Optimal Four-Dimensional Route Searching Methodology for Civil Aircrafts

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Abstract. The work is devoted to the analysis of problems in the implementation of four-dimensional navigation routes in civil aviation, the determination of the minimum necessary requirements for a decision support system that would provide a solution to these problems, as well as the development of a methodology for optimal four-dimensional route searching to provide the crew with a set of necessary information on possible flight strategies in case of difficult weather conditions. In the course of the work, the analysis of discrete and continuous optimization methods, as well as methods of operational trajectory planning has analyzed. The developed methodology for the optimal four-dimensional route searching is based on the A-star method of graph theory using the cellular decomposition of three-dimensional airspace. The methodology provides solutions for 4 optimization criteria's, takes into account the influence of wind conditions and no fly zones, as well as the aircraft performances. In the conclusion of the work, experimental results are presented that confirm the effectiveness of the proposed method.

Keywords: Decision support system · Flight management system · 4-D navigation

1 Introduction

A key function of four-dimensional navigation is the aircraft's ability to arrive at a required point in space at a required time of arrival (RTA). Existing modern flight management systems already perform such a function. This function is called RTA.

First of all, in order to perform the function, the crew at the stage of pre-flight preparation must enter the following minimum necessary information by the interaction with the human-machine interface:

– waypoint – determine the waypoint in the flight plan with the time restriction;
– RTA – determine the desired arrival time at a given waypoint of the route;
– type of RTA – determine the time limits that must be carried out by the aircraft. Three types of restrictions that are currently supported: AT - at a strictly specified time; AT or Before (AB) - at a specified time of arrival or earlier; AT or After (AA) - at a specified time of arrival or later.

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Further, after calculating the time profile of the flight during its execution, the function provides continuous time of arrival errors monitoring. Acceptable error is limited by regulatory documentation [1, 2].

During the flight along the route, a situation may occur when the error exceeds the acceptable values. In these cases the system will respond with an information message about the inability to arrive in time. Also, if complex weather conditions or conflict situations arise with the other air traffic participants along the formed route, the reaction of the system will also be just a notification.

Thus, as a result of the analysis of the RTA function principle of operation, we can conclude that in the event of an emergency, the system will respond only a notification that it is impossible to provide the current time limit.

But such functionality may not be enough in the context of global management of four-dimensional trajectories where the world civil aviation community is currently moving.

A system providing four-dimensional trajectories support must be resistant to external disturbances leading to route changes, such as: difficult weather conditions along route sections, conflict situations with other aircraft, restricted areas. The system should simplify the decision-making process as much as possible and provide the crew with the most complete necessary information.

In such situations, today the air traffic controller is responsible for making decisions, as well as maintaining and controlling each aircraft. In conditions of high airspace congestion, such situations will at best lead to a violation of the integrity of the control of the four-dimensional trajectories of each air traffic participant, and in the worst case, catastrophic situations are possible.

2 Decision Support System Functions

To solve the problems identified as a result of the analysis that arise when flying along four-dimensional navigation routes, the proposed decision support system should provide:

- solving the problem of the optimal four-dimensional route searching;
- issuing the necessary information to the information-control field of the cockpit about available flight strategies in a specific typical situation.

Let us consider in more detail the task of finding the optimal four-dimensional route, since it is this function of the system that must solve the navigation problem.

First of all, during the optimal route searching, it is necessary to determine optimization criteria. For the problem under consideration, it is necessary to find four optimal routes according to the following criteria:

- minimization the difference between the RTA at the point and the estimated time of arrival (ETA). This criterion has the highest priority, as it determines the availability of a solution that meets the requirements of four-dimensional navigation [2]. A solution to this criterion does not always exist, therefore, in its absence, a solution is not provided;

- fuel consumption minimization;
- flight time minimization;
- Multi-criteria task: fuel consumption and flight time minimization.

In order to find a solution by the last criterion, the value of cost index (CI) parameter is used. It characterizes the weight of two criteria in relation to each other. The parameter is entered manually by the crew or determined by the airline's strategy. The parameter, as a rule, is determined by a value from 0 to 99. The extreme values of the parameter characterize the criteria of fuel consumption and flight time minimization.

