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Optimization of air traffic service route networks with intersection angle constraints

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Abstract: On a daily basis, thousands of aircraft move through the airspace, with their management entrusted to specialized teams of specialists from Air Navigation Service Providers (ANSPs). To ensure effective and efficient air traffic management (ATM), ANSPs continually develop innovative methods to modernize and automate the processes involved in ATM. One of the key areas of focus in this effort is the optimization of air traffic service route networks, which contributes to increasing airspace capacity, reducing congestion, and enhancing the efficiency of air traffic services. This paper proposes a model for ATS route network optimization using the A-star algorithm to minimize route distances. The study analyzes three key scenarios, considering the presence and absence of angle constraints at route intersection points. Optimizing the ATS route network provides substantial benefits in enhancing the quality of ATM services and reducing operational costs for airlines. The model has been successfully implemented within the Ho Chi Minh Area Control Center (ACC HCM) airspace. The results of the model's application demonstrate its high efficiency and practical value, particularly in airspaces with high traffic density.

Key words: air traffic management (ATM), optimization model, ATS route network, minimization of length, intersection angle, A-star algorithm, Ho Chi Minh Area Control Center (ACC HCM) airspace.

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Оптимизация сети маршрутов обслуживания воздушного движения с ограничением углов пересечения

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Аннотация: Ежедневно в воздушном пространстве перемещаются тысячи воздушных судов (ВС), управление которыми осуществляется профессиональной командой специалистов – поставщиков аэронавигационного обслуживания. Для обеспечения качественной и эффективной организации воздушного движения (ОрВД) поставщики аэронавигационного обслуживания непрерывно разрабатывают новые подходы к модернизации и автоматизации всех процессов, связанных с этим. Одним из ключевых направлений является оптимизация сети маршрутов обслуживания воздушного движения (ОВД), что способствует увеличению пропускной способности (ПС) воздушного пространства (ВП), снижению загруженности и повышению эффективности предоставления ОВД. В данной статье рассматривается разработка модели оптимизации сети маршрутов ОВД с использованием алгоритма A-star с целью минимизации расстояний маршрутов. Исследование включает анализ с учетом и без учета угловых ограничений в точках пересечения маршрутов в трех основных сценариях. Оптимизация сети маршрутов ОВД приносит значительные преимущества в повышении качества предоставления услуг ОрВД и снижении эксплуатационных расходов для авиакомпаний. Эта модель была успешно применена в ВП районного диспетчерского центра (РДЦ) Хошимина. Результаты применения модели демонстрируют высокую эффективность и практическую ценность при ее использовании в ВП с высокой интенсивностью.

Ключевые слова: ОрВД, модель оптимизации, сеть маршрутов ОВД, минимизация протяженности, угол пересечения, алгоритм A-star, ВП РДЦ Хошимина.

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Introduction

The development of air navigation is moving towards improving the technical base, including automation, communication, navigation and surveillance. Regularity, safety and efficiency of air transportation largely depend on the introduction of innovative technologies, especially in the field of automation and optimization of air traffic management processes. In the context of increasing air traffic, optimization of the ATS route network using modern solutions is of critical importance. This helps achieve a balance between capacity, safety and economic efficiency. This helps to achieve a balance between capacity, safety and economic efficiency. The study of this topic highlights key approaches for creating a more flexible and sustainable ATM system.

This paper considers the problem of developing an ATS route network optimization model taking into account the angle constraints at route intersection points, in accordance with DOC 4444[1], in order to ensure lateral separation when using navigation aids. To achieve this goal, the authors investigated a number of optimization algorithms, such as Dijkstra's algorithm [1], genetic algorithms [2], the GNN algorithm [3], and the A-star algorithm [4]. Each of the investigated algorithms has its own limitations, which makes the selection of the most suitable one extremely important. Dijkstra's algorithm, although simple to implement and provides accurate determination of the shortest routes, becomes extremely resource-intensive when analyzing large and complex route networks, which reduces its practical applicability in heavily loaded airspace conditions [5]. Genetic algorithms demonstrate flexibility in finding solutions, but require significant time and computing power for convergence, which limits their use in real-time conditions, while not guaranteeing the optimal solution in a given time, and in some cases can even turn into an infinite loop [2]. The GNN algorithm, based on the use of graph neural networks, is promising for the problem of finding the shortest route, but the lack of a guarantee of an optimal solution, as well as a strong dependence on large volumes of training data, difficulty in scaling, limited interpretability and sensitivity to changes in the graph structure make its practical application difficult [6]. Unlike other methods, the A-star algorithm combines key advantages, allowing you to take into account many factors and constraints to find optimal solutions even in complex and changing conditions. One of its main advantages is the use of a heuristic approach, which significantly speeds up the search process, directing it to the most promising areas of the solution space. This makes the algorithm especially effective when working with large networks and under limited time. In addition, A-star has high accuracy and predictability, since it aims to minimize the total route cost at each step, which helps to find a truly optimal route. Its ability to take into account dynamic changes in the network, such as sudden load increases or changing conditions, allows maintaining high performance in real time. Due to these features, A-star has proven itself as a reliable tool for solving route optimization problems in complex ATM systems. Over the past few years, many notable studies have been presented [7–13] devoted to the application of the A-star algorithm and its various modifications to finding optimal routes for vehicles and robots, taking into account the given constraints and operating conditions. However, most of these studies focus on the optimization of only one route and do not yet consider the interrelationships between routes when multiple routes need to be optimized simultaneously, as, for example, in ATS route network optimization problems. This aspect opens a new direction of research with great prospects for further development of methods based on the A-star algorithm.

[1] Doc 4444. (2016). Procedures for Air Navigation Services: Air Traffic Management, Section 5.4.1. 16th ed. ICAO, 530 p.

Based on the analysis of various route optimization algorithms, the A-star algorithm was selected as the basis for developing the ATS route optimization model. Ho Chi Minh Area Control Center will be selected as the object for applying the developed model, which will allow adapting the algorithm to real conditions and testing it on a specific route network, taking into account the specifics of the region. This approach ensures the practical applicability of the solution and its compliance with current ATM requirements.

There are 22 airfields of various departments located on the territory of the Ho Chi Minh Area Control Center, 14 of which are civil aviation, including 5 international airports: Tan Son Nhat (Ho Chi Minh City), Cam Ranh (Khanh Hoa), Da Nang, Phu Quoc (Kien Giang), Can Tho. A number of airfields are classified as joint basing or use. Every day, Ho Chi Minh City ACC specialists service about 1,500 aircraft (including aircraft flying to/from airports in the region, as well as transit flights), of which more than 50% are foreign airlines. The Ho Chi Minh City ACC area of responsibility is crossed by aircraft flows connecting the countries of Southeast Asia and Australia with Europe and back, flights from Northeast Asia to Australia and New Zealand, as well as routes connecting Indonesia, Malaysia, Thailand and Vietnam with other countries of the Asia-Pacific region. Given the high air traffic density and limited geographical ground width in some areas (due to the shape of Vietnam), the ACC HCM airspace is often overloaded, especially during peak hours or adverse weather conditions. In addition, the ACC HCM airspace structure is characterized by a large number of ATS routes intersecting in the south-north and east-west directions, resulting in the formation of numerous hot spots with high ATS density. This feature complicates the design of the ATS route network and requires more optimal solutions.

Research methods and methodology

Optimization model of ATS route network based on A-star algorithm

The A-star algorithm is one of the most efficient and widely used informed search methods in graph theory, designed to find a route with a minimum cost between two nodes. Its main idea is to combine a heuristic approach with an exact calculation of the route cost, which significantly speeds up the search process compared to non-optimized methods. The algorithm starts by considering all adjacent nodes to the initial one, choosing the node with the minimum value of the cost function $f(n)$, which is calculated as the sum of two components: $g(n)$ – the cost of the route from the initial node to the current one and $h(n)$ – a heuristic estimate of the remaining distance to the end point. Thus, the route cost function is defined as:

$$f(n) = g(n) + h(n). \quad (1)$$

The objective of developing an ATS route network optimization model is to find the optimal route between airports/navigational aids/waypoints (hereinafter collectively referred to as waypoints (WPs)) with the minimum travel distance while observing the given constraints. In other words, it is necessary to select the optimal route from the set of all possible routes in the graph representing optimal routes that satisfies all the requirements.

