ISSN 1648-7788 / eISSN 1822-4180

VILNIUS TECH
Vilnius Gediminas Technical University

AVIATION

2025
Volume 29
Issue 2
Pages 104–117
https://doi.org/10.3846/aviation.2025.23635

OPTIMIZING AIRWAY NETWORK EFFICIENCY WITH THE A-STAR ALGORITHM: A CASE STUDY OF HO CHI MINH FIR

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Article History:
- received 24 September 2024
- accepted 3 February 2025

Abstract. Airway network optimization is crucial for airspace planning, addressing high traffic density and alleviating pressure on Air Traffic Controllers. With the rapid growth of civil aviation, overloaded airways and congestion have become significant challenges. Vietnam's air transport sector plays a vital role in economic and social development, enhancing connectivity across the Asia-Pacific region. Additionally, Vietnam has led the global recovery of domestic aviation post-COVID-19 and, as the world's fifth fastest-growing aviation market, is expected to reach 150 million air transport passengers by 2035. This highlights Vietnam's dynamic growth and strategic importance within global aviation. However, this rapid expansion has exposed vulnerabilities in Vietnam's airways, particularly within the Ho Chi Minh Flight Information Region (HCM FIR), where congestion and overload are evident, especially during adverse weather. To address these challenges, this study proposes optimizing the airway network in 2D space using the A-star algorithm, tailored for the HCM FIR. This approach aims to reduce flight distances, improve operational efficiency, and ease ATC workloads, marking a critical step toward enhancing Vietnam's airspace management system.

Keywords: airway network optimization, 2D space, Ho Chi Minh Flight Information Region, A-star algorithm, flight distance, prohibited and restricted areas, airspace.

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Notations

Abbreviations

ADS-B – automatic dependent surveillance-broadcast;
AIP – aeronautical information publication;
ATC – air traffic control;
ATCs – air traffic controller;
ATM – air traffic management;
DME – distance measuring equipment;
GPS – global positioning system;
HCM FIR – Ho Chi Minh Flight Information Region;
NDB – non-directional beacon;
PBN – performance-based navigation;
RNAV – area navigation;
VATM – Vietnam Air Traffic Management Corporation.
VOR – VHF omnidirectional radio range.

1. Introduction

The aviation industry, which originated in the early twentieth century and boasted a history spanning over a century, has consistently evolved in response to global dynamics. As shown in the Quarterly Air Transport Chartbook (International Air Transport Association [IATA], 2023), through continuous innovation, the aviation industry has reinforced its position as a key sector in global transportation. Following the gradual recovery from the COVID-19 pandemic, it demonstrated significant growth, evidenced by an increase in the number of passengers and the volume of goods transported. The intensifying competition among airlines has introduced numerous challenges, particularly in the realm of optimizing the airway network. This issue has garnered substantial attention, prompting the establishment of Air traffic management agencies and the application of various methods and algorithms for the design and organization of airway networks. Pursuing more optimal airways and trajectories is increasingly becoming a focal point within the international aviation industry, a trend that is evident in countries and regions globally, including Vietnam.

The aviation sector in Vietnam is primarily structured around three essential elements: ATM, airport management, and airline operations. The principal function of ATM is to foster the development of the aviation sector while ensuring security and safety, with the airway network serving as a fundamental component of ATM. Constructing an airway network that adheres to the triad of "safety, effectiveness, and efficiency" is essential for enhancing ATC capabilities and ensuring flight safety. Moreover, an efficient airway system can significantly contribute to economic and tourism development and foster strong diplomatic relationships between Vietnam and the global community.

Nevertheless, Vietnam's aviation system faces significant challenges due to limitations in funding, facilities, and infrastructure. PBN has been increasingly adopted in certain segments of Vietnam's airway network, offering enhanced flexibility and efficiency in route design. However, the predominant approach to airway establishment in the country remains grounded in traditional methods, relying on the interconnection of ground-based navigation stations. This conventional system presents significant limitations, including suboptimal route distances and reduced adaptability. Furthermore, the reliance on terrestrial navigation infrastructure poses considerable challenges in remote or oceanic areas, where such infrastructure is sparse or absent. The continuous growth in air traffic is pushing conventional navigation systems to their limits, necessitating the development of alternative solutions with enhanced capacity. Various modern approaches, such as Air Traffic Flow Management or Flexible Use of Airspace, have been adopted at Vietnam to enhance capacity and mitigate congestion in airspace and airways. Despite these efforts, the issue of congestion remains unresolved. Therefore, it is crucial to explore new scientific approaches to further enhance capacity and reduce airspace congestion. Optimization algorithms, facilitated by advancements in computer science, represent a promising method for addressing these challenges. Globally, numerous studies have explored optimization algorithms as solutions to these issues. This was discussed in detail by Skrypnik et al. (2019), who developed algorithms for aircraft track optimization in flexible routing, utilizing satellite navigation systems to enhance flight path accuracy and efficiency. The topic was further explored by Emani et al. (2022), who focused on optimizing route networks in Dakar airspace through surface navigation, employing integer linear programming and the Dijkstra algorithm to identify optimal routes. The impact of air traffic flow management strategies on airline costs was analyzed by Maristany de las Casas et al. (2021), highlighting the importance of efficient routing in cost reduction. Additionally, Lee et al. (2023) examined airspace designs and operations for Unmanned Aircraft Systems traffic management at low altitudes, emphasizing the need for optimized airspace structures. Furthermore, the complexities in trajectory optimization were underscored by Neretin et al. (2022), who analyzed human interaction and weather effects on aircraft trajectory prediction via artificial intelligence. The studies mentioned above have provided significant motivation and demonstrated the effectiveness of applying optimization algorithms to the design of airway systems. However, to the best of our knowledge, no existing research has comprehensively designed an entire airway network while accounting for real-world constraints. This highlights an important research gap: the need to develop an optimization model capable of addressing the complexity of designing an entire network under practical constraints.

Building upon the success of these studies, which underscore the potential of optimization algorithms in identifying optimal routes for ATM systems, it is crucial to investigate their adaptability to diverse national contexts, especially those characterized by distinct operational and regulatory constraints. Most existing studies either focus on general applications or are region-specific, offering limited insight into addressing unique challenges posed by individual airspaces. This gap is especially evident in Vietnam, where no research has yet explored the application of optimization algorithms to its airway network. This presents a significant opportunity to improve ATM and airway design within the HCM FIR. Such an endeavor could address local issues in Vietnam's aviation system, including limited navigation infrastructure and rising air traffic congestion, while also offering a robust and generalizable framework applicable to other global airspaces.

