective and safe operations in airspace. The universal and harmonized Air Traffic Management (ATM) process has contributed to increased safety and reduced the impact of adverse factors, such as adverse weather conditions, technical and operational issues, volcanic dust etc. Nevertheless, it is essential to obtain information on the planned operation prior to flight in order to balance airspace capacity vs. aircraft operator (AO)[1] demand. The integrated ATM process (Fig. 1) consists of the Air Traffic Services (ATS), Air Traffic Flow and Capacity Management (ATF[c]M) and Airspace Management (ASM).

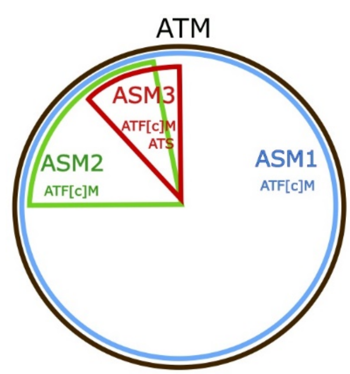

Figure 1. Integrated ATM process

[1] AO is a broader term than Airspace User (AU), and encompasses, in addition to an organization involved in air operations and its pilots, the activities aimed at improving flight efficiency [1]

978-1-7821-2734-7/20/$31.00 ©2020 IEEE

Consequently, ASM is a practice that derives from Flexible Use of Airspace (FUA), and allows the deliberate and effective utilization of an airspace in 3 (three) levels. ASM Level 1 (strategic) facilitates airspace preparation (long time horizon); ASM Level 2 (pre-tactical) involves flight plan preparation, submission and treatment (120 h before flight); ASM Level 3 (tactical) relates to the day of flight and involves Estimated Off-Block Time (EOBT) allocated as per AO demands (Fig. 2).

Before a flight can be operated in the controlled airspace, it is compulsory for the AO to prepare and submit a flight plan (Filed Flight Plan – FPL or Repetitive Flight Plan – RPL[2]). The flight plan has to be submitted to the Integrated Initial Flight Plan Processing System (IFPS) in a universal form that encompasses all the significant information about the planned route. The document is submitted for the purposes of the Network Manager Operations Centre (NMOC) to provide ATF[c]M services (mostly on ASM Level 1 and ASM Level 2) and for ATS (mostly on ASM Level 3). This information facilitates determining the predicted location and the time at which the aircraft will enter individual sectors (with the dimensions and volume determined at the strategic level – ASM Level 1). The major purpose of FPL submission is to prevent exceeding the airspace volume, while ensuring not to overload the operational abilities of Air Traffic Control Officers (ATCO), since airspace volume is determined according to the operational abilities of ATCO. FPL also allows to optimize airspace utilization, providing access to all the necessary flight data, composed according to the AO's intentions. This provides ATCO with the data on the expected air traffic before its occurrence in real time, leading to higher efficiency in aircraft separation activities and potential conflict solving [2].

Flight planning requires referring to the Aeronautical Information Publication (AIP) that lists the rules in force in the country where the flight will be performed. Furthermore, the AO is obligated to check the meteorological information [3]. However, for short range flights, at the flight planning stage, forecasts of weather impact are considered mostly to ensure flight safety or for navigational aid, without having regard to the benefits according to user preferences. Additionally, AOs mostly choose their paths so as to find the shortest possible connection between the departure and arrival aerodromes (points) on the chart. However, it is possible to obtain much greater benefits during the cruise phase than at any other stage, as well as experience major setbacks. This paper presents an automatic flight planning method based on graph theory and data processing techniques. Information about the airspace conditions is contained in the created discrete airspace model. An example of automated flight planning using the developed method is presented on a hypothetical setup of a Full Free Route Airspace (FRA). Full FRA means there are no airways and no fixed waypoints. However, the solution can be successfully applied in a Free Route Airspace (not Full FRA, so with predefined waypoints) or with respect to ATS Route Network configuration (with a reference to waypoints and airways). The automatic seeking process requires the introduction of departure (entry) and arrival (exit) points solely for the purpose of supporting AO in the process of path selection. As part of this study, the system generated waypoints in reasonable locations, as connections between the segments of the entire path. Waypoints are generated to avoid exclusion areas or to find a better path, which in practice, can be missed or not taken into consideration by a human operator, whereas the alternative routes may be favorable as well.

2. Flight planning process

Any flight planned to be performed partially or entirely in a controlled airspace covered by the Initial Flight Plan Processing System Zone (IFPZ or ICAO EUR) must be reported using the required FPL (or RPL) form [4]. A controlled airspace is an airspace with defined dimensions where air traffic control services are provided for Instrument Flight Rules (IFR)[3]. Air Traffic Control (ATC), which is one of the ATS components, includes Area Control Service (ACC), Approach Control Service (APP) and Aerodrome Control Service (TWR). Air traffic supervision is a necessity, since flight planning is a process characterized by limited accuracy. Each service fulfills the control duties of an airspace in a designated area – CTR controls the Control Zone (CTR), APP controls the Terminal Control Area (TMA) and ACC controls the Area Control Center (ACC) (Fig.3). The cruise phase, as the object of this study, takes place in ACC, and it is the longest part of the whole path (this will be

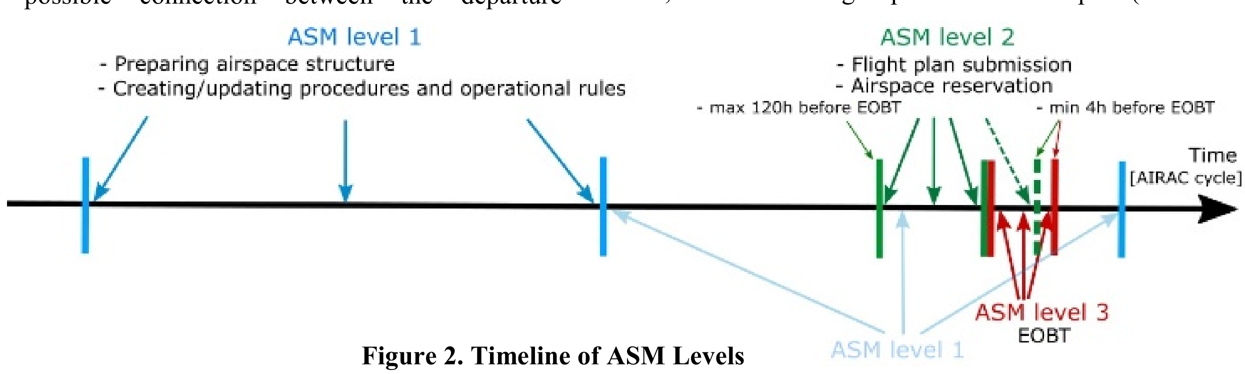

Figure 2. Timeline of ASM Levels

[2] This distinction is not crucial in this paper, so whenever FPL is mentioned this also refers to RPL.

[3] Even for VFR flights in accordance with the airspace classification

discussed in greater detail in chapter 3) [5][6][7][8].

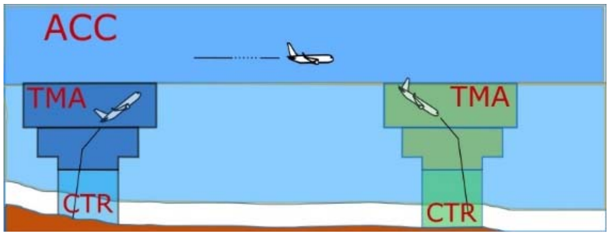

Figure 3. Vertical cross-section of an airspace

FPL submission to the IFPS must be preceded by thorough and precise preparation. FPL contains all the data about the planned operation crucial to perform the flight, such as:

- aerodrome of departure
- aerodrome of destination (alternative aerodrome as well),
- time (EOBT),
- cruising speed,
- flight level (FL),
- aircraft type
- route
- other (that are not take into consideration in this paper)

Routes may be described as waypoints and airways (if an airspace is in the ATS Route Network configuration) or as waypoints only (if an airspace is in the Free Route Airspace configuration) [4].After FPL preparation (which is the AO's responsibility), submission and processing in the IFPS (ATF[c]M task), an Operational Reply Message (ORM) is sent to the AO with an indication. ORMs carry the information that FPL is acknowledged (ACK), rejected (REJ) or has to be changed though manual treatment by the IFPS staff (MAN) (Fig.4).

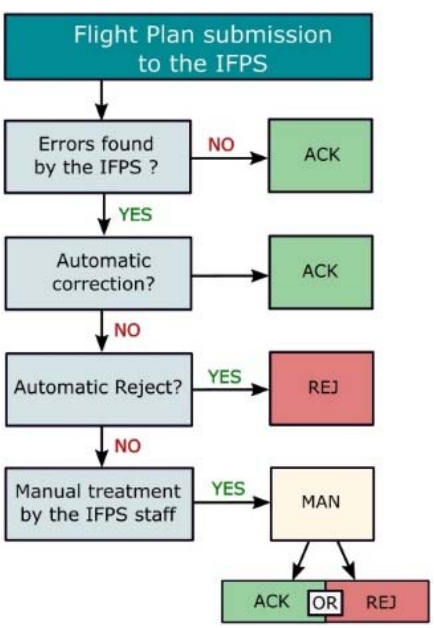

Figure 4. FPL treatment after submission

At present, approximately 3% of roughly 30,000 flights are rejected in Europe daily. If the FPL is classified as ACK, then the data about the planned flight is distributed to an appropriate Air Navigation Service Provider(s) (ANSP). The ANSP fulfills the function of ATC in a given country, involved in supporting operations in the airspace where the flight is to be performed (ACC, TMA, CTR).

