Traffic & Transportation

Collaborative 4-Dimentional Trajectory Optimisation for High-Density Flow Corridors

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Original Scientific Paper
Submitted: 28 Aug 2024
Accepted: 31 Jan 2025

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Publisher:
Faculty of Transport and Traffic Sciences, University of Zagreb

ABSTRACT

Flow corridors are novel types of flexible tube-shaped airspace developed to accommodate the rapid growth in air traffic. In the context of 4D-trajectory-based operation (4D-TBO), given the temporal-spatial characteristics of the airspace, it is crucial to ensure that the workload in high-density corridors does not significantly increase due to additional time constraints. Therefore, it becomes imperative to explore more efficient and reliable methods for generating 4D trajectories in these new airspace prototypes. This paper proposes a multi-aircraft optimisation method aimed at maximising system-wide benefits within flow corridors. Specifically, based on a collaborative decision-making (CDM) mechanism with an emphasis on negotiation capabilities required by the new air traffic management system, we focus on developing a collaborative optimisation process treated as a pure-strategy game and establishing a collaborative flight mechanism as a decision criterion. We employ a distributed auction algorithm with a distributed computing structure to find a weak Pareto-Nash equilibrium that guarantees individual preferences while improving throughput and fuel economy. We demonstrate our approach through numerical experiments conducted in one of China's busiest en-route areas. The results show significant improvements in throughput and fuel economy without compromising safety while maintaining computational performance even with increasing fleet size.

KEYWORDS

flow corridor; 4D trajectory; collaborative decision-making; pure-strategy game; collaborative optimisation.

1. INTRODUCTION

The rapid expansion of global air traffic demand results in flight delays, congestion, and even pollution, posing a significant challenge to air traffic management (ATM). Enhancing operational efficiency while ensuring safety has emerged as a focal point within the civil aviation industry.

The flow corridor is a novel airspace structure formally proposed by the Federal Aviation Administration (FAA) for the Next Generation Air Transportation System (NextGen) program [1]. It is defined as a long and narrow air route connecting high-demand areas [2, 3]. Three of the prominent characteristics that distinguish them from today's airways are: (1) unidirectional parallel or multi-layered lanes to achieve high throughput with low workload; (2) the implementation of self-separation management, which are technically supported by area navigation (RNAV) capabilities; (3) dynamic activation or de-activation as needed. Using large-scale simulation, authors show that corridors can be viewed as an advanced concept of enabling high throughput, the reduction of complexity in controller workload, flight delays [4, 5], and environmental impact [6] for the future air transportation system.

In order to achieve high throughput and efficiency with low collision risk in the corridor, current research has mainly focused on self-separation procedures, collision probability analysis [7, 8], structural configuration [9] and corridor networks [10, 11]. A prototype concept of a self-separation corridor was initially proposed, which enables the creation of high-density corridors [12]. Appropriate operational procedures are also necessary, and self-separation algorithms have been extensively studied. Nakamura et al. [13] investigated a basic self-separation algorithm using heading changes for one-way high-density traffic flow to accommodate the maximum traffic volume and to prevent a deadlock in a narrow corridor, the algorithm was further improved by utilising information about surrounding aircraft [14, 15]. Tian et al. [16] developed a dynamic stochastic simulation modelling framework for assessing the speed-based operational procedure in flow corridors.

The throughput is limited by the number of lanes, and multiple lanes can greatly increase the throughput. Two typical multi-lane structures are parallel and multi-layered corridors. Parallel-lane corridors with lane-switch manoeuvres inevitably increase the throughput but also increase the collision risk. Ye et al. [17, 18] a trade-off between throughput and collision risk for parallel Q-routes. The multi-layered corridor is the airspace's flight level structure, the altitudes of which reserved for corridor traffic might vary in order to accommodate different aircraft performance ranges or to avoid turbulence. Muna et al. [9] proposed a multi-layered corridor model beginning with some definitions that are related to its structure, and the concept of throughput and collision probability of an air corridor are introduced. Morooka et al. [19] clarified the feasibility of a multi-layered corridor via a comparison of the direct operation costs of the trajectories in layered and non-layered flow corridors.

Although a well-designed self-separation procedure and structure help accommodate a higher density of traffic and provide reduced workloads, however, to overcome the inefficiencies, previous research generally presents the combination of aircraft speed and altitude to achieve optimum allocation using a central decision-making mechanism in traditional ATM, there was limited communication between airlines, inadequate information sharing, and a lack of comprehensive understanding of the overall air traffic situation. Moreover, the optimal cruising altitude and speed vary for each aircraft, and there is a noticeable competition among the aircraft, especially in high-density flow corridors. Therefore, it is imperative to engage in collaborative behaviours and negotiate trajectory operations for the fleet. In the context of the collaborative decision-making (CDM) concept, the traffic situations in the surroundings can be perceived by utilising accurate information acquired from the airborne systems, and negotiations are facilitated to enable collaborative flights between airlines. Yang et al. [20] proposed an optimisation model for the en-routes and slots resource allocation problem, incorporating the principles of collaborative decision-making. Erkan et al. [21] presented an approach for optimising the sequencing of arrivals and departures under the CDM mechanism. Xu et al. [22] proposed a collaborative air traffic flow management (ATFM) framework to optimise the allocation of delays and a mixed integer linear programming (MILP) model was formulated and solved. Chen et al. [23] propose a cooperative slot secondary assignment model and an improved intelligent algorithm is designed to optimise the flight plan and minimise passenger time delay. Murça et al. [24] argued that since individual and system-level efficiency is affected by routing preferences, airline preference should be considered during collaborative air traffic management. There has been a paucity of research considering the differences in aircraft performance and individual preferences during the negotiation process. Since the composition of aircraft types varies over time, it is necessary to adjust tactical strategies collaboratively to ensure system-wide benefits and accommodate different aircraft performance ranges and following speeds effectively.

