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Methods for Choosing Optimal Routes in the Free Routes Airspace

Dmitriiev Oleh[1], Kushnerova Nadiia[2], Lisevych Serhii[3]
[1,2,3]*Flight Academy National Aviation University, 1, Dobrovolskohostreet, Kropyvnytskyi, 25005, Ukraine*

ABSTRACT :*The object of research is the process of preparing the initial data and forming priorities when choosing the optimal flight route in the airspace of free routes.The aim of the work is to develop algorithms for the dynamic construction of optimal free flight routes in the FRA airspace, considering the requirements of reliability, safety and flight efficiency.To achieve the goal set in the work, the following methods were used: a systematic approach, comparison, analysis and synthesis, a logical method.As a result of this thesis, the basic principles of flying in the airspace of free routes were analyzed in detail and an assessment of their profitability was given. The main provisions of the documents of ICAO, the European Organization for the Safety of Air Navigation (EUROCONTROL), as well as the national regulatory rules regarding the FRA, are analyzed. Also analyzed are the plans for the development of the airspace of Ukraine.In addition, an algorithm for calculating the basic elements for flights in the airspace of free routes is proposed. Based on the results of research and calculations, results were obtained that can be used for further implementation and use.The results can be used for further implementation of the methodology for determining the optimal route when flying in the airspace of free routes.*

KEYWORDS *Airspace of free routes, maximum flight efficiency, orthodromic route, economy.*

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I. INTRODUCTION

A dynamic ATC concept called Free Flight is currently being implemented. This is the first practical attempt to systematize and combine air traffic control facilities that have appeared in recent years into a single complex. The main goal of the concept is to provide aircraft crews with the freedom to choose the trajectory of movement along the route, speed and profile. At the same time, the autonomy characteristic of visual flight should be effectively combined with the reliability of safe separation of aircraft, provided by the instrument flight technique. In this case, the possible intervention of controllers becomes a means of guaranteeing the safety of flights and the correct functioning of automatic systems[1, 2]

Free Flight is designed to improve flight safety, airspace capacity, operational efficiency and economic performance. The ultimate goal of the Free Flight concept is to move to Free Route Airspace (FRA) and phase out the old ATS route network.

The airspace of free routes implies aircraft flights on shorter and more profitable routes for airlines with fewer route control points in comparison with the existing network of ATS routes.

These routes are expected to improve airspace efficiency while reducing fuel consumption, emissions and controller-pilot communications [3].

II. MATERIALS AND METHODOLOGY

Choosing a route for each case is a complex multipurpose optimization problem with several constraints. When choosing a route, civil aviation operators need to take into account several important factors [4, 11]:

- wind at flight altitude;
- weather along the route;
- military activity;
- conflict zones;
- the cost of the flight;
- traffic on this route;
- traffic patterns around airports.

There are quite a few ways to solve routing problems [5, 6]. Almost all of them are heuristic and metaheuristic methods, since exact algorithms do not always give a ready-made solution in an acceptable time for a large problem size.

Exact methods are based on a complete enumeration of all possible solutions, which, in turn, makes them ineffective.

Heuristic algorithm (heuristic) **-** an algorithm for solving a problem, including a practical method that is not guaranteed to be accurate or optimal, but sufficient for solving the problem. Allows you to speed up the solution of the problem in cases where the exact solution cannot be found. Heuristic methods produce a relatively limited search for solutions and usually find a fairly good solution in a reasonable amount of time. But these methods also have a disadvantage, namely, they are approximate.

Metaheuristic are the most effective, but these methods have a parameter that directly affects the result based on the input data, and in practice you have to debug this parameter anew each time.

To implement the algorithm for choosing the optimal route, you can try to apply the Clark-Wright method, optimizing the constraints of this problem.

The Clark-Wright method belongs to the number of approximate, iterative methods and is intended for the computer solution of the route selection problem. The solution error does not exceed 5-10% on average. The advantages of the method are its simplicity, reliability and flexibility, which makes it possible to take into account a number of additional factors that affect the final solution of the problem.

The criterion of optimality can be the minimum distance, time and cost of the flight along the route.

