Hindawi
International Journal of Aerospace Engineering
Volume 2023, Article ID 5530977, 15 pages
https://doi.org/10.1155/2023/5530977

Research Article

An Efficient Trajectory Negotiation and Verification Method Based on Spatiotemporal Pattern Mining

Yongqi Liu,[1] Miao Wang,[1] Zhaohua Zhong,[2] Kelin Zhong,[3] and Guoqing Wang[1]

[1]*School of Aeronautics and Astronautics, Shanghai Jiao Tong University, Shanghai, China*
[2]*China Aeronautical Radio Electronics Research Institute, Shanghai, China*
[3]*COMAC Shanghai Aircraft Design and Research Institute, Shanghai, China*

Correspondence should be addressed to Miao Wang; miaowang@sjtu.edu.cn

Received 8 June 2023; Revised 21 November 2023; Accepted 24 November 2023; Published 12 December 2023

Academic Editor: Binbin Yan

Copyright © 2023 Yongqi Liu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In trajectory-based operations, trajectory negotiation and verification are conducive to using airspace resources fairly, reducing flight delay, and ensuring flight safety. However, most of the current methods are based on route negotiation, making it difficult to accommodate airspace user-initiated trajectory requests and dynamic flight environments. Therefore, this paper develops a framework for trajectory negotiation and verification and describes the trajectory prediction, negotiation, and verification processes based on a four-dimensional trajectory. Secondly, users predict flight trajectories based on aircraft performance and flight plans and submit them as requested flight trajectories to the air traffic management (ATM) system for negotiation in the airspace. Then, a spatiotemporal weighted pattern mining algorithm is proposed, which accurately identifies flight combinations that violate the minimum flight separation constraint from four-dimensional flight trajectories proposed by users, as well as flight combinations with close flight intervals and long flight delays in the airspace. Finally, the experimental results demonstrate that the algorithm efficiently verifies the user-proposed flight trajectory and promptly identifies flight conflicts during the trajectory negotiation and verification processes. The algorithm then analyzes the flight trajectories of aircrafts by applying various constraints based on the specific traffic environment; the flight combinations which satisfy constraints can be identified. Then, based on the results identified by the algorithm, the air traffic management system can negotiate with users to adjust the flight trajectory, so as to reduce flight delay and ensure flight safety.

1. Introduction

With the continuous and rapid growth of the global air transport industry, the number of civil aviation aircraft continues to rise, and the traffic flow and flight safety issues caused by flight delays and air traffic jams are becoming more and more frequent [1].

To cope with the continuous and rapid growth of traffic flow, improve the safety level of flight operation, and reduce flight delay, in 2004, Europe proposed the Single European Sky ATM Research (SESAR) [2]; in 2005, the United States proposed the Next Generation Air Transportation System (NextGen) plan [3]; and in 2012, the International Civil Aviation Organization (ICAO), with the vision of the Global Air Traffic Management Operational Concept (GATMOC), proposed the long-awaited Aviation System Block Upgrade (ASBU) plan [4]. However, whether it is the United States' NextGen, Europe's SESAR development plan, or the ICAO's ASBU plan, trajectory-based operations will be the core technology of air traffic management in the future.

In trajectory-based operations, trajectory negotiation and verification are key components [5], which assist users in improving flight efficiency and reducing flight conflicts. Therefore, the trajectory negotiation and verification architecture for air traffic management systems and airspace users were studied. Gardi et al. [6] introduced the conceptual design of a novel four-dimensional trajectory planning, negotiation, and verification (4-PNV) system capable of automatically negotiating and verifying the trajectory in complex air traffic situations and adopting adequate separation and avoiding criteria to resolve traffic conflicts. Lunlong and Jiongpo [7] analyze the functional requirements and architecture of the new generation of flight management system (FMS); the new generation of FMS system is required to be interoperable with the future ground-based four-dimensional trajectory planning, negotiation, and verification (4-PNV) system to achieve trajectory-based operations. In order to deal with uncertainty and improve the efficiency of trajectory negotiation, Hunter et al. [8] proposed a cloud-based automatic trajectory negotiation service (ATNS) system, which is independent of the traditional national airspace system (NAS) architecture and has the capability of rapid deployment, increasing the flexibility of airspace users in uncertain situations. In order to reduce the negotiation time, Idris et al. [9] analyzed the cooperation scheme and automation system used by the flight crew and dispatcher for route change requests, which improves the accuracy and flexibility of route change and avoids increasing the controller's workload. Trajectory negotiation is helpful to reduce flight conflicts; as an important indicator, researchers have paid attention to flight safety during trajectory negotiation. Park and Menon [10] proposed a new trajectory negotiation mechanism to distribute the benefits of trajectory-based operations fairly among all stakeholders, while minimizing the cost of deviation from the desired trajectory of each aircraft, in order to ensure fairness and prevent flight conflicts. To improve the real-time performance of conflict detection at low altitude, Miao et al. [11] proposed a flight conflict detection algorithm based on the multilevel grid spatiotemporal index, which transformed the traditional trajectory-traversing multivariate conflict computation into a grid conflict state query of distributed grid databases.

Although trajectory negotiation has attracted the attention of researchers around the world, the current methods make it challenging to explore the potential information from trajectories proposed by users. With the advancement of computer technology in recent years, data mining and machine learning techniques have become increasingly popular. In order to analyze potential risks from a large quantity of historical trajectory data, Zhang et al. [12] proposed an end-to-end framework based on the depth automatic encoder network that can effectively identify typical spatial anomalies in a timely manner. Olive and Basora [13] proposed a framework based on automatically encoded artificial neural networks for detecting and identifying anomalies. The experimental results can improve safety models and support stakeholders such as airlines and airports to optimize their operating models. To overcome the shortcomings of converting the flight trajectory into a time series of equal length, Liu et al. [14] proposed a trajectory three-channel image representation method, which maps trajectory information to a three-dimensional matrix; the results indicate that this method can analyze the similarity between different trajectories and detect anomaly trajectories. In order to improve the efficiency of conflict resolution in the process of trajectory negotiation, Kim et al. [15] proposed a data-driven conflict resolution generator that uses machine learning technology to automatically generate conflict resolution strategies based on information extracted from flight data. To reduce flight conflicts and ensure flight safety, changing the flight route through trajectory negotiation has become a research hotspot. Evans et al. [16] developed a method for calculating the acceptability of aircraft rerouting using data mining techniques, so as to reduce the workload during the rerouting procedure. However, few studies have been conducted in the preflight and in-flight stages to mine and analyze flight trajectories proposed by users for detecting flight conflicts and identifying flight combinations with close flight intervals and long flight delays in congested airspace; thus, it is of great significance to conduct research on trajectory negotiation and verification methods based on spatiotemporal weighted data mining algorithms.

In light of the challenges associated with the negotiation and verification of four-dimensional trajectory, this paper seeks to ensure the safety of airspace operations while increasing the flight efficiency of users. Therefore, this paper develops a system architecture for air-ground trajectory negotiation and verification in trajectory-based operations. First, the system enables the air traffic management system and users to initiate flexible trajectory negotiation requests based on the airspace traffic environment and flight preferences of aircrafts. Second, a spatiotemporal weighted pattern mining algorithm is proposed, which takes flight delay time as weight information and analyzes flight trajectory information proposed by users by setting horizontal and vertical flight interval constraints and weight constraint. Finally, the experimental results demonstrate that the algorithm accurately identifies potential conflicts and flight combinations with close flight intervals and long flight delays in the airspace, thereby enabling ATM and users to collaboratively adjust the flight trajectory, reduce flight delay, and ensure the airspace operation safety. The highlights of our proposed method are shown as follows:

(1) In trajectory-based operations, a framework for trajectory negotiation and verification is developed to assist the air traffic management system and users in initiating trajectory negotiation based on flight preferences and airspace traffic environment

(2) A spatiotemporal weighted pattern mining algorithm is proposed, which accurately identifies potential flight conflicts and flight combinations with low flight efficiency from user-proposed trajectories. The method is then validated in the airspace by imposing various constraints

The remainder of the paper is organized as follows. Section 2 systematically introduces the system architecture for trajectory prediction, negotiation, and verification. The mining process of the spatiotemporal weighted algorithm is described in Section 3. The experimental test results are shown in Section 4. The conclusion of the paper is presented in Section 5.

2. Trajectory Prediction, Negotiation, and Verification System

2.1. Trajectory Prediction Method. In trajectory-based operations, the airspace users will negotiate with the air traffic management system during the preflight and in-flight

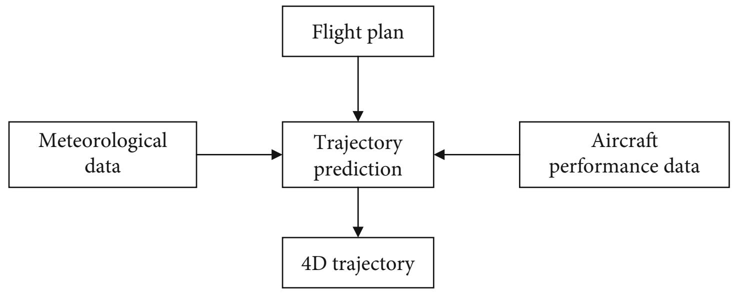

Figure 1: Trajectory prediction flow chart.

phases. As shown in Figure 1, the airspace user must first predict the four-dimensional trajectory of the aircraft based on its flight performance, flight plan, and meteorological conditions [17].