Traditional methods like Dijkstra's algorithm, Bellman-Ford algorithm, and integer linear programming, though commonly used in network optimization, have notable limitations in dynamic environments such as aviation. While Dijkstra's algorithm efficiently computes static shortest paths, it struggles with dynamic constraints like restricted airspaces and weather changes, with runtime increasing exponentially with graph size (Jurkiewicz et al., 2021; Shahi et al., 2020). Similarly, Bellman-Ford algorithm, though capable of handling graphs with negative edge weights, has a slow convergence time and high memory usage (Nazarifard & Bahrepour, 2017). Furthermore, its ability to process negative edge weights is irrelevant in aviation, where all edge weights (e.g., distance, time) are non-negative. Integer linear programming, though effective for multi-objective optimization, requires substantial computational resources, making it unsuitable for real-time applications (Alves & Clímaco, 2008; Altamiranda, 2019).

The A-star algorithm emerges as a promising solution due to its ability to handle the complex and dynamic constraints inherent in the aviation environment. By integrating heuristic methods, A-star strikes a balance between computational efficiency and solution quality, enabling it to dynamically adapt to constraints like restricted airspaces or weather disruptions. Leveraging A-star's capabilities can address pressing challenges in aviation planning, offering a more advanced and scalable alternative to traditional approaches while setting the stage for advancements in airspace optimization tailored to Vietnam's specific needs and beyond.

This paper introduces an innovative approach to optimize airway networks in the HCM FIR by employing the A-star algorithm. The innovation of this study lies in its adaptation of the A-star algorithm to address aviation-specific challenges, including minimizing flight distances while considering constraints such as navigation system capacity, restricted and prohibited airspaces, and designated flight corridors. A significant contribution of this work is the development of a program implemented in Python, leveraging the language's extensive libraries and straightforward syntax to facilitate the A-star algorithm's application in aviation planning. The program uses advanced data structures such as priority queues and dictionaries to efficiently manage open and closed sets of nodes, ensuring scalability for real-world applications. The research further validates the algorithm through simulations and case studies within the HCM FIR, demonstrating its capability to enhance airway efficiency and reduce congestion. In the proposed model, the A-star algorithm successfully identified optimal flight paths, achieving a reduction in average flight distances by 3–7% while alleviating congestion in high-traffic airspace sectors. Furthermore, the designed airways can be configured, if desired, to completely avoid restricted and prohibited areas, providing flexibility in airway planning.

The contributions of this study are twofold, reflecting both theoretical advancements and practical applications. Firstly, it presents a robust framework tailored to address airway optimization challenges specific to Vietnam's aviation system, incorporating aviation-specific constraints into the A-star algorithm. This innovative approach not only enhances the algorithm's applicability in ATM but also establishes a foundation for future advancements in navigation technologies. Secondly, the research outcomes have far-reaching implications for real-world ATM operations and advanced simulation environments, offering pathways to more efficient and safer aviation practices.

In addition to its technical contributions, the study underscores significant economic and environmental benefits. By optimizing airways, it achieves fuel cost savings and reduces greenhouse gas emissions, aligning with global trends toward greener aviation practices. Furthermore, this research paves the way for integrating cutting-edge technologies, such as artificial intelligence and advanced optimization algorithms, into ATM systems. Such integration holds the potential to transform the operational capacity and efficiency of airspace management, benefiting not only Vietnam's aviation system but also the broader global aviation community.

2. Presentation of the HCM FIR

The rapid development of the aviation industry coupled with the increasing volume of flights, raises issues concerning airspace and the optimization of airspace capacity, contributing to ensuring safety, efficiency, cost-effectiveness, and environmental sustainability of an ATM system. Particularly in the Asia-Pacific region, demand for domestic and international travel by air is growing, becoming one of the fastest growing regions in the world (Asian Aviation, 2024). Vietnam is situated as a gateway for aviation commerce in the region, and Vietnam's FIR has high flight densities and growth rates globally (averaging 17% annu-

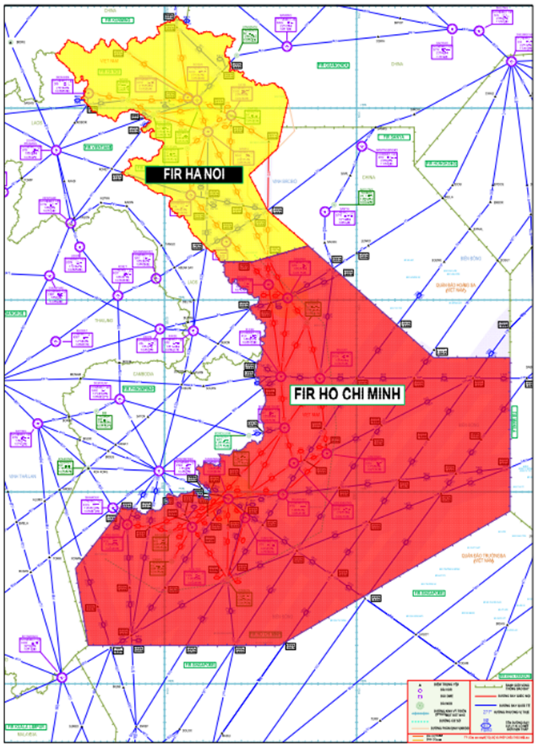

Figure 1. The HCM FIR (Vietnam Aeronautical Information Centre, 2021)

ally). Vietnam's airspace, managed by the VATM, accommodates over 2,000 flights daily (Vietnam Air Traffic Management Corporation, 2017), with the HCM FIR serving as a key area. Specifically, the North-South corridor is one of the world's ten busiest airways (OAG Aviation Worldwide Limited, 2024), with nearly 700 flights per day, accounting for approximately 35% of Vietnam's total air traffic network (Vietnam Air Traffic Management Corporation, 2017).

Vietnam is divided into two FIRs: the Hanoi FIR and the Ho Chi Minh FIR, as illustrated in Figure 1. The HCM FIR extends from the 17th parallel to the 7th latitude north, spanning the width between the Vietnam-Laos and Vietnam - Cambodia borders, and reaching as far as 114 degrees east longitude. This airspace encompasses the southern region of Vietnam and a significant portion of the East Sea, as depicted in Figure 1. Currently, within the HCM FIR, the Vietnam aviation industry operates 21 international routes and 21 domestic routes (Vietnam Air Traffic Management Corporation, 2019). In particular, this FIR also serves as a critical intersection for regional routes, including 20 airways such as A1, A470, A901, B583, R214, R471, R468, and others. These flight routes within the HCM FIR connect major points such as Ho Chi Minh City, Phan Thiet, Phu Cat, Con Son, Da Nang, Bangkok, the Philippines, Singapore, Hong Kong, etc. Based on the characteristics of flight operations, airway networks, communication systems, navigation, and surveillance infrastructure, the HCM FIR is divided into 7 sectors. Within these sectors, there are 2 prohibited areas, 9 restricted areas, and 33 danger areas (Vietnam Air Traffic Management Corporation, 2024).