If the routing problem is reduced to minimizing the flight distance from the departure aerodrome to the destination aerodrome, then it can be represented by the following dependence:

$$\mathbf{M = F(S) \rightarrow min,} \quad (1)$$

where F (S) is a function of distance dependence.

The distance between the airfields in a straight line is known. But when departing from the airfield, crossing the borders of FRAU areas and when arriving at the destination airfield, it is necessary to use certain FRA points, which will increase the flight distance along the route, then

$$\mathbf{S = f(FRA),} \quad (2)$$

where S is the flight distance along the route, FRA **-** a condition that the flight route must pass through the FRA points.

When determining the route, one cannot ignore such an important factor as the activation of restrictive zones, which can significantly change the overall length of the route. Therefore, it is advisable to supplement the previous formula with one more variable

$$\mathbf{S = \{f(FRA), R\},} \quad (3)$$

where R is the possible activation of the restrictive zones.

It is also worth paying attention to the influence of weather conditions (Wx) on the flight, but this dependence is very small.

Taking into account all the conditions, the general form of the routing problem can be written as:

$$\mathbf{M = F(\{f(FRA), R, Wx\}) \rightarrow min.} \quad (4)$$

Then with restrictions

$$\mathbf{S_{MIN} \leq S \leq S_{MAX},} \quad (5)$$

where S_{MIN} is the straight-line distance between the departure aerodrome and the destination aerodrome;

S_{MAX} is the distance between the departure aerodrome and the destination aerodrome along the route of the fixed ATS network.

Considering that the FRA point must be passed only once $\mathbf{\Sigma X_i = 1,}$

where Xi is the selected FRA point on the route.

The essence of the method lies in the fact that, starting from the fixed network of ATS routes, step by step go to the optimal FRA route.

To do this, it is necessary to compile a matrix of kilometre wins. When compiling it, it is necessary to take into account the conditions given above. Based on this, a value such as the virtual distance between the FRA points is entered.

Virtual distance is the actual distance between waypoints, adjusted up or down using various factors depending on factors taken into account.

Then, FRA route options are compiled, but after each iteration, an additional distance constraint is checked - whether the FRA route distance falls within the interval between the minimum (S_{MIN}) and maximum distance (S_{MAX}).

Thus, when using this route optimization method, various factors affecting the total flight distance were additionally taken into account. Given these parameters, Clark-Wright route optimization can become more accurate and cost effective. The costs of implementing this algorithm are low, which, given the great savings in time and money for developing the optimal route, is quite favorable conditions for flight planning for various planning systems and airlines.

As the main indicators of flight efficiency when choosing the FRA route, the following can be used [6, 7]:

- indicator of non-orthodromicity of the route;
- an indicator of the total consumption of aviation fuel by all aircraft in the FRA area during the analyzed period of time;
- an indicator of the expected number of potential conflict situations at the points of convergence and intersection of routes;
- indicator of the risk of aircraft collisions (in units of accidents per flight hour) in the FRA area as a whole and in individual airspace elements (adjacent flight levels, parallel routes, route crossing points, etc.);
- indicator of the congestion of FRA areas by the number of aircraft simultaneously on control at different hours;
- an indicator of the total number of sectors in the analyzed FRA area, at which air traffic service (control) is possible without violating the established standards for the capacity of the ATC sectors.

Further in this paper, two of the listed indicators will be considered: the non-orthodromicity indicator of the route (δ) and the indicator of the total consumption of aviation fuel (Q).

In the process of choosing the optimal routes, in particular, the existing restrictions should be taken into account:

- technical data of the operated aircraft (the determined routes for the recommended distances and altitudes must be feasible for any of the operated aircraft in any, including the worst operating conditions);
- geographic, administrative-political and departmental restrictions (where necessary, points of intersection of state borders and borders of FRA regions, restrictive zones, etc. should be taken into account).

To assess the non-orthodromicity of routes in the FRA area, it is necessary:

1.In addition to the existing aircraft route scheme, prepare the FRA route scheme in the analyzed FRA area on the same scale. To do this, on the selected flight, connect the departure aerodrome, FRA points and the destination aerodrome with straight lines.

