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A PERFORMANCE-BASED APPROACH TO AIRSPACE OPTIMIZATION USING WIND-OPTIMAL TRACKS NETWORK IN HO CHI MINH FIR

Summary. With the fast-paced development of the aviation industry, air traffic is also increasing, leading to the problem of how to control the traffic safely, and effectively, and increase the capacity of airspace. Therefore, numerous approaches

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have been taken to cope with this, including optimal models - an effective approach to addressing airspace congestion issues worldwide. However, the application of these models in Vietnam remains relatively limited. In this research, we aim to address the issue of airspace congestion and how to enhance safety and efficiency by developing an algorithm capable of automatically detecting and resolving conflicts. This is achieved by adjusting the entry time and flight level (FL) of aircraft operating within the Wind-Optimal Track Network (WOTN) model that we have developed for the Ho Chi Minh Flight Information Region (HCM FIR). The research contributes to the advancement of air traffic management (ATM) systems, particularly in the context of HCM FIR, minimizing air traffic controller (ATC) workload, and offering valuable insights for enhancing operational efficiency and safety in the airspace.

Keywords: optimization method, Ho Chi Minh Flight information region, detect and resolve conflicts, WOTN model, aircraft entry time, flight level

1. INTRODUCTION

The aviation industry is a highly dynamic field worldwide, and this trend is particularly evident in Vietnam. Considering civil aviation activities, Vietnam has experienced significant growth in the number of flights and flight frequency. In 2023, the total air transport market reached approximately 74 million passengers, a 34.5% increase compared to 2022 and 93.6% compared to 2019 (pre-Covid-19). Cargo transport also played a role, with 1.1 million tons of goods transported, representing a 9.3% decrease from 2022 but still 87.3% of the 2019 level. International passenger transport reached 32 million passengers, 1.7 times higher than in 2022 and 77% compared to 2019. The Civil Aviation Authority of Vietnam (CAAV) and Vietnamese airlines forecast this promising growth trend. The projected demand for air passenger transport in 2024 is 80 million passengers, including 38.3 million domestic passengers and 41.7 million international passengers. Evaluating the supply capacity of Vietnamese airlines, the CAAV estimates that passenger transport volume will reach 80.3 million passengers in 2024 (a 7.1% increase compared to 2023). Specifically, domestic passengers are expected to be 38.5 million (a 10.5% decrease from 2023), while international passengers will reach 41.8 million (a 30.6% increase from 2023) (Vietnam News, 2023). In the context of rapid aviation growth, ensuring safety, efficiency, and cost-effectiveness remains a priority for regulators and airlines. However, these objectives are increasingly challenged by persistent congestion and structural bottlenecks – particularly within the HCM FIR, one of the busiest and most complex airspaces in Southeast Asia. Addressing these challenges requires strategies that optimize the use of existing resources, as large-scale infrastructure expansion is often complex and costly. Among the most promising approaches is the development of models and algorithms to optimize airways. Numerous studies on optimizing flight routes or flight trajectories have been conducted globally, including works by Rosenow et al., Yan et al., Xiangyu et al., and Nguyen et al. One of the challenges is optimizing flight tracks based on existing factors, with the wind being a critical natural element. After evaluating the Wind-Optimized Trajectory Network (WOTN) system applied to the North Atlantic region, we conducted research on the applicability of the WOTN model within HCM FIR. Our study considered wind conditions and the current airspace structure, and yielded promising results regarding its applicability.

The ultimate goal is to explore the feasibility of an optimization approach for airspace resource utilization, thereby reducing congestion and workload for air traffic controllers. This research is conducted in the context of Vietnam's rapidly developing aviation management capabilities. Regulatory agencies and airlines face pressure to find effective solutions for airspace congestion, ensuring flight safety, and optimizing operational costs. Moreover, the effective deployment of the flight track optimization model and algorithms has the potential to draw aircraft from neighboring routes, thereby enhancing overall traffic throughput within the HCM FIR. Developing flight path optimization models and collision resolution algorithms will yield tangible benefits, enhancing overall aviation performance and meeting the country's economic and social development needs.

2. INTRODUCTION TO HCM FIR

The HCM FIR, formerly known as the Saigon FIR before 1975, was established at the 1959 Regional Air Navigation Meeting in Rome. Following 1975, portions of the FIR were temporarily managed by Hong Kong, Bangkok, and Singapore, until full control was returned to Vietnam on December 8, 1994. Covering a vast area over Vietnam and the East Sea, and bordered by Laos and Cambodia, the HCM FIR faces mounting challenges in managing rising air traffic volumes. In 2023, air traffic within the region rebounded to pre-pandemic levels, with approximately 1,000 flights per day during peak periods, including 600 overflights, driven by a 41.8% surge in passenger demand. However, infrastructure and air traffic service (ATS) capacity have not kept pace, leading to congestion and delays, especially during peak hours or adverse weather. The current airspace design, characterized by overlapping routes and frequent intersections, further exacerbates in-flight conflict risks, particularly during altitude transitions (Figure 1). Notably, the Hanoi-Ho Chi Minh City route ranked as the fourth busiest globally in 2024, with 10.6 million seats (OAG, 2024).