When forming each of the described criteria, the following factors must be considered:

- wind value and direction along the calculated flight path;
- zones of difficult weather conditions or areas of space prohibited for flight;
- aircraft flight performances, especially for the vertical flight profile calculating.

Each of these factors significantly affects the final result, namely, the calculated parameters of the optimal route. Ignoring these factors in the calculations will lead to an erroneous final result, which with a high degree of probability will not be optimal by the desired criterion.

If with forbidden zones everything is quite simple - it is forbidden to cross certain zones of space when constructing a route, with the aircraft flight characteristics - one cannot ignore the capabilities of the aircraft in terms of speed limits, altitudes, masses, set gradients, etc., then in order to show the importance of accounting wind conditions when searching for the optimal route for each of the described criteria, we consider global wind maps at altitudes of approximately 20,000 feet and 35,000 feet, shown in Figs. 1, 2, respectively.

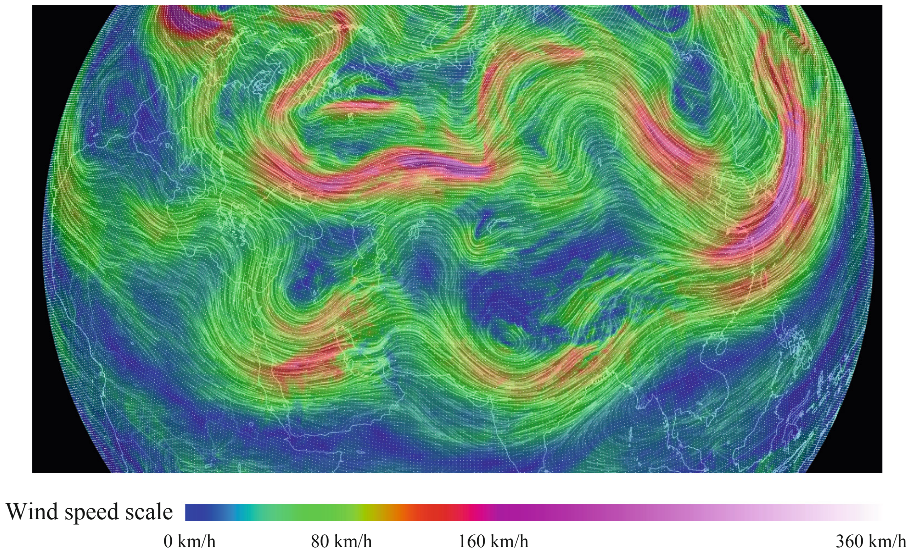

Fig. 1. 20,000 feet global wind map

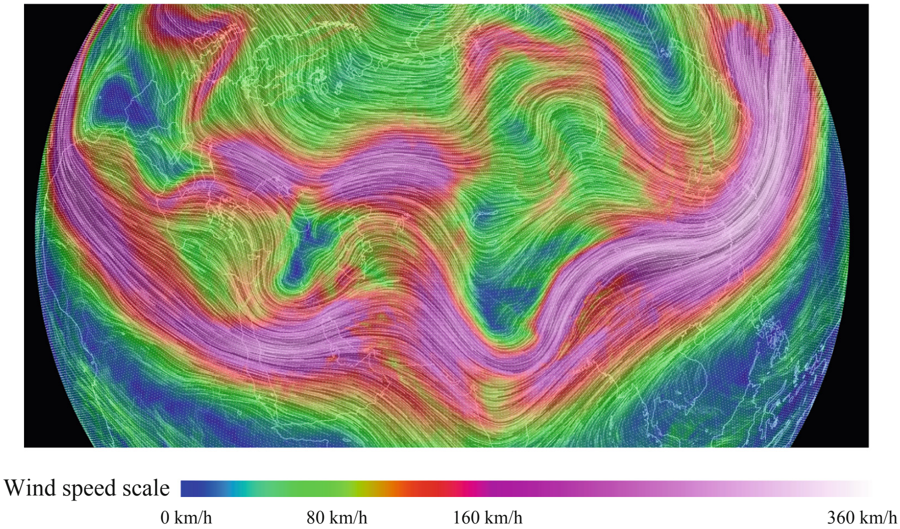

Fig. 2. 35,000 feet global wind map

The following conclusions can be drawn from these figures:

– wind direction is constant only in certain areas;
– with an increase in flight altitude, the wind strength changes significantly (usually increases), and the direction changes only partially.

