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Research article

An en route capacity optimization model based on air traffic control process

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Abstract: In order to resolve the imbalance of demand-capacity and airspace congestion, improve the performance of the en route air traffic management, promote the development of air traffic control automation system in the future, this paper proposes an En route air traffic control process model from the perspective of operation requirements. Taking the minimization of operation time, instantaneous density, maximum lateral displacement and air traffic controllers' workload as the optimization objectives, the commonly used air traffic control instructions such as climb and descent and speed restriction are set as constraints, the algorithm is designed based on the air traffic control scheme, and a complete air traffic control process are modeled which outputs instructions for each aircraft. Finally, the model is applied to a case study in the northwest region of China. The simulation results show that compared with the actual operation process, the total operation time is reduced by 18.6%, the variance of the lateral displacement and the vertical separation are efficiently reduced, and the en route air traffic capacity is improved. The proposed model envisages the following two innovations: (i) the whole process of air traffic controllers' command is considered in the model, especially the control scheme and different types of instructions, and (ii) the en route historical trajectory data of aircraft is used to as the key parameters of the input data to efficiently yield the acceptable results of the model. By quantifying the operation requirements of air traffic control, this model can also balance the distribution of traffic flow density, reduce the utilization rate of horizontal airspace, alleviate flight conflicts on air routes, and lessen the workload of controllers.

Keywords: air traffic control automation; en route capacity; air traffic control instructions

1. Introduction

According to an air traffic forecast scenario that Aviation Industry Corporation of China identified as the most-likely scenario for China, the revenue passenger kilometer (RPK) will increase to 3.3 trillion passenger kilometers by the year 2020, which is 175% more than in 2019 with an average annual growth of 5.3%. It is also predicted that the growth rate of air traffic demand for transport services will outpace the growth rate of the airport infrastructure development and of the available airspace resources [1]. This will result in the imbalance of demand-capacity and flight delays which may cause safety and congestion issues in the air traffic management (ATM) system. Therefore, it is critical to improve the performance of ATM system from the aspects of increase capacity and efficiency of the airspace, such as terminal maneuvering area (TMA) and area control center (ACC). Compared with TMA, the en route traffic congestion in ACC becomes more and more prominent in crowded airspace around the world [2]. Hence, the issue of en route capacity has attracted considerable attention in the academic literature recently. However, most scholars address the evaluation of en route capacity and the route network structure optimization, the issues of en route capacity improvement from the perspective of air traffic control operation are rarely discussed in existing studies. Another motivation for this paper is to study the command process of Air traffic controller (ATCO) to establish an en route capacity optimization model. Air traffic control is currently performed by human controllers using radar displays and voice communication with pilots [3]. The U.S. NextGen (Next Generation Air Transportation System) envisions an ATM system that allocates functions to the human and automation and between different stakeholders such as pilots and controllers in a significantly different manner than today's system. These concepts promise increases in capacity while simultaneously improving safety. For example, in an automation controlled or managed airspace, a computer can perform certain tasks that are needed to separate aircraft and hence the airspace may be able to accommodate a larger amount of traffic [4]. To improve the performance of ATC, mainly in anticipation of increasing levels of air traffic, research effort has been devoted over the last decade on creating tools to assist ATC with trajectory prediction, conflict detection and resolution tasks [5]. However, the best of the author's knowledge, no air traffic automation model with aircraft historical trajectory data has been comprehensively analyzed yet.

The primary goal of our research is to present an en route capacity optimization model to improve the route capacity and decrease the workload of ATCO, and promote the development of ATC automation system in the long run. The main developments are summarized as follows: (i) development of an en route capacity optimization model considering the whole process of ATCO command; (ii) the en route historical trajectory data of aircraft is used to as the key parameters of the input data. Finally, a real-world case study is conducted to demonstrate the validity of the proposed approach.

The remainder of this paper is organized as follows: Section 2 discusses previous related work and establishes the contributions of this paper, Section 3 presents the proposed model, while Section 4 describes the results of the application of the proposed model. Finally, Section 5 summarizes the research conclusions and provides directions for future research.

2. Literature review

Despite the goal of improving route capacity, the focus of this paper is on ATCO workflow-based optimization model, so the literature on air route capacity evaluation and route network optimization will not be discussed in this section.

Today, the ATC automation system only plays an auxiliary role, and the performance of the air traffic management system mainly depends on the level of the service provided by air traffic controller [6]. The operation state of air traffic flow is directly related to the capacity of aviation system. Before takeoff, aircraft file flight plans which cover the entire flight. During the flight, ATCO sends additional instructions to them, depending on the actual traffic, to improve traffic flow and avoid dangerous encounters. The primary concern of ATC is to maintain safe separation between the aircraft [7]. The control command of the controller is to provide control services, coordinate the flight conflicts caused by the operational requirements of different aircraft, and at the same time ensure the effective use of airspace resources. According to the process of air traffic control, the research of ATC automation system mainly focuses on trajectory prediction, conflict detection and conflict resolution.

Inseok Hwang et al. designed interactive multiple model (IMM) and residual mean interactive multiple model (RMIMM), and analyzed the conflict detection problem in multi aircraft scenarios based on the model [8]. Liu et al. predicted the transition between flight states by stochastic linear hybrid system [9]. Porretta et al. proposed a kinematic model, which considered the influence of wind and aircraft intention information, and verified the feasibility of the model through real data [10]. Kaneshige et al. also proposed a track prediction method based on kinematic model [11]. The flight process is divided into two stages: horizontal plane and altitude profile. Based on the flight time, fuel consumption and other indicators, the difference between no trajectory prediction and with trajectory prediction was compared. It is proved that trajectory prediction can improve the efficiency of trajectory operation. Tang proposed a flight contour clustering method based on tweed and K-means algorithm [12]. Tastamberkov et al. achieved 4D track fitting prediction by regression method [13]. In view of the fact that neural network can infinitely approximate any complex nonlinear relationship, Shi proposed a track prediction model based on long-term memory (LSTM) network [14]. The four interaction layers of the repeat module in LSTM enable it to connect the long-term dependence to the current prediction task. Zhang et al. proposed to use ant lion optimization (ALO) algorithm to optimize LSTM neural network, which provides a good reference for trajectory prediction [15]. Cui et al. proposed a trajectory prediction model with higher accuracy on the basis of previous track prediction research, aiming at the defects of traditional technology, recurrent and multilayer neural network structure [16]. The algorithm can provide an ideal conflict solution for each aircraft in a short time.