The trajectory prediction refers to the estimation of future longitude, latitude, altitude, and time based on the flight plan of the aircraft, the expected environmental conditions, and the performance model of the aircraft. The four-dimensional trajectory is derived by integrating time into the three-dimensional trajectory, which consists of two parts: the horizontal flight profile and the vertical flight profile [18]. The horizontal flight profile consists of segments of straight flight and segments of curved flight. There are two types of turning segment: fly-by and fly-over. When calculating the horizontal flight profile, the waypoint information from the flight plan is retrieved first, and then, the waypoints are connected sequentially to form straight-line segments. Since the great circle route is the shortest distance on the surface of the sphere, it is used to connect adjacent waypoints; the horizontal flight profile is then obtained by adding turn segments at the turn positions according to the heading changes between the great circle routes [19, 20].

When calculating the vertical flight profile, the aircraft is initially regarded as a mass point, and the relationship between the force acting on the aircraft and the rate of change of potential energy and kinetic energy is expressed through the energy equation, and a full energy model is established, as shown in

$$(\mathrm{Thr}-D)\bullet V_{\mathrm{TAS}} = m g_0 \frac{dh}{dt} + m V_{\mathrm{TAS}} \frac{dV_{\mathrm{TAS}}}{dt}, \quad (1)$$

where Thr represents the thrust and D represents the drag. This paper uses the aircraft performance data provided by the base of aircraft data (BADA) database to calculate the thrust and drag, m represents the aircraft mass, g_0 represents the gravitational acceleration, h represents the geodetic altitude, and V_{TAS} represents the true airspeed.

Then, the velocity in the vertical direction of the aircraft is calculated by controlling the thrust and speed of the aircraft, as shown in

$$\frac{dh}{dt} = \frac{(\mathrm{Thr}-D)\bullet V_{\mathrm{TAS}}}{m g_0}\left[1+\left(\frac{V_{\mathrm{TAS}}}{g_0}\right)\left(\frac{dV_{\mathrm{TAS}}}{dh}\right)\right]^{-1}. \quad (2)$$

To eliminate the influence of meteorological conditions, the rate of climb or descent (ROCD) is used to express the rate of climb and descent of the aircraft, as shown in

$$\mathrm{ROCD} = \frac{dH_{\mathrm{p}}}{dt} = \frac{T-\Delta T}{T}\left[\frac{(\mathrm{Thr}-D)\bullet V_{\mathrm{TAS}}}{m g_0}\right] f\{M\}, \quad (3)$$

where H_{p} represents the barometric altitude, T represents the atmospheric temperature, ΔT represents the temperature difference, and $f\{M\}$ represents the energy sharing factor, which indicates the amount of energy allocated for climbing or descending, as shown in

$$f\{M\} = \left[1+\left(\frac{V_{\mathrm{TAS}}}{g_0}\right)\left(\frac{dV_{\mathrm{TAS}}}{dh}\right)\right]^{-1}. \quad (4)$$

Finally, the four-dimensional trajectory from the departure airport to the arrival airport is predicted.

2.2. Trajectory Negotiation Architecture

2.2.1. Trajectory Negotiation Initiated by User. Trajectory negotiation can effectively satisfy user flight preferences and reduce flight delay, so this paper proposes a trajectory negotiation architecture based on references [21, 22] that allows airspace users to initiate trajectory negotiation requests during the preflight and in-flight stages. Before the flight, the airspace user utilizes the FMS to calculate the four-dimensional trajectory based on aircraft performance, flight plan, and other data and then transmits the flight trajectory to the trajectory negotiation system through the data link. During flight, the airspace user monitors the airspace traffic environment and airspace meteorological conditions. If a better route is available or an emergency such as airborne equipment failure occurs, the FMS system will recalculate the four-dimensional trajectory based on the current flight status and aircraft performance, and the new trajectory is transmitted to the trajectory negotiation system through the data link. After receiving the flight trajectories sent by the users, the trajectory negotiation system verifies the user-requested flight trajectory to ensure the minimum flight separation constraints are met. When the requested trajectory satisfies constraints, the air traffic management system will send the trajectory permission to the user, who will then send the confirmation information to conclude the trajectory negotiation procedure, as shown in Figure 2. When the requested trajectory proposed by the

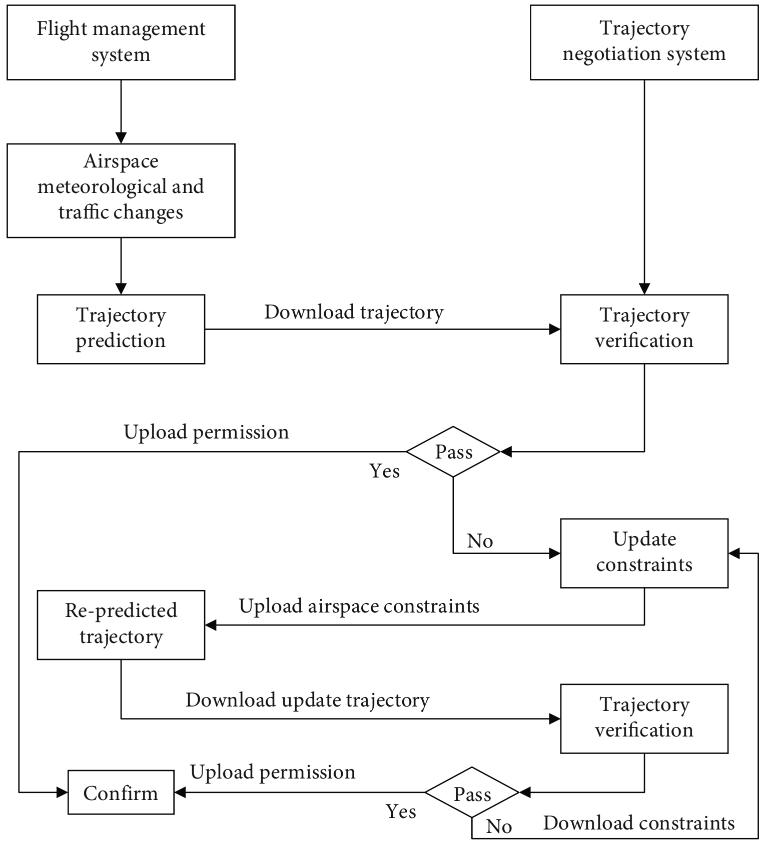

Figure 2: Flow chart of the trajectory negotiation initiated by airspace user.

user violates the minimum separation constraints, it indicates the presence of a potential flight conflict; the ATM will allocate the airspace constraints in coordination with the airspace traffic environment and send the airspace constraints to the aircraft through the data link [23, 24]. The FMS system will then recalculate the requested flight trajectory and send it to the trajectory negotiation system for trajectory verification. The air traffic management system will continuously adjust the airspace constraints until an agreement is reached with the user.

2.2.2. Trajectory Negotiation Initiated by ATM. The main objective of the air traffic management system is to reduce flight conflicts and flight delays. However, airspace convective weather and no-fly zones, among other factors, often cause flight delays and decrease flight efficiency. Therefore, the air traffic management system must identify flight combinations in the airspace with close flight intervals and long flight delays and then negotiate with these users to adjust the user's flight trajectory to improve airspace operation efficiency. During the trajectory negotiation process, the trajectory negotiation system transmits the airspace constraints (including speed, altitude, and time) to the user through the data link. After receiving the airspace constraints, the FMS system is used to calculate the requested flight trajectory based on the aircraft's performance, constraints, and status. When the requested flight trajectory violates the airspace constraints sent by the trajectory negotiation system, the user will negotiate with the air traffic management system to adjust the airspace constraints and recalculate the flight trajectory until an agreement is reached, as shown in Figure 3. When the requested trajectory satisfies the airspace constraint, the FMS system will send it to the trajectory negotiation system for verification. If the verification fails, the air traffic management system and the user will negotiate to adjust the airspace constraint until they reach an agreement. When the trajectory system passes the verification, it will send the permission information to the airspace user, who will then be able to fly based on the updated trajectory, thereby enhancing the flight efficiency.

