

## Research Article

# Optimal Design of Flow Corridors to Minimize Environmental Impact with Consideration of En-Route Weather Conditions

Bojia Ye <sup>1</sup>, Bo Liu,<sup>1</sup> Aolin Xue,<sup>2</sup> and Yong Tian<sup>1</sup>

<sup>1</sup>College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

<sup>2</sup>Zhengzhou Airport Operation Command Center, Zhengzhou 450000, China

Correspondence should be addressed to Bojia Ye; [bye@nuaa.edu.cn](mailto:bye@nuaa.edu.cn)

Received 21 June 2020; Revised 17 August 2020; Accepted 23 August 2020; Published 3 September 2020

Academic Editor: Stefan Balint

Copyright © 2020 Bojia Ye 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.

The flow corridor is a new type of flexible tube-shape airspace developed to better accommodate high levels of traffic for future air transportation systems. To take advantage of its prominent dynamic characteristic, exploring the flexibility deployment of flow corridors by considering favourable weather conditions is a prerequisite. This paper proposes an optimal design method to minimize the total flying cost within flow corridors with consideration of environmental impacts. We first specify the contrail and CO<sub>2</sub> emissions as concerned environmental indicators for flexible deployment of flow corridors. Then, incorporating these two indicators into the objective function, an optimization model is presented to optimize the spatial location of flow corridors with consideration of the traffic demand, aircraft performance, and weather conditions. The genetic algorithm is selected for model resolution, and the proposed method is applied in Chinese airspace for case study with benefits assessment. Results show that the optimized 7 flow corridors cover 4.03% of flight demand in China, and the total flying cost with them could be further reduced by 3.19% with the proposed optimal design method.

## 1. Introduction

With the continuous growth of air transportation around the world, the sustainable development in civil aviation has attracted many attentions from the public and authorities. The global Air Traffic Management (ATM) system is currently undergoing rapid change and evolution towards to the next generation air transportation system, including

Performance Based Navigation (PBN), Trajectory-Based Operations (TBO), and Continuous Descent Operations (CDO). How to establish a new safety, efficiency and cost-effectiveness air transportation system with environmental sustainability has become an important research topic. [1–3].

The flow corridor is a new type of flexible tube-shape airspace developed to better accommodate high levels of traffic for future air transportation system [4]. It integrates a range of new airspace prototypes, including dynamic airspace super sectors (DASS) [5], high-volume tube-shaped sectors (HTS) [6], freeways [7], tubes [8, 9], self-separation corridor (SSC) [10], and dynamic multitrack airways (DMA) [11]. The prominent characteristics of flow corridors that would distinguish from the current airway system include allowance for multiple (parallel) lanes of traffic, aircraft self-separated flying within the lanes, and dynamic and flexible deployment.

Many design methods for flow corridor have been proposed to take good advantage of its new prominent characteristics, including city-pairs based methods, airport clustering methods, and traffic density-based methods. Yousefi started from the daily flights between city pairs and proposed a city-pair based idea to design flow corridors [6]. Wing et al. [11] presented a flow corridor deployment method according to the distance and traffic demand. Sridhar et al. [12] clustered the airports by Clustering by Region Growing (CRG) and Weighted-Proximity Classifier (WPC) and designed a flow corridor network with the cluster centers. Xue and Kopardekar [13] took the great circle trajectory of the aircraft as basis and proposed flow

corridors based on Hough transform. Yousefi et al. [14] used the actual flight radar track to optimal design flow corridors on speed vectors. Kotecha and Hwang [15] studied the design and optimized the flow corridor network based on point to point operations data for the top 500 airports in USA. Han et al. [16] selected the analytic hierarchy process and adopted the planning method of MAKLINK diagram to design flow corridors. Gupta et al. [9] transformed the design of flow corridors into a multicommodity flow problem and solved it with a mixed integer programming model. Some other studies also refer to the operation rules within flow corridors [17–19].

Until now, the optimal design methods for flow corridors tend to focus on the demand and efficiency with the purpose of increasing capacity or alleviating traffic congestion. There is a lack of research and models that aim at optimal design of flow corridors with consideration of environmental impacts. Different from previous studies, we take advantage of flow corridors' prominent dynamic characteristic, exploring the flexibility deployment of flow corridors to minimize the total flight cost with consideration of environmental impacts. The contrail and CO<sub>2</sub> emissions are considered as concerned indicators, and an optimization model is presented to optimize the spatial location of flow corridors with consideration of the traffic demand, aircraft performance, and weather conditions (wind, temperature, humidity, etc.). The genetic algorithm is selected for model resolution, and the proposed method is applied in Chinese airspace for case study with benefits assessment.

The rest of the paper is organized as follows: Section 2 introduces the main environmental impacts that may be caused by flow corridors. Section 3 proposes an optimization model and solution algorithm for optimal design of flow corridors with consideration of environmental impacts. Section 4 employs a numerical case study with benefits assessment. Section 5 provides some conclusions and indicates the next research steps.

## 2. Concerned Environmental Indicators for Flow Corridors

One of the prominent characteristics of flow corridors that distinguish them from nowadays airways is the dynamic and flexible deployment, which allows flow corridors to be shifted to avoid severe weather and take advantage of favorable weather conditions [14]. Since the most natural home of flow corridors is in high-altitude airspace, contrail and carbon dioxide (CO<sub>2</sub>) emissions are the main environmental impacts, which can lead to greenhouse effect [20, 21].

Thus, we took the contrail and CO<sub>2</sub> emissions as concerned environmental indicators in this study and try to reduce these two indicators while designing flow corridors. Modeling details pertaining to contrail generation and CO<sub>2</sub> emissions are presented below.