There has been a lot of research to solve the problem of aircraft conflict detection in the presence of uncertainty. The most common way is to treat the expected positions of the aircraft as random variables and assume that they follow a probability distribution. Paielli and Erzberger modeled the lateral error and longitudinal error of the track as a normal distribution with a constant increase in the variance over the entire time range, and estimated the conflict probability on this basis [17]. Krozel and Peters proposed a non-deterministic conflict detection model for two aircraft, in which the relative position, speed and heading between them are considered to obey a Gaussian distribution [18]. Prandini et al. proposed a probabilistic model for mid-term conflict detection, in which the tracking error obeys a normal distribution, and its variance increases over time [19]. Prandini et al. also proposed a short-term conflict detection model, in which the motion of the aircraft is treated as a deterministic motion plus Brownian motion disturbance. Jacquemart and

Morio considered Brownian motion and the variance that grows over time, not only can estimate the probability of aircraft collision, but also use an interactive particle system algorithm suitable for the estimation of the probability of a small probability event to estimate the possibility of aircraft collision [20]. Shi et al. proposed a fast algorithm based on the idea of position space discretization to calculate the conflict probability. And on this basis, a method based on three-dimensional Brownian motion using coordinate transformation and the Bachelier-Levy theorem to estimate the probability of conflict is proposed [21]. Most probabilistic conflict detection methods are based on calculating the conflict probability, that is, the probability that the distance between a pair of aircraft is less than the specified minimum [22,23]. Blom and Bakker proposed and analyzed feature matrices, such as crossover probability and overlap probability [24,25]. However, it is difficult to obtain an accurate calculation result of the conflict rate through analysis, so some studies have adopted geometric approximation or hypothetical methods to solve this problem. For example, the approximation proposed by Paielli and Erzberger is based on a constant speed cross trajectory, but the stability of this method is not good. If one of the aircraft is turning, it may cause the calculation to fail [17,26]. In addition, Liu and Hwang used the classical approximation results for the Gaussian quadratic form through series expansion [27].

The optimization method is the most studied method, usually combining the kinematics model of the aircraft with a set of cost matrices, and determining the best conflict resolution strategy by solving the trajectory of the maximum cost. The core of this optimization method is a reasonable definition of the cost function. Typical costs include fuel consumption, time consumption, and work load. Mixed integer linear and nonlinear programming are commonly used methods to resolve conflict resolution problems. In order to obtain the optimal trajectory for conflict resolution, Cafieri et al. established two mixed-integer linear programming models with the goal of minimizing the total flight time, each of which allows only one factor of speed or heading to change [28]. Alonso Ayuso et al. proposed a hybrid 0-1 nonlinear model based on geometric structure in order to obtain the best strategy for conflict avoidance of different aircraft configurations. With the goal of minimizing aircraft acceleration changes, the model is solved by linear approximation using iterative Taylor polynomials [29]. Omer proposed a mixed integer linear model based on spatial discretization. With the optimization goal of minimizing fuel consumption and delay time, the continuous speed vector is considered comprehensively, as well as the limitation of speed, acceleration and yaw rate, to ensure the feasibility of the actual planned trajectory [30]. Intelligent optimization algorithms have also been widely used in trajectory planning. Zhou et al. improved the genetic algorithm considering the arrival time constraints, and realized the UAV trajectory planning in a dynamic environment. Because of its strong parallel computing capability and global search capability, it can quickly obtain the global optimal solution [31]. The rolling time domain method completes the real-time update of planning sub-objectives through the advancement of rolling windows, and is often combined with fuzzy logic and swarm intelligence algorithms to improve the efficiency of local trajectory planning. Hu improved the ant colony algorithm for UAV static trajectory pre-planning, and proposed an artificial bee colony algorithm to realize dynamic trajectory planning considering sudden threats [32]. The study found that the introduction of random ant colony can expand the search space and obtain more diverse solutions, while the bee colony algorithm can well complete the local trajectory correction. In addition, Chiang et al. used the spatiotemporal flow method to solve the conflict problem, which uses the graphic search method in discrete time and space to find a conflict free trajectory for the aircraft through iteration [33]. Tomlin et al. proposed a conflict resolution method based on Lie algebra and Hamilton Jacobian equation [34]. Bicchi used optimal control and game theory to solve the problem of aircraft conflict. The model assumes that the linear speed of aircraft is constant, and takes airspeed, course, longitude and latitude as optimization parameters [35]. Goodchild et al. proposed a collaborative optimal conflict resolution algorithm based on distributed artificial intelligence by using dynamic optimization algorithm [36]. Bayen et al. proposed a Lagrange model based on simple conflict resolution instruction, which allows aircraft to fly at different altitudes [37]. Durand et al. established an unsupervised learning neural network to calculate the approximate optimal trajectory of two aircraft in conflict. When collision is detected, the three-layer neural network only changes the course. By using genetic algorithm to help train neural network, this method can solve the conflict of no more than three aircraft [38].

In summary, the current research primarily paid attention to the efficiency and accuracy of conflict detection, trajectory prediction and conflict resolution in the field of ATC automation system study. However, very little of them considered the key factors of the whole ATC process in actual operation, such as the issue of different restriction instructions and control scheme. In addition, the historical trajectory data of aircraft are not commonly used to deal with the problem of ATC automation system. To this end, this paper aims to propose an en route capacity optimization model from the aspect of ATCO's instruction on account of the characteristics of the historical trajectory data of aircraft.

3. Methodology

In this section, we present an en route capacity optimization model with the consideration of ATC command process to fulfill the following operational requirements: there is no flight conflict on the route; the traffic flow is less than the capacity; the ATCO workload is reduced; the density distribution of aircraft is balanced; and the lateral occupied space is minimized. For the reason that better meet the actual en route operation, the historical trajectory data of aircraft are processed and used as the input of this model.

3.1. Hypothesis

In most cases, the airspace of en route flight belongs to controlled airspace in which all the maneuvers of aircraft, i.e., climb, descent, acceleration and deceleration require the instructions of the ATCO. Usually, there is only one ATCO in the designated airspace unit. Before the aircraft arrives at the airspace unit under his/her jurisdiction, ATCO will prepare a preliminary control scheme based on the scheduled arrival time and its operational needs. When the aircraft actually arrives at the airspace unit, ATCO will issue more detailed control instructions according to the current airspace conditions.

In the whole process of air traffic control, the ATCO needs to consider many factors, coordinate different operational objectives, and avoid potential risks between aircraft. For the convenience of research, it is necessary to simplify the complexity of the real- life problem and facilitate the calculation. Refer to [3,4,7], the following assumptions are made:

1). Unless otherwise specified, "route" in this paper refers to a route within the airspace under the jurisdiction of the ATCO. And there is no alternative route for the aircraft to fly.