2.3. Trajectory Verification Architecture. To ensure the safety of airspace operations, the trajectory negotiation system must verify the flight trajectories proposed by users. The trajectory negotiation system receives the flight trajectory information sent by users through the data link and then verifies the user's flight trajectory at each moment by calculating the horizontal and vertical distances between the user's flight trajectories in the airspace [6]. If the flight interval between users is less than the minimum flight separation constraint, it indicates that potential flight conflicts between aircrafts exist. Therefore, the ATM must negotiate with users to adjust flight trajectory and ensure flight safety within the airspace. As shown in Figure 4, when the flight interval

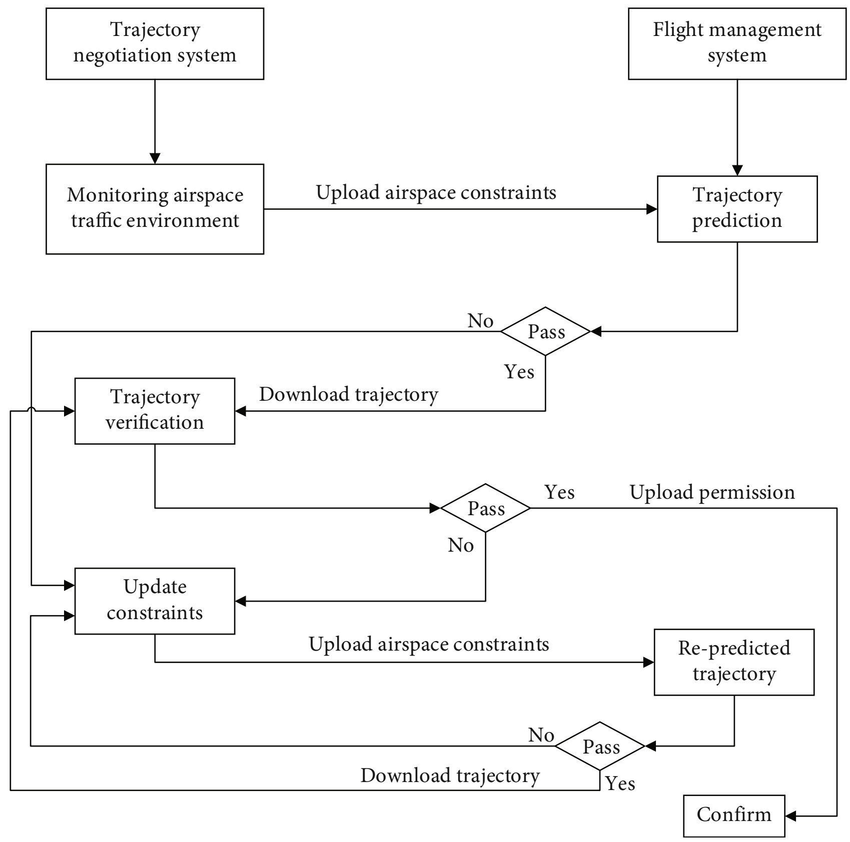

Figure 3: Flow chart of the trajectory negotiation initiated by ATM.

between aircrafts satisfies the minimum flight separation constraint, the time is updated until the trajectory verification is complete.

2.4. Problem Description of Trajectory Negotiation and Verification. In trajectory-based operations, four-dimensional trajectory negotiation and verification can detect flight conflicts, reduce flight delay, and improve airspace operation efficiency. Therefore, before or during flight, the user transmits the four-dimensional trajectory to the air traffic management system. Then, in order to ensure flight safety, after receiving the user's proposed flight trajectory, the air traffic management system verifies whether the proposed flight trajectory satisfies the set horizontal and vertical flight separation constraints. Secondly, in the process of airspace operation, meteorological hazards, no-fly zones, etc., will cause the aircraft to deviate from the economic speed and altitude, causing flight delay and reducing flight efficiency; therefore, the ATM must identify flight combinations with a long flight delay and close flight interval so that the air traffic management system and users can negotiate to adjust flight trajectories and reduce flight congestion and flight delay.

Therefore, how to quickly and accurately identify flight combinations that violate the minimum flight separation constraint from a large number of trajectory information at different times to ensure flight safety and how to identify flight combinations with close flight intervals and long flight delays in the airspace, in order to improve flight efficiency, have great significance.

3. Spatiotemporal Weighted Pattern Mining Algorithm

This paper proposes a spatiotemporal weighted pattern mining algorithm based on the works of Kiran et al. and Kelin et al. [25, 26] to improve airspace operation efficiency and ensure flight safety. As shown in Figure 5, this algorithm identifies flight combinations that violate minimum separation constraints by first analyzing the flight trajectory proposed by users, so that the air traffic management system and users can negotiate to adjust the flight trajectory, eliminate flight conflicts, and ensure flight safety. Second, the algorithm can obtain flight combinations with close flight intervals and long flight delay by analyzing the flight trajectory and the user's flight delay information in airspace with heavy traffic and then negotiate with the user to adjust the flight trajectory to increase flight efficiency.

3.1. Algorithm Definition. In order to explain the operation process of algorithm in detail, the hypothetical data in a similar format to experimental data are used in this paper, as shown in Tables 1–3. Among them, Table 1 is the flight database, which represents the users of the airspace at various times. Table 2 is a spatiotemporal database that uses time (s), latitude (°), longitude (°), and altitude (m) to represent the position information of each aircraft at different times; t represents the different flight times, f represents the different aircraft in the airspace, and data in brackets represents the latitude, longitude, and altitude of the aircraft at different

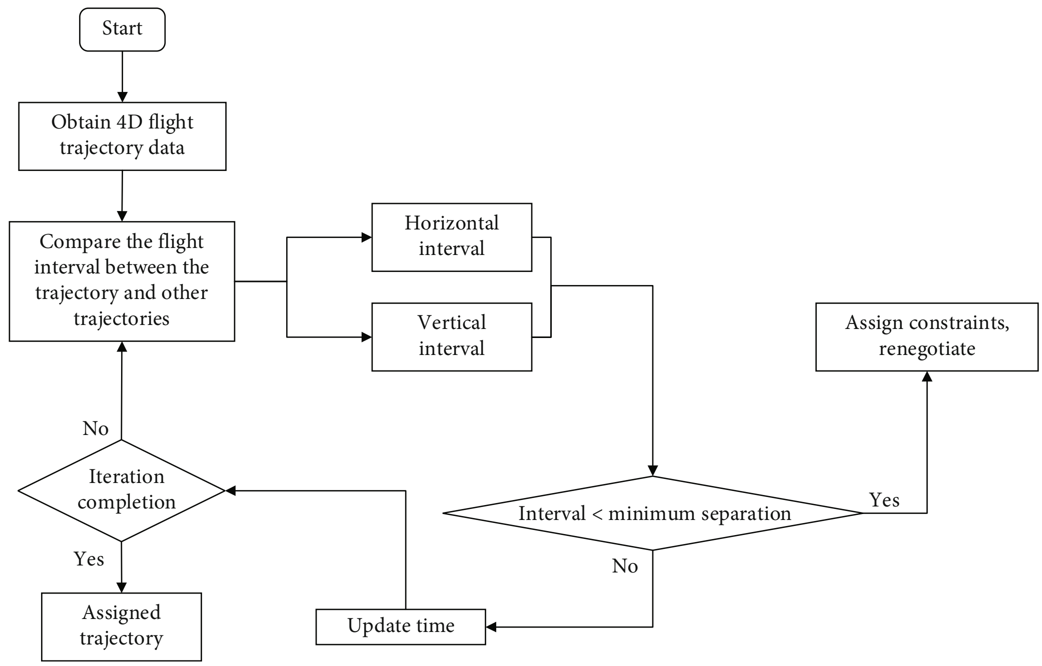

Figure 4: Flow chart of the trajectory verification.

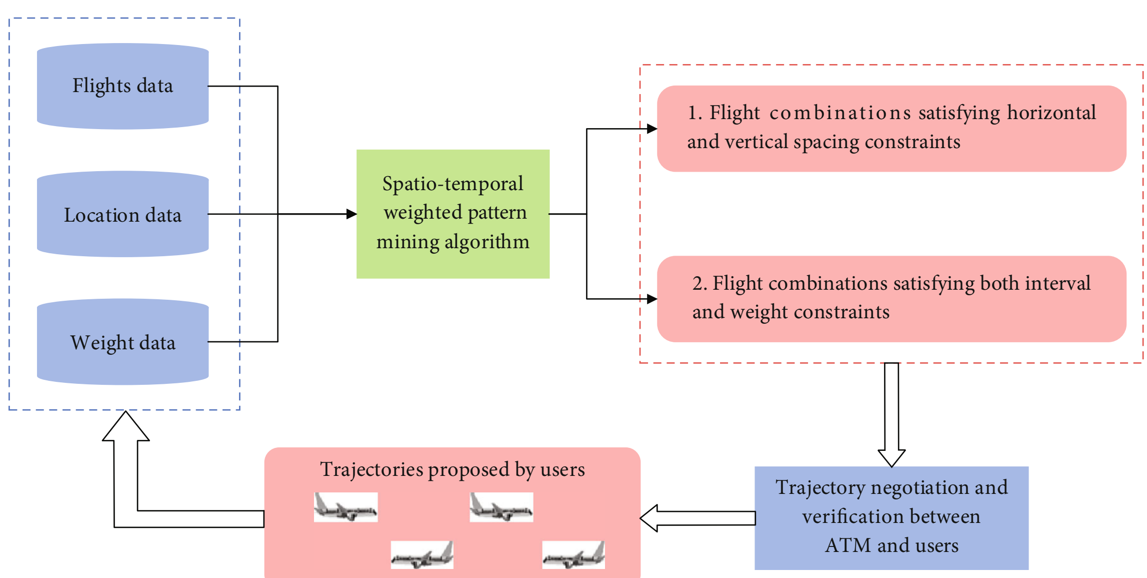

Figure 5: Schematic diagram of algorithm operation.

Table 1: Flight database.

t	f
t_1	$f_1 f_2 f_3 f_4$
t_2	$f_1 f_2 f_3 f_4$
t_3	$f_1 f_2 f_3 f_4$
t_4	$f_1 f_2 f_3 f_4$
t_5	$f_1 f_2 f_3 f_4$

times. Table 3 is a weight database that represents the minutes of a flight delay, and the definitions used to understand the operation of the algorithm are given below.