**2.1. Contrail Generation.** Contrail is commonly referred to as aircraft smoke plume. It is a phenomenon of condensation

of water vapor formed by the exhaust of aircraft engines cooling in the air and may eventually evolve into cirrus clouds, which can reflect a large amount of long-wave radiation on the ground surface and exacerbate the greenhouse effect.

According to the Schmidt–Appelman standard [22], if the relative humidity (RH<sub>w</sub>) of the environment is greater than or equal to some certain critical humidity (RH<sub>C</sub>) and the relative humidity of the ice surface (RH<sub>i</sub>) is greater than 100% at the same time, the continuous contrail will be generated. The formula for calculating RH<sub>C</sub> can be expressed as

$$RH_C = \frac{G(T - T_{\text{CONT}}) + e_{\text{sat}}^{\text{liq}}(T_{\text{CONT}})}{e_{\text{sat}}^{\text{liq}}(T)}, \quad (1)$$

$$e_{\text{sat}}^{\text{liq}}(T) = e_0 \cdot 10^{(aT/b+T)}, \quad (2)$$

$$T_{\text{CONT}} = -46.46 + 9.43 \ln(G-0.053) + 0.72 \ln^2(G-0.053), \quad (3)$$

$$G = \frac{EI_{\text{H}_2\text{O}} \cdot C_P P}{\epsilon Q(1 - \eta)}, \quad (4)$$

where  $e_{\text{sat}}^{\text{liq}}(T)$  is the saturated water vapor pressure at atmospheric temperature (unit: pa), and  $e_0 = 6.11$  hpa is defined as the corresponding saturated water vapor pressure at 0°C. Equation (2) is Magnus saturated vapor pressure formula, in which  $a = 9.5$ ,  $b = 265.5$  [23], and  $T_{\text{Cont}}$  is the critical temperature required for contrail formation (unit: °C).  $EI_{\text{H}_2\text{O}} = 1.25$  is water vapor emission index, and  $C_P = 1004$  is specific heat capacity at constant air pressure (unit J/kg · K).  $P$  is atmospheric pressure (unit: pa). In equation (4),  $\epsilon = 0.622$  is the ratio of the molecular weight of water to the average relative molecular weight of dry air.  $Q = 4.3 \times 10^7$  is fuel combustion value (unit J/kg).  $\eta = 0.15$  is average efficiency of engine propulsion.

The formula for calculating RH<sub>i</sub> on the ice surface can be given by

$$RH_i = RH_w \frac{6.0612 \exp\left(\frac{18.102T}{249.52+T}\right)}{6.1162 \exp\left(\frac{22.577T}{237.78+T}\right)}. \quad (5)$$

When RH<sub>i</sub> is greater than 100%, the contrail can exist for a long time [24].

**2.2. CO<sub>2</sub> Emissions.** The CO<sub>2</sub> emitted by aircraft comes from the combustion of aviation fuel and accounts for 70% of the emitted gas. CO<sub>2</sub> emissions are not affected by the location of the aircraft but related to the emission index and fuel consumption. The emissions of CO<sub>2</sub> can be expressed as

$$E_{\text{CO}_2} = EI_{\text{CO}_2} \cdot FW_m, \quad (6)$$

where  $E_{\text{CO}_2}$  is the CO<sub>2</sub> emission amount (unit: kg) and  $EI_{\text{CO}_2}$  is the index of CO<sub>2</sub> emission. The aviation fuel emission index refers to the mass of gas generated per unit mass of fuel

consumption  $EI_{CO_2} = (3.155 \text{ kg/kg})$ , which means that burning 1 kg of fuel generates 3.155 kg of  $CO_2$ .  $FW_m$  is the fuel consumption of aircraft  $m$  (unit: kg), which is related to aircraft type, fuel flow rate, and flying time. Usually, the short-term climate impact of  $CO_2$  emissions is less prominent than that of contrail [13, 14].

### 3. Optimization Modeling for Design of Flow Corridors

In order to optimize flow corridors to alleviate environmental impact with consideration of en-route weather conditions, an optimization model is proposed for searching the best spatial deployment for flow corridors by considering air traffic demand, aircraft performance, and weather conditions.

Usually, weather conditions data are collected from different meteorological stations that are discrete and uneven distributed, so we discretized the airspace into 3-dimensional grid cells ( $X$ ,  $Y$ , and  $Z$  axes) with discrete weather conditions, as shown in Figure 1. Flow corridors are supposed to be deployed within some of the grid cells, and a sequence of grid cells from the origin to the destination can represent an alternative flow corridor design.

Some basic design principles are presented as follows:

- (1) All flow corridors are supposed to be deployed at one of the alternative flight levels, which follows the proposed deployment rules for flow corridors [7].
- (2) Meteorological conditions within each grid are treated the same as the center of the grid and are supposed to be consistent with the weather prediction results.
- (3) Aircraft conflicts between different flow corridors are not considered in the model, since the potential conflicts at crossing parts can be supposed to be solved by the well design of crossing structure [8].
- (4) Aircraft conflicts within flow corridors are not considered in the model, since the potential conflicts can be supposed to be solved by aircraft self-separating algorithm for the flow corridors.
- (5) Only the reference Mass, the cruising Mach number, and fuel consumption are considered in the model, while the change of aerodynamics is not considered in the planning stage.