2.Measure or calculate the orthodromic distance (L_{*k}) for the FRA route and compare it with the length of the fixed ATS network (L_k)

$$\mathbf{\Delta L_k = L_k - L^*_k}, \; k = \overline{1, m} \; . \tag{6}$$

3.Calculate the value of the shift in kilometers (δk) of one aircraft of each k-th flight (aircraft flow)

$$\boldsymbol{\delta_k = \frac{\Delta L_k}{L^*_k} \cdot 100\%.} \tag{7}$$

4.Rank the flows according to the non-orthodromicity indicator and build a diagram of the non-orthodromicity of the aircraft routes.

For the indicator of non-orthodromicity, the concept of flight inefficiency is introduced, which is defined as the ratio of the distance of the actual flight (planned flight) to the distance of the direct route (orthodromy), and expressed as a percentage.

Based on which airspace factor needs to be assessed, different distances can be measured.

To assess the expected aviation fuel savings when comparing the FRA route with the route of the existing ATS route network, it is necessary to:

1.Determine the distance savings (ΔLk) that each aircraft flies along the proposed (L * k) FRA route in comparison with the existing (Lk) fixed route of the ATS network

$$\Delta L_k = L_k - L^*_k. \tag{8}$$

2.Calculate the expected fuel economy ΔQ (kilograms per month):

$$\Delta Q = \sum_{k-1}^{m} P_k \Delta L_k, \tag{9}$$

where P_k is the power (fuel consumption) of each k-th flight (aircraft flow) (kg/km per month);
m is the number of flights (aircraft flows).

The characteristic Pk ($k = \overline{1, m}$) of the aircraft flow power, which expresses the unit costs of aviation fuel of all aircraft per one kilometer of the route, has an important property for designing routes - independence from the route. It reflects the number and composition of aircraft types for which it is necessary to provide a route in the FRA.

The resulting new sequence of aircraft flows k = 1, m in descending order of Pk values is used to organize the processes of sequential search and selection of acceptable options for choosing aircraft routes.

This articlewill consider the procedure for selecting the optimal flight route from the departure aerodrome of Lviv to the destination aerodrome Kharkiv / Osnova in the airspace of free routes of Ukraine (FRAU).

The distance between these aerodromes according to the orthodrome (the shortest distance between two points) depending on the units of distance used (NM or km) is determined using the formulas of spherical trigonometry

$$\mathbf{DIST_{NM} = arccos[sinLAT_1 \times sinLAT_2 + cosLAT_1 \times cosLAT_2 \times cos(LONG_2 - LONG_1)] \times 60\ [NM]} \tag{8}$$

where 60 is the number of nautical miles (NM) in 1° of the equatorial arc;

DIST = arccos [sin49º48′35″ × sin49º55′37″ + + cos49º48′35″ × cos49º55′37″ × cos(36º17′24″ − − 23º57′30″)] × 60 = **476,4NM (883 km)**

The route provided by the aircraft operator, considering the network of fixed routes or FRA routes, will, of course, be a little longer.

III. RESULTS AND DISCUSSION

As an example of aircraft, we can consider a modern medium-haul passenger aircraft Embraer-135.

After a thorough analysis of the existing network of ATS routes on the route maps of Ukraine (ENR 6.1, ENR 6.2), as well as on the SID maps for Lviv airfield and on STAR maps for Kharkiv airfield, the shortest route without restrictions is determined. The coded names of the points, the vertical boundaries in the areas between the points and the distances between the points are presented in Table 1.