The CDM concept outlines a 4D exchange system between air and ground, known as the 4D-trajectory negotiation and validation (4-TNV) system [25, 26], the air transportation system is transitioning towards 4D-trajectory-based operations (4D-TBO), which constitute the fundamental capability of the NextGen and SESAR programs [27]. The objective is to effectively manage uncertainties associated with 4D trajectory evolution [28,29] while imposing time constraints known as a required time of arrival (RTA) at several checkpoints [30,31]. In a 4D flight environment, flow corridors are bundles of nearly parallel assignments for 4D trajectories (4DT) [32]. These planned trajectories must specify each aircraft's position at specific times to ensure conflict-free operations and minimise fuel costs through potential manoeuvres such as speed adjustments and changes in flight levels. Yousefi and Zadeh [33] modelled these 4DTs as fluid flows grouped based on predetermined proximity parameters, clustering aircraft with adjacent state vectors into the same flow corridor. However, their focus primarily lies on macroscopic traffic flow analysis without guiding actual flight operations. Moreover, there is currently a lack of research on how to implement 4D trajectories in this new airspace prototype. In fact, the operating efficiency of a corridor may decrease with a limited number of lanes when additional time constraints are imposed; therefore, optimisation methods applied in current airways might become invalid when guaranteeing both flight economy and time constraints, especially under high traffic density. Also, due to the uneven distribution of traffic demand in space and time, specific consideration should be given to temporal-spatial characteristics of airspace to avoid congestion or waste of scarce airspace resources.

The objective of this paper is to present an optimisation framework for multi-layer corridors and generate optimised 4D trajectories at the tactical level, aiming to demonstrate collaborative flight management for high-density flow. The main contributions of this study are fourfold: (1) we develop a flexible operational strategy incorporating layered-lane-switch behaviour that ensures optimal fuel efficiency and RTA constraints; (2) we investigate a temporal-spatial collaborative flight mechanism by modelling the optimisation process as a pure strategy, facilitating efficient utilisation of airspace resources while satisfying system-wide benefits and individual preferences; (3) to address the trade-off between throughput, safety, and fuel efficiency in flow corridors, we employ the Nash-Pareto approach to simultaneously produce Nash-equilibrium solutions and Pareto non-dominated solutions for assigned speeds in each lane as well as the optimal 4D trajectories; (4) we propose a distributed auction algorithm (DAA) with its distributed computing structure to generate candidate trajectories for each aircraft, accommodating individual preferences and variations in aircraft performance while mitigating computational burden arising from increasing traffic flow.

2. THE DESCRIPTION OF 4D TRAJECTORY IN FLOW CORRIDOR

2.1 The corridor structure

A multi-layered structure is anticipated to enhance the throughput of flow corridors, which play a crucial role in managing high-volume en-route traffic. As illustrated in *Figure 1*, the multi-layered corridor comprises n levels without any parallel routes, and $H = \{H_1, H_2, \ldots, H_n\}$ denotes the set of flight levels. The length of the flow corridor is denoted as L and it is evenly divided by multiple virtual waypoints with a distance d between consecutive nodes. It is assumed that there are m waypoints at each level, including entrance and exit waypoints, resulting in a total of $n \times m$ waypoints within the corridor.

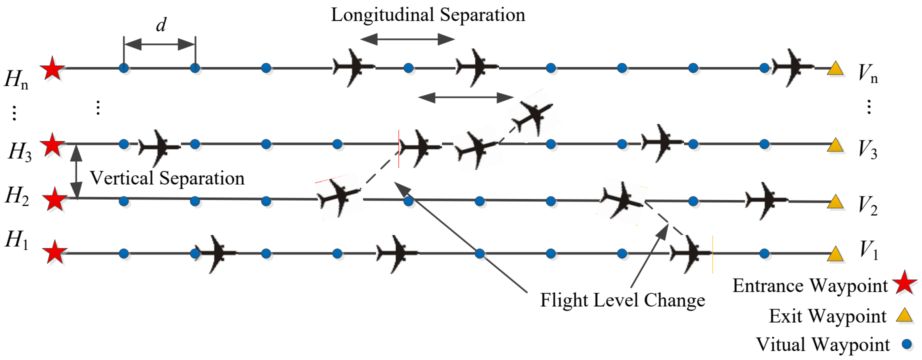


Figure 1 – illustration of flow corridor and the proposed strategy

2.2 Mathematical description of the 4D trajectory

We denote $P = \{1, 2, \ldots, p, \ldots n \times m\}$as the sequence number set, where p ($p \in P$) represents the sequence number. The trajectory of flight i can be described as a sequential series of waypoints $\{p_i^1, p_i^2, \ldots, p_i^r, \ldots p_i^m\}$, where p_i^r represents the r^{th} waypoint visited by flight i within the corridor. Finally, the discrete 4D trajectory of flight i can be described as $P_i = \{p_i^1(t_{i,1}), p_i^2(t_{i,2}), \ldots, p_i^r(t_{i,r}), \ldots p_i^m(t_{i,m})\}$, where $t_{i,r}$ is the time at which the r_{th} waypoint is visited by flight i. Let $t_{i,1}=\alpha_i$, and $t_{i,m}=o_i$, thus further describing the 4D trajectory of flight i as $P_i = \{p_i^1(\alpha_i), p_i^2(t_{i,2}), \ldots, p_i^r(t_{i,r}), \ldots p_i^m(o_i)\}$, indicating both sequences of waypoints and their corresponding arrival times. For instance, if it takes 13:10 to enter the corridor from the 15th waypoint, then α_i=13:10 and $p_i^1(\alpha_i)$=15.

2.3 The operation strategies for multi-aircraft in flow corridor

The 4D flight trajectory imposes strict time constraints on each aircraft. Therefore, it is crucial to improve the efficiency of trajectories in the flow corridor while ensuring safety, considering the limited number of lanes and time constraints. With this purpose in mind, two strategies can be considered: first come, first serve (FCFS), a well-known and classical principle in air traffic management; and a method proposed in this study as depicted in *Figure 1*. In FCFS, the flight level of each aircraft is determined based on entrance and exit required time of arrival (RTA), with the self-separation procedure used in [17] for managing separations by adjusting speed to meet exit RTAs and fuel economy requirements. The proposed method dynamically adjusts the allocation of specified speeds for each lane based on fleet composition represented by speed set $V=\{V_1, V_2,\ldots,V_n\}$. Under this strategy, an aircraft only needs to maintain its speed at the assigned flight level while maintaining proper separation from lead aircraft. To meet RTA constraints within limited routes that restrict cruising speeds, aircraft are allowed to change flight levels for velocity adjustment. However, this strategy increases the complexity of multi-aircraft trajectory optimisation, making it more challenging. Hence, ensuring flight safety and improving operational efficiency requires not only appropriate negotiation of lane speeds but also coordination of their 4D trajectories throughout the entire flight process.