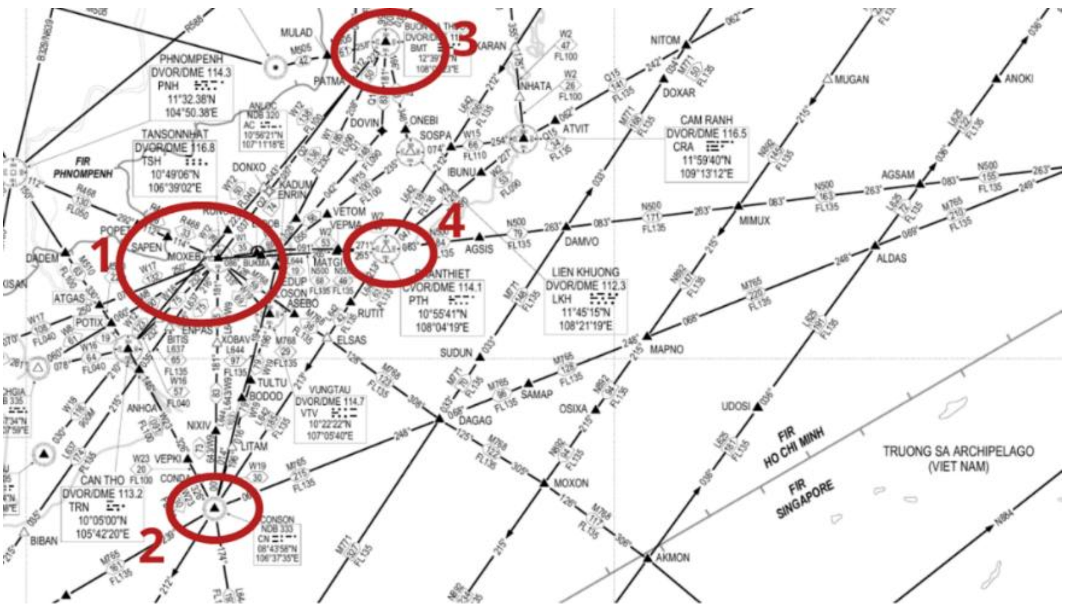

Fig. 1. Flight routes structure and complex airway intersections in HCM FIR

The congestion is further complicated by the FIR's complex airspace structure, particularly at critical intersections like BMT. Military activities and adverse weather conditions also contribute to delays, with heavy rainfall and strong winds during the rainy season (May to December) exacerbating the problem. Military flights at military airports such as Bien Hoa Air Base, or at dual-use airports like Cam Ranh, may require civilian flights to alter their routes or schedules to avoid these airport areas. This factor reduces the optimization of airspace capacity for civilian purposes. Additionally, flight operations must be designed to avoid restricted, prohibited, and dangerous areas within the FIR, further complicating the challenge, described in Figure 2. Despite substantial investments in infrastructure and new technologies, these challenges persist. As a result, finding more optimal solutions, including the application of airspace optimization models such as the Wind-Optimal Track Network (WOTN) in the HCM FIR, has become a top priority for Vietnam's civil aviation sector (Figure 3).

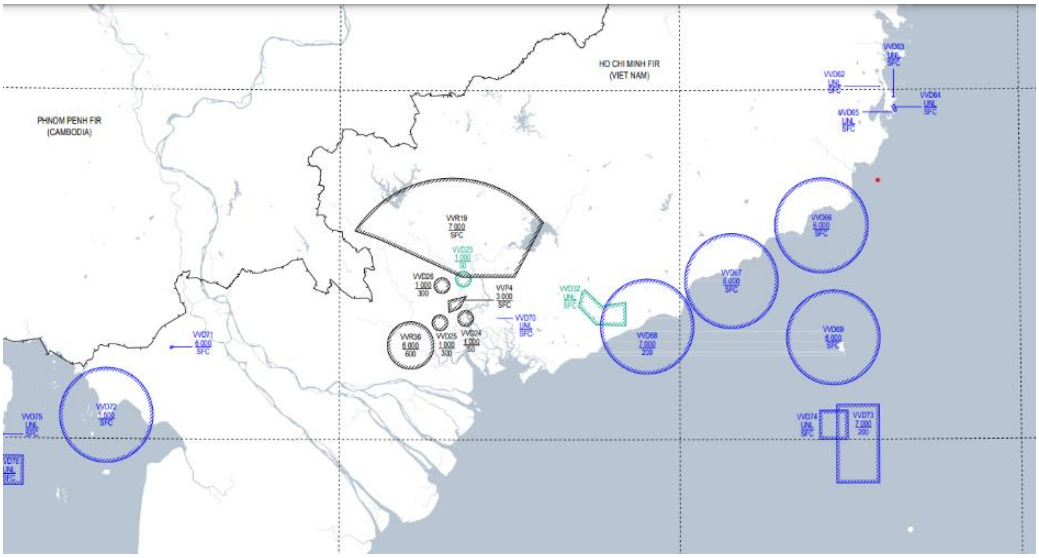

Fig. 2. Chart of prohibited, restricted, and dangerous areas in southern Vietnam

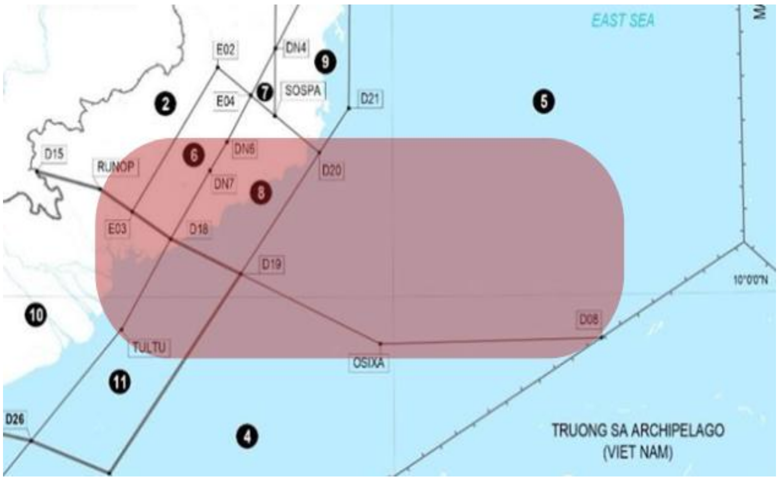

Fig. 3. The area for developing the WOTN model within HCM FIR

3. APPLICATION OF WOTN MODEL IN HCM FIR

3.1. Model construction

The Wind-Optimal Track Network (WOTN), proposed by Imen Dhief in 2018, represents an advanced route architecture tailored to leverage prevailing jet streams, effectively minimizing flight time and fuel consumption in transoceanic operations. By aligning parallel tracks with dominant wind patterns, WOTN facilitates optimal utilization of tailwinds, resulting in more efficient flight paths. Furthermore, the application of reduced separation standards, made feasible through high-fidelity ADS-B surveillance, markedly enhances airspace capacity while preserving strict safety margins. This novel design accommodates controlled re-routing within the network, allowing traffic to adapt more dynamically to variations in wind patterns or operational constraints such as contingencies. Furthermore, because WOTN spans a broader lateral corridor, it can better accommodate higher traffic volumes, alleviating congestion around conventional oceanic waypoints. Overall, the WOTN approach combines enhanced performance with improved flexibility, offering a sustainable and robust solution that advances operational efficiency and cost-effectiveness for airlines flying across oceanic airspace.

The HCM FIR encompasses a vast expanse of oceanic airspace that is frequently influenced by persistent monsoonal wind patterns (Nguyen et al., 2024). Given the dynamic and seasonally varying nature of these atmospheric flows, the implementation of the Wind-Optimal Track Network (WOTN) in this region presents a particularly advantageous solution. The continuous presence of strong prevailing winds over the South China Sea provides ideal conditions for optimizing route structures in alignment with WOTN principles. By enabling the dynamic alignment of flight tracks with dominant wind currents, the WOTN architecture can significantly enhance fuel efficiency, reduce carbon emissions, and increase overall operational predictability for flights transiting this high-traffic, weather-sensitive region. Consequently, the HCM FIR stands out as a highly suitable candidate for the application of WOTN, supporting both the region’s growing air traffic demands and broader goals for sustainable aviation.