At the next step of solving the problem of the optimal route searching, it is necessary to calculate the parameters of each of the sections of the route trajectory, such as: fuel consumption, flight time, climb gradient, required climb distance, etc. The calculation of these parameters is performed in the performance database (PDB) [3]. In the PDB for a specific aircraft for all phases of flight, calculation tables of parameters are given depending on the given mode and flight conditions.

Also, during the process of solving the air navigation problem, it is necessary to choose a coordinate system suitable for it, since the accuracy of the calculation of the navigation parameters of the aircraft location, as well as the parameters of the calculated trajectory, depends on its choice. Since when solving the problem, it is necessary to consider ranges of more than 500 km, it must be taken into account that the meridians converge at the poles of the Earth, and, therefore, depending on latitude, the price of dividing the degree of longitude will change in linear terms. To account for these distortions, a transformation in the Gauss-Kruger projection is used. The map sweep in the Gauss-Krueger projection is shown in Fig. 3.

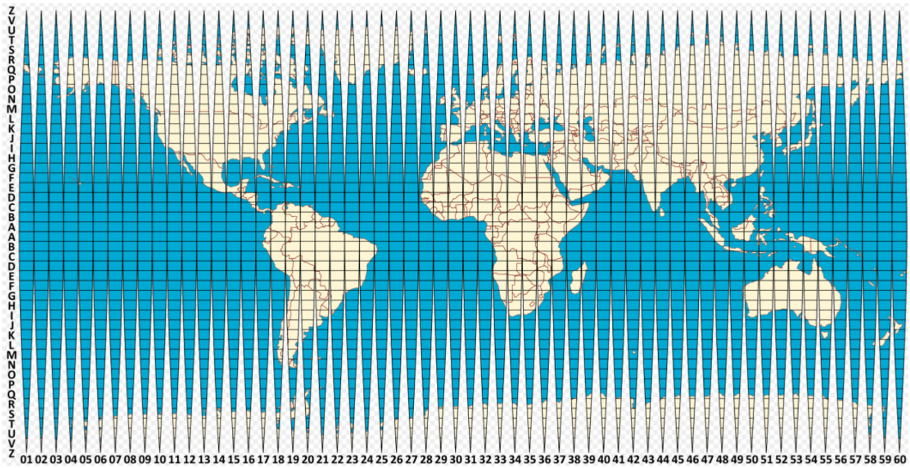

Fig. 3. Map sweep in the Gauss-Kruger projection

The use of the Gauss-Krueger projection provides the possibility of constructing a system of plane rectangular coordinates on the territory of the entire Earth and makes it possible to obtain rather large sections of the earth's surface with almost no distortion. Due to this, graph theory methods become applicable when searching for the optimal route. Also, when forming the vertices of the graph, it becomes possible to calculate the values of the information necessary at the vertices of the graph, for example:

- accessibility of a cell for flight (projection of forbidden zones);
- the value and direction of the wind at each ceil of airspace.

The ability to calculate for each vertex of the graph of meteorological and navigation information makes it possible to solve with high accuracy the task of finding the optimal route according to the given criteria.

3 Methodology of Optimal Four-Dimensional Route Searching

As a result of the analysis of scientific papers [4–7] on the subject of the problem in which various approaches to solving the problem of the optimal route searching are given, the following conclusions are drawn:

- for the task of the optimal four-dimensional route searching, the procedure for planning a three-dimensional trajectory and determining the speed profile is divided into two stages. The first step is to search for the trajectory in the horizontal plane, and then on its basis the optimization of the vertical profile is performed. But even taking into account the influence of all the described factors, such division into two stages will lead to an erroneous result as a result of the search for the optimal trajectory according to the required criteria for four-dimensional navigation.