Since ATF[c]M activities support an AO, the FPLs accepted via the IFPS, if requisite, are distributed to the Enhanced Tactical Flow Management System (ETFMS). The ETFMS that is supported by an ATC Unit(s) proceeds to reprocess and edit the FPLs according to the airspace situation as per the report obtained from the ATC Unit(s) (Fig.5). The real time actions (tactical management), performed through the ETFMS, contribute to achieving better performance of traffic flow as impacted by adverse weather conditions, technical issues or organizational matters that lead to delays. Those actions adapt the declared flight operations to the actual situation in the airspace on the day of operation, and facilitate maintaining airspace order [4][9].

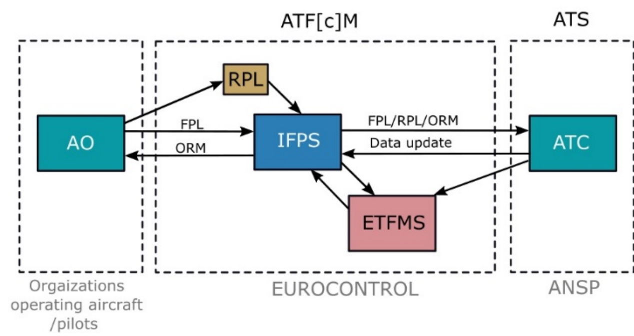

Figure 5. The process applied to the FPLs submitted to IFPS

An AO submitting an FPL has no guarantee that the planned route will be accepted. An AO's route may be rejected even if it initially appeared certain. However, it is possible that even more beneficial paths exist, where the traffic is not so high to cause rejection. With manual consideration, a human can overlook a large number of conceivable routes that without complex calculations can be seen as not as favorable as the routes usually chosen. However, since the IFPS receives the FPL which is based on airspace conditions altered from distance between two points only, then over the course of a day delays may accumulate. As the value of minimum delay is the major factor taken into consideration in ATM efficiency, the planned paths based on complex airspace conditions may alleviate the disproportions on the AO-ATF[c]-ATC line, reducing the number of actions that need to be performed by ETFMS, thus reducing IFPS staff and ATCO workload as well.

3. Factors considered in Flight Planning and the practice of factor evaluation

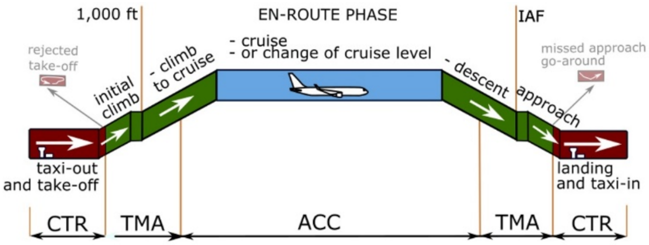

Figure 6. Flight phases

Flight phases scrupulously define entire mechanisms – the position of an aircraft (Fig.6) and the activities of crewmembers along the entire trajectory – from the aerodrome of departure to the aerodrome of arrival. The factors that influence flight may vary depending on the flight phase. This variance is not only caused by different impact intensities, but also depends on the maneuvers that an aircraft may perform. (i.e. during take-off and landing phases a headwind is helpful, but necessitates leaving a longer time gap between successive aircraft making their final approach) [10][11][12]. Since considering the entire trajectory is a broad field, this study will focus on the En-Route Phase. Because deviations between the FPL and the actual situation have impact on other phases of flight in the time dimension, the En-Route Phase is a field worth examining. As the longest part of the flight, the En-Route Phase provides opportunities to obtain numerous benefits, not only for a single flight. Delays during the En-Route Phase affect other flights, occupying TMA capacity when waiting for the approach decision or directly in the neighborhood of an aerodrome, while executing the holding procedure at the Initial Approach Fix (IAF). In the case of busy airports, any time-related deviations disturb traffic order. This generates considerable stress for the ATCO.

A navigation principle is that a path between two points should be planned so as to determine the shortest way connecting these points. On the spherical Earth model in long-range air navigation it is useful to define geodesic or great circles (GC or orthodrome). However, in practice, short-range navigation uses rhumb lines (loxodrome). Loxodrome navigation facilitates navigating because it is based on travelling along a line, crossing all meridians at the same angle. An aircraft flies with constant heading connecting two points on the chart. For long-range flights, even the GC does not guarantee reaching the shortest flight time [13]. As explained by airline pilots, finding the shortest route is not only a problem of choosing between GC and Rhumb Line. There are intricate matters involved, including ones concerned with international law [14].

Unavailable airspace

For the purposes of as efficient airspace utilization as possible, according to one of FUA-related activities, an airspace is treated as one continuum for both civil and military operations. Located in NMOC, the Airspace Management Cell (AMC) is responsible for Temporary Airspace Allocation (TAA). AMC-Manageable Area is significant at the pre-tactical ASM level 2 allocation. The TAA process consist of Temporary Airspace Reservation (TRA) and Temporary Airspace Segregation (TSA), depending on the nature of an operation (Fig.7). TRA is a configuration that allows to exclude certain airspace volume for special tasks (reserved for aviation authority), however under permission, other traffic is allowed under control of ATC. TSA, is a configuration, which does not allow traffic in the specified airspace volume, in time of its activation. Areas are often excluded due to environmental impact (i.e. thunderstorms), but mostly for civil military activities such as tests, trainings, research and development actions or rocket lunching. There exists an even more flexible airspace reservation method, Dynamic Airspace Configuration (DAC), where allocation and reservation is defined as a Dynamic Mobile Area (DMA). DMA does not demand to occupy full airspace predicted to be utilized during entire activity, but defines variable geographical location and volume in manners aimed at reducing traffic reorganization. One DMA concept defines the timeframe that a certain volume of excluded area is moving together with an aircraft [15][16].

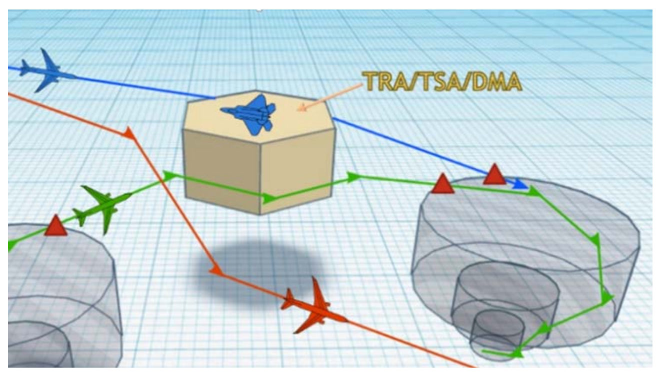

Figure 7. Temporary Airspace Allocation

TSA/TRA activation forces traffic flow reorganization, causing limitations on some connections. The discrete airspace model prepared for the study involves an established boundary where TSA/TRA is activated. It was assumed in this study that the excluded area (with specified boundaries) causes the exclusion of each cell of the airspace model covered by this area (even if this only concerns a part of it).

Wind

Since an aircraft travels in the air mass, and the air moves relative to Earth, the ground speed (GS) of an aircraft is different than its airspeed. The planned flight path is the desired track and the actual track is the result of an aircraft's heading and velocity, with the impact of wind speed and direction. So the track is deviated from aircraft heading at an angle called the Drift Angle (DA). DA is calculated in accordance with the True Aircraft Speed (TAS) vector. Hence, the ground speed is a sum of the vectors TAS and wind speed (V) at an angle called the Wind Track Angle (WTA) which is situated between aircraft heading and wind direction (W) (Fig.8).

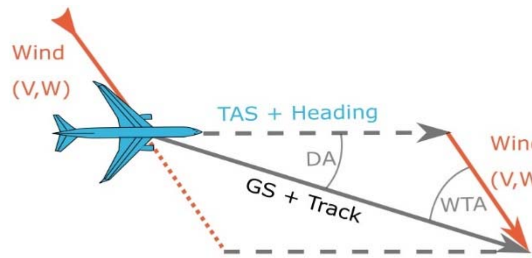

Figure 8. The impact of wind direction and velocity on the desired track of an aircraft

Flight time (T) can be expressed using the following formula:

$$T = \frac{60 \cdot L}{GS}\ [minutes] \tag{1}$$

Where:
L – distance
GS – ground speed – described as follows:

$$GS = TAS \cdot \cos(DA) + W \cdot \cos(WTA) \quad \text{[knots]} \tag{2}$$

TAS – true airspeed
DA – drift angle
W – wind direction
WTA – wind track angle

$$\sin(DA) = \frac{V}{TAS} \cdot \sin(WTA)\ [degrees] \tag{3}$$

Where:

$$WTA = W - DTM\ [degrees] \tag{4}$$

DTM – Magnetic track (heading)
If the WTA exceeds the range between 0 and $+/-180[deg]$, the angle value shall be subtracted from the WTA's explement, resulting in the changed +/- sign [17].
In the developed solution the winds are displayed in a chart (a two-dimensional airspace model) in a manner that demonstrates the benefits or adverse factors of their presence on the flight. Wind has considerable influence on direction and velocity. While tailwind can reduce cruise time, headwind results in a longer flight. Crosswind, depending on the DA formed with an aircraft may have negative or positive influence (Fig. 9). The data about wind velocity and wind direction is visualized as a single layer in the chart. Wind barbs were used for visualization purposes.