To apply the model to the HCM FIR, five evenly spaced entry points were established along the eastern boundary of the HCM FIR, adjacent to the Singapore FIR, specifically within sectors 4 and 5. The flight tracks extend from the Tan Son Nhat DVOR/DME station to a point near ALDAS (Coordinates: 10° 48′ 59″ N, 112° 22′ 08″ E), with five corresponding exit points. This configuration forms a system of five parallel westbound tracks, each with a length of 336 nautical miles (NM). Each track comprises 13 nodes, and the lateral separation between adjacent tracks is 20 NM. The resulting system covers an airspace of approximately 336 × 80 NM^2. Nodes on the first (rightmost) flight track are numbered sequentially from 1 to 13 in the westward direction, corresponding to the direction of aircraft movement. Numbering continues consecutively across the remaining tracks, forming a total of 65 nodes. This structure defines the spatial and operational domain for model implementation (Figure 4).

Because the parallel tracks in the system are already 20 NM apart by design, the system assures lateral separation. The application of the 20 NM separation between tracks is based on the communication, navigation, and surveillance requirements for reduced oceanic separation. In terms of longitudinal separation, the system will apply separation based on time. Based on the information provided by Imen Dhief, 2018, a 3-minute vertical separation standard is considered reasonable. This standard is equivalent in terms of distance between waypoints and can be applied to the new system in Vietnam, in comparison to the 30 NM separation mentioned above, provided that all aircraft comply with RNP 4. In operation, a 3-minute separation is the time required for the fastest commercial aircraft (*Vmax = 600 kts = 10 NM/min*) to fly through the distance between the waypoints is *28 NM ≈ 30 NM*. Additionally, aircraft can be required to fly at specific Mach numbers over the ocean as part of their clearance, so the separation between two aircraft will remain constant if both use the same Mach number.

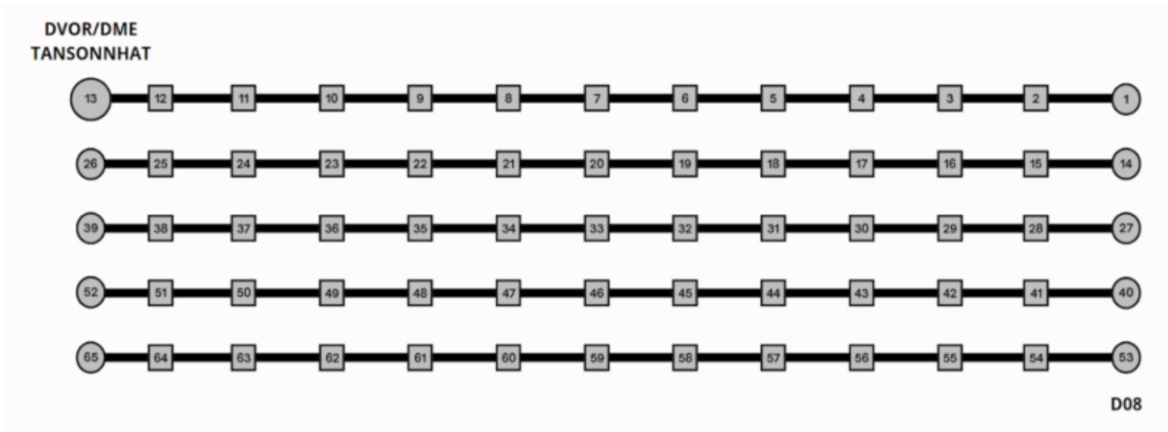

Fig. 4. Number of nodes in the system

The length of the route will be affected if the aircraft changes the flight track, requiring adjustments in the separation requirements. Considering the 2D trajectory, if the aircraft changes its flight tracks, it will require:

- Distance: $\sqrt{28^2 + 20^2} = 4\sqrt{74} \sim 34{,}5\ NM$ (1)
- Angle: $\arctan\left(\frac{20}{28}\right) \approx\ 36°$ (2)

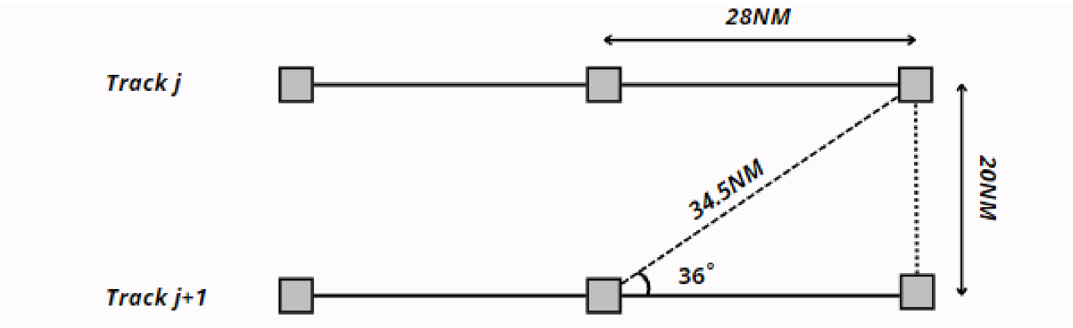

Fig. 5. Distance and angle when an aircraft changes the track

The aircraft will now need longer time to complete the remaining 4.5NM, compared to 3 minutes to fly 30NM on the same track. Considering the highest speed ($Vmax\ =\ 600\ kts\ =\ 10NM/min$), flying will take an additional 0.4 minutes. Therefore, 3.4 minutes is the new vertical separation standard if aircraft change their flight tracks.

As all flight levels in RVSM airspace are available to aircraft operating from east to west, each aircraft will comply with the vertical separation standard by performing a vertical separation of one flight level at a distance of 1000 feet. To ensure a performance difference when the aircraft climbs to a flight level, an additional 0.2 minutes will be added to the vertical separation of 3.2 minutes of flight time when an aircraft changes its flight level with other aircraft on the same track (Imen Dhief, 2018).

3.2. Comparison between the new model and existing airways in HCM FIR

To conduct the comparison, flight route N500 was selected due to its alignment with the direction of the proposed system. This route, when traversed from west to east, terminates at the TSH waypoint—consistent with the construction reference point of the system—and exhibits a flight direction closely matching that of the intended track. Flight time data for the N500 route, specifically between the PANDI and TSH waypoints, is analyzed using records obtained from the FlightAware database. The study encompasses aircraft types A20N, A320, A321, A330, and B737, with the corresponding results summarized in Table 1.

Tab. 1

Total flight time and average speed of different aircraft types on the PANDI to TSH segment

Type of aircraft	Speed (knots)	Flight time (minutes)
A20N	484	57.5
A320	472.06	60.24
A321	490	56
A330	482.67	57.33
B737	474	59

- Total average flight time of the aircraft:

$$\frac{57.5 + 50.24 + 56 + 57.33 + 59}{5} = 56.014\ (minutes) \quad (3)$$

- Average velocity from PANDI point to TSH point:

$$\frac{484 + 472.06 + 490 + 482.67 + 474}{5} = 480.546\ (knots) \quad (4)$$

The next step in the comparison is to calculate the flight times within our system. Since the system does not begin at the same point, PANDI, as the N500 flight path, we calculate the time from when the aircraft enters the HCM FIR at PANDI, until it enters the system, and continues until it reaches the end of the system. The assumed flight path is depicted in Figure 6.