Since the A-star algorithm is a graph theory-based route optimization search, the most important input data are the coordinates of the WPs and the weighted values of the distances between them.

Figure 1*A* illustrates the process of searching for the optimal route, starting from the initial WP (red square) and ending with the final WP (green square), passing through intermediate WPs (white squares). The search is performed based on the parent-child relationships between WPs (details are given in the next section of the article) and predetermined distance values. The WP network contains blocked WPs (black squares) that cannot be used to construct a route. This may be due to their location in a restricted area, a flight restriction zone, or a dangerous area, or because their operation in real conditions is impossible due to weather conditions, technical malfunctions, or other factors. Figure 1*B* shows the optimal route found after analyzing all possible routes between WPs (where WPs are

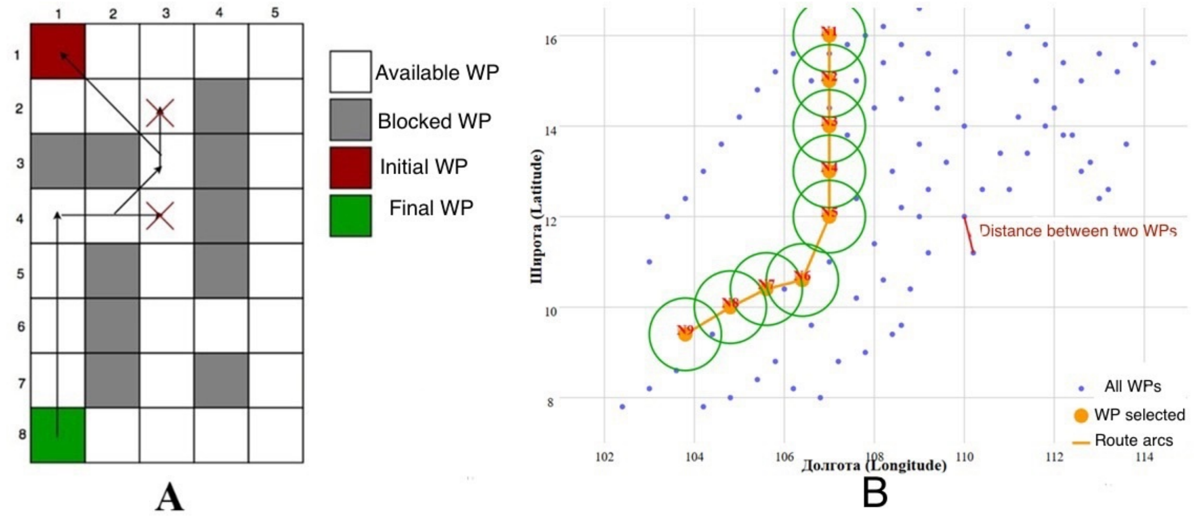

Fig. 1. Illustration of input data and their relationships in the A-star algorithm

defined by latitude and longitude) connecting the initial WP N1 and the final WP N9.

Stages in the development of a route network optimization model ATS

The first and most important stage is to define the purpose and objectives of the model. This stage is the basis for further research, since the correct definition of goals allows not only to direct efforts in the right direction, but also to minimize possible errors in the selection of methods and modeling tools. It is important to understand that each additional parameter or constraint can significantly change the nature of the problem, and therefore their careful consideration at the initial stage guarantees more accurate and effective results. In this article, the purpose of the model is to find the optimal configuration of the ATS route network with the minimum length of each route, while taking into account the angular values in the WP at the intersections of the routes. Three scenarios were considered within the model:

scenario 1: no restrictions are imposed on the intersection points of routes in the WP that form the routes. All WPs can connect routes at an arbitrary angle without any additional conditions;

scenario 2: a restriction is imposed on the intersection angle of routes in the WP network if the WP is intermediate on the ATS route (i.e. this restriction does not apply to the initial and final WP of the ATS routes);

scenario 3: a restriction on the intersection angles of routes is imposed for all WPs except for the TSH WP. The TSH WP is excluded from the constraint conditions, since it plays a key role in the network, being a connecting element for many routes. In particular, the TSH WP is the initial WP for 8 out of 20 ATS routes selected for optimization. Introducing a restriction on the intersection angles in this WP may lead to the impossibility of constructing a complete set of optimal routes that satisfy all the conditions.

The next stage is the formation and refinement of a mathematical model with well-defined target functions and a system of constraints. In this paper, the authors used a mathematical model and optimization method based on the A-star algorithm with the Euclidean heuristic function [14]. Each ATS route is represented by a graph $G^m = (N^m, F^m)$, where the set of nodes $N = \{N_0^m,\ N_1^m, \dots, N_{last}^m\}$ represents the route WP and the set of arcs $F = \{F_0^m, F_1^m, \dots, F_{last}^m\}$ represents direct connections between two adjacent WPs on the ATS route m, including such characteristics as an angle (θ) and a distance (d).

The construction of the target function plays a key role in the correct formulation of the optimization problem. In this study, the target function represented in the equation (2) is used for all

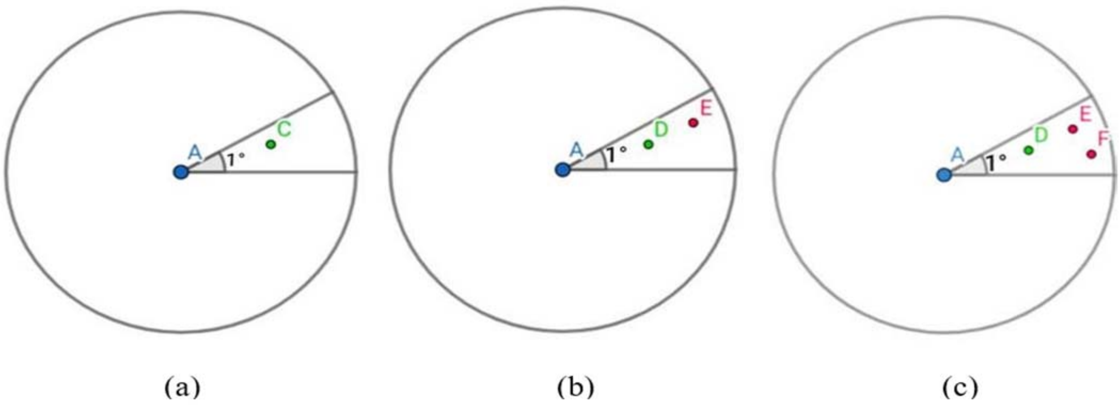

Fig 2. Illustration of the connections between the waypoint of the route (waypoint A is the parent)

three scenarios. In scenarios 2 and 3, in addition to fulfilling the target function, the model must consider the construction of optimal routes that satisfy the angle constraints at route intersections in the three scenarios. However, the conditions for applying equation (3) vary from scenario to scenario. Specifically, in scenario 2, equation (3) is valid for all RTPs except N_0^m and N_{last}^m. In scenario 3, equation (3) does not apply if $(N_0^m = TSH) \vee (N_{last}^m = TSH)$.

$$\mathrm{D_m} = \sum_{N=N_0^m}^{N_{last}^m - 1} d_{N,N+1}^m \rightarrow \min, \quad (2)$$

where $d_{N,N+1}^m = \sqrt{(x_{N+1} - x_N)^2 + (y_{N+1} - y_N)^2}$,

$$\Delta\theta_q^{m,n} = \left|\theta_{q,p}^m - \theta_{q,p'}^n\right| \geq \theta_{\min}, \quad (3)$$

where $\Delta\theta_q^{m,n}$ – is the angle between the ATS routes in WP q, p and p' – are the WPs following q on routes “m” and “n” respectively.

