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Research Article

Air Traffic Safety Assurance Based on Flight Plan Risk Assessment and Early Warning

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This article presents a novel risk assessment method for aircraft flight plans in a four-dimensional trajectory-based operation background. With the increasing air transport volume and airspace demand and during the allocation and modification of flight plans, safety should also be considered in addition to economic benefits and competitiveness. By employing the time geography concept, this article first quantifies the space-time accessibility and estimates the visiting probability of aircraft in the four-dimensional trajectory-based operation context. On this basis, this article studies the method and process to evaluate the conflict risk between one flight plan and a special airspace, the weather-influenced airspace, and another flight plan. This article also proposes the conflict risk alerting strategy. The achievements of the study are expected to provide assistance for air traffic controllers in strategic conflict avoidance and are of great significance in assuring air transport safety.

1. Introduction

A flight plan is the core product of an airline, and the basis of the airline company's business activities is an important basis for providing air traffic services. A reasonable flight plan helps reduce the potential conflict risk of aircraft, ensure air transport safety, and balance airspace utilization [1, 2]. Civil airspace resources are limited, and airspace resources are becoming increasingly tense with the continuous increase in air traffic demand. The competition for airspace resources between aircraft is bound to cause conflicts, which seriously affects the service quality of air transportation and causes great safety risks.

Under the current air transport management system, the formulation of flight plan is completed by the airline. The economic benefit and competitiveness of the flight plan is the primary consideration of airlines [3]. The impact of flight planning on air traffic safety has not been fully and scientifically assessed. Studies on conflict risk assessment methods for flight plans are insufficient [4].

However, the increase in air traffic demand and the demand for airspace resources bring greater challenges to air transport safety, especially under the operation concept of four-dimensional trajectory-based operations, which allow aircraft pilots to fly a relatively free trajectory as long as the waypoints to pass and the arrival time of each waypoint's requirements are met [5]. The controller and pilot workload consequently increased, and the airspace could not achieve effective use.

Therefore, this study proposes a novel conflict risk assessment method for flight plans, which aims to quantify the conflict risk of aircraft flight plans, provide a multidimensional reference for air traffic management, further adjust flight plans before flight departure, minimize conflict risks during the strategic phase, and eventually maximize air transport safety.

This article is structured as follows. After this introduction, Section 2 reviews the researches on air traffic safety assurance from two aspects: risk identification and monitoring and risk warning. Section 3 introduces the problem to be solved by analysing the concept of four-dimensional trajectory-based operation and the challenges and opportunities that it brings to the modern air transport industry. Section 4 proposes the quantification method of the space-time accessibility of flight plans and the calculation method of the visiting probability of aircraft in the context of four-dimensional trajectory-based operation. The conflict risk assessment method between one flight plan and a special airspace, a weather-influenced airspace, and another flight plan is also addressed in Section 4. The risk assessment process is elaborated, and the alerting strategy for flight plan adjustment is outlined as well. Section 5 provides a three-aircraft scenario to verify and illustrate the proposed risk assessment method. Section 6 summarizes the main results of this article and discusses future research directions.

2. Literature Review

Since the birth of aircraft in the early 20th century, the aviation industry has begun to explore how to ensure flight safety, especially in terms of how to avoid various flight errors or mistakes and ensure the safety management of passengers, flight attendants, and ground staff. In the research results of risk identification and monitoring, many scholars have conducted in-depth research on air traffic safety from the main dimensions, including people, equipment, environment, and management, and on the objects and technologies in the risk monitoring process.

Some researchers study the aircraft conflict risk by analysing main influencing factors, especially human factor, and establish a model between these factors and the conflict risk [6, 7]. Eyferth et al. established an air traffic controller's psychological activity model and outlined the factors to which the controller paid attention when a traffic collision occurred [8]. Shyur quantified the aviation risk caused by human error by studying aviation accidents and safety indicators and introduced the baseline risk function as a quadratic curve function into aviation risk assessment to obtain a proportional hazard model. The model is used to investigate nonlinear aviation safety factors to assess safety risks [9]. Kirwan and Gibson considered that the ATM is human-centred in recent decades and studied a human reliability assessment tool for air traffic safety management [10].

Conflict risk has also been assessed by predicting and estimating aircraft conflict probability [11–13]. Pérez-Castán et al. defined conflict risk as the combination of conflict probability between aircraft pairs and estimated air traffic flow, and he proposed a new approach to determine the conflict probability [11]. Netjasov presented a framework for airspace planning and a conflict risk assessment method using the conflict probability. The presented method has been verified to be effective in both en route and terminal manoeuvring airspaces [14]. Lehouillier et al. use a geometrical approach to explore the aircraft conflict resolution problem under uncertainties caused by the wind effect, aircraft speed prediction and flight delay in the execution of manoeuvres. Monte Carlo simulation was conducted to validate the method, and the results show that it can generate 10 solutions for 35 aircraft within 3 minutes [15]. Data driven is also one of the major research directions to assess the risk. Natalia and Salvatore proposed a novel quantitative risk assessment method for a civil airport based on historical data of aircraft accidents for nearly 30 years [16]. Oztekin develop a safety assessment tool for air traffic control system, in which safety associated with an ATC facility is modelled as an influence network using a set of risk factors [17].