3. MODEL FORMULATION

3.1 Optimisation objective

The overcrowding of airspace may result in a decline in operational efficiency; therefore, the decision variables for permitting flight set F^{in} to enter the corridor and determining the 4D trajectory combination $TP=\{P_1,P_2,\ldots,P_i,\ldots,P_{n^p}\}$ must be carefully balanced between throughput and fuel efficiency. Subsequently, two optimisation objectives are established by considering both traffic demand and fuel efficiency.

1) Maximising throughput

The escalating demand for air traffic has resulted in a growing scarcity of airspace resources. Consequently, one of the key objectives in this model is to maximise flow corridor throughput, which is tantamount to minimising the number of flights without access to the corridor.

$$\min(N_{ap}-n^p) \tag{1}$$

$$n^p=\sum_{i\in F}\lambda_i \tag{2}$$

$$\lambda_i=\begin{cases}1 & \text{if flight } i \text{ is permitted to enter}\\ 0 & \text{else}\end{cases} \tag{3}$$

where N_{ap} represents the total number applying for entry into the corridor; n^p denotes the number permitted to enter into the corridor, and $n^p \le N_{ap}$; F represents the flight set applying for entry into the corridor.

2) Maximising average standard ground range

Fuel efficiency has always been a primary focus of the aviation industry as a crucial aspect of airspace resource allocation impact. The standard ground range (SGR) serves as a critical performance parameter for analysing fuel consumption over a given distance, representing the ground distance travelled (in nautical miles) per unit mass of burned fuel (in kilograms). This metric establishes a direct relationship between fuel consumption and distance, making it valuable for monitoring fuel efficiency at any given time.

$$\max \overline{SGR} = \frac{\sum_{i \in F^{in}} SGR_i}{n^p} \tag{4}$$

SGR can be calculated according to the following equation:

$$SGR_i = \frac{L_i}{fb_i} = \frac{L_i}{\sum_{i \in F^{\text{in}}} \sum_{k \in T} ff_{ik} \cdot t_{ik}} \tag{5}$$

where L_i is the ground distance of flight i; fb_i is the fuel consumption; t_{ik} is k^{th} time instance; T is the time set; ff_{ik} is the fuel flow rate at k^{th} time instance, and is calculated using the fuel consumption method in [34].

3.2 Constraints

1) Constraint of entry time separation

The separation distance between the flight and the leading aircraft at the corridor entrance should not be less than the minimum safety time interval.

$$\varepsilon_{ij} \cdot \left| \alpha_i - \alpha_j \right| \geq \delta_{\min} \tag{6}$$

$$\varepsilon_{ij} = \begin{cases} 1 & \text{if aircraft } i \text{ and } j \text{ are flying at the same altitude} \\ \infty & \text{else} \end{cases} \tag{7}$$

where $\delta_{\min}$ is the safety time interval.

2) Constraint of exit time separation

The separation distance between the flight and the leading aircraft at the corridor exit should not be less than the minimum safety time interval.

$$\varepsilon_{ij} \cdot \left| o_i - o_j \right| \geq \delta_{\min} \tag{8}$$

3) Separation constraint

The time interval between visits to each waypoint is recorded, ensuring that when two aircraft consecutively cross the same waypoint, the time separation should be larger than the safety time interval, thereby leading to conflict-free 4D trajectories.

$$\left| t_i^p - t_j^p \right| \geq \delta_{\min} \tag{9}$$

where t_i^p is the time that flight i flies through the waypoint p.

4) RTA constraint

Assume that flight i changes its flight level at r^{th} and q^{th} waypoints, $r,q \in P$, and t_r is the duration of climbing or descending for a single level.

$$t_{RTA_i} - t_w \leq \frac{(r-1)l}{V(t_{i,r})} + \frac{(q-r)l}{V(t_{i,q})} + \frac{(NM-q)l}{V(t_{i,q+1})} + \beta_i t_r \leq t_{RTA_i} + t_w \tag{10}$$

$$\beta_i=\begin{cases}2 & \text{if } V(t_{i,r})\neq V(t_{i,q})\neq V(t_{i,q+1})\\1 & \text{if } V(t_{i,r})\neq V(t_{i,q})=V(t_{i,q+1}) \text{ or } V(t_{i,r})=V(t_{i,q})\neq V(t_{i,q+1})\\0 & \text{if } V(t_{i,r})=V(t_{i,q})=V(t_{i,q+1})\end{cases} \quad (11)$$

where β_i is the frequency of flight level change, and $\beta_i \leq 2$, indicating that only up to two level adjustments are allowed; t_{RTA_i} is the pre-determined flight time of flight i, t_w is the tolerance of the arrival time error.

5) Assigned speed constraint for each lane

The assigned speeds should be within the range of aircraft performance, hence, the minimum and maximum set values of the ground speed for each lane are as follows:

$$V_{min}<V_{\text{low}}< V_{RTA,\ min} \quad (12)$$

$$V_{max}<V_{\text{high}}< V_{RTA,\ max} \quad (13)$$

where V_{min} and V_{max} are the minimum and maximum speeds allowed by aircraft performance, respectively; V_{low} and V_{high} are the minimum and maximum values of the assigned speed, respectively; $V_{RTA,\ min}$ and $V_{RTA,\ max}$ are the minimum and maximum values of the required ground speed respectively.