The value of θ_{min} depends on the navigation aids used during the WP q overflight:

- if WP q is a geographic location (the WP name is denoted by five characters): $\theta_{\min} = 30^o$;
- if the WP q is an NDB station (the WP name is denoted by two characters): $\theta_{\min} = 30^o$;
- if the WP q is a VOR station (the name of the WP is indicated by three characters): $\theta_{\min} = 15^o$.

The next step is to determine the coordinates of the input points. This model uses the coordinate data (longitude and latitude) of 130 waypoints taken from the Aeronautical Information Publication of Vietnam.[2] Of these, 114 WPs are located within the Ho Chi Minh City ACC area of responsibility, and the remaining 16 WPs are located in the airspace border areas adjacent to the Ho Chi Minh City ACC area and may affect air traffic within the Ho Chi Minh City ACC area. Since the Ho Chi Minh City ACC airspace covers both land and sea areas, we divide these 130 WPs into three areas: Land, Coast, and Sea. In particular:

- Coast: WPs located up to 30 km on either side of the coastline in the Ho Chi Minh City ACC airspace;
- Land: WPs located on land in the Ho Chi Minh City ACC airspace, with the exception of WPs classified as coasts;
- Sea: WPs located in the sea territory in the Ho Chi Minh City ACC airspace, with the exception of WPs classified as coasts.

After determining the coordinates of all the WPs, a “parent WP – child WP” relationship will be established between the WPs. To form a relationship, a circle with a fixed radius is built around each parent WP, within which the child WPs are determined. At each scanning iteration with an angular step of one degree, only one

[2] Aeronautical Information Publication: A publication issued or authorized by a State that contains long-term aeronautical information of importance to air navigation.

child WP is selected from the scanning area. This WP is determined as being at a minimum distance from the parent. The principle of selecting child WPs is visualized in Figure 2; the selected WPs are highlighted in green.

For parent waypoints located in different zones (Coast, Land, Sea), the values of the circle radius for defining child waypoints differ. These values are determined based on the applicable separation minima, the density of waypoints, and the actual distance between pairs of waypoints. If the parent waypoint is in the land zone, its child waypoint can be either in the Land zone or in the Coast zone, and the circle radius is 175 km. If the parent waypoint is in the Sea zone, its child waypoint can be either in the Sea zone or in the Coast zone, and the radius is 330 km. Finally, if the parent waypoint is located in the Coast zone, the radius for the child waypoint is 175 km if it is in the Land or Coast zone, and 330 km if the child waypoint is in the Sea zone.

After completing the construction of connections between waypoints, i.e. creating a complete directed graph, the next step is to form a list of optimal ATS routes. To accomplish this task, an analysis of statistical data on the state of air traffic in the Ho Chi Minh City ACC airspace for three months – June, July and August 2024 – was conducted, including data on the number of flights performed on each route, traffic distribution by time intervals and airspace load trends. Based on the data obtained and taking into account expert assessments, an assessment was made of the significance of real connections between waypoints in aviation operations. In this case, such factors as air traffic density, route connectivity with key regions and the operational efficiency of their use were taken into account.

After the analysis, 20 ATS routes, including both domestic and international routes in the Ho Chi Minh City ACC, were selected for optimization. The optimal routes should have clearly defined start and end waypoints, which can be airports or transfer points. A detailed list of the 20 optimal routes is presented in Table 1.

In order to ensure that the model meets the functional requirements at the strategic design stage and to reduce the complexity of the problem while maintaining the possibility of application in most real situations, it is necessary to introduce a number of assumptions along with the objective function and constraints defined in the mathematical model [14]. The use of assumptions allowed not only to adapt the mathematical model to real operating conditions, but also to ensure its compliance with the specific features of the system, including the technical infrastructure, organizational aspects of ATS and traffic stability. The following assumptions were used in the model:

- navigation infrastructure: all systems and devices supporting navigation (e.g. VOR, DME, GPS) are assumed to operate in normal mode and provide stable coverage;
- airspace characteristics and ATS unit organization: the airspace structure and boundaries, as well as the capabilities of the ATS unit, are considered fixed and unchanged throughout the entire period of operation;
- traffic intensity and density are considered constant, without the influence of emergency situations or a sharp increase in demand.

Based on the improved mathematical model, the data on the waypoint and optimal ATS routes, and the adopted assumptions, a software model for optimizing the ATS route network was developed in Python [15].

Figure 3 shows a flow chart of a simple algorithm for finding the optimal route using the A-star algorithm taking into account angle constraints. Angle constraints are implemented at the stage of assessing possible directions of movement to ensure sufficient lateral separation on the routes. The algorithm sequentially checks all feasible nodes, assessing their cost based on a combined criterion that includes the route length and the intersection angle of the routes. For scenario 1, a similar algorithm scheme is used, but the angle checking stages are skipped. This option is an alternative approach that can be used depending on the conditions of the problem. Both approaches are acceptable and are used in different situations depending on the route requirements.

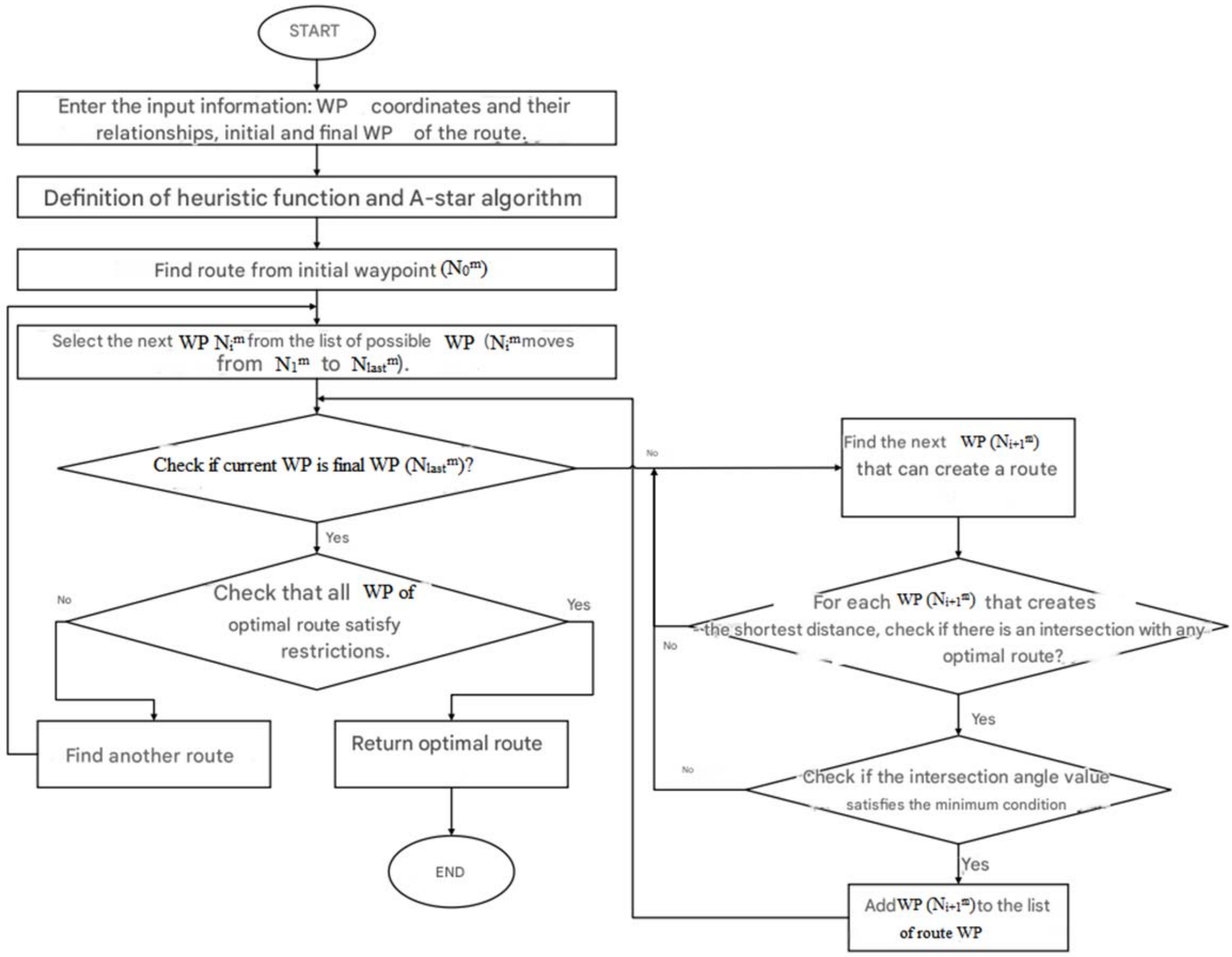

Fig. 3. Block diagram of the algorithm for finding the optimal route taking into account the constraints on the angle between intersecting routes

Results of the ATS route network optimization model

A detailed comparison of each route (including route length and route of waypoint) for all three scenarios is presented in Table 1.