In general, scholars have made many research achievements on air traffic conflict risk management and mainly focused on risk identification methods, evaluation methods and monitoring technologies. In the construction of index systems and risk evaluation, fuzzy comprehensive evaluation, analytic hierarchy processes or weighted average methods are often used for comprehensive risk evaluation [13, 18–20]. Besides, the early warning idea is reflected in safety risk management in the aviation field, and attempts have been made in the aspects of early warning principles, methods, and technical support in formulating management standards and norms [21]. However, there are few studies on aviation safety early warning management to avoid conflict from the perspective of prevention. Therefore, under the 4D TBO framework in next generation air transport system, this article proposed a flight plan risk assessment method by quantifying potential conflict probability of flight plan, thus the first barrier of aviation safety can be established by early warning and strategically optimize the flight plan.

3. Research Background and Problem Description

Currently, the task of air safety assurance generally focuses on the real-time aircraft safety separation maintenance. Specifically, the ground controller monitors the real-time aircraft' positions and status, and predict their future tracks and potential conflict between aircraft. For the aircraft to involve in potential conflict, the controller gives instructions by adjusting the heading, speed, and altitude to maintain the safety separation between aircraft. In view of the uncertainty of track prediction, many studies have divided the problem of conflict detection into deterministic and probabilistic conflict detection according to the model of uncertainty; meanwhile, conflict resolution methods have also developed from imperative to automatic track planning. With the increasing flight flow, the workload of ground controllers far exceeds their rated working capacity, especially in peak hours and some high-flow and high-density airspaces. Controller are faced with tremendous work pressure, and the safety of whole aviation system also suffer certain hidden dangers.

The future air traffic management system proposes the concept of four-dimensional trajectory-based operation (4D TBO), which provides support for active aircraft safety assurance [22]. Specifically, the key to the four-dimensional trajectory-based operation is to integrate the time dimension into the trajectory, and to accurately reflect the entire flight process by accurately describing the spatial position and time of each point on the trajectory [23, 24]. Trajectory information is able to share between the aircraft, the airline, and the air traffic control department, promote the coordinated decision-making of all departments. The whole process of ensuring the operation of the aircraft is visible, controllable, and accessible [25, 26]. By designing an effective uncongested flight trajectory for the aircraft in advance in the strategic phase and the pretactical phase, the air traffic controller's workload in the tactical phase is expected to be reduced, so that the number of aircraft that can be handled in each working hour unit can be increased, thereby increasing the airspace capacity. Besides, under the framework of the four-dimensional trajectory-based operation, the aircraft can realize the trajectory sharing between the aircraft, thus improve the pilot's situational awareness and autonomy for trajectory modification. Airspace users have higher flexibility to optimize their operation by selecting the optimal trajectory. At the same time, four-dimensional trajectory-based operation enables different safety separation criteria according to aircraft performance. Digital track management will greatly improve the automation level of air traffic control. Four-dimensional trajectory-based operation makes it possible to accurately grasp the aircraft's flight intentions, improve the predictability of the trajectory, and ensure the overall performance of the air traffic management network. Therefore, four-dimensional trajectory-based operation is an effective means to manage the airspace under the conditions of large flow, high density, and small safety separation in the future, which can significantly reduce the uncertainty of aircraft trajectory and improve the safety and utilization of airspace and airport resources [27].

At present, active safety is an important development direction of traffic system safety theory in road, railway, and maritime transportation system. Therefore, the aviation system should also focus on active conflict avoidance, which advance the air safety assurance work to the strategic stage, and adjust the flight plan with high-conflict risk to a reasonable level through the safety assessment of flight plan and early warning. In traditional air traffic control system, the flight planning phase is relatively separated from the execution phase. A flight plan containing basic information on the aircraft's flight intent was formulated and submitted several days before performing the flying mission. Economic benefit and operation efficiency are the most important objectives to achieve when designing a flight plan to maximize the airline's interests [28, 29]. Therefore, to advance the air safety assurance work to the strategic stage, it is important to propose a safety assessment method for flight plan, which is able to provide a quantitative evaluation criterion for flight plan adjustment and early warning, and provide better assurance for the aviation system.

4. Methods

4.1. Aircraft Accessibility and Visiting Probability. Since the 4D flight plan limits all passing air waypoints of aircraft and the corresponding arrival times of each waypoint, the space-time reachable area of the aircraft is limited when flying on each air route segment. The basis of flight plan risk assessment is to determine the aircraft's space-time reachable area and calculate the aircraft's visiting probability to each point inside, which are elaborated in this section.

4.1.1. Aircraft Reachable Domain Generation. Under the operation concept of four-dimensional trajectory-based operation, the range of motion of aircraft is limited to a certain space-time airspace, which is defined as the space-time accessibility of aircraft [30]. The space-time accessibility of the aircraft can reflect the pros and cons of the flight plan. A good flight plan will not give the aircraft very high accessibility, since this will increase the uncertainty during the flying process. However, it should have certain accessibility to ensure freedom for aircraft autonomous trajectory planning.

The aircraft accessibility is measured by its space-time reachable area, which can be obtained by the intersection of two cones, as illustrated in Figure 1: (1) one reverse cone with the vertex at the origin waypoint, its height is the flight duration between waypoints, and its radius is the multiplier of the flight duration and maximum flying velocity of aircraft and (2) one forward cone with the vertex at the destination waypoint and same height and radius as the reverse cone.