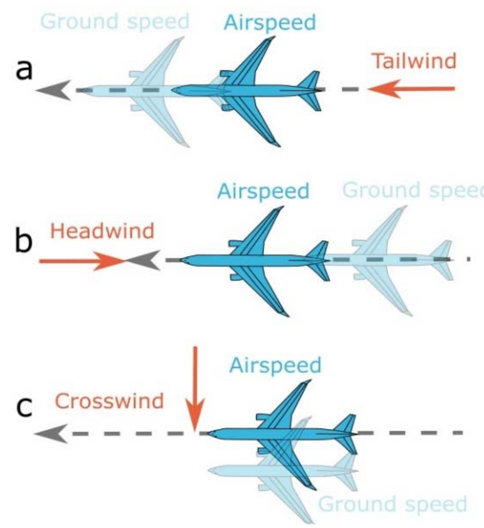

Figure 9. Result as the sum of vectors on the aircraft ground speed

Wind barbs provide a highly intuitive graphical representation of wind speed and direction. The direction is indicated by the angle of the long flagpole (towards the plain end) and is based on a 36-point compass. Half barb denotes wind speed in the range between 2 and 7 knots (averaged to 5 knots for the purposes of this study). Full barb represents wind speed in the range between 8 and 12 knots (averaged to 10). A triangle (pennant) represents the wind velocity in the range between 48 and 52 knots. Multiple barbs and pennants are summed up to indicate the speed. For the purposes of this study, all wind barbs are averaged to values presented in the picture below (Fig.10). In the configuration presented in the picture, all wind blows from the west (W) [18][19].

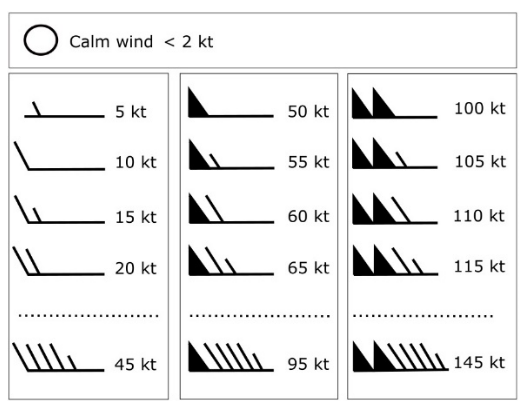

Figure 10. Result as a sum of vectors on the aircraft ground speed

Thunderstorm
A thunderstorm is a good example of a factor that reduces weather forecast accuracy. The growth and expansion of storms is nonlinear, sometimes very violent. For this reason the weather 2 hours prior is highly unpredictable [20]. There is a relation between storm dimension and predictability. Greater storms are easier to detect and their growth can be

more accurately predicted. However, smaller storms are easier to avoid [21][22].

By looking at the formation of storm cells it is possible to observe the presence of a variety of adverse factors such as rainfall, hail, lightning strikes and turbulences. A lighting strike does not pose so much danger to crewmembers or passengers (it only reduces comfort) as it does to avionics [23]. Lightning strike risk is much greater on 8,000-14,000 feet than on cruise level [24]. However on the highest levels, the current is higher and reaches the value around 24kA(17kA at lowest levels) [25]. Protection systems against lighting strikes can be divided into three categories – construction, fuel and avionics. In spite of these efficiently working systems, the most effective measure against lighting strikes is still thunderstorm avoidance. The method involves avoiding storm cells within a minimal radius of 20NM [24]. However any situation demands individual interpretation, because cumulonimbus clouds may reach altitudes up to 60,000 feet, and can develop rapidly [23]. However, the main reason for avoiding thunderstorms is to not expose an aircraft to turbulences, where severe or even extreme accelerations are common. Gust loads can be so severe to cause even structural damage [26]. Therefore, since a cloud occupies a certain volume, the airspace capacity decreases. As in aviation it is forbidden to fly into storm cells (cumulonimbus clouds must be avoided) in this paper's calculation method, thunderstorms can be considered a completely excluded area (similarly as TSA or TRA).

Turbulences

Turbulences are defined as unexpected bumps that happen during flight in scales of 10÷1000m [27]. Turbulence is caused by irregular air movements and results in unintended changes in flight parameters. The presence of turbulence worsens travelling comfort, but in severe or extreme cases might involve danger of injury or aircraft damage. Since jet engines are sensitive to air intake, turbulence has a very negative impact on the engine and might cause compressor stall, as it is characterized by an irregular airflow. Turbulence can be classified according to their causes into convective (caused by vertical air movements – for every rising air current, there is a downward current), mechanical (i.e. in the neighborhood of mountains – mountain waves) and shear turbulence (generated between layers created by the direction (or speed) of two different wind currents, particularly between the core of the jet stream and surrounding air). All of these form as a result of the presence of different variations (mechanical or convective) in the atmosphere and reach altitudes high enough to create possibilities of vertical avoidance or can be sustained by an aircraft flying through them (if turbulence does not exceed the established threshold) (Fig.11) [28] [26][29].

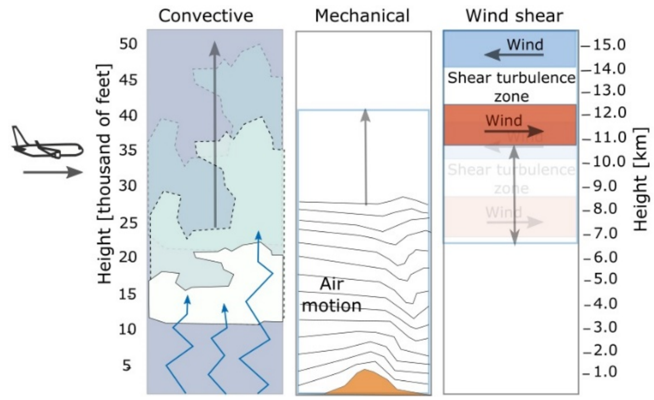

Figure 11. Visualization of turbulence causes according to their nature

In airborne observations of turbulence they are reported as verbal pilot reports (PIREPS) and aircraft based observations. In spite of the widespread use of PIREPS, this method is not a certain measure [27]. Pilots advised of upcoming turbulence by other pilots flying ahead, gain information about the impact of turbulence on the aircraft. Intensity is rated according to its influence on aircraft controllability, structural integrity and performance. However, PIREPS use only verbal notation, which may be interpreted in various ways depending on flightcrew experience or aircraft characteristics [28].

More accurate records regarding turbulence can be obtained by using in situ aircraft data. There are three turbulence indicators, namely Vertical Acceleration, Eddy Dissipation Rate (EDR), and Derived Equivalent Gust Velocity (DEGV). EDR and DEVG are successfully used in the Aircraft Communication Addressing and Reporting System (ACARS) and Aircraft Meteorological Data Reporting (AMDAR) as they provide objective measurement. The data is used especially for enhanced weather monitoring, support forecasting and alerting.

The turbulence impact indicator used for this study was DEGV, an algorithm successfully implemented in British Airways i.e. DEGV estimation based on aircraft information, such as vertical acceleration, mass, altitude, and airspeed. As an aircraft-independent measure of turbulence, DEVG can be expressed by the following formula:

$$U_{de} = \frac{Am|\Delta n|}{V} \tag{5}$$

Where:

$|\Delta n|$ - peak modulus value of aircraft normal acceleration from 1g (in units of g)

m – total aircraft mass (in metric tones)

V – calibrated airspeed (in knots)

A – estimated specific aircraft parameter; it varies according to flight conditions;

The A parameter can be approximated in following formulae:

$$A = \overline{A} + c_4(\bar{A} - c_5)(\frac{m}{\overline{m}} - 1) \tag{6}$$

$\bar{A}$ – parameter formulated in equation:

$$\bar{A} = c_1 + [\frac{c_2}{c_3 + H(kft)}] \quad (7)$$

Where:
H – altitude (in thousands of feet)
$\bar{m}$ – aircraft reference mass (in metric tones)
$c_1, c_2, \dots, c_5$ – empirical constants, depending on various aircraft (based on flight profiles (Truscott 2000) [27][30].

Since the formula U_{de} uses calibrated airspeed (CAS), then we need to apply the following formula to convert a TAS into CAS:

$$CAS = a_0\sqrt{5[\left(\frac{q_c}{P_0}+1\right)^{\frac{2}{7}} - 1]} \quad (8)$$

Where:
a_0 – sonic speed at sea level
q_c – impact pressure expressed as follows:

$$q_c = P[(1 + 0.2M^2)^{\frac{7}{2}} - 1] \quad (9)$$

M – Mach number
P – static pressure (depending on altitude)[4]
P_0 – static air pressure at sea
P – pressure on the flight level (table on mathpages.com)
Mach number is described by the equation below:

$$M = \frac{TAS}{a} \quad (10)$$

Where
a – sonic speed at Outside Air Temperature (OAT) which can be determined via:

$$a = \sqrt{\gamma RT} \quad (11)$$

where:
γ – ratio of specific heats (γ for air is equal to 1.4)
R – gas constant (R for air is ~287J/kgK)
T – OAT (expressed in Kelvin degrees)
For this research, OAT is 216.65K (as -56.5 Celsius degrees)[5] [32]

The result of the U_{de} calculation is expressed in [m/s]. DEVG, as an important factor in aviation, widely used in the consideration of turbulence impact on an aircraft is also expressed in DEVG Index form. The Index is the number assigned to value sections (x≤A<x') derived from the formula U_{de}. The table below presents the correlation between DEVG values and verbal notation of intensity of turbulence [33][34].