The analysis of the data from Table 1 allows to highlight a number of key conclusions about the influence of constraints on the results of constructing ATS routes. It is noteworthy that 6 ATS routes: TSH – DAN, CRA – PQU, TSH – IGARI, TSH – DUDIS, TSH – POPET and TSH – AKMON, which demonstrate completely identical results in all three scenarios. This fact indicates their stability to changes in the algorithm operating conditions and the preservation of optimal parameters when varying constraints. At the same time, the routes DAN – PQU, CRA – DAN, PANDI – IGARI, ANINA – ARESI and PCA – TRN showed completely different results in all scenarios. This indicates a high sensitivity of these routes to changes in conditions, especially those associated with angular restrictions on route intersection.

A comparative analysis of all three scenarios shows that scenario 1 with the minimum number of restrictions provides the smallest values of route length. In this case, the algorithm operates in the most "free" conditions, providing minimum distances. On the contrary, in scenario 3, where the maximum number of angular restrictions is set, an increase in length is observed, which is associated with more stringent conditions imposed on route construction.

Table 1

Comparison of the results of three scenarios for optimizing the ATS route network

ATS route	Scenario 1	Scenario 2	Scenario 3
TSH – DAN	612.2 km TSH – DONXO – MULAD – DADEN – TATIM – DAN	612.2 km TSH – DONXO – MULAD – DADEN – TATIM – DAN	612.2 km TSH – DONXO – MULAD – DADEN – TATIM – DAN
CRA – PQU	602.2 km CRA – SOSPA – LKH – KADUM – SAPEN – KISAN – PQU	602.2 km CRA – SOSPA – LKH – KADUM – SAPEN – KISAN – PQU	602.2 km CRA – SOSPA – LKH – KADUM – SAPEN – KISAN – PQU
TSH – ARESI	930.2 km TSH – ENRIN – SOSPA – ATVIT – NITOM – MESOX – ARESI	931.7 km TSH – VETOM – IBUNU – NITOM – MESOX – ARESI	931.7 km TSH – VETOM – IBUNU – NITOM – MESOX – ARESI
TSH – IGARI	548.1 km TSH – BITIS – ANHOA – BIBAN – IGARI	548.1 km TSH – BITIS – ANHOA – BIBAN – IGARI	548.1 km TSH – BITIS – ANHOA – BIBAN – IGARI
TSH – BUNTA	732.0 km TSH – DONXO – MULAD – MUMGA – CQ – BUNTA	741.6 km TSH – KADUM – PATMA – MEVON – MUMGA – CQ – BUNTA	741.6 km TSH – KADUM – PATMA – MEVON – MUMGA – CQ – BUNTA
DAN – PQU	885.7 km DAN – TATIM – DADEN – MULAD – DONXO – POPET – KISAN – PQU	947.4 km DAN – VILOT – XAQUA – ENGIM – BMT – DOVIN – DONXO – POPET – DADEM – PQU	982.7 km DAN – PATNO – XAQUA – ENGIM – BMT – DOVIN – DONXO – POPET – DADEM – OSOTA – PQU
CRA – BUNTA	539.1 km CRA – KARAN – ASUKU – BUNTA	539.1 km CRA – KARAN – ASUKU – BUNTA	553.6 km CRA – KARAN – VIMUT – ITBAM – BUNTA
TSH – DUDIS	424.8 km TSH – XOBAV – LITAM – DUDIS	424.8 km TSH – XOBAV – LITAM – DUDIS	424.8 km TSH – XOBAV – LITAM – DUDIS
TSH – POPET	82.6 km TSH – POPET	82.6 km TSH – POPET	82.6 km TSH – POPET
EXOTO – ESPOB	1105.2 km EXOTO – VEPAM – KARAN – ELSAS – CN – ESPOB	1105.2 km EXOTO – VEPAM – KARAN – ELSAS – CN – ESPOB	1108.8 km EXOTO – VEPAM – NHATA – ELSAS – CN – ESPOB
DUDIS – DONDA	1027.5 km DUDIS – DAGAG – SUDUN – DAMVO – NITOM – DAMEL – DONDA	1042.6 km DUDIS – DAGAG – ATVIT – DAMEL – DONDA	1042.6 km DUDIS – DAGAG – ATVIT – DAMEL – DONDA
MIGUG – MELAS	1110.3 km MIGUG – MESOX – MUGAN – MIMUX – MAPNO – OSIXA – MOXON – MELAS	1162.4 km MIGUG – MESOX – AGSAM – ALDAS – OSIXA – MOXON – MELAS	1162.4 km MIGUG – MESOX – AGSAM – ALDAS – OSIXA – MOXON – MELAS
AKMON – ARESI	788.8 km AKMON – UDOSI – ALDAS – AGSAM – ANOKI – ARESI	852.3 km AKMON – MAPNO – MIMUX – ANOKI – ARESI	852.3 km AKMON – MAPNO – MIMUX – ANOKI – ARESI
CRA – DAN	471.2 km CRA – KARAN – KAMGO – PCA – KUMUN – DAN	475.7 km CRA – NOBID – BANSU – SADIN – DAN	501.4 km CRA – NOBID – PCA – KUMUN – DAN
TSH – PANDI	806.3 km TSH – BUKMA – MATGI – AGSIS – DAMVO – MIMUX – AGSAM – PANDI	851.8 km TSH – VEPMA – AGSIS – DAMVO – MUGAN – PANDI	851.8 km TSH – VEPMA – AGSIS – DAMVO – MUGAN – PANDI
TSH – AKMON	486.4 km TSH – LOSON – MOXON – AKMON	486.4 km TSH – LOSON – MOXON – AKMON	486.4 km TSH – LOSON – MOXON – AKMON

Continuation of Table 1

ATS route	Scenario 1	Scenario 2	Scenario 3
PANDI – IGARI	1258.2 km PANDI – ALDAS – MAPNO – SAMAP – CN – VIGEN – BITOD – IGARI	1356.8 km PANDI – ALDAS – DAMVO – SAMAP – LITAM – VIGEN – BITOD – IGARI	1364.0 km PANDI – ALDAS – DAMVO – SAMAP – LITAM – VIGEN – IPRIX – IGARI
PQU – IGARI	367.3 km PQU – ADBOP – IGARI	367.3 km PQU – ADBOP – IGARI	417.4 km PQU – ADBOP – SAMOG – IGARI
ANINA – ARESI	758.5 km ANINA – MUMGA – VIMUT – VEPAM – DAMEL – MESOX – ARESI	782.2 km ANINA – MUMGA – VIMUT – DONDA – ARESI	882.5 km ANINA – MUMGA – VIMUT – DONDA – MIGUG – ARESI
PCA – TRN	563.7 km PCA – NOBID – PATMA – DONXO – RUNOP – MOXEB – TRN	593.9 km PCA – NOBID – ONEBI – ENRIN – ENPAS – TRN	654.3 km PCA – SADAS – BMT – VETOM – LOSON – TRN