According to the analysis of aircraft performance data, the economic cruising speed increases with altitude, thus leading to the assigned lane speeds:

$$V_1<V_2<\ldots<V_n \quad (14)$$

6) Flight level change constraint

In order to ensure flight safety, it is assumed that only a single flight level can be altered at a time, as depicted by:

$$|\ H(t_{i,\text{k}+1})\text{-}\ H(t_{i,\text{k}})\ \ | \leq 2000\text{ft} \quad (15)$$

4. OPTIMISATION ALGORITHM

4.1 Collaborative flight mechanism

Although each aircraft has its optimal altitude for efficient flight, there exists a cooperative relationship rather than a competitive one among aircraft in utilising limited airspace resources within a corridor. The effectiveness of allocating airspace resources directly depends on the trajectory optimisation process. In this section, we apply game theory [35,36] to solve allocation problems and establish a collaborative optimisation mechanism for multi-aircraft 4D trajectories within the flow corridor. Our objective is to maximise throughput and fuel economy as decision criteria. We model the negotiation process of multi-aircraft as a pure strategy game, with flights $F=\{1,2,\ldots,N_{\max}\}$ participating in bidding for corridor airspace resources. After submitting their candidate trajectories, some individuals compromise by modifying their submissions to optimise system performance. Subsequently, all aircraft effectively coordinate to fly through the corridor, ensuring that decision-makers achieve satisfactory results aligned with their interests. If no aircraft can unilaterally improve its 4D trajectory further once the strategies of other participants are determined, then this combination of strategies is defined as a Nash equilibrium. In other words, the flight set allowed to enter the corridor is denoted as $F^{in}(F^{in}\in F)$, the optimised set of 4D trajectories is represented by $TP^*=\{P_1^*,P_2^*,\ldots,P_i^*,\ldots,P_{n^p}^*\}$, and the strategy combination $G=(F^{in}, TP^*)$ constitutes a weak Pareto-Nash equilibrium point for the multi-objective game.

$$G=(F^{in},TP^{*})=\begin{cases} n^{p}\left(\forall i\in F^{in}\cap P_{i}\in P^{*}\right)\geq n^{p}\left(\forall j\in F'\cap P_{j}\in P'\right),\ F^{in}\neq F',P^{*}\neq P' \\ \overline{SGR}_{i}\left(P_{1}^{*},P_{2}^{*},...,P_{i}^{*},...,P_{n^{p}}^{*}\right)\leq\overline{SGR}_{i}\left(P_{1}^{*},P_{2}^{*},...,P_{i},...,P_{n^{p}}^{*}\right) \end{cases} \tag{16}$$

4.2 Pareto optimality

The multi-aircraft collaborative flight optimisation problem can be reformulated as a classical travelling salesman problem. By employing the non-dominant sequencing genetic algorithm with an elitist strategy (NSGA-Ⅱ) [37], the Pareto optimal solution for flight trajectories considering multiple optimisation objectives can be efficiently obtained, thereby establishing a solid foundation for collaborative flight optimisation.

1) Encoding

The chromosome is encoded using real numbers. A multilayered code is employed in this study, with two layers utilised to represent the flight set allowed to enter the corridor and their corresponding trajectories. In order to enhance the likelihood of attaining the global optimal solution, it was necessary for us to generate diverse individuals within the population, where a certain proportion of chromosomes must possess a Hamming distance greater than a specified value.

2) Fitness function

According to the characteristics of a single value, non-negative and maximisation, the objective functions in *Equations (1) and (4)* are transformed as follows:

$$Fit_{1}=\left(N_{ap}-\sum_{l\in F}\lambda_{l}\right)^{-1} \tag{17}$$

$$Fit_{2}=\frac{\sum_{i\in F^{in}}SGR_{i}}{n^{p}} \tag{18}$$

3) Realisation process

— Step 1: Initialise a random population.
— Step 2: Perform tournament selection, crossover and mutation of the initial parent solutions to generate an offspring solution.
— Step 3: The current parent solutions are merged with offspring solutions. Compute the fitness function and perform fast, non-dominant sorting on all individuals of the population to generate a Pareto front.
— Step 4: Based on the crowding distance, select some optimal individuals to update a new parent population and put (N, P_{best}) into the Pareto solutions.
— Step 5: Repeat steps 2 to 4 until the terminal generation, and output the solution set whose individual rank is calculated as the top one to the resulting Pareto solution.

4.3 Distributed auction algorithm

The problem is formulated as a nonlinear optimal control problem. To mitigate the computational burden associated with solving mixed integer nonlinear programming, we employ the distributed auction algorithm (DAA) as the negotiation protocol to determine the Nash equilibrium of 4D trajectories. The DAA emulates an auction process, where each aircraft bids to modify its current trajectory during each iteration. Only the aircraft, the trajectory of which not only minimises its own cost but also maximises overall system performance, is permitted to make changes, while other aircraft maintain their existing trajectories. Leveraging its decentralised nature, a centralised multi-aircraft flight path optimisation problem is decomposed into n^p 4D trajectory optimisation problems, and the framework of the proposed algorithm is described as follows. *Figure 2* illustrates a flowchart depicting this process.

Algorithm 1 – Framework of distributed auction algorithm

Input: Flight information, including aircraft type, entry and exit RTAs
Output: Pareto solution
Set maximum number of iterations N_g
For n=1,2,…, N_g
  For N in N_{max}
    Generate the flight set C_j(j=1,2,…,Y, $Y=C_{N_{\max}}^{N}$), initialise 4-D trajectory of each flight $P_i(i\in C_j)$
    For i in C_j
      Calculate fb_i, and search P_i^* which minimises $\overline{SGR}\left(P_1^n,\cdots,P_i^*,\cdots,P_N^n\right)$, and let
    $\Delta fb=\overline{SGR}_i\left(P_1^n,P_2^n,...,P_i^n,...,P_N^n\right)-\overline{SGR}_i\left(P_1^n,P_2^n,...,P_i^*,...,P_N^n\right)$ Find
    $g=\arg\max\Delta fb$, and update
      $P_g^{n+1}=P_g^*,P_i^{n+1}=P_i^n,\forall i\neq g$
    End for
  End for
End for

According to the proposed distributed auction algorithm, the theoretical analysis of computational complexity is summarised in *Table 1* and expressed in the form of O(n). The computational time T_c can be computed as:

$$T_c=N_e\times\text{CPU time.} \quad (19)$$

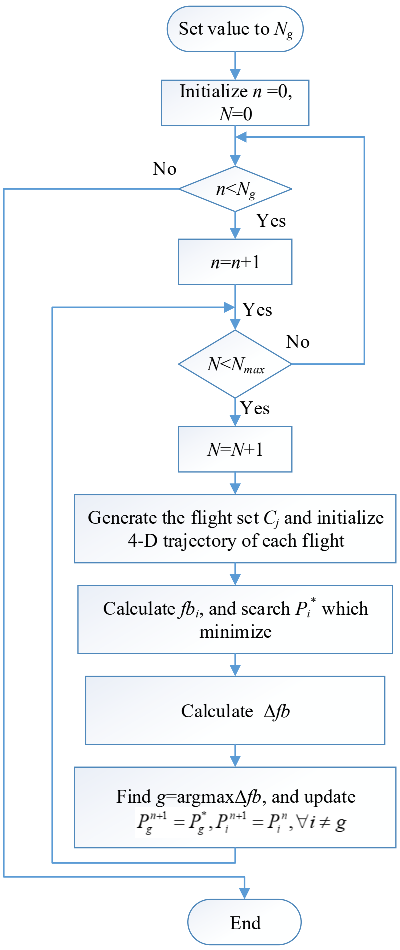


Figure 2 – The flowchart illustrating the implementation of DAA integrated with NSGA-II