2). Aircraft should fly along the route direction when entering or exiting the route. The entry and exit process to the route is not considered in this paper.

3). If ATCO does not issue maneuver instructions, the aircraft will only move in a straight line at a constant speed.

4). Aircraft will not change its heading and flight level simultaneously.

5). There is no convective weather or military activities.

6). The clearance interval is 2 minutes at the exit waypoint of the route in radar control circumstances.

7). Repeated climb and descend, or repeated acceleration and deceleration instructions are not allowed.

8). The rate of climb, rate of descent, acceleration and deceleration of aircraft are limited respectively. The average value, maximum value and minimum value are extracted from the historical radar data of the aircraft on the route. The average value is taken as the default value, and the maximum value and minimum value are used to set the limit interval.

Although the above assumptions were made during the modeling, it did not have much impact on the practicability and validity of the model, mainly because most of the assumptions occurred infrequently during the en-route operation phase of the aircraft. Taking the military activities as an example, if the military activities such as artillery fire around the route are considered, the instructions issued by ATCO will become much more complicated, i.e., lateral displacement is forbidden, or the en route holding procedure will be conducted. However, these situations are not common.

3.2. Notations

To facilitate the model elaboration, the notations and definitions used hereafter are summed up in Table 1.

Table 1. Parameters and variables in the proposed model.

Parameters	
Δt_i	Operation time of the i^{th} aircraft on the route
$Y_{\max}$	Maximum value of lateral displacement of all aircraft
M	Number of ATC instructions issued by ATCO which are different from the control scheme
$\mathrm{var}(Sepa_i)$	Separation between the i^{th} aircraft and the preceding aircraft
$a_{\max}$	Maximum value of acceleration of aircraft
a_{mean}	Average value of acceleration of aircraft
b_{mean}	Average value of deceleration of aircraft
$b_{\min}$	Minimum value of deceleration of aircraft

Continued on next page

Parameters	
v_1	Speed of aircraft before speed adjustment, i.e., initial speed
v_2	Target speed
$gradC_{\max}$	Maximum value of climb gradient of aircraft
$gradC_{mean}$	Average value of climb gradient of aircraft
$gradD_{mean}$	Average value of descent gradient of aircraft
$gradD_{\min}$	Minimum value of descent gradient of aircraft
h_1	Flight altitude of aircraft before the flight level adjustment, i.e., initial altitude
h_2	Target altitude
v	Velocity during the flight level adjustment
$Ldel$	Distance the aircraft is delayed
$tdel$	Time the aircraft is delayed
ΔL	Actual delayed distance of aircraft
α_1	Angle of first turn
$\alpha_1+\alpha_2$	Angle of second turn
L_{MK}	Distance of MK segment
D_{slope}	Slope distance between the aircraft and other aircraft on the route
D_{len}	Longitudinal distance between the aircraft and other aircraft on the route
D_{ver}	Vertical distance between the aircraft and other aircraft on the route
$X_{c_i}^h$	Position of the i^{th} aircraft receiving flight level adjustment instructions
$X_{c_i}^v$	Position of the i^{th} aircraft receiving speed adjustment instructions
a_i	Acceleration of the i^{th} aircraft receiving speed adjustment instructions
$grad_i$	Gradient of the i^{th} aircraft receiving flight level adjustment instructions
S_i	Conflict resolution strategy used by the i^{th} aircraft

3.3. Objective function

In order to improve the efficiency of the route as much as possible on the premise of ensuring safety, the process of the ATCO commanding the aircraft in the en route phase is analyzed firstly when proposing this optimization model.

Assuming that there are N aircraft entering the route in turn, ATCO takes over the aircraft from the upstream route one by one, command the aircraft on the principle of first come, first serve (FCFS), and then transfers them to the downstream route at the exit waypoint. The ATCO should not only ensure the safety separation between aircraft, but also guarantee the operation efficiency of the route, that is, reduce the total time of all aircraft occupying the route. In some circumstances, if the longitudinal separation cannot be met, ATCO will issue instructions to aircraft to execute lateral displacement to avoid conflicts, which leads to the increase of the airspace resources usage. Thus, the shorter distance of lateral displacement which aircraft conduct on the route, the better. Furthermore, because aircraft is unevenly distributed on the route, the instantaneous density distribution of the route is also inhomogeneous which raises the safety risk. Therefore, the smaller the variance of longitudinal separation is, the better. In addition, the less instructions issued by ATCO that are different from the initial control scheme, the lower workload.

In the light of the discussions above, we propose the following mathematical model which considers the total operation time of all aircraft on the route, instantaneous density of the route, maximum lateral displacement, and ATCO's workload.

$$\min Z = \sum_{N} \Delta t_i + Y_{\max} + M + \mathrm{var}(Sepa_i) \tag{1}$$

where Δt_i is the operation time of the i^{th} aircraft on the route, in seconds; $Y_{\max}$ is the maximum lateral displacement of all aircraft, in meters; M is the number of instructions issued by ATCO different from the control scheme which represents the workload of ATCO; $\mathrm{var}(Sepa_i)$ is the variance function of longitudinal separation between the i^{th} aircraft and the preceding aircraft that quantifies the instantaneous density of the route.

Since the dimensions and magnitudes of the above four indicators are not the same, for the convenience of modeling, normalization is adopted to make the value of them between 0 and 1. The normalization formula used in this section is as follows:

$$x^* = \frac{1}{1+x} \tag{2}$$

Hence, the newly proposed en route capacity optimization model is given by Eq (3).

$$\min Z = \frac{1}{1+\sum_{N} \Delta t_i} + \frac{1}{1+Y_{\max}} + \frac{1}{1+M} + \frac{1}{1+\mathrm{var}(Sepa_i)} \tag{3}$$

3.3. ATCO instruction modelization

In order to be more in line with the actual operation, the proposed route capacity optimization model is implemented by taking the consideration and judgment of the ATCO when issuing the control instructions as the process. Taking into account the main responsibilities of the ATCO in commanding the aircraft, it mainly includes the formulation of control scheme, flight conflict detection, conflict resolution, and the final issue of instructions. Since the process of conflict detection and conflict resolution directly affects the speed, heading and flight altitude of the commanded aircraft, the ATCO instruction modelization can be divided into six parts: speed adjustment instruction, flight level adjustment instruction, lateral displacement instruction, the establishment of control scheme, flight conflict detection and flight conflict resolution.

3.3.1. Speed adjustment instruction

In the actual operation process, the speed of the aircraft is difficult to maintain at a constant value which often fluctuates in small amplitudes. And speed changes are more complicated when aircraft in the stage of acceleration or deceleration. To simplify the problem, it is assumed that the aircraft fly at a constant speed or conduct a constant acceleration and deceleration on the route.