Table 2

Partial results of angle calculation in scenarios 2

Node	route1	WP_in route1	WP_out route1	route2	WP_in route2	WP_out route2	Angle
ALDAS	route_17	PANDI	ALDAS	route_12	ALDAS	OSIXA	169.8021
ALDAS	route_12	AGSAM	ALDAS	route_17	PANDI	ALDAS	32.84379
ALDAS	route_17	ALDAS	DAMVO	route_12	AGSAM	ALDAS	122.7799
ALDAS	route_12	ALDAS	OSIXA	route_17	ALDAS	DAMVO	34.57419
DAMVO	route_15	DAMVO	MUGAN	route_17	ALDAS	DAMVO	31.84812

Table 3

Partial results of angle calculation in scenarios 3

Node	route1	WP_in route1	WP_out route1	route2	WP_in route2	WP_out route2	Angle
AKMON	route_13	AKMON	MAPNO	route_16	MOXON	AKMON	58.08929
AKMON	route_16	MOXON	AKMON	route_13	AKMON	MAPNO	58.08929
ALDAS	route_17	PANDI	ALDAS	route_12	ALDAS	OSIXA	169.8021
ALDAS	route_12	ALDAS	OSIXA	route_17	ALDAS	DAMVO	34.57419
ALDAS	route_17	ALDAS	DAMVO	route_12	AGSAM	ALDAS	122.7799

When comparing scenarios 1 and 2, it can be noted that, in addition to the previously mentioned 6 routes, identical results were obtained for the following routes: CRA – BUNTA, EXOTO – ESPOB and PQU – IGARI. This indicates the absence of a significant impact of the restrictions introduced in scenario 2 on these routes and the preservation of their optimality. A comparative analysis of scenarios 2 and 3 allows to highlight the following routes: TSH – ARESI, TSH – BUNTA, DUDIS – DONDA, MIGUG – MELAS, AKMON – ARESI and TSH – PANDI. These routes demonstrate identical results and are longer than the corresponding routes in scenario 1. This indicates a noticeable impact of the angular restrictions introduced when constructing the ATS route network optimization model.

To check the accuracy and correctness of the algorithm, an Excel file was created with data on the intersection angles of the optimization lines for scenarios 2 and 3. Table 2 presents a part of the intersection angle results for scenario 2, and Table 3 – for scenario 3. For example, in the second row of Table 2 (highlighted in yellow), the ALDAS waypoint is the intersection of two segments: PANDI – ALDAS of route 17 (PANDI – IGARI) and ADLAS – OSIXA of route 12 (MIUG – MELAS), forming an angle of 169.802°. In scenario 2, 38 angles were calculated, and in scenario 3 – 75 angles. All calculated values correspond to the established constraints.

Figures 4, 5 and 6 sequentially illustrate the optimization results of 20 ATS routes corresponding to scenarios 1, 2 and 3.

When analyzing Figures 5 and 6, which illustrate the ATS routes in scenarios 2 and 3, it can be seen that in order to meet the requirements for angular constraints at route intersections, the optimal trajectories become jagged, frequently changing direction. These direction changes result in complex routes with multiple waypoints, which is especially noticeable on the following routes: DUDIS – DONDA, MIGUG – MELAS, AKMON – ARESI and PANDI – IGARI. Such route configurations can create significant difficulties for piloting and ATS. Excessive jaggedness of routes requires increased attention from the crew and more frequent course corrections,