Table 1 – Computational complexity

For loop	Number of executions N_e	Asymptotic time
1	$1+N_g+N_g$	O(n)
2	$N_g \times(1+N_{max}+N_{max})$	O(n^2)
3	$N_g \times N_{max} \times(1+Y+Y)$	O(n^3)
Total	$1+N_g+N_g+N_g \times(1+N_{max}+N_{max})+N_g \times N_{max} \times(1+Y+Y)$	O(n^3)

5. NUMERICAL RESULTS

5.1 Scenarios

In this section, we present the results obtained from numerical simulations and analyse a scenario of the cruise section between Guangzhou Baiyun and Shanghai Hongqiao airports, which represents one of the busiest air routes in China. The simulation analysis focuses on a high-altitude airspace corridor with entrance and exit locations at coordinates (114.7649, 24.1804) and (120.9337, 29.8962) respectively. We suppose that the horizontal route of the corridor is constructed along the Great Circle route connecting these two points, spanning a total distance of 475 nautical miles, as depicted in *Figure 3*. The vertical route within this corridor comprises three flight levels: FL370, FL390 and FL410. To ensure proper separation between aircraft, the corridor is divided into 19 virtual segments, with each segment spaced at intervals of 25 NM.

The flight data were collected from 13:00 to 15:00 between 9 May and 10 June 2019. *Table 2* presents the distribution of aircraft types based on these statistical findings. A minimum horizontal distance and time separation of 5 NM and 1 min, respectively, have been enforced, along with an additional buffer separation of either 2 NM or 0.5 min. The BADA [38] defines a time window of 30 seconds to allow for a more stringent error tolerance during en-route flights.

Figure 3 – The horizontal trajectory of the corridor

In this simulation, weather forecast data are retrieved from The International Grand Global Ensemble (TIGGE) database of the European Centre for Medium-Range Weather Forecasts (ECWMF). Wind forecast data with UTC time ranging from 05:00 to 06:00 are selected within the longitude range of 114°~121°and latitude range of 24°~30°. A total of 35 scheduled flights are involved in this simulation, and the specific number for each type is listed in *Table 2*. The entry and exit required time of arrival (RTA) values for flights intending to enter the corridor during the period 13:00-14:00 are randomly generated based on individual aircraft performance ranges and airspeed distributions. All numerical experiments have been conducted under these specified conditions.

Table 2 – Composition of aircraft type

Aircraft type	B738	A320	A330	B787
Percentage	33%	37%	19%	11%
Number of aircraft	10	13	7	4

5.2 Results and discussions

To assess the performance and efficacy of our proposed method, we compare it with the FCFS strategy described in Section 2 and a multi-objective multi-memetic algorithm (MOMMA)[39], referred to as collaborative optimisation (CO). MOMMA employs multiple local search operators to effectively solve this large-scale bi-objective problem, while NSGA-II serves as the global search component within MOMMA. The parameters for both MOMMA and NSGA-II are provided in *Table 3*. Additionally, two extra parameters, namely flight set $\lambda_1^{F^{in}}$ and trajectories λ_1^{TP}, indicate the weighted factors for the local search operators. The optimal solutions of the two objective functions are illustrated in *Figures 4* and *5*, respectively. It is worth noting that as the number of generations increases, individuals gradually converge towards the optimal direction, ultimately enabling the search for Pareto optimal solutions within the action space. As depicted in *Figure 4*, the optimal solution for the maximum throughput of FCFS and MOMMA converges to 16 and 28, respectively. The proportions of permitted entries into the corridor are 45.7% and 80%, while the number of denied entries rapidly decreases from 33 to 8 in the 50th generation when adopting the CO strategy. Furthermore, with this strategy, the proportion of permitted entries reaches 88.6%, achieving improvements of 42.9% and 8.6% compared to FCFS and MOMMA strategies, respectively.

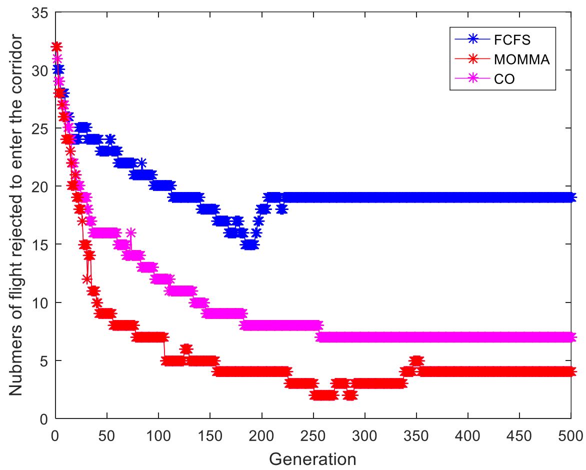


Figure 4 – Optimisation process of the number of flights rejected to enter the corridor