**3.1. Objective Function.** The objective function proposed in this model is to minimize the Total Flight Cost (TFC) for all aircraft flying within flow corridors with consideration of environmental impacts. The TFC consists of direct operating cost [25], including the cost of aircraft flying time, fuel consumptions, contrail generation, and  $CO_2$  emissions, and equations can be expressed as follows:

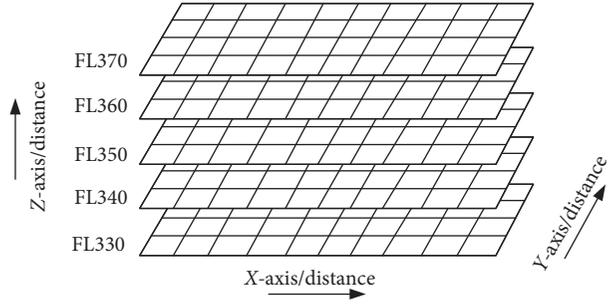


FIGURE 1: Airspace discretized into 3-dimensional grid cells.

$$\text{Min TFC} = \text{Min} \left\{ \sum_{c \in S} \sum_{\omega \in W} \text{TFC}_{\omega,c,l} \right\}, \quad \forall l \in \{L\}, \quad (7)$$

$$\text{TFC}_{\omega,c,l} = \sum_{i \in I} \lambda_i^\omega \xi_i^l \varphi_i^c (C_{i,l}^T + C_{i,l}^F + C_{i,l}^{\text{CONT}} + C_{i,l}^{\text{CO}_2}), \quad (8)$$

$$C_{i,l}^T = P_T \sum_{k \in K_C} t_{i,k}^l, \quad (9)$$

$$t_{i,k}^l = \frac{L_{i,k}^l}{(V_i^l + WS_k^l \cdot \cos WA_k^l)}, \quad (10)$$

$$C_{i,l}^F = P_F \sum_{k \in K_C} EG \cdot FF_i^l t_{i,k}^l, \quad (11)$$

$$C_{i,l}^{\text{CONT}} = P_{\text{CONT}} \sum_{k \in K_C} \eta_k \cdot L_{i,k}^l, \quad (12)$$

$$C_{i,l}^{\text{CO}_2} = P_{\text{CO}_2} \sum_{k \in K_C} EG \cdot FF_i^l \cdot t_{i,k}^l \cdot EI_{\text{CO}_2}. \quad (13)$$

Equation (7) represents the objective function that aims to minimize TFC of aircraft flying within all flow corridors, where  $c$  represents one of the initial flow corridors,  $S$  is the initially designed flow corridors set,  $\omega$  represents the time period within the deployment time ( $W$ ) of flow corridors,  $l$  represents the flight level on which flow corridors can be deployed, and  $L$  is the alternative flight levels set. It implies that the designed flow corridors will be deployed on some alternative flight level with the minimum TFC. Equation (8) shows the major TFC components of flight  $i$  at flight level  $l$ , including the time cost ( $C_{i,l}^T$ ), the fuel cost ( $C_{i,l}^F$ ), the contrail generation cost ( $C_{i,l}^{\text{CONT}}$ ), and the  $CO_2$  emissions cost ( $C_{i,l}^{\text{CO}_2}$ ), where  $i$  represents a flight, and  $I$  is the flight set that takes use of flow corridors.  $\lambda_i^\omega$ ,  $\xi_i^l$  and  $\varphi_i^c$  are Boolean variables indicating whether the flight  $i$  is using the flow corridor  $c$  at the flight level  $l$  at the time period  $\omega$ .  $\lambda_i^\omega$  is set as 1 when both the departure and arrival time of flight  $i$  are within the deployment time of flow corridors,  $\xi_i^l$  is set as 1 if flight  $i$  is using the flight level  $l$ , and  $\varphi_i^c$  is set as 1 if flight  $i$  is using the flow corridor  $c$ .

Equations (9)(13) present modeling details pertaining to the major components.  $k$  represents a grid, and  $K_c$  is an alternative grid set for flow corridor  $c$ .  $P_T$ ,  $P_F$ ,  $P_{CONT}$  and  $P_{CO_2}$  are cost indexes for components,  $t_{i,k}^l$  represents flying time from grid  $k-1$  to  $k$  at flight level  $l$  of flight  $i$ ,  $L_{i,k}^l$  represents flying distance of flight  $i$  from grid  $k-1$  to grid  $k$  at flight level  $l$ ,  $V_i^l$  is the reference cruising airspeed (true airspeed) of flight  $i$  at flight level  $l$  relating to aircraft type, and  $WS_k^l$  and  $WA_k^l$  are the predicted wind speed and direction within the grid  $k$  at flight level  $l$  collected from meteorological stations.  $EG_i$  and  $FF_i^l$  represent the number of engines and fuel flow rate for flight  $i$  relating to aircraft type,  $EL_{CO_2}$  represents the  $CO_2$  emission index,  $\eta_k$  is a Boolean variable indicating whether contrail is generated in grid  $k$ , and value 1 means the weather conditions will generate contrail in the grid  $k$ .

The key point of the objective function is to find the optimal grid sets ( $K_c$ ) for the initial designed flow corridors to minimize the Total Flight Cost (TFC). When searching the optimal grid sets, some constraints are presented as follows.

### 3.2. Constraints

**3.2.1. Flow Corridor Set Size Constraints.** Only when the daily flight frequency between city pairs (flow<sub>C</sub>) exceeds the threshold value (threshold), a flow corridor can be constructed, which is given by

$$\text{flow}_C \geq \text{threshold}. \quad (14)$$

**3.2.2. Flight Level Boundary Constraint.** The alternative flight level should not exceed the specified flight level boundary, the minimum flight level (FL<sub>min</sub>), and the maximum flight level (FL<sub>max</sub>), which is given by

$$FL_{\min} \leq l \leq FL_{\max}. \quad (15)$$

**3.2.3. Total Length Constraint for Flow Corridors.** The growth length of the optimized set should not exceed 10% of that of the length before the optimization ( $L_0$ ), which is given by

$$\sum_{k \in K_c} L_{i,k}^l \leq L_0, \quad (16)$$

where  $L_0$  represents the length before optimization.