– for the task of the optimal four-dimensional route searching, only criteria for fuel consumption and flight time minimization are used. This does not take into account the most important optimization criterion for the four-dimensional navigation problem – time delay minimization.

Therefore, it is imperative to have a procedure that would optimize the three-dimensional trajectory in one step, taking into account the factors influencing it.

The methodology that provides the search for solutions to the problem of planning the optimal four-dimensional route must meet the following requirements:

– search for solutions according to four optimality criteria:
  - time delay minimization;
  - flight time minimization;
  - fuel consumption minimization;
  - fuel consumption and flight time minimization.
– consider airspace parameters (wind, restricted zones, zones of difficult weather conditions) and aircraft flight performances;
– ensure the calculation of many existing four-dimensional trajectories in one step without dividing the vertical profile from the horizontal one.

This technique can be represented in the form of an algorithm consisting of 8 consecutive steps.

The block diagram of the developed algorithm for the optimal four-dimensional route searching that satisfies the above requirements is presented in Fig. 4.

At step 1, the input data necessary for the operation of the optimal route search algorithms is entered.

At step 2, the airspace parameters are loaded. By airspace parameters we mean information about the wind in each cell of the space and the presence of restricted zones for flight or zones of difficult weather conditions.

At step 3, the function calculates the parameters of the set of existing four-dimensional trajectories. The function provides a search for a set of trajectories for all acceptable flight speeds, as well as for all acceptable flight levels. This function is based on the algorithm of A-star graph theory methods and is used to solve the problem in the two-dimensional space. In order to take into account the flight capabilities at a different altitude from the initial altitude, the function provides an additional calculation for the climb and descent profiles for the corresponding trajectories. The result of the A-star algorithm for each flight speed and altitude is the calculation of the flight cost function. To calculate the cost of the flight, the CI value is taken equal to 0, which generally corresponds to the criterion of minimum fuel consumption. Thus, the result for each search cycle with a fixed altitude and speed of flight is one of the most fuel-efficient trajectory. And the result of the whole function is a lot of fuel-efficient trajectories for all permissible altitudes and speeds.