Table 1. DEVG index

DEVG Index	Meaning	Acceleration (A)	Acceleration DEVG (A)
0	None	**A**<0.15g	**A**<2m/s
1	Light	0.15g≤**A**<0.5g	2m/s ≤**A**<4.5m/
2	Moderate	0.5g≤**A**≤1.0g	4.5m/s ≤**A**≤9m
3	Severe	**A**>1.0g	**A**>9m/s

Estimating the DEVG for any possible connection allows to obtain the turbulence index for each possible path. For this study, information about the exceeded threshold of the DEVG index will be displayed. The chart used in this study will be partially covered by turbulence forecasts. The established turbulence value is g=0.0÷g=0.8, a value that exceeds the rate of an aircraft's normal acceleration. Since DEVG is sensitive to empirical constants $c_1, c_2, \dots, c_5$ for this research we use two different aircraft—Airbus A320 and Boeing 737-700 (c-constants are from table Truscott B), 2000).

Aircraft type

When considering the type of aircraft in flight planning or during research and development activities it is important to compare aircraft performance resulting from construction to operational environment. The Aircraft Performance Database contains aircraft data, including technical dimensions and parameters important for operation, that can be used to obtain an accurate aircraft model capable of supporting computation in different flight phases [35].

This information aids the process of rating an aircraft's behavior when subjected to turbulence in this study. In this process, it is important to take into account the Maximum Take-Off Weight (MTOW), since the total mass of an aircraft ready for flight can affect turbulence impact. The table below (prepared on the basis of the Aircraft Performance Database) presents the selected aircraft dimensions, performance, fuel consumption (based on airliners.net) and accommodation. Fuel consumption is crucial for estimating the overall flight cost. Accommodation, if required, would be crucial to extract information about the estimated cost for any seat or other economic calculations for the purposes of fleet management.

Table 2. Selected aircraft dimensions, performance and fuel consumption

	Airbus A320	Boeing 737-700
Accommodation	150 passengers (two classes) or up to 180 (one class layout)	128 passengers (two classes) or 149 (all tourist class configuration)
Range	Short to medium range single aisle airliner. In service since 1988.	Short to medium range airliner. In service since 1997.

[4] Air pressure density is available on: [31]

[5] Temperature at proper altitudes: [26]

Wing Span	34.1m	34.3m
Length	37.57 m	33.6 m
Height	11.76 m	12.6 m
Power plant	2 x 111kN CFM56-5A1 or 2 x 118kN CFM56-5A3 or 2 x 125kN IAE V2500 turbofans	2 x 89 kN CFM56-7 or 2 x 107 kN CFM56-7HGW turbofans
MTOW	73900kg	66300kg
TAS	450kt	460kt
Ceiling	390FL	410FL
Range	2700NM	2500NM
Fuel consumption*[6]	2430kg/h	2420kg/h

The data about aircraft performance in this study is used to estimate safety, comfort and economy of flight (route charges or overall flight costs).

Fuel Consumption

The table above contains information about approximate fuel consumption. Fuel consumption is indicated as a parameter of endurance, it defines total time that an aircraft can stay in the air on one fuel tank. It is determined by airspeed, air density, and throttle settings [37].

Since the path seeking process will be carried out between two specified airports only, our elaboration is based on generalized fuel consumption per time unit, provided in kg/h, (based on airliners.net). If a study concerns several different aerodromes (different distances), then the fuel consumption formula should be introduced, because variations might occur depending on weight and route length.

Charges

The economy of ATM revenue requires the recovery of costs for their services rendered to AO. On behalf of European Member States, the Central Route Charges Office (CRCO) bills and collects route charges. En-route charges are based on harmonized principles for any member state of the European Organization for the Safety of Air Navigation (EUROCONTROL). Billing involves a single charge per flight using three fundamental elements:

- Distance Factor
- Unit Rate of Charge
- Aircraft Weight Factor.

The Distance Factor and Unit Rate of Charge are different for each charging zone, so the operation of multiplying these three components must be repeated for each charging zone overflown using the relevant data, as shown below:

$$Total\ Charge\ [Euro] = \sum_i^n Ch_i + \cdots + Ch_n \qquad (12)$$

where:

Ch_i – charge rate for each single flight path section crossing

$$Ch_i = Df * Wf * Ur \qquad (13)$$

i-charging zone (country); i-number corresponding to the number n of states planned to be overflown;

Df – distance factor equal to distance (in kilometers) divided by 100 (one hundred) in the great circle distance; aerodrome of departure or aerodrome of arrival is treated as entry or exit point that constitute the distance value in an individual charging zone.

Wf – weight factor, equation component depending on metric tons of an aircraft (rounded to one decimal), and result rounded to second decimal; expressed as follows:

$$Wf = \sqrt{MTOW/50} \qquad (14)$$

Ur – unit rate specified individually for each state (applicable for a given calendar year, from 1st January each year), the picture (Fig.12) presents unit rates (expressed in Euro) applied on the chart in accordance to the table contained in the *Final data for the establishment of the cost-bases and unit rates, Information paper – CER-111-2018-3670, 19.11.18, Enlarged Committee for Route Charges.*

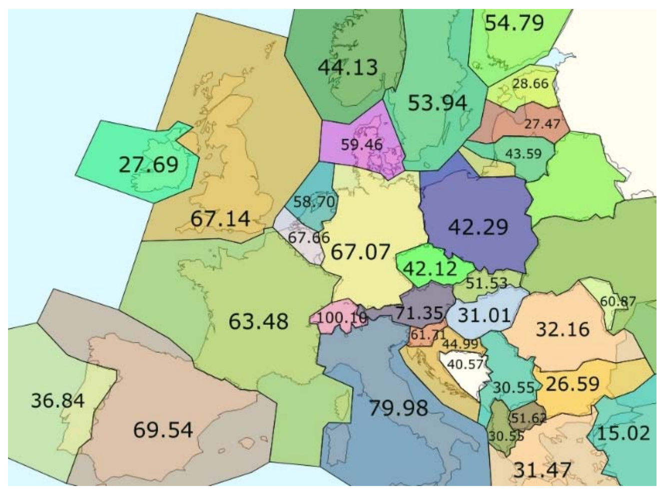

Figure 12. Unit charge rates in various European countries

Unit rates are expressed in national currencies, however, due to several considerations, they are converted into Euro. The charging zone division follows the division of Flight Information Region (FIR) and Upper Flight Information Region (UIR), if accessible [38][39].

Factors considered in the flight planning summary

Some factors considered in the flight planning process are invariable, such as unit charges or the distance between points on the chart. However, since the FPL submission is

[6] Fuel consumption: [36]

possible 120 hours before EOBT at the latest, the conditions in an airspace may significantly change [4]. There is a limitation that the flight crew cannot identify certain weather phenomena before the flight and they are only advised about them in the air by fellow pilots flying ahead [28]. The closer to EOBT, the less available the airspace, but a greater accuracy of weather forecasts as explained on the picture (Fig.13). Forecasts based on numerical methods are more precise closer to the operational time. However predictions in interval less than 6 hours are difficult. Difficulties are caused mostly by data assimilation or rapid weather changes. However, an AO should find a balance between weather forecast precision and airspace availability, since the volume of an airspace is decreasing as it gets closer to EOBT.

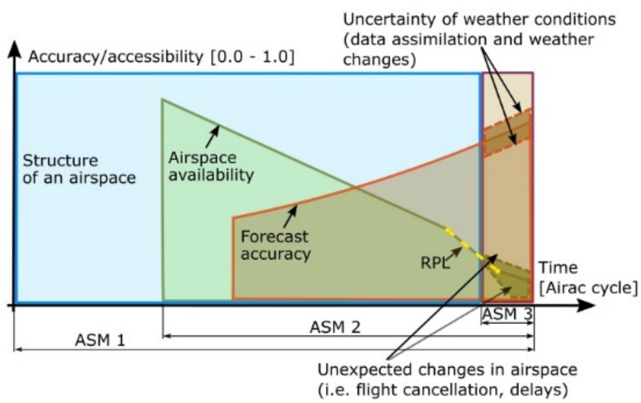

Figure 13. Weather forecast accuracy to airspace accessibility ratio

Well managed air traffic, balanced with airspace structure and information about weather forecasts may have a positive impact on flight paths in FPL preparation. Short range flight trajectories, determined on the basis of airspace structure and in the statement of airspace conditions may bring benefits at various levels. Each single flight may be beneficial according to AO intentions, however a reduced flight time also reduces the risk of potential delays. Moreover, the overall air traffic density can be reduced through wider traffic distribution relating to airspace conditions, and weather impact on flights may be less significant, so the differences between FPLs and the ATC-reported situation may be minimized.

4. AIRSPACE MODEL

To make the automatic route planning process possible we previously built a discrete airspace model (A), which reproduces airspace conditions in a certain approximation. The model consists of a set of cells. Cells are placed adjacent to one another to cover the entire airspace model (Fig.14). Unit cells (X_i) (cube-shaped) store record data with values representing specific airspace conditions in a given area.

Figure 14. An airspace model making up the basis for the method is based on

Record data is described in vector form using the following formula:

$$A = \begin{bmatrix} X_1 \\ \dots \\ X_n \end{bmatrix} \quad (15)$$

where:
A – vector representing the entire airspace
n – number of cells in the airspace cluster
X_i – unit cell, where:

$$X_i \; [z_1, z_2, z_3, \dots, z_m] \quad (16)$$

where:
z_j – record data that contains j – parameters (i.e. wind velocity, wind direction). A record representing specific airspace parameters can be introduced into the model automatically (via proper access to weather data) or manually

```
Model(A)
    for i ← 1 to n
        do for j ← 1 to m
            X_i[z_j] ← airspace parameters
```

The record containing data values for any single unit cell makes it possible to express information about the airspace in the form of mathematical equations. The use of equations allows the calculation of airspace conditions based on the possible connections between graph vertices located in the center of each cell. Since a vertex (node) has been placed in the center of each cell, graph theory was used to obtain the most suitable route in accordance with the AO's preferences. The path is recognized as the result of evaluation of data values contained in the airspace model in relation to the search method applied to the graph-based seeking principle. For a graph-network approach, an airspace is mapped by a graph. The selected graph-based route is described as a formula:

$$G = \langle V, E, W \rangle \quad (17)$$

where:
G – selected path,
V – set of graph nodes along the route
E – set of graph edges

W – weights based on conditions along the edge, between a pair of nodal points

On the basis of airspace conditions and selected criteria, the method allows to display the most favorable route(s). Model accuracy is somewhat related to edge length [40].