**3.3. Solution Method for the Model.** The model considers many flow corridors across the airspace between busy airports or city-pairs, serving a large number of flights with different aircraft, which can lead to a great calculating workload when we search the optimal solution. This is a complex search problem with fast request in response time. The genetic algorithm with elitist retention strategy [26, 27] is selected to solve the proposed model in this paper. Genetic algorithm is a variant of stochastic beam search algorithm,

which is proved to be efficient when it is used to solve complex problems. Compared with the traditional optimization algorithm, genetic algorithm based on biological evolution has good convergence and robustness. The process of searching is simple, and the probability mechanism is used for iteration, which has randomness. It is this unique search method that makes genetic algorithm avoid the local minimum trap that other optimization algorithms often encounter. When genetic algorithm is used to solve practical problems, the optimal individuals that represent the best solution for the problem will be kept all the time, while the worse individuals will be abandoned during the searching process. It has the advantages of good convergence and computational efficiency, which meets the requirement of fast-time searching for this model. For the problem of flow corridors optimization to minimize environmental impact, the steps of the genetic algorithm are as follows:

- Step 1 *Gene Coding.* Coding based on the grid number. Each flight path of the aircraft in the airspace is determined by the grid serial number method; take an individual; for example, {0, 1, 11, 21, 22, 23, 24, 35, 45, 55, 65, 66, 67, 72, 85, 88, 99} represents a path that is coded by a sequence of grid serial numbers.
- Step 2 *Generation of Initial Population.* Set the population size and generate the initial path randomly according to the position and direction of the aircraft's starting and ending points.
- Step 3 *Design Fitness Functions.* For the optimization problem in this study, the objective function is to minimize the total flight cost of traffic flow within flow corridors. Equation (17) is selected here to represent the individual fitness function:

$$\text{Fit} = \left( \sum_{c \in S} \sum_{w \in W} \text{TFC}_{w,c,l} \right)^{-1}. \quad (17)$$

- Step 4 *Genetic Operator.* The key parameters of the genetic algorithm are set, including the population size, termination evolution algebra, crossover probability, mutation probability, and variation mode.
- Step 5 *Elite Retention Strategy.* Determine whether the gene meets the constraint conditions; if not, discard the gene. Merge the processed child population with the parent population, calculate the fitness value of the gene, use the elite retention strategy to retain the gene corresponding to the better solution, and generate a new population as the new parent population. Elite individuals are the individuals with the highest fitness value searched by genetic algorithm so far, which have the best genetic structure and excellent characteristics. The elitist reservation is that the optimal individuals will not be lost and destroyed by selection, crossover, and mutation in the evolutionary process of genetic algorithm.

Step 6 *Comparison*. Compare the evolutionary algebra and termination evolutionary algebra in the genetic algorithm. If the two are equal, the iterative process will be ended and the optimal path will be obtained. Otherwise, return to Step 4 and continue.

## 4. Numerical Case Study

This section employs the proposed optimal design method for flow corridors in Chinese airspace for case study with benefits assessment.

### 4.1. Description of the Test Site

*4.1.1. Initial Design of Flow Corridors.* For the initial design of flow corridors, the history operational data for all flights on July 3, 2017, were parsed to obtain the busy city pairs in China. Then, the city-pair based method [12] was used to construct the primary Chinese flow corridors. This is a reasonably good design method for flow corridors, since most flights have already flied between these city pairs.

The unidirectional flight frequency threshold (threshold) between city pairs is the key parameter determining the size of flow corridors set. The threshold value is set as 60 flights/day for case study in this research, which implies that the flow corridors will be deployed between the city pairs with more than 60 flight/day. Based on the statistic results, 7 city pairs in China satisfied the flight frequency requirements, which are Beijing-Shanghai, Shenzhen-Shanghai, Shenzhen-Beijing, Chengdu-Beijing, Shanghai-Guangzhou, Beijing-Guangzhou, and Hangzhou-Beijing as shown in Table 1. These 7 city pairs accommodate about 4.03% of flight demand in China.

Then, the related en-route entry and exit points were selected based on these city pairs, and 7 flow corridors were initially designed by using great circle routes. The entry and exit points with the length of flow corridors are shown in Table 2.

*4.1.2. Weather Data Collection and Preprocess.* To optimize the flow corridors configuration, the airspaces were discretized into 3-dimensional grid cells based on the initial deployment. The basic grid size is set as 30 km \* 30 km, and the whole airspace is divided into 62 \* 71 grids with unique serial numbers. That is, the East-West length of the selected airspace is 62\*30 km, and that of the north-south direction is 71\*30 km. Five alternative flight levels (10100 m, 10400 m, 10700 m, 11000 m, and 11300 m) were considered for flow corridors deployment, and predicted weather conditions were collected from 42 adjacent meteorological stations with spatial interpolation method. For example, Figures 2 and 3 show the temperature and relative humidity distribution in the concerned airspace at the flight level 11300 m. Figure 4 shows the relative humidity (colored surface) and critical relative humidity (dark red surface) at the flight level 11300 m. Figure 5 shows the relative humidity of the ice at the flight level 11300 m. With these processes, each grid can

TABLE 1: Traffic demand between cities that satisfies the flight frequency requirement.