The first step of aircraft space-time accessibility quantification is to determine the maximum cruising velocity V_m of the aircraft according to the aircraft type, which can be found in the flight plan. Next step is to calculate the set $R_s(t)$ of all discretization units that can be reached at time t after the aircraft leaves the first waypoint s denoted by (x_s, y_s) at time t_s.

$$R_s(t) = \{(x, y)\} \mid \sqrt{(x - x_s)^2 + (y - y_s)^2} \leq (t - t_s) \times V_m. \tag{1}$$

Then, we calculated the set $R_e(t)$ of all discretization units that can reach the second waypoint e denoted by (x_e, y_e) at time t_e.

$$R_e(t) = \{(x, y)\} \mid \sqrt{(x - x_e)^2 + (y - y_e)^2} \leq (t - t_e) \times V_m, \tag{2}$$

where (x, y) represents the coordinate of the discretized unit.

The space-time reachable area $R_{es}(t)$ of the aircraft at time t can be obtained as the intersection of $R_s(t)$ and $R_e(t)$.

$$R_{es}(t) = \{R_s(t) \cap R_e(t)\}. \tag{3}$$

Details on the motivation and principle of reachable domain generation can be found in our previous work [31]. The reachable area $R_{es}(t)$ indicates the space-time accessibility of the aircraft on the air route segment r with origin waypoint s and destination waypoint e. The reachable domain $R_{es}(t)$ of the aircraft A on the air route segment r can be written as R_{Ar}. The reachable area represents the space that the aircraft can reach on the premise of meeting the requirements of passing the waypoint during flight. Computing based on maximum speed is a minimum condition, which can ensure that conflicts are avoided to the greatest extent. Further constraints, such as the over point speed limits, may narrow the reachable space and reduce the conflict

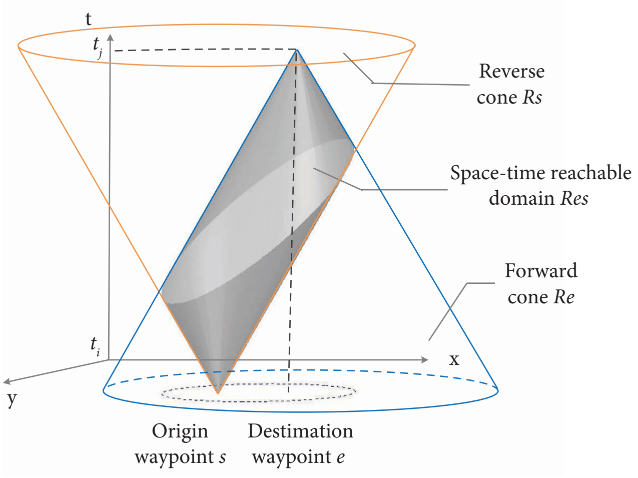


Figure 1: Illustration of space-time reachable area of aircraft.

probability and increase the accuracy of alert. This method of reachable area can be easily extended to different speed constraints by changing the V_m in equations (1) and (2) to the constrained speed value.

4.1.2. Visiting Probability Estimation. The key to risk assessment is to calculate the aircraft conflict probability, which is based on the knowledge of the potential visiting probability of aircraft to each location. The process of visiting probability calculation is as follows.

The first step is to discretize the airspace by employing grid method. As illustrated in the Figure 2, the red node represents the blue cube after discretization.

Based on the discretization, next step is to build the aircraft motion model by employing the Brownian bridge method. The expected location of aircraft A at time t satisfies the following distribution:

$$\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \mathrm{N}\left(\begin{bmatrix} \mu_X(t) \\ \mu_Y(t) \end{bmatrix}, \begin{bmatrix} \sigma_X^2(t) & 0 \\ 0 & \sigma_Y^2(t) \end{bmatrix} \right), \quad (4)$$

where

$$\mu_X(t) = \frac{(t-t_s)x_e + (t_e - t)x_s}{t_e - t_s},$$
$$\mu_Y(t) = \frac{(t-t_s)y_e + (t_e - t)y_s}{t_e - t_s}, \quad (5)$$
$$\sigma_X^2(t) = \sigma_Y^2(t) = \frac{(t-t_s)(t_e-t)}{t_e - t_s}.$$

The visiting probability to locations out of the space-time reachable area is zero. We used a truncated distribution to model the distribution probability of aircraft.

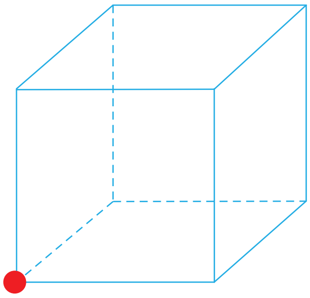


Figure 2: Illustration of airspace discretization.

$$T(x(t)) = \frac{\mathrm{N}\left(\mu_X(t), \sigma_X^2(t)\right)}{\phi(U_X(t)) - \phi(L_X(t))},$$
$$T(y(t)|x(t)) = \frac{\mathrm{N}\left(\mu_Y(t), \sigma_Y^2(t)\right)}{\phi(U_Y(t)) - \phi(L_Y(t))}, \quad (6)$$

where $T(x(t))$ is the location distribution probability along the x-axis, and $T(y(t)|x(t))$ is that along the y-axis. $\phi(\cdot)$ is the cumulative density function of the above normal distribution. $U_X(t)$ and $L_X(t)$ are the upper and lower bounds of the space-time reachable area along the x-axis at time t, and $U_Y(t)$ and $L_Y(t)$ are those along the y-axis at time t. The specific derivation and calculation process is available in our previous work. Thus, the visiting probability of aircraft A to location (x, y) at time t is able to be deduced by equation (10).