5. DATA INTERPRETATION METHOD AND ROUTE SEEKING ALGORITHM

The elaborated method that allows determination of the flight path between two points in an airspace model is based on the developed data processing methods and a route seeking algorithm – in this case the Floyd-Warshall algorithm. This algorithm was selected after considering Bellman-Ford, Dijkstra's, and Johnson's algorithms. The Floyd-Warshall algorithm resolves the All-Pair Shortest Problem. This is advantageous if we would like to seek a route from more than one (1) aerodrome (i.e. managing an aircraft's fleet). Using the Floyd Warshall algorithm ensures that after only one procedure of interpretation of the airspace, we will obtain the potential flight routes from any location to the preferred destination. The Floyd-Warshall algorithm can be modified in a way that allows a balance between more than only seeking criteria. In this study, the algorithm was applied in support of a method that allows the analysis of complex and varying airspace conditions (i.e. wind velocity and direction may significantly vary at different path sections; wind impact depends on aircraft heading at a specific segment and positive or negative influences). The most useful algorithm in addition to Floyd-Warshall was the Dijkstra algorithm. It works faster than Floyd-Warshall and the running time is equal to $O(n^2)$, where n is a number of nodes. However it can resolve a single source problem only. This means that it allows to find the shortest path from only one nodal point to another. In our case, this is a disadvantage, because if we wanted to plan a few flight paths at different aerodromes, then the algorithm would need to be run several times depending on different routes, multiplying the number of iterations. In that case, the running time would be far greater than for Floyd-Warshall [41][42].

The Floyd-Warshall algorithm is based on a directed graph G = (V, E) and uses a dynamic programming method over time $O(n^3)$. The algorithm works on the basis of observation – if between any pair of vertices I and j, in a set of n-number existing vertices, there is a shorter connection via vertex k, then the path is determined through k. The algorithm is based on a matrix and during a loop iteration a table is initiated that contains a record of the shortest path for any pair of vertices. (Fig.15) [43].

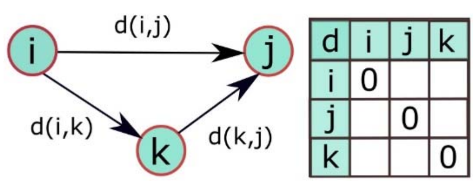

Figure 15. The Floyd-Warshall principle

In any seeking step, a shorter connection (if it exists) is added

to the matrix between a pair of points in the following manner:

Floyd_Warshall(X)
n ← rows[X]
$D^{(0)} \leftarrow X$
for k ← 1 to n
  do for i ← 1 to n
    do for j ← 1 to n
      $d_{ij}^{(k)} \leftarrow \min(d_{ij}^{(k-1)}, d_{ik}^{(k-1)} + d_{kj}^{(k-1)})$

Where I and j correspond to a single connection between two nodal points (segment) through a graph edge; k is the intermediate nodal point (assigned to the pair if algorithm found a shorter path); n is the number of nodes in the graph. The complete matrix consists of the shortest possible connections (lowest cost – i.e. time) between any pair of points, and indicates information about intermediate points. [41][44].

In our airspace model, the graph vertices are placed in the center of all cells. Since the Floyd-Warshall algorithm is based on information conveyed by the graph edge, we need to convert simple graph G (eq. 17) into a line graph L(G). The conversion process requires preserving the numbering system in order to maintain consistency between the airspace model and the matrix that is initiated to store the distance data. As a result, the new graph L(G) holds the same number of vertices as the number of edges in graph G (Fig. 16.), and each vertex of graph L(G) must be filled with information about the distance between two vertices in graph G.

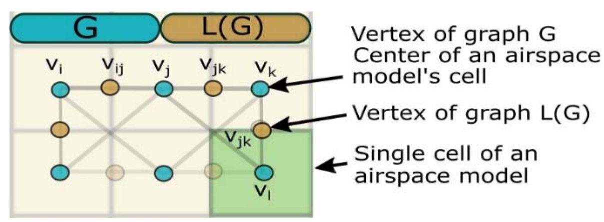

Figure 16. Converting a simple graph into a line graph

It would be easy to define the entire network with nodal points if we took into consideration a small area. However, to describe a larger area, in order not to enter all nodal points, we introduced to our method a formula that generates a grid of fixed span with an ordinal i-number of nodes:

Grid(xy)
i ← 1
  for y ← 1 to a
    do for x ← 1 to b
      $X_i(x, y) \leftarrow coordinate(x, y)$
      $i += 1$

Where i is the unit cell number; a and b describe grid span. For ATS Route Network configuration, we introduced coordinates manually, depending on the actual location of waypoints. To assign data that constitute distance information (Distance(X_i, X_j)) to a certain segment (between any possible connection of a node pair) we used Euclidean distance using the generated grid. Usually, the shortest distance route is the result of the lowest number of waypoints along a route. However if there is an airspace on the way where traffic is not allowed, the method automatically removes the connection. To apply the method, we developed a method to eliminate the connection. However the method requires finding which cells lie on the way of the connection. To determine which cells are located in the connection between a pair of nodal points we used the Voronoi Diagram. It allows assigning points belonging to the closest, predefined point, which is at the same time the center of the cell (Fig. 17a).

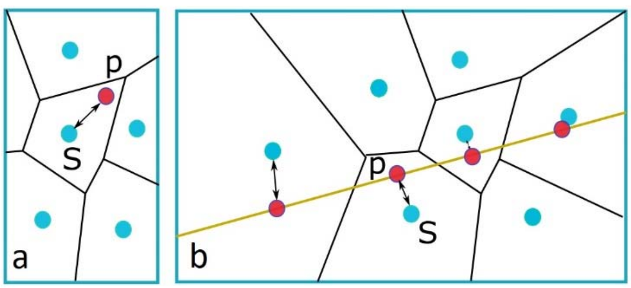

Figure 17. Voronoi tessellation (a. point to point, b. section to point)

Voronoi Diagram, also called Voronoi tessellation, is described by the following formula:

$$Vor_S(p) = \{x \in E | \forall q \in S, d(x,p) \leq d(x,q)\} \tag{18}$$

The formula says, that in a given space, which already has a defined set of points s, each point s has a region called a Voronoi Cell. Then, any point p that exists in the space closer to a point s, belongs to the certain cell as well [45].

However, to assign a *part of a segment* (section) to a certain cell center (center number) and define the distance of a section along the cell (fig. 17b), we used the equation of a line on a plane. Using this equation we determined the point of entry to and exit from each single cell. Then we obtained crucial information about each section that belongs to a segment. The entry and exit point information ascribed to any section makes it possible to estimate the location of any point on the path on the section (i.e. middle point between the entry and exit point). Applying the Voronoi Diagram formula, through comparison provided in algorithm steps, we obtained information on which cell's center was closer to the middle point lying on the section (Section_assignment(PS)). This information makes it possible to build a method for data record interpretation, considering sections and cells along segments (Fig.18). It is vital for determining the influence of various factors, such as the ratio of distance through any single cell to aircraft heading.

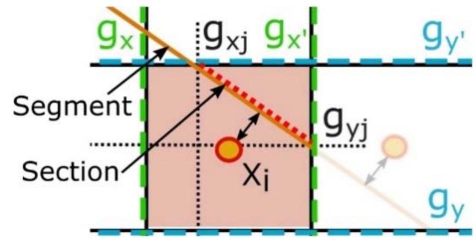

Figure 18. Section assignment process

Section assignment can be written in iteration steps. On each iteration of the loop, it is checked whether any unit cell's center is located closer to the section such as in the formula:

```
Section_assignment(PS)
for j← 1 to m (number of each possible pairs)
  min ← 1000
  do   for i← 1 to n (ordinal number of cell)
         p =: |X_ix X_iy − g_xj g_yj| + |X_ix X_iy − g_xj' g_yj'|
         if (p<min)
             min←p
             section (g_xj g_yj − g_xj' g_yj') ∈ X_i
```

In relation to the method presented above, we may interpret and then estimate the relationship between data recorded to any single cell to the aircraft parameters and performance. All evaluated data is stored using an extra auxiliary dimension added to a Floyd-Warshall initiated matrix.

However together with data interpretation, in addition to seeking better conditions in the airspace model's cells only, it is crucial to avoid cells excluded from traffic. To avoid drawing and removing graph edges manually (in our airspace model – segments), we developed a method of graph edge elimination. As explained above, to generate a grid, and locate the nodal points it was enough to introduce an algorithm. This was also the case for removing (or temporarily excluding) certain connections. The elaborated method relies on filling indicated units in a distance matrix as infinity (∞). This means that if on the way between two nodal points there is a cell (or point lying in space that belongs to the nodal point) which has been excluded from traffic (or with a defined value over the limit of tolerance), then the relevant unit in the matrix has to be filled as infinity (∞) or another high (or low) value (Fig.19). High or low, values depend on the margin of acceptance.