Table 1: Distances between the points

№	Name	CRP/NCRP	The name of the route	Vertical boundaries	Distance, km
1	*2*	*3*	*4*	*5*	*6*
1	UKLL	-	-	-	-
2	ABDAN	CRP	SID ADBAN 2A	-	112,8
3	PEPIL	NCRP	N983	2750м-FL660	22,3
4	SORON	CRP	N983	FL275-FL660	154,9
5	BUDUK	NCRP	M986	FL260-FL660	85,8
6	SLV (VOR/DME)	CRP	M986	2750м-FL660	46,4
7	KEDUB	NCRP	M986	2150м-FL660	67,2
8	BRP (VOR/DME)	CRP	A137	1500м-FL660	34,5
9	GOTAP	CRP	A137	3050м-FL660	65,6
1	*2*	*3*	*4*	*5*	*6*
10	LULAP	NCRP	A137	3050м-FL660	38,0
11	RS (NDB)	CRP	A137	FL165-FL660	109,4
12	OKSAR	NCRP	A137	FL165-FL660	55,4
13	KW (NDB)	CRP	A137	2150м-FL660	67,9
14	UKHH	-	STAR KW 3R	-	53,5
Total distance					**913,7**

There are no conditional route sections (CDRs) on this route that cause problems when flying in a predetermined echelon (FL 390).

The vertical boundaries in the table are given considering the restrictions on conditional routes. For example, the SORON-BUDUK section is a section of the conditional route of categories 1 and 2 (CDR 1,2) at flight altitudes from 2750 m to FL255; on this section MEA = 2750m, MAA = FL660; thus, the vertical boundaries on which there are no restrictions are FL260-FL660 (5th row of Table 1).

The shortest route without restrictions takes into account the flight distance on SID $DIST_{SID}$=112.8km and on STAR $DIST_{STAR}$=53.5km, has a total length of 913.7 km (493.4 NM) and involves the passage of 12 intermediate points, of which 7 are mandatory reporting points and 5 – reporting points on request.

After defining the shortest route without restrictions, the shortest restricted route is determined. The coded names of the points, the vertical boundaries in the areas between the points and the distances between the points are presented in Table 2.

This route has sections of conditional routes (CDRs) that create problems when flying in a predetermined echelon (FL 390).

Table 2: Distances between the points

№	Name	CRP/NCRP	The name of the route	Vertical boundaries	Distance, km
1	UKLL	-	-	-	-
2	ABDAN	CRP	SID ADBAN 2A	-	112,8
3	PEPIL	NCRP	N983	2750м-FL660	22,3
4	SORON	CRP	N983	FL275-FL660	154,9
5	BEMBI	NCRP	N983	FL275-FL660	153,6
6	OTPAK	CRP	N983	FL275-FL660	136,0
7	VASON	CRP	N983	FL165-FL515*	140,8
8	GASNU	NCRP	N983	FL165-FL515*	104,3
9	ADAKO	NCRP	N983	2750м-FL660	21,8
10	UKHH	-	DCT*	-	67,1
Total distance					**913,6**

This route takes into account the flight distance on SID $DIST_{SID}$ = 112.8 km and on STAR $DIST_{STAR}$ = 53.5 km, has a total length of 913.6 km (493.3 NM) and involves the passage of 8 intermediate points, of which 4 are mandatory reporting points and 4 **-** reporting points on request.

The length of these two routes is almost the same, but the shortest limited route has 1.5 times less total points and 2 times less CRP points than the shortest route without restrictions, which reduces the load on both the crew and the dispatcher.

However, the shortest restricted route has sections of conditional routes (CDRs) that create problems when flying in a predetermined echelon (FL 390). Thus, the OTPAK-VASON and VASON-GASNU sections are sections of conditional routes of categories 1 and 2 (CDR 1,2) at flight altitudes from FL165 to FL515 and are not always available (rows 7 and 8 of table 2). Another problem is the possible straightening ban (DCT) at the arrival site of ADAKO-UKHH (row 10 of table 2).

After a thorough analysis of the airspace of the free routes, the shortest FRA route without restrictions is determined on the FRAU map (ENR 6.3), as well as on the SID maps for Lviv aerodrome and on the STAR maps for Kharkiv aerodrome. Coded point names, vertical boundaries between points, and distances between points are presented in Table 3. This route should not contain areas that cause problems when flying in a predetermined echelon (FL 390).

Since the FRAU map does not show sections of routes, but only FRA points, it is necessary to measure or calculate the distances along the shortest route between all used FRA points.

The FRA points in the sequence ABDAN, SORON, OLKOM and KW NDB are selected for the shortest distance flight. The coordinates of these points (KTA) are published in the AIP of Ukraine:

The spherical trigonometry formulas discussed above are used to calculate distances.