3. Optimizing the airway network using the A-star algorithm

Optimizing flight trajectories and airways aims to identify the most efficient paths for aircraft, minimizing fuel consumption, reducing flight time, and enhancing safety. This process facilitates the coordination and optimization of air traffic flow within controlled airspace, enabling the creation of flight plans that maximize efficiency in terms of both time and fuel usage. Additionally, real-time data and predictive adjustments help avoid danger, restricted or prohibited areas. Several algorithms are currently employed to optimize flight trajectories and airways, including graph theory (Rani & Owais, 2021; Farrahi et al., 2017), which is used to model networks of possible flight paths and solve discrete optimization problems with superior performance; optimal control theory (Su et al., 2024; Gopalakrishnan & Balakrishnan, 2021), which identifies the best control strategies to minimize fuel consumption and flight time; and genetic algorithms (Dancila & Botez, 2021; Li et al., 2020), which simulate evolutionary processes to search for the most efficient airways. These methods collectively provide effective solutions to complex routing challenges in aviation.

In optimizing an airway network, each airway is treated as an independent object. It will have a feasible solution with a certain set of arcs obtained from an initial set of arcs. Graph theory methods are thus preferred for addressing the optimization of airway networks, as they provide an effective framework for modeling and solving complex airway structures.

Graph theory is a branch of mathematics that examines graphs, mathematical structures used to represent relationships between objects. A graph consists of vertices (nodes) connected by edges (links). Graphs can be undirected, where edges connect vertices symmetrically, or directed, where edges have a defined direction between vertices. This field is essential in discrete mathematics, offering versatile tools for modeling, analyzing, and solving problems in various fields. Graph theory's core concepts and algorithms provide valuable insights into understanding complex systems defined by connections and interactions.

The A-star algorithm, a cornerstone in graph theory, was first introduced as Algorithm A by Hart et al. (1968). Renowned for its efficiency, A-star synergizes the strengths of uniform cost search and greedy best-first search, A-star evaluates nodes using $f(n) = g(n) + h(n)$, where $g(n)$ is the cost from the start and $h(n)$ is a heuristic estimate to the goal. The heuristic, serving as an estimation function predicting the cost of reaching the target from each evaluated node according to the research given by Beeker (2004), is key to A-star's effectiveness. Its admissibility, ensuring it never overestimates the actual cost, guarantees that A-star always finds the shortest path if one exists. Balancing efficiency and accuracy, A-star is widely applied in complex network navigation and resource optimization.

The A-star algorithm is extensively applied across diverse fields due to its efficiency in determining optimal paths. In robotics, it plays a crucial role in motion planning by enabling collision-free navigation in complex environments, including autonomous vehicles managing traffic and obstacles (Liu & Zhang, 2022; Liu et al., 2021). In automated unloading systems, A-star optimizes movement paths, thereby minimizing costs and reducing packaging risks, as discussed by Auh et al. (2024). Within the realm of video games, it facilitates intelligent navigation for non-player characters (NPCs), supporting task execution and dynamic interactions with players (Candra et al., 2021). Geographic Information Systems (GIS) leverage A-star in applications such as Waze and Google Maps to optimize routes by accounting for topography and traffic conditions (Lerner et al., 2009). Furthermore, Chatzisavvas et al. (2024) wrote in full research that algorithm enhances drone pathfinding capabilities, aiding obstacle avoidance in agricultural and industrial operations.

In aviation, the A-star algorithm plays a crucial role in optimizing flight trajectories, achieving objectives such as minimizing flight distance, lowering fuel consumption, and alleviating congestion in high-traffic areas (Li et al., 2023; Mehmood et al., 2024). Similarly, logistics companies like UPS and FedEx utilize the A-star algorithm to streamline delivery route planning and improve overall operational efficiency, as thoroughly discussed by Taniguchi et al. (2001). In urban planning, the algorithm is applied in simulations to model traffic flows and develop efficient public transport systems, supporting the design of smart city infrastructure (Zhou et al., 2020).

Recent advancements in the A-star algorithm focus on constrained pathfinding, balancing multiple objectives while adhering to specific constraints such as mandatory or restricted waypoints, as thoroughly discussed by Xu et al. (2024). Researchers are enhancing its scalability and efficiency through dynamic heuristics that adapt to real-time data. In robotics and autonomous vehicles, hybrid A-star models integrate machine learning to improve heuristic accuracy and decision-making under uncertainty. For multi-agent systems, advanced versions of A-star enable collaborative pathfinding in dense and dynamic environments. These developments highlight A-star's evolution from a reliable tool into a versatile framework for addressing emerging challenges in modern computational systems.

The A-star algorithm, as demonstrated across diverse applications, showcases its profound influence and remarkable efficiency. Its flexibility and capability to optimize complex pathfinding and decision-making challenges have made it indispensable in numerous industries. This underscores its versatility and reaffirms its foundational role in tackling modern challenges, from automation to intelligent systems, paving the way for the advancement of cutting-edge technologies.

4. The airway network optimization model in HCM FIR

4.1. The objective function and data input

The proposed model utilizes the A-star algorithm with the primary objective of optimizing the airway from the starting point to the endpoint in terms of distance, adhering to the optimization problem constraints applied within the airspace. The objective function of the proposed model is expressed as follows:

$$D = \min \sum_{i=0}^{m-1} d_{i,i+1}^{m}, \tag{1}$$

where: d is the distance between any two consecutive points i and i+1 on path m having m nodes. D is the total distance from the start to the end node.

This research focuses on designing an objective function to evaluate the spatial relationships between waypoints along airways connecting international, domestic airports, and over-sea points. The primary goal is to minimize fuel consumption and operational costs by prioritizing the shortest paths between waypoints. The optimization process adheres to mathematical model constraints, ensuring feasibility and efficiency within the HCM FIR. The final optimal value corresponds to the evaluation function f(n) in the A-star algorithm, combining the cost function g(n), representing accumulated cost, and the heuristic function h(n), based on Euclidean distance, to estimate the remaining cost to the destination. This approach balances computational efficiency and practical applicability.

The input data for this study, including node coordinates, airspace boundaries, and design constraints, were extracted from AIP Vietnam 2024. This ensures the accuracy and reliability of the data used in the optimization model for the HCM FIR airway network. Input data includes:

- Node Set: Geographical coordinates of airports (latitude and longitude for airports), waypoints, radio navigation stations (VOR, NDB), significant intersections (points where airways intersect), connection of nodes.
- Prohibited, danger, and restricted areas: area boundaries (coordinates and limits), area type (classified as prohibited, danger, or restricted), operating times (active periods).
- Design constraints: minimum distance between parallel airways, air traffic corridor requirements (compliance with RNAV5 and RNP10 standards).

Output data includes:

- Optimized airways: list of optimized airways, distance of each optimized airways.
- Optimized network diagram: graphical representation (map with nodes and selected arcs), selected arcs (Highlighted optimized airways).