Ranking	Airport 1	Airport 2	Average daily flights
1	ZBAA	ZSSS	89
2	ZGSZ	ZSSS	78
3	ZGSZ	ZBAA	77
4	ZUUU	ZBAA	68
5	ZSSS	ZGGG	68
6	ZBAA	ZGGG	65
7	ZSHC	ZBAA	63

be initialized with predicted weather conditions, and the generation of contrails in each grid can also be estimated according to the equations proposed in Section 2. Figure 6 shows the calculated distribution of contrails in grids at the flight level 11300 m, and the purple grids represent the airspace that can generate contrails.

*4.1.3. Experiment Parameters Initialization.* The deployment time period of flow corridors is set between 08:00 and 14:00 in the experiment, and 58 flights with 9 different aircraft types are simulated to fly within the proposed flow corridors, including A320, A321, A332, A333, A388, B738, B763, B773, and B77 W. The related performance parameters for different aircraft types were obtained from the Base of Aircraft Data (BADA) published by EUROCONTROL [28], including the reference cruise speed (Mach number), number of engines, fuel flow rate in different flight level, and CO<sub>2</sub> emission index etc.

In the algorithm, the genetic algorithm parameters are set as follows: population size is 300, the termination generation is 150, crossover probability is 0.8, mutation probability is 0.01, the elite strategy keeps 4 best chromosomes for each generation, and the linear recombination and stochastic factor mutation are used in the experiment. According to previous research [29], the cost indexes PT, PF, PCONT, and PCO<sub>2</sub> are set as 0.0026 (\$/min), 11.0626 (\$/kg), 0.0021 (\$/km), and 0.5414 (\$/kg).

*4.2. Analysis of Results.* Figure 7 shows the variation of the total flight cost with the increase of population generation. The total flight cost reduced from 389,000\$ to 383,000\$ quickly within 50 generations by the proposed algorithm. From 50 to 150 generations, the total flight cost decreases slowly at first and then stays at 382,367 after 75 generations, implying that the approximate optimized results are obtained.

Figure 8 shows the initial total flight cost and optimized results from flight levels aspect. The initial total flight cost for deploying flow corridors at different flight levels is displayed by black bars, while the optimized results are displayed by red ones. It can be seen that the total flight cost at different flight levels is different than that before optimization, implying that flight level could be an important factor for flow corridors deployment. Potential reasons may include weather conditions and aircraft performance differences. For example, the weather elements (wind and temperature)

TABLE 2: The starting and ending COORDINATES of different flow corridors.

Flow corridor	Entry point coordinates (longitude latitude)	Exit point coordinates (longitude latitude)	Length (km)
ZBAA-ZSSS	LADIX (116.991667 39.129167)	DALNU (118.159167 33.818889)	600
ZGSZ-ZSSS	LMN (114.328 23.647444)	P22 (119.696667 28.443333)	831
ZGSZ-ZBAA	BUBDA (113.461111 25.867778)	WXI (114.917528 36.362139)	1176
ZUUU-ZBAA	TOREG (106.063333 31.358333)	UBLAT (113.443611 38.050278)	1005
ZSSS-ZGGG	KAKIS (119.696667 30.483333)	PLT (114.876333 25.806833)	734
ZGGG-ZBAA	LIG (113.515278 27.649417)	WXI (114.917528 36.362139)	979
ZSHC-ZBAA	DALNU (118.159167 33.818889)	TUMLO (116.794167 37.216667)	398

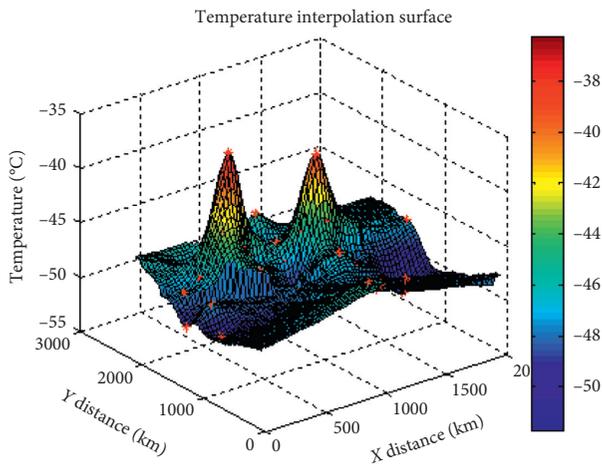


FIGURE 2: The distribution of temperature in the concerned airspace at the flight level 11300 m.

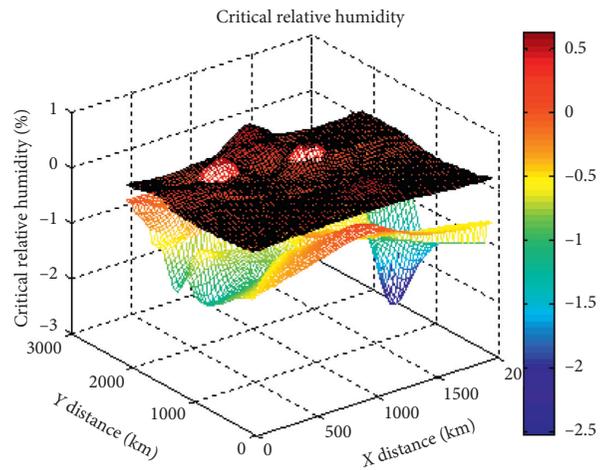


FIGURE 4: The distribution of critical relative humidity in the concerned airspace at the flight level 11300 m.