In the same way, the distances between the points SORON and OLKOM, OLKOM and KW NDB are calculated (rows 4 and 5 of table 3).

Table 3: Distances between the points

№	Name	CRP/NCRP	The name of the route	Vertical boundaries	Distance, km
1	UKLL	-	-	-	-
2	ABDAN	CRP	SID ADBAN 2A	-	112,8
3	SORON	CRP	FRA	FL275-FL660	176,5
4	OLKOM	CRP	FRA	FL275-FL660	456,3
5	KW (NDB)	CRP	FRA	FL275-FL660	129,7
6	UKHH	-	STAR KW 3R	-	53,5
Total distance					**928,8**

This route takes into account the flight distance on SID $DIST_{SID}$ = 112.8 km and on STAR $DIST_{STAR}$ = 53.5 km, has a total length of 928.8 km (501.5 NM) and involves the passage of 4 intermediate points, of which all 4 are mandatory reporting points.

The vertical boundaries of the FRA do not contradict a predetermined flight level (FL 390).

Comparing this route with the length of two previously defined routes of the fixed ATS network, you can see a slightly greater (15 km) distance. This shows that the ATS route network is designed efficiently. However, the unrestricted FRA route has a lower total number of points than the unrestricted ATS route, 6 vs. 14.

After determining the shortest FRA route without restrictions, the shortest FRA route is determined. The coded names of the points, the vertical boundaries between the points and the distances between the points are presented in Table 4.

Since the FRAU map does not plot sections of routes, but only FRA points, it is necessary to measure or calculate the distances along the shortest route between all FRA points used, as was done for the shortest FRA route without restrictions.

In the shortest limited FRA route, there are sections of the flight within several training zones (Fig. 14), which can create problems when flying on a predetermined echelon (FL 390). Information on these zones is published in the AIP of Ukraine.

This is the SORON-VASON section with a successive intersection of 3 training zones:
- UK-T727-05, vertical borders 600m-FL510;
- UK-T727-06, vertical boundaries from the earth's surface to FL510;
- UK-T727-04, vertical boundaries 600m-FL510.

Also, this is a section of VASON-KW NDB with a consecutive intersection of 3 training zones:
- UK-T727-04, vertical borders 600m-FL510;
- UK-T727-03, vertical boundaries from the earth's surface to FL510;
- UK-T732-01, vertical boundaries from the earth's surface to FL430.

These zones have the same time intervals:

MON-FRI - 05: 00-23: 59 (04: 00-01: 00); SAT - 05: 00-13: 00 (04: 00-12: 00).

Table 4: Distances between the points

№	Name	CRP/NCRP	The name of the route	Vertical boundaries	Distance, km
1	UKLL	-	-	-	-
2	ABDAN	CRP	SID ADBAN 2A	-	112,8
3	SORON	CRP	FRA	FL275-FL660	176,5
4	VASON	CRP	FRA	FL275-FL660	424,7
5	KW (NDB)	CRP	FRA	FL275-FL660	127,7
6	UKHH	-	STAR KW 3R	-	53,5
Total distance					**895,2**

Scheduled hours are specified in the daily airspace use plan (UK AUP). During activation, entry to these zones within the horizontal and vertical boundaries is prohibited.

In accordance with the general procedures in the airspace of free routes of Ukraine FRAU has vertical boundaries FL275-FL660 and night period from 22:00 to 5:00 UTC in daylight saving time or from 21:00 to 4:00 UTC in summer time.

Comparing the period of validity of FRAU and the time intervals of these training zones, we can conclude that the possibility of unrestricted flights in the period MON-FRI - 00: 00-5: 00 from October to March and 1: 00-4: 00 from March to October; SAT-SAN - 00: 00-5: 00 and 22: 00-23: 59 from October to March, 00: 00-4: 00 and 21: 00-23: 59 from March to October.

These flight periods do not present problems with flight planning in the airspace of free routes, as they do not differ much from the period of validity of FRAU.