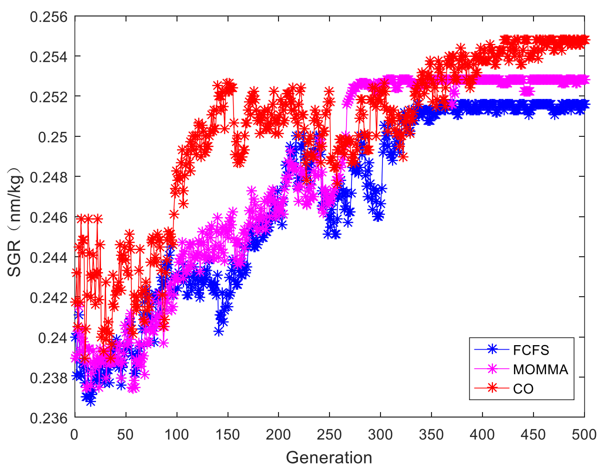


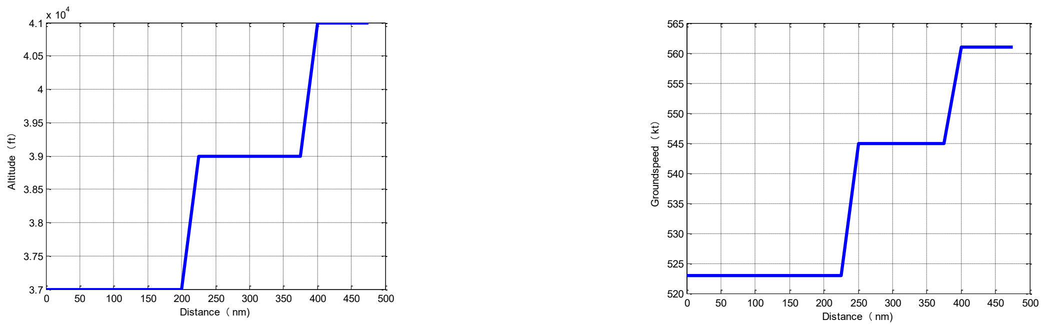
Figure 5 – Optimisation process of SGR

The variation trend of the objective function value, which indicates fuel economy, is depicted in *Figure 5*. Herein, the average specific fuel consumption (SGR) exhibits significant fluctuations with varying numbers of flights entering the corridor. Subsequently, an overall upward trend in the average SGR is observed once the number of flights stabilises. Between generations 250 and 350 of CO, it can be observed that when the number of flights entering the corridor exceeds 31, there is a slight fluctuation followed by a descent in average SGR. However, upon stabilisation at 31 flights entering the corridor, the average SGR continues to rise and eventually reaches stability with minor fluctuations around 0.2548 NM/kg. Through several simulations conducted throughout 430 iterations, convergence is achieved within the initial population of CO. One Pareto solution is selected from this converged set wherein both objective values are determined as (31, 0.2548). Furthermore, in comparison with the evolutionary curves of the other two strategies, MOMMA exhibits an earlier convergence after approximately 280 generations due to its utilisation of local search operators. However, it is evident that the CO strategy outperforms MOMMA in terms of both throughput and average SGR. The FCFS approach yields significantly lower optimal solutions compared to the other two strategies, with values of 16 and 0.2516 NM/kg, respectively. Consequently, by adopting the CO strategy, higher throughput can be achieved while simultaneously reducing total fuel consumption.

Table 3 – Parameters of NSGA-II and MOMMA

NSGA-II	MOMMA
Individuals per generation: 50 Number of generations: 500 Crossover probability: 0.8 Mutation probability: 0.01	Individuals per generation: 50 Number of generations: 500 Crossover probability: 0.8 Mutation probability: 0.05 Weighted factors of local search operators: $\lambda_1^{F^{in}}$ [0.34,0.51] λ_1^{TP} [0.40,0.55]

A typical flight example is considered, with the aircraft type being B737-800. The entry and exit required time of arrival (RTA) are 13:58:00 and 14:51:00, respectively. Consequently, the average ground speed can be calculated as 538 knots. With a flight path angle of 1°, two altitude changes occur at 24.78 min and 44.04 min, respectively. The flight levels of the optimised trajectory are FL370, FL390 and FL410, as depicted in *Figure 6a*. Their corresponding ground speeds are 523 knots, 545 knots and 561 knots, respectively. *Figure 6b* illustrates the vertical and ground speed profiles accordingly. The actual arrival time is recorded as precisely at 14:51:02 with an error margin within a time window of ±30 s; thus indicating that the RTA requirement has been successfully met.



(a) (b)

Figure 6 – The profiles of an example flight: (a) Vertical profile; (b) Speed profile

1) Throughput analysis

The number of flights entering the corridor instantaneously is presented in *Figure 7*. It should be noted that, among the three strategies, there exists a slight disparity in the aircraft count during the initial 15 minutes, which gradually amplifies with an increasing influx of flights into the corridor. When adopting the CO strategy, a greater number of aircraft can be accommodated within the corridor. The average separation is reported in the third row of *Table 4*, and it becomes apparent that CO yields significantly lower results compared to FCFS and MOMMA approaches. From this perspective, minimising flight separations to their utmost extent will greatly enhance corridor throughput.

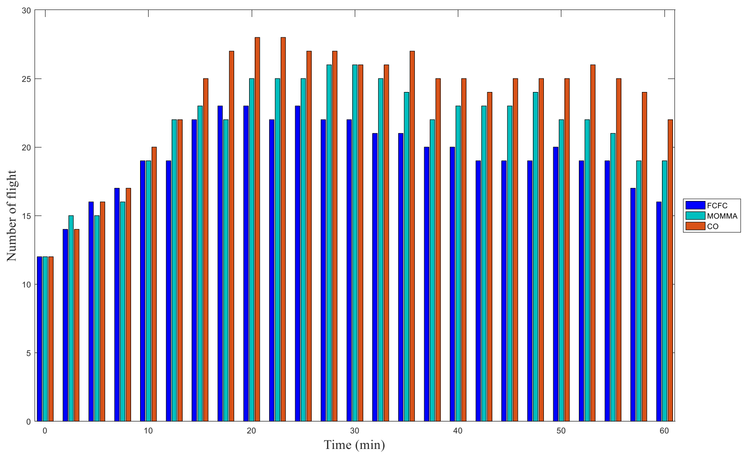


Figure 7 – Number of flight variation with time

Table 4 – Simulation results of the strategies

	Throughput	Average separation (NM)	Average SGR (NM/kg)	Fuel consumption (kg)
FCFS	16	108.7	0.2516	30304
MOMMA	28	66.7	0.2533	52510
CO	31	56.2	0.2548	57660

2) Fuel economy analysis

The average fuel consumption is incomparable due to the different compositions of aircraft types; therefore, in order to evaluate the fuel-saving abilities of these strategies, we consider the average fuel consumption for each type. The results presented in *Figure 8* demonstrate a consistent reduction in the average fuel consumption across all CO types. Taking B737-800 as an example, our approach leads to a decrease in average fuel consumption by 6.39% and 0.65% compared to the other two methods, respectively. Consequently, our approach not only enhances airspace utilisation but also improves corridor fuel efficiency.