Definition 1. The weight sum at the same time represents the sum of the corresponding weights of items in the item set X at the same time, represented by $\mathrm{ws}(X, t_i)$, and the unit is minutes: $\mathrm{ws}(X, t_i) = \sum_{x \in X} \omega(x, t_i)$.

Example 1. At the t_1 moment, $\mathrm{ws}(f_1 f_4, t_1) = \omega(f_1, t_1) + \omega(f_4, t_1) = 20 + 23 = 43$.

Table 2: Spatiotemporal database.

t	f			
	f_1	f_2	f_3	f_4
t_1	(31.51, 120.31, 9893)	(29.91, 113.73, 9532)	(31.59, 120.39, 9806)	(31.55, 120.36, 9860)
t_2	(30.56, 120.58, 9901)	(30.55, 120.56, 9894)	(31.26, 113.91, 8984)	(31.25, 113.93, 9068)
t_3	(31.31, 120.42, 9909)	(30.29, 113.31, 9625)	(30.26, 113.33, 9772)	(29.22, 120.23, 9076)
t_4	(31.36, 120.61, 9917)	(29.8, 113.3, 9636)	(31.38, 120.63, 9839)	(31.41, 120.58, 9984)
t_5	(31.61, 118.32, 9925)	(31.63, 118.36, 9896)	(31.66, 118.35, 9805)	(31.59, 118.31, 9982)

Table 3: Weighted database.

t	f			
	f_1	f_2	f_3	f_4
t_1	20	8	15	23
t_2	18	11	16	25
t_3	16	9	13	22
t_4	22	12	16	26
t_5	19	10	18	25

Definition 2. The weight sum represents the sum of the corresponding weights in the item set X at all times of the dataset, and the unit is minutes: $\mathrm{WS}(X) = \sum_{t_i \in t} \mathrm{ws}(X, t_i)$.

Example 2. At time t_1, t_4, and t_5, the combination of f_1 and f_4 satisfies the interval constraint $\mathrm{WS}(f_1 f_4) = \mathrm{ws}(f_1 f_4, t_1) + \mathrm{ws}(f_1 f_4, t_4) + \mathrm{ws}(f_1 f_4, t_5) = (20 + 23) + (22 + 26) + (19 + 25) = 135$.

Definition 3. The weighted item set X indicates that the weight sum of the item set X is larger than the set minimum weight sum constraint ($\min_{\mathrm{WS}}$), $\mathrm{WS}(X) \geq \min_{\mathrm{WS}}$.

Example 3. If $\min_{\mathrm{WS}} = 120$ and $\mathrm{WS}(f_4) = 121$, then f_4 is a weighted item.

Definition 4. The spatiotemporal weighted item set X indicates that the horizontal and vertical intervals between items in the weighted itemset are less than the set requirements for the horizontal and vertical intervals, the unit of horizontal interval is nautical miles, and the unit of vertical interval is meters, which is

$$\forall x_a, x_b \in \mathrm{X}, a \neq b, \left(\mathrm{hor}_{\mathrm{dis}(x_a, x_b)} \leq \mathrm{sep}_{\mathrm{hor}}\right) \&\& \left(\mathrm{ver}_{\mathrm{dis}(x_a, x_b)} \leq \mathrm{sep}_{\mathrm{ver}}\right). \quad (5)$$

Example 4. If $\mathrm{sep}_{\mathrm{hor}} = 5\,\mathrm{nm}$ and $\mathrm{sep}_{\mathrm{ver}} = 300\,\mathrm{m}$, at the t_2 moment, and $\mathrm{hor}_{\mathrm{dis}(f_3, f_4)} = 1.188\,\mathrm{nm}$ and $\mathrm{ver}_{\mathrm{dis}(f_3, f_4)} = 84\,\mathrm{m}$, then $f_3 f_4$ is a spatiotemporal item set.

Definition 5. $\mathrm{MWS}(X)$ represents the sum of the weights in the item set X that satisfy the interval constraint at the same time, and the unit is minutes: $\mathrm{MWS}(X) = \sum_{x \in \mathrm{X}} \omega(x)$.

Example 5. At the t_3 moment, $\mathrm{MWS}(f_2 f_3) = \omega(f_2) + \omega(f_3) = 9 + 13 = 22$.

Definition 6. $\mathrm{BNWS}(X)$ represents the maximum weight after item set X in the dataset, and the unit is minutes.

Example 6. At the t_5 moment, $\mathrm{BNWS}(f_2 f_3) = \mathrm{BNWS}(f_2 f_3, t_5) = 25$.

Definition 7. For item x in the dataset, if $\mathrm{MWS}(x) + \mathrm{BNWS}(x) \geq \min_{\mathrm{WS}}$, then x is the candidate.

Example 7. If $\min_{\mathrm{WS}} = 120$, $\mathrm{MWS}(f_1) = 95$, and $\mathrm{BNWS}(f_1) = 129$, then $\mathrm{MWS}(f_1) + \mathrm{BNWS}(f_1) = 224 > 120$; hence, f_1 is a candidate item.

Definition 8. For extension item x in the dataset, the interval constraint is satisfied with the preceding item p, which is

$$\left(\mathrm{hor}_{\mathrm{dis}(x,p)} \leq \mathrm{sep}_{\mathrm{hor}}\right) \&\& \left(\mathrm{ver}_{\mathrm{dis}(x,p)} \leq \mathrm{sep}_{\mathrm{ver}}\right). \quad (6)$$

Then, take p as the predecessor of x.

Example 8. At the t_2 moment, if f_4 is an extension item and $\mathrm{hor}_{\mathrm{dis}(f_3, f_4)} \leq \mathrm{sep}_{\mathrm{hor}}$ and $\mathrm{ver}_{\mathrm{dis}(f_3, f_4)} \leq \mathrm{sep}_{\mathrm{ver}}$ are satisfied, then f_3 is the predecessor of f_4.

3.2. Algorithm Mining Process

3.2.1. Spatiotemporal Data Mining. In order to detect flight conflict and ensure flight safety, this paper first mines the item sets that satisfy the interval constraints from the trajectory information proposed by users. The mining process begins by reading the three-dimensional position coordinates of aircrafts in the airspace at various times. Second, this paper uses the trajectory information provided by users to compare whether the horizontal and vertical intervals between aircrafts satisfy the minimum separation constraints at each moment and then identifies the flight combinations that violate the minimum flight separation constraints.

As shown in the pseudocode in Algorithm 1, the algorithm uses each item as an extension item at different times, beginning with the first item to determine the flight intervals between the extension item and the remaining items in the line. If the horizontal and vertical distances between the item

1. Input: The location and weight information of aircrafts at different times in the airspace
2. Output: Flight combinations satisfying flight interval constraints at different times
3. For extension in item sets

    Calculate the flight intervals between the expansion item and other items at the same time;
    If the horizontal and vertical intervals satisfy the interval constraints and this item is in front of the extension item
        add to predecessors
    Else if the horizontal and vertical intervals satisfy the interval constraints and this item is located after the extension
        add to candidates
    End if
    Use pruning strategy to remove some candidates
    Add candidate to the extension recursively until the candidates of the extension are empty

End for

Algorithm 1: Spatiotemporal mining algorithm.

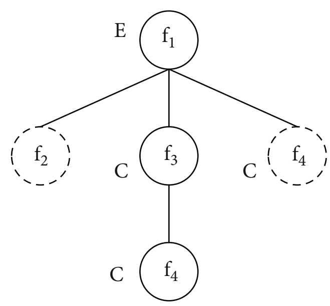

Figure 6: Schematic diagram of item expansion.

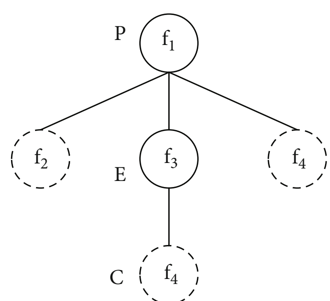

Figure 7: Schematic diagram of precursor trimming.

and the extension item are less than the minimum flight separation constraints, the item will be considered the extension item's predecessor. When the item is identical to the extension item, it will move backward. When the horizontal and vertical distances between the subsequent item and the extension item are less than the minimum flight separation constraints, the subsequent item is considered a candidate for the extension item.

This paper proposes a precursor pruning strategy to increase the algorithm's mining efficiency by removing candidate items during the algorithm's execution. When the flight intervals between the predecessor item of the extension item and each candidate item of the extension item are less than the minimum flight separation constraints, the candidate can be eliminated, thereby accelerating the algorithm's execution. The candidates are then sequentially added to the current expansion item for recursive expansion until the candidates' list is empty. Finally, each output in the expansion item is the combination of aircraft whose horizontal and vertical intervals satisfy the minimum flight separation constraints.