To calculate the distance between two geographical coordinates based on known latitude and longitude values, the Haversine formula is applied:

$$d = 2rsin^{-1}(\sqrt{sin^2\left(\frac{\phi_2 - \phi_1}{2}\right. + \cos(\phi_1)\cos(\phi_2)sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)\Bigg)} \quad (5)$$

Including:

- d: Distance between 2 points;
- r: The radius of the earth;
- ϕ_2, ϕ_1: Latitude of 2 points;
- λ_2, λ_1: Longitude of 2 points.

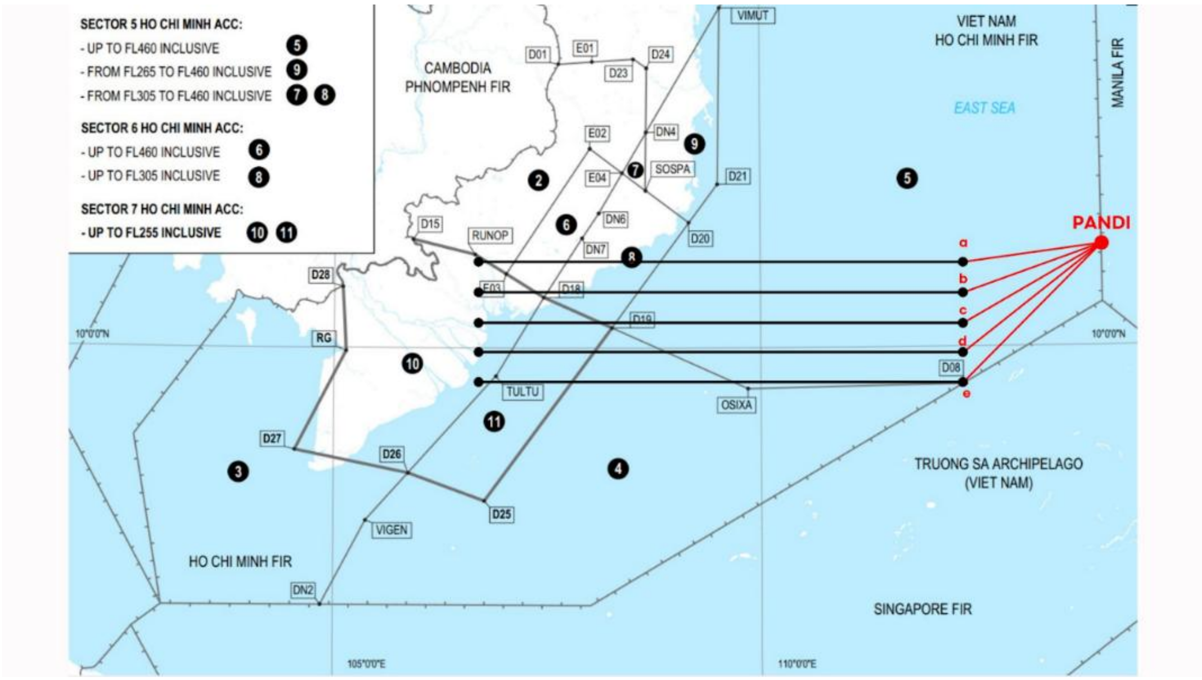

Fig. 6. Flight paths from entering HCM FIR to entering the system

Based on the above formula, we have the distance from point PANDI (11°38′06″N, 114°00′00″E) to waypoint 1 in the system (10°48′59″N, 112°22′08″E) - that is, the starting point at the line (a) in figure 9 is 190.1 km and the distance from point PANDI (11°38′06″N, 114°00′00″E) to waypoint 53 (09°33'53"N, 112°22′08″E) - that is, the starting point at line (e) in figure 9 is 290.3 km.

We have the shortest distance that the aircraft travels in the system is:

$$D_{min} = System\ length + 190.1 = 336 \times 1.852 + 190.1 = 812.372\ (km) \tag{6}$$

With the aircraft being able to change its flight path up to 4 times in the system, we can depict the longest distance an aircraft travels in the system in Figure 7.

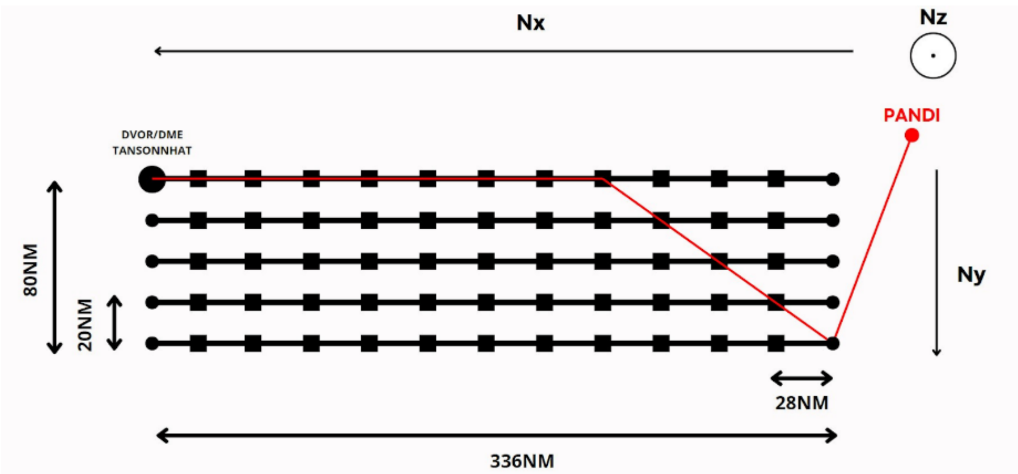

Fig. 7. The longest distance an aircraft travels in the system

With the two shortest and longest distances, combined with the average survey speed of the aircraft, we have the total average flight time of the shortest and longest in the system, respectively:

$$Total\ elapsed\ time_{min} = \frac{812.372}{480.546 \times 1.852} \approx 0.913\ (hours) = 54{,}78\ (minutes) \quad (8)$$

$$Total\ elapsed\ time_{max} = \frac{960.372}{480.546 \times 1.852} \approx 1.08\ (hours) = 64.8\ (minutes) \quad (9)$$

Based on the calculated results, the average time for an aircraft to travel through the system after entering the HCMFIR ranges between 54.78 minutes and 64.8 minutes. Compared to the average time on the N500 route, as surveyed earlier is 56.014 minutes. This indicates that the time of the proposed system can be about 2 minutes less to possibly more than 8 minutes. While this difference may not significantly impact flight time or fuel consumption, the system offers more routing options for aircraft, helping to accommodate future increases in air traffic. This, in turn, can bring economic benefits by enabling more aircraft to use Vietnam's airspace, thereby increasing revenue from ATS fees.