$$\mathrm{Prob}(x,y,t) = \frac{\mathrm{N}\left(\mu_X(t), \sigma_X^2(t)\right)}{\phi(U_X(t)) - \phi(L_X(t))} \times \frac{\mathrm{N}\left(\mu_Y(t), \sigma_Y^2(t)\right)}{\phi(U_Y(t)) - \phi(L_Y(t))} \times \frac{1}{t_e - t_s}. \quad (7)$$

The proposed method is able to extend to three-dimensional application, one approach is to generate the space-time reachable area in x–z plane with the same way as in x-y plane. By multiplying the conflict probability of x-y dimension and x–z dimension of each discretized point and adding them up, we are able to get the conflict probability of aircraft in three-dimension scale.

4.2. Flight Plan Risk Assessment. Based on the quantification of the aircraft's visiting probability of the space-time reachable area, it is possible to estimate the conflict probability and risk level of the flight plan. The most common type of conflict risk of flight plans is the entrance to a certain special airspace (SA) that is restricted to access, the airspace affected by extreme weather (WA), or the space-time reachable area of other flight plans. This section proposes three conflict risk calculation methods according to different characteristics of different types of conflict and addresses the risk assessment process and alerting strategy.

4.2.1. Conflict Risk with Special Airspace.

SA includes the airspace that is restricted for military purposes (RA) and danger airspace (DA). RA is a defined airspace that limits the entrance of aircraft in time or altitude. DA is the airspace delineated for the existence of dangerous activities during the specified time. The common characteristic of these two types of airspace is that all of them have certain open and closed times known in advance, and the size, shape, and position of the airspace often do not change with time [32]. Therefore, to facilitate calculations, these two types of airspace are often depicted by regular geometric shapes.

To generate the space-time special airspace set L, the first step is to set the plane of route segment r as the x-y plane, set the time dimension as the z-axis, and establish a three-dimensional coordinate system to represent the space-time airspace. Second, select a proper discretization parameter to discretize the space-time domain into several discretized units. Then, the discretized units of SA are marked as 1, and the rest are marked as 0 according to the information such as the location, boundary, and open time of the SA. The space-time SA set L is generated by all discretized units of 1.

Since the aircraft is strictly restricted from entering these two types of airspace, the conflict risk ($\mathrm{CR}_{\mathrm{AL}}$) between aircraft A and the two types of airspace can be obtained by the following equation:

$$CR_{AL} = \sum_{i=1}^{n} I_{\mathrm{SA}} \times \mathrm{Prob}_A\left(x_i, y_i, t_i\right), i \in \mathrm{STPCS}_{AL}, \tag{8}$$

where $\mathrm{STPCS}_{\mathrm{AL}}$ is the space-time potential conflict space between aircraft A and SA, which can be generated by intersecting the space-time reachable area of aircraft A and the space-time SA set L, as shown in Figure 3. I_{SA} is the severity index of the aircraft that enters SA, which can be decided by the air traffic controller according to their experience.

4.2.2. Conflict Risk with the Weather-Influenced Airspace.

Dangerous weather conditions such as lightning, tornadoes, thunderstorms, gusts, hail, and downhill winds in the mountains pose a safety hazard to aircraft flying and can cause flight delays and affect the operational efficiency of airspace systems. Avoidance of the airspace influenced by hazardous weather (WA) is necessary during the flying process. The characteristic of WA is that the vertical size, shape, upper and lower altitude bound, and the location of airspace tend to change over time [33]. Therefore, it is necessary to model WA according to the results of weather forecasting; then, the subsequent conflict probability calculation can be performed.

The process of generating the space-time weather influenced airspace set W as follows. First, the centre of WA is considered the centroid of its movement, and the space-time path of WA movement can be modelled according to predicted movement information, including vertical and altitude direction and velocity. Then, we determined the range of WA with a radius of the expected fluctuation capacity. Using the discretization method in Section 4.1, the discretized units of WA are marked as 1, and the remaining units are marked as 0 according to the information, including the space-time path range of WA. The space-time WA set W is generated by all discretized units of 1.

Since the entry of aircraft into the WA is not completely prohibited, it is necessary to build a model for the severity index of intruding the WA. Notice that the risk of aircraft entering the marginal of WA is much less than the risk of aircraft entering the core of WA, and we assume that the severity index of intruding the WA I_{WA} follows a normal distribution. Thus, the conflict risk (CR_{A2}) between aircraft A and WA can be obtained by the following equation:

$$CR_{AW} = \sum_{i=1}^{n} \varphi_{IA}\left(x_i, y_i, t_i\right) \times \mathrm{Prob}_A\left(x_i, y_i, t_i\right), i \in \mathrm{STPCS}_{AW}, \tag{9}$$

where $\mathrm{STPCS}_{\mathrm{AW}}$ is the space-time potential conflict space between aircrafts A and WA, which can be generated by intersecting the space-time reachable area of aircraft A and space-time WA set W, as shown in Figure 4.