Thus, the acceleration value of the aircraft on the route can be extracted from the aircraft trajectory data which are derived from the ATC automation system. The maximum value of acceleration $a_{\max}$, the average value of acceleration a_{mean}, the average value of deceleration b_{mean} and the minimum value of deceleration $b_{\min}$ can be calculated by mathematical statistics. Obviously, the minimum value of acceleration and the maximum value of deceleration are zero.

Suppose the speed of the aircraft before ATCO issue the speed adjustment instruction is the initial speed v_1 and the target speed after the adjustment is v_2, then:

$$t_1 = \begin{cases} \dfrac{v_2 - v_1}{a_{mean}} & v_1 < v_2 \\ \dfrac{v_2 - v_1}{b_{mean}} & v_1 > v_2 \end{cases} \tag{4}$$

$$l_1 = \begin{cases} \dfrac{v_2^2 - v_1^2}{2a_{mean}} & v_1 < v_2 \\ \dfrac{v_2^2 - v_1^2}{2b_{mean}} & v_1 > v_2 \end{cases} \tag{5}$$

where t_1 is the time required for speed adjustment; l_1 is the distance required for speed adjustment.

If the calculated time and distance cannot meet the requirement, the acceleration can be calculated inversely. Then judge whether it is within the range of values, otherwise use other instructions.

3.3.2. Flight level adjustment instruction

In the phase of en route flight, aircraft generally maintains at a fixed altitude, i.e., flight level. When aircraft climbs or descends, the change of speed and altitude is complicated. For the sake of convenience, it is assumed that the aircraft climbs or descends at a constant speed and gradient.

In the same way, the climb and descent gradient values of the aircraft on the route can also be extracted from the aircraft trajectory data which are derived from the ATC automation system. The maximum value of the climb gradient $gradC_{\max}$, the average value of the climb gradient $gradC_{mean}$, the average value of the descent gradient $gradD_{mean}$ and the minimum value of the descent gradient $gradD_{\min}$ can be calculated by mathematical statistics. Obviously, both the minimum value of the climb gradient and the maximum value of the descent gradient are zero.

Suppose the flight level before adjustment is the initial flight level h_1, the target flight level after the adjustment is h_2, and the speed of the aircraft during the flight level adjustment is v, then:

$$l_2 = \begin{cases} \dfrac{h_2 - h_1}{gradC_{mean}} & h_1 < h_2 \\ \dfrac{h_2 - h_1}{gradD_{mean}} & h_1 > h_2 \end{cases} \tag{6}$$

$$t_2 = \frac{l_2}{v} \tag{7}$$

where t_2 is the time required for flight level adjustment; l_2 is the distance required for flight level adjustment.

3.3.3. Lateral displacement instruction

In order to alleviate the congestion of downstream route and resolve potential flight conflicts, it is necessary for the ATCO to adjust the separation between aircraft before they converge. In addition to issue speed reduction instructions, the ATCO can also command the aircraft to make a lateral displacement to guarantee the required separation. As shown in Figure 1, there is a route with its entry waypoint and exit waypoint E and F. The green aircraft follows the yellow one. In order to ensure the required separation, the ATCO issue lateral displacement instructions to guide the green aircraft turns left from point M and flies to N, and then turns right at N to go back to the route at K. Meanwhile, the yellow aircraft maintains on the route and flies from point P to Q.

The constraints of lateral displacement instruction are as follows:

1) The purpose of the lateral displacement instruction is to delay the following aircraft by a certain distance $Ldel$ or a certain time $tdel$.

2) When selecting point N, the length of MN should be greater than two times of actual delayed distance, i.e., $2 * \Delta L$ and less than 10 km of the pilot's visual range. The initial length of MN can be set to $(5 + Ldel)$ km.

3) The angle of the first turn α_1 is generally set to 15°, 30°, 45°or 60°; the angle of the second turn $\alpha_1 + \alpha_2$ should not be greater than 120°; α_1 is generally greater than or equal to α_2.

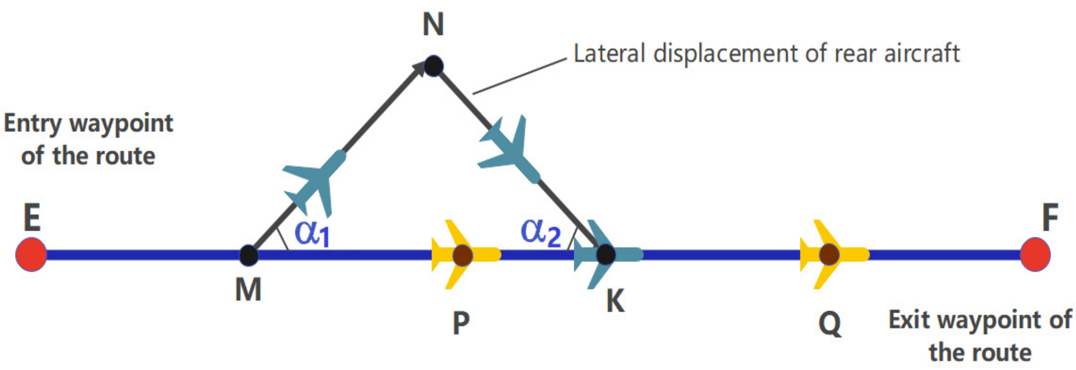

Figure 1. Schematic diagram of lateral displacement.

Taking the delay of a certain distance $Ldel$ as an example, suppose the overall speed of the aircraft is v, and the equation set formed by the constraint of the lateral displacement instruction is:

$$\begin{cases} t_1 = (5 + Ldel)/v \\ L_{MNK} = v(t_1 + t_2) \\ L_{MK} = vt_1 \cos\alpha_1 + vt_2 \cos\alpha_2 \\ \Delta L = L_{MNK} - L_{MK} \\ vt_2 / \sin\alpha_1 = vt_1 / \sin\alpha_2 \\ \alpha_1 \geq \alpha_2 \\ \delta = \Delta L - Ldel \\ \alpha_1 = 15^\circ、30^\circ、45^\circ、60^\circ \\ \alpha_1 + \alpha_2 \leq 120^\circ \\ \delta \leq Ldel \times 10\% \end{cases} \tag{8}$$

where t_1 and t_2 are the flight time of the MN and MK segments respectively, and ΔL is the actual delayed distance. Try different values of α_1 and α_2 to make sure δ is less than 10% of $Ldel$.