Table 4: Flight combinations satisfying interval constraint.

t	Combination
t_1	$(f_1 f_4)$, (f_2), $(f_3 f_4)$
t_2	$(f_1 f_2)$, $(f_3 f_4)$
t_3	(f_1), $(f_2 f_3)$, (f_4)
t_4	$(f_1 f_3 f_4)$, (f_2)
t_5	$(f_1 f_2 f_3 f_4)$

Theorem 9. *Assuming E is the extension item, C_T is the candidate item set of E and P_T is the predecessor item set of E. For any candidate item $C(C \in C_T)$, there is a predecessor item $P(P \in P_T)$, satisfying*

$$hor_{dis(P,C)} \leq sep_{hor} \& ver_{dis(P,C)} \leq sep_{ver}. \quad (7)$$

The sep_{hor} and sep_{ver} represent the minimum horizontal and vertical flight separation constraints, respectively, and then, the candidate item C can be previously extended by the predecessor item P, and C can be pruned.

Proof (proof of contradiction). For extension item E, $P(P \in P_T)$ and $C(C \in C_T)$ are the precursor and candidate items for E, respectively. If items PE and PC also satisfy the horizontal and vertical interval constraints, the item PEC can be obtained when extending P. The item EC satisfy the horizontal and vertical interval constraints when extending E. Considering that each item appears once, the EC item obtained by expanding item E is a subset of the PEC item, which contradicts the hypothesis. Therefore, the original Theorem 9 holds. □

To describe the mining process in detail, the horizontal and vertical intervals are set in this paper (for example, $sep_{hor} = 5\,\text{nm}$ and $sep_{ver} = 300\,\text{m}$), and the minimum weight constraint $min_{WS} = 120$ is set at the same time. Then, based on the three-dimensional position information, the

1. Input: Item sets that satisfy flight intervals constraints at different times
2. Output: Item sets satisfying flight intervals and weight constraint
3. For each extension
    Calculate the MWS and BNWS of the extension
    Generate single candidates
    Use a pruning strategy to prune some candidates
    Delete candidates that do not satisfy the weight constraint
    Sort Candidates
    Construct the precursor item and add the candidate item to the extension item for recursive mining until the candidate item is empty

End for

Algorithm 2: Spatiotemporal weighted pattern mining algorithm.

Table 5: MWS and BNWS data filling.

	f_{1_MWS}	f_{1_BNWS}	f_{2_MWS}	f_{2_BNWS}	f_{3_MWS}	f_{3_BNWS}	f_{4_MWS}	f_{4_BNWS}
t_1	20	23	8	0	15	23	23	0
t_2	18	11	11	0	16	25	25	0
t_3	16	0	9	13	13	0	22	0
t_4	22	42	12	0	16	26	26	0
t_5	19	53	10	43	18	25	25	0

Table 6: Generation of single candidate.

	f_1	f_2	f_3	f_4
MWS	95	50	78	121
BNWS	129	56	99	0

Table 7: Item sets satisfying intervals and weight constraint.

Number	1	2	3	4
Item set	f_1-f_3-f_4	f_1-f_4	f_3-f_4	f_4

algorithm calculates the relationship between the horizontal and vertical intervals of aircrafts and the set horizontal and vertical separation constraints and places flight combinations that satisfy the minimum separation constraints simultaneously with adjacent combinations in parentheses. Using time t_4 as an example, f_1 is used as an extension to calculate the horizontal and vertical intervals between f_1 and f_2, f_3, and f_4 firstly, the intervals between f_1 and f_2 violate the set minimum separation constraints, then delete f_2, and both f_3 and f_4 satisfy the horizontal and vertical minimum separation constraints with f_1, then f_3 and f_4 are candidates for f_1, and then, the f_3 is added as an extension item, so the current extension item is f_1f_3; then, calculate that f_4, f_1, and f_3 all satisfy the horizontal and vertical minimum separation constraints, and the f_4 is added to the current expansion item, that is, $f_1f_3f_4$. At this point, the candidate item is empty, which means that the flight combination $f_1f_3f_4$ that satisfies the minimum separation constraints is output, as shown in Figure 6.

Table 8: Flight information sheet.

Flight	Departure	Destination	Departure time
f_1	ZSHC	ZHHH	08 : 10
f_2	ZSSS	ZGHA	08 : 08
f_3	ZSHC	ZHCC	08 : 12
f_4	ZHCC	ZGHA	08 : 28
f_5	ZSNJ	ZUCK	08 : 26

When f_3 is used as the extension item, the intervals between f_1f_3 and f_3f_4 satisfy the set minimum separation constraints. Thus, f_1 is used as the predecessor item of the extension item f_3, and f_4 is used as the candidate item of the extension item f_3. However, since the precursor f_1 and candidate f_4 satisfy the minimum separation constraints, this candidate f_4 is deleted; that is, there is no output when f_3 is used as an extension, as shown in Figure 7.

The flight combinations that satisfy the minimum separation constraints at various times are then identified. As shown in Table 4, the distances between the items in brackets within the same time in the table are all less than the minimum separation constraints set by the algorithm.

3.2.2. Spatiotemporal Weighted Data Mining. In order to support the ATM system to initiate trajectory negotiation, alleviate airspace congestion; after obtaining the flight combinations that satisfy the separation constraints, the flight delay time of each flight is used as the weight information. This paper identifies the flight combinations that satisfy the flight intervals and weight constraint simultaneously

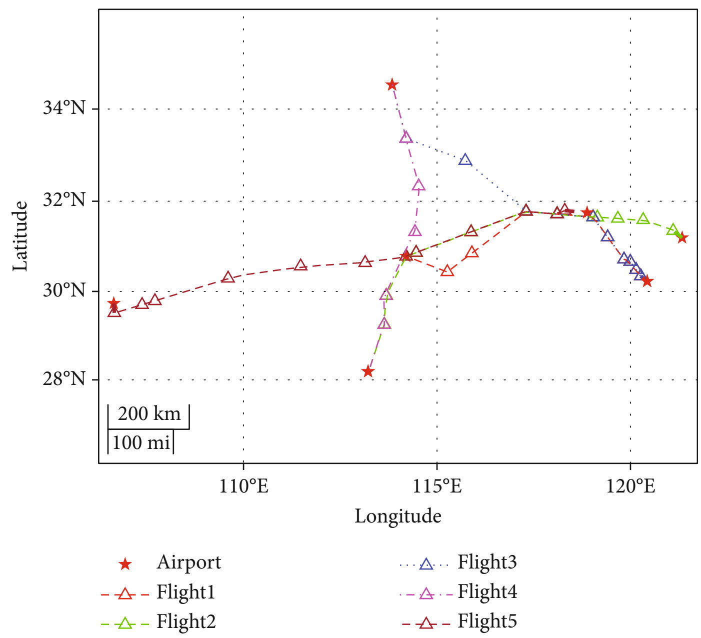

Figure 8: Schematic diagram of the flight plan.

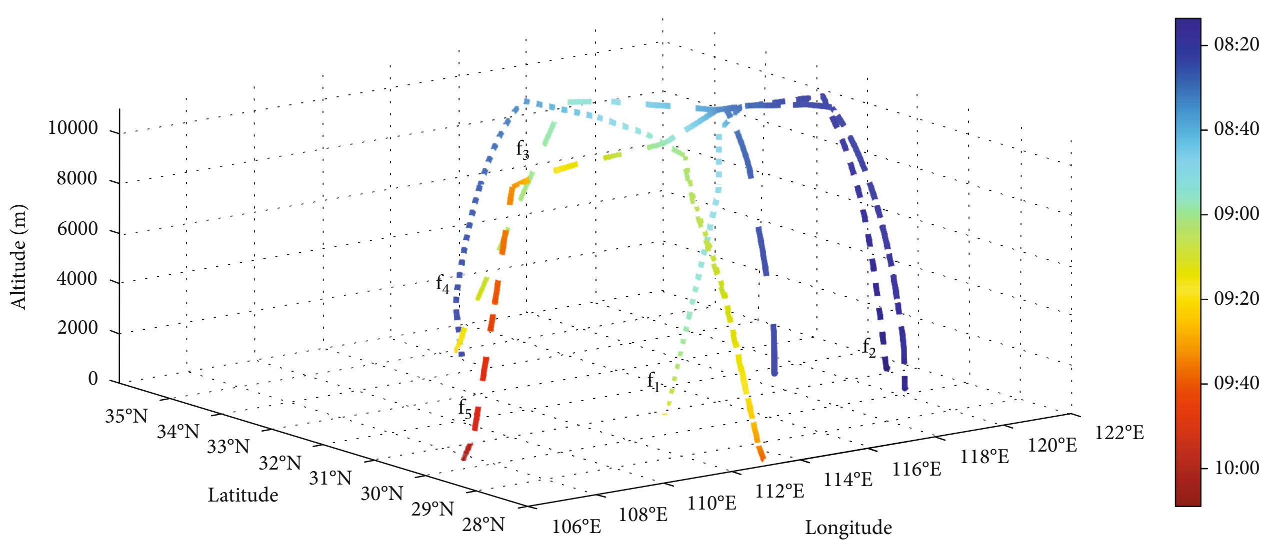

Figure 9: Schematic diagram of the four-dimensional flight trajectory before negotiation.

from the user's trajectory information; the pseudocode of the algorithm is shown in Algorithm 2.