4.2.3. Aircraft Conflict Risk between Aircraft Pairs.

There are often potential conflicts between aircraft. When the distance between two aircraft is less than the safety separation, conflict occurs [34]. Therefore, the conflict risk ($\mathrm{CR}_{\mathrm{AB}}$) between aircraft A and B can be obtained by the following equation:

$$CR_{AB} = \sum_{i=1}^{n}\sum_{j=1}^{n} I_{AB} \times \mathrm{Prob}_{AB}(i, j), i, j \in \mathrm{STPCS}_{AB},$$
$$\begin{cases} \mathrm{Prob}_{AB}(i, j) = \mathrm{Prob}_A\left(x_i, y_i, t_i\right) \times \mathrm{Prob}_B\left(x_j, y_j, t_j\right), \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} \le D, \\ \mathrm{Prob}_{AB}(i, j) = 0, \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2} > D, \end{cases} \tag{10}$$

where $\mathrm{STPCS}_{\mathrm{AB}}$ is the potential space-time conflict area between aircraft A and B, which can be generated by intersecting the space-time reachable area of the two aircraft, as shown in Figure 5. D is the safety separation criteria. i and j are any two discretization units in the potential space-time conflict domain; I_{AB} is the severity index of the conflict

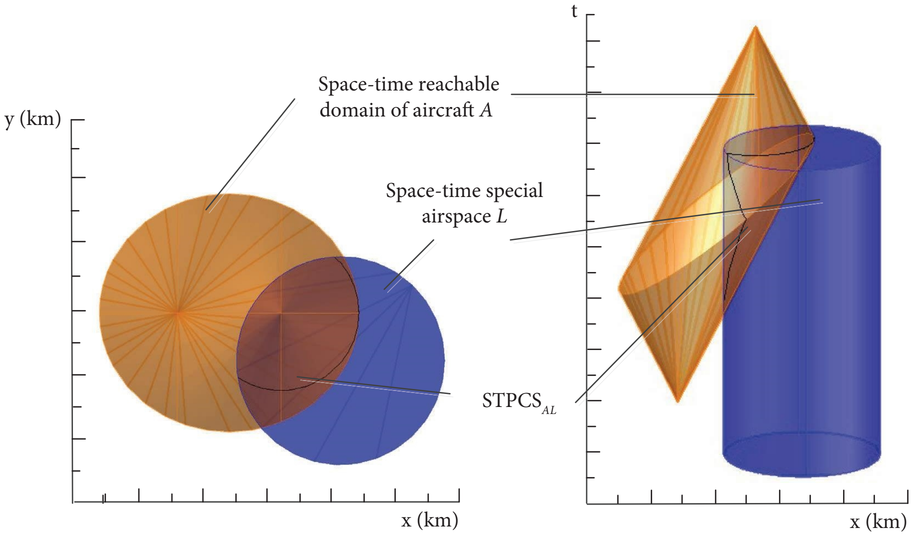


Figure 3: Conflict with the special airspace.

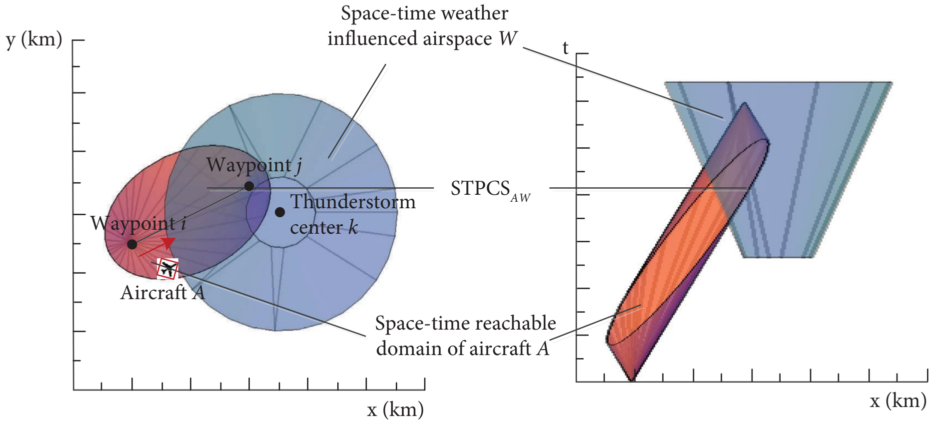


Figure 4: Conflict with weather-influenced airspace.

between aircraft pairs, which can be decided by the air traffic controller according to their experience.

4.2.4. Risk Assessment Process and Alerting Strategy. Based on the results of the conflict risk calculation of the three types of conflicts, the safety index SI_A of flight plan A can be calculated by the following equation:

$$SI_A = \frac{1}{\left(\alpha \cdot CR_{AS} + \beta \cdot CR_{AW} + \gamma \cdot CR_{AB} + 0.0001\right)}, \quad (11)$$

where α, β, γ are the weights of conflict with SA, WA, and other aircraft, respectively, which can be set and adjusted according to the requirements of the air traffic controller considering different sectors, traffic volume, and peak and low peak periods, since different airspace environments have different degrees of tolerance and restriction to various types of conflicts [35]. If the aircraft involves no conflict, we add a value of 0.0001 to the formula to ensure that the safety index is always solvable. In other words, when the flight plan can be executed with no interference, it will have a high safety index of 10000. It is noteworthy that here we consider that various type of conflict is independent, so the probability under each conflict type is superposed to obtain the total risk index of aircraft. Sometimes, superposition of multiple type of conflict may exists. In this situation, comparison between conflict probabilities of different types should be made, and the larger conflict probability is used to calculate the risk index. For example, if an aircraft's reachable area enters into a restricted airspace, we considered this flight plan have conflict risk with restricted airspace. If its reachable area also intersects with the reachable area of other aircraft, we need to calculate these two situations and judge which one has higher conflict probability. The higher conflict probability will be used to assess the conflict risk of flight plan.