Airways within the HCM FIR, specifically over land, utilize radio stations and reporting points positioned between airports. The determination of the shortest path is achieved by calculating the minimum distance from a specific point to its adjacent child nodes, ensuring optimal routing efficiency. The airspace is systematically divided

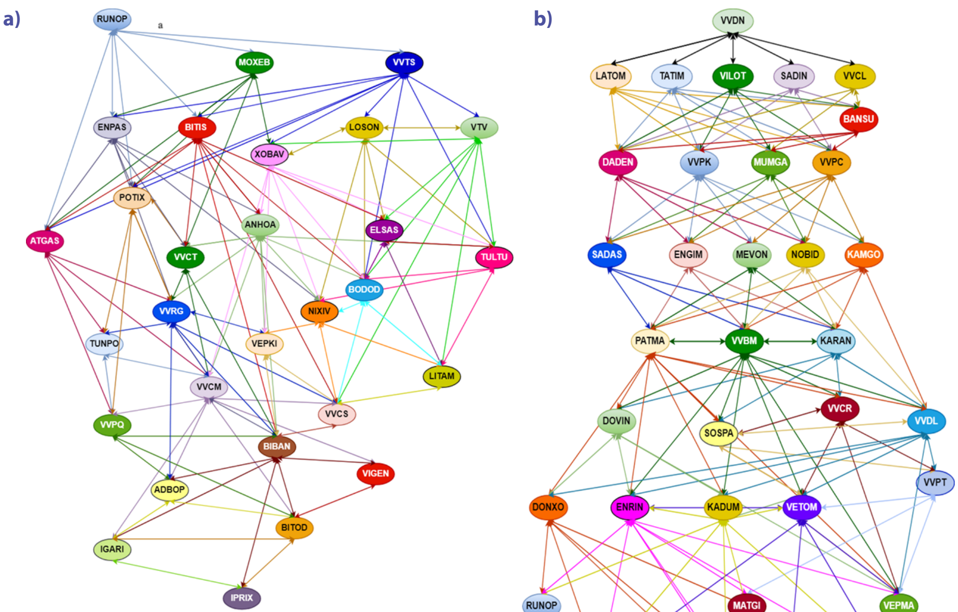

Figure 2. Relationship diagram between nodes: a – Southern land, b – Northern land

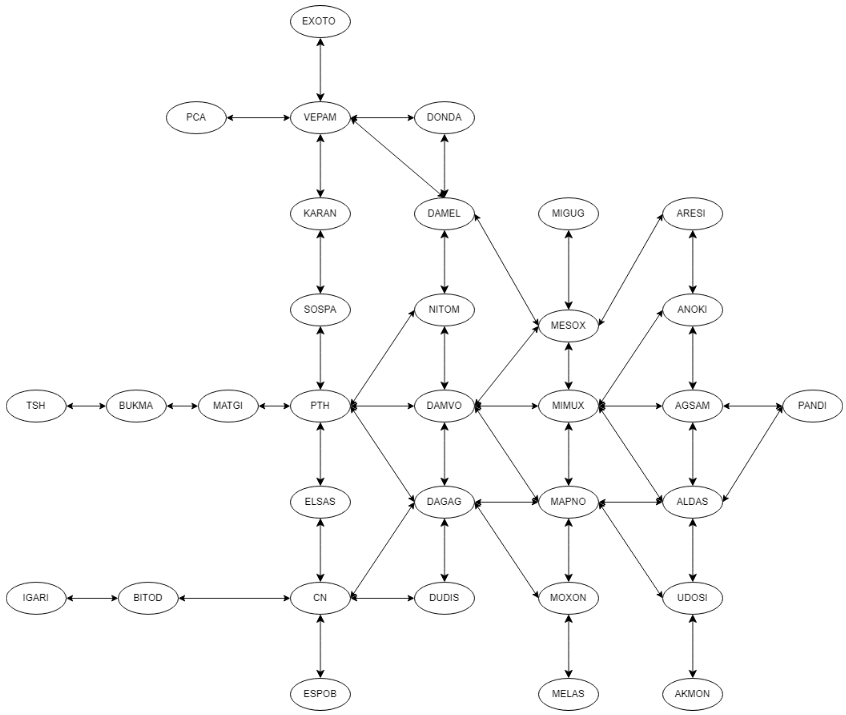

Figure 3. Relationship diagram between nodes in the oceanic airspace

into Northern and Southern sectors, with the Tan Son Nhat International Airport (VVTS) serving as both the central reference point and the boundary demarcation between these two sectors. This sectional division does not impede the analysis of airways that connect points across the boundary; instead, depending on the geographic locations of the start and end points, child nodes are evaluated dynamically either from North to South or South to North. The relationship diagram depicting the connections between nodes in the current airspace structure is presented in Figure 2. Figure 2a depicts the southern land airspace, showing the connections between navigation points (e.g., waypoints, airports, and radio navigation stations) used for airway optimization. This diagram highlights the dense network of nodes in the southern region, where high air traffic density requires careful optimization. Figure 2b focuses on the northern land airspace, outlining the node relationships in a less dense but equally critical airspace sector. It demonstrates the continuity of airways across the boundary between the northern and southern sectors.

In addition to land-based airways, oceanic airways originating from offshore reporting points are illustrated in Figure 3. This figure highlights the unique characteristics of oceanic airspace, where nodes are more widely spaced due to the vast and remote nature of the region. The diagram underscores the critical role of satellite-based navigation systems, such as GPS, in ensuring safe and efficient operations in these areas, where traditional ground-based navigation aids are sparse or entirely absent. Building airways leveraging satellite navigation systems represents a prevailing global trend, particularly in oceanic regions. Recognizing this, the authors have strategically designed and arranged nodes in these areas to align with contemporary advancements and the practical demands of the region. This approach reflects the evolving priorities of modern ATM, emphasizing innovation and adaptability to geographical challenges.

4.2. Design constraints and assumptions

In the proposed model applying the A-star algorithm for optimizing airways, the problem is to find the optimal route between navigation points. This involves selecting a set of paths such that the total travel distance is minimized compared to all other possible routes connecting one navigation point to another. The airspace structure is represented as a graph G = (N,A) where $N = \{N_0, N_1, N_2, \ldots, N_n\}$ is the is a set of nodes representing a list of input point coordinates), and $A = \{A_1, A_2, \ldots, A_k\}$ is the set of edges connecting these points. An edge in A is a straight line connecting any two points in N, and can be represented as $A(N_1,N_2)$, denoting the connection between any two nodes N_1 and N_2 and m represents the path connecting the start and end node.

The constraints applied in design models for each airway include:

- Navigation aid coverage: All navigation points and edges between consecutive points must lie within the coverage area of navigation aids to ensure the safety of aircraft passing through.

$$\forall A(i, i+1) \subseteq B^m, \tag{2}$$

where: $A(i, i+1)$: Edge between nodes i and $i+1$; B^m: Coverage area of navigation aids for airway m.