4. DETECTING AND RESOLVING CONFLICTS ALGORITHM

When introducing a new airway structure, it is essential to thoroughly evaluate its potential for generating airspace conflicts during operation. Conflict detection and prevention are critical to maintaining the safety and efficiency of air traffic, especially in complex or high-density regions. Existing methods for assessing conflict risk include geometric trajectory intersection analysis (Xuesong et al., 2025), temporal separation models (Roja Ezzati Amini et al., 2022), probabilistic conflict risk estimation (Jaime de la Mota et al., 2021), and optimization-based approaches (Shafi Imran, 2023). Each of these techniques offers unique strengths in identifying potential conflicts between aircraft. However, algorithm-based models have shown superior performance due to their adaptability and ability to process large-scale traffic scenarios. In this context, we propose an integrated model that combines the Simulated Annealing (Rui Chibante, 2010) and Sliding Window algorithms (Vladimir Braverman, 2016). This hybrid approach leverages the global search capability of SA and the real-time adaptability of the SW technique to enhance both the detection and mitigation of conflicts. The proposed model is designed to support strategic planning and operational validation of the new airway system, ensuring safer and more efficient route structures.

An algorithm has been developed in the WOTN model to detect conflicts that may occur at waypoints or links. At each node, conflict is detected between two successive flights if the time gap between two flights passing a node is smaller than the longitudinal separation (LON_{sep}). LON_{sep} equals 2 minutes for aircraft on the same track, and 3 minutes for aircraft changing tracks. Conflict at links is detected between two consecutive flights by comparing the sequence-in and sequence-out at a link (an aircraft is considered to be in a link when it enters the FIR node of a link and out when it enters the second node of a link). If the sequence is switched between two flights, which means the aircraft enters the link first and gets out second, the other aircraft enters the link second and gets out first. Additionally, flight level constraints are incorporated. Two flights are considered to be in conflict when they occupy the same flight level and the required longitudinal separation is violated. To resolve such conflicts, priority is given to adjusting the assigned flight level by increasing it by 1000 feet. If the conflict persists, the flight level is then decreased by 1000 feet. Should the conflict remain unresolved after these adjustments, the entry time is subsequently modified.

4.1. Objective function

With the strategies of how to detect conflicts we have mentioned above, we resolve conflict between two consecutive flights $f(x)$ and $f(x+1)$. The objective function for adjusting the entry time of the flight $f(x+1)$ is:

$$NEWENTRYTIME = ENTRYTIME + LONSEP - \left|t_{f(x)} - t_{f(x+1)}\right| \quad (10)$$

In addition, we developed a new objective function for adjusting the assigned flight level of the flight $f(x+1)$:

$$Adjusted\ flight\ level = Flight\ level\ \pm 10 \quad (11)$$

4.2. Flow chart

The algorithm begins by filtering the input flight data through each node in chronological order. Based on the resulting sequence and timing, it identifies potential conflicts by evaluating both flight levels and temporal conditions. A conflict is considered to occur when two flights share the same flight level and longitudinal separation requirements are violated. Conflict resolution is initiated by adjusting the flight levels. If this adjustment fails to resolve the conflict, temporal modifications are applied as a secondary strategy. Prior to resolution, accurate conflict detection is essential. In addition to the previously defined symbols x, y, and z, the algorithm also employs the following notations:

- a: Distance of the straight path segment in the filter section;
- b: Distance of the diagonal path segment in the filter section;
- c: Distance of the straight path segment in the parallel section;
- S: Distance traveled by the flight when considering the conflict node;
- V: Speed of the aircraft;
- n_j: Node j that the aircraft passes through;
- n_{j+1}: Node j+1 that the aircraft passes through;
- $t_{f(x)}$: Time the flight $f(x)$ passes through the node;
- $t_{f(x+1)}$: Time the flight $f(x+1)$ passes through the node;
- $FL_{f(x)}$: Flight level of the flight $f(x)$;
- $FL_{f(x+1)}$: Flight level of the flight $f(x+1)$.

Next, the algorithm resolves conflicts based on flight levels as follows.

If adjusting flight levels (Figure 9) fails to resolve a conflict, the algorithm switches to timing adjustments, addressing time-based conflicts at nodes and links. Flowcharts in Figures 10 and 11 outline the time-based resolution for nodes and links, respectively. The algorithms (Figures 8-11) are implemented in Python 3.

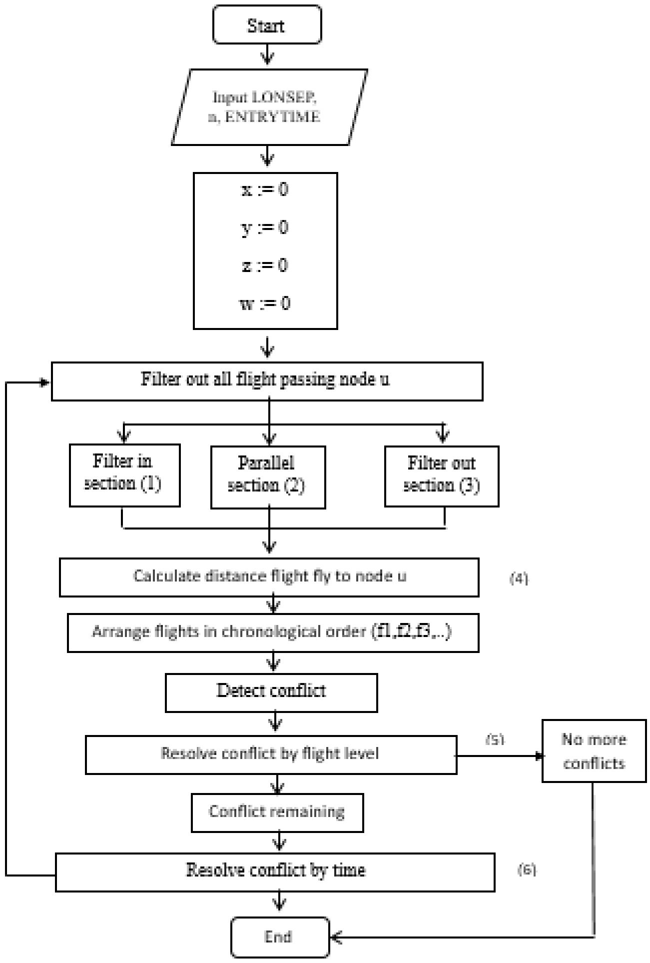

Fig. 8. Overall process flow chart

4.3. Results and Analysis

To assess the system's conflict detection and resolution performance, a dataset of 500 real-time flights was analyzed, with LON_{sep} values tested at 3, 4, 5, 6, and 7 minutes to evaluate their effects on conflict frequency and resolution approaches. Table 2 summarizes the findings, detailing total conflict flights, node and link conflicts, and resolution methods: increasing or decreasing flight level (FL) and time adjustments.