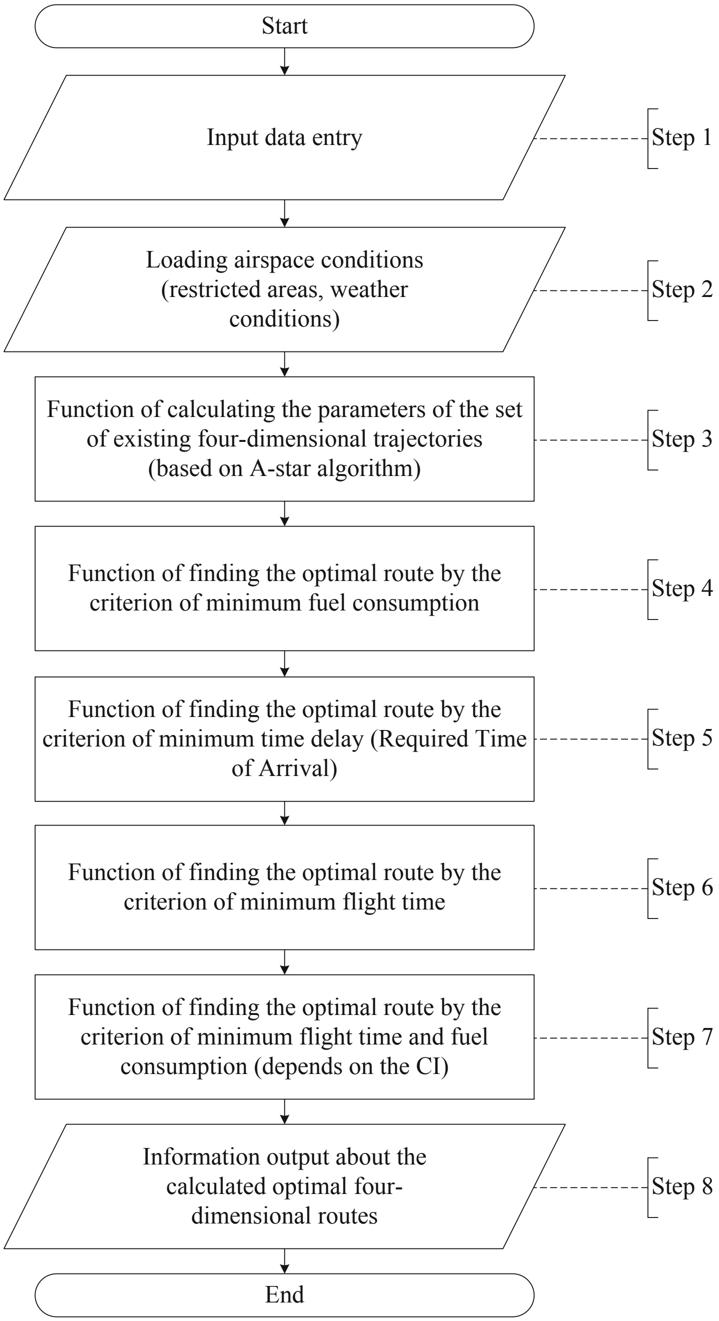

Fig. 4. Block diagram of the search algorithm for the optimal four-dimensional route

For each flight path according to the results of step 3, the following are calculated:

- amount of fuel consumed;
- flight time;
- flight distance;
- the coordinates of each cell in the airspace through which the calculated trajectory passes in the local topocentric and geodetic coordinate systems.

At steps 4–7, the search for the optimal route is performed according to the optimization criteria.

As a result, we get solutions based on four optimization criteria. These results can be provided for decision making to the crew.

4 Experimental Results

In order to confirm the correctness of the algorithm's operation, comprehensive testing was carried out for many different conditions. The main results are given by an example. Let us consider the situation when a zone of difficult weather conditions arises on the cruise phase of flight, which does not allow to fly the predefined route anymore. It is necessary to find 4 optimal routes from the start point with the coordinates of the aircraft position to the final point of the cruise phase (top of descent point). The initial flight parameters are shown in the following Table 1.

Table 1. Initial flight parameters.

Start altitude, ft	Aircraft weight, kg	Start point coordinates	End point coordinates	UTC	RTA
30000	40000	N55° E037°	N55° E044°	21:00:00	21:43:00

In order300 to demonstrate the necessity to take into account each of the requirements for the methodology for finding the optimal four-dimensional route, first of all, we will perform the algorithm without the influence of the wind with the loaded data of the zones of difficult weather conditions.

Information about optimal routes without wind influence is presented in Table 2.

Table 2. Information about optimal routes without wind influence.

Criteria\Info	Altitude, ft	Speed, mach	Distance, NM	Fuel consumption, kg	Enroute time
Minimum fuel	40000	0.74	275	1084	00:38:58
Minimum time	40000	0.78	285	1112	00:38:01
Minimum fuel/time	40000	0.76	282	1096	00:38:29
Minimum delay	40000	0.72	275	1120	00:43:00

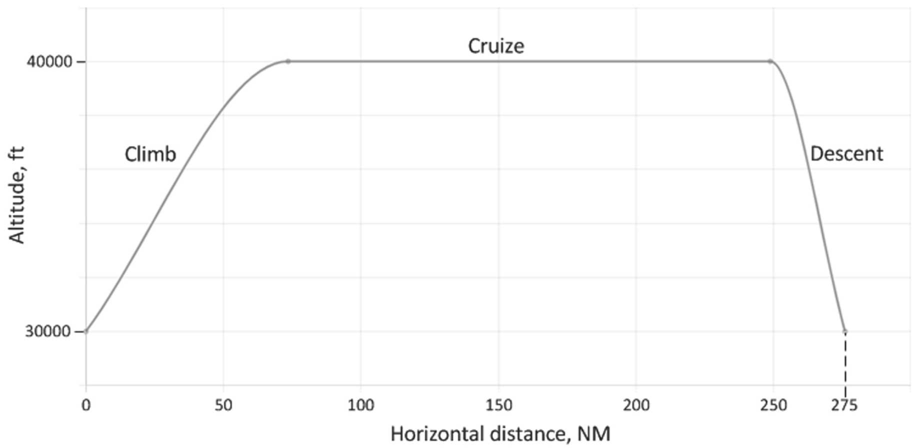

Fig. 5. Vertical profile of the minimum fuel optimal route without wind influence