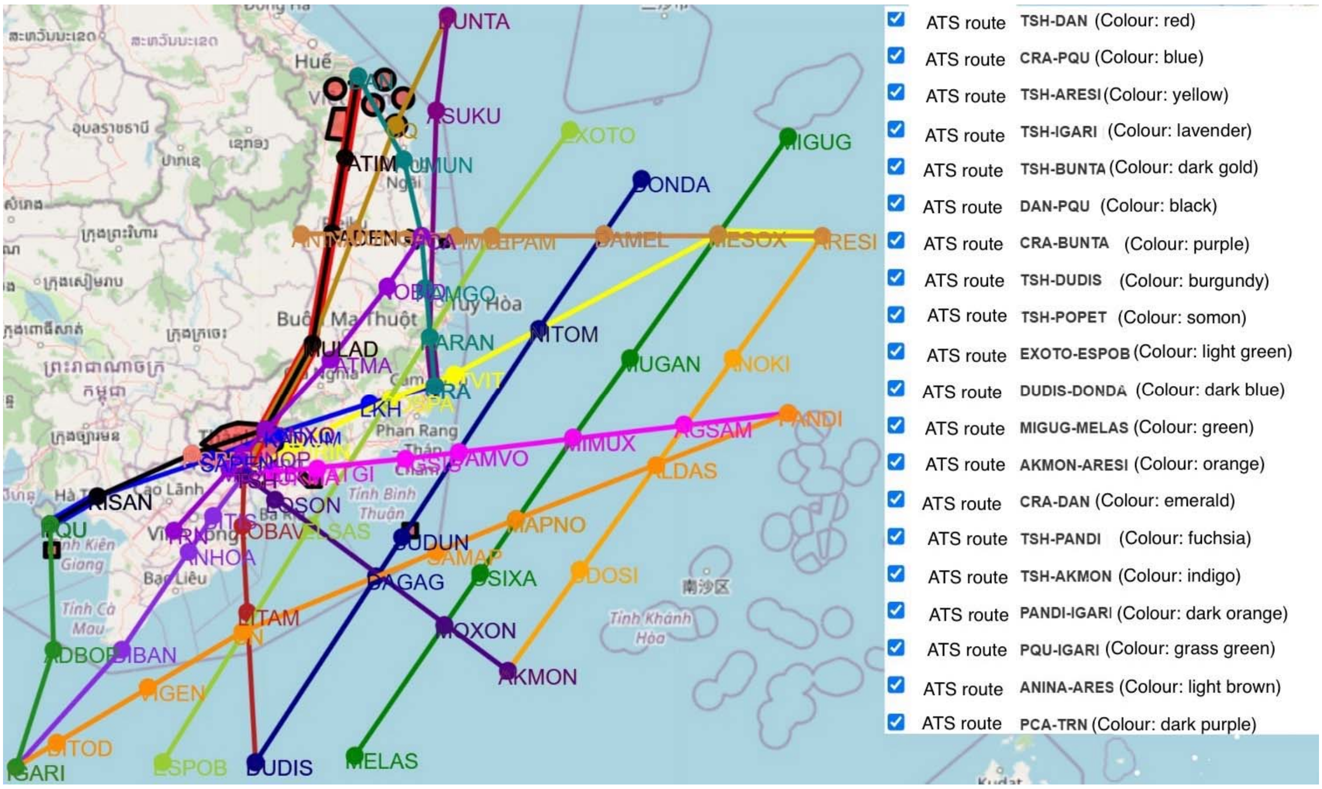

Fig. 4. Optimal results for 20 ATS routes in scenario 1

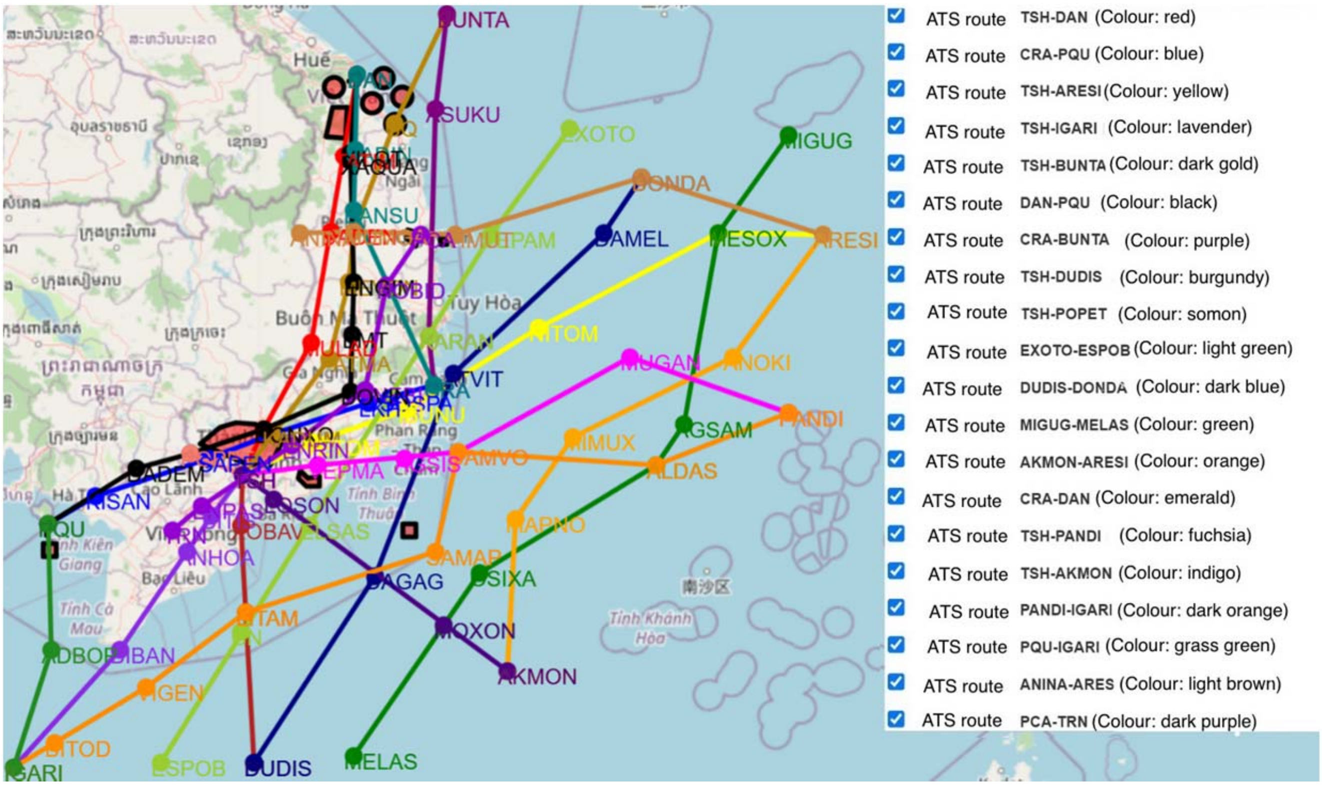

Fig. 5. Optimal results for 20 ATS routes in scenario 2

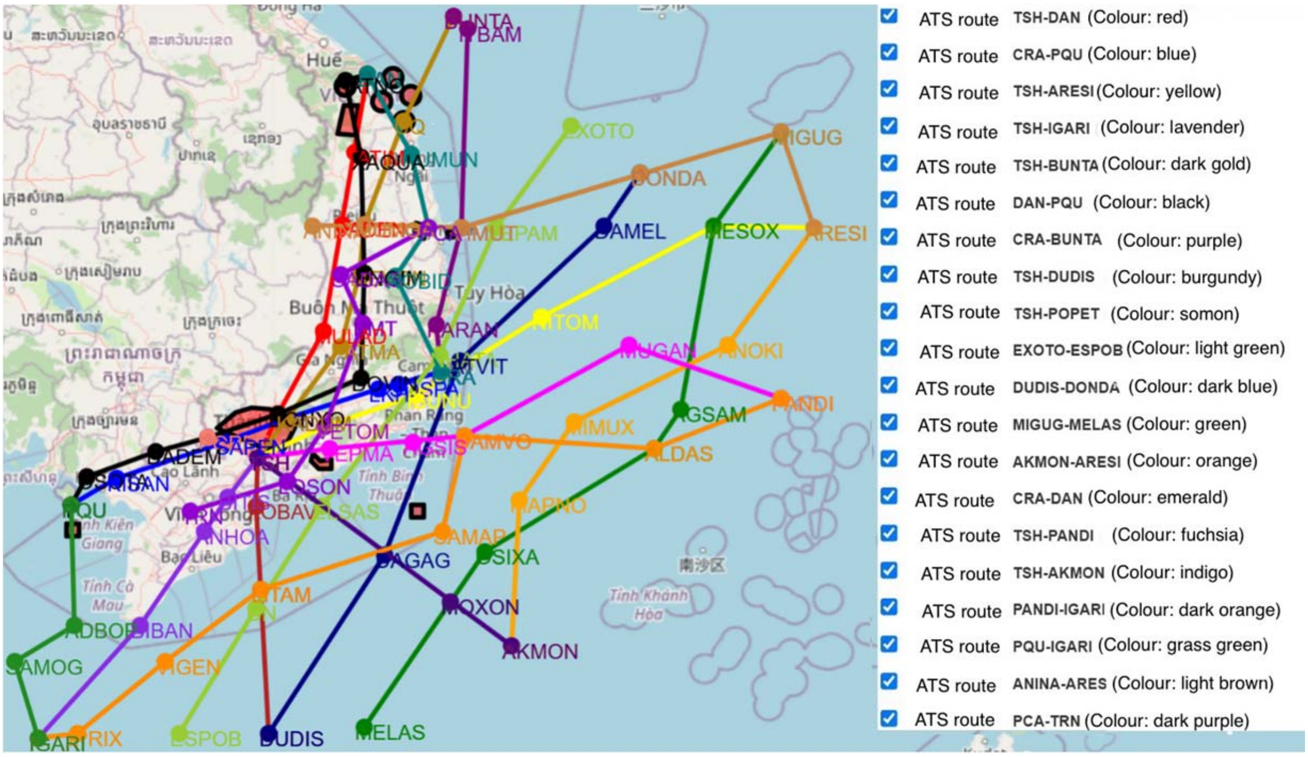

Fig. 6. Optimal results for 20 ATS routes in scenario 3

which increases the cognitive load on pilots and controllers. In addition, such routes can increase the overall flight time and fuel burn. Constant direction changes cause additional loads on the onboard navigation systems and the autopilot, and can also affect the comfort of passengers and crew due to frequent bank and course changes, especially in turbulent conditions.

In contrast, scenario 1 generates predominantly straight routes, which not only provide a simpler and more understandable flight profile for the crew, but also help reduce operating costs. Such routes reduce the number of maneuvers, minimizing the need for frequent corrections, which reduces the overall flight time and reduces fuel consumption. This contributes to increased cost-effectiveness and environmental friendliness. From a safety perspective, reducing the number of maneuvers reduces the risk of crew and air traffic controller errors, and reduces the likelihood of conflicts with other aircraft in a busy airspace.

In addition, in scenarios 2 and 3, the route intersection angles in the waypoints exceed the minimum value established by equation 3, which, theoretically, facilitates the maintenance of lateral separation by controllers using NDB, VOR or GNSS on intersecting ATS routes. However, in real conditions, in addition to using lateral separation, when it is impossible or insufficient to provide it, the controller can also apply vertical and longitudinal separation to ensure safe and efficient air traffic control. Therefore, the advantages that scenarios 2 and 3 can potentially provide are not so significant as to outweigh their disadvantages when applied, especially in the airspace of Vietnam. The peculiarities of the location of the national border of Vietnam, which determine the restrictions on the use of airspace in the border strip, create additional difficulties in ensuring safe separation.

Thus, despite the apparent advantages of scenarios 2 and 3, their implementation may be less effective than expected, especially in complex and congested air traffic conditions. Although these scenarios offer theoretically optimal routes taking into account angular restrictions at their intersections, scenario 1 remains the most preferable for practical application. It provides an optimal balance between operational efficiency, economic feasibility and safety level, which makes it optimal for ATS route planning. Nevertheless, scenarios 2 and 3 can be effectively used in conditions when a large spatial volume allows for the formation of a relatively conflict-free airspace structure, and in the event of a change in the air, air navigation or meteorological situation along the route according to the plan, the use of scenarios 2 and 3, with relatively large distances between waypoints, provides flexibility and high efficiency of alternative routes.