The fuel savings results for each flight are depicted in *Figure 9*, with 90.3% of flights exhibiting reduced fuel consumption. However, it is worth noting that 6.5% of optimised flights experienced an increase in fuel burn, which ultimately contributes to an overall improvement in fuel economy for the entire corridor at the expense of individual interests. This significant observation suggests that participants strive to foster a collaborative concept during the negotiation process and develop strategies aimed not only at maximising their own interests but also at achieving global optimality for the entire system.

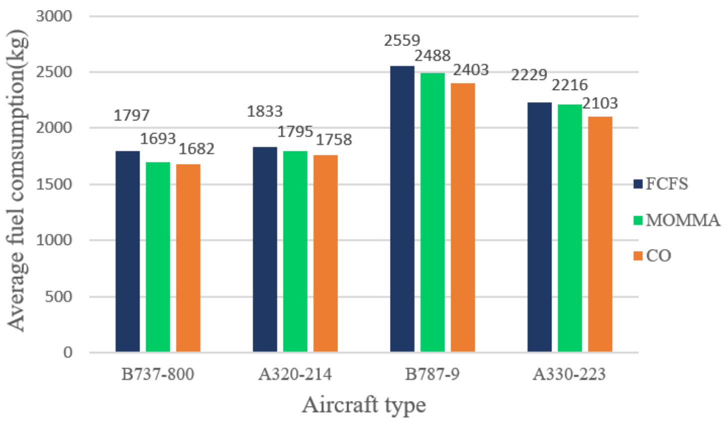


Figure 8 – Comparisons of the fuel consumption of each aircraft type

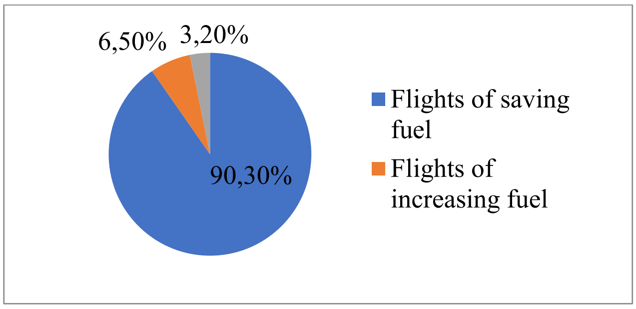


Figure 9 – Fuel consumption changes using CO

3) Safety analysis

To assess flight safety, *Figure 10* illustrates the flight separation of these strategies. Since the flight separation of FCFS and MOMMA is a continuous variable due to potential inconsistencies in the speeds of adjacent aircraft, only the minimum separation of FCFS is depicted in *Figure 10*. The red solid line represents this minimum safety separation, with all flight separations positioned above it. Furthermore, the respective minimum separations for the three strategies are 8.4 NM, 8.6 NM and 9.7 NM, respectively. It can be observed that all aircraft within the corridor maintain safe separations, with FCFS exhibiting flight separations closer to the minimum requirement.

Due to the presence of uncertainty in airspace, a buffer distance should be added, and a specific range defined as the separation adjustment threshold (SAT) should be maintained, represented by the green dotted line in *Figure 10*. Therefore, the number of instances where separation is less than SAT is also recorded; for most cases among the three strategies, separations remain greater than SAT and only five out of thirty-one flight pairs are spaced less than SAT when implementing the CO strategy, while six out of sixteen flight pairs result from using FCFS. In other words, collaboratively optimised trajectories maintain compact and relatively uniform separation.

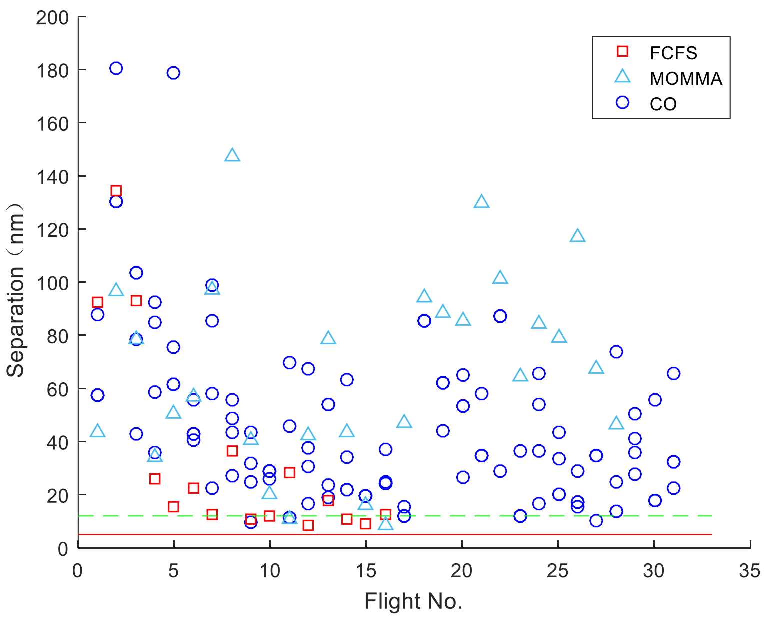


Figure 10 – Separation distribution

The time intervals for visiting specific waypoints at FL390, as determined by the collaborative optimisation method, are presented in *Table 5*. It is noteworthy that all of these intervals exceed the minimum separation time requirement. The number of occurrences where the interval falls below SAT (1.5 min) is indicated as $C_{\delta<SAT}$. Importantly, this situation only arises twice, thus ensuring effective self-separation. From a flight safety perspective, the risk of losing separation can be mitigated through the implementation of the collaborative optimisation strategy, leading to enhanced operational safety within the corridor.