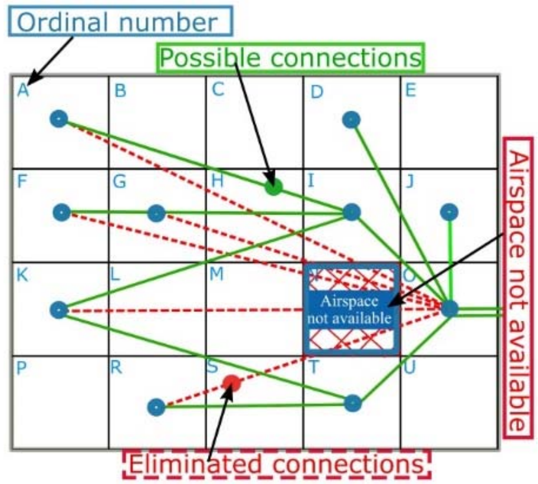

Figure 19. The method of graph edge elimination

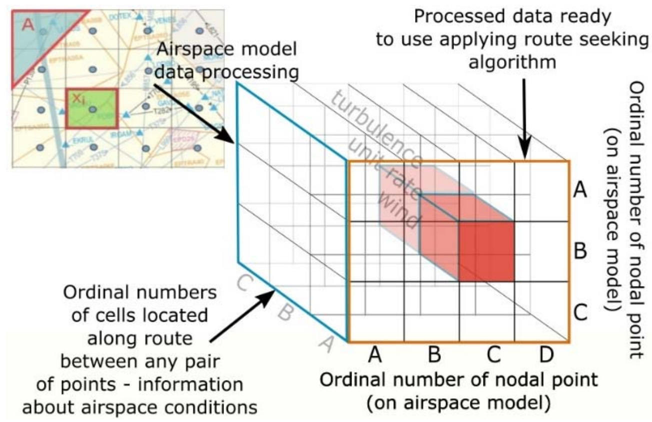

Figure 20. Three-dimensional matrix that stores more detailed information for the purposes of solving the two-dimensional route seeking problem

The method of graph edge elimination is described using the following algorithm:

```
Edge_elimination(K)
x_w ← ∞ (or value high enough to exceed limit)
check_the_edge_from_to(x_i,x_n)
    for i← 1 to m
        if (== w)
            route_from_to(x_i,x_n)← ∞
        else
            route_from_to(x_i,x_n) ←En-route data
                                    evaluation(x_i,x_n)
```

Data evaluation can be implemented in one iteration (En-route_data_evaluation(x_i,x_n)) describing airspace conditions along the segment as well. The X_w is defined as a cell excluded from traffic. If between the declared nodal points there is an excluded cell, then the algorithm which has information about the section assigned to this cell, assigns the value of infinity to the segment (removes the connection). In another situation, when there is no excluded cell on the way, the calculations about airspace conditions are allowed to run. The information about the exact unit cells located along the segment is saved to the initiated matrix. The information on the reason for eliminating the connection can be displayed as well. However, for the purposes of storing complex information we extended the Floyd-Warshall initiated matrix. The added third dimension provides more detailed information about the connections expressed in a two-dimensional table (Fig.20). The number of filled cells in the third dimension depends on the number of cells along the segment. Any possible connection on an airspace model is built (or removed) in the same way, preparing the matrix for the application of the Floyd-Warshall algorithm.

However, before running the Floyd-Warshall algorithm loop iteration it is worth describing the impact of airspace conditions (such as wind, turbulence, route charges, distance) on the cruise (time, cost, comfort and also distance). During the conditions interpretation and evaluation loop iteration described already, there is a reference to aircraft heading (and any heading change according to a path along segments) and airspace conditions (i.e. the impact of wind may vary considerably according to wind direction and aircraft heading). This makes it possible to modify cruise time with respect to the conditions in an airspace (Fig.21). This also facilitates rating the impact of turbulence on connections. If turbulence is detected, it can be estimated whether it is greater than the defined limit of tolerance. If it is greater, the segment can be treated as not allowed (removed completely or for some types of aircrafts). If turbulence is lower than the established margin of acceptance, data on the strength of impact on the plane can be found.

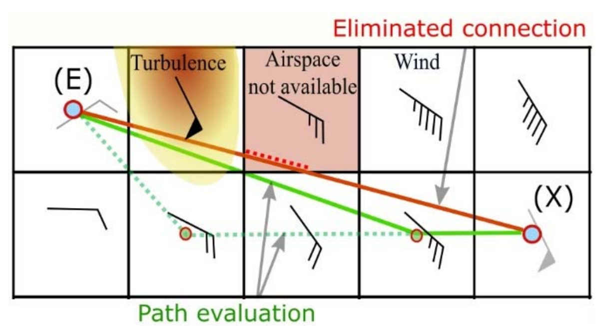

Figure 21. Path evaluation on the basis of airspace conditions

In this way, all data about airspace conditions is stored in the airspace model. The impact of airspace conditions on a given connection is stored in the third dimension using the methods presented in this chapter and equations from Chapter 3.

The process of seeking the route runs on the basis of the Floyd-Warshall algorithm (explained at the beginning of this chapter), i.e. from each possible connection, the algorithm selects the "lowest cost" route. However cost can be manually defined according to preferences. The entire assigned route is then expressed written in the following form:

$$route\ [a] = \sum_{i}^{n} segment_{i,j} + segment_{j,k} + \cdots \\ \ldots + \ segment_{n-1,n} \tag{18}$$

a – seeking criteria
i, j, k – number of segments included in the assigned route
n – overall number of segments included in the assigned route
segment – part of a route, and a connection between a pair of nodal points, along which sections can be distinguished; sections are defined by distance within an individual cell of an airspace model and facilitate interpreting conditions entered in a given cell to be overflown; Each segment consists of a minimum of two sections, because:
section – part of a segment, along which the assigned route crosses the cell, section is properly evaluated due to airspace conditions that are present in a certain cell.
A segment can be described as follows:

$$segment[i,j] = \sum_{i}^{m} section * cell_a \\ + section * cell_b + \cdots + section * cell_m \tag{19}$$

where:
m – number of cells located along one segment
section – in this case this value stands for distance or time

To summarize, the entire data processing procedure can be performed following the steps presented below:

Data processing steps:
1 construct Grid(x,y)
2 fill Model(A)
3 estimate Distance (X_i, X_j)
4 process of Section_assignment(PS)
5 Segment processing:
5' do Edge_elimination(K) of required
5" or En-route_data_evaluation(x_i,x_n)
6 apply the Floyd_Warshall(X)

Since, after running a Floyd-Warshall loop iteration, the two-dimensional matrix is filled with ordered lowest-cost connections in the airspace model, then one extra dimension constitutes a numeric description of the route. In that way, the data stored in a two-dimensional airspace model, after running the process presented in the paper, was converted into numerical information expressing the impact of airspace conditions on an aircraft. Information about complex conditions and the impact of these conditions on trajectory is essential to obtain approximate data about the benefits or disadvantages of potential routes (Fig.22).

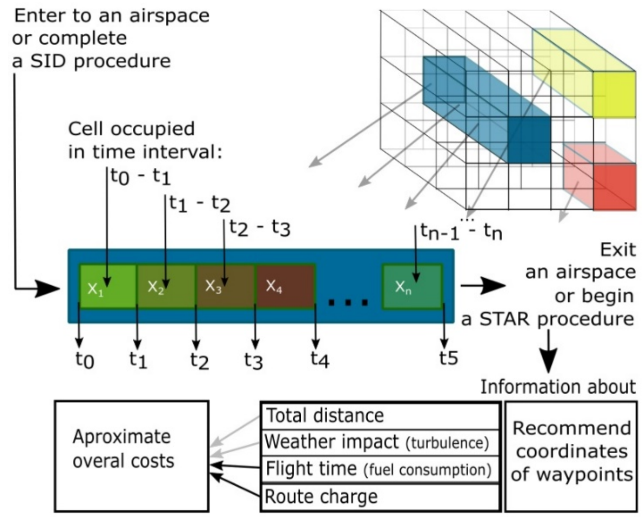

Figure 22. Visualization of a user friendly interface for the purposes of defining routes

However, as it would be preferable to select the path by balancing between more than one criterion, then the evaluation of conditions in certain cells requires the introduction of appropriate operations. In that case the assignment of segments comprised in the route should be considered via appropriate manipulation of the selected number of criteria [a], [b], [.], [n].

Balancing between multiple criteria can lead to a more practical result, i.e., comparing flight time and information about aircraft fuel consumption to route charges may result in finding the lowest estimated overall costs of the en-route phase.

6. Automatic Route Planning

During the examination of the presented method, specific conditions were defined and inserted into the constructed airspace model. The entire situation is presented in the picture (Fig.22), with identified routes. It is assumed that the specified airspace is treated as a Full Free Route Airspace, so the following should be taken into account:

- The airspace contains
  - accessible and excluded cells (not allowed for traffic – TRA/TSA, Storm)
  - no fixed waypoints (temporary waypoints are proposed by the algorithm using the elaborated method to avoid excluded areas or to find the best path); in the FRA or ATS Route Network configuration, waypoints must be defined by the user
- Distance is in respect to an assumed coordinate system
- Cruise time is calculated taking into account wind velocity and wind direction components, drawing on the data from the Aircraft Performance Database

- Route charges depend on the great circle and a given country's unit charge
- Turbulence is established as deviation in the range between 0 and 0,8G (the threshold of peak modulus value $|\Delta n|$ will be conducted on two types of aircraft)

This stage does not take into account:

- Air traffic (only weather factors and airspace structure)
- Flight level changes (only 2D research)
- Restrictions (there are no forbidden connections in addition to exclusion areas or conditions exceeding the established threshold)

Records entered during data processing:

- Cell's edge length – 27NM (~50km)
- Wind with variable direction and heterogeneous velocity distribution
- Two different middle range aircraft, Airbus A320 & Boeing 737-700 (only for the study of turbulence impact)
    - Cruise speed – 450kt
    - Altitude – 35,000 feet
    - Aircraft total mass is set as MTOW

Request:

- Find the path between Budapest and Nantes with the following characteristics:
    - Shortest route,
    - Shortest time,
    - Cheapest route (according to route charges)
    - Cheapest route in overall (according to route charges and fuel consumption – 2500kg/h; 2€/Liter Jet-1 Gas; 1Liter Jet-1 Gas =~0,8kg; Fuel consumption for both aircraft =~1800Litres/h)
    - It is not allowed to exceed the established boundary value of DEVG according to appropriate aircraft constants based on the flight profiles

At this stage, we assumed that weather forecasts are one hundred (100) percent accurate. The consideration of weather accuracy to airspace availability rate is a subject for another elaboration.