For the convenience of calculation, the arc of the turn is not considered in the above formula. However, when the turning angle is less than 60 degrees, the distance error will increase by about 4%, which cannot be ignored. To this end, modify the equations as follows:

$$\begin{aligned} \tilde{\Delta L} = \Delta L &+ r \cdot \alpha_1 - 2r \cdot \tan(\alpha_1/2) \\ &+ r(\alpha_1 + \alpha_2) - 2r \cdot \tan[(\alpha_1 + \alpha_2)/2] \\ &+ r \cdot \alpha_2 - 2r \cdot \tan(\alpha_2/2) \\ r = \frac{90 \cdot v^2}{281 \cdot \pi \cdot \tan 25^\circ} & \end{aligned} \tag{9}$$

3.3.4. Control scheme

Control scheme is always prepared in advance by ATCO before commanding the aircraft and the potential conflicts are not considered. In order to shorten the operation time of each aircraft and increase the efficiency of the route, aircraft that needs to accelerate will be commanded to accelerate as soon as it enters the route, and the one that needs to decelerate will be commanded to decelerate until it leaves the route. In most cases, flight level adjustment instruction is issued in the middle of the route segment, and it may be modified according to the subsequent situation. The process of control scheme is shown in Figure 2.

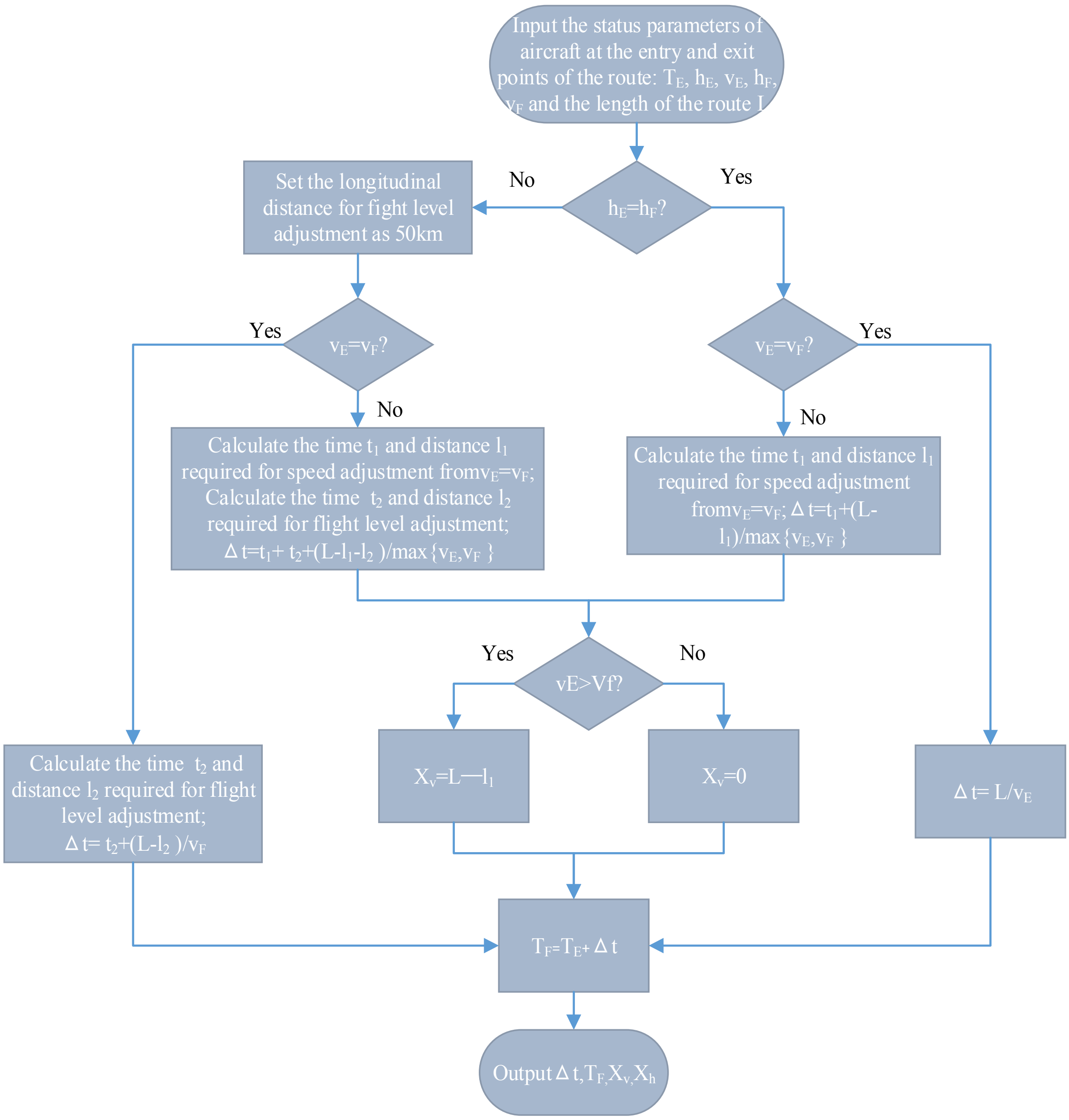

Figure 2. Flowchart of the control scheme.

3.3.5. Flight conflict prediction

Firstly, by establishing the kinematic equation of the aircraft, the slope distance between any two aircrafts or the projection distance in three directions at any time can be calculated by using the distance formula between two points.

When an aircraft joins the route, its kinematic equation is as follows:

$$X_i = x_i(t); Y_i = y_i(t); Z_i = z_i(t) \quad t_0^{(i)} \le t \le t_L^{(i)} \tag{10}$$

The slope distance, longitudinal distance, and vertical distance between this aircraft and other aircraft on the route are:

$$\begin{cases} D_{slope} = \sqrt{(X_i - X_m)^2 + (Y_i - Y_m)^2 + (Z_i - Z_m)^2} \\ D_{len} = \sqrt{(X_i - X_m)^2} \\ D_{ver} = \sqrt{(Z_i - Z_m)^2} \end{cases} \tag{11}$$

According to the criteria of ICAO Doc4444 "Air traffic management" and the national regulation "Civil aviation air traffic management regulations" in China, in radar control circumstances, the en route longitudinal separation of aircraft should not be less than 20 km, and the vertical separation should not be less than 300 m. In order to simplify the calculation, for each moment in the time range, the first step of flight conflict detection is to judge whether the slope distance of two aircraft D_{slope} is greater than the required minimum value which is $\sqrt{20000^2 + 300^2}$ meters. If yes, it means that the required safety separation is met; otherwise, the second step is to judge whether the longitudinal distance between the aircraft and other aircraft D_{len} is greater than 20 km or the vertical distance between the aircraft and other aircraft D_{ver} is greater than 300 m, and if yes, the required safety separation is met.