- Valid airway path: An airway m must connect the start and end points, no edges enter the start or leave the end of the airway.

$$d^m_{i_p,0} = d^m_{i_m,i_p} = 0, \quad (3)$$

where: $d^m_{i_p,0}$: Distance to enter the start point is zero; $d^m_{i_m,i_p}$: Distance to exit the end point is zero.

- Restricted Area Avoidance: Airways must not traverse dangerous, restricted, or prohibited areas. In this proposed model, we considered two prohibited areas named VVP3 and VVP4, a dangerous area named VVD32.

$$\sum S^m_k \times A^m_{i,i+1} = 0,\ A(i,i+1) \in A_m \text{ and}$$
$$segment\ A(i,i+1) \cap S^k_m = \varnothing, \quad (4)$$

where: S^m_k: Area of the restricted Area Avoidance k in the airspace structure for airway m.

- Flow conservation at each point: For any intermediate point i (excluding the start and end points), the number of incoming edges must equal the number of outgoing edges, except for the start and end node.

$$\sum_{i\in N^-(j)} O^m_{i,j} = \sum_{i\in N^+(j)} O^m_{i,j},\ m \in M,\ \forall N_m - \{0, m\}. \quad (5)$$

In addition to the aforementioned constraints, the design will also adhere to specific ICAO-prescribed standards for airway spacing, including:

- The lateral extent of the flight corridor for continental airways must fully comply with the coverage of ground-based navigation aids within the airspace structure. To be specific, the proposed model assumes RNAV5 for continental airways, with a safety flight corridor of approximately 20 nautical miles (38.52 km).
- The distance between two parallel airways established over oceans, assuming RNP10 is approximately 70 nautical miles (129.04 km).

To address the potential limitations of the A-star algorithm in fully reflecting real-world scenarios, the following assumptions were incorporated into the model:

- Navigation Infrastructure: All navigation aids (e.g., VOR, DME, GPS) are fully operational and provide consistent coverage within their respective areas.
- Airspace Characteristics: Prohibited, restricted, and danger areas are static during operations, with their boundaries and active periods clearly defined and consistent.
- Weather Conditions: Meteorological conditions are stable, and the optimization process does not account for dynamic changes, such as thunderstorms or turbulence.
- Traffic Flow: Air traffic flow and density remain within manageable limits, with no significant deviations caused by emergencies or sudden surges in demand.

These assumptions reflect the planning context of designing an optimal airway network, typically undertaken during the management planning stage. At this stage, adverse weather conditions and equipment failures are generally not accounted for. Similarly, challenges related to prohibited or restricted areas can often be resolved through coordination between military and civil aviation authorities. While these assumptions simplify the complexities of real-world scenarios, they ensure that the results of the selected optimal air route network remain largely unaffected by occasional deviations or unforeseen events.

By establishing a controlled framework, this model strikes a balance between theoretical optimization and practical applicability within the HCM FIR. Simplifying complex real-world dynamics enables analysis and solution development using established optimization tools and methodologies. Future research could address the model's abstractions by incorporating variable factors such as meteorological changes, dynamic air traffic patterns, and real-time operational constraints. Such advancements would enhance the model's accuracy and reliability, ensuring its robustness in addressing the dynamic challenges of modern aviation.

5. Results

The research team utilized the A-star algorithm, implemented in Python (Figure 4) and integrated with the Plotly library within the Google Colab environment, to determine optimal airways that satisfy the defined design constraints. Python is a versatile programming language widely favored in scientific research for its simplicity, extensive libraries, and robust community support. Developed by Van Rossum and Drake (2009) with a focus on readability, Python facilitates efficient data analysis, visualization, machine learning, and computational modeling across diverse scientific disciplines. Python's broad applicability spans fields like physics, biology, chemistry, and engineering, where it is used for simulations, modeling, and data-driven research. Supported by a large and active community, Python continues to drive scientific innovation and discovery worldwide.

To satisfy the constraint that the airway must not pass through restricted or prohibited areas, these area will be defined geometrically using polygons. The nodes and arcs forming the airway will then be analyzed for potential intersections. If any node or arc is found to violate this constraint by penetrating these zones, it should be removed from the airway (as illustrated in Figure 5).

Since the model incorporates additional constraints related to allowing airways to traverse restricted or prohibited areas, the programming outcomes are classified into two categories: those that adhere to the constraints by avoiding restricted or prohibited areas, and those that do not conform to these constraints.

Figures 6 and 7 show the optimal results graphically in the two scenarios. In both categories, the results include 19 airways, corresponding to the number of airways in the input data. Table 1 presents the optimal results, including the distances and waypoint names that define the airways.

```python
def astar(start, end, nofly_areas, excluded_nodes):  2 usages
    open_set = []
    closed_set = []
    A = []
    open_set.append(start)
    while open_set:
        current = open_set[0]
        for i in range(1, len(open_set)):
            if open_set[i].f < current.f or (open_set[i].f == current.f and open_set[i].h < current.h):
                current = open_set[i]
        open_set = [node for node in open_set if node != current]
        closed_set.append(current)
        if calculate_distance(current, end) < 0.1:
            path = []
            temp = current
            while temp:
                path.append(temp)
                temp = temp.previous
            for i in A:
                i.g = 0
                i.h = 0
                i.f = 0
                i.previous = None
            return path[::-1]
        for child in current.children:
            if child in excluded_nodes:
                continue
            if is_arc_in_noflyarea(current, child, nofly_areas):
                continue
            A.append(child)
            if child not in closed_set:
                temp_g = current.g + calculate_distance(current, child)
                new_path = False
                if child in open_set:
                    if temp_g < child.g:
                        child.g = temp_g
                        new_path = True
                else:
                    child.g = temp_g
                    new_path = True
                    open_set.append(child)
                if new_path:
                    child.h = heuristic(child, end)
                    child.f = child.g + child.h
                    child.previous = current
    return None
```

Figure 4. A Python Implementation of the A-Star algorithm

```python
def is_node_in_noflyarea(node, nofly_areas):  1 usage
    point = (node.x, node.y)
    for area in nofly_areas:
        polygon_coords = [(coord["lat"], coord["lon"]) for coord in area["coords"]]
        polygon = Polygon(polygon_coords)
        if polygon.contains(Point(point)):
            return True
    return False
def is_arc_in_noflyarea(node1, node2, nofly_areas):  2 usages
    line = LineString([(node1.x, node1.y), (node2.x, node2.y)])
    for area in nofly_areas:
        polygon_coords = [(coord["lat"], coord["lon"]) for coord in area["coords"]]
        polygon = Polygon(polygon_coords)
        if line.intersects(polygon):
            return True
    return False
```

Figure 5. Code to avoid restricted or prohibited areas in pathfinding

The airways are shown passing through waypoints, with details provided on waypoint names and the distances between them. The gray and yellow circles indicate the coverage of NDB and VOR stations, respectively. Meanwhile, the blue rectangles represent the flight corridors of the airways.