As the algorithms presented in the previous chapters are introduced along with equations that allow evaluating conditions as inserted into airspace model data (Fig. 23), the results obtained are presented in the table (Table 3) below. All results – paths in the airspace – with original number is demonstrated in the picture.

As we can see, flight number 1 is a result of requesting the shortest possible route. However the FPL was designed to pass through an area of severe turbulence. The acceleration g, in areas with the presence of severe turbulence was established at the peak modulus value $|\Delta n| = 0.8$. According to data constants $c_1, c_2, \ldots, c_5$ and Aircraft Performance Database with regard to two different aircraft types – Airbus A320 and Boeing 737-700, the DEVG on route number 1 is as follows:
U_{de} = 9.24 for A320 and
U_{de} = 8.81 for B737
and duration of severe turbulence is 17 minutes.
So, on route number 1, for the A320 the DEVG Index exceeds the threshold of acceptance.
For that reason, an alternative shortest-distance path for A320 was sought. This produced route number 5. The picture and the table demonstrate that there are no significant differences in distance or flight time. However, path number 5 runs through moderate turbulence for a considerably longer time (lasts 41 minutes). In comparison, the B737 is exposed to moderate turbulence for only 8 minutes, in path number 1 (however, for 17 minutes to severe turbulence).

As presented in the example, the shortest flight duration is assigned to path number 2. That is caused by the favorable influence of wind direction and high velocity on aircraft heading.
By comparing path 1 and 2 we can observe a promising example of the advantages that can be obtained by using the method. As the most desirable aspect in an ATM mission is

Figure 23. Visualization of result – paths in the airspace – with original number

Table 3. Result according to the criteria provided in the request.

Path	Distance (NM)	Time (min)	Route Charges (Euro)	Fuel consumption (Liters of Jet-1)	Fuel consumption charges (Euro; price of Jet-1 ~2E/Litre)	Overall costs of en-route (Euro)	Distance and duration of flight in turbulence			Criteria
							s	m	l	
							distance			
							time			
1	811	116	1156	6013	12027	13183	351	54	108	Distance
							52	8	17	
2	843	108	1265	5619	11239	12503	166	191	0	Time (Fuel consumption)
							27	25	0	
3	859	125	1135	6489	12978	14113	0	271	54	Route Charge
							0	42	8	
4	847	109	1241	5622	11245	12487	168	109	0	Overall costs
							22	14	0	
5 (1’)	814	117	1226	6044	12089	13315	243	271	0	Turbulence < DEVG index 9 (Airbus) distance
							35	41	0	
6	865	110	1272	5725	11451	12723	140	0	0	Turbulence < moderate index 5 (Airbus)
							18	0	0	
7	890	112	1278	5816	11632	12910	0	0	0	Turbulence free path
							0	0	0	
8 (3’)	864	125	1142	6488	12976	14119	110	217	0	Route Charge 9<DEVG (Airbus)
							16	33	0	

to reduce delays, achieving the shortest time of air operations releases airspace volume for other flights. However, from an economic point of view, the method allows to strike a balance between shortest time and cost of flight.

Close to trajectory number 2 is path number 4, which is based on the lowest overall cost of flight. The estimation for flight is based on route charge (unit rates are ascribed as white values on the chart) and fuel consumption in reference to Jet-1 Gas (2 Euros) price. This demonstrates that there is a close relationship between the seeking criteria to find minimum flight time and minimum overall cost. Comparing trajectories number 2 and 4, we can see that 4 is more advantageous, while costs are much lower in proportion to higher cruise time. Since trajectory number 3 is based only on route charge, excluding fuel consumption, the path was assigned over a long way, where unit charges are lower than in other countries. However, the resulting overall costs are high enough for this manner to fail as a way of seeking the cheapest route (the consumed fuel makes the costs considerably higher). Furthermore, route 3 is not allowed for A320. As the trajectory along the conditions exceeding DEVG Index 3 was the cheapest, in respect to route charge only a path for A320 was sought as alternative. As a result, the lowest charge route was identified as path number 8. In turn, path number 6 was found to run along a route where turbulence intensity was less than moderate. However, similarly as path number 7 (which was identified as the turbulence free path), path number 6, and cruise time did not significantly vary between the lowest cost and lowest time of cruise paths.

This example demonstrates that all excluded areas were avoided, which proves that the elaborated method of graph edge elimination is functional. This opens the opportunity to further reduce the distance to be flown around those regions in further studies. Furthermore, as we can see, the method described in this study allows interpreting conditions and assigning routes according to the provided request.

The captured data, which describe the routes identified in this study, allow to conclude, considering the complex airspace conditions, that the most beneficial path must not be based on the distance only. With regard to wind direction and velocity, the lowest distance path does not equal the lowest time or lowest cost route (plot 1, plot 2) (Fig. 24, 25). However, depending on the criteria selected by an AO in the flight planning process, the cruise time reduction constitutes an alternative to overall costs reduction (plot 3) (Fig. 26).

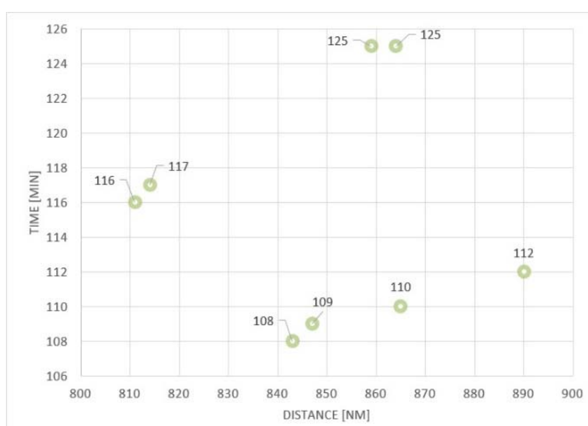

Figure 24. Time – distance diagram

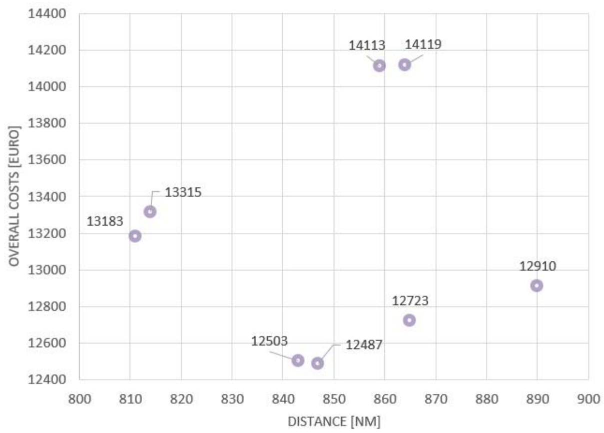

Figure 25. Overall costs – distance diagram

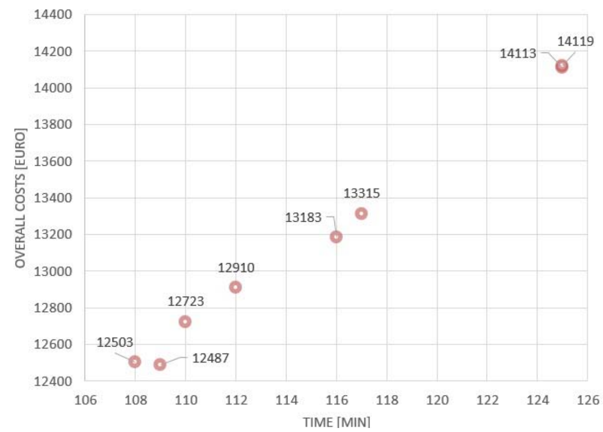

Figure 26. Overall costs – time diagram

7. Summary

The elaborated method can be used to solve route seeking problems, while the evaluation of complex conditions requires a specific approach. After initiating and filling a three-dimensional matrix, using the Floyd-Warshall algorithm, the method allows to generate temporary waypoints at spots that seem to be the most favorable considering the requested seeking criteria.

Quite profitable mechanism from this elaboration is obtained method that allows to use Floyd-Warshall algorithm in seeking "low-costs" route based on more than only one criterion. Since all airspace data is inserted into a two-dimensional model, the fact that the method allows the conversion from a two-dimensional table into a three-dimensional matrix, containing complex data in respect to aircraft heading is also of interest from the point of view of data processing systems, and is left for further exploration.

It was established that the size of unit cells affects the accuracy of the method, and along with forecast accuracy may introduce dynamically changing parameters. Variations could be due to the ratio of weather accuracy [0-1] to airspace availability [1-0] (Fig.27).