This route takes into account the flight distance on SID $DIST_{SID}$ = 112.8 km and on STAR $DIST_{STAR}$ = 53.5 km, has a total length of 895.2 km (483.3 NM) - the closest to the orthodrome and involves the flight of 4 intermediate points, of which all 4 are items of mandatory reporting.

Comparing this route with the length of the two previously defined routes of the fixed ATS network, you can see a smaller distance, a smaller total number of points and a smaller number of CRP points. For clarity, the distance from the departure aerodrome of Lviv to the aerodrome of destination Kharkiv for different conditions can be summarized in the table (table 5).

Table 5: Distance from aerodrome of Lviv to the aerodrome of destination Kharkiv

light	Distances, km				
	On orthodromy	On the ATS routes		On FRA routes	
		No restrictions	With restrictions	No restrictions	With restrictions
UKLL-UKHH	883	913,7	913,6	928,8	895,2

To assess the unorthodromic nature, the length of the shortest ATS network route without restrictions (Lk) and the length of the FRA route with restrictions (L * k) will be compared (formula 6).

$$\Delta L_k = = 913.7 - 895.2 = 18.5\text{km}.$$

Next, the value of the overflight of kilometers (δk) of one aircraft in each flight is calculated (formula 7)

$$\delta_k = \frac{18.5}{895.2} \cdot 100\% = 2.07\%$$

It is possible that this figure is small by the standards of annual costs of airlines. But, first, only the worst conditions were taken into account (for example, in terms of takeoff / flight weight, values of altitude and descent distances, specific range, number of flights). Under better conditions, the benefits will be greater.

Secondly, it is a saving for only one direction of flight. As a rule, the airline has a much larger number of destinations.

Third, a small modern and very economical Embraer-135 aircraft was used as an example of an aircraft. On other types of aircraft, the benefits may be greater.

And last but not least, we should not forget about reducing emissions, as well as a significant reduction in the total number of route points, CRPs, while reducing the load on both the crew and the controller, which will ultimately lead to increased safety and efficiency.

IV. CONCLUSION

As a result of this work, the basic principles of flights in the airspace of free routes were analyzed in detail and an assessment of their profitability was given. The main provisions of the documents of ICAO, the European Organization for the Safety of Air Navigation (EUROCONTROL), as well as national regulatory rules regarding the FRA are analyzed. The plans for the development of the airspace of Ukraine have also been analyzed.

In addition, an algorithm for calculating the main elements for flights in the airspace of free routes is proposed.

To prove the viability of the methods for choosing the optimal routes, the flight performance characteristics of the modern medium-haul passenger aircraft Embraer-135 were analyzed and the economic indicators in a specific flight were determined.

Calculations have been performed in both metric and non-metric units, which makes them universally applicable.

Based on the results of research and calculations, results were obtained that can be used for further implementation and use.

If necessary, performance can be assessed for different types of aircraft using a number of variables (eg aircraft weight, fuel consumption).

When choosing the optimal FRA routes, it is necessary to pay attention to the main strategic objectives that define the airspace concepts, such as:flight safety, carrying capacity, efficiency, access, environment.

FRA is being implemented worldwide as part of the transition to performance-based navigation. These procedures provide significant economic benefits. But it must be remembered that the economic benefits and safety of aviation in aviation are compromised as two mutually constraining factors.

It is important to note that FRA is key to achieving free routing through airspace towards business trajectories (least-cost trajectories) and 4D profiles (lateral, vertical and time-guided). Most of the implementations have already exceeded the requirements stipulated by the regulation by 2022 [8].

FRA is a way to overcome the efficiency, capacity and environmental challenges facing aviation.

It is possible that free flight is not ideal. When it is put into operation, it is necessary to take phased steps and assess the progress achieved, and in order to achieve an acceptable level of flight safety and a solid economic basis for civil aviation activities, some flight freedoms must be sacrificed and transferred to the ATC service [9].

Over the past 15 years, ATC systems have been upgraded to include conflict detection tools using ground-based aircraft trajectories that are updated in real time as they fly. These trajectories are likely to be more stable than today's operations and, as a consequence, help improve predictability. Investments made in these new systems provide added value by allowing operations on free routes and, as a result, improving the quality of service [10].

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