To identify flight combinations that satisfy both the intervals and weight constraint, each item is read from the flight combinations that satisfy the interval constraints at each moment, and the MWS and BNWS values are filled for each item, where MWS represents the weighted sum of the items that occur at the same time moment and BNWS represents the maximum sum of weights behind the item at each time, as shown in Table 5. Then, when the expansion item is empty, each item that satisfies the interval constraints is read from the flight combinations, along with a check to determine whether the item appears only once. If it only appears once, the BNWS of the item is assigned to the candidate item; if another item with the same name is read, it is determined if the items are at the same time. If it is located at different times, the item's weight is added to the MWS, and the item's BNWS is determined based on whether or not it only appears once at that time. If the item is present at the same time, the values of BNWS and the temporarily stored BNWS are compared, and the larger BNWS is used as the item's temporary BNWS. If the item appears for the last time at this moment, the BNWS of the item is computed, and a single candidate item is generated, as shown in Table 6.

When the extension item is not empty, the precursor pruning strategy is employed to first remove candidate

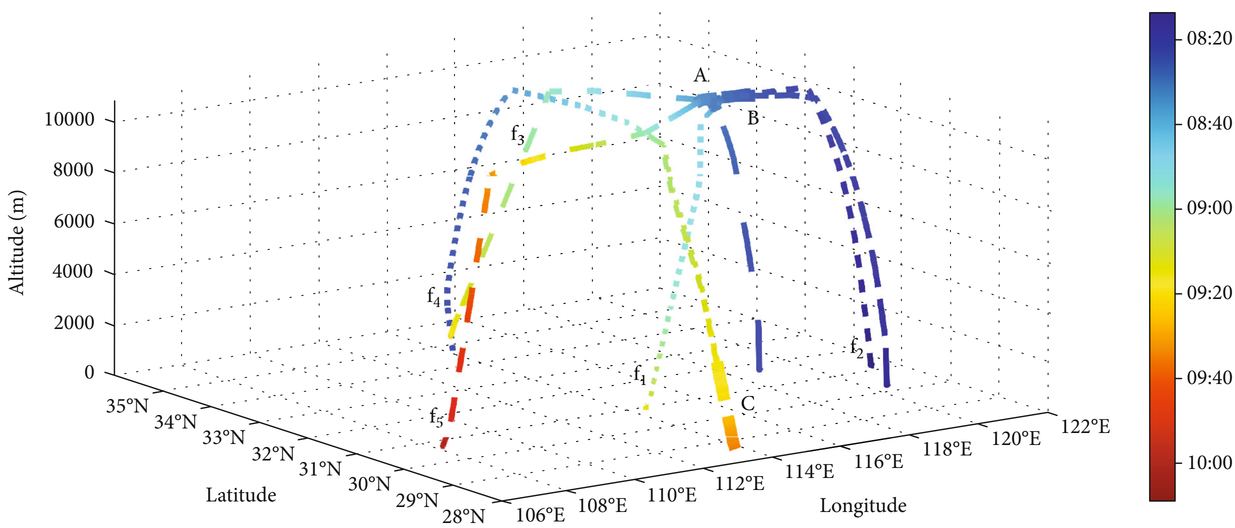

Figure 10: Schematic diagram of flight trajectory mining results.

Table 9: Altitude change after trajectory negotiation.

	Before negotiation	After negotiation
f_2	36000 ft	32000 ft

items. Second, the algorithm described above is used to calculate BNWS for extension items and candidate items, and then, candidates are generated if the extension item is not empty. After calculating the single candidate of the extension item, the proposed candidate pruning strategy is applied to prune the single candidate item to increase the algorithm's efficiency.

Theorem 10. *For candidate item $C(C \in C_T)$, $MWS(C)$ represents the weights sum of candidate item C at various times, and $BNWS(C)$ represents the maximum weight sum of the subsequent item of candidate item C, satisfying*

$$MWS(C) + BNWS(C) < \min_{WS}. \quad (8)$$

The $\min_{WS}$ represents the minimum weight sum constraint, then the combination of candidate C and subsequent items is still less than the minimum constraint, and C can be pruned.

Proof (proof of contradiction). For candidate item C that satisfies weight constraint, $\mathrm{MWS}(C)$ represents the sum of weights of C items in the database, and $\mathrm{BNWS}(C)$ represents the maximum weight of subsequent items that appear with item C at the same time. If $\mathrm{MWS}(C) + \mathrm{BNWS}(C)$ is less than $\min_{WS}$, it means that the item sets combined with item C and subsequent items still violate the weight constraint, which contradicts the hypothesis. Therefore, the original Theorem 10 holds. □

After a single candidate has been determined, each item is individually identified as an extension item. In the mining process, when the extension item is empty, the single candidate item generated above is used as an extension item, the items following the extension item are used as candidates for recursive mining, and the predecessor pruning strategy is used to delete the candidate items to reduce the computational complexity of the algorithm. When the extension item is not empty, the candidate items are added to the extension item as new extension items in turn, and the candidate item's subsequent items are used as new candidate items. At the same time, the predecessor pruning strategy is used to remove candidate items, and then, recursive mining is performed. Finally, the algorithm identifies flight combinations that satisfy the intervals and weight constraint, as shown in Table 7.

4. Analysis of Experimental Results

In order to verify the effectiveness of the spatiotemporal weighted pattern mining algorithm proposed for four-dimensional trajectory negotiation and verification, the trajectory negotiation initiated by the user and the air traffic management system is tested, respectively. The experimental platform is a laptop with an i5 2.5 GHz processor, Windows 10 operating system, and 8 GB of memory.

4.1. Trajectory Negotiation Initiated by the User. In order to explain the user-initiated trajectory negotiation process in detail, this paper assumes that there are flights f_1-f_5 in the airspace, with the departure and destination airports and expected departure time listed in Table 8. As depicted in Figure 8, the flight plan is then formulated for airspace users through collaborative allocation based on the route resources in the airspace and is represented by a series of waypoints.

In trajectory-based operations, the airspace user calculates the four-dimensional trajectory based on the flight plan information and the aircraft performance, including take-off weight, aerodynamic performance, and engine thrust; the four-dimensional trajectories of flights f_1-f_5 are shown in Figure 9; the time information of the four-dimensional

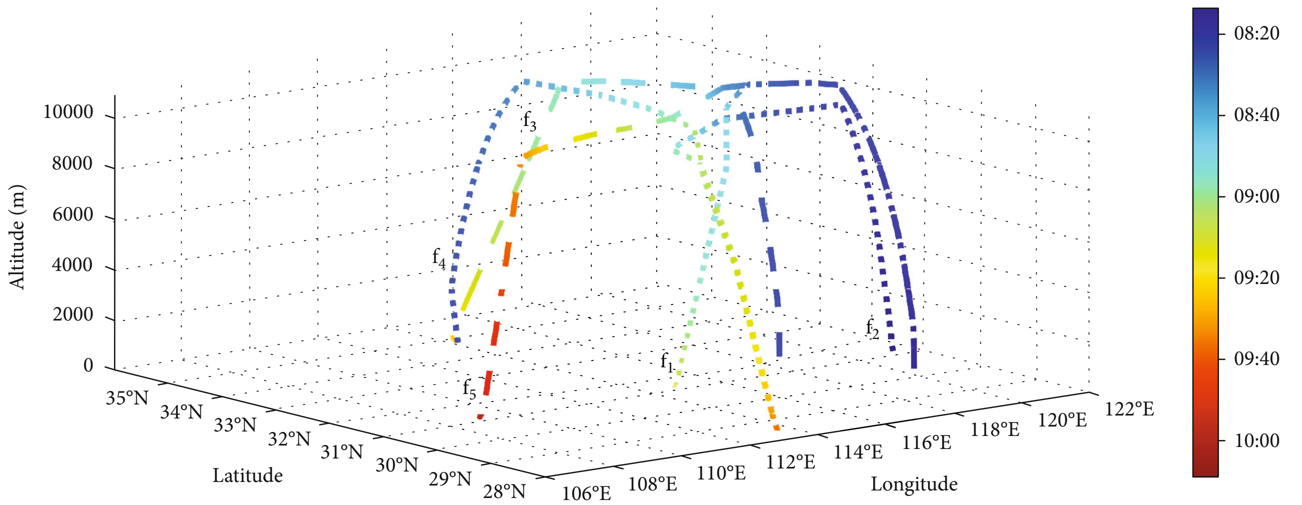

Figure 11: Schematic diagram of four-dimensional trajectory after negotiation.

trajectory is represented by gradient color; if the colors of the flight trajectories are the same, it means that the users are at the same flight time. Then, the flight trajectory is transmitted through data link to the air traffic management system for negotiation.

In order to ensure the flight safety of airspace users, when the air traffic management system receives the flight trajectories sent by airspace users, it will analyze the flight trajectory data containing time and space information, and then, the flight conflicts are detected by identify the flight combinations that violate the flight separation constraints. As shown in Figure 10, flight trajectories that violate the flight separation constraints are depicted by bold curves in figures A, B, and C, indicating that flight conflicts occurred in areas A, B, and C. Area A indicates that the flight trajectories proposed by flights f_2 and f_5 violate flight separation constraints at the top of flight f_5's climbing area, area B indicates that the flight trajectories proposed by flights f_1 and f_2 violate flight separation constraints during the cruise phase, and area C indicates that the flight trajectories proposed by flights f_2 and f_4 violate flight separation constraints during the landing phase. Therefore, the air traffic management system must negotiate with the user to adjust the airspace constraints based on the mining results, in order to resolve the flight conflict and ensure the safety of airspace operation.