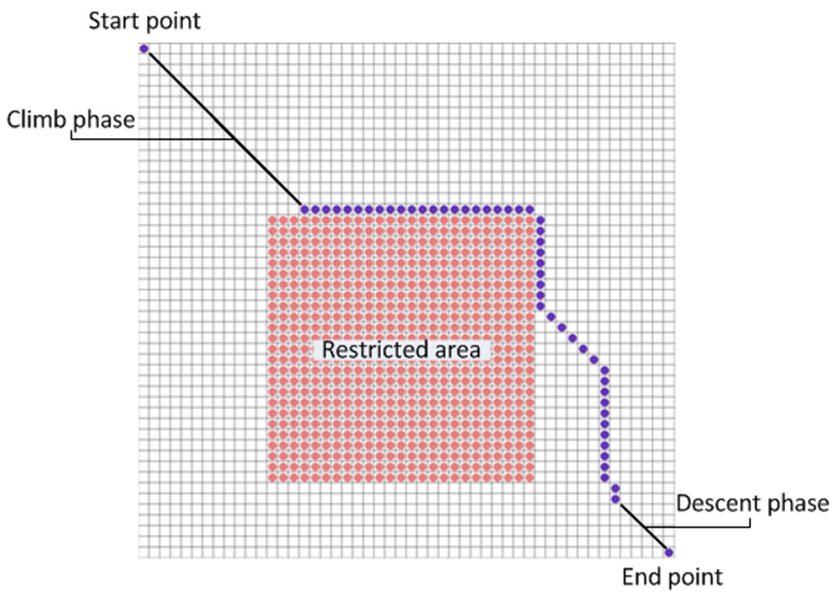

Fig. 6. Horizontal profile of the minimum fuel optimal route without wind influence

As an example, Figs. 5, 6 show the trajectories of the vertical and horizontal profiles of the route, which is optimal according to the criterion of minimum fuel consumption without taking into account the wind influence.

The next step is to perform the algorithm with similar initial data and zones of difficult weather conditions, but with the influence of wind. The direction of the wind is divided into tailwind and headwind zones. Graphical interpretation of the wind for the test is shown in Fig. 7.

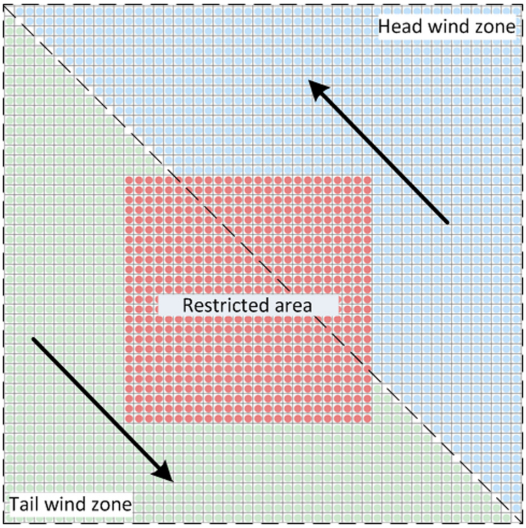

Fig. 7. Wind direction zones for the test

Information about optimal routes with wind influence is presented in Table 3.

Table 3. Information about optimal routes with wind influence.

Criteria\Info	Altitude, ft	Speed, mach	Distance, NM	Fuel consumption, kg	Enroute time
Minimum fuel	36000	0.8	302	1024	00:36:17
Minimum time	36000	0.81	301	1038	00:35:40
Minimum fuel/time	36000	0.8	302	1024	00:36:17
Minimum delay	36000	0.72	302	1065	00:43:00

Figures 8, 9 show the trajectories of the vertical and horizontal profiles of the route, which is optimal according to the criterion of minimum fuel consumption with taking into account the wind influence.