It was observed that the two proposed models yield identical results for 17 out of 19 airways, with discrepancies found in the VVTS - VVCS and M768 (for further details, refer to Figures 8 and 9).

Depending on the requirements of airspace users and civil aviation authorities, the design results can be selected under two scenarios. However, the author's group chose the option that does not impose strict adherence to the constraints on establishing airways through restricted and prohibited areas for the following reasons:

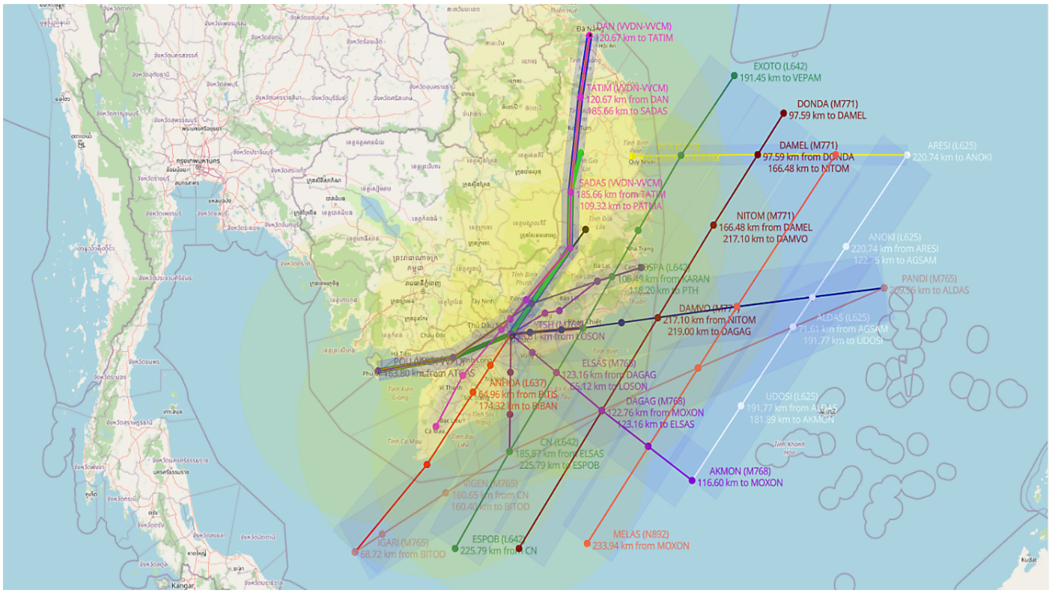

Figure 6. The airspace network that does not adhere to restricted and prohibited area constraints

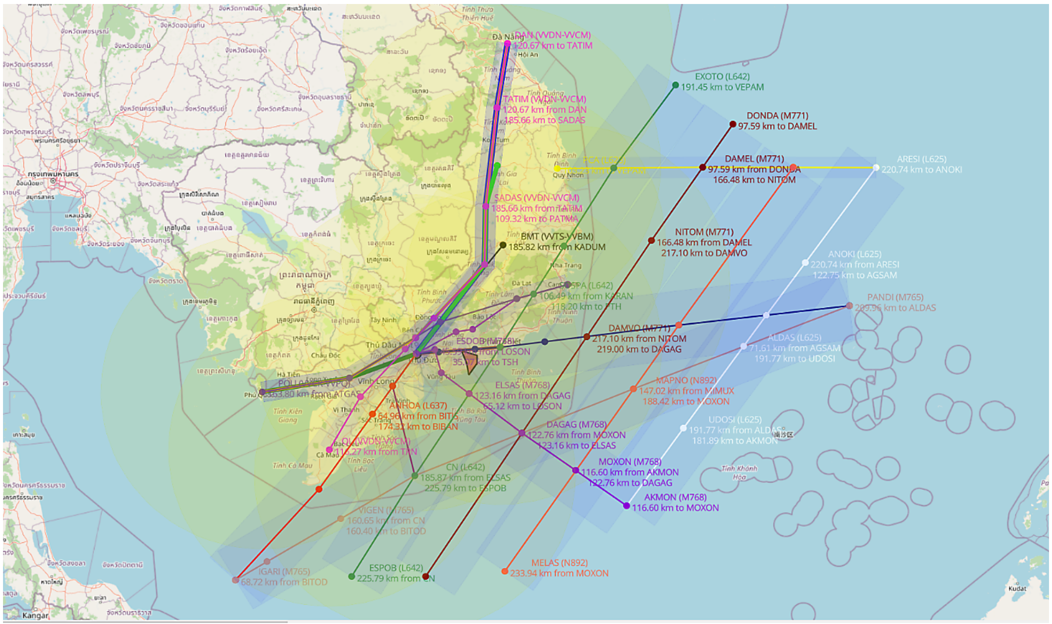

Figure 7. The airspace network that adheres to restricted or prohibited area constraints

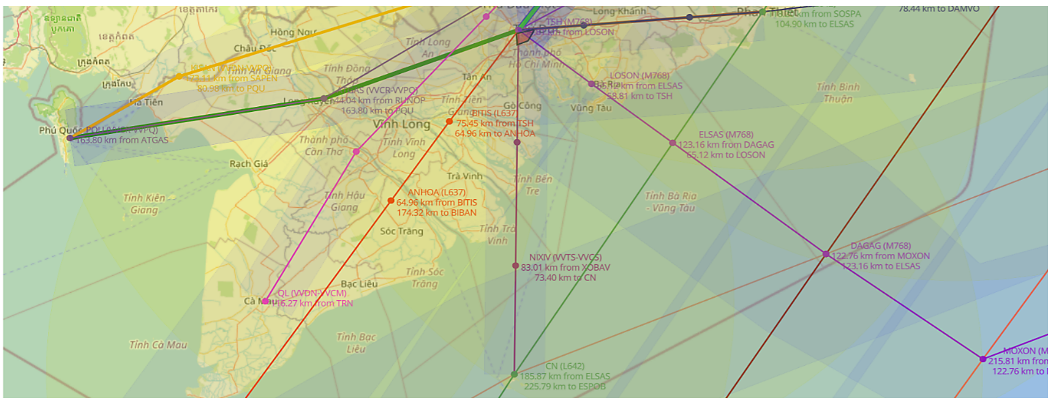

Figure 8. The summary of the results for the VVTS - VVCS and M768 airways (when not avoiding the prohibited area – VVP4)