The data in Table 2 reveals several key trends. First, the model successfully detected all conflicts across all LON_{sep} values, demonstrating its robustness in identifying potential conflicts in real-time air traffic scenarios. As LON_{sep} increases from 3 to 7 minutes, the total number of conflict flights rises consistently, from 98 at 3 minutes to 138 at 7 minutes. This increase suggests that larger time separations between aircraft, while intended to enhance safety, may inadvertently lead to more frequent conflict scenarios, particularly at nodes. Specifically, conflicts at nodes rise from 50 at LON_{sep} of 3 minutes to 110 at 7 minutes, indicating that longer separation times may cause bottlenecks at critical airspace intersections, where aircraft trajectories converge.

Tab. 2

Number of conflicts by type and resolution method

LON_{sep} value	Total conflict flights	Total conflict flights at nodes	Total conflict flights at links	Total conflict flights solved by adjusting flight level		Total conflict flights solved by adjusting time
				Increasing flight level	Decreasing flight level	
3 mins	98	50	48	24	1	24
4 mins	108	64	44	30	2	22
5 mins	130	88	42	31	1	49
6 mins	133	100	33	36	1	48
7 mins	138	110	28	38	2	44

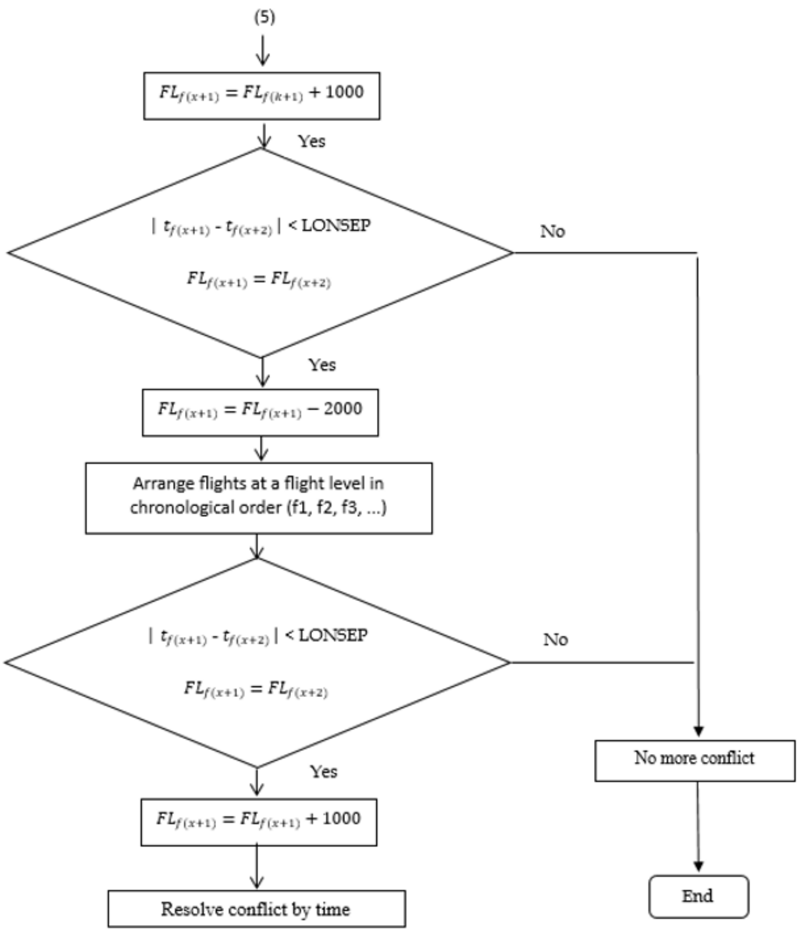

Fig. 9. Flowchart for resolving conflicts by flight level

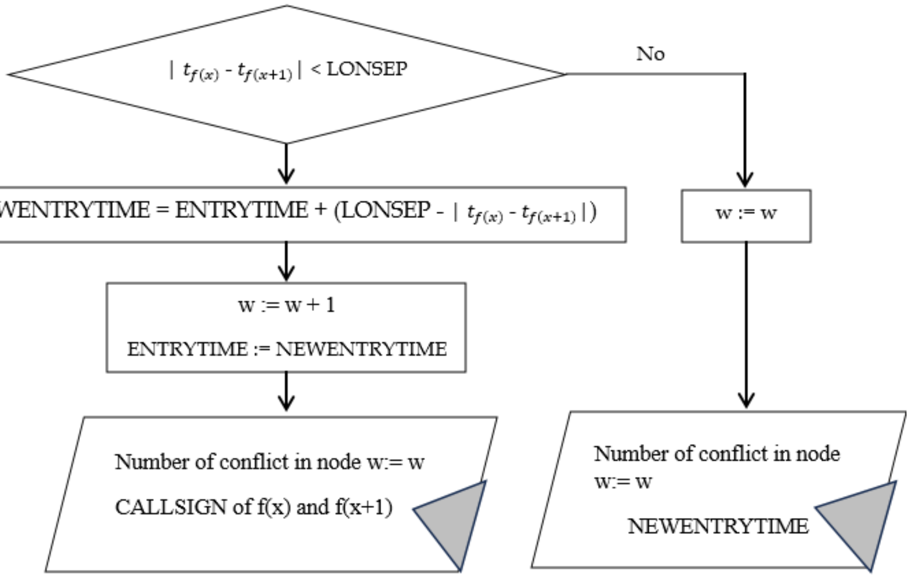

Fig. 10. Flowchart for resolving conflicts at nodes by time

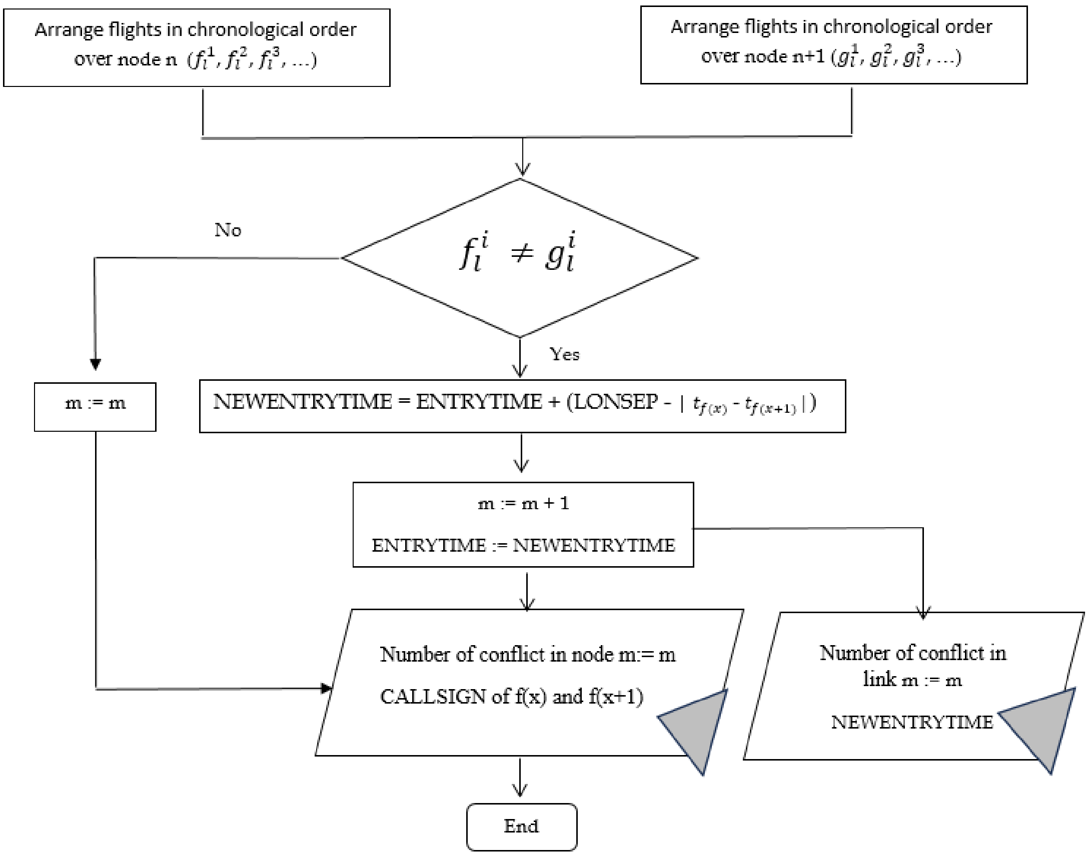

Fig. 11. Flowchart for resolving conflicts at links by time

Conversely, conflicts at links—representing interactions between aircraft along their flight paths – exhibit a different trend. While the number of conflicts at links increases modestly from 48 to 52 as LON_{sep} rises from 3 to 6 minutes, a notable decrease to 28 is observed at LON_{sep} of 7 minutes. This reduction suggests that a larger time separation effectively mitigates overtaking scenarios along flight paths, as aircraft are spaced further apart temporally. The inverse relationship between conflicts at nodes and links highlights a trade-off: while increasing LON_{sep} reduces link conflicts by providing greater temporal buffers, it exacerbates node conflicts due to the clustering of aircraft at airspace junctions.

The resolution strategies employed further illuminate the system's adaptability. Across all LON_{sep} values, the majority of conflicts are resolved by adjusting flight levels, either by increasing or decreasing them. For instance, at LON_{sep} of 3 minutes, 24 conflicts are resolved by increasing flight level, and only 1 by decreasing it, while 24 are addressed through time adjustments. As LON_{sep} increases to 7 minutes, the reliance on flight level adjustments remains dominant, with 38 conflicts resolved by increasing flight level and 2 by decreasing it, alongside 44 resolved through time adjustments. This distribution indicates that flight level adjustments are the preferred method for conflict resolution, likely due to their immediate applicability in maintaining safe separation without significantly altering flight schedules. However, the increasing use of time adjustments at higher LON_{sep} values (e.g., 44 at 7 minutes compared to 24 at 3 minutes) suggests that temporal adjustments become more critical as separation requirements grow, ensuring that aircraft entry times into the system are staggered to avoid conflicts. An important implication of these findings is the impact of LON_{sep} on airspace utilization efficiency. While a LON_{sep} of 3 minutes results in fewer conflicts (98 total) and allows for more frequent aircraft movements (approximately 3 minutes per flight), a LON_{sep} of 7 minutes, despite reducing link conflicts, leads to a higher total conflict count (138) and reduces the throughput of aircraft in the airspace. This trade-off between safety and efficiency is a critical consideration for ATM. For example, a 3-minute separation enables higher airspace utilization, which is optimal for busy air traffic scenarios, whereas a 7-minute separation, while safer in terms of link conflicts, may underutilize the airspace, potentially leading to delays and increased operational costs.