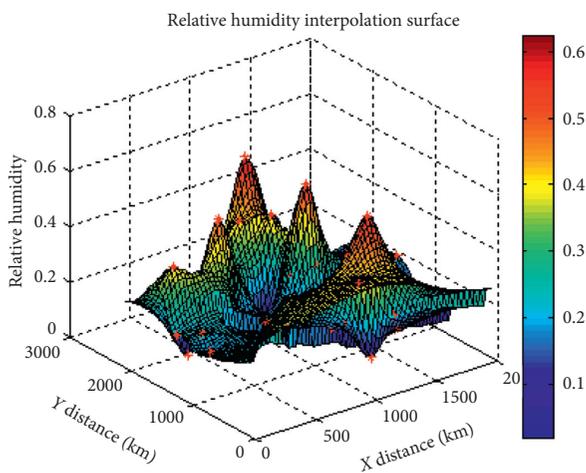


FIGURE 3: The distribution of relative humidity in the concerned airspace at the flight level 11300 m.

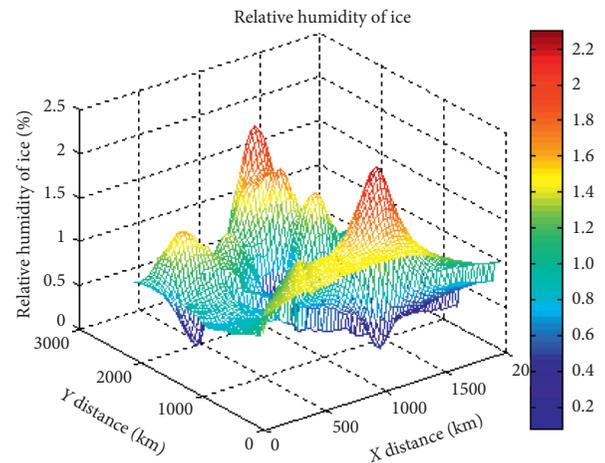


FIGURE 5: The distribution of relative humidity of the ice in the concerned airspace at the flight level 11300 m.

are usually different at different altitudes, then the True Air Speed (TAS) and fuel flow rate for the same type of aircraft at different altitudes will be different. The weather factors considered in this paper include wind, temperature, and humidity. From the analysis in Chapter 2 and the objective function in Section 3.1, it can be seen that they not only affect the generation of carbon dioxide emissions and condensation, but also affect the flight time and fuel emissions of aircraft.

After optimization, the results show that the total flight cost at all flight levels can be decreased, and when the flow corridors are deployed at the flight level 11300 m, the minimum total flight cost is obtained.

Table 3 also shows the minimum total flight cost with the major components, including time cost, fuel cost, CO<sub>2</sub> emissions cost, and contrail generation cost. In general, the

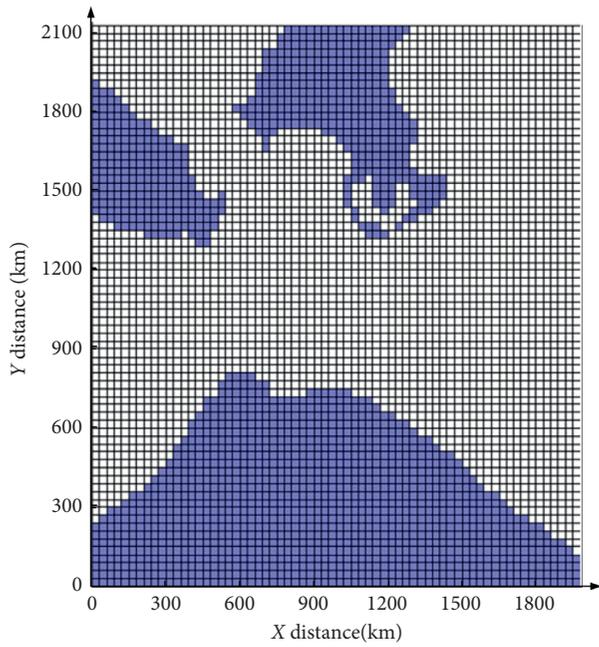


FIGURE 6: Contrails generation in the concerned airspace at the flight level 11300 m.

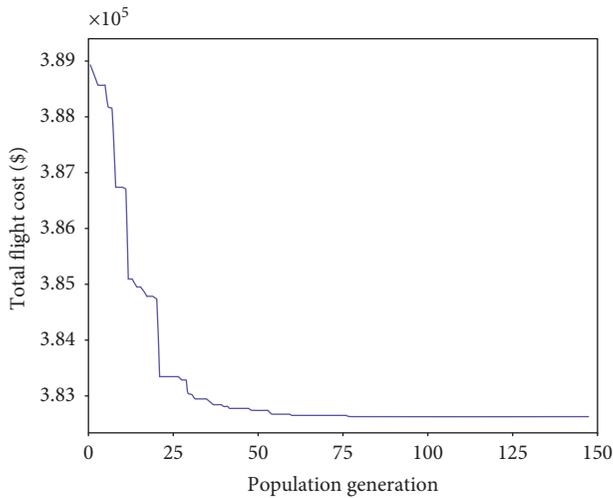


FIGURE 7: Variation of the total flight cost with the increase of population generation.

reduction rate for total flight cost is 3.19% after optimization with the time cost (2.74%), fuel cost (3.21%), CO<sub>2</sub> emissions cost (2.74%), and contrail generation cost (7.60%). A noticeable point is that although the reduction rate for contrails generation is the maximum, fuel cost reduction is the dominant component for the total flight cost reduction. In addition, although both the fuel cost and CO<sub>2</sub> emissions should be calculated in practice, these two indexes are linearly dependent, which leads to the same reduction rate for fuel cost and CO<sub>2</sub> emissions.