After identifying flight combinations that violate the minimum flight separation constraints in the airspace based on the four-dimensional trajectory information proposed by the user, the air traffic management system negotiates with the user to allocate the airspace constraints according to the airspace traffic environment. Then, the cruise altitude of the f_2 is adjusted through negotiation, as shown in Table 9.

After trajectory negotiation, the f_2 recalculates the trajectory and sends it to the air traffic management system, and then, the flight conflicts are detected by identifying the flight combinations that violate the flight separation constraints. As shown in Figure 11, there are no flight conflicts in the airspace, thereby ensuring the safety of airspace operations.

Table 10: Flight information table.

Flight	Departure	Destination	Departure time
f_1	ZUCK	ZSSS	08 : 15
f_2	ZHCC	ZSNJ	08 : 46
f_3	ZGHA	ZSSS	08 : 38
f_4	ZGHA	ZHCC	08 : 35
f_5	ZHCC	ZSHC	08 : 49
f_6	ZHCC	ZSNB	08 : 45
f_7	ZGHA	ZSNJ	08 : 40
f_8	ZUCK	ZSHC	08 : 02
f_9	ZUCK	ZHCC	08 : 10

4.2. Trajectory Negotiation Initiated by Air Traffic Management System. To improve airspace operation efficiency, the air traffic management system monitors the operational status of air traffic, so as to detect the airspace congestion caused by the aircrafts with close flight interval and long flight delay in time. For aircraft flying through congested airspace, the air traffic management system needs to negotiate with users to adjust flight trajectories, reduce flight delays, and alleviate airspace congestion.

In order to explain the trajectory negotiation process initiated by ATM, this paper assumes the user's departure and destination airports and planned departure time in the airspace, as shown in Table 10. Then, each airspace user is assigned a flight plan based on the airspace route resources. As shown in Figure 12, different colors represent the flight plans of different users, where the airport is represented by the five-pointed star, the waypoint by triangle, and the flight route by the dotted line.

After obtaining the flight plan, the airspace user calculates the four-dimensional flight trajectory based on the flight plan, aircraft performance, and other information, as shown in Figure 13. The color gradient curve represents the user's four-dimensional flight trajectory, with different

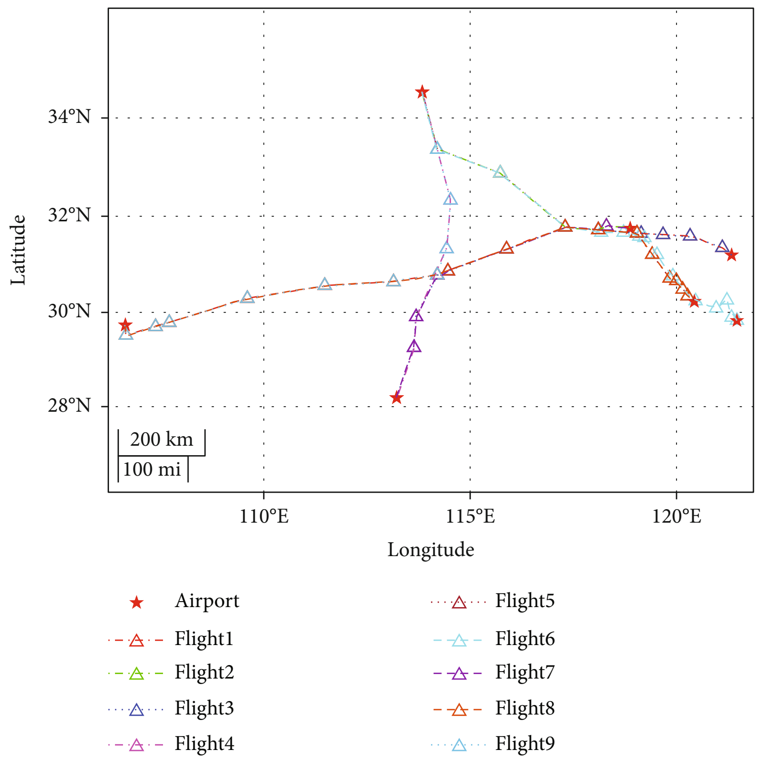

Figure 12: Schematic diagram of the aircraft flight plan.

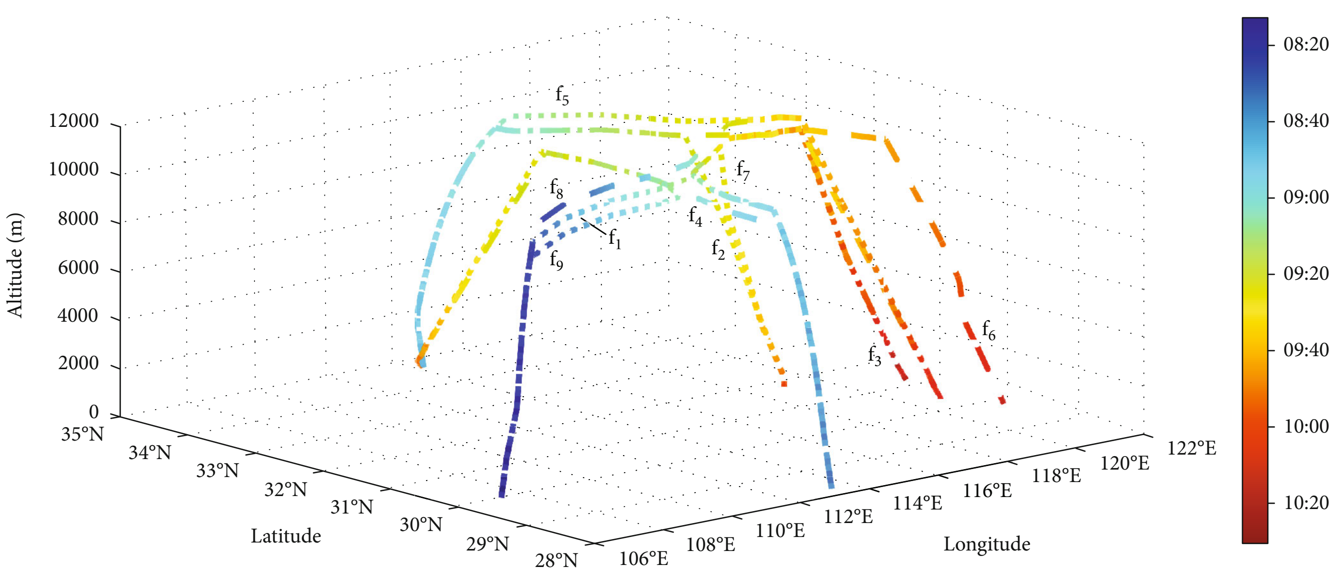

Figure 13: Schematic diagram of the four-dimensional trajectory of aircrafts in the airspace.

colors indicating different flight times. Then, the flight trajectory is transmitted to the air traffic management system, which first analyzes the four-dimensional trajectory information of all airspace users by setting the horizontal and vertical flight separation constraints. Figure 13 illustrates that the four-dimensional trajectories proposed by flights f_1-f_9 satisfy the flight separation constraints at various times, and there are no potential flight conflicts in the airspace.

For users who satisfy the minimum flight separation constraints in the airspace, the air traffic management system analyzes the airspace traffic environment based on flight interval and flight delay information, detects the congested airspace in a timely manner, and then negotiates with flights with close flight intervals and long flight delay to adjust flight trajectory to alleviate airspace traffic congestion and improve flight efficiency. Therefore, it is assumed that the flight delay information of airspace users at each flight time

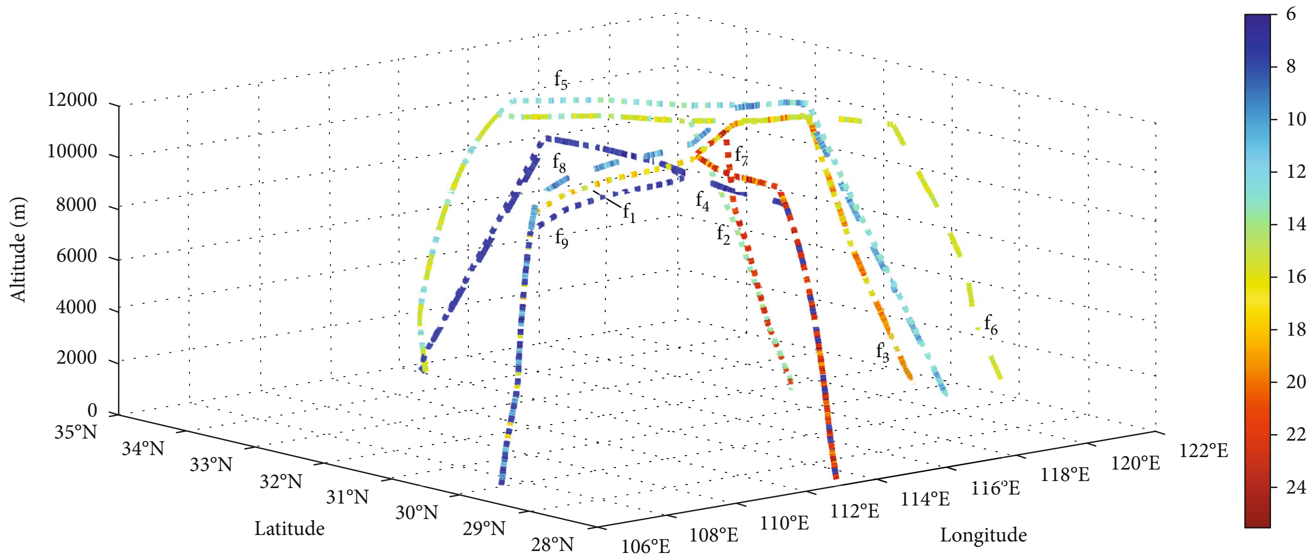

Figure 14: Schematic diagram of flight delay.