3.3.6. Conflict resolution plan

For the purpose of lower cost, the priority order when the ATCO formulate conflict resolution strategies is as follows:

1) Issue the speed adjustment instruction which can be satisfied by adjusting the position in the control scheme when the instruction is issued, i.e., X_v.

2) Issue the flight level adjustment instruction which can be satisfied by adjusting the position in the control scheme when the instruction is issued, i.e., X_h.

3) Issue lateral displacement instruction

The lateral displacement in the conflict resolution plan is only to allow the front and rear aircraft to meet the required safe separation, that is, the longitudinal distance between the two aircraft at least 20 km.

Suppose the speeds of the front and rear aircraft are v_2 and v_1 respectively, and the new equations are as follows:

$$\begin{cases} L_{PQ} = v_2 t \\ L_{MNK} = v_1 t_1 + v_1 t_2 \\ t = t_1 + t_2 \\ L_{MK} = v_1 t_1 \cos\alpha_1 + v_1 t_2 \cos\alpha_2 \\ {vt_2}/{\sin\alpha_1} = {vt_1}/{\sin\alpha_2} \\ \alpha_1 \geq \alpha_2 \\ \alpha_1 = 15^\circ、30^\circ、45^\circ、60^\circ \\ \alpha_1 + \alpha_2 \leq 120^\circ \\ L_{KQ} = L_{MP} + L_{PQ} - L_{MK} \\ \delta_2 = L_{KQ} - 2\times 10^4 \\ 0 \leq \delta_2 \leq 2\times 10^4 \times 10\% \end{cases} \tag{12}$$

In addition, when it is necessary to optimize the trajectory and adjust the separation, these strategies of the conflict resolution solutions mentioned above can also be used.

3.4. Algorithm design

The uncertain part of the whole model is whether to modify the control scheme and how to modify it, the key parameters of the conflict resolution strategy and the unknown variables in the objective function. Therefore, the decision variables are added as shown in Table 2.

Table 2. Values of variables.

Expression	Connotation	Value (EMPL = 1)	Value (EMPL = 0)
EMPL	0–1 variable, equal to 1 means the i^{th} aircraft executes the control scheme, equal to 0, the opposite	1	0
$X_{c_i}^h$	The position of the i^{th} aircraft receiving the flight level adjustment instruction	50 km	$[0, L]$
$X_{c_i}^v$	The position of the i^{th} aircraft receiving the speed adjustment instruction	See 2.4	$[0, L]$
a_i	The acceleration of the i^{th} aircraft receiving the speed adjustment instruction	See 2.4	$[b_{\min}, a_{\max}]$
$grad_i$	The gradient of the i^{th} aircraft receiving the flight level adjustment instruction	See 2.4	$[gradD_{\min}, gradC_{\max}]$
S_i	The conflict resolution strategy used by the i^{th} aircraft, equal to 0 means not to use, equal to 1 means to modify the control scheme, and equal to 2 means to use the lateral displacement strategy.	0	1 or 2

The solving steps of the model in this paper are as follows in Figure 3.

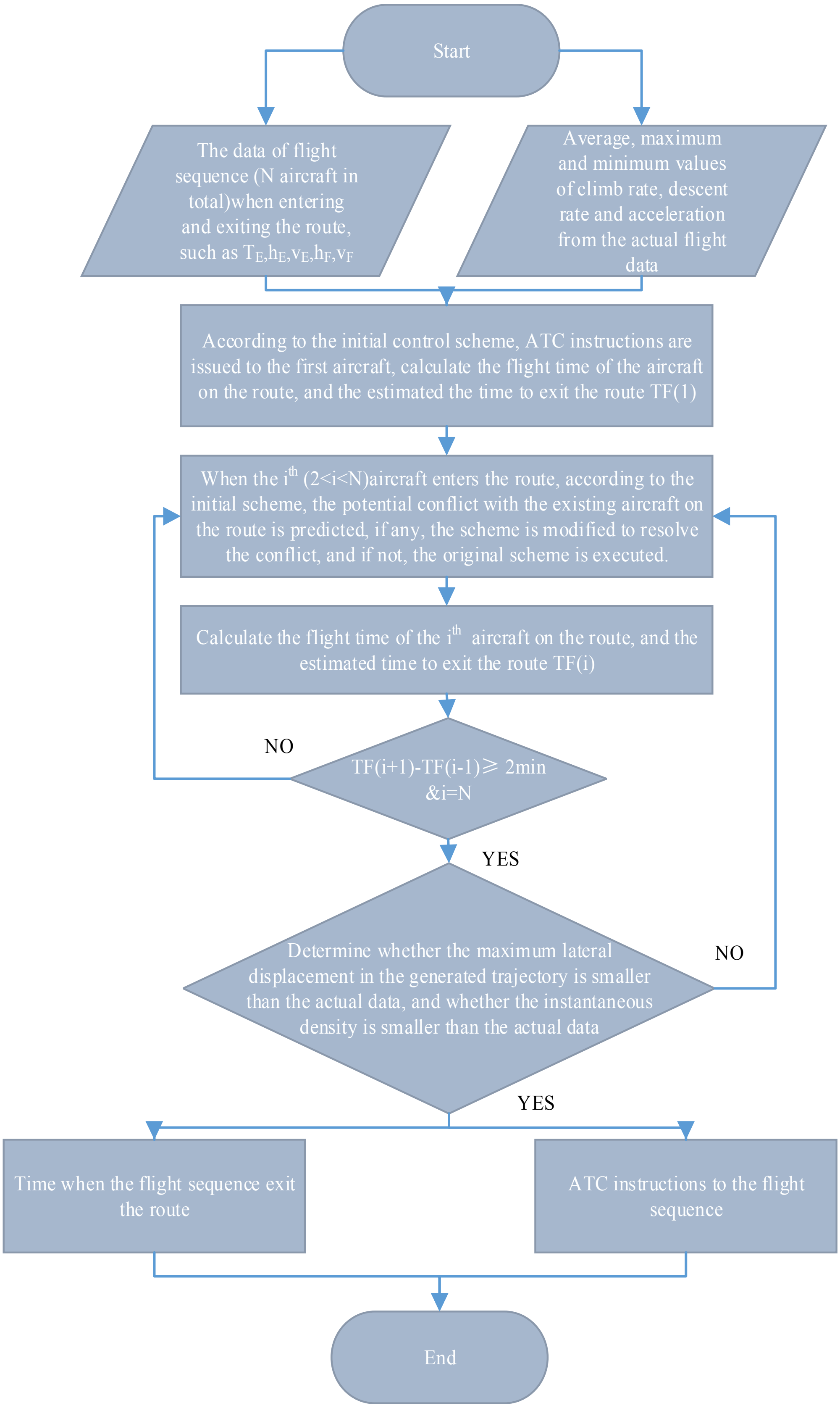

Figure 3. Flowchart of the solving steps of the proposed model.