Figure 12 showcases the results of the conflict detection and resolution algorithm, detailing the adjusted entry times and flight levels determined by the system. The dataset includes key flight parameters such as aircraft names, pre-adjustment entry times, aircraft types, speeds, flight routes, and original flight levels. Flights with adjusted flight levels are highlighted in green, while those with modified entry times are marked in red for easy identification. For example, FDX928 shows a flight level adjustment from FL370 to FL360, while VJC275 entry time shifts from 10:10 to 10:14 to avoid conflicts. The algorithm demonstrates its capability to handle various types of aircraft and differing speeds effectively.

The results obtained through the model can serve as a decision-support tool for ATM authorities. By simulating different separation standards and their impact on conflict rates and resolution strategies, stakeholders can make data-driven decisions to optimize traffic flows. The flexibility of the model also allows for future integration with dynamic re-routing algorithms and machine learning-based trajectory prediction systems, which can further enhance conflict resolution efficiency.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1		Flight Numb	Entry time	djust Tim	Type	Velocity	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	Adjust FL	FL
26	24	FDX510	08:30:00	08:30:00	B787	510	53	54	42	30	31	32	33	34	9	10	11	12	13	360	360
27	25	FDX928	08:32:00	08:32:00	B787	500	1	15	29	30	31	32	33	34	35	49	63	77	78	370	360
28	26	VJC133	08:34:00	08:34:00	A320	520	27	28	42	43	57	58	59	60	74	75	76	77	78	380	370
29	27	VJC135	08:35:00	08:35:00	A330	530	66	54	42	30	31	32	33	34	35	49	63	64	65	350	350
30	28	VJC775	08:49:00	08:49:00	A320	520	27	28	29	30	44	45	46	47	48	49	63	77	78	240	240
31	29	VJC845	08:55:00	08:55:00	A321	540	40	41	29	30	44	45	46	47	48	49	63	77	78	300	300
32	30	MAS391	09:01:00	09:01:00	B738	510	1	2	3	4	5	6	7	8	9	10	11	12	13	360	360
33	31	BAV1421	09:07:00	09:07:00	A321	480	53	54	55	56	57	58	59	60	61	62	63	64	65	180	180
34	32	HVN1347	09:12:00	09:12:00	A321	320	1	15	29	30	31	32	33	34	48	62	63	64	65	160	160
35	33	CPA799	09:14:00	09:14:00	A333	520	40	54	68	69	70	71	72	73	61	62	63	64	65	380	380
36	34	SIA893	09:15:00	09:15:00	B77W	540	27	41	42	56	70	71	72	73	61	49	37	25	13	390	380
37	35	MAS377	09:17:00	09:17:00	A332	500	66	54	42	43	44	45	46	47	48	36	24	12	13	390	390
38	36	CPA719	09:20:00	09:20:00	A333	500	66	67	55	56	57	58	59	60	48	36	24	25	26	370	370
39	37	HVN503	09:36:00	09:36:00	A321	500	1	2	16	30	31	32	33	34	35	36	37	38	39	380	380
40	38	HVN131	09:41:00	09:41:00	A321	500	27	28	29	30	31	32	33	34	35	36	37	38	39	320	320
41	39	HVN933	09:45:00	09:45:00	A321	510	14	28	42	43	44	45	46	47	48	36	24	12	13	340	340
42	40	VJC305	09:51:00	09:51:00	A320	520	14	28	42	43	44	45	46	47	48	62	63	64	65	280	280
43	41	VJC173	09:57:00	09:57:00	A330	510	66	67	68	69	70	71	72	73	74	75	76	77	78	400	400
44	42	VJC631	10:01:00	10:01:00	A320	460	1	2	16	17	18	19	20	21	22	23	24	25	26	220	220
45	43	VJC245	10:04:00	10:04:00	A321	530	66	54	42	17	5	6	7	8	9	10	11	12	13	360	360
46	44	CSN553	10:07:00	10:07:00	A321	520	1	2	3	17	18	19	20	21	22	23	24	25	26	340	340
47	45	VJC275	10:10:00	10:14:00	A320	530	1	15	29	30	31	32	33	34	48	62	76	77	78	320	320
48	46	HVN1183	10:14:00	10:14:00	A321	530	40	41	42	43	44	45	46	47	48	62	76	77	78	300	300
49	47	HVN255	10:17:00	10:17:00	A359	540	1	2	3	4	5	6	7	8	9	23	24	25	26	400	400