In our study, the whole flying procedure is divided into several air route segments, we tried to calculate the conflict probability on each air route segments and sum them up to reflect the total conflict risk of the whole flying procedure.

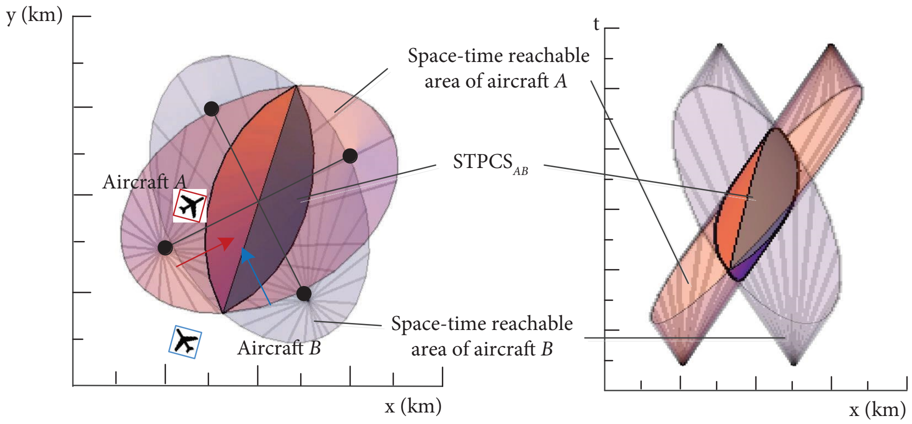


Figure 5: Conflict of flight plan between aircraft pairs.

Based on the proposed flight plan risk assessment method, the risk assessment process can be conducted as follows.

Step 1. M hours before the beginning of the flight mission, extract the information including the flight model, waypoints, planned time of passing each waypoint, and maximum flight velocity according to flight plan F_A of aircraft A.

Step 2. Number the route segment formed by each set of two waypoints r, $r = 1, 2, 3, \ldots, k$;

Step 3. Extract the airspace configuration information related to flight plan F_A, determine whether the airspace contains a special airspace, and generate a space-time special airspace set L according to the boundary, location, and opening time of the special airspace;

Step 4. Extract the airspace meteorological information related to flight plan FA, determine whether there is hazardous weather that affects the aircraft's flying activities, and generate a space-time weather-influenced airspace set W according to the type of hazardous weather, expected spread range and velocity, occurrence period, and moving trajectory;

Step 5. Generate the space-time reachable area RAr, $r = 1, 2, 3, \ldots, k$, on the route segment r of flight plan FA. The set of RAr on all route segments is defined as the space-time reachable area of flight plan FA, which is denoted by RA;

Step 6. Determine the space-time reachable areas RA, RB, . . ., RN for each aircraft $A, B, \ldots, N$ with flying missions;

Step 7. Determine whether the space-time reachable area of the aircraft and the corresponding space-time SA set L, space-time WA set W, and space-time reachable areas of other aircraft RA, RB,. . ., RN intersect. If the intersection is an empty set, output the safety index value of 10000 and offer the instruction of "no need to further adjust the flight plan";

Step 8. Calculate the conflict risk and safety index if there is an intersection set and conduct safety alert according to the value of the safety index. Determine the threshold value according to different airspace situations and different requirements, and compare the safety index value with the threshold value of alerting. For flight plans with safety index values greater than the threshold, output the instructions of "safety not guaranteed" and "flight plan adjustment recommended," and trigger a secondary level warning; for flight plans with safety index values lower than the threshold, output the instructions of "high conflict risk", "please adjust flight plan," and trigger a first-level warning.

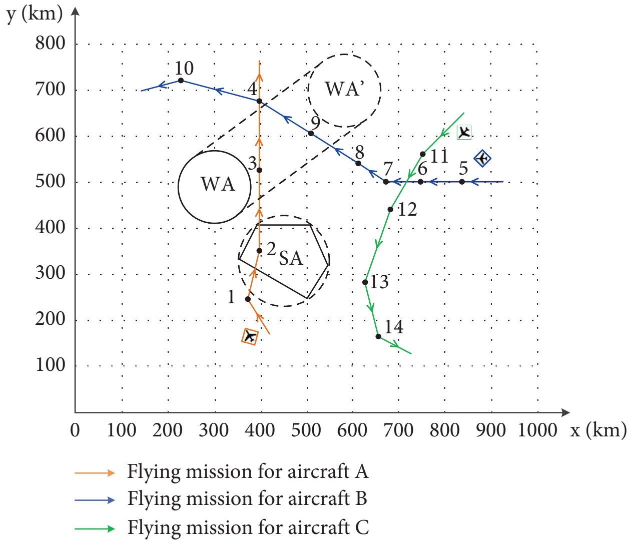


Figure 6: Flight plan of aircraft (A, B, and C) and the airspace environment.

5. Simulation Results and Discussions

To validate the effectiveness of the proposed flight plan risk assessment method, this section adopts a three-aircraft scenario by considering conditions with and without the three types of conflict.