Figure 9 shows the optimal results for designed Chinese flow corridors deployed at the flight level 11300 m. Although the shape of the flow corridors is no longer great circle

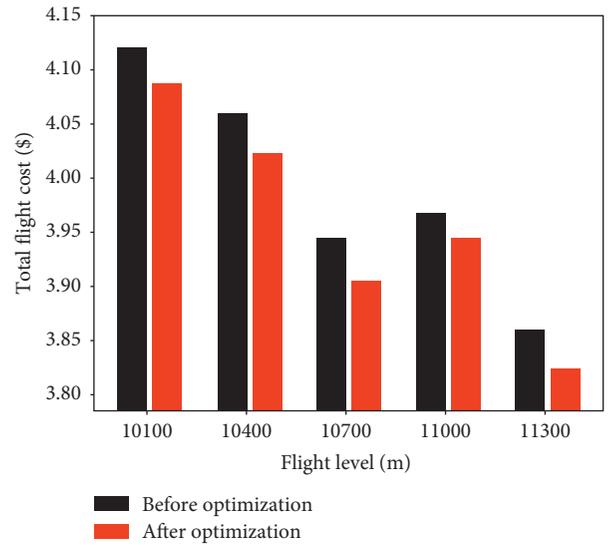


FIGURE 8: Initial total flight cost and optimized results at different flight levels.

TABLE 3: The minimum total flight cost with major components.

Total flight cost	Before optimization	After optimization	Reduction rate (%)
Time cost (\$)	41,378	40,244	2.74
Fuel cost (\$)	346,147	335,036	3.21
CO <sub>2</sub> emissions cost (\$)	4,628	4,501	2.74
Contrails cost (\$)	2,801	2,588	7.60
In total (\$)	394,955	382,367	3.19 A

routes, with the dynamic and flexible deployment of flow corridors, the total flight cost with environmental impact

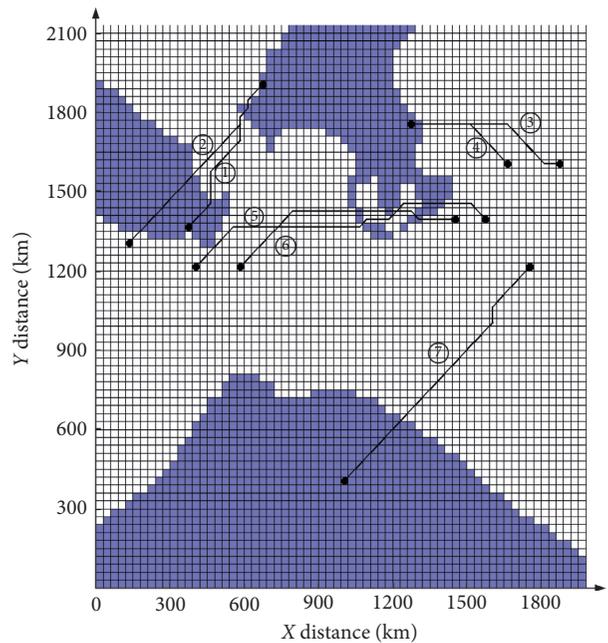


FIGURE 9: Optimization results for designed Chinese flow corridors deployed at the flight level 11300 m.

could be reduced with consideration of the en-route weather conditions.

## 5. Conclusions

This paper presented an optimal design method for flow corridors to minimize the total flying cost with consideration of environmental impacts. The proposed optimization model integrated the cost of aircraft flying time, fuel consumptions, contrail generation, and CO<sub>2</sub> emissions together and optimized the spatial location of flow corridors by using genetic algorithm with consideration of the traffic demand, aircraft performance, and weather conditions.

The proposed optimal design method for flow corridor is applied in Chinese airspace for numerical case study with benefits assessment. The results obtained show that the designed 7 flow corridors cover 4.03% of flight demand in China, and the total flight cost could be reduced by 3.19% with the proposed optimization model. Although flow corridors can be deployed on one flight level, the deployed flight level should be considered carefully since the total flight cost is usually differently caused by the inconformity of weather conditions and aircraft performance. Although the reduction rate for contrails generation is the maximum in the numerical case, fuel cost reduction is the dominant component for the total flight cost reduction.

The optimal design method presented in this paper could be applied in flexible deployment of flow corridors, which is in alignment with flow contingency management and trajectory management in the future air transportation systems. Future works include extending the model to flow corridors network design as well as incorporating some spatial-temporal factors.

## Data Availability

The mat 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 are no conflicts of interest regarding the publication of this paper.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China (nos. U1933119 and 61671237).