Fig. 12. Flowchart for resolving conflicts at links by time

5. CONCLUSION

This study introduces a novel airspace structure by applying the WOTN model to the HCM FIR, along with the development of a conflict detection and assessment program using a simulated dataset of 500 aircraft operating within the proposed model.

The application of the WOTN model in the Ho Chi Minh FIR is feasible and offers substantial support for flight planning, conflict detection, and resolution. As a result, the system has the potential to reduce the workload of air traffic controllers. Additionally, it enables more flexible and optimized routing options for individual flights, supplementing the existing structured ATS route system without limitations on the number of usable routes.

The findings demonstrate the system's effectiveness in detecting and resolving conflicts across various LON_sep values. Nevertheless, the observed increase in total conflicts with higher LON_sep values highlights the importance of a balanced approach when determining separation standards, ensuring both safety and operational efficiency. Future research may investigate hybrid strategies that dynamically adjust flight levels and timing, possibly incorporating machine learning techniques for real-time conflict prediction and mitigation. Furthermore, examining the impacts of aircraft type, speed, and route complexity on conflict patterns could further improve system performance under varying traffic conditions.

References

1. Imen Dhief. 2018. „Optimization of aircraft trajectories over the North Atlantic Airspace". *PhD thesis.* Toulouse, France: Université Paul Sabatier.
2. Jaime de la Mota, María Cerezo-Magaña, Alberto Olivares, Ernesto Staffetti. 2023. „Data-Driven Probabilistic Methodology for Aircraft Conflict Detection Under Wind Uncertainty". *Transactions on Aerospace and Electronic Systems* 59(5): 5174-5186. ISSN: 1557-9603. DOI: https://doi.org/10.1109/TAES.2023.3250204.
3. Nguyen Ngoc Hoang Quan, Le Minh Hoang, Dinh Trinh Binh, Nguyen Thu Thao, Le Toan Thinh, Nguyen Van Tien Son, Vu Nguyen Hoang Vu. 2024. „Constructing optimization model based on WOTN model in Ho Chi Minh flight information region". In: *International Symposium on Aircraft Technology, MRO & Operations*". Vietnam Aviation Academy, Hochiminh city, Viet Nam. 27-29 August 2024.

4. Nguyen Ngoc Hoang Quan, Vladimir N. Nechaev, Vyacheslav B. Malygin. 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* 3: 64-85. ISSN: 2312-1327. DOI: https://doi.org/10.51955/2312-1327_2025_1_64.
5. OAG. 2024. *The busiest flight routes of 2024*. Available at: https://www.oag.com/busiest-routes-world-2024.
6. Roja Ezzati Amini, Kui Yang, Constantinos Antoniou. 2022. „Development of a conflict risk evaluation model to assess pedestrian safety in interaction with vehicles". *Accident Analysis & Prevention* 175: 106773. ISSN: 0001-4575. DOI: https://doi.org/10.1016/j.aap.2022.106773
7. Rosenow Judith, Martin Lindner, Joachim Scheiderer. 2021. „Advanced Flight Planning and the Benefit of In-Flight Aircraft Trajectory Optimization". *Sustainability* 13(3). ISSN: 2071-1050. DOI: https://doi.org/10.3390/su13031383.
8. Rui Chibante. 2010. *Simulated Annealing, Theory with Applications*. London: Intechopen. ISBN: 978-953-307-134-3.
9. Shafi Imran, Muhammad Fawad Mazhar, Anum Fatima, Roberto Marcelo Alvarez, Yini Miró, Julio César Martínez Espinosa, and Imran Ashraf. 2023. „Deep Learning-Based Real Time Defect Detection for Optimization of Aircraft Manufacturing and Control Performance". *Drones* 7(1): 31. ISSN: 2504-446X. DOI: https://doi.org/10.3390/drones7010031.
10. Shangyao Yan, Ching-Sheng Sun, Yi-Hsuan Chen. 2023. „Optimal routing and scheduling of unmanned aerial vehicles for delivery services". *Transportation Letters* 16(7): 764-775. ISSN: 1942-7867. DOI: https://doi.org/10.1080/19427867.2023.2237736.
11. Viet Nam News. „Vietnamese aviation predicted to transport over 80 million passengers next year". Available at: https://vietnamnews.vn/society/1638458/vietnamese-aviation-predicted-to-transport-over-80-million-passengers-next-year.html.
12. Vladimir Braverman. 2016. *Sliding Window Algorithms*. In: Kao M.Y. (eds). *Encyclopedia of Algorithms*. Springer, New York, NY.
13. Xiangyu Wang, Yanping Yang, Dong Wang, Zijian Zhang. 2022. „Mission-oriented cooperative 3D path planning for modular solar-powered aircraft with energy optimization". *Chinese Journal of Aeronautics* 35(1): 98-109. DOI: https://doi.org/10.1016/j.cja.2021.04.015.
14. Xuesong Wang, Ruolin Shi, Andreas Leich, Hagen Saul, Alexander Sohr, Xiaoxu Bei. 2025. „Conflict extraction and characteristics analysis at signalized intersections using trajectory data". *International Journal of Transportation Science and Technology* 16(7): 764-775. ISSN: 1942-7867. DOI: https://doi.org/10.1080/19427867.2023.2237736.

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