To evaluate the efficiency of the optimization model, the results of the routes from scenario 1 (the selected scenario) are compared with the current routes used in real conditions. Table 4 shows that in 20 ATS routes, the distance was reduced on 15 routes compared to the existing ones. Among them, some optimized routes significantly reduced their length, for example, the DAN – PQU route decreased by 83.6 km (8.6%). The new routes are more direct, which simplifies aircraft piloting, reduces fuel consumption and shortens the flight time. This helps to reduce the number of hot spots, reduce the likelihood of conflict situations, reduce the amount of airspace traffic coordination for controllers and reduce the frequency of radio exchange between aircraft crews. Thus, the workload of both controllers and aircraft crews is reduced, which in turn increases the airspace PS and improves its efficiency.

Table 4

Comparison of the results of the optimized routes in scenario 1 with the actual routes

ATS route	Scenario 1	The actual route
TSH – DAN	612.2 km TSH – DONXO – MULAD – DADEN – TATIM – DAN	648.9 km TSH – KADUM – PATMA – SADAS – DADEN – LATOM – PATNO – DAN
CRA – PQU	602.2 km CRA – SOSPA – LKH – KADUM – SAPEN – KISAN – PQU	615.7 km CRA – SOSRA – LKH – VETOM – AC – ESDOB – TSH – ATGAS – TUNPO – PQU
TSH – ARESI	930.2 km TSH – ENRIN – SOSPA – ATVIT – NITOM – MESOX – ARESI	934.8 km TSH – ESDOB – AC – VETOM – LKH – SOSRA – CRA – ATVIT – NITOM – MESOX – ARESI
TSH – IGARI	548.1 km TSH – BITIS – ANHOA – BIBAN – IGARI	552.3 km TSH – BITIS – ANHOA – BIBAN – BITOD – IGARI
TSH – BUNTA	732.0 km TSH – DONXO – MULAD – MUMGA – CQ – BUNTA	757 km TSH – KADUM – PATMA – BMT – NOBID – PCA – ASUKU – BUNTA
DAN – PQU	885.7 km DAN – TATIM – DADEN – MULAD – DONXO – POPET – KISAN – PQU	969.4 km DAN – SADIN – BANSU – MUMGA – BMT – DOVIN – AC – TSH – ATGAS – TUNPO – PQU
CRA – BUNTA	539.1 km CRA – KARAN – ASUKU – BUNTA	540.8 km CRA – NHATA – KARAN – KAMGO – PCA – ASUKU – BUNTA
TSH – DUDIS	424.8 km TSH – XOBAV – LITAM – DUDIS	425.4 km TSH – XOBAV – NIXIV – CN – DUDIS
TSH – POPET	82.6 km TSH – POPET	82.6 km TSH – SAEN – POPET
EXOTO – ESPOB	1105.2 km EXOTO – VEPAM – KARAN – ELSAS – CN – ESPOB	1105.3 km EXOTO – VEPAM – KARAN – SOSPA – PTH – ELSAS – CN – ESPOB
DUDIS – DONDA	1027.5 km DUDIS – DAGAG – SUDUN – DAMVO – NITOM – DAMEL – DONDA	1027.5 km DUDIS – DAGAG – SUDUN – DAMVO – NITOM – DAMEL – DONDA
MIGUG – MELAS	1110.3 km MIGUG – MESOX – MUGAN – MIMUX – MAPNO – OSIXA – MOXON – MELAS	1110.3 km MIGUG – MESOX – MUGAN – MIMUX – MAPNO – OSIXA – MOXON – MELAS

Continuation of Table 4

ATS route	Scenario 1	The actual route
AKMON – ARESI	788.8 km AKMON – UDOSI – ALDAS – AGSAM – ANOKI – ARESI	788.8 km AKMON – UDOSI – ALDAS – AGSAM – ANOKI – ARESI
CRA – DAN	471.2 km CRA – KARAN – KAMGO – PCA – KUMUN – DAN	474.1 km CRA – KARAN – KAMGO – PCA – KUMUN – CQ – DAN
TSH – PANDI	806.3 km TSH – BUKMA – MATGI – AGSIS – DAMVO – MIMUX – AGSAM – PANDI	806.4 km TSH – BUKMA – MATGI – PTH – AGSIS – DAMVO – MIMUX – AGSAM – PANDI
TSH – AKMON	486.4 km TSH – LOSON – MOXON – AKMON	486.4 km TSH – LOSON – MOXON – AKMON
PANDI – IGARI	1258.2 km PANDI – ALDAS – MAPNO – SAMAP – CN – VIGEN – BITOD – IGARI	1258.2 km PANDI – ALDAS – MAPNO – SAMAP – CN – VIGEN – BITOD – IGARI
PQU – IGARI	367.3 km PQU – ADBOP – IGARI	392.1 km PQU – ADBOP – BITOD – IGARI
ANINA – ARESI	758.5 km ANINA – MUMGA – VIMUT – VEPAM – DAMEL – MESOX – ARESI	758.6 km ANINA – DADEN – PLK – MUMGA – PCA – VIMUT – VEPAM – DAMEL – MESOX – ARESI
PCA – TRN	563.7 km PCA – NOBID – PATMA – DONXO – RUNOP – MOXEB – TRN	564.1 km PCA – NOBID – BMT – PATMA – DONXO – RUNOP – MOXEB – TRN

Conclusion

In the modern world, one of the areas of improvement of air navigation services is the introduction of efficient flight paths, which implies: transition from ATS routes to zonal navigation routes, creation of airspace zones with free routing; creation or modification of departure and landing approach patterns at airports based on the balance of the economy of airspace users and the ANSPs; increasing the availability of airspace for all users by reducing the number and duration of flight restriction zones.

At the same time, in real conditions, when the formation of the airspace structure is influenced by conflicts of interests of many airspace users, for example, in the Moscow zone of the Unified ATM System, as well as in conditions of reduced airspace capacity due to changes in the meteorological situation, the introduction of bans and restrictions on the usage of the airspace, creating an opportunity for promptly changing flight trajectories along optimal ATS routes is one of the ways to maintain flight safety at an acceptable level.

The article presents the methodology and results of modeling the optimization of ATS routes in three cases: with and without angular restrictions, as applied to the airspace of the Ho Chi Minh City ACC. The obtained results demonstrate the efficiency and performance of the model, as well as its ability to provide solutions for improving the ATS route network. The model is universal and can be easily implemented in the airspace of various regions by changing the input data (coordinates).

In the future, the authors plan to improve the model so that it can offer alternative routes in cases where the main routes become unavailable (due to adverse weather conditions or other restrictions). Such alternative routes will become an effective backup tool in cases of reduced airspace capacity due to restrictions on its use related to the implementation of state priorities in the use of airspace, as well as changes in meteorological conditions or other factors affecting flight safety.

References

1. **Dolnikov, V.L., Yakimova, O.P.** (2011). Basic graph algorithms: Lecture notes. Yaroslavl: YarGU, 80 p. (in Russian)

2. **Korotkin, A.A., Krasnov, M.V.** (2020). Genetic algorithms: Tutorial. Yaroslavl: YarSU, 40 p. (in Russian)

3. **Gafarov, F.M., Gilemzyanov, A.F.** (2024). Neural networks in PyTorch: Tutorial. Kazan: Kazanskiy federal'nyy universitet, 106 p. (in Russian)

4. **Laparra, D.M.** (2019). Pathfinding algorithms in graphs and applications. Universitat de Barcelona, 39 p.