## References

- [1] International Civil Aviation Organization, *Global Air Navigation Plan*, International Civil Aviation Organization, Montreal, Canada, 2016.
- [2] Federal Aviation Administration, *NextGen Implementation Plan-FAA*, Federal Aviation Administration, Washington, DC, USA, 2017.
- [3] European Organisation for the Safety of Air Navigation, *Guidance Material for SESAR Deployment Programme Implementation*, European Organisation for the Safety of Air Navigation, Brussels, Belgium, 2018.
- [4] Federal Aviation Administration, *Concept of Operations for the Next Generation Air Transportation System*, Federal Aviation Administration, Washington, DC, USA, 2010.
- [5] J. Alipio, P. Castro, H. Kaing et al., "Dynamic airspace super sectors (DASS) as high-density highways in the sky for a new US air traffic management system," in *Proceedings of the IEEE Systems and Information Engineering Design Symposium*, pp. 57–66, Charlottesville, VA, USA, April 2003.
- [6] A. Yousefi, G. Donohue, and L. Sherry, "High-volume tube-shape sectors (HTS): a network of high capacity ribbons connecting congested city pairs," in *Proceedings of the 23rd Digital Avionics Systems Conference*, Salt Lake City, UT, USA, October 2004.
- [7] H. Hering, "Air traffic freeway system for Europe," Technical Report 20/05, Eurocontrol Experimental Centre, Cedex, France, 2005.
- [8] R. Hoffman and J. Prete, "Principles of airspace tube design for dynamic airspace configuration," in *Proceedings of the 8th AIAA-ATIO Conference*, p. 8939, Washington, DC, USA, September 2008.
- [9] G. Gupta, B. Sridhar, and A. Mukherjee, "Freeways in the sky: exploring tube airspace design through mixed integer programming," in *Proceedings of the INFORMS Annual Meeting*, p. 6824, Washington, DC, USA, February 2008.
- [10] A. D. Mundra and E. M. Simmons, "Self-separation corridors," in *Proceedings of the IEEE/AIAA 26th Digital Avionics Systems Conference*, Dallas, TX, USA, October 2007.
- [11] D. J. Wing, J. C. Smith, and M. G. Ballin, "Analysis of a dynamic multitrack airway concept for air traffic management," Technical Report NASA/TP-2008-215323, Langley Res. Center, Hampton, VA, USA, 2008.
- [12] B. Sridhar, S. Grabbe, K. Sheth, and K. Bilimoria, "Initial study of tube networks for flexible airspace utilization," in *Proceedings of the AIAA Guide, Navigation, Control Conference*, Portland, Oregon, August 2006.
- [13] M. Xue and P. H. Kopardekar, "High-capacity tube network design using the Hough transform," *Journal of Guidance, Control, and Dynamics*, vol. 32, no. 3, pp. 788–795, 2009.
- [14] A. Yousefi, A. N. Zadeh, and A. Tafazzoli, "Dynamic allocation and benefit assessment of NextGen flow corridors," *Transportation Research Part C*, vol. 33, pp. 297–310, 2013.
- [15] P. Kotecha and I. Hwang, "Optimization based tube network design for the next generation air transportation system (NextGen)," in *Proceedings of the AIAA Guide, Navigation, Control Conference*, p. 5860, Portland, Oregon, August 2009.
- [16] C. Han, X. Zhang, K. Cai, and Q. Pan, "Improvements of tube design for trunk routes in China," in *Proceedings of the 2011 IEEE International Conference on Vehicular Electronics and Safety*, Amsterdam, Netherlands, November 2011.
- [17] Y. Nakamura, N. Takeichi, and K. Fukuoka, "A self-separation algorithm using speed control for width-limited high density air corridor," in *Proceedings of the 29th International Council of Aeronautical Sciences*, pp. 1–10, Beijing, China, September 2014.
- [18] Y. Zhang, J. Shortle, and L. Sherry, "Methodology for collision risk assessment of an airspace flow corridor concept," *Reliability Engineering and System Safety*, vol. 142, pp. 444–455, 2015.
- [19] Y. Tian, Y. Dong, B. Ye, and L. Wan, "A framework for the assessment of distributed self-separation procedures for air traffic in flow corridors," *IEEE Access*, vol. 7, pp. 123544–123557, 2019.
- [20] C. S. Dorbian, P. J. Wolfe, and I. A. Waitz, "Estimating the climate and air quality benefits of aviation fuel and emissions

- reductions,” *Atmospheric Environment*, vol. 45, pp. 2750–2759, 2011.
- [21] B. Sridhar, N. Y. Chen, and H. K. Ng, “Aircraft trajectory design based on reducing the combined effects of carbon-dioxide, oxides of nitrogen and contrails,” in *Proceedings of the Modeling and Simulation Technologies Conference*, Kolkata, India, January 2014.
- [22] U. Schumann, “Formation, properties and climatic effects of contrails,” *Academie Des Sciences Comptes Rendus Physique*, vol. 6, pp. 549–565, 2005.
- [23] L. Luo, X. Wang, and P. Yu, “The compare and research of the calculate formula of the saturation water steam pressure,” *Meteorological, Hydrological and Marine Instruments*, vol. 4, pp. 24–27, 2003.
- [24] O. A. Alduchov and R. E. Eskridge, “Improved magnus form approximation of saturation vapor pressure,” *Journal of Applied Meteorology*, vol. 35, no. 4, pp. 60–609, 1996.
- [25] A. Valenzuela and R. Damián, “Optimization of aircraft cruise procedures using discrete trajectory patterns,” *Journal of Aircraft*, vol. 51, pp. 1632–1640, 2014.
- [26] L. He, K. Wang, G. Li, and H. Jin, “Elitist preserved genetic algorithm and its convergence analysis,” *Control and Decision*, vol. 15, pp. 63–66, 2000.
- [27] X. Wang, R. He, and X. Zhang, “Improvement of genetic algorithm with best elitist preserved method,” *Mini-Microsystems*, vol. 26, pp. 833–835, 2005.
- [28] Eurocontrol Experimental Centre, “User manual for the base of aircraft data (BADA) revision 3.8,” Technical Report no. 11/06, Eurocontrol Experimental Centre, Brétigny-sur-Orge, France, 2011.
- [29] Y. Tian, L. Wan, B. Ye, and D. Xing, “Cruise flight performance optimization for minimizing green direct operating cost,” *Sustainability*, vol. 11, p. 3899, 2019.