Table 5 – Time separations flying across some waypoints of FL390

Waypoint no.	Number of flights	Average time separation (min)	Minimum time separation (min)	$C_{\delta<SAT}$
21	5	8.2	4.7	0
23	6	7.3	4.7	0
25	6	7.1	5.0	0
27	7	6.9	3.3	0
29	7	7.1	1.3	1
31	6	6.6	3.2	0
33	8	6.2	4.3	0
35	8	7.5	1.2	1
37	7	11.7	6.3	0
39	7	9.9	5.1	0

5.3 Simulation of increasing traffic flow density

The number of flights applying for entry gradually increased from 15 to 39 in order to verify the effectiveness of the proposed method in our experiment. The implementation was carried out using MATLAB on a desktop PC equipped with a 3.4 GHz Intel i7 CPU and 32 GB of RAM. To assess the computational speed and success rate of the GAs, each scenario with the same N_{ap} value was executed 50 times. *Table 6* presents the average separation, fuel consumption $\overline{fb}$ for a single B738, average calculation time t_c and success rate R_s. *Figure 11* illustrates the relationship between the average fuel consumption of B738 and throughput. It is evident that as more aircraft enter, there is a decrease in operational efficiency regarding fuel economy. This can be attributed to overcrowded routes introducing additional constraints and interference among aircraft, consequently leading to inevitable deviations from their optimal trajectories. Therefore, a trade-off between throughput and fuel efficiency must be carefully considered. *Figure 12* demonstrates that the utilisation of distributed computing in CO leads to only marginal increases in computation time as the number of flights applied to entry increases. Even for the largest number of flights in the simulation, the computation can be completed within 3 minutes. Given that operational changes need to be implemented within a 15-minute tactical cycle for air traffic control, this approach is well-suited at the tactical level. However, when comparing the computing speeds of FCFS and MOMMA with CO, it becomes evident that both are slower. Moreover, as the number of flights increases, there are substantial variations in computation time observed. Additionally, CO ensures an average success rate of 98.7%, indicating that in most scenarios, an optimal solution can be successfully identified within GAs' maximum generation.

Table 6 – Results of the increasing number of aircraft

N_{ap}	FCFS				MOMMA				CO			
	T_p	$\overline{fb}$ per B738(kg)	t_c (s)	R_s	T_p	$\overline{fb}$ per B738(kg)	t_c(s)	R_s	T_p	$\overline{fb}$ per B738(kg)	t_c(s)	R_s
15	15	1629	25.77	50/50	15	1518	14.89	50/50	15	1559	17.14	50/50
18	15	1656	36.02	49/50	18	1561	21.44	50/50	18	1533	25.43	50/50
21	16	1742	49.13	50/50	21	1580	32.30	50/50	21	1592	38.13	50/50
24	16	1706	64.52	49/50	24	1607	53.19	50/50	24	1581	55.27	50/50
27	16	1728	82.44	50/50	26	1643	76.07	50/50	27	1593	72.88	49/50
30	16	1732	111.23	50/50	27	1652	87.22	49/50	30	1663	84.05	50/50
33	16	1722	133.15	50/50	27	1651	111.29	50/50	31	1684	105.53	49/50
36	16	1727	158.08	48/50	28	1706	134.75	48/50	32	1678	122.47	47/50
39	17	1740	197.98	50/50	29	1698	157.53	50/50	32	1659	146.75	49/50

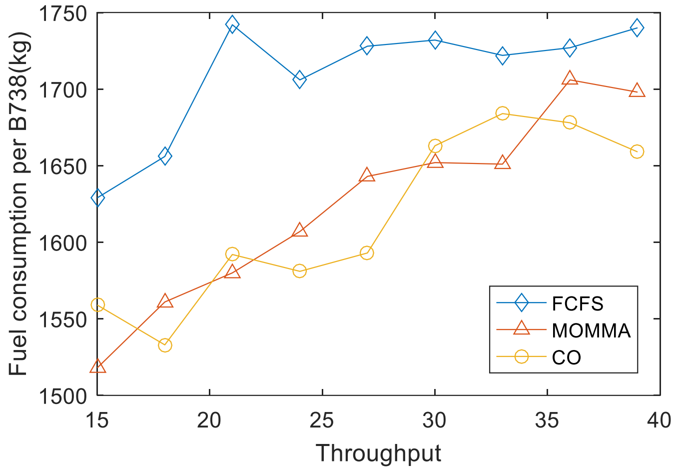


Figure 11 – The correlation between throughput and average fuel consumption

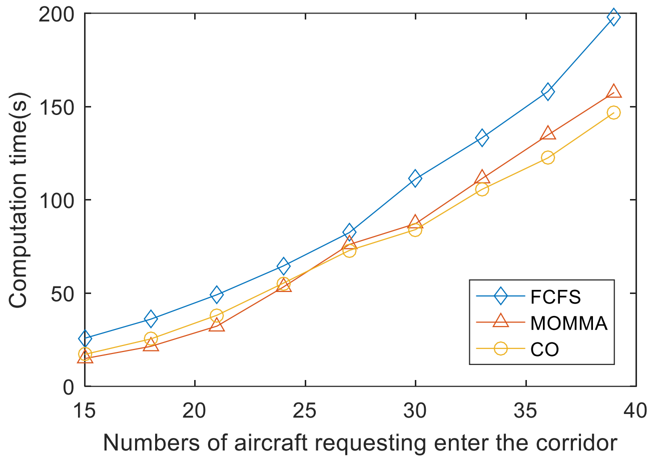


Figure 12 – Relationship between the number of flights and computing time

6. CONCLUSION

The present work develops a method for collaborative optimisation of 4D trajectories among multiple aircraft in a flow corridor. It explicitly considers the RTAs at the entrance and exit of the corridor within the context of a 4D flight environment. The proposed method introduces a novel collaborative flight mechanism to maximise both the throughput and fuel economy of the corridor while considering trade-offs between system-wide benefits and individual preference. Furthermore, to address computational burden concerns in high-density traffic flow scenarios, a distributed auction algorithm is adopted as an aircraft negotiation protocol. A case study is presented to demonstrate that implementing this method significantly increases the throughput of the flow corridor without compromising safety, thereby enabling higher airspace utilisation. Additionally, optimised trajectories within the flow corridor exhibit global fuel efficiency benefits. Importantly, an increase in traffic density does not impose an excessive computational burden.

Future work will include extending the corridor structure to two or more parallel routes, and an advanced optimisation method will be improved to allow a more flexible operation mode for the flow corridor, providing the possibility of realising the concept of free flight.

ACKNOWLEDGEMENTS

This research has been supported by the project titled Research on Aviation Operation Safety Management and Risk Warning Technology Based on Data Technology, No. MJ-2017-J-91, and the project titled Study on Four-Dimensional Trajectory Prediction and Optimisation Technology under Uncertain Meteorological Conditions, No. Y202456176.

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