5. **Jurkiewicz, P., Biernacka, E., Domżał, J., Wójcik, R.** (2021). Empirical time complexity of generic Dijkstra algorithm. *In: IFIP/IEEE International Symposium on Integrated Network Management*. France: Bordeaux, pp. 594–598. DOI: 10.48550/arXiv.2006.06062

6. **Khemani, B., Patil, S., Kotecha, K. et al.** (2024). A review of graph neural networks: concepts, architectures, techniques, challenges, datasets, applications, and future directions. *Journal of Big Data*, vol. 11. ID: 18. DOI: 10.1186/s40537-023-00876-4 (accessed: 12.01.2025).

7. **Skrypnik, O.N., Nechaev, E.E., Arefyeva, N.G., Arefyev, R.O.** (2019). Optimization of an aircraft flight trajectory in the GLONASS dynamic accuracy field. *Civil Aviation High Technologies*, vol. 22, no. 5, pp. 19–31. DOI: 10.26467/2079-0619-2019-22-5-19-31

8. **Nurlybayev, M.A., Almazkhan, N.A.** (2023). Application of path finding algorithms for control of airfield-based unmanned aircraft for collision prevention. *In: Energetika, upravleniye i avtomatizatsiya: innovatsionnyye resheniya problem: materialy II Vserossiyskoy nauchno-prakticheskoy konferentsii obuchayushchikhsya i prepodavateley*. St. Petersburg: VSHTE SPbGUPTD, pp. 23–26. (in Russian)

9. **Zhang, H., Tao, Y., Zhu, W.** (2023). Global path planning of unmanned surface vehicle based on improved a-star algorithm. *Sensors*, vol. 23, issue 14, ID: 6647. DOI: 10.3390/s23146647 (accessed: 12.01.2025).

10. **Chatzisavvas, A., Dossis, M., Dasygenis, M.** (2024). Optimizing mobile robot navigation based on a-star algorithm for obstacle avoidance in smart agriculture. *Electronics*, vol. 13, issue 11, ID: 2057. DOI: 10.3390/electronics13112057 (accessed: 12.01.2025).

11. **Kabir, R., Watanobe, Y., Islam, M.R., Naruse, K.** (2024). Enhanced robot motion block of A-star algorithm for robotic path planning. *Sensors*, vol. 24, issue 5, ID: 1422. DOI: 10.3390/s24051422 (accessed: 12.01.2025).

12. **Farid, G., Cocuzza, S., Younas, T., Razzaqi, A.A., Wattoo, W.A., Cannella, F., Mo, H.** (2022). Modified A-Star approach to plan the motion of a quadrotor UAV in three-dimensional obstacle-cluttered environment. *Applied Sciences*, vol. 12, issue 12. ID: 5791. DOI: 10.3390/app12125791 (accessed: 12.01.2025).

13. **Yoo, Y.D., Moon, J.H.** (2025). Study on A-Star algorithm-based 3D path optimization method considering density of obstacles. *Aerospace*, vol. 12, issue 2. ID: 85. DOI: 10.3390/aerospace12020085 (accessed: 12.01.2025).

14. **Nguyen, N.H.Q., Nechaev, V.N., Malygin, V.B.** (2025). Mathematical model and application of the A-star algorithm to optimize ATS routes in the area control center Ho Chi Minh airspace. *Crede Experto: transport, society, education, language*, no. 1, pp. 64–85. DOI: 10.51955/2312-1327_2025_1_64 (in Russian)

15. **Van Rossum, G., Drake, F.L.** (2009). Python 3 Reference Manual. CreateSpace, Scotts Valley, CA, USA, 242 p.

Список литературы

1. **Дольников В.Л., Якимова О.П.** Основные алгоритмы на графах: текст лекций. Ярославль: ЯрГУ, 2011. 80 с.

2. **Короткин А.А., Краснов М.В.** Генетические алгоритмы: учеб.-метод. пособие. Ярославль: ЯрГУ, 2020. 40 с.

3. **Гафаров Ф.М., Гилемзянов А.Ф.** Нейронные сети в PyTorch: учеб. пособие. Казань: Казанский федеральный университет, 2024. 106 с.

4. **Laparra D.M.** Pathfinding algorithms in graphs and applications. Universitat de Barcelona, 2019. 39 p.

5. **Jurkiewicz P.** Empirical Time Complexity of Generic Dijkstra Algorithm / P. Jurkiewicz, E. Biernacka, J. Domżał, R. Wójcik // IFIP/IEEE International Symposium on Integrated Network Management. France: Bordeaux, 2021. pp. 594–598. DOI: 10.48550/arXiv.2006.06062

6. **Khemani B., Patil S., Kotecha K. et al.** A review of graph neural networks: concepts, architectures, techniques, challenges, datasets, applications, and future directions [Электронный ресурс] // Journal of Big Data. 2024. Vol. 11, ID: 18. DOI: 10.1186/s40537-023-00876-4 (дата обращения: 12.01.2025).

7. **Скрыпник О.Н.** Алгоритмы оптимизации траекторий воздушных судов при гибкой маршрутизации / О.Н. Скрыпник, Е.Е. Нечаев, Н.Г. Арефьева, Р.О. Арефьев // Научный вестник МГТУ ГА. 2019. Т. 22, № 5, С. 19–31. DOI: 10.26467/2079-0619-2019-22-5-19-31

8. **Нурлыбаев М.А., Алмазхан Н.А.** Применение алгоритмов поиска пути для контроля беспилотных летательных аппаратов аэродромного базирования для предотвращения столкновений // Энергетика, управление и автоматизация: инновационные решения проблем: материалы II Всероссийской научно-практической конференции обучающихся и преподавателей. Санкт-Петербург, 22 декабря, 2022. СПб.: ВШТЭ СПбГУПТД, 2023. С. 23–26.

9. **Zhang H., Tao Y., Zhu W.** Global path planning of unmanned surface vehicle based on improved a-star algorithm [Электронный ресурс] // Sensors. 2023. Vol. 23, iss. 14. ID: 6647. DOI: 10.3390/s23146647 (дата обращения: 12.01.2025).

10. **Chatzisavvas A., Dossis M., Dasygenis M.** Optimizing mobile robot navigation based on a-star algorithm for obstacle avoidance in smart agriculture [Электронный ресурс] // Electronics. 2024. Vol. 13, iss. 11. ID: 2057. DOI: 10.3390/electronics13112057 (дата обращения: 12.01.2025).

11. **Kabir R.** Enhanced robot motion block of a-star algorithm for robotic path planning / R. Kabir, Y. Watanobe, M.R. Islam, K. Naruse [Электронный ресурс] // Sensors. 2024. Vol. 24, iss. 5. ID: 1422. DOI: 10.3390/s24051422 (дата обращения: 12.01.2025).

12. **Farid G.** Modified A-Star approach to plan the motion of a quadrotor UAV in Three-Dimensional Obstacle-Cluttered Environment / G. Farid, S. Cocuzza, T. Younas, A.A. Razzaqi, W.A. Wattoo, F. Cannella, H. Mo [Электронный ресурс] // Applied Sciences. 2022. Vol. 12, iss. 12. ID: 5791. DOI: 10.3390/app12125791 (дата обращения: 12.01.2025).

13. **Yoo Y.D., Moon J.H.** Study on A-Star algorithm-based 3D path optimization method considering density of obstacles [Электронный ресурс] // Aerospace. 2025. Vol. 12, iss. 2. ID: 85. DOI: 10.3390/aerospace12020085 (дата обращения: 12.01.2025).

14. **Нгуен Н.Х.К., Нечаев В.Н., Малыгин В.П.** Математическая модель и применение алгоритма A-star для оптимизации маршрутов ОВД в воздушном пространстве районного диспетчерского центра Хошимина // Crede Experto: транспорт, общество, образование, язык. 2025. № 1. С. 64–85. DOI: 10.51955/2312-1327_2025_1_64

15. **Van Rossum G., Drake F.L.** Python 3 Reference Manual. CreateSpace, Scotts Valley, CA, USA, 2009. 242 p.

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