4. Case study

4.1. Data selection

This paper takes one route of Xi'an control area in northwest of China as the case study. The route selected is part of air route G212 from waypoints WJC to OKVUM whose length is 128 kilometers and magnetic course is 57 degrees, as shown in Figure 4.

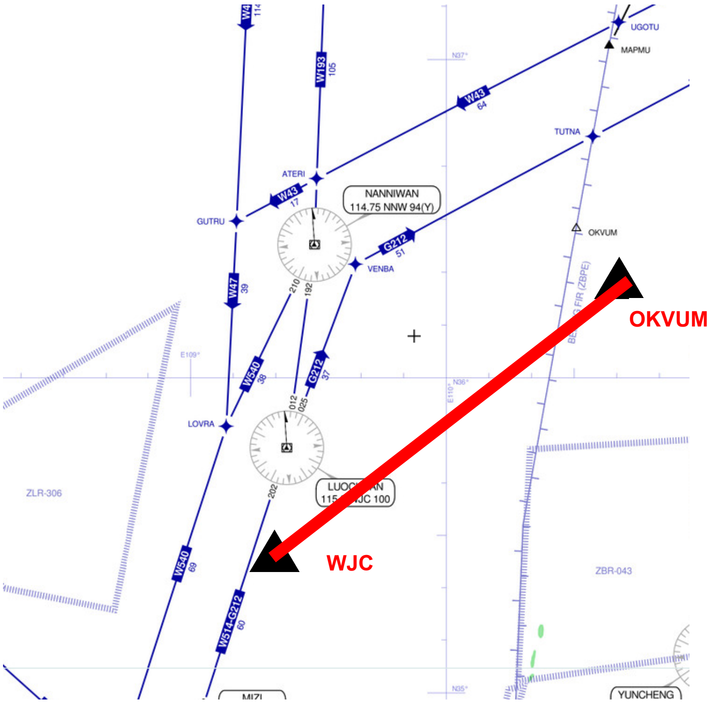

Figure 4. Route selected in the case study.

trackID=0001047E callSign=[] [19]

10:08:59	116.9660	36.1014	6004	566	1.00
10:09:03	116.9650	36.1062	6004	556	11.00
10:09:07	116.9650	36.1117	6004	556	11.00
10:09:11	116.9570	36.1299	6004	810	19.00
10:09:15	116.9640	36.1263	6004	587	9.00
10:09:19	116.9590	36.1387	6004	686	13.00
10:09:23	116.9580	36.1455	6004	686	13.00
10:09:27	116.9540	36.1562	6004	743	15.00
10:09:31	116.9530	36.1637	6004	746	15.00
10:09:35	116.9540	36.1689	6004	714	13.00
10:09:39	116.9520	36.1764	6004	723	14.00
10:09:43	116.9500	36.1836	6004	723	14.00

Figure 5. Historical trajectory data of the aircraft.

The aircraft trajectory data used in this paper is the flight information of the aircraft recorded by the control radar in the airspace, with a total of 6 days. The Radar data is derived from the air traffic control automation system and is updated every 4 seconds. After parsing and transcribing, it is saved in a format that is easy to read and manipulate, such as txt format. Figure 5 shows the data header and part of the trajectory data of one aircraft. The data header contains the track number, the aircraft call sign and the number of recorded trajectory points. Trajectory data shows the flight time, longitude, latitude, altitude, airspeed and magnetic heading of the aircraft from left to right.

4.2. Model results and analysis

In the modeling process, it is necessary to set parameters for the speed adjustment and flight level adjustment instructions issued by ATCO. The actual operational data of the route are extracted by mathematical statistics method, and the average value of the obtained parameters is shown in Table 3.

Table 3. Values of the model input parameters.

Parameters	$gradC_{\max}$	$gradC_{mean}$	$gradD_{mean}$	$gradD_{\min}$	$a_{\max}$	a_{mean}	b_{mean}	b_{min}
Value	0.147	0.019	−0.022	−0.119	89.2	13.9	−12.5	−89.4

Table 4. Input data of the model (first 40 flights).

S.N.	T_E	ActT_F	h_E	h_F	v_E	v_F
1	0:14:02	0:25:02	11300	10100	200	220
2	0:14:34	0:32:06	10100	10100	210	200
3	0:18:46	0:29:34	10100	10100	220	250
4	0:24:14	0:35:06	10100	10100	220	280
5	1:51:54	2:2:38	10700	10700	200	290
6	1:53:14	2:4:02	11600	11300	180	270
7	2:20:38	2:32:10	8900	8900	190	220
8	2:27:42	2:38:50	8900	10100	200	350
9	2:46:54	2:57:54	8900	10700	160	250
10	3:13:22	3:24:38	10700	10700	200	320
11	7:11:38	7:23:06	8900	8900	160	350
12	7:33:54	7:44:50	11300	10100	250	270
13	7:43:18	7:54:38	8900	8900	200	270
14	7:46:02	8:02:10	10100	8600	190	140
15	8:15:06	8:26:10	10700	10100	200	220
16	8:24:30	8:36:19	7200	8900	230	280
17	8:44:10	8:56:58	8400	7800	−210	−190
18	8:44:46	8:56:03	6900	8900	210	200
19	8:48:58	9:00:10	10100	10100	160	320
20	8:58:34	9:10:07	7500	10700	250	250
…	…	…	…	…	…	…

In order to facilitate model simulation, the trajectory data of aircraft is simplified. For example, the speed of the aircraft is rounded up to the next 10 knots increment, and the altitude of the aircraft is rounded according to the flight level. Part of the data is shown in Table 4, where $\mathrm{Act}T_F$ is the actual departure time of each flight.

According to the model proposed in Section 3, the results are obtained in Table 5.

Table 5. Output data of the model (first 40 flights).