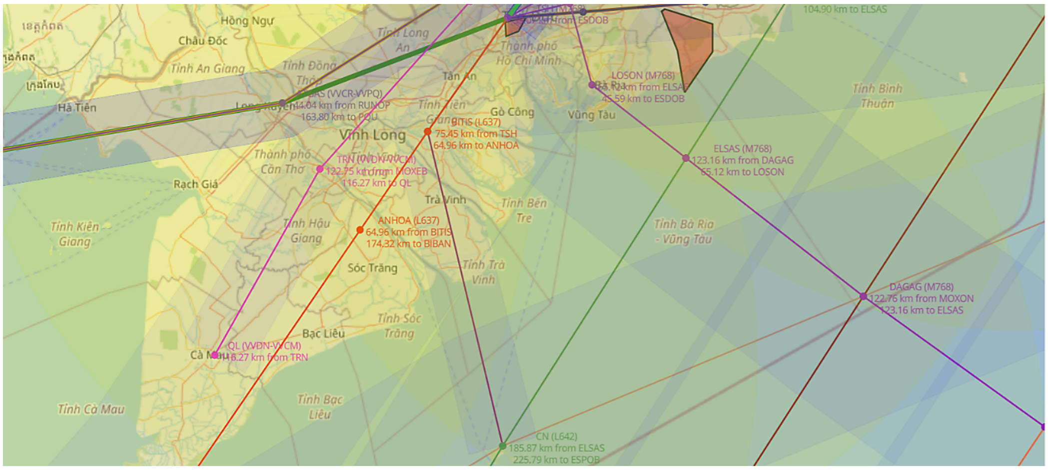

Figure 9. The summary of the results for the VVTS - VVCS and M768 airways (when avoiding the prohibited area – VVP4)

Table 1. A summary of the results obtained from the model

Airway name	Results that do not adhere to constraints avoiding restricted, prohibited areas	Results that adhere to constraints avoiding restricted, prohibited areas
VVTS - VVDN	626.32 km TSH - KADUM - PATMA - SADAS - TATIM - DAN	
VVTS - VVCR	313.23 km TSH - ENRIN - VETOM - LKH - CRA	
VVTS - VVPQ	295.85 km TSH - ATGAS - PQU	
VVTS - VVPT	155.58 km TSH - BUKMA - MATGI - PTH	
VVTS - VVBM	260.47 km TSH - KADUM - BMT	
VVTS - VVPK	399.09 km TSH - KADUM - PATMA - SADAS - PLK	
VVTS - VVCS	231.76 km TSH - XOBAV - NIXIV - CN	250.83 km TSH - BITIS - CN
VVDN - VVPQ	911.88 km DAN - TATIM - SADAS - PATMA - DONXO - RUNOP - ATGAS - PQU	
VVCR - VVPQ	608.18 km CRA - LKH - KADUM - RUNOP - ATGAS - PQU	
VVDN -VVCM	871.46 km DAN - TATIM - SADAS - PATMA - DONXO - RUNOP - MOXEB - TRN - QL	
L628	583.08 km PCA - VEPAM - DAMEL - MESOX - ARESI	
N500	806.33 km TSH - BUKMA - MATGI - PTH - AGSIS - DAMVO - MIMUX - AGSAM - PANDI	
L637	548.08 km TSH - BITIS - ANHOA - BIBAN - IGARI	
M765	1258.20 km PANDI - ALDAS - MAPNO - DAGAG - CN - BITOD - IGARI	
L642	1105.22 km EXOTO - VEPAM - KARAN - SOSPA - PTH - ELSAS - CN - ESPOB	
M771	1027.47 km DONDA - DAMEL - NITOM - DAMVO - DAGAG - DUDIS	
N892	933.63 km MESOX - MIMUX - MAPNO - MOXON - MELAS	
L625	788.76 km ARESI - ANOKI - AGSAM - ALDAS - UDOSI - AKMON	
M768	486.45 km AKMON - MOXON - DAGAG - ELSAS - LOSON - TSH	508.30 km AKMON - MOXON - DAGAG - ELSAS - LOSON - ESDOB - TSH

Compliance with Prohibited Areas: The airways VVTS - VVCS and M768 both avoid the prohibited area VVP4. Specifically, both airways have longer total distances compared to the cases that do not adhere to the restricted and prohibited area constraints. However, the prohibited area VVP4 has a vertical limit from the ground up to 3000 meters, which does not include flight levels. Since VVTS - VVCS and M768 are designed not only for domestic flights but also for overflights through the HCM FIR, the prohibited area VVP4 does not impact these operations.

Design Considerations: The departure and arrival procedures for these airways have been specifically designed to avoid the restricted or prohibited area. Thus, within the regional airspace network, choosing the airways that pass through the prohibited area for VVTS - VVCS and M768 helps to optimize the airways distance and enhance operational efficiency.

More optimized for distance and operating conditions: The result of passing through the prohibited area VVP4 leads to an increase in distance by 19.97 km (8.22%)

Table 2. Comparison of the optimal airways and the actual airways in the HCM FIR

Airway name	Actual airways	Optimal airways
VVTS - VVDN	631.43 km TSH - KADUM - PATMA - SADAS - MUMGA - BANSU - SADIN - DAD	626.32 km TSH - KADUM - PATMA - SADAS - TATIM - DAN
VVTS - VVCR	314.04 km TSH - AC - VETOM - LKH - SOSPA - CRA	313.23 km TSH - ENRIN - VETOM - LKH - CRA
VVTS - VVPQ	301.71 km TSH - ATGAS - TUNPO - PQU	295.85 km TSH - ATGAS - PQU
VVTS - VVPT	(–) Have not put into practice	155.58 km TSH - BUKMA - MATGI - PTH
VVTS - VVBM	260.66 km TSH - KADUM - PATMA - BMT	260.47 km TSH - KADUM - BMT
VVTS - VVPK	399.09 km TSH - PATMA - SADAS - PLK	399.09 km TSH - KADUM - PATMA - SADAS - PLK
VVTS - VVCS	231.76 km TSH - XOBAV - NIXIV - CN	231.76 km TSH - XOBAV - NIXIV - CN
VVDN - VVPQ	969.36 km DAN - SADIN - MUMGA - DOVIN - AC - TSN - ATGAS - TUNPO - PQU	911.88 km DAN - TATIM - SADAS - PATMA - DONXO - RUNOP - ATGAT - PQU
VVCR - VVPQ	615.74 km CRA - SOSPA - LKH - VETOM - AC - TSH – TSH - ATGAS - TUNPO - PQU	608.18 km CRA - LKH - KADUM - RUNOP - ATGAT - PQU
VVDN -VVCM	(–) Transit	871.46 km DAN - TATIM - SADAS - PATMA - DONXO - RUNOP - MOXEB - TRN - QL
PCA -ARESI (L628)	583.08 km PCA - VIMUT - VEPAM - DAMEL - MESOX - ARESI	583.08 km PCA - VEPAM - DAMEL - MESOX - ARESI
TSH - PANDI (N500)	806.33 km TSH - BUKMA - MATGI - PTH - AGSIS - DAMVO - MIMUX - AGSAM - PANDI	806.33 km TSH - BUKMA - MATGI - PTH - AGSIS - DAMVO - MIMUX - AGSAM - PANDI
TSH - IGARI (L637)	548.08 km TSH - BITIS - ANHOA - BIBAN - IGARI	548.08 km TSH - BITIS - ANHOA - BIBAN - IGARI
PANDI - IGARI (M765)	1258.20 km PANDI - ALDAS - MAPNO - DAGAG - CN - BITOD - IGARI	1258.20 km PANDI - ALDAS - MAPNO - DAGAG - CN - BITOD - IGARI
EXOTO - ESPOB (L642)	1105.22 km EXOTO - VEPAM - KARAN - SOSPA - PTH - ELSAS - CN - ESPOB	1105.22 km EXOTO - VEPAM - KARAN - SOSPA - PTH - ELSAS - CN - ESPOB
DONDA - DUDIS (M771)	1027.47 km DONDA - DAMEL - NITOM - DAMVO - DAGAG - DUDIS	1027.47 km DONDA - DAMEL - NITOM - DAMVO - DAGAG - DUDIS
MESOX - MELAS (N892)	933.63 km MESOX - MUGAN - MIMUX - MAPNO - OSIXA - MOXON - MELAS	933.63 km MESOX - MUGAN - MIMUX - MAPNO - OSIXA - MOXON - MELAS
ARESI - AKMON (L625)	788.76 km ARESI - ANOKI - AGSAM - ALDAS - UDOSI - AKMON	788.76 km ARESI - ANOKI - AGSAM - ALDAS - UDOSI - AKMON
AKMON - TSH (M768)	486.45 km AKMON - MOXON - DAGAG - ELSAS - LOSON - TSH	486.45 km AKMON - MOXON - DAGAG - ELSAS - LOSON - TSH