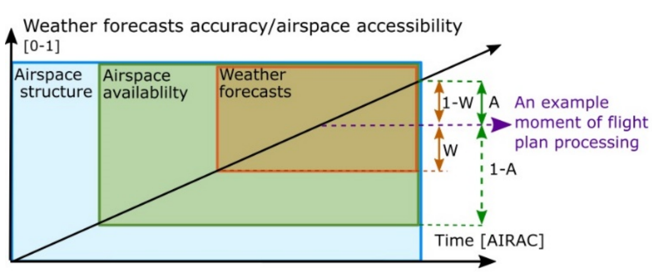

Figure 27. Variations accuracy due to airspace accessibility

This method can by successfully applied in various branches of transportation or even for the control of Remotely Piloted Aircraft Systems (RPAS). In the case of RPAS operations, autonomic flight can be programmed in a known area, (e.g. in urbanized areas for carrying loads between hospitals). For the purposes of minimizing flight time circle (or each parameter) to avoid an excluded area (i.e. a building in the case of RPAS), or to provide time-trajectory based conflict detection, it is necessary to plan flights in as much detail as possible to determine excluded areas using computational geometry. Since this study is based on Full Free Route Airspace configuration, similarly – with some modification, the method may find application in an ATS Route Network configuration or Free Route Airspace. The flight planning process taking into consideration the complex airspace conditions can bring benefits not only for the AO, but as it places a lower workload on the ATC, it might lead to enhanced airspace capacity.

References

[1] SESAR Concept of Operations Step 1, nr B4.2, Edition 2013 (Ed. 01.00.00)

[2] European Route Network Improvement Plan, Part 3: Airspace Management Handbook Guidelines for Airspace Management. Edition 5.4, November 2017

[3] [EUROCONTROL Specification for the Initial Flight Plan, Edition 1.3, 26.02.2018, Reference nr: EUROCONTROL-SPEC_0101

[4] IFPS User's Manual, Network Manager, Edition Number 23.0, Edition Validity Date 07.05.2019

[5] ICAO Annex 2 to the Convention on International Civil Aviation, Rules of the Air, Tenth Edition, July 2005

[6] ICAO Annex 11 to the Convention on International Civil Aviation, Air Traffic Services, Thirteenth Edition, July 2001

[7] ICAO, ICAO Doc 4444: PANS – ATM, Procedures for Air Navigation Services - Air Traffic Management. Sixteenth Edition, 2016

[8] Romanowski P., Lewandowski Z.,Aspekty prawne realizacji operacji lotniczych z wykorzystaniem bsp w rejonie odpowiedzialności FIR Warszawa, Wojskowy Instytut Techniczny Uzbrojenia, Zielonka, Polska, ISSN 1230-3801

[9] EUROCONTROL CFMU, General & CFMU Systems*, Edition 14.0, 18.03.2010*
[10] The roadmap for delivering high performing aviation for Europe, European ATM Master Plan, Executive View, Edition 2015
[11] Phase of Flight, Definition and Usage Notes, Commercial Aviation Safety Team/International Civil Aviation Organization, April 2013
[12] Safety Report 2014, International Air Transport Association, Edition 55, April 2018
[13] Daidzic, N. E. (2017). Long and short-range air navigation on spherical Earth. International Journal of Aviation, Aeronautics, and
Aerospace, 4(1). http://doi.org/10.15394/ijaaa.2017.1160
[14] https://www.mapgenix.com/news/great-circle-vs-rhumb-line/ (access: 01.10.2019)
[15] European Route Network Improvement Plan, Part 2: ATS Route Network,ARN Version 2017-2019/21, Edition 1.0, July 2017
[16] Drupka, G., Rogalski, T., (2017). Computational geometry draft to avoid Dynamic Mobile Area in Advanced Airspace Management service, Monografia „Poszerzamy Horyzonty, Tom V", ISBN: 978–83–63216–09-2
[17] Domowicz J., Szutowski L., Podręcznik Pilota Samolotowego, Wydanie piąte, Poznań 2008, ISBN 978-83-902291-4-0
[18] https://www.aviationweather.gov/taf/help?page=inter (access: 08.10.2019)
[19] https://www.weather.gov/hfo/windbarbinfo (access: 08.10.2019)
[20] National Research Council of the National Academies, Weather Forecasting Accuracy for FAA Traffic Flow Management, A workshop Report, The National Academies Press, Washington, D.C., 2003 ISBN 0-309-08731-7
[21] http://www.free-online-private-pilot-ground-school.com/Aviation-weather-reporting.html (access: 15.09.2019)
[22] https://www.nap.edu/read/10637/chapter/1#ii (access: 02.10.2019)
[23] F. A. Fisher, J. A. Plumer, Lightning Protection of Aircraft, National Aeronautics and Space Administration, U.S. Government Printing Office, 1977
[24] Rash C., E., When lighting strikes, Aerosafetyworld, June 2010, (access on flightsafety.org)
[25] P. Laroche, P. Blanchet, A. Delannoy, F. Issac. Experimental Studies of Lightning Strikes to Aircraft. AerospaceLab, 2012, p. 1-13. Hal-01184400
[26] Advisory Circular, Aviation Weather, U.S. Department of Transportation, Federal Aviation Administration, AC No: 00-6B, AFS-400, 8/23/16
[27] [Kim S.H., Chun H.Y., Chan P.W., Comparison of Turbulence Indicators Obtained from In Situ Flight Data, Journal of Applied Methodology and Climatology 56, March 2017, DOI:10.1175/JAMC-D-16-0291.1
[28] Van Dyke D., Forecasting, detecting and avoiding turbulence, Professional Pilot, Vol 53 No 8, ISSN: 0191-6238, August 2019
[29] [G. Ellrod, P. Lester, and L. Ehernberger, Clear Air Turbulence, Encyclopedia of Atmospheric Sciences, pp. 393–403, 2003
[30] Truscott B., EUMETNET AMDAR, AAA AMIDAR Software Developments – Technical Specification. Doc. Ref. E_AMIDAR TSC/003. Met Office: Exeter
[31] https://www.eoas.ubc.ca/courses/atsc113/flying/met_concepts/02-met_concepts/02a-std_atmos-P/index.html, access: 09.09.2019
[32] Laudański L.,M., Piętnaście wykładów aeromechaniki, Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 1999, ISBN 83-7199-109-6
[33] Kim S.H., Chun H.Y., Aviation turbulence encounters detected from aircraft observations: spatiotemporal characteristics and application to Korean Aviation Turbulence Guidance, Meteorological Applications 23(4):594-604, Royal Meteorological Society 2016, DOI:10.1002/met.1581
[34] Sharman R., Lane T., Aviation Turbulence, Springer International Publishing, Switzerland 2016, ISBN 978-3-319-23629-2
[35] Nuic A., Poles D., Mouillet V., BADA: An advanced aircraft performance model for present and future ATM systems, International Journal Of Adaptive Control And Signal Processing, 2010, DOI: 10.1002/acs.1176
[36] https://www.airliners.net/forum/viewtopic.php?t=1355819 (access 07.09.2019)
[37] Phillips W.F. ,Mechanics of Flight, Second Edition, John Wiley & Sons, Inc., 2010, ISBN 978-0-470-53975-0
[38] Final data for the establishment of the cost-bases and unit rates, Information paper – CER-111-2018-3670, Enlarged Committee for Route Charges, EUROCONTROL, 19.11.18
[39] Customer Guide to Charges – Central Route Charge Office, EUROCONTROL, 02.2019
[40] Drupka G., Majka A., Rogalski T., An Airspace Model Applicable for Automatic Flight Route Planning Inside Free Route Airspace, Scientific Letters of Rzeszow Univeriosity of Technology, Vol.XXXV, 2018, ISSN 0209-2689
[41] [Cormen T.H, Leisterson Ch. E., Rivest R. L., *Wprowadzenie do algorytmów*, WNT Warszawa 1997
[42] Abu-Ryash H., Tamimi A., Comparison Studies for Different Shortest path Algorithms, International Journal of Computers and Applications, Vol.14(No.8) May 2015, DOI:10.24297/ijct.v14i8.1857
[43] Kemp J.,M., All-Pairs Shortest Path Algorithms Using CUDA, Durham theses, Durham University 2012, Available at Durham E-Theses Online: http://etheses.dur.ac.uk/5564/
[44] Djojo M., A., Karyono K., Computational load analysis of Dijkstra, A*, and Floyd-Warshall algorithms in mesh network, 2013 International Conference on Robotics, Biomimetics, Intelligent Computational Systems, IEEE, 2013, DOI: 10.1109/ROBIONETICS.2013.6743587
[45] Reem D., An Algorithm for Computing Voronoi Diagrams of General Generators in General Normed Spaces, 2009 Sixth International Symposium on Voronoi Diagrams, Copenhagen, Denmark, IEEE, DOI: 10.1109/ISVD.2009.23

Biography

Grzegorz Drupka, *assistant professor at the Rzeszow University of Technology. In 2019 he completed his Ph.D. studies in the field of Machine Design and Maintenance at the Faculty of Mechanical Engineering and Aeronautics. He worked for the Single European Sky ATM Research – SESAR project. He was fellow at the European Organization for the Safety of Air Navigation – EUROCONTROL headquartered in Brussels, in Network Manager/Operations Planning. Having earned his MSc (Eng) degree at the Faculty of Fire Safety Engineering specializing in safety analyses in aviation, he began his experience at Pratt and Whitney.*

Andrzej Majka*, professor at the Rzeszow University of Technology, in the Department of Aircraft and Aircraft Engines. Project manager of the SESAR 2020 PJ06.02 ToBeFREE and PJ10.05 PROSA. Member of Applied Vehicle Technology expert group of NATO Science and Technology Organization*

Tomasz Rogalski *professor at the Rzeszow University of Technology, head of the Department of Avionics and Control.*