S.N.	EMPL	Xc_i^h	Xc_i^v	a_i	$grad_i$	S_i	Δt_i	T_F	$\alpha_{1/2}$
1	1	50000	0	13.9627	0.0153	0	581.8	00:23	
2	0		127836.6	−12.5463		2	134	00:25	60°/65°
3	0		0	13.9627		2	188	00:35	60°/65°
4	0		0	13.9627		2	200	00:37	60°/65°
5	1		0	13.9627		0	442	01:59	
6	1	50000	0	13.9627	0.0038	0	475	02:01	
7	1		0	13.9627		0	582	02:30	
8	1	50000	0	13.9627	−0.0154	0	368	02: 34	
9	1	50000	0	13.9627	0.0199	0	513	02:55	
10	1		0	13.9627		0	402	03:20	
11	1		0	13.9627		0	369	07:18	
12	1	50000	0	13.9627	0.0154	0	474	07:42	
13	1		0	13.9627		0	475	07:51	
14	1	50000	127342.4	−12.5463	−0.0218	0	674	07:57	
15	1	50000	0	13.9627	0.0077	0	582	08:25	
16	1	50000	0	13.9627	0.0199	0	457	08:32	
17	1	50000	0	13.9627	0.0077	0	674	08:33	
18	1	50000	127836.6	−12.5463	−0.0256	0	609	08:55	
19	0		0	13.9627		1	423	08:56	
20	1	50000			0.0410	0	512	09:07	
…	…	…	…	…	…	…	…	…	…

Table 6. Comparison of simulation results and actual trajectory data.

	Average operation time (Seconds)	Maximum lateral displacement distance (Meters)	$\mathrm{var}(Sepa)$ (Meters)	Capacity (Flights/hour)
Actual trajectory	691.65	36790.8	1030	20.8
Simulation results	562.78	15669.6	820	25.6

Statistical analysis of the input data according to the aircraft trajectory and the simulation results of the optimization model is shown in Table 6. According to the comparison in this table, it can be seen that the total operation time is reduced by 18.6%; the maximum lateral displacement distance is magnificently reduced by 57.4%; the variance of the separation of aircraft are also reduced by 20.3%; and the en route capacity is improved by 23%.

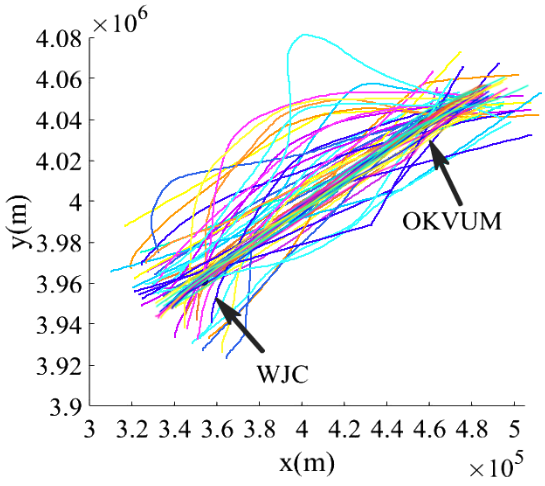

Figure 6. Plane view of the historical trajectory.

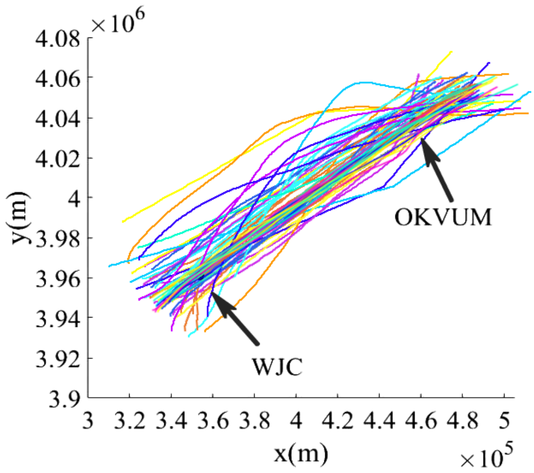

Figure 7. Plane view of the simulated trajectory.

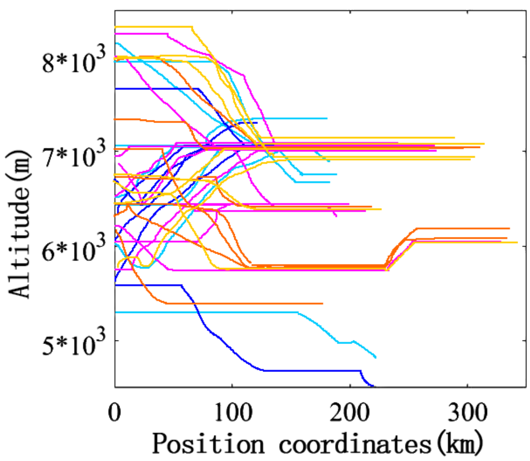

Figure 8. Profile view of the historical trajectory.

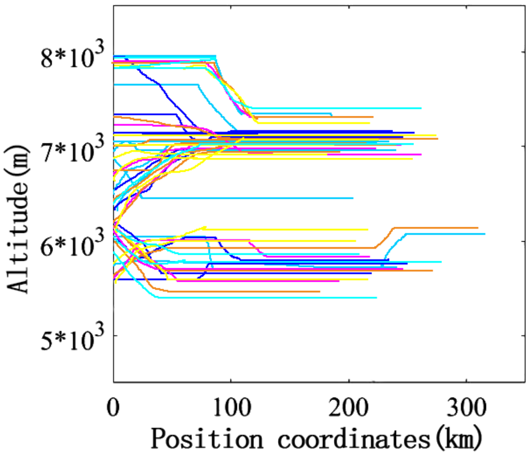

Figure 9. Profile view of the simulated trajectory.

Figures 6–9 demonstrate the plane view and profile view of the aircraft trajectory on this route before and after optimization. It can be seen intuitively from the above figures that the en route capacity optimization model established according to the ATCO's command process can effectively reduce the en route lateral displacement distance and the amount of flight level changes of aircraft, so as to improve the route utilization efficiency and reduce the workload of ATCO and pilots.

5. Conclusions

The improvement of the en route capacity problem has increasing drawn the attention of the research community, policy makers and professionals in the ATC community. Existing research has placed the main focus on the capacity evaluation and route structural optimization, but there is still ample room for further investigation of the en route capacity optimization model. This paper presents an en route capacity optimization model to improve the route capacity and decrease the workload of ATCO. Compared with the available approaches, the proposed model envisages the following two innovations: (i) the whole process of ATCO command is considered in the model, especially the control scheme and different types of instructions, and (ii) the en route historical trajectory data of aircraft is used to as the key parameters of the input data to efficiently yield the acceptable results of the model. A case study is conducted to validate the applicability and feasibility of the model. Results show that the total en route operation time, maximum lateral displacement distance and variance of the separation of aircraft will be considerably reduced, while the capacity and the utilization efficiency will be increased as compared to the conventional model. Although, the experimental results are encouraging in terms of the ability of the proposed capacity optimization model to tackle en route problem instances, further experimentation is required to: (i) ensure that the proposed model performs well on the route network instances that resemble more closely to real-world cases, and (ii) generalize the results regarding the implications of aircraft classifications.

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Conflict of interest

The authors declare there is no conflict of interest.

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