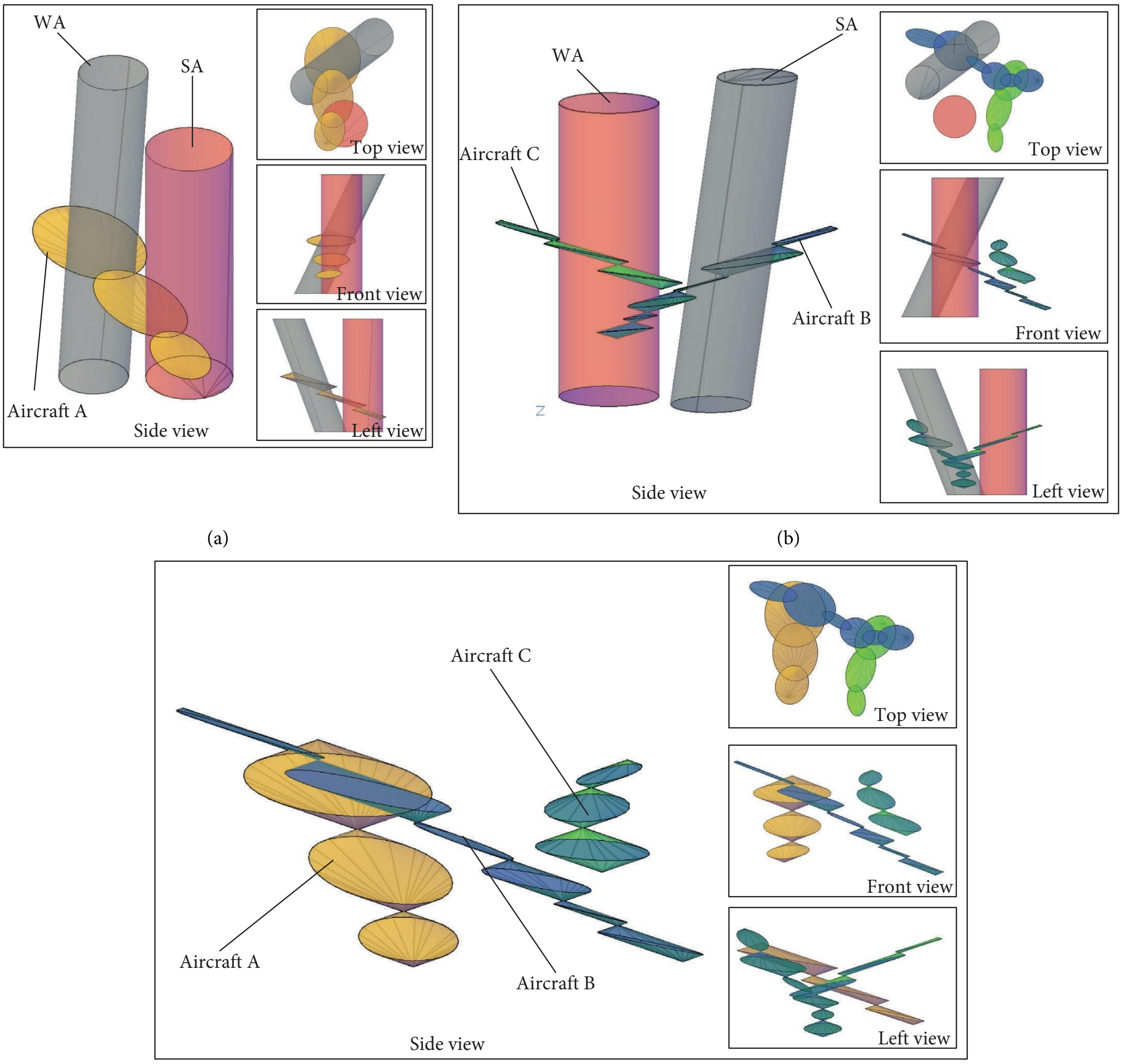
The simulation airspace configuration is illustrated in Figure 6. WA is a thunderstorm area initially at location (300, 490), moves northeast from 14 : 14 : 00 to 15 : 14 : 00,

Table 1: 14 waypoints' locations.

Waypoint no	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Location	(375, 245)	(400, 350)	(400, 525)	(400, 675)	(840, 500)	(750, 500)	(675, 500)	(615, 540)	(512, 605)	(230, 720)	(750, 560)	(680, 440)	(635, 285)	(645, 175)

Table 2: Passing waypoints and time of arrival for aircraft (*A*, *B*, and *C*).

Aircraft	Passing waypoints	Time of arrival
A	1-2-3-4	14:25:10–14:35:10–14:50:00–14:06:50
B	5-6-7-8-9-4-10	14:19:00–14:27:20–14:33:10–14:41:40–14:49:30–15:02:30–15:14:00
C	11-12-13-14	14:38:00–14:50:00–15:01:40–15:09:30



(a)

(b)

(c)

Figure 7: Conflict situation: (a) conflict of aircraft *A*; (b) conflict of aircraft *B*; and (c) conflict of aircraft *C*.

and arrives at location (580, 700) after 60 minutes of movement. The influence radius of the thunderstorm area is approximately 80 km. SA is a polygonal sector with restricted access due to military control, which can be abstracted by its adjacent circle. Besides, the conflict probability of different particle size may have some differences due to calculation error, but there will be no tremendous differences in the order of magnitude. Thus, to balance between the calculation efficiency and accuracy, the discretization parameter is set to be 5 km × 5 km × 10 s. In this example, SA is represented by a circle with a centre at (450, 330) and a radius of 100 km. Detailed parameters of each flight plan can be found in Tables 1 and 2. For example, the flight plan of aircraft *A* will pass waypoint 1 at 14 : 25 : 10, waypoint 2 at 14 : 35 : 10, waypoint 3 at 14 : 50 : 00, and finally waypoint 4 at 14 : 06 : 50. The maximum speed of the aircraft *A*, *B*, and *C* is assumed to be 0.279 km/s.