Table 11: Mining results under different constraints.

Horizontal interval constraint (nm)	Vertical interval constraint (m)	Minimum weight constraint	Flight combinations
5	300	0	0
8	600	15000	f_2-f_7
12	900	10000	f_2-f_6, f_2-f_7, f_5-f_8
15	1200	5000	f_1-f_3, f_2-f_6, f_2-f_7, f_3-f_7, f_4-f_9, f_5-f_8

is shown in Figure 14. The curves in Figure 14 represent the flight trajectories of different users, and the color of the curve represents the flight delay information at different locations.

Then, this paper mines the four-dimensional trajectory and flight delay information of users in the airspace by setting different horizontal and vertical interval constraints and minimum weight constraint, as shown in Table 11. The flight combination identified by mining is zero when the minimum horizontal and vertical interval constraints are set, indicating that there are no flight conflicts in the airspace. When a smaller flight interval and a larger weight constraint are set, the algorithm identifies fewer flight combinations, whereas when a larger flight interval and a smaller weight constraint are set, it identifies more flight combinations.

Therefore, the air traffic management system can adjust the flight intervals and weight constraint according to different traffic environments flexibly. When airspace traffic is severely congested and route resources are limited, smaller horizontal and vertical interval constraints and larger weight constraint can be imposed to negotiate with users and give priority to flights with significant delays and close flight intervals. When the flight density in the airspace is low, and there are sufficient available route resources, larger horizontal and vertical intervals and smaller weight constraint can be set and then negotiated to solve the flights with lighter flight delay, so as to improve the efficiency of airspace operations, alleviate airspace traffic congestion, and decrease flight delay.

5. Conclusions

This paper first develops a framework for trajectory prediction, negotiation, and verification to ensure flight safety and improve flight efficiency in trajectory-based operations. Secondly, a spatiotemporal weighted pattern mining algorithm is proposed for trajectory negotiation and verification. Experimental results indicate that the algorithm can identify flight combinations that violate the minimum flight separation constraints during trajectory verification and that flight combinations that satisfy the set constraints are accurately identified according to the different airspace operating states, so as to support the air traffic management system and users to manage the flight trajectory collaboratively. Additionally, collaborative decision-making between the air traffic management system and users is being considered, including airspace resource allocation and four-dimensional trajectory optimization.

Data Availability

Data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgments

This research was funded by the Natural Science Foundation of Shanghai (20ZR1427800).

References

[1] International Civil Aviation Organization (ICAO), *Report of the Asia/Pacific Area Traffic Forecasting Group*, Technical Report, ICAO, Montreal, QC, Canada, 2012.

[2] SESAR, *European ATM Master Plan—Executive View*, Technical Report, Publications Office of the European Union, Luxembourg, 2020.

[3] A. B. Fernandes, S. Atkins, K. Leiden et al., *Concept of Operations for Management by Trajectory*, NASA/CR-2018-220090, 2018.

[4] ICAO, *Aviation System Block Upgrades—The Framework for Global Harmonization*, Technical Report, ICAO, Montreal, QC, Canada, 2016.

[5] J. Klooster, S. Torres, D. Earman et al., "Trajectory synchronization and negotiation in trajectory based operations," in *29th Digital Avionics Systems Conference*, Salt Lake City, UT, USA, 2010.

[6] A. Gardi, R. Sabatini, T. Kistan, Y. Lim, and S. Ramasamy, "4 dimensional trajectory functionalities for air traffic management systems," in *2015 Integrated Communication, Navigation and Surveillance Conference (ICNS)*, Herdon, VA, USA, 2015.

[7] Z. Lunlong and L. Jiongpo, "Analysis of requirements and architecture of the next generation flight management system," in *2020 7th International Conference on Information Science and Control Engineering (ICISCE)*, pp. 1678–1682, Changsha, China, 2020.

[8] G. Hunter, A. Fernandes, B. Capozzi, and T. Barney, "An enhanced autonomy approach to automated trajectory negotiation," in *AIAA Aviation 2020 Forum*, pp. 1–14, VIRTUAL EVENT, 2020.

[9] H. Idris, S. Harrison, and D. Wing, "Cooperative automation supporting pilot-dispatch negotiation of enroute trajectory change requests," in *2018 Aviation Technology, Integration, and Operations Conference*, pp. 1–10, Atlanta, Georgia, 2018.

[10] S. G. Park and P. K. Menon, "Game-theoretic trajectory-negotiation mechanism for merging air traffic management," *Journal of Guidance, Control, and Dynamics*, vol. 40, no. 12, pp. 3061–3074, 2017.

[11] M. Shuangxi, C. Chengqi, Z. Weixin et al., "A low-altitude flight conflict detection algorithm based on a multilevel grid spatiotemporal index," *ISPRS International Journal of Geo-Information*, vol. 8, no. 6, p. 289, 2019.

[12] Z. Weining, H. Minghua, and D. Jinghan, "An end-to-end framework for flight trajectory data analysis based on deep autoencoder network," *Aerospace Science and Technology*, vol. 127, article 107726, 2022.

[13] X. Olive and L. Basora, "Detection and identification of significant events in historical aircraft trajectory data," *Transportation Research Part C: Emerging Technologies*, vol. 119, article 102737, 2020.

[14] Y. Liu, K. K. H. Ng, N. Chu, K. K. Hon, and Z. Xiaoge, "Spatio-temporal image-based flight trajectory clustering model with deep convolutional autoencoder network," *Journal of Aerospace Information Systems*, vol. 20, no. 9, pp. 575–587, 2023.

[15] K. Kim, R. Deshmukh, and I. Hwang, "Development of data-driven conflict resolution generator for en-route airspace," *Aerospace Science and Technology*, vol. 114, article 106744, 2021.

[16] A. D. Evans, P. Lee, and B. Sridhar, "Predicting the operational acceptance of airborne flight reroute requests using data mining," *Transportation Research Part C: Emerging Technologies*, vol. 96, pp. 270–289, 2018.

[17] S. Mondoloni and N. Rozen, "Aircraft trajectory prediction and synchronization for air traffic management applications," *Progress in Aerospace Sciences*, vol. 119, pp. 100640–100643, 2020.

[18] A. Nuic, "User manual for the base of aircraft data (BADA) revision 3.10," *Atmosphere*, vol. 1, pp. 1–109, 2010.

[19] G. Ghazi, R. M. Botez, C. Bourrely, and A. A. Turculet, "Method for calculating aircraft flight trajectories in presence of winds," *Journal of Aerospace Information Systems*, vol. 18, no. 7, pp. 442–463, 2021.

[20] W. Xinwei, L. Bai, S. Xichao et al., "Autonomous dispatch trajectory planning on flight deck: a search-resampling- optimization framework," *Engineering Applications of Artificial Intelligence*, vol. 119, article 105792, 2023.

[21] A. Gardi, R. Sabatini, K. D. Ridder, S. Ramasamy, and L. R. Salazar, "Automated intent negotiation and validation system for 4-dimensional trajectory based operations," in *Proceedings of European Navigation Conference (ENC 2013)*, pp. 1–12, Vienna, Austria, 2013.

[22] A. Gardi, R. Sabatini, and T. Kistan, "Multiobjective 4D trajectory optimization for integrated avionics and air traffic management systems," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 55, no. 1, pp. 170–181, 2019.

[23] Y. Xinyong, G. Xiaohua, W. Lei et al., "Cooperative multi-uav task assignment in cross-regional joint operations considering ammunition inventory," *Drones*, vol. 6, no. 3, p. 77, 2022.

[24] G. Xiaohua, W. Lei, Y. Xinyong et al., "Conditional probability based multi-objective cooperative task assignment for heterogeneous UAVs," *Engineering Applications of Artificial Intelligence*, vol. 123, pp. 106404–106422, 2023.

[25] R. U. Kiran, P. P. C. Reddy, K. Zettsu, M. Toyoda, M. Kitsuregawa, and P. K. Reddy, "Discovering spatial weighted frequent itemsets in spatiotemporal databases," in *2019 International Conference on Data Mining Workshops (ICDMW)*, pp. 987–996, Beijing, China, 2019.

[26] Z. Kelin, L. Yongqi, C. Yong, W. Miao, X. Gang, and W. Guoqing, "An efficient spatiotemporal weighted mining algorithm for flight delay analysis in single pilot operations mode," in *Seventh Asia Pacific Conference on Optics Manufacture and 2021 International Forum of Young Scientists on Advanced Optical Manufacturing (APCOM and YSAOM 2021)*, pp. 764–770, Hong Kong, Hong Kong, 2022.