Results of the analysis of two examples show that, despite the distance increasing of the route as a result of the route searching with the wind influence, the fuel consumption has decreased. It can also be seen from the results that in order to obtain a more favorable result, it is necessary to analyze the three-dimensional space, because in the result another flight level has selected as an optimal level.

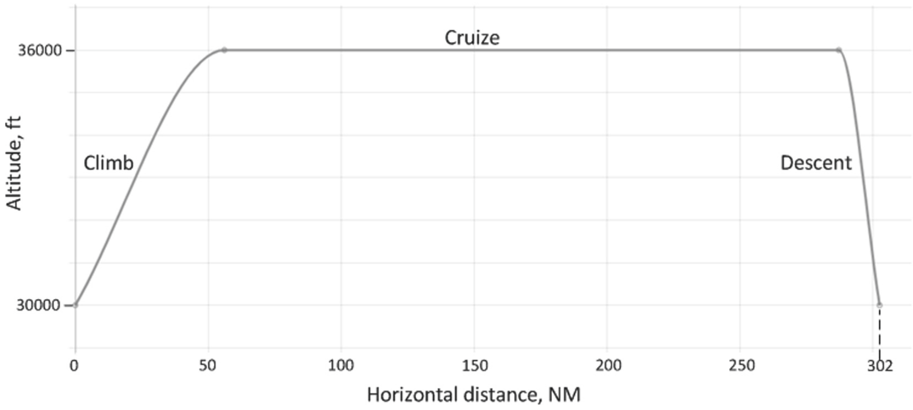

Fig. 8. Vertical profile of the minimum fuel optimal route with wind influence

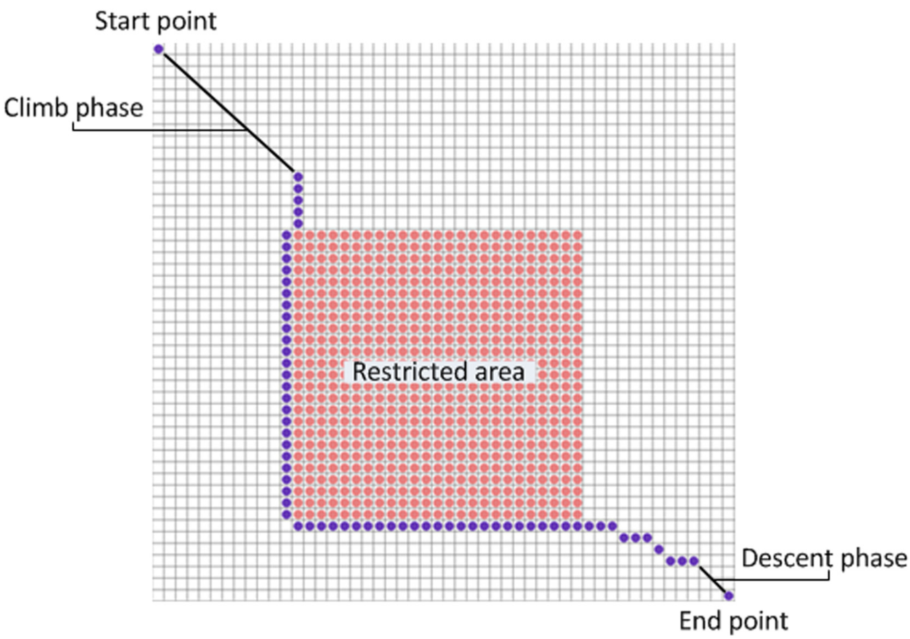

Fig. 9. Horizontal profile of the minimum fuel optimal route with wind influence

5 Conclusion

As a result of the work, the analysis of the problems that arise when performing four-dimensional navigation routes in civil aviation is performed, the requirements for a decision support system that will provide a solution to these problems are identified, and the methodology for the optimal four-dimensional route searching is developed.

The results of the conducted testing confirmed the adequacy of the results of the algorithm, and also confirmed the need to take into account each factor that effects on the searching results for the optimal four-dimensional route.

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