By generating the space-time reachable area of 3 aircraft in each route segment, we find that aircraft *A* has conflicts with SA, WA, and aircraft *B*. Besides, Aircraft *B* has conflicts

Table 3: Conflict probability of each aircraft.

Aircraft	*A*				*B*				*C*			
Conflict with	SA	WA	*B*	*C*	SA	WA	*A*	*C*	SA	WA	*A*	*B*
Conflict probability	0.083	0.458	$9.25e-15$	0	0	0.066	$9.25e-15$	0	0	0	0	0

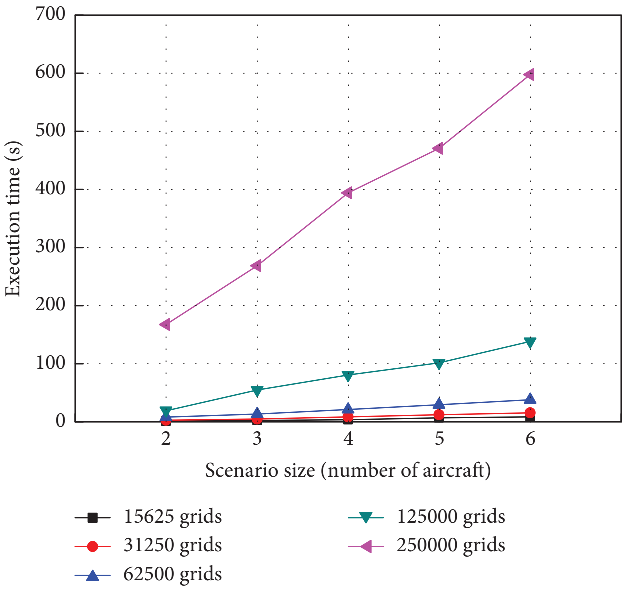


Figure 8: Relation between execution time and scenario size.

with aircraft *A* and WA. Aircraft *C* has no conflicts. The conflict situation is shown in Figure 7.

In this case, we assume that the weight of conflict with SA is set to 3, the weight of conflict with WA is set to 2, the weight of actual conflict with other aircraft is set to 4, and the weight of potential conflict with other aircraft is set to 1.

The results show that the conflict probability of each aircraft is shown in Table 3.

Using equation (10), we can obtain the safety index of flight plans *A*, *B*, and *C*. The results show that the flight plan of aircraft *A* has a very low safety level of 1.05, which requires subsequent flight plan adjustment to improve its safety index to an acceptable level. Aircraft *B* has a reasonable safety level of 36.90, which must be considered during the flying process. Aircraft *C* has a very high safety level of 10000.

Besides, to analyse how the algorithm scales with scenario size, the algorithm was performed for two to six aircraft situations. Each situation was performed three times to achieve an average execution time. As illustrated in Figure 8, the algorithm execution time increases linearly with scenario size.

Comparing with conventional tactical aircraft conflict detection and resolution method, the proposed flight plan risk assessment method is able to judge potential conflicts and estimate conflict probability and evaluate flight plan risk before aircraft takeoff; by optimizing the flight plan, the proposed method has great potential in avoiding tactical aircraft conflict risk and establish the first barrier of the aviation safety.

6. Conclusions

This study provides a quantitative basis for the risk assessment of flight plans in the context of four-dimensional trajectory-based operations. Taking the flight plan as the input, before the flying mission starts, the space-time reachable area between every two waypoints is calculated for each aircraft. The problem of when and where will have potential conflicts which can be also determined by finding the intersection of the space-time reachable areas of aircraft pairs. Aircraft motion considering various uncertain factors is considered a random Brownian motion. The definition of the safety index is proposed, and its calculation process and category method are addressed.

The proposed risk assessment method is expected to effectively reduce aircraft conflict risk through flight plan adjustment in the strategic stage, which will improve the safety of the entire air transport system and balance the high-speed growth of air traffic demand and limited airspace resources. In addition, because the proposed risk assessment method can serve as an assistant for flight plan adjustment in the strategic stage, it can greatly reduce the workload of air traffic controllers and pilots caused by trajectory adjustment in the tactical stage, reduce the impact on flight due to uncertainties, improve the on-time rate of flights and reduce conflict risks.

Determine various types of conflict risk weight coefficients and alarm thresholds according to different scenarios is a rather complex problem, since different airspace environments have different degrees of tolerance and restriction to various types of conflicts. First, scientific classification should be carried out for different airspace scenarios. Then, according to the actual aircraft operation data and historical warning data, the conflict risk weight coefficient and early warning threshold should be determined for each classification. This conflict risk coefficient and threshold should also be verified by the experienced air traffic controllers. Through this combination of subjective and objective methods, it is possible to ensure that the determination of the conflict risk weight coefficient and threshold is consistent with the actual situation, which can assist the system to provide timely, accurate, and reliable early warning information. On the basis of the conflict risk assessment framework proposed in this article, reasonably determining the conflict risk weight coefficient and alarm threshold is the key to the practical application of this method, which is also our main further research work.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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