for the VVTS - VVCS and 21.85 km (4%) for the M768. Additionally, the aircraft must change its heading multiple times. Therefore, selecting a direct flight path, in the absence of constraints to avoid the VVP4 area, would be a more optimal solution.

To provide a more detailed and objective evaluation of the model's effectiveness, the authors compared the model's optimal airway results with the actual airways currently in use within the HCM FIR, as show in Table 2.

Based on the results obtained from the proposed model developed by the research team, the following conclusions have been made:

Firstly, the results indicate that 6 out of 19 airways have been optimized with reduced flight distances, with the largest reduction observed on the airway connecting Da Nang and Phu Quoc international airports, which decreased by 57.48 km (5.9%). These optimized airways also utilize fewer waypoints, thereby reducing coordination tasks and workload for ATC units. The remaining 13 out of 19 airways maintain the same distance as the actual airways in use.

Secondly, some newly designed airways do not pass through certain waypoints or reporting points as the current airways do. For instance, the airway from Tan Son Nhat International Airport to Da Nang International Airport bypasses the DADEM and LATOM points, opting instead for TATIM, while the airway from Tan Son Nhat International Airport to Phu Quoc International Airport bypasses TUNPO and instead utilizes ATGAS.

Thirdly, the newly designed airways are notably straighter and more direct, facilitating easier navigation for pilots and ATCs. This streamlined design helps reduce the workload for ATC in the context of increasing air traffic density and development.

Fourthly, the research team asserts that these airways are optimal when considering other factors such as PBN requirements and separation standards. The designed airways meet horizontal separation standards, and the intersections of the airways satisfy necessary conditions, thus avoiding the need for ATC to expand either of the horizontal separation criteria.

Fifthly, for the flight path from Da Nang International Airport to Ca Mau Airport and from Cam Ranh International Airport to Phu Quoc International Airport, there are currently no direct flights, with connections only available through major airports such as Tan Son Nhat or Noi Bai. The research team has proposed direct airways to save costs and time for both airlines and passengers. Additionally, flights to Phu Quoc typically transit through Cambodia's Phnom Penh FIR. The model has redesigned this airways to remain entirely within the HCM FIR, thereby avoiding flights through foreign airspace. While this redesign does not shorten the distance compared to current airways, it reduces coordination efforts with Cambodia's Phnom Penh ATC and lowers costs associated with flying through foreign airspace.

Sixth, all airways over Vietnamese land are covered by existing navigation systems (VOR, DME, GPS) and surveillance systems (radar, ADS-B). For international oceanic airways, all airways are covered by surveillance systems. In terms of navigation, some airways fall outside the coverage of the VOR and DME systems. However, in these international oceanic areas, Vietnam utilizes the GPS system for navigation, thereby ensuring the safety of aircraft operations.

In addition, the research team has also investigated the development of an airway from Tan Son Nhat International Airport to Phan Thiet Airport to support future flights once the Phan Thiet airport becomes operational.

6. Conclusions

The topic "Optimization of the Airway Network System in HCM FIR using the A-star Algorithm" represents a significant advancement in optimizing Vietnam's airway network system. The research team proposes a method using the A-star algorithm to find the optimal airways through 19 airways, with the origin points mainly being the DVOR/DME TSH stations and the destination points being the DVOR/DME, NDB stations of 70 airports, ranging from international to domestic airports within the country (within the coverage range of approximately 300 km of the navigation stations in the area). Additionally, there are airways from the mainland to the sea, combined with 4 parallel airways in the East Sea area. During the forecasting process, the research team clearly defined the project's objectives and gathered essential information about the airway network system and the locations of navigation stations. The team then developed and tailored the A-star algorithm to meet the specific requirements of the airway system, ensuring more accurate and efficient airways optimization.

Our team's contributions include demonstrating the efficiency of 19 current airways through algorithmic analysis and proposing a new, more optimal airways. A completely new network system model was developed, with a focus on applying the A-star algorithm to optimize the airway network within the HCM FIR. Testing and analysis of the results have confirmed the feasibility and effectiveness of the proposed method, showcasing its potential to improve ATM.

The model utilized in this research can be readily adapted for deployment in various airspace structures by modifying the input waypoint coordinates. This flexibility enhances its applicability to diverse locations and regions worldwide.

Author contributions

Nguyen Ngoc Hoang Quan, Vu Thi Hoai An and Le Hoang Mai for the design and development of the data analysis.

Nguyen Mai Phuong, Nguyen Thi Thuy Trang were responsible for data collection and analysis.

Nguyen Ngoc Hoang Quan, Le Thi Thu Tra and Nguyen Ngoc Nhu Y were responsible for data interpretation.

Le Hoang Mai wrote the first draft of the article and Nguyen Ngoc Hoang Quan reviewed and edited the article for the last time.

Disclosure statement

On behalf of the author group, I, Nguyen Ngoc Hoang Quan, declare that there are no competing financial, professional, or different personal interests associated with this article.

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